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Application of dynamic models during design of a hybrid diesel-fuelled PEMFC[1] system with fuel reformer

Peter de Vos MSc AMIMarEST1), Erik Versluijs BSc2) ,
Douwe Stapersma MSc, FIMarEST, CEng3), Isaac Barendregt MSc4)

1) Department of Marine Engineering, Delft University of Technology
Delft, The Netherlands
2) Delft University of Technology / Netherlands Defence Academy
Den Helder, The Netherlands
3) Department of Military Platform Systems, Netherlands Defence Academy
Den Helder, The Netherlands
4) Sea Systems Branch, Netherlands Defence Materiel Organisation
Den Haag, The Netherlands

Abstract

Design of a hybrid diesel-fuelled PEMFC system for application onboard naval ships is challenging for multiple reasons. The fact that new technologies are used is only one of them. Less obvious, but also very challenging is for instance choosing the ratio between installed battery capacity and fuel cell power. This ratio is a typical design issue for hybrid systems. Dynamic models are necessary to find an optimal solution to this issue. In this paper the developed dynamic models are discussed, some in more detail, after which simulation results will be shown.

Keywords

Fuel cells; Battery; Design issues of hybrid systems; Dynamic simulation.

Introduction

Increasing global awareness on climate change and fossil fuel dependency has put fuel cells (FC’s) on the map as potential prime movers of the future. This can be concluded from the numerous FC demonstration projects, in both the automotive as shipping industry. The Dutch navy, amongst other navies, have recognized fuel cells as silent alternatives for typical diesel-generator sets as well. Main advantages of naval ships equipped with FC's and fuel reformer are: (ref. (Barendregt, 2009) and (van Oosten, 2006))

- decreased noise and infrared signature,
- reduction of vulnerability,
- fuel flexibility,
- potential for higher system efficiency over the complete power range, and
- reduction of harmful emissions to the air.

For these reasons a hybrid Polymer Electrolyte Membrane Fuel Cell (PEMFC) system with fuel reformer is anticipated as possible power generation system on board naval ships. Such a system can be as small as a few kW’s for auxiliary power generation or as big as multiple MW’s for all required power in all electric ships, e.g. submarines.

The reformer and fuel cell system deliver electric power, which can be stored in the battery. The addition of the battery to the system makes it “hybrid”. The electric power stored in the battery can be utilized when more power is required by the ship than is delivered by the fuel cells. Using the battery in this way is called load leveling or peak shaving.

Application of the battery in this system is actually not optional, it is necessary. The dynamics of the reformer and to a lesser extent the fuel cell are too slow to follow rapid load changes. To deal with this phenomenon an energy storage device needs to be added to the system to provide or absorb extra power when strong power fluctuations occur. Hydrogen storage within the reformer could be considered but for safety reasons a battery pack is considered to be best suited as energy storage device onboard naval ships.

The advantage of using a battery is that it becomes possible, depending on the load profile, to install smaller power generation devices, i.e. reformer + PEMFC’s. This is possible because the battery can be used to temporarily supply power as well. Then the fuel reformer

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[1] PEMFC = Polymer Electrolyte Membrane Fuel Cell

and fuel cell system can be designed for average power instead of maximum power, which results in a smaller and thus cheaper power generation system. It could mean a smaller and cheaper total system too. This causes an extra degree of freedom arising in the system design: the ratio between installed battery capacity and installed power.

The ratio between the installed power source (reformer + fuel cell) and the nominal power required by the ship is called the hybridization degree (Pede, 2003). The size of components in the system can be adjusted in order to find the hybridization degree with the best fuel efficiency, which further depends on the load profile, the lay-out of the system and the control strategy.

The relation between the control strategy and the component sizing aspect should be recognized (Joong Kim, 2006). A change in hybridization degree may be expected when selecting a different control strategy. The same is true for the load profile and the dynamic behavior of the system. Change of load profile or system (dynamics) will result in a change of control strategy and the hybridization degree must be reconsidered too.

So the load profile and dynamics of the system in conjunction with the selection of a control strategy are the key factors when it comes to determining the hybridization degree and therefore a dynamic model is required to properly guide the designer, i.e. simulation driven design. The objective of this paper then is:

Describe the dynamic models that need to be utilized during system design to find the optimum ratio between battery capacity and installed power for typical load profiles.

