PEM Fuel Cell system analysis

SARY Monychot & NIANG Bora

October 7, 2024

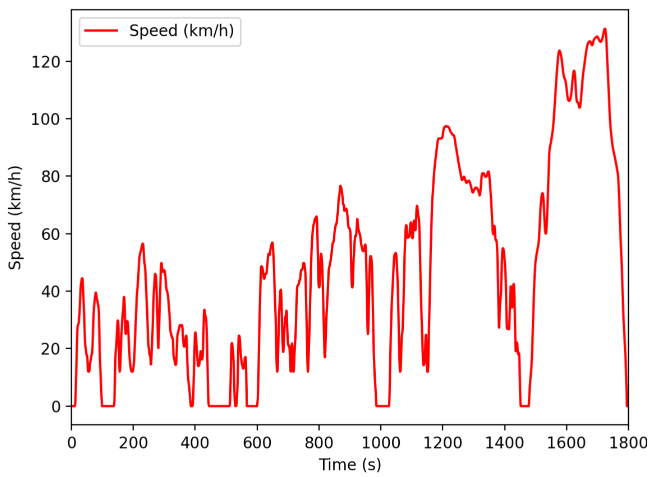
Contents

1 Calculation of the power demand inside the vechicle

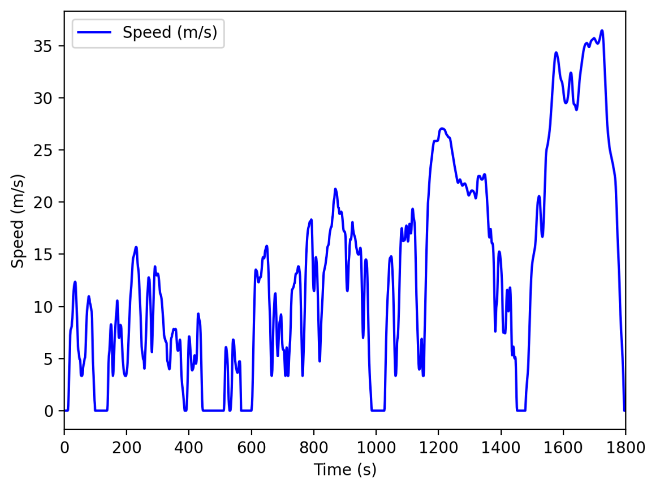
- The specification of the vehicle are the following:
  - Weight $M = 2000kg$
  - Front area $A = 2.25m^2$
  - Drag coefficient (or air penetration coefficient) $C = 0.29$
  - Rolling Resistance coefficient $C_r = 0.0115$
- The efforts applied on the vehicle in the rolling direction have to following expression:
  - Air penetration :
  $$F = \frac{1}{2}\rho_{air}v^2CA \tag{1.1}$$
  with $\rho_{air} = 1.2kg/m^3$
  - Rolling resistance :
  $$F = MgC_r\cos\alpha \tag{1.2}$$
  with $g = 9.81m/s^2$ and α the slope angle
  - Climbing or descent :
  $$F = Mg\sin\alpha \tag{1.3}$$

1.1 Calculate and plot the instant power provided by the vechicle powertrain for the road cycles " WLTC "

⋆ Consider a flat road ($\alpha = 0$)



(a) Speed Profile in km/h



(b) Speed Profile in m/s

Figure 1: Graph of the Speed Profile in km/h and Speed in m/s

1.1.1 Calculation

To calculate the **Instant Power**, we need to study of the *force* that have action on the car. By using second Newton's law with the Figure (2) shown below, we can assume that there are 4 forces that have action on thecar while driving.

