33rd Electric Vehicle Symposium (EVS33)
Portland, Oregon, June 14 - 17, 2020

Simulation and energy management of a fuel cell hybrid heavy-duty truck

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Summary

This paper describes the modelling, simulation and energy management of a fuel cell hybrid heavy-duty truck. For this purpose, a longitudinal dynamic model of a 26t truck was set up and the load requirement for the drive train was determined based on a driving cycle. To meet this load requirement as efficiently and dynamically as possible three different energy management strategies were implemented, tested and the impact on the overall system was analysed. In addition, the behaviour of the hybrid system with the various energy management strategies with different battery capacity is shown and analysed.

Keywords: heavy-duty, fuel cell vehicle, power management, efficiency, simulation

1 Introduction

Climate change and the resulting legal requirements make it necessary to advance and implement the electrification of the truck sector. Heavy-duty-vehicles generate around a quarter of CO_2 emissions in road traffic in the EU [1]. Thus, the Heavy-duty-vehicles sector has a relevant global warming potential. Due to the low gravimetric energy density of batteries and long charging times, battery electrical powered trucks are not an alternative for fossil fuel powered trucks [2]. Fuel cell vehicles bring a significant environmental benefit for the commercial vehicle sector, especially when the hydrogen is generated using renewable energy sources. To exploit the environmental benefit, the efficiency of the hydrogen production process and the usage is currently must be increased [3, 4].

Because fuel cell systems (FC-system) are not very dynamic, hybridization using a battery or super capacitor is required. This enables the hybrid system to react quickly to load fluctuations, to call up a higher output and to reduce the consumption of hydrogen. Accordingly, it is important to carry only the maximum amount of energy required in the heavy-duty-vehicles and thus to efficiently distribute the vehicle's power requirement to the energy storage/converter using an intelligent energy management system. This creates a field of tension between ranges of heavy trucks, space requirement of the FC-system and battery, payload and comfort.

Past research activities have already discussed various energy management strategies (EMS) in a wide variety of applications [5–12]. S. Njoya Motapon [10] in particular compared different EMS (fuzzy logic, PI-controller, state machine, cost-function-based optimization strategy). As a use case, he used a fuel cell hybrid emergency power system of a more-electric aircraft. Qi Li [11] described the use of energy management based on fuzzy logic in hybrid vehicles. Pablo Garcia [12] uses a state machine to implement the energy management of an fuel cell hybrid tramway.

This paper takes up the knowledge gained in the previous research activities and transfers it to the energy management of a heavy-duty truck. Three different EMS are compared: PI-controller, state machine control strategy and rule based fuzzy logic strategy. Moreover, the dimensioning of the energy storage is discussed.

2 Description of the heavy-duty truck and wiring topology

The heavy-duty truck regarded here is a Mercedes-Benz Actros, which is being converted from an internal combustion engine to a hybrid fuel cell drive train. The truck is emblematic of the 26t class. The hybrid drive train contains a fuel cell as well as the associated hydrogen pressure tanks and a modular battery storage. The selected hybrid system topology corresponds to that shown in Figure 1. The energy for the drive system is provided by a fuel cell, connected at the DC level and a modular battery storage. The battery is directly connected to the converter. The fuel cell is connected over a DC/DC converter and can therefore operate in a different voltage level than the battery. The DC/DC converter serves as a corresponding compensation from one source to the other. The required drive power is provided by the fuel cell and the difference is loaded or taken into the battery. This principle is also referred to as "free power distribution". The advantage is the power dynamics that will be buffered by the battery as well as the comparatively simple design of the converter.

