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Minimization of Hydrogen Consumption via Optimization of Power Allocation Between the Stacks of a Dual-Stack Fuel Cell System

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ABSTRACT

A dual-stack fuel cell model was developed to simulate the hydrogen consumption a fuel cell-powered vehicle for a specific drive cycle. Two fuel cell stacks, each consisting of 65 parallel cells at different aging status and thus with different efficiency profiles (i.e., low and high) were considered. A constrained optimization for power distribution between individual stacks was performed where the objective function was to minimize the hydrogen consumption while meeting the total demand. For proper power management each stack has its own power controller which manipulates the stack current to control the stack power at its desired-set point. Computed optimal power values constitute the desired set-points for the local power PID controllers of the individual stacks. Closed-loop simulations were performed by simulating the developed mechanistic model together with optimization and PID controllers in SIMULINK platform. The closed loop simulations demonstrate how well the power demand of the drive cycle is tracked and the hydrogen consumption is minimized. To assess the impact of optimization strategy used, hydrogen consumption is compared to that of equal power sharing and a daisy-chain strategies. The results demonstrate that the optimization strategy effectively reduces the total hydrogen consumption.

Keywords: Proton Exchange Membrane Fuel Cells (PEMFC), Hydrogen Consumption Minimization, Power Sharing

INTRODUCTION

Fuel cells are devices that convert chemical energy into electrical energy via transfer of electrons and protons. They possess key characteristics such as high efficiency, high power density, low corrosion, low emissions and moderate operating temperatures, and those characteristics position them as highly favorable alternative power sources in the automotive industry. To meet the high-power demand of a vehicle numerous individual cells are assembled in series or parallel configurations, forming what are known as "Fuel Cell Stack." For heavy duty vehicle applications, such as trucks and buses, multiple fuel cell stacks can be combined to increase the lifetime of the vehicle and energy efficiency.

Depending on the power management algorithm, each stack can exhibit varying efficiencies over lifetime due to differences in operating conditions and the rate of cell aging. Stack efficiency directly influences the amount of hydrogen consumed by the vehicle. Thus, efficient power distribution across multiple fuel cell stacks is crucial for minimizing total hydrogen consumption while satisfying the vehicle's power requirements.

In this study, we examine a two-stack fuel cell system, with each stack having distinct efficiency profiles (high and low) to mimic different aging status. The number of parallel cells in one stack can vary and is chosen as 65 by the authors in this work. The fuel cell stacks are modeled using first principles and simulated in MATLAB Simulink environment and the effects of aging on power allocation and hydrogen consumption were analyzed. Figure 1 illustrates the architecture of the control model where a given power demand is optimally shared between the two stacks. The local power controllers of the individual stacks manipulate their currents to meet their allocated power demands.

There are several studies in the literature for hydrogen consumption minimization [1], [2] which analyze fuel cell stacks with different efficiency profiles and compare the two common optimization strategies: equal power distribution and daisy-chain configurations. In the daisy-chain strategy, power is distributed sequentially, with one stack supplying the load until it reaches its limit, then the next stack takes over. [3] employed a geometric approach to compute the optimal power distribution and to maximize the power-efficiency. [4] proposed a power allocation strategy based on particle swarm optimization (PSO) and compared its performance with an equal power distribution strategy for two different load profiles. In these studies, the efficiency curves that are utilized in optimization were estimated from the experimental data. In this study, a mechanistic fuel cell model was used to calculate the efficiency curves for investigation of the effect of different designs and operating variables and physical parameters on the optimal power allocation.