Anticipating the results one could already suspect that decreasing the size of the power generation devices in a hybrid system in this way is only possible when the operational profile, or load profile, consists of significant, short-term peaks. When the load profile contains long periods of high requested power the fuel cell and reformer will still have to be designed to deliver this high power. Otherwise the required battery capacity will become too large to be practical.

Next to load leveling and PEMFC size reduction, storing energy in batteries has some extra advantages, in particular for naval ships. The ship can be operated in silent power mode for limited time, i.e. with no sound and emissions from the reformer system, by running completely on battery power. And finally the battery module offers UPS (Uninterrupted Power Supply) functionality: emergency power can be delivered to the ship at failure of fuel cell or reformer.

In this paper the dynamic model of the diesel-fuelled PEMFC system with reformer is described shortly first, after which the battery model is described in more detail. After that the tested load profiles, the electrical system lay-out and control of the complete system are discussed. Then simulation results will be shown. The paper concludes with a discussion of the different optimization aspects that can be researched by application of the dynamic models in early design: i.e. lowest system dimensions, lowest system costs, highest system efficiency for a mission.

Diesel-fuelled PEMFC system

To produce electricity, hydrogen has to be provided to the anode side and oxygen to the cathode side of a Polymer Electrolyte Membrane Fuel Cell (PEMFC). Onboard naval ships, NATO standard logistic fuel F76 diesel is used, which contains a lot of chemically bonded hydrogen. Thus F76 has to be converted onboard to “free” the hydrogen, so it can be used in a PEMFC. A steam reformer is used to crack the long hydrocarbons of F76 diesel and create a hydrogen rich gas mixture. In Figure 1 a simplified schematic overview of the reformer system and PEMFC is shown.

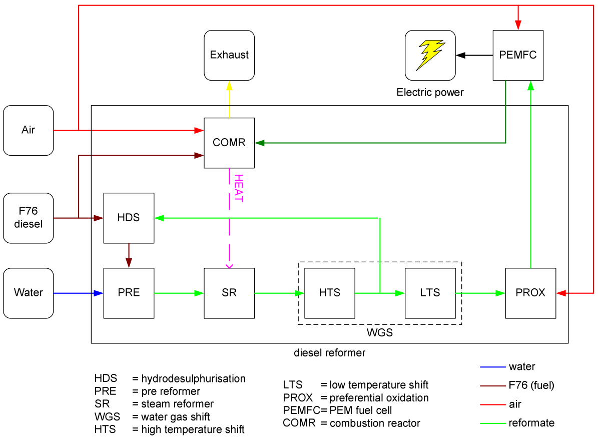

Figure 1: Simplified schematic overview of diesel-fuelled PEMFC system.

The reformer system consists of seven main reactors, of which the different functions are discussed in this section. Feed flows to the reformer system are air, F76 diesel and water. All feed flows are first brought to system conditions. F76 diesel and water are evaporated using the systems waste heat and an exhaust gas turbine pressurizes the air.

The first step in the steam reforming process is two-stage desulphurization of the F76 diesel. The first stage is the hydrodesulphurization reactor (HDS), which brings together the gaseous F76 fuel flow and hydrogen. A catalyst ensures the hydrogen bonds with the sulphur in F76 to form hydrogen sulfide (H_2S). This H_2S is removed from the gas flow in a zinc oxide bed in the second stage.

The next reactor in the system is the pre-reformer (PRE). In this reactor the long hydrocarbons of the desulphurised fuel are cracked into methane mainly. To make this possible steam is provided to the PRE. The resulting flow goes into the steam reformer (SR). In the SR most methane is split into hydrogen according to reaction (1). This reaction is highly endothermic: heat is therefore provided to the SR by the combustion reactor (COMR) to keep the desired temperature in the SR.

$$CH_4 + H_2O \rightleftarrows 3H_2 + CO \qquad (1)$$

More hydrogen is gained from the reformate flow coming from the SR by converting CO residues to CO_2 and hydrogen using the water gas shift reaction (2). Removing carbon monoxide (CO) from the reformate flow is also necessary to prevent CO-poisoning of the PEMFC.

$$CO + H_2O \rightleftarrows H_2 + CO_2 \qquad (2)$$

This water gas shift reaction takes place in the water gas shift reactors (WGS). Equilibrium of equation (2) is favored to the hydrogen side at lower temperatures, but the kinetic reaction rate is small at lower temperatures. Therefore equilibrium is first reached in the high temperature water gas shift reactor (HTS). The reformate gas is then cooled and a new equilibrium, containing more H_2 and less CO as before, is found in the low temperature shift reactor (LTS).

