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Control strategy of Fuel cell-Battery hybrid system for optimizing Lift truck load cycle

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Abstract— **Material handle vehicles are irreplaceable and widely used in industry. In indoor operations and other conditions which have strict requirements, lift trucks, powered by lead acid batteries, dominates. The weaknesses of battery modules are a short working time and a long charging time which result in cost increase. The solution is the high efficiency, zero emission energy produced with fuel cell. In this article, an analyses and optimization of the Fuel Cell – Battery hybrid system were provided. For the specific application an optimal battery capacity and fuel cell stack power were determined. An optimum energy strategy has been defined for different operation cycles and working conditions. A numerical model of specific forklift powered by Fuel Cell – Battery hybrid system has been made and validate with available experimental data. Simulations have been made according to standard for different operating cycles and validated with an experimental data. Optimal battery size of 10 Ah and Fuel cell power of 11 kW is determined for 3-tonne forklift working according to VDI 60 load profile.**

Keywords— *Hybrid lift truck; PEMFC-battery power pack; Load cycle simulation; Control strategy*

I. INTRODUCTION

The fuel cell hybrid energy systems (FCHV) have the biggest potential for final step in the transition of the industrial, earth moving, loading and for sure transportation sectors to the environmentally friendly power train especially in heavier vehicles such as trucks and lift truck [1]. An energy distribution comparison is carried out between fuel cell electric vehicle and fuel cell hybrid electric vehicle, FCHEV has more preferable results than FCEV, for this study's parameters [2]. In commercial fuel cell power module the novelty in the energy storage technology is using metal hydride (MH) H_2 storage tank. The major problem for fuel cell commercialization is durability. 5000h is a minimum life of the fuel cell power pack to be competitive with classic IC-power train [3]. The main aging-accelerator is the load dynamics [4]. The fuel cell lifetime can be increased by controlling the load dynamics. The future of fuel cell electric vehicle (FCEV) depends on its cost and performance competitiveness in the automobile market. The sensitivity analysis suggests that hydrogen price and fuel cell system cost are the major uncertainties that determine cost competitiveness of FCEVs [5].

Many researches deal with the strategy to control the power and load of FC-Battery hybrid systems for automotive applications. For optimal power management strategy several techniques are used such as convex optimization and dynamic programming [6].

This article deals with the use of Proton-Exchange Membrane Fuel Cells (PEMFC)-Battery hybrid power pack configurations for a lift truck application. The investigation of PEMFC-Battery hybrid is performed with load profile for lift truck according to the VDI 60 standard. Based on operation states, an optimal energy management strategy is proposed. The strategy determines the operating point of each component of the system to maximize the system efficiency and propose technique to optimized system based on criteria and parameters such as: the hydrogen consumption, the overall efficiency, the state of charge and the stability of DC bus voltage.

The main objective of this article is determination of the optimum energy strategy for different operation cycles and working conditions

The main research outcome of the herein presented study is a novel control strategy to optimize PEM FC-Battery hybrid system in real conditions.

II. DESCRIPTION OF THE FUEL CELL BATTERY POWERED LIFT TRUCK

The system was built around STILL RX60-30L 3-tonne electric forklift and then converted to fuel cell-battery power pack with metal hydride storage extension tank [7]. In material handling equipment, PEMFCs are better alternative than lead-acid batteries, primarily because time for the replacement is not needed and PEMFC can always provide full power to the truck during entire shift, even in low ambient temperature such as – 30 °C. Also, battery degradation is avoided and other losses such as 14% of lift truck speed over the last half of the battery charge. With PEMFC the lift truck operates always at peak speeds, independent of how much fuel is left in the tank. For the subject research a lift truck is equipped with a lead acid battery 80 VDC, with a capacity of 25 Ah and with PEMFC power module 80 VDC manufactured by GenDrive. The metal hydride hydrogen storage extension tank CGH2 MH (P= 350 bar) is installed as well [7].

The power for the PEM fuel cell – battery power pack model for lift truck is controlled with DC/DC bidirectional converter. It operates on different voltage level and controls the process of charging and discharging of the battery. The battery is coupled to the DC bus directly and PEM fuel cell is connected to the bus with a unidirectional DC/DC converter. In that way, the Fuel cell output power is controlled.

The presented lift truck power pack system uses the same DC bus voltage as the battery voltage, and direct bus voltage regulation is avoided. Due to several advantages this control

of Fuel cell-battery hybrid power pack is favourable for lift truck application.

