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Optimizing the Purging Interval of 1 kW PEM Fuel Cell Control System in Fuel Cell Vehicles

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Abstract

This study aimed to explore and understand the duration of purging in fuel cell control systems and their application in fuel cell vehicles. The control system significantly impacts the overall performance and efficiency of vehicles or devices utilizing fuel cell technology. The research method involved modeling and simulation using the SIMULINK-MATLAB platform. The modeling was performed with a program and then validated using test data. This approach allowed researchers to replicate and analyze system dynamics virtually, enabling the identification of empirical models for existing systems. Additionally, by understanding the model and simulation, the performance characteristics of the given parameters could be determined before physical implementation. The study results showed that the modeling, conducted using a transfer function model 0.02635 s + 1.036/s + 0.04359, matched the test results with an 87.19% fit to the estimation data. This high level of validity indicates that the model identification was suitable for this study. The contribution of our study is to address the lack of research modeling the purging interval of fuel cell vehicles based on road test data.

Keywords:

fuel cell vehicle, purging interval, SIMULINK-MATLAB simulation, control system, transfer function model

1. Introduction

Proton Exchange Membrane Fuel Cell (PEMFC) is a type of fuel cell that operates at a low temperature, around 60–80 ºC (Peksen, 2021). This makes PEMFC suitable for use in motorized vehicles, including both passenger and commercial vehicles. Beyond serving as the primary propulsion power source, PEMFC can also be utilized as an additional power source in hybrid vehicles, enhancing their efficiency and performance (Raceanu et al., 2022). Fuel cell electric vehicles (FCEVs) offer several advantages, such as zero harmful tailpipe emissions, broad operating power capabilities, and short refueling times. The only byproducts of FCEVs are water and heat (Mancino et al., 2023). Market research anticipates significant growth in the fuel cell vehicle market by 2030. However, a crucial prerequisite for this growth is the development of a robust and reliable infrastructure to support fuel-cell vehicles (Manoharan et al., 2019).

A purge process is recommended at the start-up and shut-down of the fuel cell and test system. Typically, in laboratory testing, fuel cell purging is done using inert gases such as nitrogen. However, during fuel cell vehicle operation, the purging process employs hydrogen from the fuel cell system. This purge process is necessary to improve stack durability (Fauziah et al., 2023) and to manage the water vapor produced by electrochemical reactions, which can lead to flooding (Pedicini et al., 2023).

The purging interval and duration must be carefully adjusted to ensure optimal cleaning without causing damage to the fuel cell stack or impairing system performance (Jian et al., 2018).

Studies modeling the purging interval of fuel cell systems are growing. Niu et al (2024) analyzed and optimized the purge strategy for PEMFC, particularly focusing on unmanned aerial vehicle (UAV) applications, seeking the optimal purge strategy to ensure stable power output and consistent cell voltage of PEMFCs. Wang et al (2024) conducted three different start-stop tests during the purge test to find the optimal startup and shutdown process. Lu et al (2024) estimated the impacts of several operating conditions on PEMFC performance during operation with anode purges. Fauziah et al. (2023) evaluated the performance of a 1 kW PEMFC with a dead-end anode type and determined its empirical models.

Nevertheless, these previous studies solely relied on modeling analysis, resulting in gaps in the analysis using empirical data from real-world road tests. Our study aims to fill this gap by modeling the purging interval of a commercial 1 kW fuel cell system based on road test data. The results are expected to contribute to optimizing fuel cell applications in vehicles.

2. Methods

The stages of the study are illustrated in Figure 1. The study begins by collecting or using data from previous studies. This data is processed into a table showing the relationship between load and purging time. The data is then imported into MATLAB for curve fitting using the available toolbox. This process involves trial and error to determine the most suitable equation model for the input data. Once an appropriate equation is obtained, the model is created and then simulated using SIMULINK. The simulation results are validated against actual test data. If the simulation matches the test data, the model is considered appropriate. If not, the model creation is repeated to achieve a suitable model. The results of data validation confirm the accuracy of the model.