To protect the PEMFC anode catalyst from CO-poisoning the last bit of carbon monoxide has to be removed from the fuel. This is done using air in the preferential oxidation reactor (PROX) according to the reaction shown in (3).

$$2CO + O_2 \rightleftarrows 2CO_2 \qquad (3)$$

The reformate leaving the PROX contains mostly hydrogen, excess water (steam), some carbon dioxide and small traces of methane and carbon monoxide. This hydrogen-rich gas mixture flows to the anode side of the PEMFC. Pressurized air is provided to the cathode side of the PEMFC. The overall reaction taking place in the PEMFC is (4);

$$O_2 + 2H_2 \rightleftarrows 2H_2O \qquad (4)$$

At the anode side of the PEMFC hydrogen is split into protons and electrons. The electrons are transferred to the cathode side through an external circuit thus delivering electric power. The protons are transferred to the cathode side through the fuel cell's polymer electrolyte.

The residual flows leaving the PEMFC are combusted in the COMR, together with air and F76 Diesel, to provide heat for the SR. Exhaust gas from the COMR is used for heating the reformate and feed water flows and for driving an exhaust gas turbine, after which it is emitted to the environment.

The complete reformer + fuel cell system has been modeled in Matlab® and Simulink® using the "Volume Thermodynamics" method (van Oosten, 2006).

Battery model

To get better insight in battery behavior in cooperation with the reformer and fuel cell system a model of a battery was created. The battery model represents the characteristics of a Li-ion battery cell, of which the advantages compared to lead acid and NiMH cells are; higher energy density, no memory effect, high charge/discharge efficiency, fast charging possible, low self discharge, low maintenance characteristics and no problems with deep discharge. Higher purchasing cost is the biggest disadvantage of Li-ion technology, but in the past decade this technology has been developing rapidly, resulting in decreased cost and intrinsically safe Li-ion batteries. Due to the many advantages and positive developments in the past decade the choice is made to concentrate on Li-ion technology for energy storage in this project, but given the right manufacturer data the battery model can also be applied for other battery technologies.

The characteristics used to create this model are shown in Figure 2; these characteristics were obtained from a marine electric services supplier. The different lines represent the cell voltage when discharged at constant current. In the legend the number represents the discharge current compared to the current at which the battery is completely discharged in one hour, the latter usually designated 1C in the battery community.

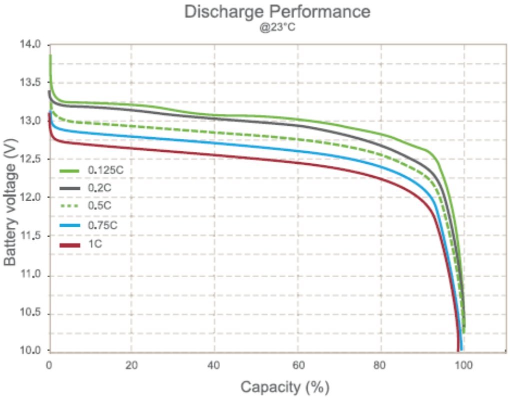

Figure 2: Battery characteristic.

A battery is a voltage source with some specific properties (van der Nat, 1998):

- Total energy that can be obtained from a battery (i.e. capacity) depends on discharge current.
- The open cell voltage of the battery cell depends on battery (dis)charge state.
- The actual cell voltage depends on the current and (dis)charge state.
- A polarization effect occurs from discharge to charge conditions and causes voltage shift.

These battery characteristics are modeled using the modeling theory of (Stapersma, 2000) and summarized in (van der Nat, 1999). Data of Li-ion batteries is fitted to create the model. The model is made suitable for discharge and charge operation.

