Fuzzy Logic Based Power Distribution Strategy for Hybrid Fuel Cell Vehicle

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Abstract: Currently zero emission vehicles are the need of automotive industry. This research focuses on design of powertrain and power distribution strategy for fuel cell hybrid vehicle. Vehicle driven only by fuel cell as a single source have various disadvantages such as sluggish response to transient power requirements, higher fuel consumption, no provision for storage of energy during lost during braking, higher cost, lower range, more packaging space required. To overcome this, fuel cell can be combined with auxiliary energy storage source. This paper proposes powertrain topology for vehicle with Fuel cell and battery (FC+B) combination. Power split strategy is defined using Fuzzy logic. Simulations are performed in MATLAB SIMULINK for FTP-75 drive cycle. Results of proposed strategy are compared with FC alone powertrain. Results shows that with proposed powertrain configuration, fuel consumption is reduced thereby achieving higher driving range.

Keywords: Hybrid vehicle, Fuzzy logic, Fuel cell, Battery.

1. Introduction

With rapid decrease in fossil fuels and increase of global warming, it becomes necessary to develop clean source of energy for automotive sector [1]. Various alternate fuels such as CNG, Biodeisel, Ethanol are available worldwide [2]. Ugurlu et.al [3] suggested electric and fuel cell vehicle as stand out option due to their zero emissions. However, there are many drawbacks of conventional battery operated vehicles as mentioned below:

- Customers are susceptible to buy battery electric vehicle due to its lower range which makes it difficult to use for long distance travel [4].To improve range, battery with higher capacity needs to be selected which in turn increases space required.
- Charging time is very high.
- Battery life is less.

To overcome these drawbacks of battery operated vehicles, Fuel cell is identified as one of the better options of clean and reliable energy [6]. Fuel cell is considered as a potential source of energy for automotive sector due to its low noise, zero emission [7]. Currently many fuel cell buses, trucks are operating on worldwide [8].

Main challenge in fuel cell vehicle is design of powertrain and power split strategy [9]. Sid et.al [10] summarized various power distribution strategy used in Fuel cell operated buses. Various authors have proposed fuel cell driven powertrain for heavy vehicles such as Trucks, buses. [11-15]. Some of the authors have proposed fuel cell driven powertrain for tramway [14].

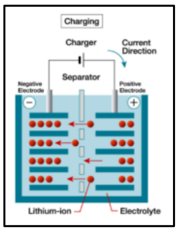
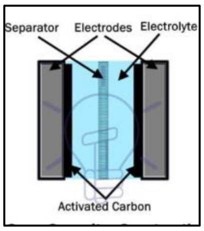
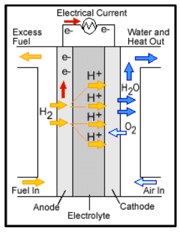
Property	Batteries	Ultra capacitor	Fuel Cell
Construction			
Charge/ Discharge Time	1 to 10hrs	Milliseconds to Seconds	-
Operating Voltage (V)	1.25 to 4.2	2.3 to 2.75	0.6
Life (hrs,cycles)	150 to 1500 cycles	50000+ hrs. Unlimited cycles	1500 to 10000 hrs.
Power Density (kW/kg)	0.005 to 0.4	10 to 120	0.001 to 0. 1
Energy Density (Wh/kg)	8 to 600	1 to 10	300 to 3000

Table 1. Comparison of energy sources

Consider the vehicle driven by fuel cell as the only source of energy. In this case Fuel cell needs to provide power requirement at all times as there is no other auxiliary source. So, rated capacity of fuel cell needs to be selected in such a way that it meets power demands at all the times. This will lead to selection of fuel cell with higher rated power. Size of Hydrogen storage tank required will be also higher. This will lead to practical difficulties of packaging components in vehicle. Also fuel cell have sluggish response to input signal. So, vehicle will have sluggish response when power demand is transient. Life of fuel cell decreases due to continuous power fluctuations based on power demand. There is no provision in powertrain to store energy during braking intervals. Furthermore cost of fuel cell will also increase.

