ISSN: 2834-4928

Research Article

Journal of Electrical Electronics Engineering

Optimal Control Strategy for PEM Hybrid Electric Vehicle using Matlab Simulink

Ajay Ahuja[1]*, D. R. Waghole[1] and Sushil S. Ramdasi[2]

[1]*Research Scholar (Mechanical Engg), Dr. Vishwanath Karad MIT World Peace University, Pune India*

[1]*Associate Professor, (Mechanical Engg), Dr. Vishwanath Karad MIT World Peace University, Pune India*

[2]*Deputy Director, Automotive Research Association of India, Pune India*

***Corresponding Author**
Ajay Ahuja, Research Scholar (Mechanical Engg), Dr. Vishwanath Karad MIT World Peace University, Pune India.

Submitted: 30 Mar 2023; **Accepted:** 06 April 2023; **Published:** 21 April 2023

Citation: Ahuja, A., Waghole, D. R., Ramdasi, S. S. (2023). Optimal Control Strategy for PEM Hybrid Electric Vehicle using Matlab Simulink. *J Electrical Electron Eng, 2*(2), 97-108.

Abstract
The conventional fossil fuels are being replaced by alternate energy sources very fast. This is mainly due to the limited resources left in the Nature and the polluting characteristic of fossil fuel. Only thirty additional years are left for the supply of fossil fuels. The extreme climate change is largely attributed to automotive fossil fuel burning. The advent of pure Electric vehicles has resulted in reduction of harmful greenhouse gas emissions. It addresses the answer to the concerns of oil resource depletion, air pollution and climate changes. The benefit of using electric power in automotive sector is immense. However, the outcome of hybrid EVs can surpass pure EVs due to its capability of charging on the go, hence no extra charging time. In absence of any moving parts in a fuel cell, the maintenance and noise are also minimal. PEM fuel cell is a most eligible power source having reduced emissions and high efficiency characteristics. The efficiency of hybrid vehicle is a result of charging effectiveness. Control Strategy plays an important role in conservation and elevating energy whenever required. These are the energy power banks to optimize battery sizing and minimize losses. This paper explains a control strategy to enhance efficiency of FCHV system along with reduction of hydrogen consumption. This is achieved by maximizing fuel cell efficiency by balancing the power split between battery and fuel cell. The rule based strategy results in maximizing fuel cell system efficiency by sustaining the state of charge (SOC) of the battery. The SOC is aimed to be kept around a value which can address extremely low charge and high charge condition of the battery. At the same time, load on fuel cell is switched in a manner so as not to have a sudden ascent or descent of power, which helps in preventing the terminal deterioration in the fuel cell. Hence, PEMFC works as Range extender to the powertrain system and charges the battery while the vehicle is moving. The fuel cell efficiency and durability is maximized by balancing the power split between battery and fuel cell. The rule based strategy is applied in order to maximize fuel cell system efficiency and sustaining the state of charge (SOC) of the battery.

Keywords: FC, PEMFC, Hybrid, Regeneration, FCHEV, PEM, Fuel Cell, IDC, MIDC, Control Strategy, Efficiency, Optimal Control

Introduction

A Proton Exchange Membrane Fuel Cell (PEMFC) has gained importance in mobile and automotive applications due to its ease of control. PEMFC along with battery can fully replace an internal combustion engine (ICE) and this is the reason PEMFC system in an automobile is becoming a huge success [1]. This is due to its simple architecture, high power density, stability, and quick start at low operating temperatures. PEM Fuel cells offer low weight and volume as compared to other fuel cells. PEM Fuel cells require pure Hydrogen in mobile containers in automobiles for electrochemical reaction on the go. The efficiency of usage of Hydrogen in PEM fuel cell is greatly emphasized. Design optimization and durability of PEMFC is highly desired in a Hybrid electric vehicle. This may be directly attributed to control strategy used in PEMFC hybrid electric vehicle. If PEMFC is only used as the energy source to the vehicle powertrain, the large fluctuations at the outlet may reduce the life of it [2].

The performance of PEMFC is estimated using Mathematical models and the Control Strategy is devised to maximize fuel efficiency using simulation in MATLAB/Simulink. The Battery is usually coupled parallelly with fuel cell through a DC/DC converter. The battery provides the transient power to the powertrain and gets charged with fuel cell and regenerative braking during braking and slow down. The parallel arrangement of two energy sources, battery and fuel cell through DC/DC converter provides a quick startup of vehicle and makes possible the charging of battery using regenerative braking. This application of parallel energy sources can be experienced in Toyota Mirai and Honda FCX Clarity [3-5].

Literature Review

Won (2006) assessed the effect of different control calibrations and strategies in the power split, the vehicle efficiency, the battery utilization, and the PEMFC oxygen starvation. The assessment is performed on a model for two different driving cycles, FTP having mild and US06 having aggressive accelerations. Load-following to load-leveling control strategies were used in PEMFC operation to determine the required battery sizing in hybridization and the associated trends in the fuel economy.

Tao (2006) has done mathematical modeling of PEMFC to carry out a comprehensive parameter sensitivity examination and model validation.

San Martin (2010) has described both a theoretical and an experimental study of the dynamic performance of a commercial fuel cell and has analyzed the flow of hydrogen and air in the fuel cell.

Aziz (2011) explains the mathematical model of PEMFC using MATLAB/Simulink software. The paper provides the calculation of cell voltage, dynamic response and thermodynamic response. This model is used to analyze the PEMFC behavior and the characteristic of output values at different parameters.

Gao (2011) has presented a multiphysical PEMFC stack model suitable for real-time emulation and can be used in the hardware-in-the-loop applications.

Zhang (2013) presented a control design methodology for a 60 kW PEMFC generation system for residential applications. The results showed that the adaptive control strategy proposed was robust with respect to system variation and power demand.

Pratik (2013) has performed modeling and simulation of Polymer Exchange Membrane Fuel Cells, PEMFC for electrical energy generation systems.

Glazer (2013) has performed modeling and analysis of Fuel Cell Hybrid Vehicle, in which the fuel cell system is integrated with an on-board rechargeable energy storage system (RESS) for electric energy supply to propulsion and auxiliary systems, using MATLAB/Simulink.

Ziogou (2017) developed and demonstrated a novel strategy called Model Predictive Control (MPC) to achieve the power in demand while operating at a safe region, avoiding starvation, and concurrently minimize the fuel consumption at stable temperature conditions.

Raees (2018) has presented this research paper with a system-level model of a PEMFC plug-in series hybrid electric vehicle. With the help of this model, performance, energy efficiency and carbon footprint of H2EV are analyzed based on different standard drive cycle tests.

Mohiuddin (2018) has studied the mathematical simulation and experimentation of 1.2W PEMFC using MATLAB under steady state condition and has determined the polarization curve, power and efficiency curves of the fuel cell. He has also simulated and correlated with experiment the amount of hydrogen usage.

Lazar (2019) has presented a 1D PEMFC model which estimates the cell voltage based on activation, ohmic and concentration overpotentials using MATLAB/Simulink, suitable for real-time applications.

Stefan (2020) aims to develop new strategies for PEMFC system control that will minimize the degradation processes and provide high efficiency throughout optimal control. This study covers the main processes and working principles of PEMFC. Optimal control of such a system can improve efficiency and hence reduce the cost of ownership.

Anilkumar (2020) has performed Design and testing of proton exchange membrane fuel cell (PEMFC) power pack for platform vehicle.

Nazar (2020) has demonstrated the mathematical and MATLAB simulation model of 1 kW (28.8Vdc) PEMFC system to analyze the behavior of hydrogen fuel utilization. Two cases have been designed to evaluate the performance of this model. In the first case, fuel cell parameters are examined with and without a fuel regulator that controls the hydrogen fuel rate while in the second case, the operating temperature of a fuel cell stack is varied to observe the impact on the system.

Chatterjee (2020) has performed electric vehicle modeling and has studied the effect of different parameters on performance and efficiency of electric vehicle by using SOC estimation technique. Yousef (2021) has performed numerical modeling and evaluation of PEM used for Fuel Cell vehicles and studied the effects of various parameters.