The battery capacity is dependent on discharge current i.e. when discharged at high current less energy is available compared to discharge at lower current. To model this properly a distinction is made between the real discharge state (x) and a pseudo discharge state (y). The real discharge state (x), see eq. (5), is a ratio between the capacity that left the cell (Q) and the maximum battery capacity (C_∞) in [Ah] available when it is discharged at almost zero current. A discharge state of x = 0 means the battery is fully charged, x = 1 holds for an empty battery.

$$x = \frac{Q}{C_\infty} \; [\text{-}] \qquad (5)$$

In other literature the state of charge (SoC) if often used to designate the state of the battery. The relation between the SoC and the discharge state (x) is:

$$x = 1 - SoC \; [\text{-}] \qquad (6)$$

The pseudo discharge state (y), see eq. (7), is defined as the ratio between the capacity that left the cell (Q) and the total capacity available at the instantaneous current (C_t (I)).

$$y = \frac{Q}{C_t(I)} \text{ [-]} \tag{7}$$

The pseudo discharge state will differ more from the real discharge state at higher discharge currents. When the pseudo discharge state reaches a value of one this means the battery is empty for the instantaneous current, but could still produce energy at lower current.

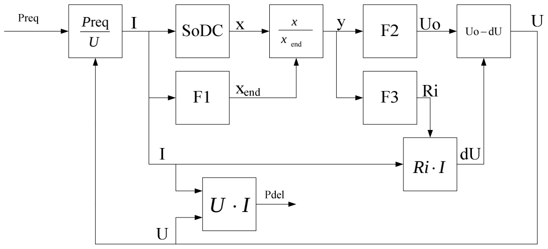

Figure 3: Battery model.

In Figure 3 the general layout of the battery model is shown. In the battery model the discharge state is monitored and the pseudo discharge state is determined using the delivered current. From the pseudo discharge state the open cell voltage (Uo) is determined and the actual cell voltage (U) of the battery is calculated. The voltage drop has the size of the internal resistance (Ri) multiplied with the current (I).

Input of the battery model is the power requested from the battery (P_{req}), which is positive for discharging and negative for charging the battery. This power is divided by the cell voltage (U) from the last simulation step to find the cell current (I). The state of charge of the battery has to be known, so the cell current is integrated according to eq. (8) in the SoDC (state of discharge) block of Figure 3. This results in the discharge state (x).

$$x(t) = x_0 + \int_0^t \frac{I}{C_\infty} \cdot dt \tag{8}$$

The cell current is also used to determine the actual cell capacity (C_t (I)) which gives x_{end} in the F1 function block, see eq. (9).

$$\frac{x}{y} = \frac{C_t(I)}{C_\infty} = x_{end} \tag{9}$$

The combination of x divided by x_{end} gives the pseudo discharge state (y). In function blocks F2 and F3 the open cell voltage (Uo) and internal resistance (Ri) are determined from the pseudo discharge state. In combination with the current these give the actual cell voltage U, see eq. (10):

$$U(y, I) = Uo(y) - I \cdot Ri(y) \tag{10}$$

All function blocks (F1, F2, and F3) contain fit functions, which are set during initialization of the model to obtain the right characteristic. The three fit functions are different for charging and discharging. The product between the actual cell voltage and current then gives the power that is delivered by or fed into the battery.

The battery model has been programmed in Matlab® & Simulink®. The cell voltage during discharging according to the model is shown in Figure 4. This figure can be compared to Figure 2.

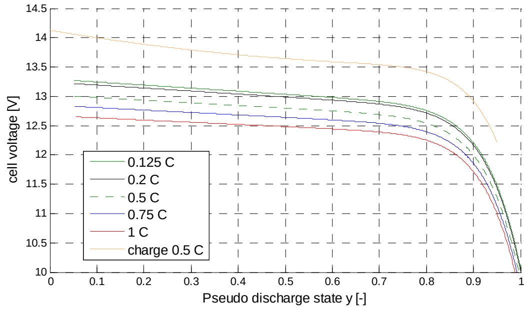

Figure 4: Cell voltage from battery model.