To overcome this, various secondary energy sources can be combined with fuel cell to get hybrid powertrain. Popular among these are battery, supercapacitor. Table [1] shows comparison of fuel cell, supercapacitor, Batteries in context of energy density, power density, life cycle. It can be inferred from Table [1] that fuel cell have very low power density and higher energy density. Therefore it is not suitable to meet peak power requirement. Conventional batteries have low power density and higher energy density. These are suitable to provide low power for longer period of time. Super capacitor have very higher power density. These can be used to meet peak and transient power requirements. Various authors have tried to combine fuel cell with any of the above secondary energy sources and design hybrid powertrain. This work majorly focuses on hybridization of fuel cell with battery .Correspondingly, Energy management strategy is defined using fuzzy logic.

This paper is organized as follows -.i) Vehicle model, calculation of forces acting on vehicle ,power demand based on drive cycle, Fuel cell, Battery model ii) Powertrain topology and power distribution strategy for Hybrid power train. iii) Comparison of simulation results using MATLAB Simulink.

2. System model and Powertrain topology.

2.1 Vehicle Model:

Firstly we need to calculate forces acting on vehicle when it is driving. Acceleration force, Rolling force, Aerodynamic force, Gradient force acts on vehicle during running condition.

Vehicle parameters considered for simulation are given in Table2.

Vehicle mass (kg)	m	1000
Coefficient of Rolling resistance	C_r	0.015
Air density (kg/m^3)	ρ	1.225
Vehicle Frontal area (m^2)	A_f	2.1
Coefficient of Drag	C_d	0.4
Wheel radius (m)	R	0.282

Table 2. Parameters for simulation

Forces can be calculated as given below.
Acceleration Force- Force acting due to vehicle acceleration. It is given by Eq. [1]

$$F_a = ma \tag{1}$$

where, a = vehicle acceleration

Rolling Force- Force acting due to rolling resistance between tyre and ground. It is given by Eq. [2]

$$F_r = mgC_r \tag{2}$$

Aerodynamic Drag Force- Force acting due to air resistance. It is given by Eq. [3]

$$F_d = \frac{1}{2}\rho\, C_d\, A_f v^2 \tag{3}$$

Gradient Force- Force acting due to gradient. It is given by Eq. [4]

$$F_g = mg\ \sin\theta \tag{4}$$

In this study θ is considered as 0 degree

Total Tractive Force F_t = F_a + F_r + F_d + F_g (5)

Total power demand can be calculated as product of total tractive force and vehicle speed

Total power demand P_d= Total Tractive Force X Vehicle speed (6)

For the purpose of simulation, we need driving cycles for reference. It is the plot between velocity and time. There are many standard driving cycles which can be used for simulation of vehicle. In this work FTP 75 is considered as standard drive cycle. Figure.6 shows Velocity vs. time requirement of FTP 75 cycle. Based on this, power demand is calculated as per Eq. [6]

2.2 Fuel Cell Model

Fuel cell is an electrochemical device that converts chemical energy into electrical energy. It does not emit any harmful gas. Various types of fuel cell are available - Alkaline fuel cells (AFC), Phosphoric acid fuel cells (PAFC), Molten carbonate fuel cells (MCFC), Solid oxide fuel cells (SOFC), Proton exchange membrane fuel cells (PEMFC), Direct methanol fuel cells (DMFC). Amongst these, for automotive application Polymer electrolyte membrane (PEM) type of fuel cell are used due to their ability to operate at relative low temperature, quick start up time, high power density. [16]. Hydrogen and oxygen are used as input to fuel cell and it gives water as output.
Hydrogen consumption can be calculated as below [16,17]

$$m_{H_2} = \int_0^t \frac{P_{FC}(t)}{\eta_{FC}\rho_{H_2}} dt \tag{7}$$

P_{FC} =Fuel cell output Power, η_{FC}= FC efficiency,
ρ_{H_2}=low calorific value for hydrogen

Generally, fuel cell have maximum efficiency when it operates between one third to two third of its rated power [16]. Figure.1 shows fuel cell efficiency with respect to power demand.