- The first force is to make the car move in direction. It called the force from motor or machine of the car (F_{motor})

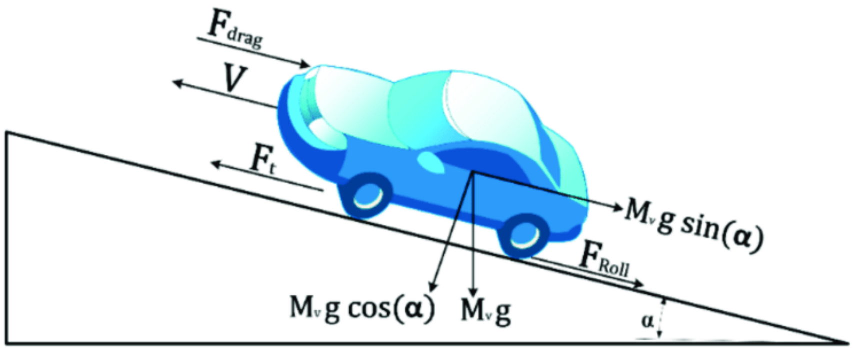


Figure 2: Speed (km/h) of the vechicle powertrain by time (s)

- The second force is the rolling force from the car wheels. It called **Rolling Resistance** ($F_{rolling}$)
- The third force is the climbing or descent force (F_{climb})
- The fourth force is the force from the air friction. we can called it Air penetration (F_{air}).

Using second Newton's law, we can written :

$$\overrightarrow{F}_{motor} - \overrightarrow{F}_{rolling} - \overrightarrow{F}_{climb} - \overrightarrow{F}_{air} = m\overrightarrow{a} \tag{1.4}$$

$$\overrightarrow{F}_{motor} = \overrightarrow{F}_{rolling} + \overrightarrow{F}_{climb} + \overrightarrow{F}_{air} + m\overrightarrow{a} \tag{1.5}$$

since a is the acceleration of the vechical in time t, as we written :

$$\overrightarrow{a} = \frac{\mathrm{d}\overrightarrow{v}}{\mathrm{d}t} = \frac{\Delta v}{\Delta t} \tag{1.6}$$

By using Equation (1.6), we can get the result of acceleration on the Figure (3)

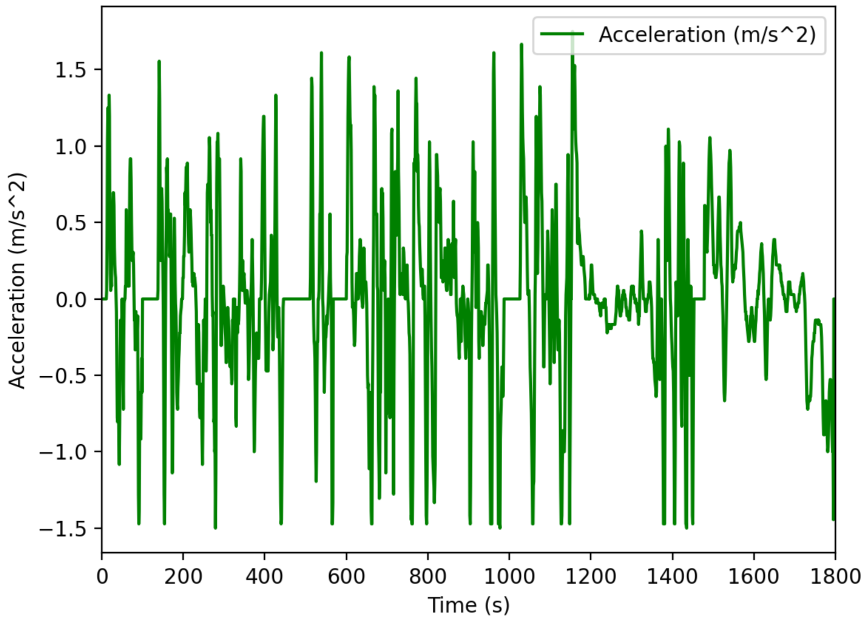


Figure 3: Acceleration (m/s^2) of the vechicle powertrain by time (s)

According to the graph, it shown that the vechical did not have the stable speed drive on the. At the some time (t), the vechical increasing the speed immediately. In contrast, at some time (t), the vechical reducing the speed quickly as shown in the Figure (3).

- For calculate F_{air} by using Equation (1.1) , we got :

$$F_{air} = \frac{1}{2}\rho_{air}v^2CA = \frac{1}{2} \times 1.2 \times v^2_{m/s,t} \times 0.29 \times 2.25 \tag{1.7}$$

In this section, to calculate F_{air} we need to get the speed in each time t in m/s^2 to analyze in the Equation (1.7) By using the Equation (1.1), we got the result of the force air penetration by shown in below graph.