Hybrid diesel-fuelled PEMFC system model

Combining the reformer, fuel cell and battery model results in a model in which the complete hybrid diesel-fuelled PEMFC system can be simulated. Typical load profiles serve as input for this model.

Load profiles

During this project two different load profiles are used. The first is based on electrical load measurements onboard an air defense frigate of the Dutch navy. The load profile was scaled to the nominal reformer + PEMFC size of 2.5 MW. The resulting load profile, which actually sometimes exceeds 2.5 MW, is shown in Figure 5. Exceeding 2.5 MW is possible due to the presence of the battery in the system, which can level the short-term power peaks. This load profile is used to investigate the possibility of application of the hybrid diesel-fuelled PEMFC system for electric power generation onboard naval ships (i.e. excluding propulsion power).

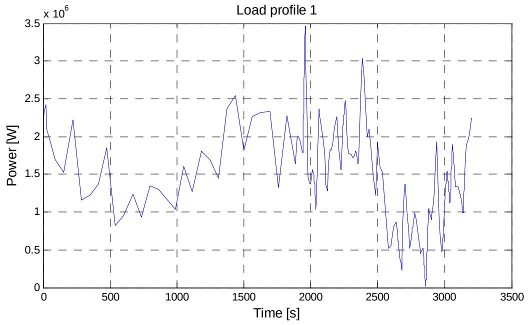

Figure 5: Load profile 1 (electric load of naval ship).

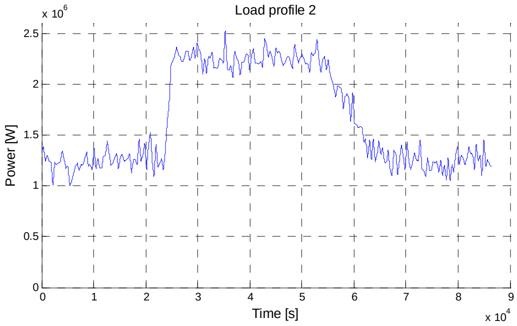

Figure 6: Load profile 2 (all electric ship).

The second load profile represents the load profile of an all electric ship (AES). In an AES the main part of the electric power is required for propulsion, meaning high power is required for longer periods of time (no short-term peaks). This load profile is also scaled to a nominal power of 2.5 MW, which is not exceeded in this case. The resulting load profile is shown in Figure 6.

Electrical system lay-out

Converters are needed between the components in order to assure system operation, safety and reliability. Since each converter has an efficiency of slightly less than unity and the amount of power that flows through each converter depends on the load profile and control strategy, the way in which the different components are connected has an influence on the total system efficiency as well. A system lay-out as shown in Figure 7 is assumed to be the most efficient for both load profiles as a relatively large part of the total energy flow from the PEMFC will directly go to the grid. If the load profile or control strategy dictates otherwise however, this solution will not be the most efficient. The various submodels (battery, reformer + PEMFC) are connected accordingly in the complete model.

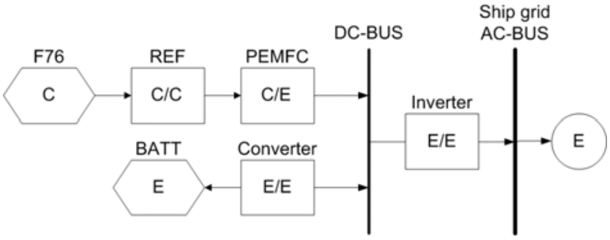

Figure 7: Energy Flow Diagram of system configuration.

Control strategy

The control strategy also plays an important role in the total system efficiency. The control system determines, amongst others, how the required power is divided over the fuel cell and battery. It also keeps the battery discharge state within set limits. In this paragraph the (basic) control strategies implemented in this project are presented.

The first load profile is controlled through a constant load mode. The reformer dynamics are not fast enough to follow the rapid power changes of the first load profile, therefore the constant load mode is used. The fuel cell delivers a certain constant power and the battery provides or absorbs the rest power, which equals the power the fuel cell is deviating from the load profile.