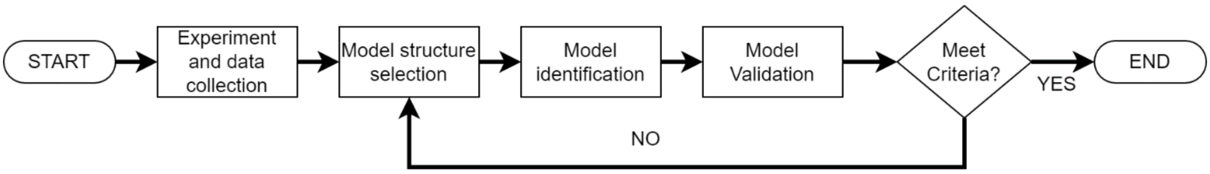

Figure 1. Study stages to find out the appropriate simulation model.

2.1 Experiment and Data Collection

The data collection process involves operating a fuel cell vehicle equipped with a data logger to measure and store all pertinent test information during a road test. During this phase, the fuel cell vehicle is actively driven, and the data logger records comprehensive data on vehicle performance, operational parameters, and other relevant variables. The parameters collected include voltage and current from the fuel cell to the motor, purging duration, and drive distance. The load experienced by the fuel cell varies according to how the driver uses the throttle pedal while driving. The route includes straight lanes, uphill, and downhill sections, causing variations in load due to differing power demands based on the desired acceleration and speed.

2.2 Model Structure Selection

The model structure selection method involves inputting the collected data into a spreadsheet and then performing curve fitting. Through this process, a model in the form of a non-linear transfer function was derived. A transfer function is a mathematical representation used to model the dynamic behavior of a linear time-invariant (LTI) system. It is typically expressed in the frequency domain as the ratio of the Laplace transform of the system's output to the Laplace transform of its input, assuming all initial conditions are zero. In MATLAB, transfer functions are represented using the *tf* object, which encapsulates the numerator and denominator polynomials of the transfer function. This allows for efficient analysis, design, and simulation of control systems within the MATLAB environment. The curve fitting process using imported data can be done manually with the *fit()* and *fitobject* commands, which contain information about the adjusted curve. This object can be used to display a curve, calculate a curve value for a specific point, or obtain curve parameters. Alternatively, the Curve Fitter toolbox in the apps section of MATLAB, illustrated in Figure 2, can be used.

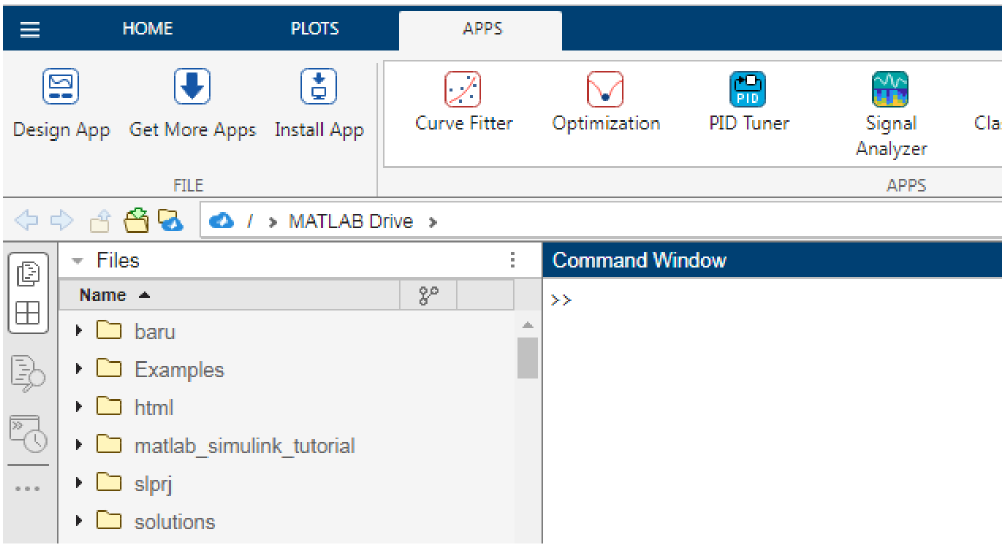

Figure 2. Curve fitter toolbox display in MATLAB.