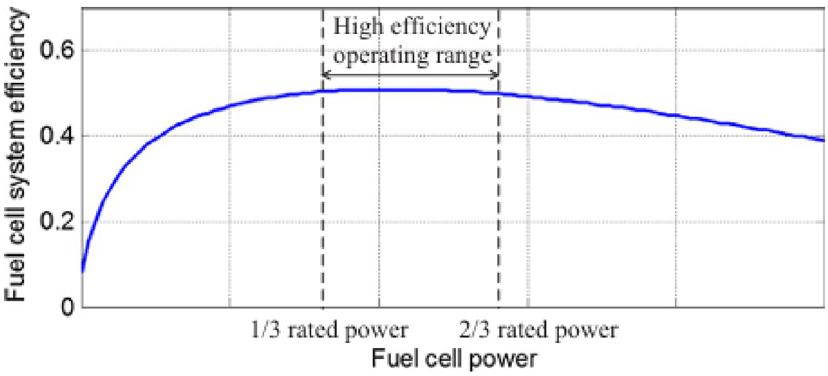


Figure 1. Fuel cell efficiency versus Power

Since fuel cell is unidirectional voltage source, it is unable to store braking energy and it gets wasted.

2.3 Battery Model

A battery functions as an electrochemical cell that converts chemical energy into electrical energy. One of the primary benefits of utilizing batteries in vehicles is their superior energy density when compared to fuel cell stacks. Various types of batteries are employed in electric vehicles, but this study focuses on lithium-ion batteries due to their enhanced performance relative to other battery types and their prevalent use in transportation applications.

Instantaneous SOC of battery can be calculated:

$$SOC_B(t) = SOC_{initial} - \eta_b \int \frac{i_b(t)}{3600\, Q_b}\, dt \tag{8}$$

$SOC_{initial}$= Initial SOC, $i_b(t)$= Battery current , η_b =Charge and discharge efficiency of battery, Q_b=Battery nominal capacity

The battery's state of charge ranges from 0%, indicating a depleted battery, to 100%, signifying a fully charged battery.

3. Power train topology

Two different powertrain topologies for vehicle are compared in this work.

3.1 FC Alone

In this case, fuel cell is considered as the only power source. Power requirement throughout cycle needs to be provided by fuel cell only. So, we need to select fuel cell with higher power rating such that it meets peak power requirement.

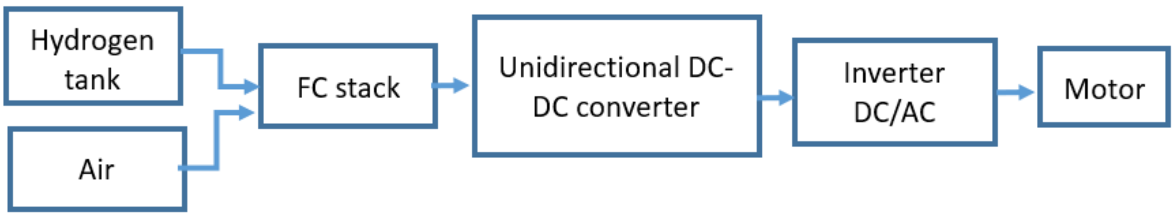


Figure 2. Block diagram Fuel cell driven powertrain

3.2 FC/Battery

In this case, fuel cell is considered as energy generating source. Additionally, battery is used as a secondary source. It can store energy during braking. At any point of time, Power demand should match with power supplied by battery and fuel cell. In this case efficient energy management strategy needs to be defined.