METHODOLOGY

The power and efficiency model for the fuel cell is taken from the work of [5] and the fundamental equations are presented below:

$$E = E^0 - \frac{RT}{nF}\ln\frac{\prod p_{products}^{v_i}}{\prod p_{reactants}^{v_i}} \quad (1)$$

$$E_{oc} = N \times E \quad (2)$$

$$V_{act,loss} = \frac{NRT}{n\alpha F}\ln\frac{j_{fc}}{j_0} \quad (3)$$

$$V_{ohm,loss} = R_{ohm} \times j_{fc} \quad (4)$$

$$V_{conc,loss} = N \times c\ln\frac{j_L}{j_L - j_{fc}} \quad (5)$$

$$V_{fc} = E_{oc} - V_{act,loss} - V_{ohm,loss} - V_{conc,loss} \quad (6)$$

$$P_{fc} = i \times V_{fc} \quad (7)$$

$$\eta_{thermo} = 0.83 \quad (8)$$

$$\eta_{fuel} = \frac{1}{\lambda} \text{ where } \lambda = \frac{\frac{i}{nF}}{\dot{v}_{fuel}} \quad (9)$$

$$\eta_{voltage} = \frac{V_{fc}}{E_{oc}} \quad (10)$$

$$\eta = \eta_{thermo} \times \eta_{fuel} \times \eta_{voltage} \quad (11)$$

$$\dot{m}_{H_2} = \frac{Ni(MW_{H_2})}{nF\eta_{fuel}} \quad (12)$$

The partial pressures, p in atm, in Eqn. 1 are calculated from a separate mechanistic model [6], [7].

The objective function for the optimization is to minimize the total hydrogen consumption rate (kgs^{-1}) of two fuel cell stacks, formulated as follows:

$$\min_{i_1,i_2} \dot{m}_{H_2,total} = \frac{Ni_1(MW_{H_2})}{nF\eta_{fuel1}} + \frac{Ni_2(MW_{H_2})}{nF\eta_{fuel2}}$$

s.t.

$$8 \le i_1, i_2 \le 300$$

$$P_{fc,1} + P_{fc,2} = P_{demand}$$

The decision variables in this optimization are the fuel cell currents. The usage of the DC-DC converter establishes the minimum current at 8, while the maximum current of 300 is defined by the limiting current density value. The algorithm computes the optimal individual stack currents, and thus the optimal power outputs of each stack, $P_{fc,1}^{opt}$ and $P_{fc,2}^{opt}$ as depicted in Figure 1. Above optimization has a global and unique optimum since the objective function is linear in the decision variables i_1, i_2 and the constraints define a closed convex feasible set. We used MATLAB's fmincon function with the Sequential Quadratic Programming (SQP) algorithm to solve the optimization.

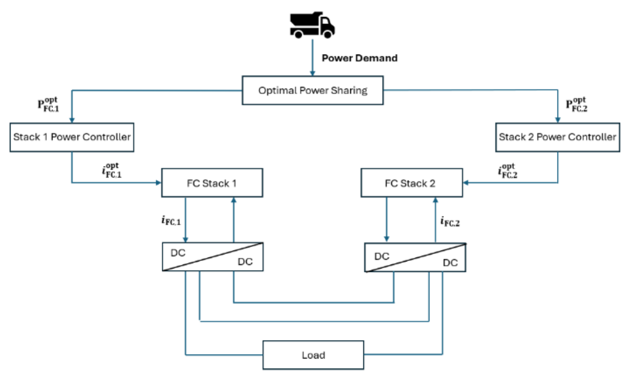

Figure 1. Model architecture and control strategy

RESULTS

Aging and/or degradation are the two key factors that directly impact the lifespan and performance of fuel cell stacks. Degradation can occur in various components of the fuel cell, such as the catalyst, membrane, and gas diffusion layers. Each of these components contributes to performance losses in specific ways, such as reducing the exchange current density, increasing ohmic resistance, or decreasing the limiting current density. Collectively, these effects diminish the power output of the fuel cell stack over time.

In this study, the electron transfer coefficient (α) is used to indicate the level of degradation/aging in the fuel cell stack. α values are between 0 and 1; and it is well known that [5] lower values result in increased voltage losses indicative of increased degradation/aging.

In the results to follow, the optimal power values are provided as set-points to the local PID controllers that adjust the currents. Due to the inherently slow response time of the fuel cell, the stack powers reach their set-points within 100 sec with a smooth response.