2.3 Model Identification

The *tfest* function in MATLAB is used for estimating transfer functions from measured input-output data. This function is part of the System Identification Toolbox and allows users to fit a transfer function model to the data by determining the parameter coefficients of the numerator and denominator polynomials. The function of *tfest* supports both continuous-time and discrete-time transfer function models and provides options for specifying the model order and handling various data preprocessing tasks. This function is essential for identifying the dynamic characteristics of a system based on empirical data, facilitating the development and refinement of control strategies. A transfer function is expressed as $sys(s) = N(s)/D(s)$, where $s = jw$ and $N(s)$ and $D(s)$ are the numerator and denominator polynomials, respectively. Using *tfest*, trial and error can be performed with variations in the number of zeros and poles in the numerator and denominator to find the best-fitting model.

2.4 Model Validation

Model validation was performed by inputting the collected data. Subsequently, the fit to the estimation data was examined. This process was repeated continuously to achieve the highest fit value to the estimation or until the criteria were met. Once obtained, this function transfer aligns with the actual conditions. Figure 3 shows a block model representing the test data results and the identification model for the system. The inclusion of a gain in this block facilitates graph interpretation, enabling an analysis of the level of conformity between the predicted model and the actual system. This visual representation aids in enhancing the clarity of the analysis, making it more accessible for researchers and readers to assess the accuracy of the model predictions compared to the real-world system. The signals originate from a uniform number block to represent loads with values ranging from 5 to 30. The data are the output of a curve block derived from a data lookup based on data collection. The transfer function (*tf*) is the output of the signal after being simulated within the model.

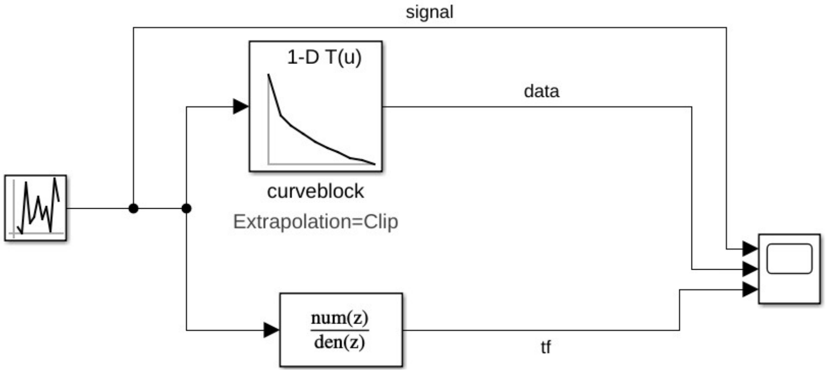

Figure 3. SIMULINK model for data validation.

2.5 Fuel Cells

The fuel cell used is a proton exchange membrane (PEM) type, specifically the Horizon H-1000XP model, with a capacity of 1000 watts, as specified in Table 1. Figure 4 presents a simplified schematic of this fuel cell, which is installed in a light electric vehicle with a motor capacity of 1 kW and a motor voltage of 36 Volts. This vehicle is equipped with a 30Ah lithium battery connected in parallel with the fuel cell stack. The power contribution between the battery and fuel cell is referred to as the hybridization ratio (Bonnet et al., 2021). The hybrid use of fuel cells and batteries extends the driving range and enhances the vehicle's overall reliability (Kurniawan et al., 2020). The vehicle does not feature regenerative braking functionality and thus requires a charger connected to the grid for battery charging.

Table 1. Specification of Horizon PEMFC H-1000XP.

Parameters	Values
Type of fuel cell	PEM
Number of cells	50
Rated power	1000W
Rated performance	30V@33.5A
Reactants	Hydrogen and Air
External temperature	5 35°C
Max stack temperature	65°C
Composition	99.99% dry H_2
H_2 pressure	7.2–9.4 Psi
Humidification	Self-humidified
Cooling	Air
Weight	5kg
Dimensions	203x104x264 mm
Flow rate at rated output	12.5L/min
Peak efficiency of stack	59%