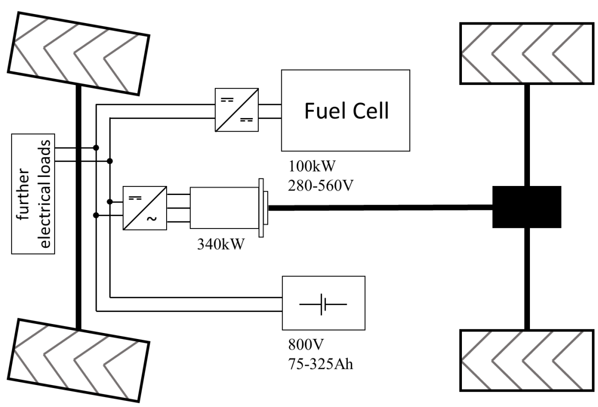

Figure 1: Vehicle topology

2.1 Vehicle model

By means of a longitudinal dynamics model, the required driving force, total power at the drive wheels and the energy requirement are determined. A modified Heavy Heavy-Duty Diesel Truck (HHDDT) cycle acts as the input variable for the model, which is described in more detail in Chapter 3.1. As shown in Figure 2, the forces acting on the vehicle while driving by transient conditions are primarily determined by the total mass of the vehicle, the speed, acceleration and the gradient of the road.

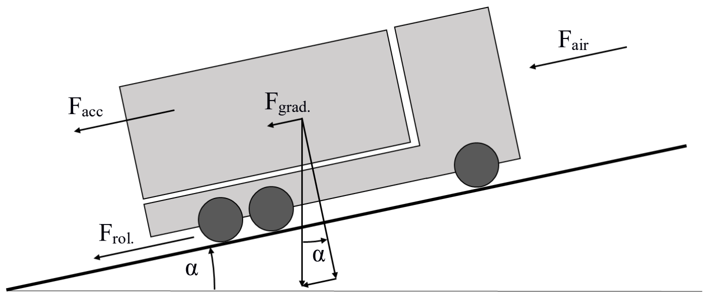

Figure 2: Resistance forces that affect a moving vehicle

The traction force $F_{tr.}$ required to move the truck results from the driving resistance acting during driving, which includes the acceleration ($F_{acc.}$), gradient (F_{grad}), roll ($F_{rol.}$) and aerodynamic (F_{air}) resistance.

$$F_{tr.} = F_{acc.} + F_{grad.} + F_{rol.} + F_{air} \tag{1}$$

2.1.1 Acceleration resistance

In order to accelerate a vehicle, the acceleration resistance ($F_{acc.}$) must be overcome. In addition to the translational acceleration of the vehicle, there is also an acceleration of the rotary masses, such as the tires and the electric motor. This is taken into account by the rotational inertia factor e.

$$F_{acc.} = \left(e * m_{empty} + m_{payload}\right) * a \tag{2}$$

m_{empty} is the empty mass of the truck and $m_{payload}$ the payload.

2.1.2 Gradient resistance

The gradient resistance increase when driving uphill and decrease when driving downhill. It is generally zero in standard drive cycles.

$$F_{grad.} = m_{total} * g * \sin \alpha \tag{3}$$

g is the gravitational constant and α the pitch angle of the hillside.

2.1.3 Rolling resistance

The rolling resistance is caused on the friction between road and tires and the deformation work of the tires. It can be approximate as:

$$F_{rol.} = f_{rol.} * m_{total} * g * \cos \alpha \tag{4}$$

The rolling resistance is characterized by the rolling resistance coefficient $f_{rol.}$.

2.1.4 Aerodynamic resistance

If an open body, such as a vehicle, moves at a constant speed through a liquid or a gas, the aerodynamic resistance must be overcome to maintain its state of motion. It increases quadratically with the driving speed v_∞ and can be calculated as:

$$F_{air} = \frac{\rho_{air}}{2} * v_\infty^2 * c_w * A \tag{5}$$

The aerodynamic resistance is characterized by the drag coefficient c_w that quantify the drag of the truck and depends of the cross-sectional area A of the vehicle. ρ_{air} is the density of the air.

2.1.5 Required power

The power required $P_{req.}$ to maintain the current vehicle condition at the drive wheels of the vehicle results from the multiplication of the traction force $F_{tr.}$ and the current driving speed v_∞.

$$P_{req.} = F_{tr.} * v_\infty \tag{6}$$

The parameters used for the simulation of the heavy-duty truck can be found in Table 1.