Pengli (2022) summarizes and concludes various energy management strategies at the current stage and analyses the main roles, advantages and disadvantages of various energy management strategies.

Luciani (2022) examines different control strategies for optimizing the power split between the battery and PEMFC in order to maximize the system efficiency and reduce hydrogen fuel consumption. Different rule-based control strategies for PEMFC are analyzed with the aim of maximizing system efficiency while establishing a constant battery state of charge (SOC).

Yifan (2022) proved in his research that in high-powered application scenarios, a multi-stack PEMFC system has many advantages such as higher robustness, lifetime, and reliability than a single-stack system.

Zecchi (2022) and his work aims to develop a mathematical model for the simulation of a PEMFC hybrid powertrain. The work starts from modeling a single cell to obtain information on the entire stack. The model obtained was integrated into a simulation tool that simulates the longitudinal dynamics of hybrid electric vehicles and fully electric vehicles.

Research Methodology with hybrid PEMFC vehicle

The Hybrid Electric Vehicle (HEV) gets the required power from battery source or PEMFC or both. At the same time, battery gets charged by the Fuel cell. The vehicle runs on IDC or MIDC cycle, having the phases of Acceleration, Deceleration and Cruise during the cycle. The PEMFC, however, can't shift over the phases so quickly. Hence, the control strategy is used to be implemented in a manner that PEMFC provides power only during Cruise and not during Acceleration. The Control Strategy depends on the value of SOC, Acceleration of the vehicle and Power demand by the vehicle. This prevents quick change of stresses in PEMFC. The battery is charged during the cycle to attain a sustaining level of SOC, which ensures maximum power to be taken from battery during launch or acceleration of the vehicle. At the same time, it ensures minimizing the fluctuations in FC and preventing starvation. To avoid undesirable thermal stresses during the FC cycle, it is exercised to run at two levels of power output, one maximum and another to the minimum level to avoid large fluctuations of fuel flow over the whole cycle.

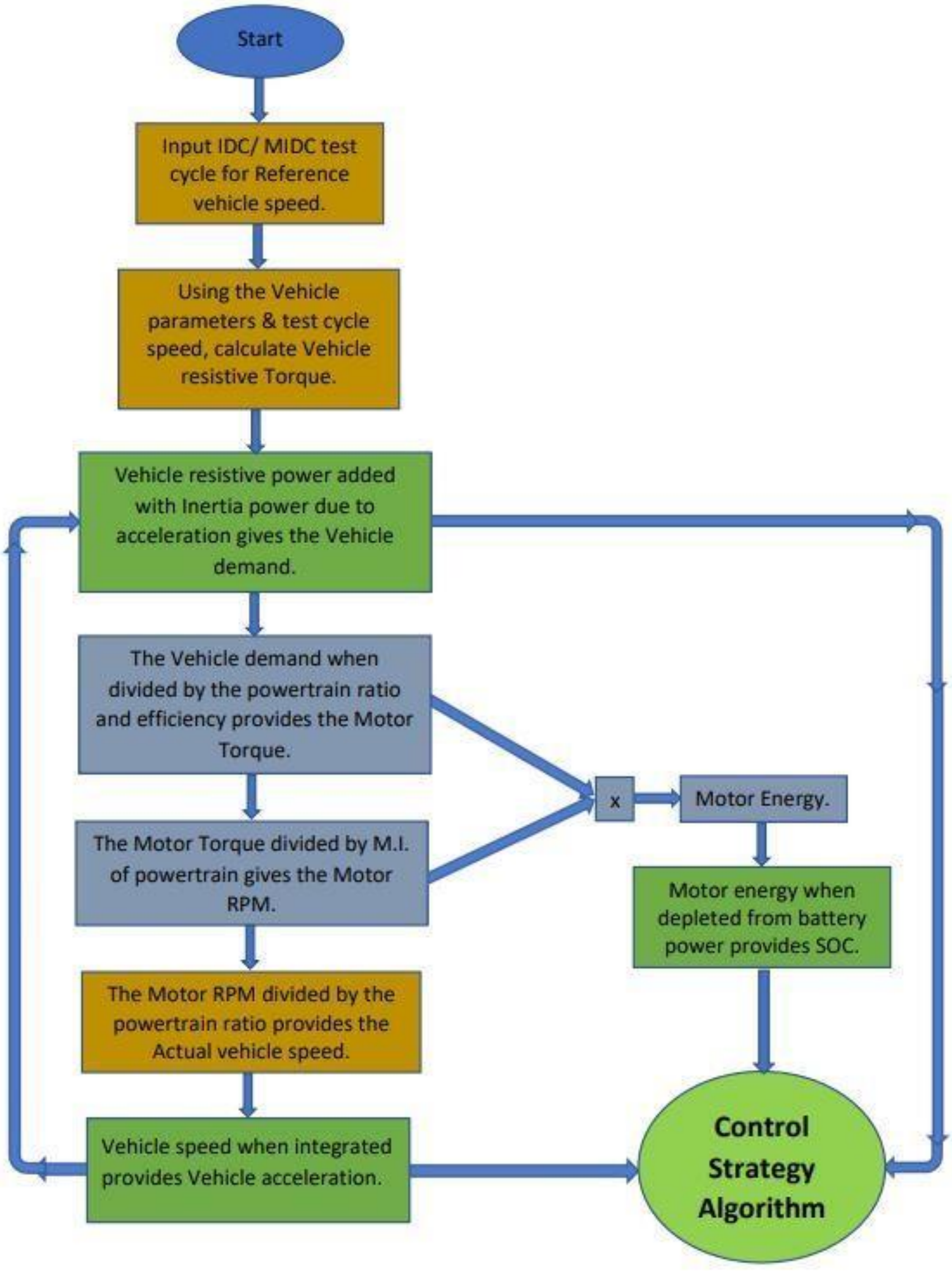

Figure 1: Research Methodology for Control Strategy Algorithm

The sustained charging or discharging in battery has been simulated using extrapolation of SOC gain or loss during one cycle. The excess power from FC during the cycle is used to charge auxiliary battery for the subsidiary functions in the vehicle. The research methodology used for hydrogen consumption on hybrid PEMFC vehicle is direct correlation between practical usage and that achieved through simulation during the IDC and MIDC cycles. The SOC, Acceleration and Power demand values on a vehicle have been compared with simulation results in MATLAB/ Simulink for achieving the optimized fuel consumption.

PEM Fuel Cell – Mathematical approach

A PEMFC comprises of an anode, a cathode and an electrolyte. The Anodes and Cathodes in a Polymer Electrolyte Membrane Fuel Cell (PEMFC) are separated by Catalyst layers. The Catalyst layer in a PEMFC separates the hydrogen molecules into positive Hydrogen ions and electrons, when hydrogen gas passes over the anode through channels. The permeable Polymer Electrolyte Membrane (PEM) allows only positive Hydrogen ions to pass through it. At the same time, the negatively charged electrons released from Hydrogen at Anode pass to the external circuit through the PEM in the form of current. This flow of electrons is the Electrical energy which performs work.

The electrochemical reactions in case of a PEM fuel cell may be enumerated as:

Anode reaction:

$$H_2 \rightarrow 2H^+ + 2e^-$$

Cathode reaction:

$$½O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

Overall reaction:

$$H_2 + ½O_2 \rightarrow H_2O + heat$$

(Exothermic reaction, ΔH= -286 kJ mol^{-1})

On the other side of PEMFC, Oxygen is supplied to the cathode through channels. The electrons returning from the external circuit react with oxygen at the cathode to make negatively charged Oxygen ions. Water is formed by the combination of positively charged Hydrogen ions passing through the PEM and the negatively charged Oxygen ions from Cathode. This is an exothermic reaction and the heat produced in the fuel cell can be utilized for heating cabins during winter.

