Optimal Control Strategy for PEM Electric Vehicle using Matlab Simulink

Ajay Ahuja (ajay_design@hotmail.com)
Dr. Vishwanath Karad MIT World Peace University

D R Waghole
Dr. Vishwanath Karad MIT World Peace University

Sushil S Ramdasi
Automotive Research Association of India

Research Article

Keywords: FCHEV, FCHV, PEMFC, LHV, Hybrid, Regeneration, FC, IDC, MIDC, Control, Strategy, Efficiency, Optimal Control

Posted Date: February 8th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2553426/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
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 conserving 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 maximising fuel cell efficiency by balancing the power split between battery and fuel cell. The rule based strategy results in maximising 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.

1 Introduction

A Proton Exchange Membrane Fuel Cell (PEMFC) has gained importance in stationary as well as mobile and automotive applications. 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. 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. PEM Fuel cells require pure Hydrogen in chambers in automobiles for electrochemical reaction on the go. The efficiency of usage of Hydrogen in PEM fuel cell is greatly emphasized. This may be directly attributed to control strategy used in PEM fuel cell. Design optimization is required to achieve greater efficiency of a PEMFC. The performance of PEMFC is estimated using Mathematical models and 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 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 may be witnessed in Toyota Mirai and Honda FCX Clarity [2, 4].
2 PEM Fuel Cell

A PEM fuel cell consists of an anode, a cathode and an electrolyte. The Polymer Electrolyte Membrane (PEM) is separated from Anode and Cathode electrodes by Catalyst layers. In a PEM fuel cell, hydrogen gas is allowed to pass to the anode through channels, where a catalyst layer separates the hydrogen molecules into positive Hydrogen ions and electrons. The Polymer Electrolyte Membrane (PEM) is permeable so as to allow positive Hydrogen ions to pass through it. The negatively charged electrons released from Hydrogen at Anode pass through the PEM to the external circuit in the form of current. This flow of electrons is the Electrical energy performing work [1, 4].

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

Anode reaction:

\[ H_2 \rightarrow 2H^+ + 2e^- \]

Cathode reaction:

\[ \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \]

Overall reaction:

\[ H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{heat} \]

(Exothermic reaction, \( \Delta H = -286 \text{ kJ mol}^{-1} \))

On the other side of PEM fuel cell, Oxygen is supplied to the cathode through channels. At the cathode, the electrons returning from the external circuit react with oxygen to make negatively charged Oxygen ions. The positively charged Hydrogen ions passing through the PEM combine with the negatively charged Oxygen ions from Cathode to form Water. The formation of Water is an exothermic reaction and generates heat which can be used in many ways outside the fuel cell.

3 Mathematical Model

In a PEM fuel cell, when there is no current flowing through the external circuit, the potential difference between Anode and Cathode defines the ideal Open circuit Voltage. It is also termed as Nernst potential or Reversible voltage of the cell. Voltage losses take place when the current flows through the external circuit. The three losses involved in fuel cell output voltage include Activation Voltage drop, Ohmic Voltage drop and Concentration Voltage drop. The output Cell voltage may be enumerated as follows [3]:

\[ V_{Cell} = E_{nernst} - \Delta V_{act} - \Delta V_{ohm} - \Delta V_{conc} \]

where:
• $E_{nernst}$ = Reversible Voltage between Anode and Cathode
• $\Delta V_{act}$ = Activation Voltage drop
• $\Delta V_{ohm}$ = Ohmic Voltage drop
• $\Delta V_{conc}$ = Concentration Voltage drop

The gross Output Power of PEM fuel cell is defined as:

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

where:

• $n$ = Number of cells in series connection
• $i_{Cell}$ = Cell current

The pure Hydrogen fuel consumption (kg/s) can be obtained as:

$$ \dot{m}_{H_2} = \frac{i_{Cell} \times M_{H_2}}{n_e F} $$

3

where:

• $M_{H_2}$ = Molecular mass of Hydrogen
• $n_e$ = No. of electrons transferred per mole of reactant (2)
• $F$ = Faraday constant (96,485 Coulomb/mole)

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

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

4

where:

• $\lambda$ = Stoichiometric ratio
• $M_{Air}$ = Molecular mass of Air
• $n_e$ = No. of electrons transferred per mole of reactant (4)
• $F$ = Faraday constant (96,485 Coulomb/mole)