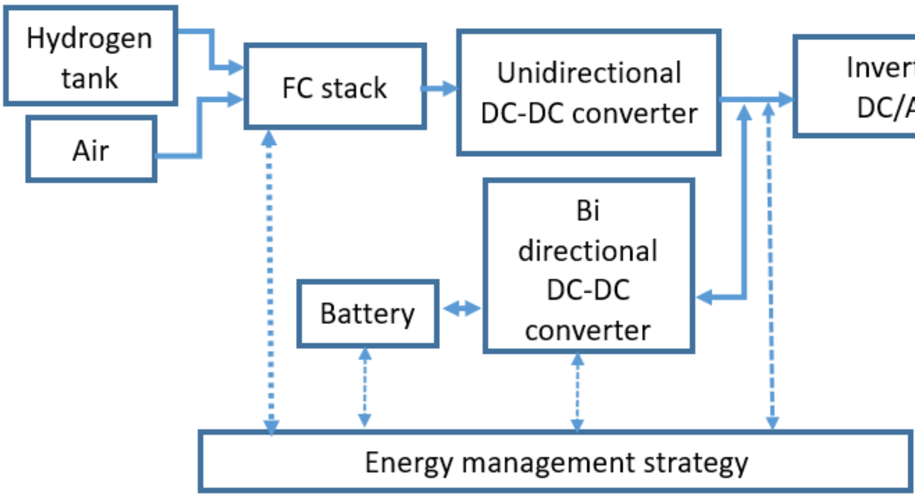


Figure 3. Block diagram of Fuel cell+ Battery driven powertrain

4. Power Distribution strategy

In order to split demand power demand between battery and fuel cell , fuzzy logic is used. Figure 4. shows algorithm for fuzzy logic. Here input variables are Power Demand (P_d,) and battery SOC (SOC_{bat},). Output of fuzzy logic controller is Fuel cell Power (P_{fc},). The controller connects its output to inputs through a series of IF-THEN rules. The IF segment of a rule defines the condition under which the rule is applicable, while the THEN segment indicates the output variable values necessary to produce the controller's output. Each variable is assigned a degree of membership based on the established membership functions. The membership degrees of the IF segments across all rules are assessed, and the output values in the THEN segments are averaged and weighted according to these membership degrees.

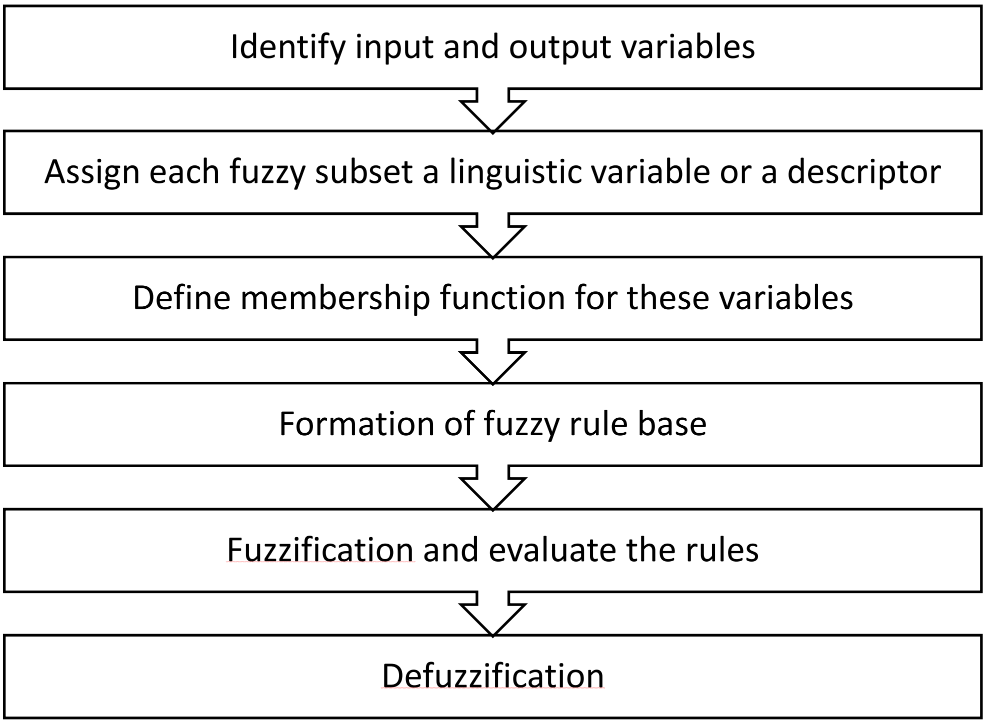


Figure 4. Fuzzy logic algorithm

Membership functions for input and output variables is shown in Figure 5. Rules are defined by IF THEN logic and AND operator. For Example- If SOC_{bat} is Low and P_d is positive High , then P_{fc} is in range of HIGH-2. Total 18 such rules are defined using Fuzzy logic. These are simulated using MATLAB interface. Table 3. shows rule base for fuzzy controller.