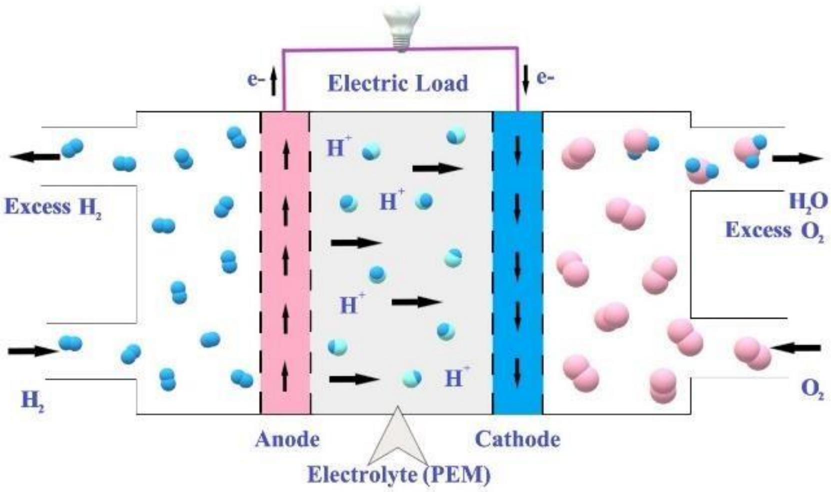

Figure 2: Polymer Electrolyte Membrane Fuel Cell (PEMFC) [5].

In a PEMFC, the ideal Open circuit Voltage is defined as the potential difference between Anode and Cathode when there is no current flowing through the external circuit. It is also termed as Nernst potential or Reversible voltage of the cell. Voltage losses are inevitable when the current flows through the external circuit. There are three losses involved in fuel cell output voltage, which include Activation Voltage drop, Ohmic Voltage drop, and Concentration Voltage drop. The output Cell voltage may be expressed as follows [27].

$$V_{Cell} = E_{nernst} - \Delta V_{act} - \Delta V_{ohm} - \Delta V_{conc} \quad (1)$$

With 'n' number of cells in PEMFC in series, the gross Output Power is defined as:

$$P_s = n * V_{Cell} * i_{Cell} \quad (2)$$

The pure Hydrogen fuel consumption (kg/s) can be obtained based on the current flowing in the PEMFC circuit, as:

$$\dot{m}_{H_2} = \frac{i_{Cell} * M_{H_2}}{n_e F} \quad (3)$$

The molar proportion of Oxygen in Air is 0.21. So, the Air mass flow rate (kg/s) can be obtained by using the equation:

$$\dot{m}_{Air} = \lambda * \frac{i_{Cell} * M_{Air}}{(0.21 * n_e F)} \quad (4)$$

The water produced (kg/s) in the PEMFC can be obtained as:

$$\dot{m}_{H_2O} = \frac{i_{Cell} * M_{H_2O}}{n_e F} \quad (5)$$

The difference between the heat generated and the amount of heat removed by the cooling system, defines the change in Heat within a PEMFC. This is represented by the expression [6].

$$\Delta\dot{Q} = \dot{Q}_{gen} - \dot{Q}_{rem} \quad (6)$$

The heat generated by the PEMFC is a function of Power and Efficiency, and may be calculated as:

$$\dot{Q}_{gen} = P_s\left(\frac{1}{\eta_{fc}} - 1\right) \quad (7)$$

The thermodynamic efficiency is an important parameter of a fuel cell and may be defined as the ratio of output power to the lower heating capacity of hydrogen consumed [7].

$$\eta_{fc} = \frac{P_s}{\dot{m}_{H_2} . LHV_{H_2}} \quad (8)$$

Power is a function of cell voltage; hence the thermodynamic efficiency may be simplified as:

$$\eta_{fc} = \frac{2\ V_{Cell}\, F}{M_{H_2} . LHV_{H_2}} \quad (9)$$

PEM Fuel Cell System

The use of PEMFC for automotive application is beneficial in many ways to the environment. If pure hydrogen is fed to the

PEMFC, there is no CO2 emission, only water is produced along with heat. Hydrogen is fed through the pressurized containers and oxygen is supplied through abundant air in atmosphere. To increase the efficiency in terms of hydrogen usage, the unused hydrogen is fed back into the system with humidity as required in the system and air is supplied through the compressor. In the ionic process inside the fuel cell, a lot of water is also formed. The same is extracted through the condenser from the air outlet and is again fed to the system for humidification, to avoid carbon deposition on electrodes. The formation of water inside the fuel cell is an exothermic reaction. The heat produced in the process has to be released out of the fuel cell through cooling circuit, which may be utilized for heating other systems [28-35].

A PEM fuel cell physical system may be classified in mainly four sub-systems:

Hydrogen Sub-System

Hydrogen is fed in pure form in order to avoid CO_2 emissions. The major challenge is in storing the hydrogen as it occupies a large volume, hence needs compression. In order to gain higher utilization efficiency, the excess hydrogen is fed back to the system.

Oxygen Sub-System

Air is present in abundance, hence compressed to the fuel cell. It is supplied with at least twice the stoichiometric ratio for better efficiency and life span.

Humidifier Sub-System

Both the input reactant gases are humidified to have reactions at controlled temperatures and reduce carbon deposition with a better life span.

Cooling Sub-System

The fuel cell reactions are exothermic in nature and release a lot of heat which needs to be stabilized in order to reduce thermal stresses and maximizing power output by reducing the various losses. The cooling system maintains optimal stack temperature by releasing the excess heat.

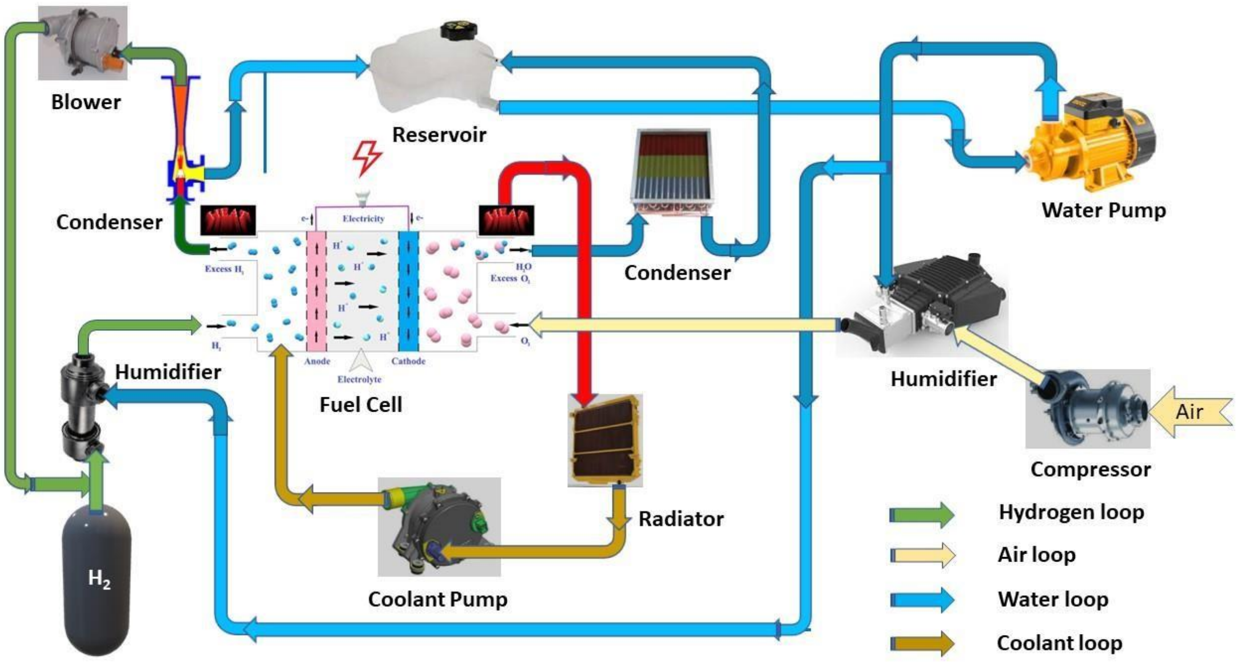

Figure 3: PEMFC Flow Schematic

The fuel cell power output largely depends on the stack temperature including that of the cell structure and electrolyte. The stack temperature in turn depends on the supply of reactant gases, the exhaust and the heat balance of the fuel cell. It has to be maintained to maximize power and enhance efficiency. The input and output controls play an important role in improving the overall efficiency and life span of the fuel cell [36-42]. There is an auxiliary power required to control the above sub-systems which contribute largely to the fuel cell efficiency.