In order to successfully implement hybrid functionalities of the forklift, the AVL – Cruise M program was used. The fuel cell model is based on analytical electro-chemical equations derived from the polarization curve of the cathode side of the PEMFC. The approximate solution of the equations takes into account the oxygen and proton transport losses in the Catalyst layer, and the oxygen transport losses in the Gas diffusion layer for different temperature, relative humidity and gas pressure on the cathode side. The model can be utilized to evaluate the electrical properties such as voltage, power, power loss, the fuel cell efficiency and the gas properties such as total amount of consumed oxygen and hydrogen. In the fuel cell component, in addition to the fuel cell, a simple compressor model can be activated so that the power consumption of the compressor, which significantly influences the operating efficiency of the fuel cell system, can be taken into consideration. Number of cells in a stack is 75, Cathode gas properties is considered as 21 % Oxygen Initial conditions are: cathode inlet gas pressure is 2 bar and relative conditions are 70%. Fuel cell properties are shown in Table 1.

Table 1. Fuel cell properties

Cell area	370 cm^2
Catalyst layer proton conductivity	3 A/Vm
Open circuit voltage	1.23 V
Catalyst layer thickness	0.01 mm
Gas diffusion layer	0.2 mm
Maximum current	1000 A

The battery model is based on an equivalent electrical circuit, and it can predict the voltage response to a current at a particular state of charge (SOC) and temperature. The basic model consists of a controlled voltage source and an Ohmic resistance used to describe the instantaneous voltage response to a current input. In an advanced model, one or more RC networks could be added to the electrical circuit to predict the transient voltage response to a dynamic current load.

The battery voltage depends on the battery state of charge. During the discharge of the battery there is a drop of individual cells as well as entire battery. Therefore, it's necessary to determine the limits of the battery, state of charge, not only due to the voltage drop but also to extend the battery life. The rated battery capacity is 25 Ah.

The battery state of charge indicates the remaining battery capacity relative to the rated capacity. State of charge is an important parameter in battery management. It precision adjustment is demanding and necessary to maintain an acceptable life span and safe use of the battery. Heavy-duty test of the forklift was performed according to the standard VDI 60/VDI 2198 for lift trucks. The standard defined time 1 min per 1 hour, requested for operations: driving, lifting for the distance, L =30 m, between lifting/dropping points.

III. RESULTS AND DISCUSSION

Before starting the simulation, it is necessary to determine the driving conditions under which the vehicle will be exposed, and according to that conditions, choose the appropriate driving cycle. VDI 60 driving cycles describe the actual loads that might occur during driving.

First simulation was made with following parameters: number of fuel cell's in a stack is 75, cell area 370 cm^2, battery voltage 75 V, rated battery capacity is 25 Ah, and the default current 125 A With this current value fuel cell power is maintained on 11 kW. A conclusion after this simulation was that SOC of battery is remaining at a reasonable level. The fuel cell start powering the battery, when the state of charge is 50 % and the fuel cell stops when the state of charge is 82 % (Figure 1.). During the entire operation, the output current of the fuel cell is stable, and the output power of the fuel cell gradually follows the load power request, preventing the impact of load abrupt changes on the fuel cell. The battery is charged and discharged according to the power of the load. Reacted hydrogen mass flow is between 0.13 g/s and 0.15 g/s. Calculating it back to "normal" conditions the amount would be between 10 Nl/min and 15 Nl/min per 1 kW. The reacted hydrogen mass is 0.45 kg.
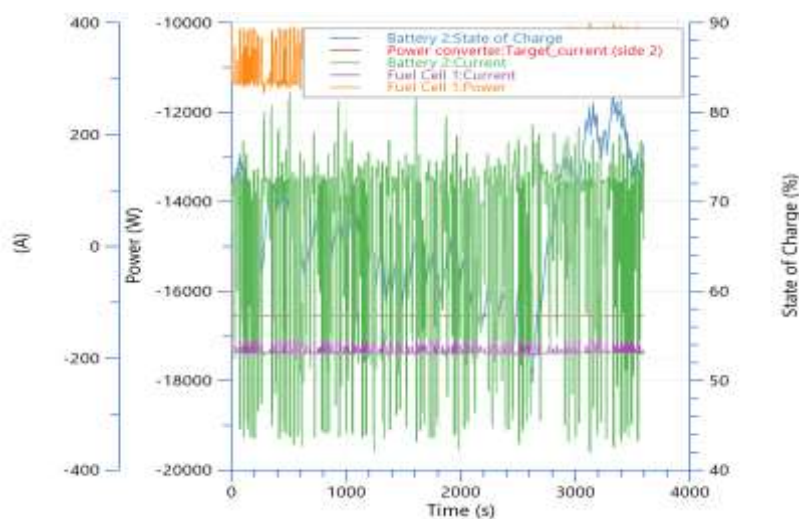