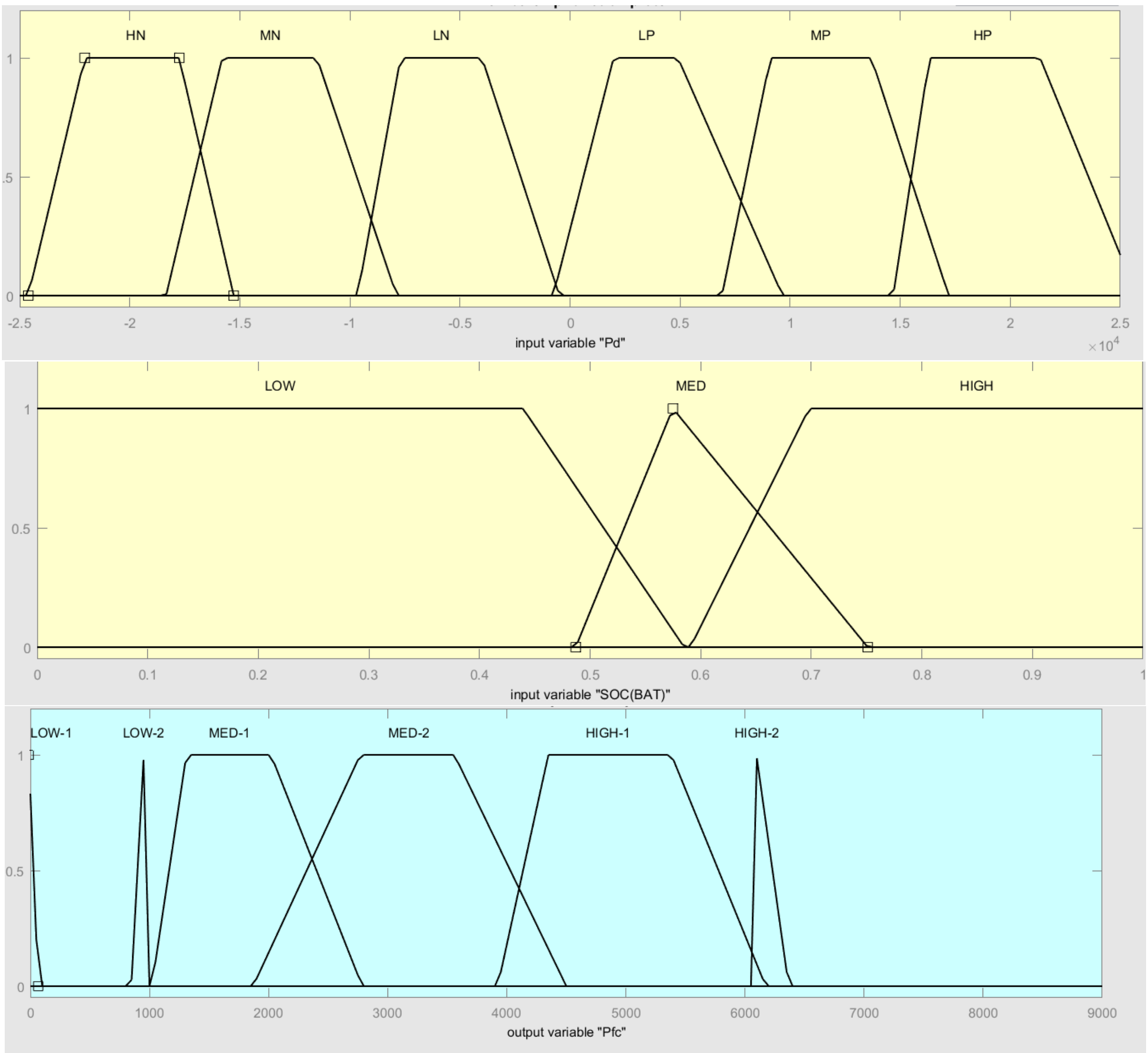


Figure 5. Fuzzy logic Membership function plots (MATLAB)

P_{fc}	Power Demand (P_d)					
SOC $_{bat}$	HN	MN	LN	LP	MP	HP
Low	LOW-1	LOW-2	MED-1	MED-2	HIGH-1	HIGH-2
Medium	LOW-1	LOW-1	LOW-2	MED-1	MED-2	HIGH-2
High	LOW-1	LOW-1	LOW-1	LOW-2	MED-2	HIGH-1

Table 3. Fuzzy logic rule base

H=High,M=Medium, L-Low, N=Negative, P=Positive

5. Results and Discussion

Simulations are performed in MATLAB Simulink.
For Powertrain I –Fuel cell as the only power source-
In this case, fuel cell is considered as the only power source. As per velocity and power demand graph in Figure 6, Peak power requirement during cycle is 22 KW. This power requirement needs to be provided by fuel cell only. So, we need to select fuel cell with power rating higher than 22 KW. Fuel cell with rated power of 25KW is selected in this study. To operate vehicle for 1400 seconds as per FTP 75 cycle, hydrogen required is 0.082 kg .Since density of hydrogen varies with pressure, if it is stored at lower pressure, volume of tank required will be very high. In order to reduce volume of tank required to store this much mass of hydrogen, it is stored at higher pressure of about 350 bar. So, to store 0.082

kg of Hydrogen at 350 bar volume of tank required is 3.25 Liters. It can be seen in Figure 6. that fuel cell power is fluctuating continuously.