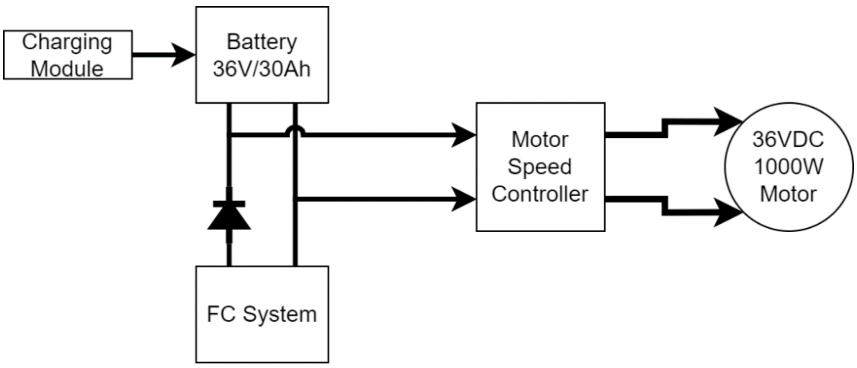

Figure 4. Fuel cell and battery installation in the vehicle.

Figure 5 illustrates the electrical and control diagram of the fuel cell system used in this study. Solenoid valves manage the hydrogen gas system's inlet and outlet, simplifying operation (Xu, 2023). During operational phases, the supply valve remains fully open, while the purge valve is always closed and only opens according to control settings. It is noted that the actual flow rate is always higher than the stoichiometric flow rate (Bartolucci et al., 2023). The output power from the fuel cell is used for internal electrical consumption, with the remaining power dedicated to the vehicle load. Initially, the system relies on the battery for startup. Once operational, all electrical needs are supplied by the fuel cell stack. When the fuel cell cannot provide sufficient power, the battery will supply the necessary power (Muñoz et al., 2017).

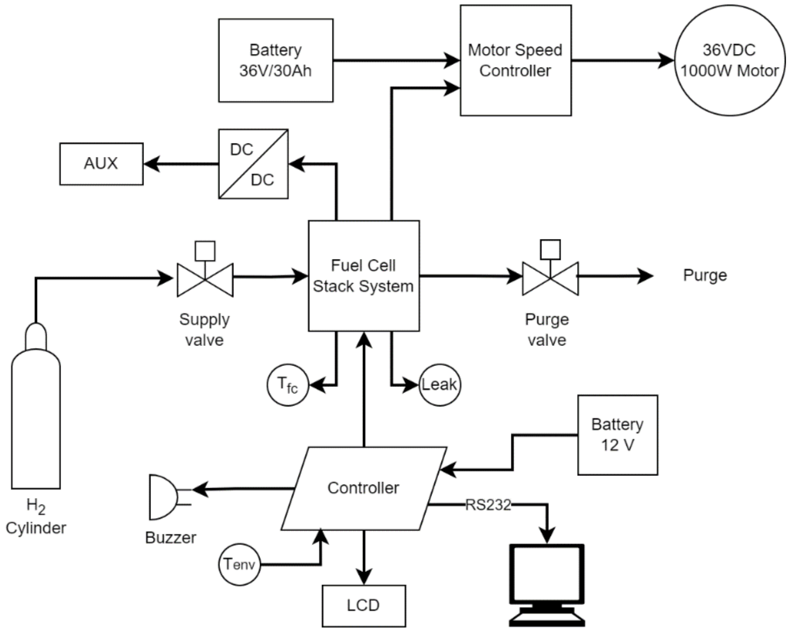

Figure 5. Electric circuit diagram of the horizon H1000-XP fuel cell system connected to FCEV.

2.6 Simulation

To identify the modeling, an estimate of the transfer function model, using the *tfest* and grey box method modeling techniques, is employed to characterize the system. The goal is to construct mathematical models that represent the behavior of a dynamic system based on input and output data. The grey box method helps to reduce the complexity of the unknown system while improving accuracy (Rogers et al., 2017). The model was validated using the SIMULINK application within MATLAB, with variable input. We utilized MATLAB version R2023b, available online for a limited duration at no cost. This software choice facilitated the modeling process and provided cost-effective access to the necessary tools and functionalities required for the analysis.