Case 1: Equal Fuel Efficiency and Different Degradation Levels

Case 1.1: α_1=0.6 and α_2=0.4, λ_1= λ_2=1.2

The first case examines the impact of different degradation levels on power distribution and compares hydrogen consumption across three different strategies. For Case 1.1 analysis, α values of 0.6 and 0.4 were chosen for stacks 1 and 2, respectively. The fuel efficiency η_{fuel} of each stack is set equal to 0.8333 which corresponds to 20% of excess hydrogen feed (λ_1= λ_2=1.2). Due to degradation, stack 2 has lower α value, which leads to a decline in power output and efficiency. The superimposed power outputs of both stacks are shown in Figure 2.

In the equal distribution strategy [2], the power produced by each stack is equal, with each contributing half of the total power demand, as shown in Figure 3. Since stack 2 experiences higher degradation compared to stack 1, its current and therefore its hydrogen consumption is higher, as shown in Table 1. In the daisy-chain strategy [8], stack 1 serves as the primary energy source due to its higher power output and efficiency. When the total power demand exceeds the maximum capacity of stack 1, stack 2 compensates for the power gap. Otherwise, stack 2 idles at its minimum power P=637 W, as illustrated in Figure 4. Since stack 1 meets most of the power demand, its hydrogen consumption is significantly higher than that of stack 2 (see Table 1). Optimization approach adjusts the power level for each stack based on the stack efficiency without using any priori rule as in equal power and daisy-chain strategies. Optimal power allocated to each stack is shown in Figure 5. Comparing with Figures 3 and 4, we see that in optimal allocation stack 2 power idles less than daisy-chain; therefore, less power is needed from stack 1. This results in lower currents in stack 1 and less hydrogen consumption, which is proportional to the current. Table 1 shows that optimization gives the least hydrogen consumption (0.4249 kg), for the given drive cycle with duration of 4000 sec. This is a 5.29% improvement over the daisy-chain algorithm. However, the improvement of the optimization strategy over the equal distribution algorithm (0.96%) is not very significant in this scenario. This is because the α values and the performance of the fuel cell stacks are quite similar, and the fuel efficiencies of the stacks are the same. Nevertheless, these small percentage improvements will result in significant hydrogen saving considering the overall lifetime of the vehicle.

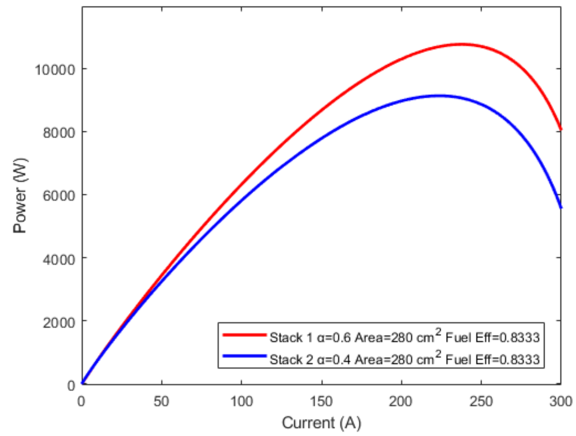

Figure 2. Current vs power curves for both stacks.

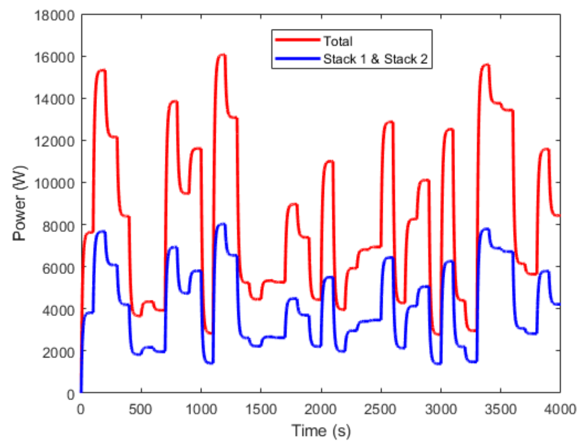

Figure 3. Power sharing using equal distribution strategy.