The Compressor, Blower, Water pump and Coolant pump power put together constitutes the Auxiliary power requirement.

$$P_{Aux} = P_{Comp} + P_{Blower} + P_{Humidifiers} + P_{Cooling} \quad (10)$$

And, the system efficiency is defined as:

$$\eta_{sys} = \frac{P_s - P_{Aux}}{\dot{m}_{H_2} . LHV_{H_2}} \quad (11)$$

Vehicle Powertrain Architecture

Fuel cell may not be used alone to provide power to the vehicle. This is due to two main reasons, firstly due to power demand variation, it can deteriorate the cells faster and secondly, it may require a large storage of hydrogen on the go for a desired range of automobile. An FCHEV gets its power from a fuel cell and a battery in parallel for a vehicle powertrain. The demand power at wheels is met by fuel cell and battery by means of electric motor and gear train sub-system. The electric motor gets the power from an inverter which in turn is power boosted by DC/DC converter from the fuel cell and battery [43-47].

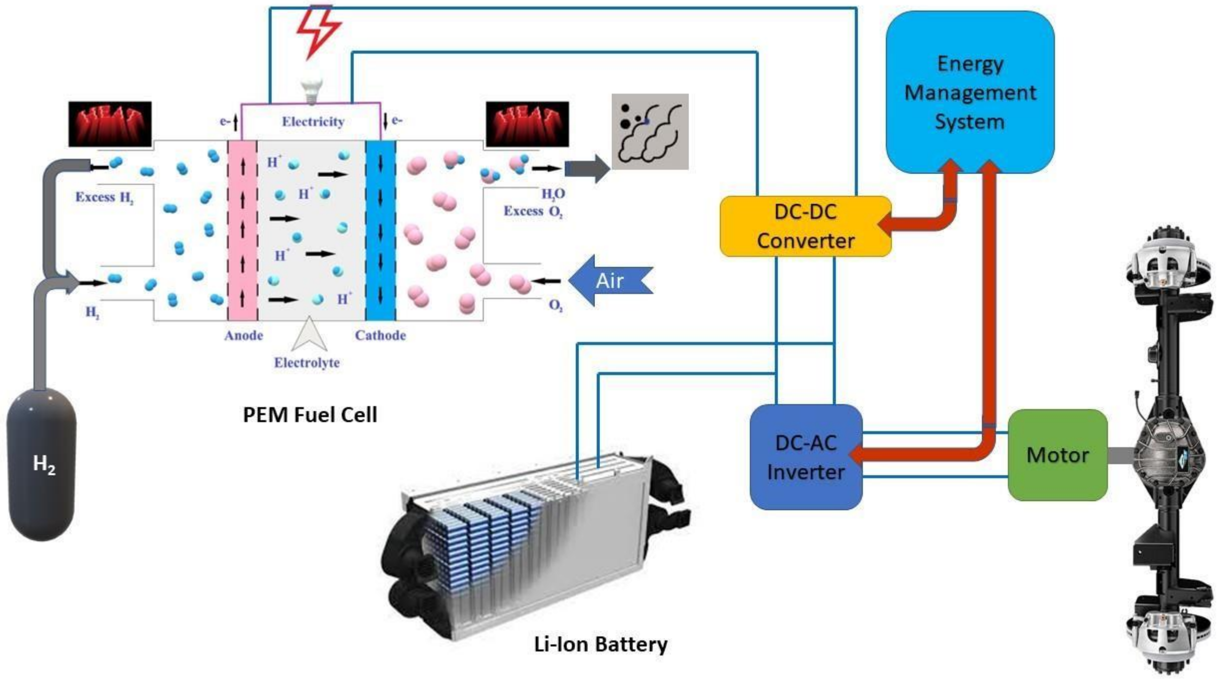

Figure 4: Hybrid PEM Fuel Cell Electric Vehicle [5].

The power required by the vehicle at the wheels include the rolling resistance of tires, the power due to aerodynamic drag, the power required to overcome the slope and power for vehicle acceleration. The resistive force is a function of vehicle velocity and may be enumerated, based on dynamometer measurement as:

$$F_{res} = \{A + (B * v) + (C * v^2)\} + \{Ma^2\} \quad (12)$$

The demand torque at the wheel becomes:

$$T_{wheel} = F_{res} * R_{wheel} \quad (13)$$

And the demand torque at the Motor becomes:

$$T_{motor} = \frac{T_{wheel}}{(N * \eta)} \quad (14)$$

The demand power by the Motor becomes:

$$P_{demand} = \frac{T_{motor} * \omega_{motor}}{\eta_{motor}} \quad (15)$$

The power in demand at the wheels is fulfilled either by Battery or by Fuel cell or both, hence:

$$P_{demand} = P_{batt} + P_{fc} \quad (16)$$

The Vehicle power architecture constitutes PEM Fuel Cell, Li-Ion Battery, DC/DC Converter, Inverter and Motor. The Battery is connected after the DC/DC Converter so as to get the Boost voltage for charging. It is in parallel to the Boost Converter & Inverter. Normally, the Boost voltage is set 10~15% higher than the Battery discharge voltage [26].

Fuel Cell Control Strategy

A PEMFC is a green source of energy for mobile and automobile applications. However, any impurity and starvation of hydrogen may lead to faster catalyst degradation, shorter catalyst life and oxidation of electrodes. All this may lead to temperature variations during power demand fluctuations and efficiency decline [48-56].

The overall objective of Control Strategy is to match the power demand in an optimum manner with maximizing efficiency and durability. This may be sub-divided and achieved with the following points:

- Minimizing hydrogen fuel consumption and air supply to the fuel cell.
- Maintaining a stable stack temperature for ensuring appropriate gas humidification.
- Avoiding input reactant gases starvation.
- Minimizing load fluctuations and thermal stresses on the fuel cell.

The safe operation of PEMFC is achieved by avoiding Cathode and Anode starvation, which is accomplished by supplying the input reactants, hydrogen and air in a certain excess ratio. Normally, the air excess ratio is taken as 2.0 and for hydrogen, it may be taken as 1.5 or 2.0 [16]. With the on-point power demand, the control system aims to maximize power and maintain the stack temperature by maintaining the excess ratio and controlling the cooling sub-system. This leads to achieving power demand with minimal load fluctuations on the fuel cell. The output power demand is controlled by distribution of power from Fuel cell and Battery. To satisfy these conditions, the fuel cell power is controlled within a minimal hydrogen flow control range. The control strategy for hydrogen and oxygen usage play an important role in minimizing fuel consumption and maximizing fuel cell performance efficiency [57-62].

To avoid large power fluctuations, vehicle power demand is set to be fulfilled by Battery during acceleration. The Fuel cell may take over during the cruise when acceleration is minimum, and Battery may get Regeneration power during negative acceleration. During all other phases, the excess power from Fuel cell may be utilized to charge Battery. However, FC is set to operate at a maximum or a minimum power rating. The power is primarily supplied by fuel cell through the DC/DC boost converter. The battery takes the regenerative energy during braking and fills up the gap of instantaneous power demand when fuel cell power is not sufficient. This may happen during acceleration. At the same time, during cruise phase of cycle, FC power is utilized directly to power the wheels.

To maximize efficiency and durability or life of a fuel cell, the Vehicle powertrain may operate in various operating modes depending upon the Power demand, Vehicle acceleration and SOC of Battery [63-65].

Hybrid Mode

This mode characterizes if the power required by the motor is greater than the maximum power of FC. During this, Fuel cell operates at its maximum power and the remaining power is supplied by the Battery.

FC Mode

In this mode, the power required by motor is in between the maximum and minimum set power of FC. During this, the Fuel cell operates at its maximum and powers the motor. At the same time, remaining FC power is utilized to charge the Battery.