Table 1: Vehicle parameter

Parameter	Value
Overall vehicle weight	10 – 26t
Auxiliary consumers	approx. 15kW
Front face	8m²
C_w	approx. 0.8
Rolling resistance	approx. 0.008
Rotational inertia factor	1.16
Powertrain efficiency	90%
maximum drive power	340kW
degree of recuperation	30%

2.2 Simulation of the hybrid power system

The heavy-duty truck is simulated in MathWorks® Simulink. A simplified form of the simulation model is shown in Figure 3.

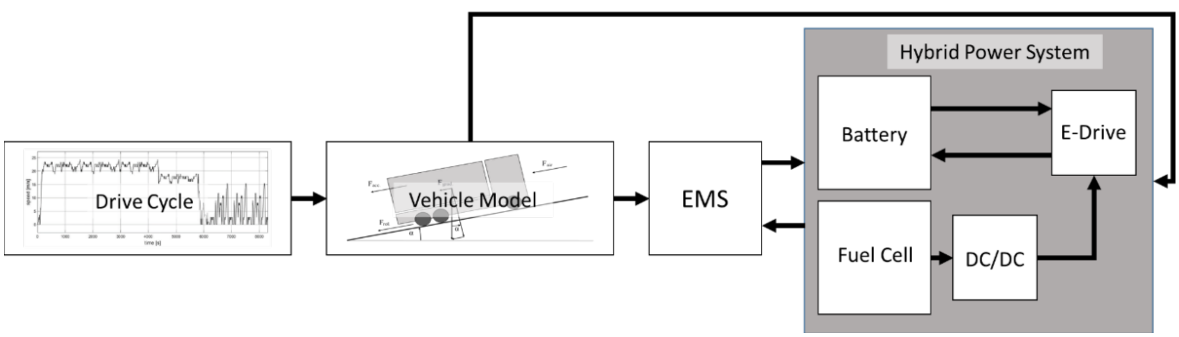

Figure 3: Interconnection topology of the simulation model

To simulate the hybrid power system standardized Simscape Blocks are used. In particular, the fuel cell and battery model are based on the papers of S. Njoya Motapon [13] and Olivier Tremblay [14]. The DC/DC convertor is based on a power-controlled conversion of the voltages. [22] The voltage V_{FC} and current I_{FC} of the fuel cell are multiplied in order to obtain the power. After deducting the efficiency η_{DCDC}, this power is divided by the current battery or DC link voltage V_{DC}, whereby the current I_{DC} is calculated.

$$\left. \frac{V_{FC} * I_{FC}}{\eta_{DCDC}} \middle/ V_{DC} \right. = I_{DC} \tag{7}$$

The sub-models are configured using technical data (Table 2). A FC-system is used with a peek power of 100kW and a modular Li-Ion battery storage with 40 to 325Ah.

Table 2: Hybrid system parameter

Parameter	Value	Parameter	Value
Efficiency e-machine	95%	Operation temperature	60°C
Efficiency fuel cell	57%	Nominal battery voltage	800V
Efficiency DC/DC	97%	Battery capacity	40 - 325Ah
Fuel cell power	11 - 100kW	Start SOC	80%

3 Load demand and energy management

A crucial part for the hybrid system is the distribution of the power loads among the energy sources. Therefore, the EMS is required. The main criteria for a EMS is steady state of charge (SOC) of the battery combined with an increasing system efficiency, improvement of the dynamic and power density of this hybrid system.

3.1 Driving cycle

The following investigations and statements are based on a 400km drive cycle (Figure 4). This cycle was assembled from parts of the standardized HHDDT Cruse Mode cycle and represent a typical user case. The HHDDT therefore is developed at the West Virginia University in cooperation with the California Air Resources Board for Chassis dynamometer test development. The cycle simulates a constant driving at max. speed on the highway as well as the way off the highway where stop and go traffic are common. To reach the 400 km distance the cycle will be repeated 3.1 times.