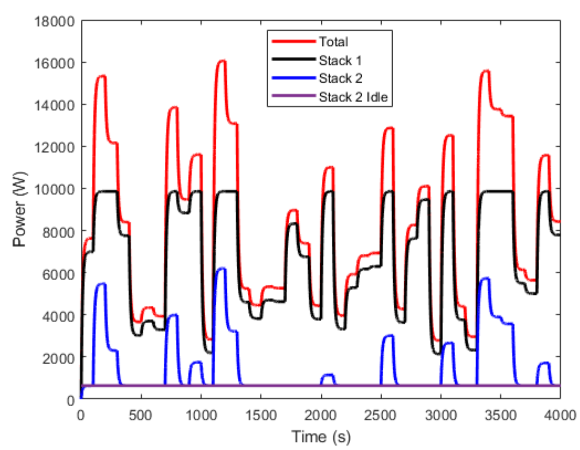

Figure 4. Power sharing using daisy-chain strategy.

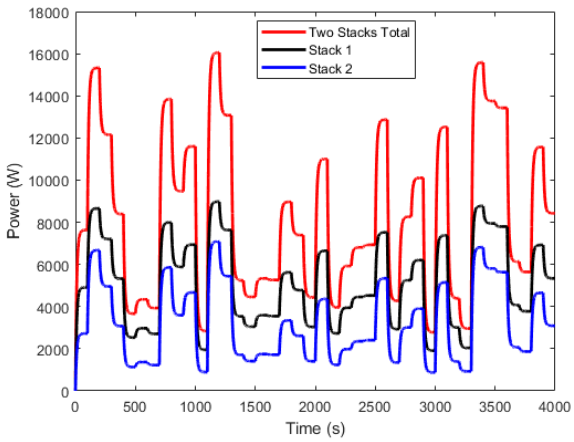

Figure 5. Power sharing using optimization strategy.

Table 1: Total Hydrogen Consumption of the Stacks with Different Strategies where α_1=0.6, α_2=0.4 and $\lambda_1 = \lambda_2$=1.2

Strategy	Stack 1 H_2 Consumption (kg)	Stack 2 H_2 Consumption (kg)	Total H_2 Consumption (kg)
Equal distribution	0.2043	0.2247	0.4290
Daisy-chain	0.3727	0.0759	0.4486
Optimization	0.2582	0.1667	0.4249

Case 1.2: α_1=0.6 and α_2=0.25, $\lambda_1 = \lambda_2$=1.2

For Case 1.2 analysis, the α values were set as 0.6 and 0.25, and thus differences between the power and efficiency curves of the stacks are much larger. The same drive cycle data was used as the power demand input. With the new degradation level, stack 2 can produce a maximum of 6510 W (Figure 6). In the equal distribution scenario, when the power demand for each stack exceeds 6510 W, a power deficit occurs for stack 2 which is set to be met by stack 1. Figure 7 displays that the black and blue lines do not overlap at power demands higher than 6510 watts which is the result of modification in the algorithm. In this case, the equal distribution algorithm consumed the maximum hydrogen (0.4854 kg), as shown in Table 2. Power demand was successfully met in the daisy-chain algorithm. In this scenario, stack 1 again served as the primary power source, while stack 2 mostly operated at its idle power. Compared to the previous scenario, hydrogen consumption for stack 1 remained constant, as its α value did not change. However, the decrease in α value for stack 2 from 0.4 to 0.25 led to an increase in the current required for the same power demand in stack 2 which resulted in operating at lower efficiency. As a result, hydrogen consumption for stack 2 increased in this case (see Tables 1 and 2). Finally, the optimization algorithm successfully met the entire power demand, relying more on stack 1 (higher efficiency) and less on stack 2 (lower efficiency) (Figure 8). The increase in hydrogen consumption for stack 1 is due to the higher power production, and less power was produced by stack 2, resulting in reduced hydrogen consumption compared to the previous scenario. Similar to the previous case, the optimization strategy consumed the lowest hydrogen amount (see Table 2). However, the greater difference in α values made the daisy-chain scenario more favorable than in the previous case. As a result, the improvement of optimization over the daisy-chain scenario decreased but still demonstrated better performance, with 2.15% less hydrogen consumption. The equal distribution scenario showed the worst performance, with the optimization strategy achieving a 6.94% improvement over it.