3. Results and Discussions

The curve fitting using MATLAB shows that the purging interval does not follow a linear equation but rather a nonlinear one. This nonlinear purging interval supports the findings of Fauziah et al. (2023), concluding that the purging interval decreased exponentially with increased load. The complexity of the relationship between the purging interval and other variables is evident through the nonlinear nature of the established equation. This emphasizes the need for sophisticated analytical tools and methods to accurately capture and model these intricate dynamics.

Figure 6 illustrates the curve depicting the relationship between the magnitude of the load applied to the fuel cell and the duration or distance of purging, which is commonly managed using methods such as PI logic and fuzzy logic (Radica et al., 2021). As the load increases, the purging duration becomes shorter. This is expected, as the purging process aims to expel impurities and non-reactive hydrogen gas, though it also results in a loss of energy as hydrogen is released into the atmosphere (Szwajca et al., 2022).

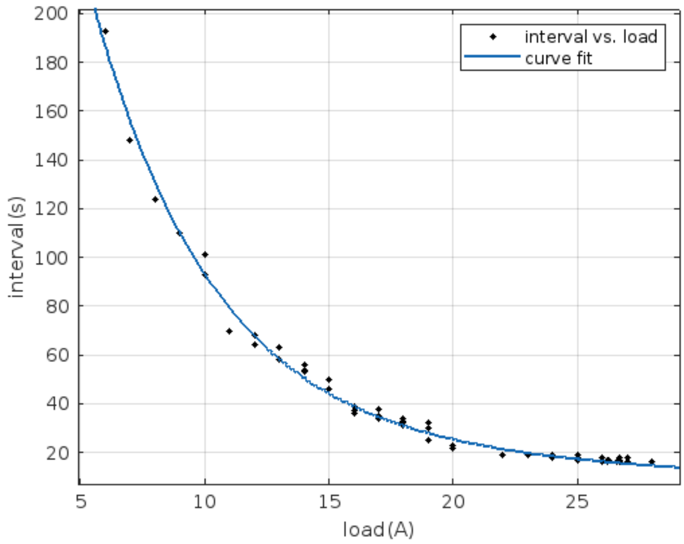

Figure 6. Curve fit results between test data for the interval between purging duration and load on the fuel cell system.

Based on the outcomes of the Transfer Function Estimation (TFEST) using various transfer function models, the fitting results to the estimation data show a percentage match of 85.68% for a model with one pole and zero, and 87.19% for a model with one pole and one zero, among others, as depicted in Table 2. These percentages indicate the degree of alignment between the estimated transfer function models and the actual data, providing a quantitative measure of the model's accuracy in capturing the underlying dynamics of the system under investigation. The findings in Table 2 underscore the efficacy of the TFEST method in achieving a reasonable fit to the data and offer insights into the appropriateness of different model configurations for describing the system's behavior.

$$H_{(s)} = b_1 / s + a_1 \quad (1)$$

Table 2. Fit to estimation data using TFEST

Estimated using TFEST	Numerator / Denominator	Fit to estimation data
Number of poles: 1 Number of zeros: 0	[0.9223] / [s + 2.41e-07]	85.68%
Number of poles: 1 Number of zeros: 1	[0.02635 s + 1.036] / [s + 0.04359]	87.19%
Number of poles: 2 Number of zeros: 0	[-26.53] / [s^2 + 31.55 s + 1.453e^{-10}]	-54%
Number of poles: 2 Number of zeros: 1	[-0.9099 s - 52.94] / [s^2 + 48.22 s + 1.676e^{-10}]	-83.14%

The most closely aligned results were obtained with a model characterized by one pole and one zero, demonstrating a fit to the estimation data of 87.19%. The transfer function equation corresponding to this model is as follows:

$$0.02635\,s + 1.036/s + 0.04359 \quad (2)$$

Figure 7 shows the simulation results of the created model. The green line represents the signal variation indicative of a variable load, the blue line corresponds to the lookup values derived from experimental data, and the orange line reflects the modeling outcomes from the transfer function. The transfer function model generated through the TFEST process produces a gradient consistent with the actual system, represented by the blue line. Notably, the fluctuation in the purging interval aligns with changes in the load, as observed in the simulation results. This concordance underscores the efficacy of the transfer function model in capturing the dynamic interplay between purging intervals and varying loads, affirming its suitability for representing real-world system behavior.