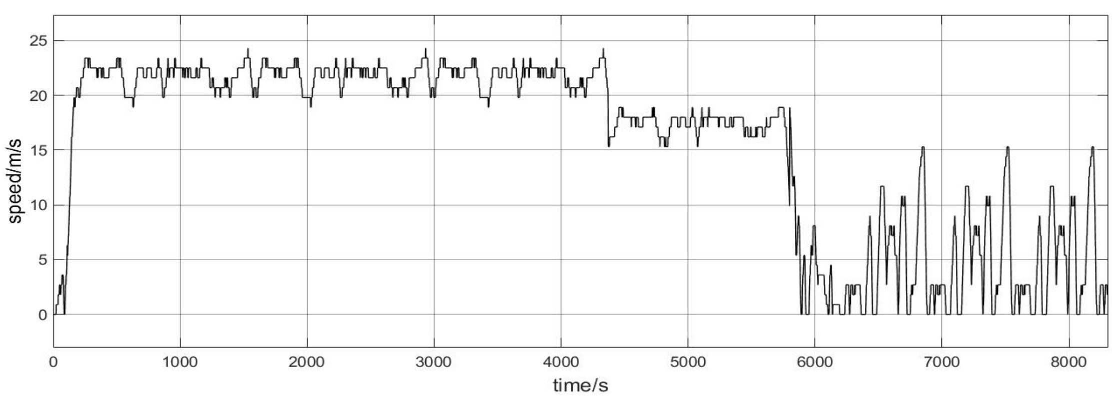

Figure 4: Drive Cycle 120km

3.2 Load and energy demand

First it is necessary to know the load demand for different drive cycles and payload of the truck. Therefore the longitudinal dynamic modell is used to calculate the energy demand (Table 3) for the acceleration, further electrical loads such as air conditioning, steering, heating need to be added. This is used to calculate the energy base load, which is required to ensure a constant SOC. The baseload is the minimum required FC-system power. In addition, a histogram (Figure 5) is used to determine the power demand per drive cycle time, which indicates the dynamic needs and the selected size of the lithium-ion battery (depends on the C rate), for the heavy-duty truck. With an energy baseload of maximum 85.3kWh, a FC-system output of maximum 100kW is sufficient.

Table 3: Energy demand test cycle “400km”

Truck load [t]	10	14	18	22	26
cycle time [h]			7.11		
Driving distance [km]			400.2		
Energy demand in the cycle [kWh]	423.8	469.2	515	560.9	606.9
Energy baseload [kWh]	59.6	66	72.4	78.87	85.3
Energy demand [kWh/100km]	105.9	117.3	128.7	140.1	151.6
Min. H_2 demand [kg]	25.2	27,9	30.6	33.36	36.1
H_2/100km [kg]	6.3	7	7.7	8.3	9

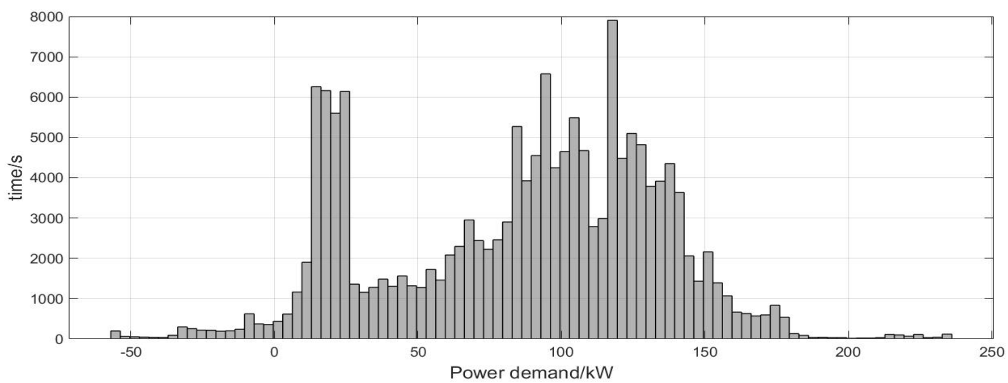

Figure 5: Histogram load demand “400km cycle” (26t)

3.3 Energy management strategies

To achieve high System efficiency, low fuel consumption, low life cycle impact and a steady SOC, different EMS are used to ensure that the FC-system and the batteries are operating in the optimal operating point, the state of the art and most commonly EMS are resented in the following.

3.3.1 PI-controller

The SOC is regulated to a fixed value using a PI-controller (Figure 6). Here, the output of the PI-controller corresponds to the battery power, which is subtracted from the load requirement in order to determine the power of the fuel cell (SOC high> BZ power low) [10].