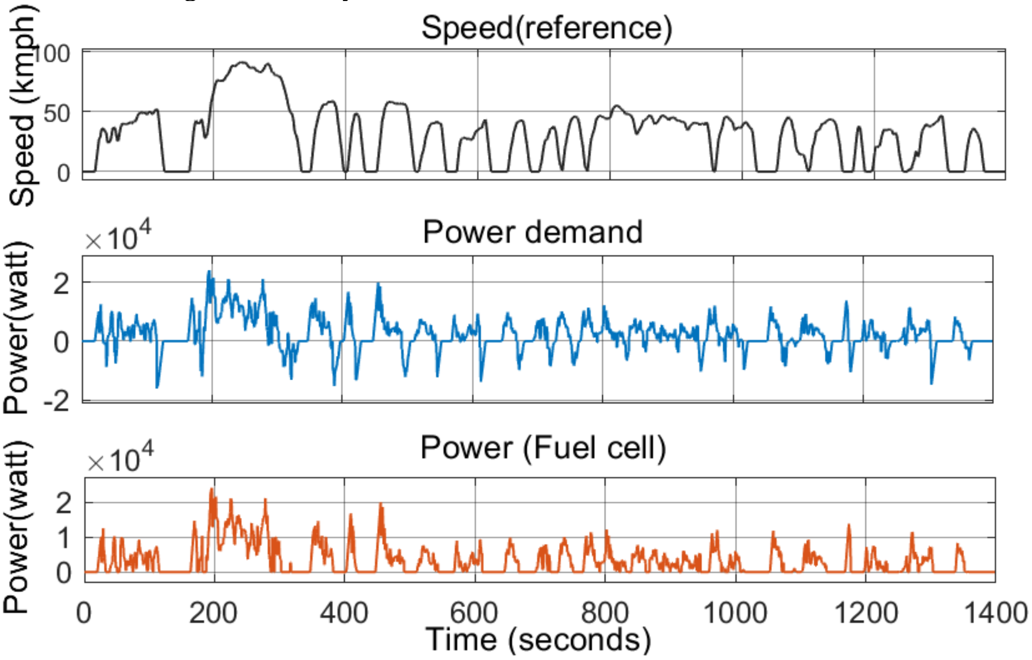


Figure 6. FC alone Powertrain (Power split)