To keep the battery state within desired values the control diagram shown in Figure 8 is used. The control input is the battery pseudo discharge state (y) and the output is the FC_Load, determined in equation (11).

$$FC\,load = \frac{Fuel\,cell\,power}{Nominal\ fuel\,cell\,power} \tag{11}$$

When the battery pseudo discharge state (y) becomes more than 0.75, i.e. when there is only 25% capacity at instantaneous current left in the battery, the fuel cell power is increased to nominal power. When y becomes less than 0.55 the fuel cell goes back to “average” power. If the battery is almost completely charged (y<0.25) the fuel cell power is decreased to 30% of nominal power until y exceeds 0.45 again.

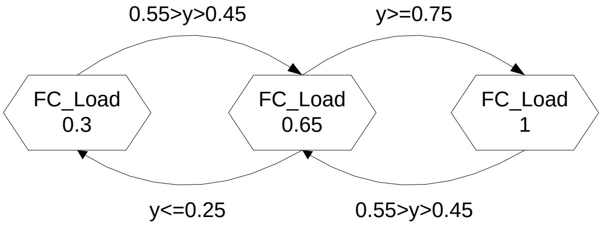

Figure 8: Battery state control diagram.

The second load profile is operated in load following mode. The reformer and fuel cell try to deliver the required power straight to the grid. The battery is only discharged when the dynamics of the reformer are too slow to follow the changing load. The battery is charged when the reformer plus fuel cell deliver a surplus of power. The battery discharge state is controlled using the same strategy as described above.

A small difference is found in the values of y which cause extra power to be delivered to or from the battery, i.e. y>0.8 results in charging the battery and y<0.2 reduces the power delivered by the fuel cell. These different values of y are a result of load following mode for load profile 2 vs. constant load mode for load profile 1. In load profile 2 if the battery has to be charged, 85 kW is added to the requested power from the fuel cell. This 85 kW is chosen because of the desired battery charge rate of 0.5C, i.e. 70 A. If y<0.2 the fuel cell power is decreased by 85 kW. This control strategy for load profile 2 results in a much smaller power step for the fuel cell + reformer when compared to load profile 1, where the requested power changes 0.35*2500=800 kW. This larger power change needs more settling time and therefore fuel cell power is adapted at y=0.75 instead of y=0.8.

The control strategy presented here is fairly basic and there is room for improvement. For instance, when the ship now requires low power for a large period of time (like in port) and the control system still “tells” the PEMFC to deliver 30% of nominal power, it is possible the battery will soon be fully charged after which delivered power is wasted. Also when required power keeps hovering around one of the set values for the battery state the control system will keep switching between different modes. A more sophisticated control system is possible when more variables are used and techniques like fuzzy logic control or neural networks are applied.

Simulation procedure

Simulations are performed using the load profiles and control strategies described above. By analyzing a load profile, while keeping the dynamic limits of the reformer + PEMFC system in mind, a first estimation can be made to determine the minimal battery capacity, depending on system lay-out and control strategy. Simulations of the dynamic model can be used to determine whether the battery capacity fits the load profile and to adapt the battery capacity if necessary. This procedure has been followed for the two load profiles above as well.

Simulation results

During simulations of the first load profile the fuel cell delivers constant power, as shown in Figure 9. In this figure the load profile, the required power from the fuel cell and the power delivered by the fuel cell are shown. The deviation between the total required power and the power delivered by the fuel cell is delivered or absorbed by the battery, see Figure 10. The real battery discharge state (x) and pseudo battery discharge state (y) are shown in Figure 11. The efficiency of the fuel cell, of the reformer and of the total system is shown in Figure 12.

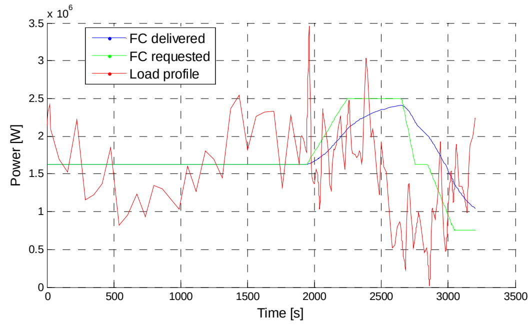

Figure 9: Load profile 1 and fuel cell power.

