38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Offline Optimal Energy Management Strategy for Predefined Path Operating Fuel Cell Hybrid Tram

Dongeon Kim[1], Jaekwang Jung[1], Minsu Kim[1], Shengxiang Fu[1,2], Chunhua Zheng[2], Heeyun Lee[3], Namwook Kim[1*]

[1]*Department of Mechanical Engineering, BK21 Four ERICA-ACE Center, Hanyang University, Ansan, Gyeonggi 15588, Republic of Korea (nwkim@hanyang.ac.kr)*

[2]*Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China (ch.zheng@siat.ac.cn)*

[3]*Department of Mechanical Engineering, Dankook University, Yongin, Gyeonggi 16890, Republic of Korea (heeyunlee@dankook.ac.kr)*

Executive Summary

As fuel cell hybrid trams gain traction as eco-friendly urban transportation, efficient energy management strategies are increasingly essential. This study converts the Equivalent Consumption Minimization Strategy (ECMS), an online control method, into an offline optimal control approach suitable for trams on predefined paths. The proposed strategy is benchmarked against a rule-based control method for hydrogen consumption and SOC maintenance and applied in scenarios with varying power demands, assuming limited foresight of the next section's driving conditions. Results demonstrated that this method adapts effectively to real-world variability in driving scenarios.

Keywords: Fuel Cell electric Vehicles, Railway Vehicles, Energy management, Advanced control of EVs, Drive & Propulsion Systems

1 Introduction

In accordance with global fuel economy regulations and the objective of achieving Net Zero by 2025, research on eco-friendly transportation systems has been actively conducted worldwide. Trams, a type of railway vehicle that operates on tracks embedded in urban roads, are being introduced in many countries and gaining new attention as a low-emission, eco-friendly form of public transport. Trams currently in operation generally utilize two types of powertrains: pure electric and fuel cell hybrid systems. In the case of pure electric trams, the battery alone supplies sufficient power to operate the electric propulsion systems such as the traction motors. However, this configuration is limited by the driving range per charge and the ability to meet power demands under various challenging driving conditions. Fuel cell hybrid systems, which combine a battery with a fuel cell stack, emerged as an alternative to meet the requirements. For the efficient operation of such a hybrid system, an effective power distribution strategy between the two energy sources is essential [1-3].

Power distribution strategy is an energy management system (EMS) that allocates total demand power across multiple energy sources. This strategy is divided into two methodologies: offline control and online control. Offline control is a robust method defined by the designer before its operation. It has benefits under predefined information, like scheduled routes. This method includes rule-based control. Online control is a flexible method that responds to external information, such as fluctuating power demands. This method includes ECMS (Equivalent Consumption Minimization Strategy) [4], which is classified as an optimal control strategy aiming to achieve optimal performance.

This study introduces the development of ECMS-based control for fuel cell hybrid systems, adapted as offline control for a predefined path (railway). We conducted simulations using a fuel cell hybrid system model to compare fuel consumption between the rule-based control and ECMS-based control under SOC maintenance conditions. Additionally, we performed a simulation of ECMS-based control by sections, assuming segments between stations to create a short-term connected environment similar to real-world driving conditions.

2 Fuel Cell Hybrid Tram Model

For simulation, we developed a fuel cell hybrid tram model consisting of two fuel cell stacks, a battery, and four motors. The system configuration of the model is shown in Figure 1.

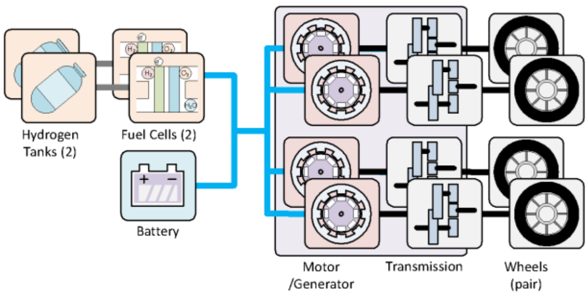

Fig.1: System Configuration of Fuel Cell Hybrid Tram

Each component inside the system has been individually developed using MATLAB/Simulink, applying specified parameters alongside their physical and mathematical characteristics.

2.1 Fuel Cell System

A fuel cell system consists of a fuel cell stack that produces hydrogen and the balance of plant (BOP) required to operate it, such as pumps and compressors. The hydrogen fuel consumption rate is calculated based on the output power of the fuel cell system, considering its system efficiency. Figure 2 shows the characteristics of a fuel cell stack.