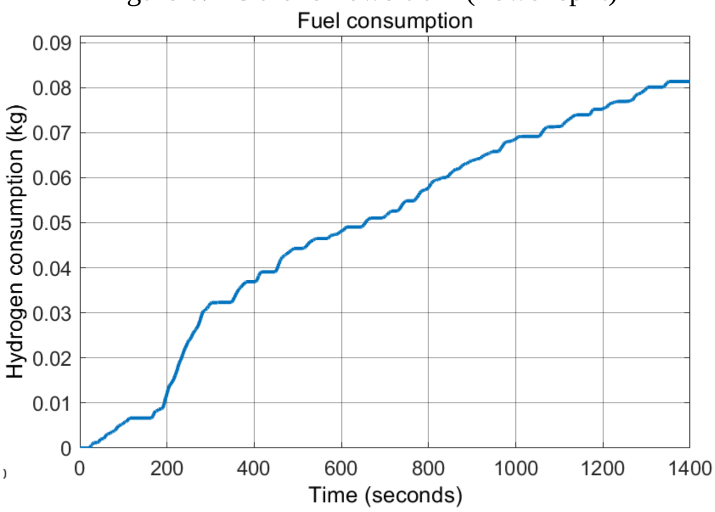


Figure 7. Fuel consumption with FC alone

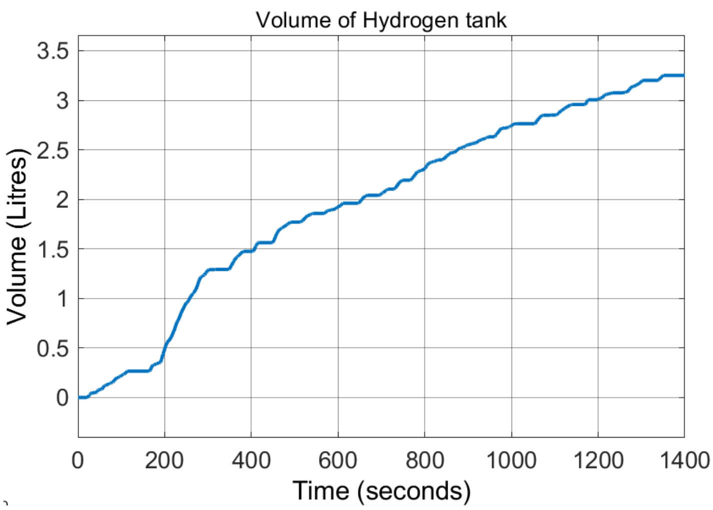


Figure 8. Volume of Hydrogen tank

For Powertrain II –Fuel cell and Battery

In this power train topology, Fuel cell is used as energy generating source and Battery is used as a secondary energy storage source. Power split between fuel cell and battery is defined using Fuzzy rule base as described earlier. Figure 9. shows power distribution between fuel cell and battery. It also shows SOC of battery at the end of driving cycle In this configuration fuel cell with rated power of 5KW is selected. Battery with 20KW is selected. To operate vehicle for 1400 seconds as per FTP 75 cycle, hydrogen required is 0.018kg. To store 0.018 kg of Hydrogen volume of tank required is 0.72 Liters. With this hybrid powertrain, one can enhance range of vehicle by selecting higher volume of storage tank. Fuel cell also charges the battery. SOC at start of cycle was set to 90%. After 1400 seconds of driving, SOC was reduced to 86%. It can be seen in Figure 9. that power fluctuations of fuel cell output power are reduced as compared to FC alone powertrain. This thereby increasing life of fuel cell [18]