Battery Mode

If the vehicle is accelerating, it draws a huge power in less time and may be served by Battery alone, in order to avoid large and frequent power fluctuations in FC.

Regeneration Mode

If the vehicle is decelerating, the regenerative energy may be utilized to charge battery. At the same time, FC may be operated at its minimum or maximum power depending on the SOC condition, to keep the Battery in Charge sustaining condition.

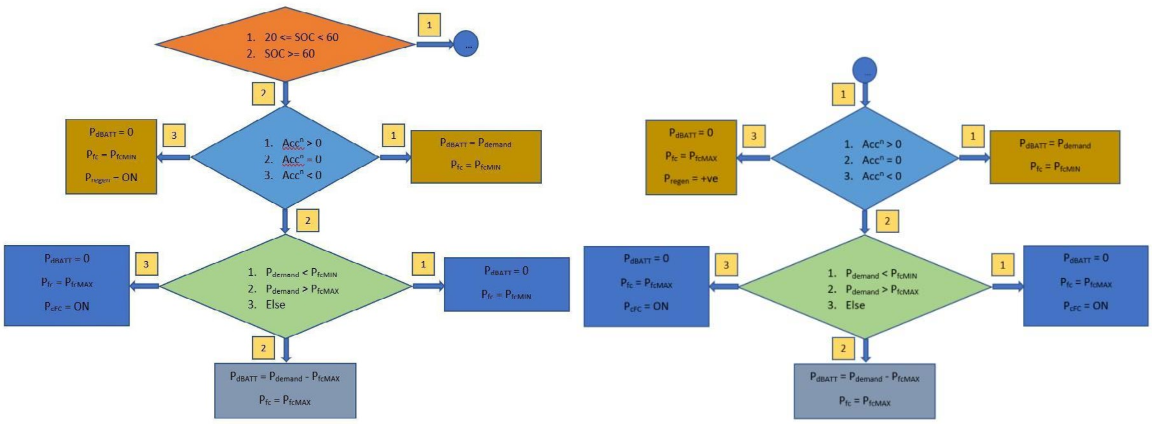

Figure 5: Control Strategy Algorithm for PEMFC

It is based on the battery SOC and vehicle Power demand that the PEMFC is set to deliver power either at minimum or maximum Power rating. Starting from a higher SOC level, the battery power is utilized until the SOC reaches its sustained charge. Once the sustaining charge is reached, fuel cell is kicked-off from its minimum-power mode to maximum-power mode and it charges the battery also during this period. By applying this strategy, the battery always stays at the sustaining charge level and fuel cell is also fully utilized at minimum hydrogen consumption level.

Starting from a lower SOC level, the PEMFC power is utilized to charge battery until the SOC reaches its sustained charge. Once the sustaining charge is reached, fuel cell is kicked-off from its maximum-power mode to minimum-power mode and it charges the battery also during this period. All this is defined in a controlled logic based on the SOC of battery, Vehicle acceleration and Power demand [40]. This strategy leads to a minimum hydrogen fuel consumption and at the same time, minimum fluctuation in PEMFC power. The FC power, during the process, is utilized to fulfill power demand at Motor, charging the Traction Battery and charging of Auxiliary Battery. Also, Battery charging is achieved through two power sources, one from the FC and another from the Regeneration.

Primarily, in case of steady-state operation of the vehicle, demand is met by the PEMFC and at the same time the fuel cell keeps the battery charged to a sustaining level for want of extra or immediate high power during acceleration. The fuel cell works as the Range extender for the vehicle and the optimal control strategy demands the battery to operate in a Charge sustaining mode. All this ends up into maximizing the system efficiency and life span of the fuel cell [66].

Simulation Results and Discussion

The Optimal control strategy has been implemented on two driving cycles, IDC and MIDC in the MATLAB/Simulink environment. The Simulation results depict the Power demand, Battery power and FC power. The FC power is used dynamically at the maximum and minimum power levels and Battery power is used during positive vehicle acceleration; however, both are used at the time of high-power demand. With this strategy, it has been ensured that SOC profile always stabilizes to 0.6 value and ensures battery power to be always available during launch of the vehicle. At the same time, FC is also optimally used to achieve controlled hydrogen consumption [67].