The regulation requires no empirical values and can be easily adjusted.

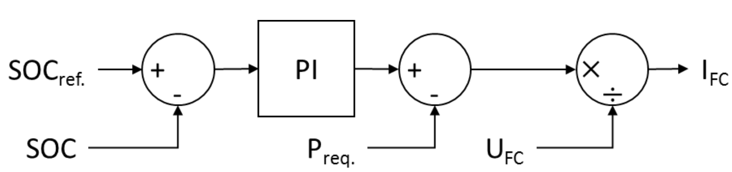

Figure 6: PI-controller

3.3.2 State machine control strategy

A well-known and simple strategy is the state machine control (SMC) [10, 12]. Based on experience and empiric data the EMS rules can be defined. This also means that the performance is highly dependent on the knowledge and experience of an expert who defines the states. A example is shown in the following Figure 7, consisting of 6 states. The FC-system power is controlled based on the battery SOC and load demand required. Because of the hysteresis control the response to changes is one drawback of this strategy. Frequency decoupling is used for the SMC strategy, to ensure that the FC-system is only exposed low frequently demands.

```
SOC_max   = 85;       Pfc_min  = 10000;
SOC_nom1 = 80;        Pfc_max = 100000;
SOC_nom2 = 60;        Pfc_opt   = 70000;

State 1 SOC > SOC_max                        > Pfc = 0;
State 2 SOC > SOC_nom1                       > Pfc = Pfc_min;
State 3 SOC > SOC_nom2 & PEMS < Pfc_opt      > Pfc = Pfc_opt;
State 4 SOC > SOC_nom2 & PEMS < Pfc_max      > Pfc = PEMS;
State 5 SOC > SOC_nom2 & PEMS > Pfc_max      > Pfc = Pfc_max;
State 6 SOC <= SOC_nom2                      > Pfc = Pfc_max;
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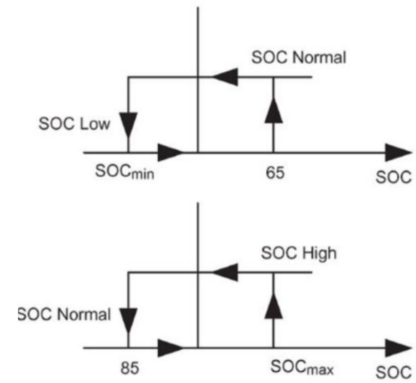

Figure 7: State machine control strategy [10]

3.3.3 Rule based fuzzy logic strategy

The rule-based fuzzy logic strategy, where the power distribution is accomplished through membership functions and the set of IF–THEN rules, is another widely used EMS [10, 11]. It can be easily tuned to achieve optimal operation, and its performance is less sensitive. Nevertheless, the