The water produced (kg/s) can be obtained as:
\[ \dot{m}_{H_2O} = \frac{i_{Cell} \times M_{H_2O}}{n_e F} \]

5

where:

- \( M_{H_2O} \) = Molecular mass of Water
- \( n_e \) = No. of electrons transferred per mole of reactant (2)
- \( F \) = Faraday constant (96,485 Coulomb/mole)

The change in Heat within a Fuel cell is the difference between the Fuel cell generated heat and rate of heat removed by the cooling system. The same is represented by the expression [5]:

\[ \Delta \dot{Q} = \dot{Q}_{gen} - \dot{Q}_{rem} \]

6

where:

- \( \dot{Q}_{gen} \) = Rate of heat generated by fuel cell
- \( \dot{Q}_{rem} \) = Rate of heat removed by cooling system

The heat generated by the fuel cell may be calculated as:

\[ \dot{Q}_{gen} = P_s \left( \frac{1}{\eta_{fc}} - 1 \right) \]

7

where:

- \( \eta_{fc} \) = Thermodynamic efficiency of fuel cell

The thermodynamic efficiency may be defined as the ratio of output power to the lower heating capacity of hydrogen consumed [6].

\[ \eta_{fc} = \frac{P_s}{\dot{m}_{H_2} \cdot LHV_{H_2}} \]

8

where:

- \( LHV_{H_2} \) = Lower Heating Value of hydrogen

The thermodynamic efficiency may be simplified as:
4 Pem Fuel Cell System

The use of PEM fuel cell for automotive application provides host of environmental benefits, such as there are no CO\textsubscript{2} emissions except for water if the fuel cell is fed with pure hydrogen. Pure hydrogen is fed through the pressurized containers and oxygen is supplied through abundant air. 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. Air is supplied through the compressor and humidification is done to avoid carbon deposition on electrodes. 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. 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 attached.

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

4.1 Hydrogen sub-system:

Hydrogen is fed in pure form in order to avoid CO\textsubscript{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.

4.2 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.

4.3 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.

4.4 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.

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 system.
fuel cell. 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.

\[ P_{Aux} = P_{Comp} + P_{Blower} + P_{Humidifiers} + P_{Cooling} \]

And, the system efficiency is defined as:

\[ \eta_{sys} = \frac{P_s - P_{Aux}}{m_{H_2} \cdot LHV_{H_2}} \]

5 Vehicle Powertrain Architecture

An FCHEV gets its power from a fuel cell and a battery in parallel for a vehicle powertrain. Till the fuel cell invokes full stack power, battery can fulfill vehicle demand of acceleration and cruise. 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 [15]. 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.

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:

\[ F_{res} = \{A + (B \times v) + (C \times v^2)\} + \{Ma^2\} \]

where:

- \( A, B, C \) = Dynamometer constants
- \( v \) = Vehicle velocity (m/s)
- \( a \) = Acceleration of Vehicle (m/s^2)

The demand torque at the wheel becomes:

\[ T_{wheel} = F_{res} \times R_{wheel} \]
And, the demand torque at the Motor becomes:

\[ T_{\text{motor}} = \frac{T_{\text{wheel}}}{(N \times \eta)} \]

where:

- \( R_{\text{wheel}} \) = Wheel radius
- \( N \) = Powertrain ratio
- \( \eta \) = Powertrain efficiency

The demand power by the Motor becomes:

\[ P_{\text{demand}} = \frac{T_{\text{motor}} \times \omega_{\text{motor}}}{\eta_{\text{motor}}} \]

where:

- \( \omega_{\text{motor}} \) = Motor speed (rad/s)
- \( \eta_{\text{motor}} \) = Motor efficiency

The demand power is fulfilled either by Battery or by Fuel cell or both, hence:

\[ P_{\text{demand}} = P_{\text{batt}} + P_{\text{fc}} \]

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 [25].

6 Fuel Cell Control Strategy

Fuel Cells are pollution-free source of energy for automobiles. In PEM Fuel Cells, pure Hydrogen is fed to the Anode which makes the whole process CO\(_2\) free. In a fuel cell system, temperature variations, hydrogen and oxygen starvation are the major factors of efficiency degradation and shorter catalysts life [17, 28].