- For calculate $F_{rolling}$, we will be using the Equation (1.2), we got :

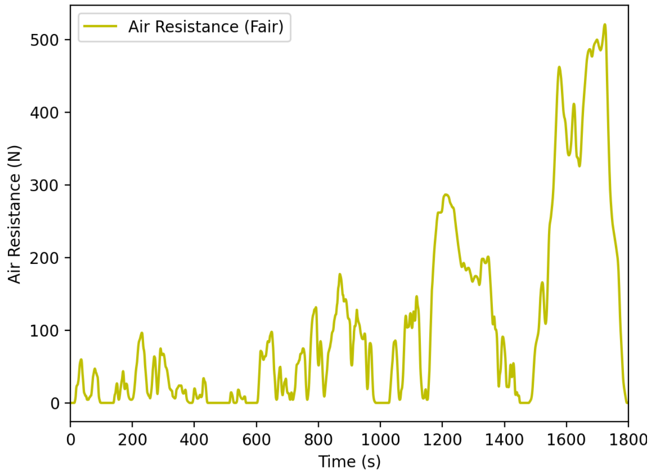
$$F_{rolling} = MgC_r\cos(\alpha) = 2000kg \times 9.81m/s^2 \times 0.0115 \times \cos(0°) = \mathbf{225.630} \tag{1.8}$$

For this force, it will be constant in time (t) becuase there is not any parameter in the Equation (1.8) will change in which time.

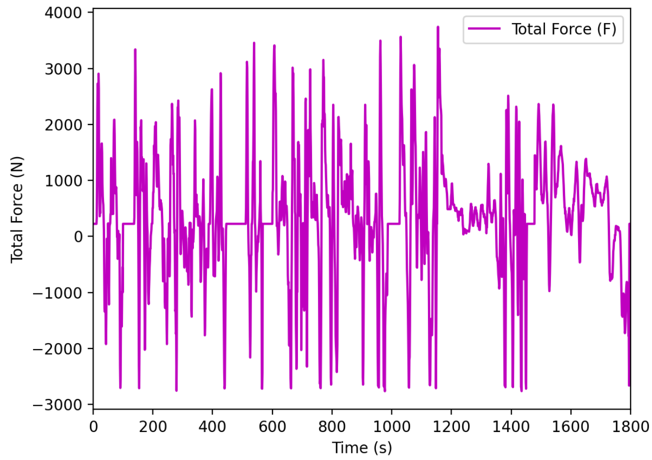
- For calculate F_{climb}, we will use Equation (1.4) then we got:

$$F = Mg\sin(\alpha) = 2000kg \times 9.81m/s^2 \times \sin(0°) = 0 \tag{1.9}$$

By using Equation (1.6), (1.7), (1.8) and (1.9) substitution into Equation (1.5). The result of total force was shown by the graph in Figure (4).



(a) Force of Air Resistance



(b) Total Force

Figure 4: Graph of the Force of Air Resistance and Total Force

To calculate Instant power we are using :

$$P = F \times v \tag{1.10}$$

The result of the instant power calcuation will be show at Figure (5)b. The instant power of the vechical are depend on two parameter :

- The total force from the vechical action (N).
- The speed that make the vechical go forward (m/s).

As now, we can write that

$$P_t = F_t \times v_t \tag{1.11}$$

The result of the instant power will show in the Figure (5).