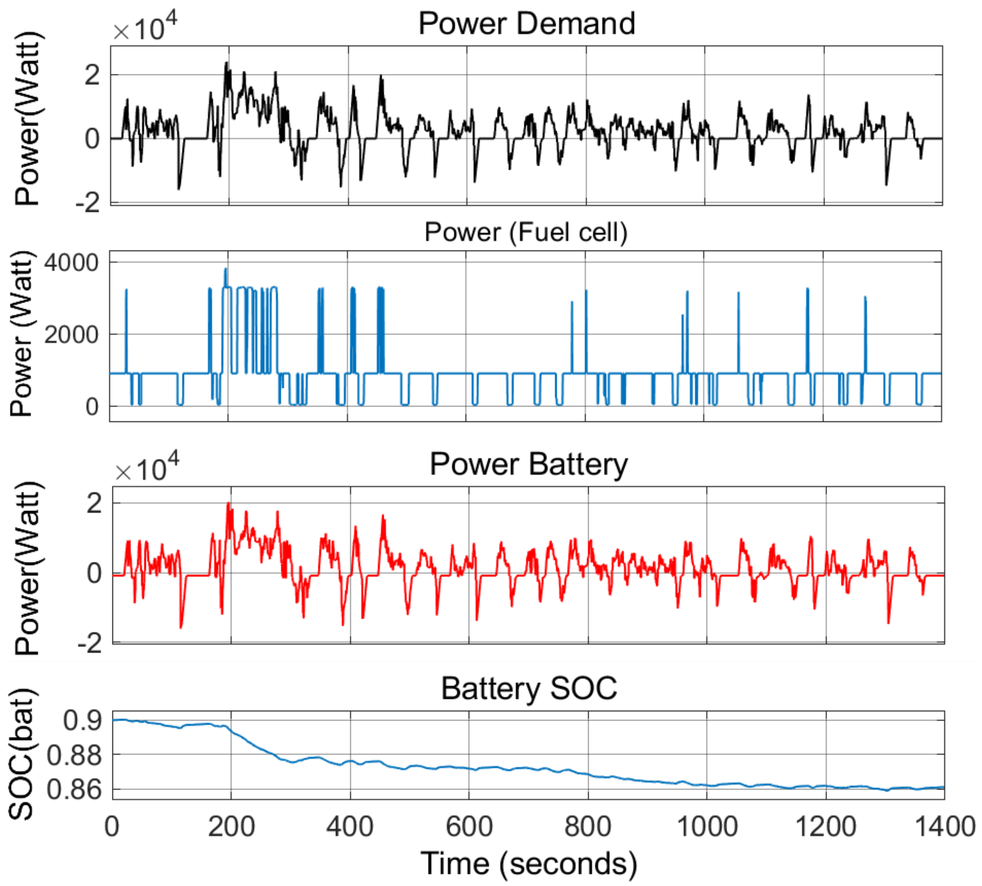


Figure 9. FC+ Battery Powertrain (Power split and Battery SOC)

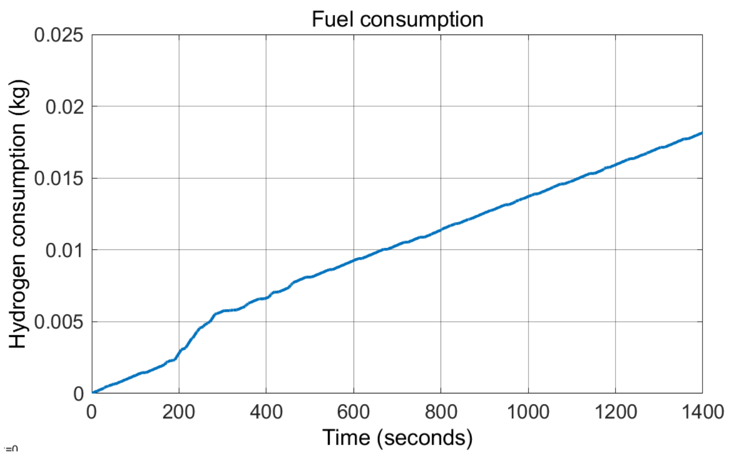


Figure 10. Fuel consumption for FC +Battery powertrain

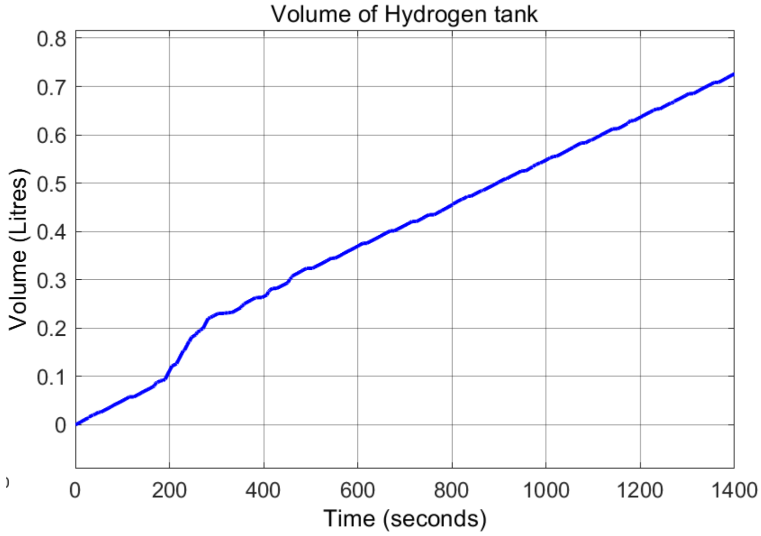


Figure 11. Volume of Hydrogen tank

	FC only	FC+B
Fuel cell (KW)	25	5
Battery (KW)	-	20
Operating time (s)	1400	1400
Hydrogen consumed(kg)	0.082	0.018
Hydrogen tank (ltrs.)	3.25	0.72

Table 4. Comparison between strategy 1 and 2

6. Conclusion

In this work, FC+ Battery powertrain is proposed and power distribution strategy based on fuzzy logic is defined. With proposed strategy we can use Fuel cell with lower power rating and combine it with Battery .With proposed powertrain energy during braking events can be stored in battery. Hydrogen consumption is reduced and thus driving range of vehicle can be increased. Since power fluctuations in Fuel cell power are reduced, life of fuel cell is also improved.

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