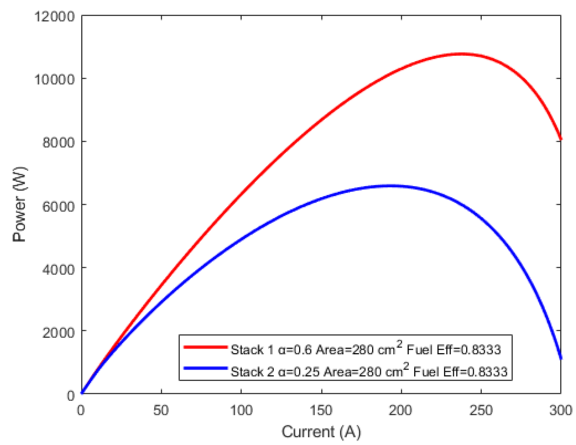

Figure 6. Current vs power curves for both stacks incorporating the new degradation level of stack 2.

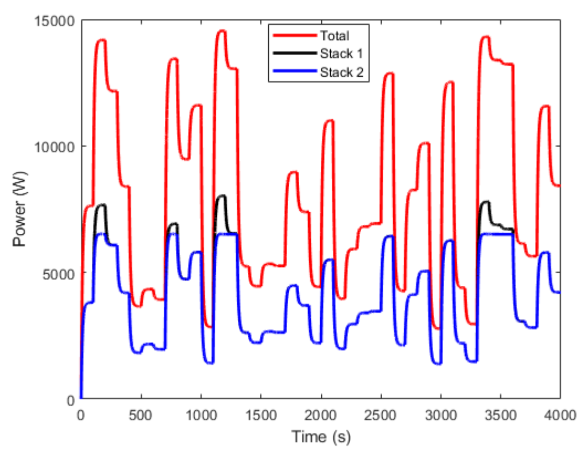

Figure 7. Power sharing using modified equal distribution strategy incorporating the new degradation level of stack 2.

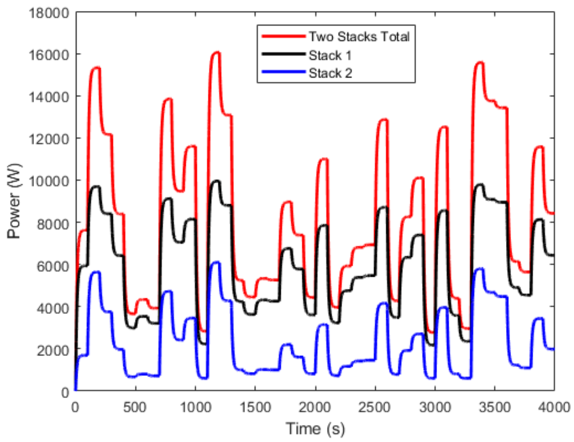

Figure 8. Power sharing using optimization strategy incorporating the new degradation level of stack 2.

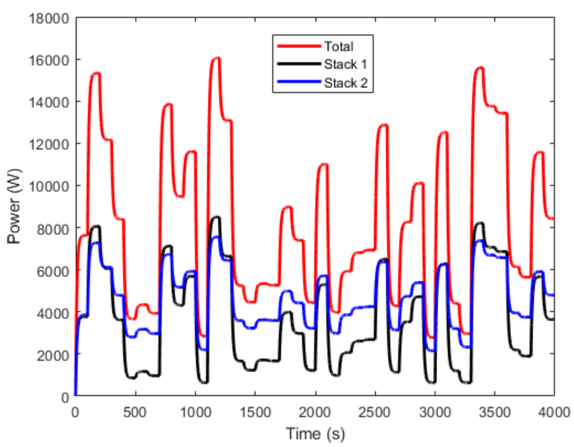

Figure 9. Power sharing between stacks using the optimization strategy with λ_1=1.5 and λ_2=1.2.