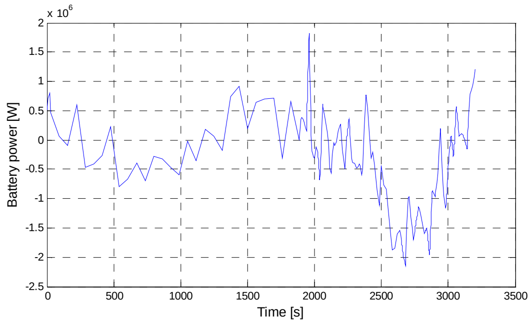

Figure 10: Battery power, load profile 1.

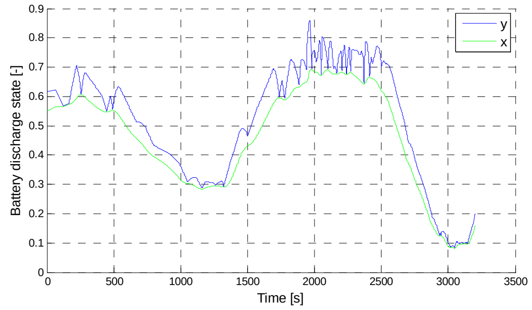

Figure 11: Battery discharge states, load profile 1.

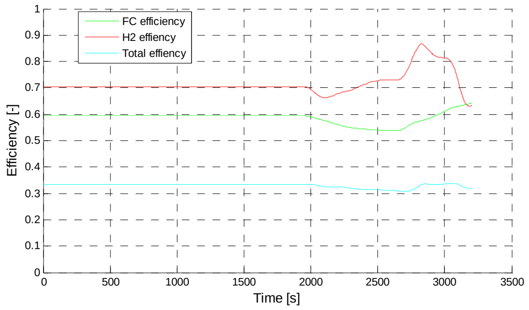

Figure 12: Efficiencies, load profile 1.

The combination of fuel cell and battery are able to deliver the requested load. A battery capacity of 19872 Ah (at 0.2C) seems to be sufficient to deal with the required load profile. The fuel cell power is increased once and decreased later when the battery pseudo discharge state passes the control limits. The total efficiency of the power source stays above 0.3.

Results of simulation with the second load profile, using the load following control strategy, are shown in Figure 13 to Figure 17. The installed battery capacity now is 13248 Ah (at 0.2C). In combination with the reformer and fuel cell this is enough to deliver the required power. In the battery power chart, Figure 14, two pulses can be recognized: one to charge the battery when y>0.8 and one to discharge the battery when y<0.2. The effect of these pulses on the battery discharge state can clearly be seen in Figure 15. The efficiencies are quite constant during the simulation, Figure 16.

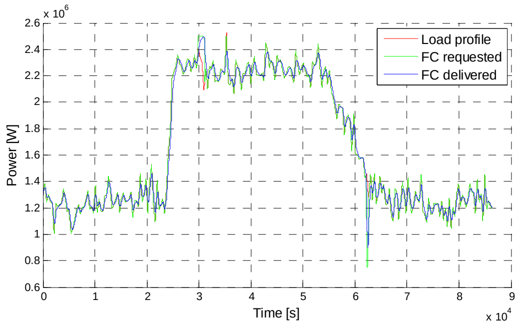

Figure 13: Load profile 2 and fuel cell power.

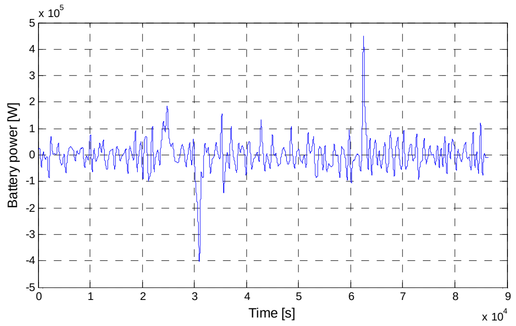

Figure 14: Battery power, load profile 2.