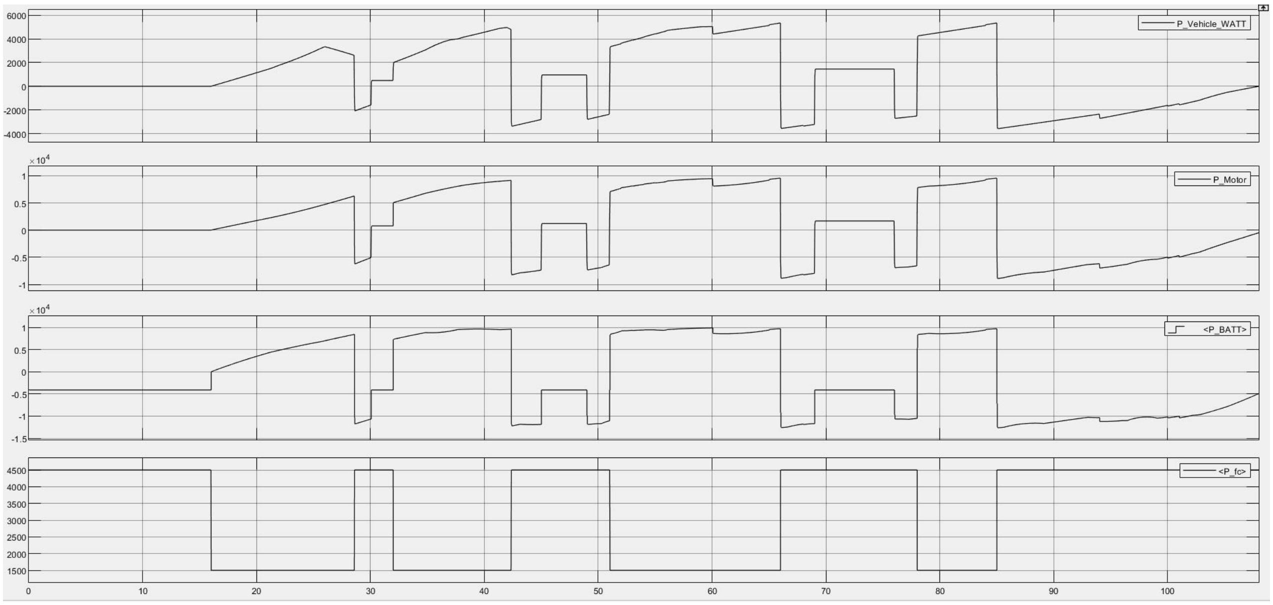

Figure 6: Hybrid PEMFC vehicle Power demand for IDC

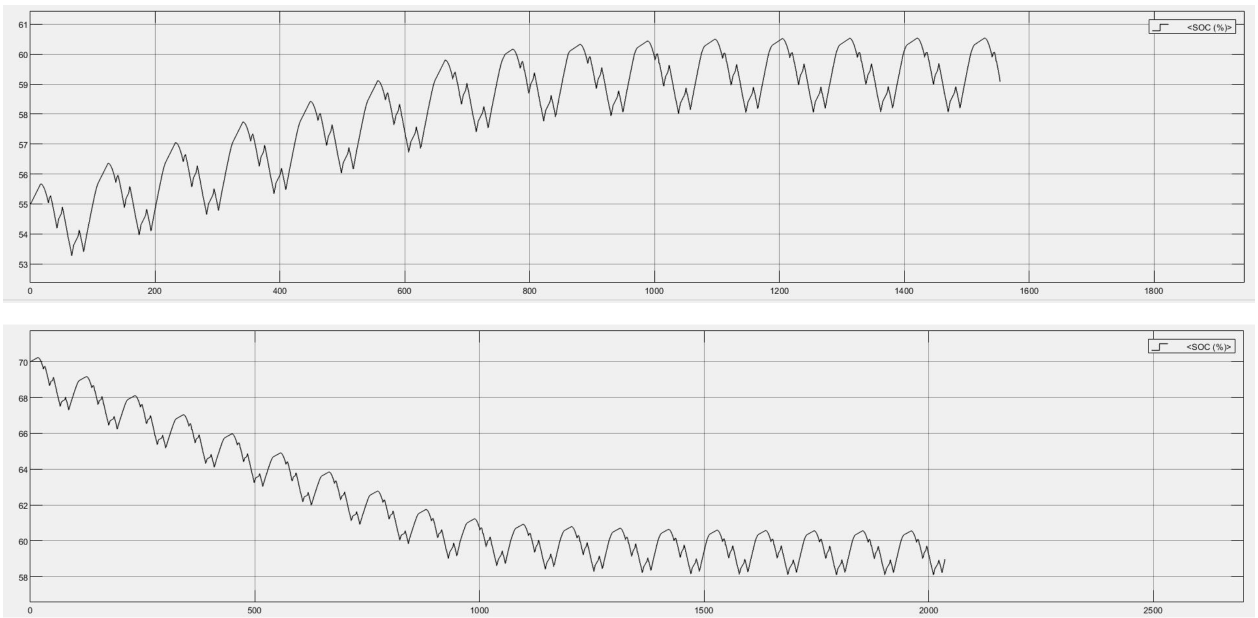

Figure 7: Hybrid PEMFC Control Strategy for IDC with sustained charge

The graphs in Fig. 7 depict the sustained charge SOC (%) and hydrogen consumption for an Automotive IDC. During every cycle, SOC gets a positive bonus to never keep the Battery below charge sustaining level. The IDC drive cycle has most of accent and descent phases, while MIDC drive cycle has cruise phase as well, and the same is utilized for Fuel cell to provide power directly at the wheels. This gives a greater efficiency during MIDC drive cycle.

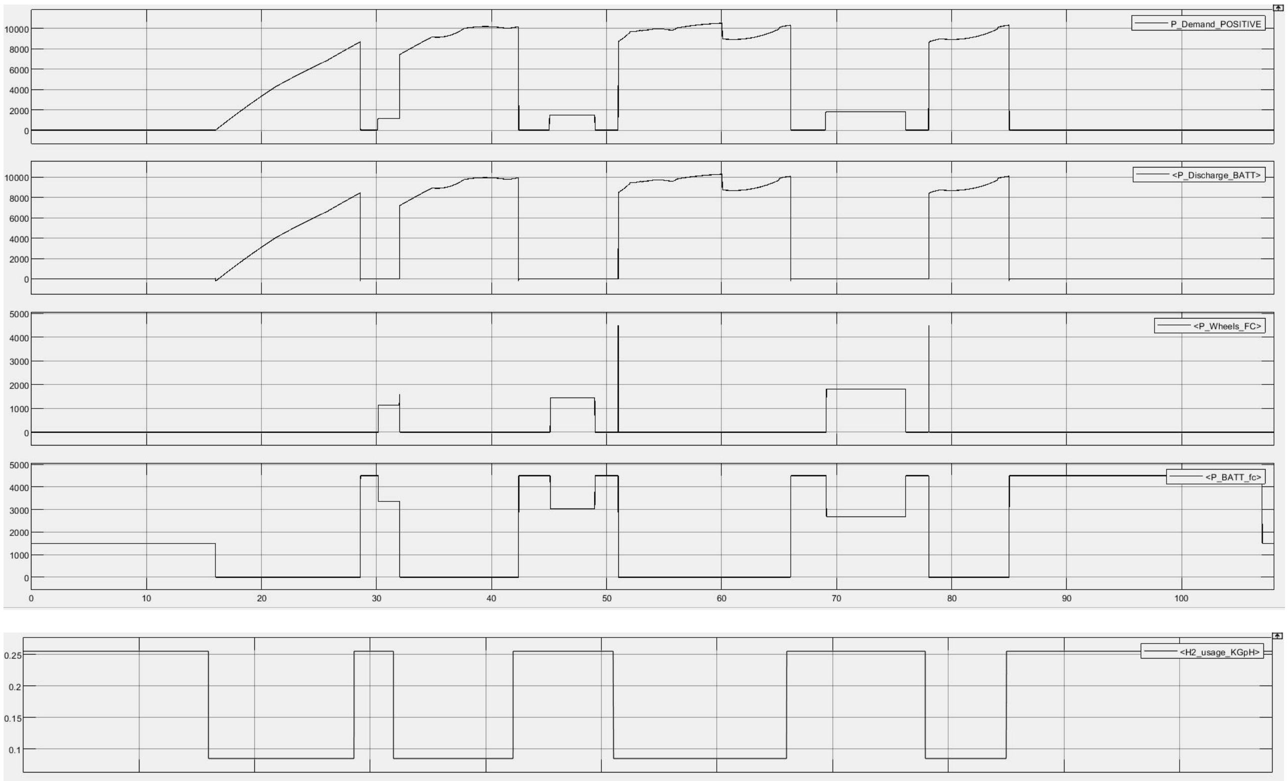

Figure 8: Hybrid PEMFC Hydrogen consumption for IDC

The simulation results of pure Electric Vehicle recorded as 80 km compares very close with the physical mileage of the pure Electric Vehicle. Moreover, for a run of 180 km of PEMEV hybrid vehicle, the simulation results provide hydrogen consumption of 1.338 kg for IDC cycle and 1.04 kg for MIDC cycle. The MIDC cycle ends up with a reduction in hydrogen consumption by 22.2% compared to IDC cycle due to its long phases of cruise and deceleration mode.

Limitations

The control strategy has been applied to gain optimization in hydrogen consumed in a hybrid PEMFC vehicle. However, this is only one out of many techniques to achieve stabilization in FC temperature. Many other techniques including effective cooling and use of nanomaterials may be used to gain hydrogen usage optimization. Other techniques may provide higher percentage optimization in usage of hydrogen. The control strategy still requires battery to be sustained around 60% state of charge, which may be optimized further to use smaller battery power source. In addition, PEMFC may be optimized for cell geometry parameters and fuel flow patterns to achieve greater optimization in hydrogen usage.

Conclusion and Future scope

The design and analysis of optimal control strategy for power management in PEMFC Hybrid Electric Vehicle has been presented in this paper. The study shows the hydrogen fuel consumption through a logic-based optimal control strategy and the power split between the fuel cell and the battery while using IDC & MIDC. The system efficiency has also been seen for the two drive cycles to understand the effect of various parameters on the efficiency and hydrogen consumption [67-71]. The aim is to achieve the minimum hydrogen fuel consumption for the two driving cycles. To achieve minimum hydrogen fuel consumption and minimum power fluctuation of PEMFC, the control strategies have worked well in both the driving cycles. In addition, a practical vehicle range has also been achieved.

Future scope of this paper includes its application in various Fuel cell systems in stationary or mobile applications. All types of fuel cells may be analyzed for optimal strategy of fuel utilization with the methodology presented in the paper. The strategy may be applied to mobile products, transportation, medical and stationary products as well, wherever Fuel Cell is used as power source.

Nomenclature

a = Acceleration of Vehicle (m/s_2)
A,B,C = Dynamometer constants
E_{nernst} = Reversible Voltage between Anode and Cathode (V)

F = Faraday constant (96,485 Coulomb/mole)
i_{Cell} = Cell current (A)
LHV_{H2} = Lower Heating Value of hydrogen (Wh/kg)
M_{Air} = Molecular mass of Air (kg/mole)
M_{H2} = Molecular mass of Hydrogen (kg/mole)
$M_{H2\ O}$) = Molecular mass of Water (kg/mole)
n = Number of cells in series connection
n_e = No. of electrons transferred per mole of reactant
N = Powertrain ratio
$\dot{Q}_{gen}$ = Rate of heat generated by fuel cell (J/sec)
$\dot{Q}_{rem}$ = Rate of heat removed by cooling system (J/sec)
R_{wheel} = Wheel radius (m)
v = Vehicle velocity (m/s)

ΔV_{act} = Activation Voltage drop (V)

ΔV_{ohm} = Ohmic Voltage drop (V)

ΔV_{conc} = Concentration Voltage drop (V)

η = Powertrain efficiency
ω_{motor} = Motor speed (rad/s)
η_{motor} = Motor efficiency

λ = Stoichiometric ratio
η_{fc} = Thermodynamic efficiency of fuel cell

Competing Interest

Although PEM Fuel cells are being used for many years in the automotive sector, however, the work shown in the paper is genuine and authentic work. All the authors of this work declare that there is no conflict of interest regarding the publication of this paper. The work presented in the paper is practical and unique to every extent possible.