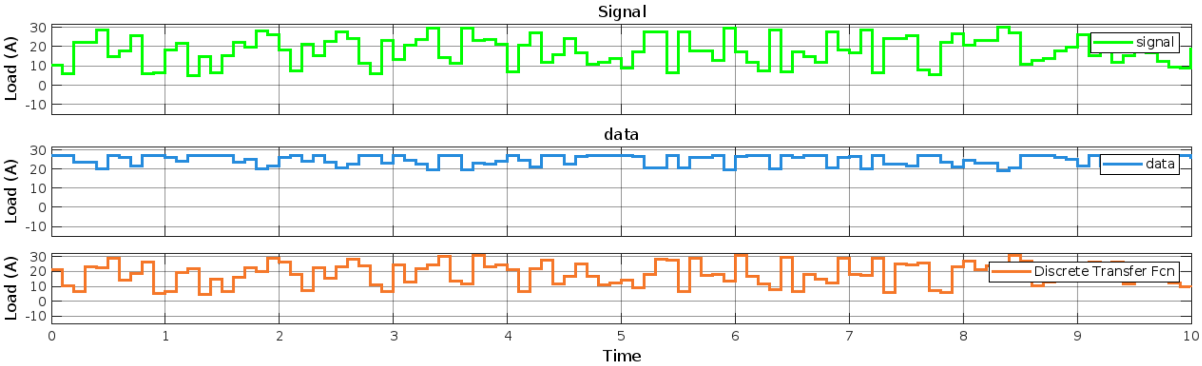

Figure 7. SIMULINK model validation graph.

4. Conclusions

Using the SIMULINK application, we determine the empirical model of a system that is not yet fully understood. The Gray Box method, which combines systems with unknown dynamics, is used in conjunction with data collection from experimental results. For fuel cell vehicles, this approach yielded a curve fitting of f(x) = ae(bx) + ce(dx) where Fx is the purging interval (s), a,b,c, and d are constants with values 554.4629, -0.2068, 30.4678, and -0.0297, respectively. The model achieved an R-square value of 0.9928, indicating a high degree of fit.

From the TFEST results, a transfer function model of 0.02635 s + 1.036 / s + 0.04359 was obtained and subsequently validated with an 87.19% fit to the estimation data. This finding is further substantiated by the modeling results and simulations, which yield graphs that align with the actual system behavior. The modeled system reacts according to the provided inputs, reinforcing the transfer function model's accuracy in capturing the real-world system's dynamic response.

This alignment between the modeled and actual system responses underscores the robustness and effectiveness of the identified transfer function in representing the system's intricacies in this study. As a contribution, this study complements and enriches the research conducted by Fauziah et al. (2023), not only by determining the empirical model but also by enabling simulation, thereby expanding the scope of understanding of the purging process in fuel cell vehicles. For further research, we recommend using a data acquisition system with a low-order measurement duration or in the millisecond range to obtain more comprehensive purging data measurements.

References

Bartolucci, L., Cennamo, E., Cordiner, S., Donnini, M., Grattarola, F., Mulone, V., & Pasqualini, F. (2023). Fuel cell hybrid electric vehicles: Fuel cell experimental characterization and modeling towards the development of a hardware-in-the-loop platform for advanced powertrain design. *Journal of Physics: Conference Series*, *2648*(1), 012063. https://doi.org/10.1088/1742-6596/2648/1/012063

Bonnet, C., Raël, S., Hinaje, M., Guichard, S., Habermacher, T., Vernier, J., François, X., Péra, M.-C., Lapicque, F., Université de Lorraine, CNRS, LRGP, F-54000 Nancy, France, Université de Lorraine, GREEN, F-54000 Nancy, France, H2SYS SAS, H2Sys, Campus of the Technology

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Fauziah, K., Kurniawan, Kurniasari, A., Astriani, Y., Samodra, B., Rostyono, D., & Eniya Listiani Dewi. (2023). Performance test of 1 kW PEM fuel cell system to determine its empirical model. *Evergreen*, *10*(3), 1982–1990. https://doi.org/10.5109/7151761