Table 2: Total Hydrogen Consumption of the Stacks with Different Strategies where α_1=0.6, α_2=0.25 and λ_1= λ_2=1.2

Strategy	Stack 1 H_2 Consumption (kg)	Stack 2 H_2 Consumption (kg)	Total H_2 Consumption (kg)
Equal distribution	0.2043	0.2811	0.4854
Daisy-chain	0.3727	0.0889	0.4616
Optimization	0.3166	0.1351	0.4517

Case 2: Different Fuel Efficiencies and Degradation Levels (α_1=0.6 and α_2=0.4, λ_1=1.5 and λ_2=1.2)

Aging results in several changes in the structure of the catalyst layer of fuel cells which can hinder the smooth movement of hydrogen molecules resulting in lower fuel efficiency and higher hydrogen feed excess ratio, λ. In case study 2, λ_1 was set to 1.5. Optimal power distributions are shown in Figure 9. Since λ_1 is higher than λ_2, the power allocated to stack 2 is increased. As a result, the hydrogen consumption of stack 2 is higher than that of stack 1, as presented in Table 3. Table 3 summarizes the hydrogen consumption across all strategies, showing that the daisy-chain strategy performs the worst, while the optimization strategy achieves the best results.

Table 3: Total Hydrogen Consumption of the Stacks with Different Strategies where α_1=0.6, α_2=0.4 and λ_1=1.5 and λ_2=1.2

Strategy	Stack 1 H_2 Consumption (kg)	Stack 2 H_2 Consumption (kg)	Total H_2 Consumption (kg)
Equal distribution	0.2553	0.2247	0.4800
Daisy-chain	0.4658	0.0759	0.5417
Optimization	0.2264	0.2512	0.4776

CONCLUSION

Minimizing fuel consumption of a vehicle is one of the most crucial tasks for automotive producers to be competitive in the market. Likewise, for a fuel cell-powered vehicle the focus is mainly on minimizing the hydrogen consumption via distributing the demanded power effectively between fuel cell stacks. In this study, three different power allocation strategies, namely equal distribution, daisy-chain, and optimal power sharing, were compared for dual-stack fuel cell system, each stack having different aging levels. For similar aging levels of the stacks, the performance of optimization strategy equal distribution algorithm was similar. However, as the aging levels of the stacks differ, the performance of optimization strategy is superior to that of equal distribution and aligns more closely with the daisy-chain algorithm. Additionally, the impact of fuel efficiency changes, influenced by alterations in the catalyst structure, was analyzed. In all cases, the optimization strategy resulted in the lowest hydrogen consumption.

NOMENCLATURE

α	Electron transfer coefficient
c	Constant
E	Reversible cell voltage (V)
E^0	Ideal reversible voltage (V)
E_{oc}	Open circuit voltage (V)
F	Faraday's number (C)
i	Current (A)

j_0	Exchange current density (Acm^{-2})
j_{fc}	Current density (Acm^{-2})
j_L	Limiting current density (Acm^{-2})
MW	Molecular weight ($kgkmol^{-1}$)
$\dot{m}_{H_2}$	Hydrogen consumption rate (kgs^{-1})
n	Number of electrons transferred
N	Number of cells
P_{fc}	Power (W)
R	Gas constant ($Jmol^{-1}K^{-1}$)
R_{ohm}	Ohmic resistance (Ω)
T	Temperature (K)
$\dot{v}_{fuel}$	Fuel supply rate ($mols^{-1}$)
$V_{act,loss}$	Activation loss (V)
$V_{conc,loss}$	Concentration loss (V)
V_{fc}	Fuel cell voltage (V)
$V_{ohm,loss}$	Ohmic loss (V)
η	Stack efficiency
η_{fuel}	Fuel utilization efficiency
η_{thermo}	Reversible thermodynamic efficiency
$\eta_{voltage}$	Voltage efficiency
λ	Fuel stoichiometric factor

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