References

1. O'Hayre, R., Cha, S., Colella, W., Prinz, F.B. (2006). Fuel Cell Fundamentals. Wiley: Hoboken, NJ, USA.
2. Zhang, H., Li, X., Liu, X., & Yan, J. (2019). Enhancing fuel cell durability for fuel cell plug-in hybrid electric vehicles through strategic power management. Applied Energy, 241, 483-490.
3. Spiegel, C. (2011). PEM fuel cell modeling and simulation using MATLAB. Elsevier.
4. Abdul Aziz, A. F., Samosir, A. S., Kamal, K., and Amin, I. (2011). "Modeling and analyzing the proton exchange membrane of fuel cell (PEMFC) in Matlab/SIMULINK environment". ResearchGate IEEE, December.
5. Ahuja, A., Waghole, D. R., & Ramdasi, S. S. (2022). Fuel Cell Technologies for Automotive Applications.
6. J.I. San Martín, I. Zamora, J.J. San Martín, V. Aperribay and P. Eguía. (2010). "Performance Analysis of a PEM Fuel Cell". Renewable Energies and Power Quality Journal, April.
7. Al-Baghdadi, M. A. S. (2005). Modelling of proton exchange membrane fuel cell performance based on semi-empirical equations. Renewable energy, 30(10), 1587-1599.
8. Anbarasu, A., Dinh, T. Q., & Sengupta, S. (2022). Novel enhancement of energy management in fuel cell hybrid electric vehicle by an advanced dynamic model predictive control. Energy Conversion and Management, 267, 115883.
9. Ali, D. M. (2008, March). A simplified dynamic simulation model (prototype) for a stand-alone Polymer Electrolyte Membrane (PEM) fuel cell stack. In 2008 12th International Middle-East Power System Conference (pp. 480-485). IEEE.
10. Luciani, S., & Tonoli, A. (2022). Control strategy assessment for improving PEM fuel cell system efficiency in fuel cell hybrid vehicles. Energies, 15(6), 2004.
11. Nazara, K., Jafferya, M. H., Shakirb, I., Nazarc, A., and Raza, R. (2020). "Design of 1 kW high temperature PEM fuel cell system and performance analysis under different operating conditions". Elsevier, Current Applied Physics, June.
12. Rios, R., Ramos, C., & JAIRO, E. (2011). Non-Linear State Space Model and Control Strategy for Pem Fuel Cell Systems. Dyna, 78(166), 60-67.
13. Leva, S., & Zaninelli, D. (2009). Hybrid renewable energy-fuel cell system: Design and performance evaluation. Electric power systems research, 79(2), 316-324.
14. Hu, M., Gu, A., Wang, M., Zhu, X., & Yu, L. (2004). Three dimensional, two phase flow mathematical model for PEM fuel cell: Part I. Model development. Energy Conversion and Management, 45(11-12), 1861-1882.
15. Ziogou, C., Michael, C., Voutetakis, G. S., and Papadopoulou, S. (2016). "Optimum Energy Management of PEM Fuel Cell Systems based on Model Predictive Control", E3S Web of Conferences.
16. Suh, K. W., & Stefanopoulou, A. G. (2006). Effects of control strategy and calibration on hybridization level and fuel economy in fuel cell hybrid electric vehicle. SAE Paper, (2006-01), 0038.
17. Rabbani, A. (2013). Dynamic performance of a PEM fuel cell system. In DTU mechanical engineering: DCAMM special report (no. S154).
18. Liang, Y., Liang, Q., Zhao, J., & He, J. (2022). Minimum hydrogen consumption power allocation strategy for multi-stack fuel cells (MFC) system based on discrete approach. Frontiers in Energy Research, 1339.
19. Zhijun, M., Xinjian, Z., & Guangyi, C. (2005, December). Design and simulation of fuzzy controller for PEMFCs. In 2005 IEEE International Conference on Industrial Technology (pp. 220-224). IEEE.
20. Ehsani, M., Gao, Y., Longo, S., & Ebrahimi, K. (2018). Modern electric, hybrid electric, and fuel cell vehicles. CRC press.
21. Latha, K., Vidhya, S., Umamaheswari, B., Rajalakshmi, N., & Dhathathreyan, K. S. (2013). Tuning of PEM fuel cell model parameters for prediction of steady state and dynamic performance under various operating conditions. International journal of hydrogen energy, 38(5), 2370-2386.
22. Lee, D. J., & Wang, L. (2007, June). Dynamic and steady-state performance of PEM fuel cells under various loading conditions. In 2007 IEEE Power Engineering Society General Meeting (pp. 1-8). IEEE.
23. Sarmiento Carnevali, M. L. (2017). Modeling and control of PEM fuel cells.
24. Zhang, Y. Y., Zhang, Y., Li, X., & Cao, G. Y. (2013). Control design of 60 kW PEMFC generation system for residential applications. Journal of Zhejiang University SCIENCE A, 14(9), 679-685.
25. Schell, A., Peng, H., Tran, D., Stamos, E., Lin, C. C., & Kim, M. J. (2005). Modelling and control strategy development for fuel cell electric vehicles. Annual Reviews in Control, 29(1), 159-168.
26. Zecchi, L., Sandrini, G., Gadola, M., & Chindamo, D. (2022). Modeling of a Hybrid Fuel Cell Powertrain with Power Split Logic for Onboard Energy Management Using a Longitudinal Dynamics Simulation Tool. Energies, 15(17), 6228.
27. Maxoulis, C. N., Tsinoglou, D. N., & Koltsakis, G. C. (2004). Modeling of automotive fuel cell operation in driving cycles. Energy conversion and management, 45(4), 559-573.