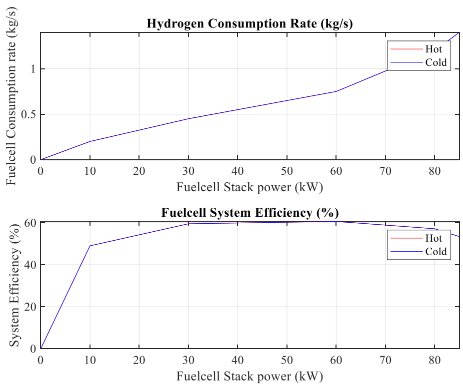

Fig.2: Fuel cell consumption rate and efficiency by stack power

2.2 Energy Storage System

Energy storage system is well known as battery and the model is represented by an equivalent circuit consisting of an internal resistance and an open circuit voltage (OCV) [5]. In this model, the battery's output voltage is calculated using Equation (1), which accounts for open voltage and losses due to internal resistance. The state of charge is governed by Equation (2).

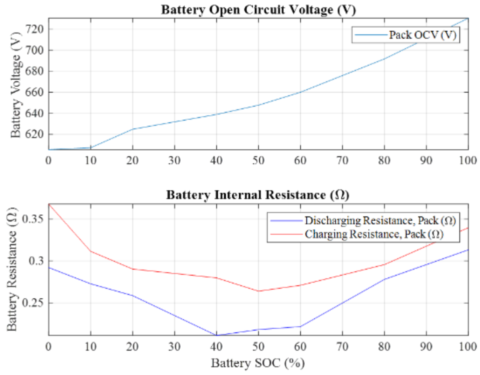

Fig.3: Battery open circuit voltage and internal resistance by SOC

$$V_0 = V_s - i_0 R_i \tag{1}$$

$$SOC = \frac{1}{C_b}\int i_0 dt \tag{2}$$

2.3 Electric motor

The current motor angular velocity and output torque determine the mechanical power. The motor power is converted from mechanical energy to electrical power using a conversion efficiency map.

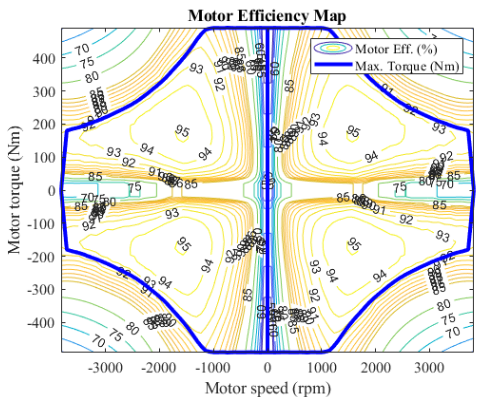

Fig.4: Electric motor efficiency map

During driving, the mechanical power is converted to electrical power, and when regenerative braking, it can be calculated as the inverse of the corresponding electrical power. The equations for the output power and efficiency map of the motor are given below.

$$P_{mech} = \omega_{mot} \times T_{mot} \tag{3}$$

$$P_{elec} = P_{mech} \times \eta_{mot}(\omega_{mot}, T_{mot})^k \tag{4}$$

$$k = \begin{cases} -1 & P_{mech} \geq 0 \\ 1 & P_{mech} < 0 \end{cases} \tag{5}$$

3 Control Strategy for Energy Management System

To operate a fuel cell hybrid system, an energy distribution controller is required to manage power from both the fuel cell stacks and the energy storage system (ESS). Achieving an optimal balance between hydrogen consumption and ESS usage in energy distribution can improve vehicle fuel economy performance. In this study, two control methodologies are proposed for achieving the performance: rule-based control and ECMS-based control.

3.1 Rule-based Control with Control Parameters

Rule-based control is a power distribution method between the fuel cell stacks and the ESS based on predetermined rules that correspond to the total power demand. The rule of fuel cell power demand is defined by its minimum power, maximum power, and optimal power at the point of maximum efficiency [6].

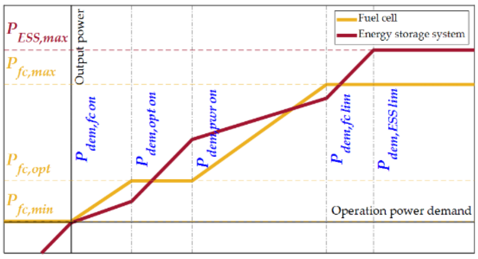

Fig.5: Rule-based control strategy with control parameters

3.2 ECMS-based Control

The ECMS (Equivalent Consumption Minimization Strategy) control strategy is an online optimal control method used to determine efficient energy consumption in the fuel cell hybrid system. A mathematical equivalent value, defined as Hamiltonian, consisting of fuel consumption rate and the derivative of SOC, is multiplied by an equivalent factor (costate) to balance the two energy sources.