fuzzy logic controller resides on the IF–THEN rules (Figure 8), which require the knowledge and experience of an expert. This scheme has a faster response to load change and is more robust. The FC-system power is obtained based on the load power and SOC membership functions and the set of IF–THEN rules. The fuzzy logic rules and the membership functions are shown in the following table. Frequency decoupling is also used for the fuzzy logic strategy.

1. If SOC H & PEMS VL then Pfc is VL
2. If SOC H & PEMS L then Pfc is VL
3. If SOC H & PEMS M then Pfc is L
4. If SOC H & PEMS H then Pfc is M
5. If SOC M & PEMS VL then Pfc is M
6. If SOC M & PEMS L then Pfc is M
7. If SOC M & PEMS M then Pfc is H
8. If SOC M & PEMS H then Pfc is H
9. If SOC L & PEMS VL then Pfc is M
10. If SOC L & PEMS L then Pfc is H
11. If SOC L & PEMS M then Pfc is H
12. If SOC L & PEMS H then Pfc is H

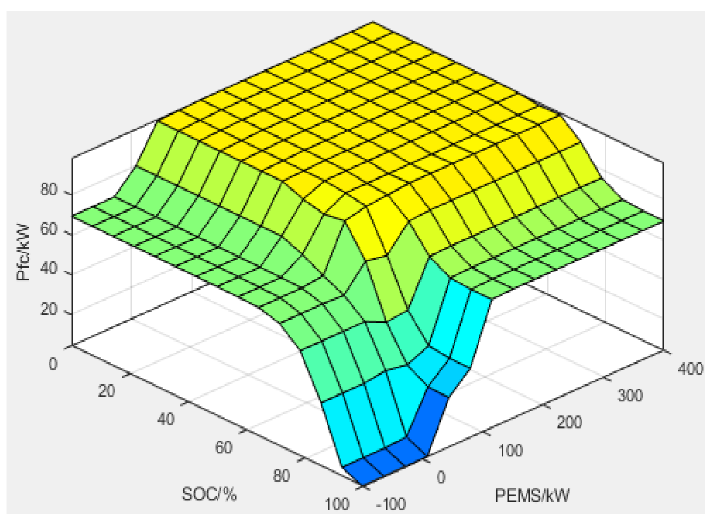

Figure 8: Characteristic rule based fuzzy logic and IF-Then rules

4 Battery impact

In this section, we will discuss the different battery impacts compared to the different EMS as well as different battery capacities. The main criteria considering this will be the expected C rates (charge and discharge), FC-system efficiency and fuel consumption for the observed driving cycle. High C rates should be avoided as they reduce the battery lifetime. Due to the heat development, an active cooling is required, which lowers the overall efficiency of the hybrid system. However, a larger battery capacity, due to a larger empty weight, leads to a lower load capacity.

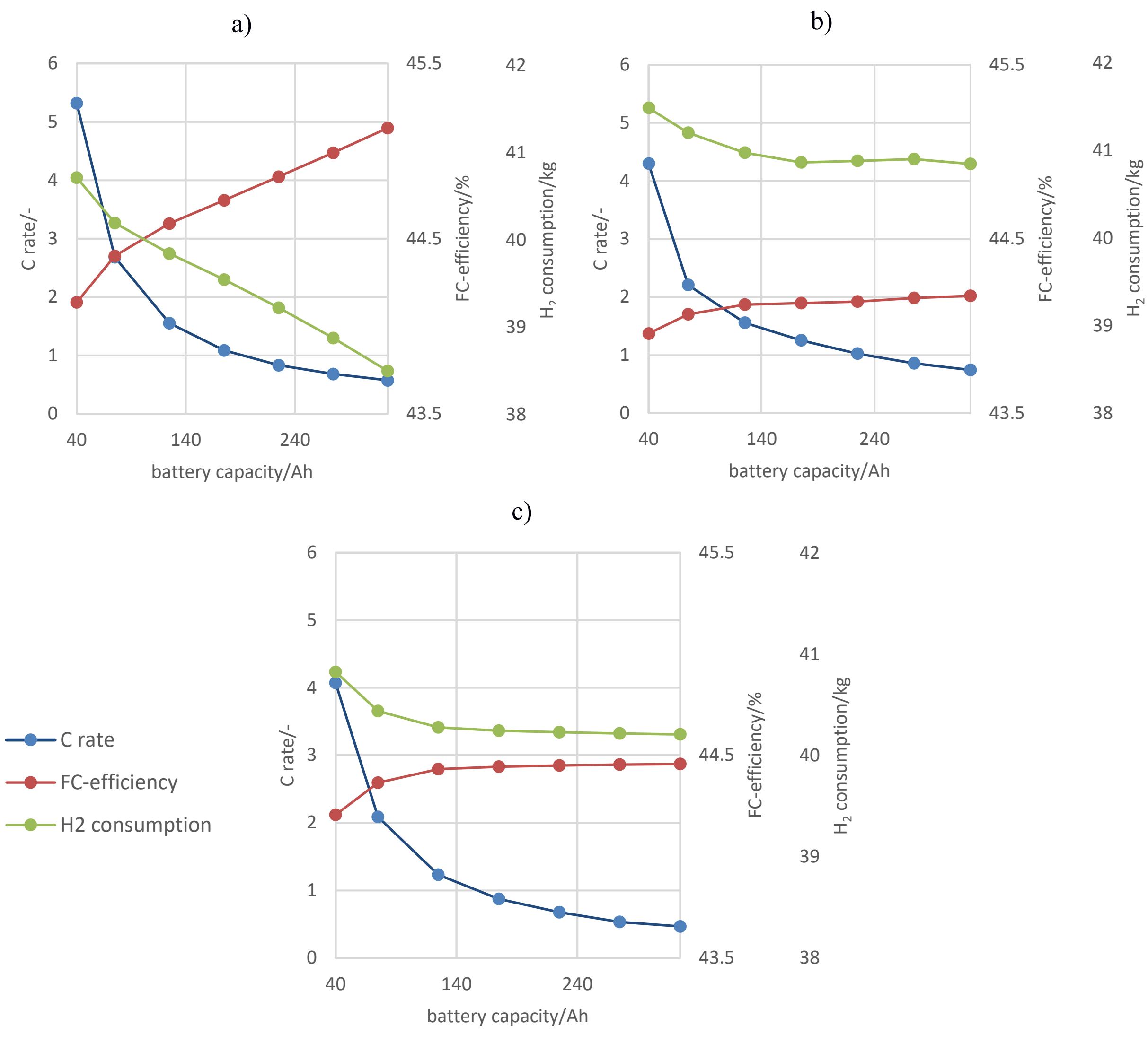

Figure 9: C rate, FC-efficiency and H_2 consumption for different battery capacities (40-325Ah) with a) fuzzy logic, b) PI-controller, c) SMC (truck load 26t)