Jian, Q., Luo, L., Huang, B., Zhao, J., Cao, S., & Huang, Z. (2018). Experimental study on the purge process of a proton exchange membrane fuel cell stack with a dead-end anode. *Applied Thermal Engineering*, *142*, 203–214. https://doi.org/10.1016/j.applthermaleng.2018.07.001

Kurniawan, K., Abdul Hamid Budiman, Ferri Hermawan, & Anton Rahmawan. (2020). Design of control and human machine interface (HMI) for proton exchange membrane fuel cell. *Indonesian Journal of Energy*, *3*(1), 12–18. https://doi.org/10.33116/ije.v3i1.46

Lu, Y., Wang, X., Yang, G., Gong, D., & Xu, S. (2024). Experimental study on the influence of operating conditions on performance decline with periodic anode purges in a vehicular PEMFC stack. *International Journal of Hydrogen Energy*, *69*, 1276–1286. https://doi.org/10.1016/j.ijhydene.2024.05.159

Mancino, A. N., Menale, C., Vellucci, F., Pasquali, M., & Bubbico, R. (2023). PEM fuel cell applications in road transport. *Energies*, *16*(17), 6129. https://doi.org/10.3390/en16176129

Manoharan, Y., Hosseini, S. E., Butler, B., Alzhahrani, H., Senior, B. T. F., Ashuri, T., & Krohn, J. (2019). Hydrogen fuel cell vehicles; Current status and future prospect. *Applied Sciences*, *9*(11), 2296. https://doi.org/10.3390/app9112296

Muñoz, P. M., Correa, G., Gaudiano, M. E., & Fernández, D. (2017). Energy management control design for fuel cell hybrid electric vehicles using neural networks. *International Journal of Hydrogen Energy*, *42*(48), 28932–28944. https://doi.org/10.1016/j.ijhydene.2017.09.169

Niu, T., Yu, X., Zhang, C., Wang, G., Han, M., Liu, H., Zhao, F., & Shuai, Q. (2024). Purge strategy analysis of proton exchange membrane fuel cells based on experiments and comprehensive evaluation method. *Fuel*, *363*, 130970. https://doi.org/10.1016/j.fuel.2024.130970

Pedicini, R., Romagnoli, M., & Santangelo, P. E. (2023). A critical review of polymer electrolyte membrane fuel cell systems for automotive applications: Components, materials, and comparative assessment. *Energies*, *16*(7), 3111. https://doi.org/10.3390/en16073111

Peksen, M. (2021). Hydrogen technology towards the solution of environment-friendly new energy vehicles. *Energies*, *14*(16), 4892. https://doi.org/10.3390/en14164892

Raceanu, M., Bizon, N., & Varlam, M. (2022). Experimental results for an off-road vehicle powered by a modular fuel cell systems using an innovative startup sequence. *Energies*, *15*(23), 8922. https://doi.org/10.3390/en15238922

Radica, G., Tolj, I., Markota, D., Lototskyy, M. V., Pasupathi, S., & Yartys, V. (2021). Control strategy of a fuel-cell power module for electric forklift. *International Journal of Hydrogen Energy*, *46*(72), 35938–35948. https://doi.org/10.1016/j.ijhydene.2021.01.225

Rogers, T. J., Holmes, G. R., Cross, E. J., & Worden, K. (2017). On a grey box modelling framework for nonlinear system identification. In N. Dervilis (Ed.), *Special topics in structural dynamics, Volume 6* (pp. 167–178). Springer International Publishing. https://doi.org/10.1007/978-3-319-53841-9_15

Szwajca, F., Berger, A., Spalletta, R., & Pielecha, I. (2022). Characteristics of fuel cells under static and dynamic conditions. *Rail Vehicles/Pojazdy Szynowe*, *3–4*, 44–52. https://doi.org/10.53502/RAIL-157516

Wang, F., Xie, M., Yang, D., Ming, P., Li, B., & Zhang, C. (2024). Study on the process of idle startup and shutdown optimization of fuel cell system. *International Journal of Hydrogen Energy*, *67*, 24–32. https://doi.org/10.1016/j.ijhydene.2024.03.348

Xu, L. (2023). Challenges and optimization of PEMFC system in vehicles. *Journal of Physics: Conference Series*, *2608*(1), 012045. https://doi.org/10.1088/1742-6596/2608/1/012045