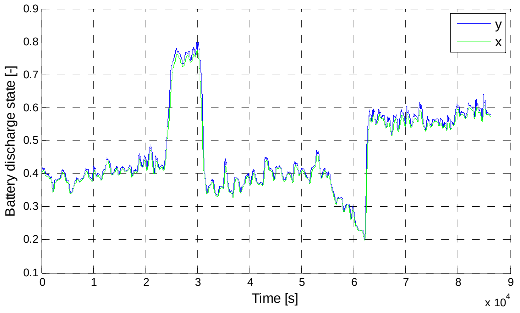

Figure 15: Battery discharge states, load profile 2.

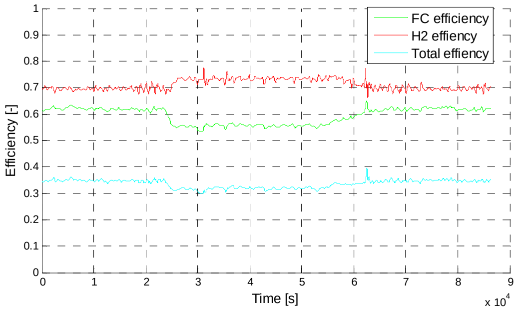

Figure 16: Efficiencies, load profile 2.

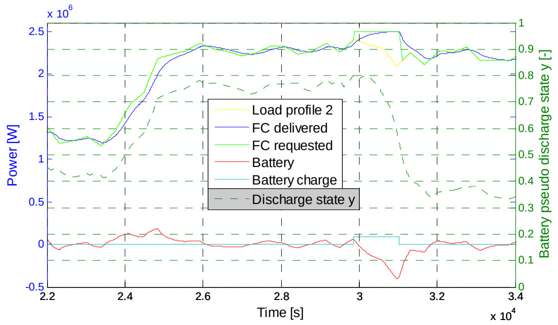

Figure 17: Load profile 2 overview, zoomed in at time interval [2.2e4 3.4e4].

In Figure 17 an overview of the requested and delivered powers and battery pseudo discharge state is shown at time interval [2.2e4 3.4e4] s. From this figure a more detailed analysis of the simulation results can be made.

During normal operation the requested power from the fuel cell + reformer equals the required power according to the load profile. At time interval [2.35e4 2.6e4] s. a delay between the requested power from the FC and actually delivered power by the FC can clearly be recognized. This delay is caused by the slow dynamics of the reformer and FC which cannot follow the steep power increase. The difference between the required power and the FC's delivered power is delivered by the battery, leading to fast discharging, which can be seen from the fast increasing battery pseudo discharge state (dashed line).

Another such delay can be recognized at t=29800 s. At that moment the power requested from the fuel cell starts to deviate from the load profile as the charge power signal is added to the load profile. The delay is shown as it takes some time for the FC to actually deliver the requested power. At t=30000 s. the delivered power by the FC starts to exceed the required power of the ship and the battery starts charging, causing the sharp decrease of the battery's pseudo discharge state. When the discharge state reaches 0.55 the charge pulse ends and the power requested from the FC equals the load profile again. This charge pulse can also be seen from the battery charge signal, which is zero most of the time, except for the charge peak between t=29800 and t=31000 s.

Conclusions

From both simulations it can be concluded that the chosen battery sizes (and hybridization degrees) are adequate for the assumed load profiles in conjunction with the adopted control strategies.

The effects of changing the battery capacity or other design parameters can be investigated with the presented models. For instance, the models can be used by the system designer to find the smallest possible dimensions of an F76 reformer + PEMFC and battery for a given load profile. This would result in a certain hybridization degree, but this is not necessarily the cheapest system. The latter depends on the purchasing costs of the different components and the models can also be used to find the economic optimum for an expected load profile. Yet another application of the models is finding the system with the best efficiency for a given mission, resulting in minimization of the operational costs.

All these different design strategies and interaction between key parameters can be investigated with the overall model of the hybrid diesel-fuelled PEMFC system. This model must be a dynamic model since the system contains both power generation and energy storage components (sharing the responsibility of delivering the required power at any time) and power and energy are related by time integration. As a matter of fact the authors hold the opinion that a model of any hybrid system needs to be dynamic, as the designer of a hybrid system needs to be able to calculate the amount of energy still available from the energy storage device at any time using an equation like equation (8), clearly showing time integration and therefore dynamics. As such this is an example of a trend towards using simulation tools in designing complex installations: simulation driven design.

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