28. Cownden, R., Nahon, M., Rosen, M. A. (2001). Modelling and analysis of a solid polymer fuel cell system for transportation applications. Int J Hydrogen Energy, 26(6):615–23.
29. Kim, J., Lee, S. M., Srinivasan, S., & Chamberlin, C. E. (1995). Modeling of proton exchange membrane fuel cell performance with an empirical equation. Journal of the electrochemical society, 142(8), 2670.
30. Qi, Y., Thern, M., Espinoza-Andaluz, M., & Andersson, M. (2018). Modeling and control strategies of proton exchange membrane fuel cells. Energy Procedia, 159, 54-59.
31. Kaya, K., & Hames, Y. (2019). Two new control strategies: For hydrogen fuel saving and extend the life cycle in the hydrogen fuel cell vehicles. International Journal of Hydrogen Energy, 44(34), 18967-18980.
32. Rowe, A., & Li, X. (2001). Mathematical modeling of proton exchange membrane fuel cells. Journal of power sources, 102(1-2), 82-96.
33. Borkovski, S., & Erkechova, M. (2020). Control approaches of pem fuel cells: a review. Industry 4.0, 5(3), 126-131.
34. Amphlett, J. C., Mann, R. F., Peppley, B. A., Roberge, P. R., & Rodrigues, A. (1996). A model predicting transient responses of proton exchange membrane fuel cells. Journal of Power sources, 61(1-2), 183-188.
35. Von Spakovsky, M. R., & Olsommer, B. (2002). Fuel cell systems and system modeling and analysis perspectives for fuel cell development. Energy Conversion and Management, 43(9-12), 1249-1257.
36. Anilkumar, G., Puneetha, N., Kumar, G. B., Palanisamy, K., & Gupta, A. (2020, September). Design and testing of proton exchange membrane fuel cell (PEMFC) power pack for platform vehicle. In IOP Conference Series: Materials Science and Engineering (Vol. 937, No. 1, p. 012007). IOP Publishing.
37. Yerramalla, S., Davari, A., Feliachi, A., & Biswas, T. (2003). Modeling and simulation of the dynamic behavior of a polymer electrolyte membrane fuel cell. Journal of Power Sources, 124(1), 104-113.
38. Kim, H. I., Cho, C. Y., Nam, J. H., Shin, D., & Chung, T. Y. (2010). A simple dynamic model for polymer electrolyte membrane fuel cell (PEMFC) power modules: Parameter estimation and model prediction. International journal of hydrogen energy, 35(8), 3656-3663.
39. Wang, Y., Chen, K. S., Mishler, J., Cho, S. C., & Adroher, X. C. (2011). A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research. Applied energy, 88(4), 981-1007.
40. Wang, Y., & Wang, C. Y. (2006). Dynamics of polymer electrolyte fuel cells undergoing load changes. Electrochimica Acta, 51(19), 3924-3933.
41. Yu, P., Li, M., Wang, Y., & Chen, Z. (2022). Fuel cell hybrid electric vehicles: A review of topologies and energy management strategies. World Electric Vehicle Journal, 13(9), 172.
42. Khan, M. J., & Iqbal, M. T. (2005). Modelling and analysis of electro-chemical, thermal, and reactant flow dynamics for a PEM fuel cell system. Fuel cells, 5(4), 463-475.
43. Musio, F., Tacchi, F., Omati, L., Stampino, P. G., Dotelli, G., Limonta, S., & Grassini, P. (2011). PEMFC system simulation in MATLAB-Simulink® environment. International Journal of Hydrogen Energy, 36(13), 8045-8052.
44. Li, C., Hu, G., Zhu, Z., Wang, X., & Jiang, W. (2022). Adaptive equivalent consumption minimization strategy and its fast implementation of energy management for fuel cell electric vehicles. International Journal of Energy Research, 46(11), 16005-16018.
45. Wang, Y., Wang, C.Y. (2005). Transient analysis of polymer electrolyte fuel cells. Electrochim. Acta, 50, 1307–1315.
46. Friede, W., Raël, S., & Davat, B. (2004). Mathematical model and characterization of the transient behavior of a PEM fuel cell. IEEE Transactions on power electronics, 19(5), 1234-1241.
47. Nazara, K., Jafferya, M. H., Shakirb, I., Nazarc, A., and Raza, R. (2020). "Design of 1 kW high temperature PEM fuel cell system and performance analysis under different operating conditions". Current Applied Physics, June.
48. Shakeri, N., and Zadeh, M. (2000). "Dynamic Modelling of Fuel Cell Systems for Electric Propulsion", IEEE.
49. Alcázar-García, D., & Martínez, J. L. R. (2022). Model-based design validation and optimization of drive systems in electric, hybrid, and plug-in hybrid and fuel cell vehicles. Energy, 254, 123719.
50. Sulaiman, N., Hannan, M. A., Mohamed, A., Ker, P. J., Majlan, E. H., & Daud, W. W. (2018). Optimization of energy management system for fuel-cell hybrid electric vehicles: Issues and recommendations. Applied energy, 228, 2061-2079.
51. Luo, Y., Wu, Y., Li, B., Qu, J., Feng, S. P., & Chu, P. K. (2021). Optimization and cutting-edge design of fuel-cell hybrid electric vehicles. International Journal of Energy Research, 45(13), 18392-18423.
52. Parambu, R. B., Dempsey, M., & Picarelli, A. (2019, February). Modelling & Analysis of a Fuel Cell Hybrid Electric Vehicle using Real-World & Standard Driving Conditions. In Proceedings of the 2nd Japanese Modelica Conference, Tokyo, Japan, May 17-18, 2018 (No. 148, pp. 99-108). Linköping University Electronic Press.
53. Wang, Y., Advani, S. G., & Prasad, A. K. (2020). A comparison of rule-based and model predictive controller-based power management strategies for fuel cell/battery hybrid vehicles considering degradation. International Journal of Hydrogen Energy, 45(58), 33948-33956.
54. Ji, C., Qiu, L., Zheng, Z., & Zhang, Y. (2021, April). Research on Energy Management Strategy of Vehicle Fuel Cell-Battery Hybrid Energy System Based on GT-SUIT/Simulink. In Journal of Physics: Conference Series (Vol. 1885, No. 4, p. 042067). IOP Publishing.
55. Jung, J. H., Ahmed, S., & Enjeti, P. (2010). PEM fuel cell stack model development for real-time simulation applications. IEEE Transactions on Industrial Electronics, 58(9), 4217-4231.
56. Song, Y., Han, K., & Li, X. (2021). Study on the fuel economy of fuel cell electric vehicle based on rule-based energy management strategies. International Journal of Powertrains, 10(3), 266-292.
57. Farhadi Gharibeh, H., & Farrokhifar, M. (2021). Online multi-level energy management strategy based on rule-based and optimization-based approaches for fuel cell hybrid electric vehicles. Applied Sciences, 11(9), 3849.
58. Liu, Y., Liu, J., Qin, D., Li, G., Chen, Z., Zhang, Y. (2020). Online energy management strategy of fuel cell hybrid elec-

tric vehicles based on rule learning. J. Clean. Prod. 260, 121017.
59. Geng, C., Jin, X., & Zhang, X. (2019). Simulation research on a novel control strategy for fuel cell extended-range vehicles. International Journal of Hydrogen Energy, 44(1), 408-420.
60. Du, C., Huang, S., Jiang, Y., Wu, D., & Li, Y. (2022). Optimization of energy management strategy for fuel cell hybrid electric vehicles based on dynamic programming. Energies, 15(12), 4325.
61. Zhou, Y., Ravey, A., & Péra, M. C. (2021). Real-time cost-minimization power-allocating strategy via model predictive control for fuel cell hybrid electric vehicles. Energy Conversion and Management, 229, 113721.
62. Yazdani, A., & Bidarvatan, M. (2018). Real-time optimal control of power management in a fuel cell hybrid electric vehicle: A comparative analysis. SAE International Journal of Alternative Powertrains, 7(1), 43-54.
63. Liu, J., Chen, Y., Li, W., Shang, F., & Zhan, J. (2017). Hybrid-trip-model-based energy management of a PHEV with computation-optimized dynamic programming. IEEE Transactions on Vehicular Technology, 67(1), 338-353.
64. Macias, A., Kandidayeni, M., Boulon, L., & Chaoui, H. (2018, February). A novel online energy management strategy for multi fuel cell systems. In 2018 IEEE International Conference on Industrial Technology (ICIT) (pp. 2043-2048). IEEE.
65. Marx, N., Hissel, D., Gustin, F., Boulon, L., & Agbossou, K. (2017). On the sizing and energy management of a hybrid multistack fuel cell–Battery system for automotive applications. International Journal of Hydrogen Energy, 42(2), 1518-1526.
66. Caux, S., Lachaize, J., Fadel, M., Shott, P., & Nicod, L. (2005). Modelling and control of a fuel cell system and storage elements in transport applications. Journal of Process Control, 15(4), 481-491.
67. Tong, S. W., & Qian, D. W. (2013). Control of a fuel cell based on the SIRMs fuzzy inference model. International journal of hydrogen energy, 38(10), 4124-4131.
68. Yang, W. C., Bates, B., Fletcher, N., & POW, R. (1998). Control challenges and methodologies in fuel cell vehicle development (SAE Paper No. 98C054).
69. Leva, S., & Zaninelli, D. (2009). Hybrid renewable energy-fuel cell system: Design and performance evaluation. Electric power systems research, 79(2), 316-324.
70. Musio, F., Tacchi, F., Omati, L., Stampino, P. G., Dotelli, G., Limonta, S., & Grassini, P. (2011). PEMFC system simulation in MATLAB-Simulink® environment. International Journal of Hydrogen Energy, 36(13), 8045-8052.
71. Pukrushpan, J. T., Peng H., and Stefanopoulou, A.G. (2004). Control-oriented modeling and analysis for automotive fuel cell systems. Journal of Dynamic Systems Measurement and ControlTransactions of the ASME, 126(1), 14-25.