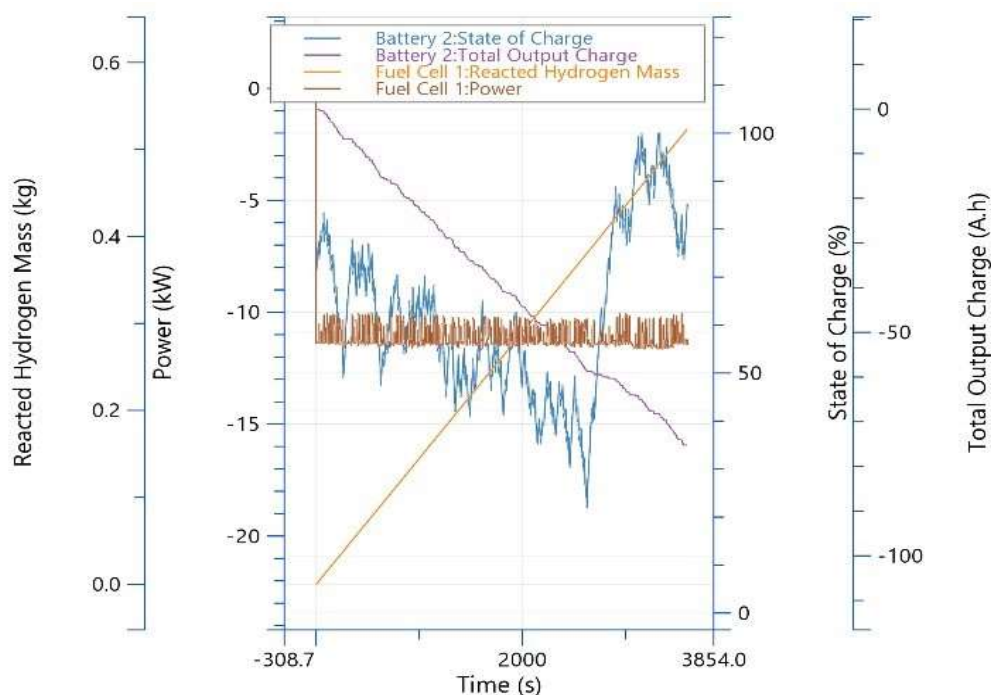Figure 1. Battery capacity 25Ah, fuel cell power 11kW, FC_75cells_370cm2; Bat:75V; Current - 125A

Figure 2. Battery capacity 10 Ah, fuel cell power 11 kW, FC_75cells_370 cm^2; Bat:75 V; Current – 125 A

For next simulation same data are used, except battery capacity. On figure 2. is shown performances for smaller battery (10 Ah). It can be seen that the fuel cell output power remains unchanged (11 kW), but the battery SOC is changed. When the state of charge is on 20 % the battery changes from the discharging state to the charging state until it is fully charged. According to that reacted hydrogen mass increased, and the value is 0.51 kg. Reacted hydrogen mass flow is between 0.135 g/s and 0.155 g/s.

During research several simulations with different current, power and load are used to demonstrate the behaviour difference.

The most important results of simulations are shown in table 2. where the optimum parameters for observed model are presented.

Table 2. Fuel cell properties of Power pack module: Fuel Cell 75 cells; 370 cm^2-Bat:75 V; Current -125 A, Battery capacity 10 Ah

	Optimal parameters
Fuel cell power kW	11
BPe kW	-25,-13
SOC %	25-100
Total output charge Ah	72 (3600)
Reacted Hydrogen Mass kg	0.52
Reacted Hydrogen mass Flow g/s	0.132-0.15
Total Output Energy MJ	22

IV. CONCLUSION

The performance of fuel cell – battery power pack for the forklift hybrid system was investigated. Model is designed in AVL Cruise M software package where VDI60 load profile was implemented. For this case study, an efficient optimal energy management strategy is proposed and elaborated. The technique to optimized PEMFC-Battery system is proposed, based on criteria which are the hydrogen consumption, the overall efficiency, the state of charge and the stability of DC bus voltage. The optimum size of fuel cell stack and battery were determined for the specific application. Optimal battery size for subject application is 10 Ah and Fuel cell power 11 kW. This energy management strategy determines the operating point of each component of the system in order to maximize the system efficiency for different operation cycles and working conditions. Proposed novel control strategy will be used to optimize PEM FC-Battery hybrid system in real environment/conditions which will be the future direction of this study.

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