The overall objective of Control Strategy is to match the power demand in an optimum manner with maximizing efficiency. 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.

In order to achieve safe operation of fuel cell, the input reactants, hydrogen and air are supplied in a certain excess ratio in order to avoid starvation at the cathode and the anode. Normally, the air excess ratio is taken as 2.0 and for hydrogen, it may be taken as 1.5 or 2.0 [15]. The control system captures the on-point power demand and aims to maximize power and maintain the stack temperature with the excess ratio and cooling sub-system control. The overall objective is to have minimal load fluctuations on the fuel cell. Although the output power demands a micro-level control of fuel input, however, in order to satisfy these conditions, the fuel cell power is controlled within a range with minimal hydrogen flow control. The control strategy for hydrogen and oxygen usage play an important role in minimizing fuel consumption and fuel cell performance degradation [30].

The Vehicle powertrain may operate in various operating modes depending upon the Power demand, Vehicle acceleration and SOC of Battery [33]:

1. **Hybrid mode**: If the power required by the motor is greater than the maximum power of FC, then Fuel cell operates at its maximum power and the remaining power is supplied by the Battery;

2. **FC mode**: If the power required by motor is in between the maximum and minimum power of FC, then the Fuel cell operates at its maximum and powers the motor. At the same time, remaining FC power is utilized to charge the Battery;

3. **Battery mode**: If the vehicle is accelerating, it draws a huge power in less time and may be served by Battery alone;

4. **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, so as to keep the Battery in Charge sustaining condition.

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 low-power mode to high-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. All this is defined in a controlled logic based on the SOC of battery, Vehicle acceleration and Power demand [39]. The FC power may be divided into two, one that is used for power demand at Motor and Auxiliary demand, and another to charge the Battery. Similarly, Battery charging may also be divided into two, one from the FC and another from the Regeneration.

The optimal control strategy demands the battery to operate in a Charge sustaining mode and the fuel cell works as the Range extender for the vehicle. Primarily, the vehicle demand is met by the battery 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. To achieve this, two output phases are set for the fuel cell, one the low-power output phase and another the high-power output phase. For avoiding a sudden variation in load power functioning of fuel cell, fuel cell is operated at two constant power values at low-power and high-power output phases. All this ends up into maximizing the system efficiency and life span of the fuel cell [40].

7 Simulation Results

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 optimally at two levels and Battery power is used at vehicle acceleration; however both are used at the time of high power demand. With this strategy, it has been ensured that SOC profile stabilizes to 0.6 value and FC is also dynamically used to achieve controlled hydrogen consumption. The MIDC cycle ends up with a much lower hydrogen consumption compared to IDC cycle due to its long phases of cruise and deceleration mode [50].

The above graphs depict the SOC (%) for an Automotive IDC. During every cycle, SOC gets a positive bonus to never keep the Battery below charge sustaining level.

8 Conclusion

The design and analysis of Optimal control strategy for power management in PEMFC Electric Vehicle has been presented in this paper. The study shows the hydrogen fuel consumption through a logic-based optimal strategy and control the power split between the fuel cell and the battery. The system efficiency has also been seen for two drive cycles to understand the effect of various parameters on the efficiency and hydrogen consumption. The bonus SOC value of 15% with each MIDC cycle is very encouraging compared to IDC cycle having 0.5% only. The hydrogen consumption per kilometer range of vehicle is also less by 21.5% in case of MIDC drive cycle. The aim is to achieve the minimum hydrogen consumption for the two driving cycles.

Declarations

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


16. YiFan Liang, QianChao Liang, JianFeng Zhao and JunNeng He, “Minimum hydrogen consumption power allocation strategy for the multi-stack fuel cell (MFC) system based on a discrete approach” Energy Research 2022.
31. Stefan Borkovski and Maja Erkechova, “Control approaches of pem fuel cells: a review” International Scientific Journal Industry 4.0


Figures

Figure 1

Polymer Electrolyte Membrane Fuel Cell (PEMFC) [4]
Figure 2

PEMFC Flow Schematic
Figure 3


Figure 4

Control Strategy Algorithm for PEMFC
**Figure 5**

PEMFC Control Strategy with IDC