As shown in Figure 9, all EMS results a significant reduction in C rates and an increase in FC-efficiency by increasing the battery capacity. The maximum increase in FC-efficiency of 1% can be achieved with the use of the fuzzy logic strategy, which leads to a remarkable reduction in hydrogen consumption. Likewise, the fuzzy logic strategy shows the highest difference in C rate dropping from 5.3 to 0.6 by increasing the battery capacity.

In contrast, the two strategies PI-controller and SMC only show a negligible increase in FC efficiency above a battery capacity of 140 Ah. The fuzzy logic forces the FC-system to provide constant power, result a greater stressed battery, the C rate increases and a higher thermal stress on the battery. Increasing the dynamic load on the FC-system reduces its service life. This creates a field of tension between the dynamics of the control strategy, FC-system and battery lifetime, system efficiency and empty weight.

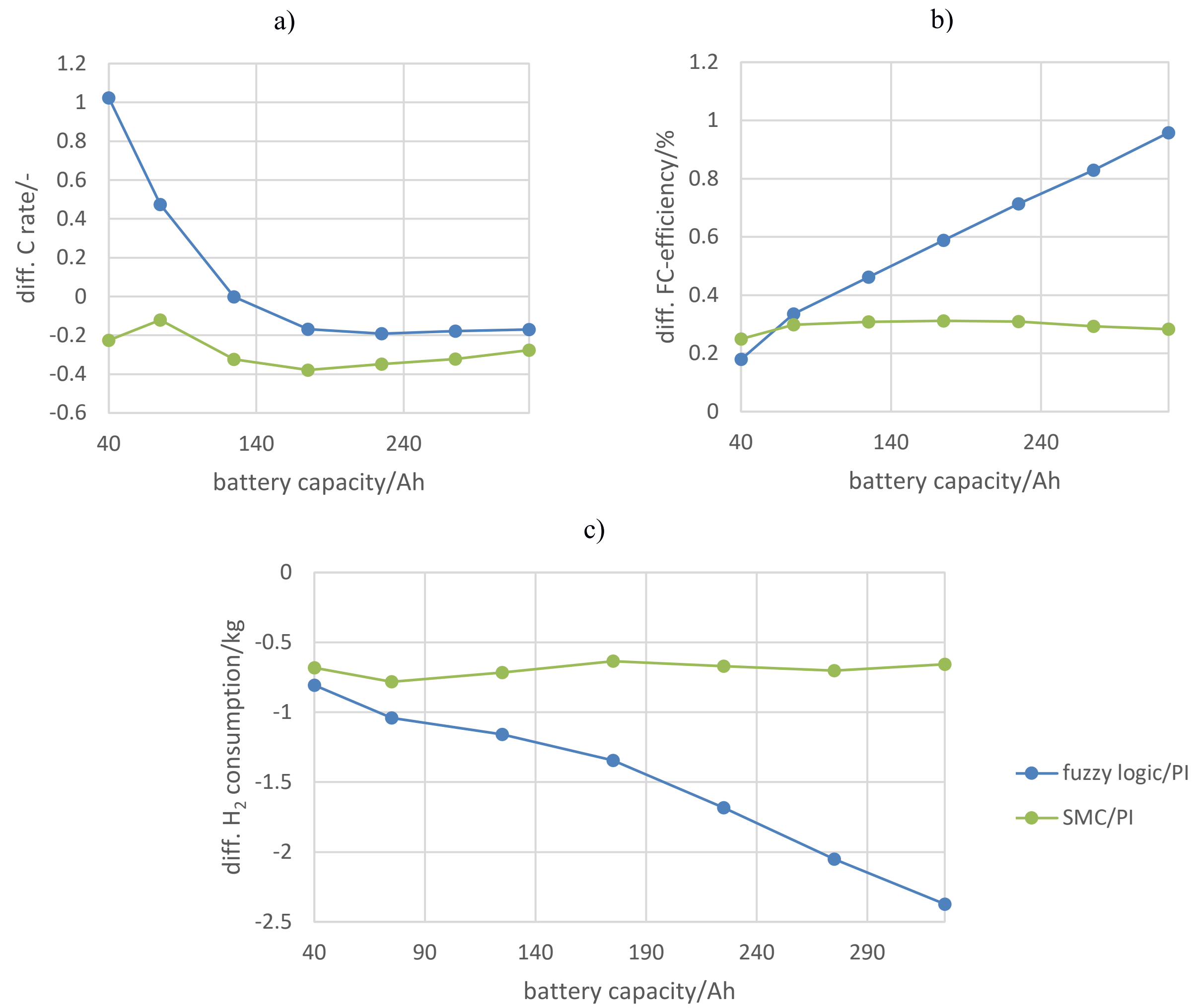

Figure 10: Fuzzy logic and SMC compared to PI-controller. Difference of a) C rate, b) FC-efficiency and c) H_2 consumption (truck load 26t)

Figure 10 shows the criteria of fuzzy logic and SMC compared to the PI-controller. The SMC shows the best C rate across the entire battery capacity range. The fuzzy logic clearly dominates in FC-efficiency and hydrogen consumption.

5 Conclusion

This paper describes the simulation of a fuel cell hybrid heavy-duty truck, dimensionalization of its energy sources and compares different energy management strategies. The simulation is based on proven modelling approaches and technical data. An adapted HHDDT drive cycle acts as input for the simulation. The FC-system is dimensioned based on the load request that occurs during the driving cycle. This results in a base load requirement of a maximum of 85.3 kWh, which must be provided by the FC-system.

Three different energy management strategies are introduced and compared in terms of the overall efficiency of the hybrid system, the stress seen by each energy sources and hydrogen consumption. The energy management strategies are a classic PI control loop, state machine controller and fuzzy logic controller. To ensure that the state machine controller and fuzzy logic controller is exposed low frequently demands, frequency decoupling is used. The criteria used to dimension the energy storage and to evaluate the energy management strategies are the base load, the C rate of the battery, the FC-efficiency and the H_2 consumption. All energy management strategies show a decrease in the C rate and an increase in FC-efficiency with increasing battery capacity (40 to 325Ah). The greatest efficiency increase of 1% and reduction of the C rate from 5.3 to 0.6 results from fuzzy logic controller. In a direct comparison of the EMS with the PI-controller, there is a small improvement in the criteria over the entire battery capacity range with the SMC. The fuzzy logic control clearly dominates in FC-efficiency and hydrogen consumption. Especially the FC-efficiency increases with an increasing battery capacity when the other two EMS are almost steady. As the overall result, a fuzzy logic control with frequency decoupling is recommended as a control strategy for use in a fuel cell hybrid heavy-duty truck.

Acknowledgments

This work was supported from the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg.

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