$$H = \dot{m}_{fc} + \lambda \cdot \dot{SOC} \tag{6}$$

$$P_{fc,opt} = \arg\min(H) \tag{7}$$

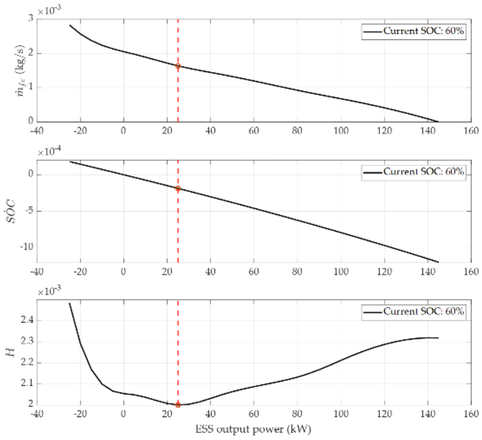

Fig.6:Optimal control determining process at specific driving condition [SOC:60%]

4 Simulation & Results

To evaluate control strategies, we used LF-LRV power cycle [7], a tram-specific driving cycle adjusted to our fuel cell hybrid system's specifications. The power cycle is divided into several sections, each assumed to represent the segments between stations.

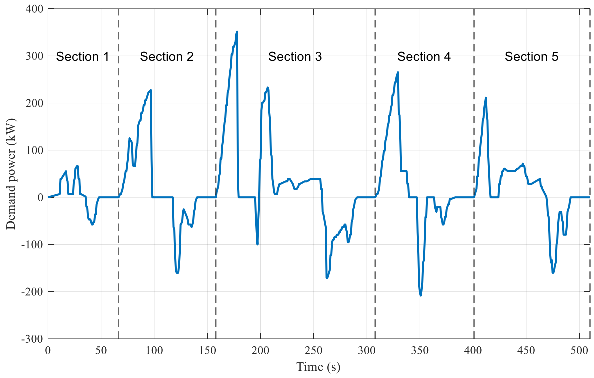

Fig.7: LF_LRV driving demand power cycle for tram

The parameters of the rule-based control and the costate for ECMS based control are optimized based on the predefined cycle, aiming for a final SOC around 60% starting from 60%. ECMS based control map can be considered as an offline control, as only costate is derived from a path under our condition. Similarly, the costates for ECMS based control by sections are optimized individually, assuming the short-term connected system. As a result, the performance of control strategies is illustrated in Table 1 below.

Table 1: Simulation Results of Control Strategies

	Optimized Rule-based	ECMS	ECMS by Sections
Fuel consumption (kg)	0.2895	0.2832	0.2869
Final SOC (%)	60.148	60.144	60.147

5 Conclusion

In this study, we proposed the ECMS-based control strategy map to achieve optimal fuel consumption performance in a fuel cell hybrid system tram. The results show that using ECMS-based control maps can save more hydrogen gas compared to the optimized rule-based control under similar final SOC conditions. Moreover, when assuming a short-term connected system, such as driving from station to station, ECMS-based control by sections also reduces fuel consumption relative to the optimized rule-based control. Based on these results, ECMS-based control strategy can be an effective choice for increasing fuel efficiency along the predefined driving path, regardless of how that path is defined.

Acknowledgments

This work was supported by the Technology Innovation Program (RS-2024-00421310, Development of power pack control optimization technology applied to single module fuel cell system) funded By the Ministry of Trade, Industry & Energy(MOTIE, Korea); and in part by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (RS-2024-00353106).

References

[1] THOMAS, C. E. Fuel cell and battery electric vehicles compared. international journal of hydrogen energy, 2009, 34.15: 6005-6020.

[2] MOHAMMED, Adem Siraj, et al. Review of optimal sizing and power management strategies for fuel cell/battery/super capacitor hybrid electric vehicles. Energy Reports, 2023, 9: 2213-2228.

[3] GARCÍA, Pablo, et al. Viability study of a FC-battery-SC tramway controlled by equivalent consumption

minimization strategy. *International journal of hydrogen energy*, 2012, 37.11: 9368-9382.

[4] SUN, Xiaoxiao, et al. A real-time PMP energy management strategy for fuel cell hybrid buses based on driving segment feature recognition. International journal of hydrogen energy, 2021, 46.80: 39983-40000.

[5] HU, Xiaosong; LI, Shengbo; PENG, Huei. A comparative study of equivalent circuit models for Li-ion batteries. *Journal of Power Sources*, 2012, 198: 359-367.

[6] JUNG, Jaekwang, et al. Optimal Energy Management Strategy for Repeat Path Operating Fuel Cell Hybrid Tram. *Energies*, 2024, 17.7: 1560.

[7] HAN, Ying, et al. Multisource coordination energy management strategy based on SOC consensus for a PEMFC–battery–supercapacitor hybrid tramway. *IEEE Transactions on Vehicular Technology*, 2017, 67.1: 296-305.

Presenter Biography

Dongeon Kim is a Ph.D. candidate in the Department of Mechanical Engineering, Hanyang University ERICA Campus, Ansan, South Korea. His Current focus is on system-level energy analysis for xEVs and optimal control-based energy management systems. He is also interested in real-world adaptation of these strategies and vehicle powertrain modeling.