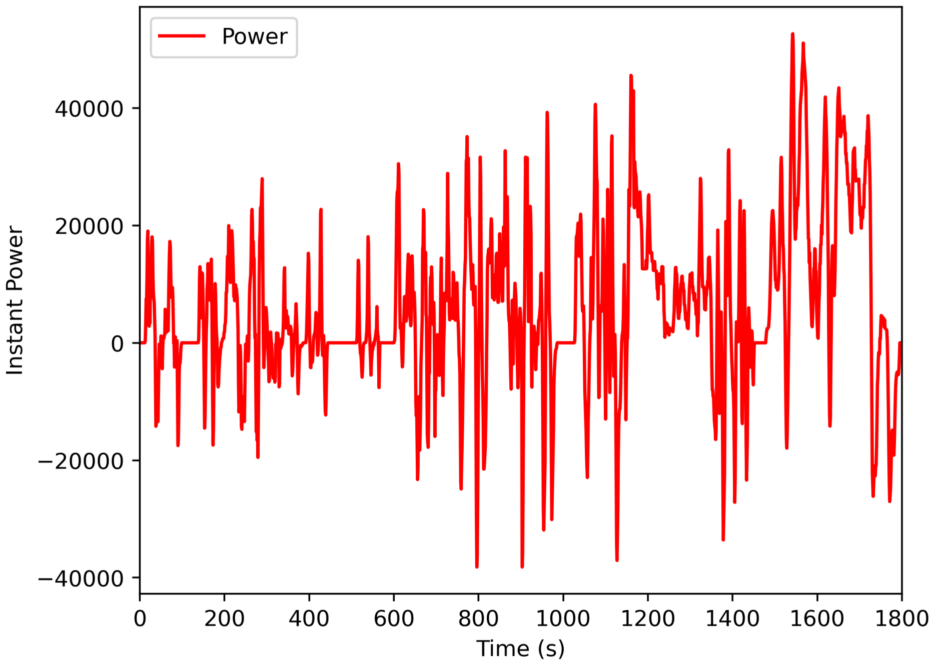


Figure 5: Instant Power of the Vechicle (W)

1.2 Calculate the instant power provide (positive) or received (negative) by the electric hybrid power source.

The vehicle auxiliaries consume an electrical power of 300W (no air conditioning, minimum consumption of all the equipment of the vehicle: sensor, supervisor,etc.) The DC/DC converter efficiency is assumed constant at 90% both direction.

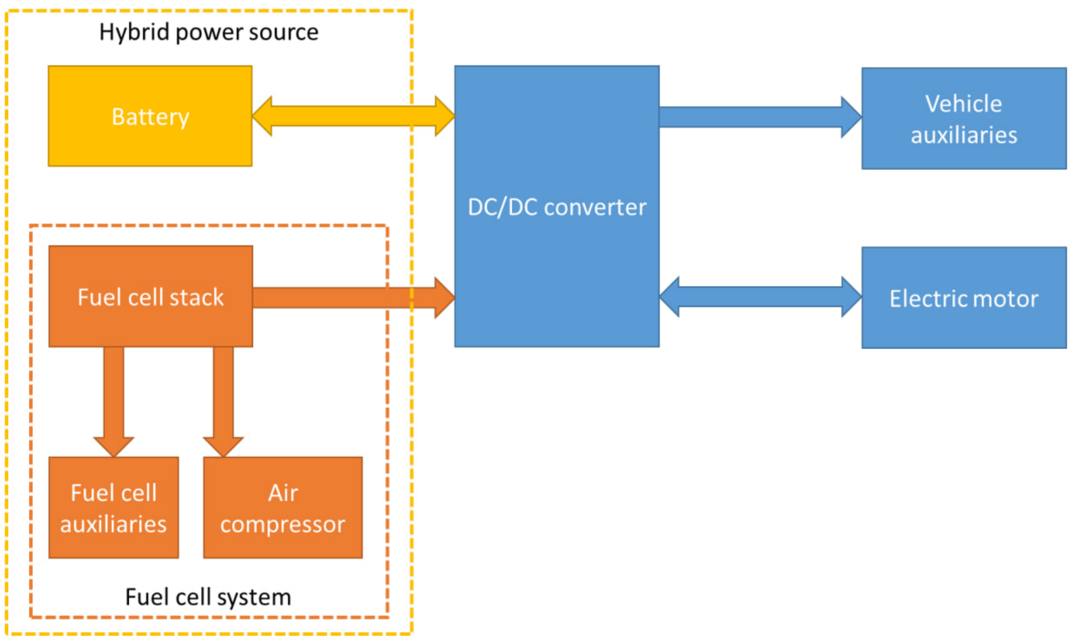


Figure 6: Hybrid system in the vehicle

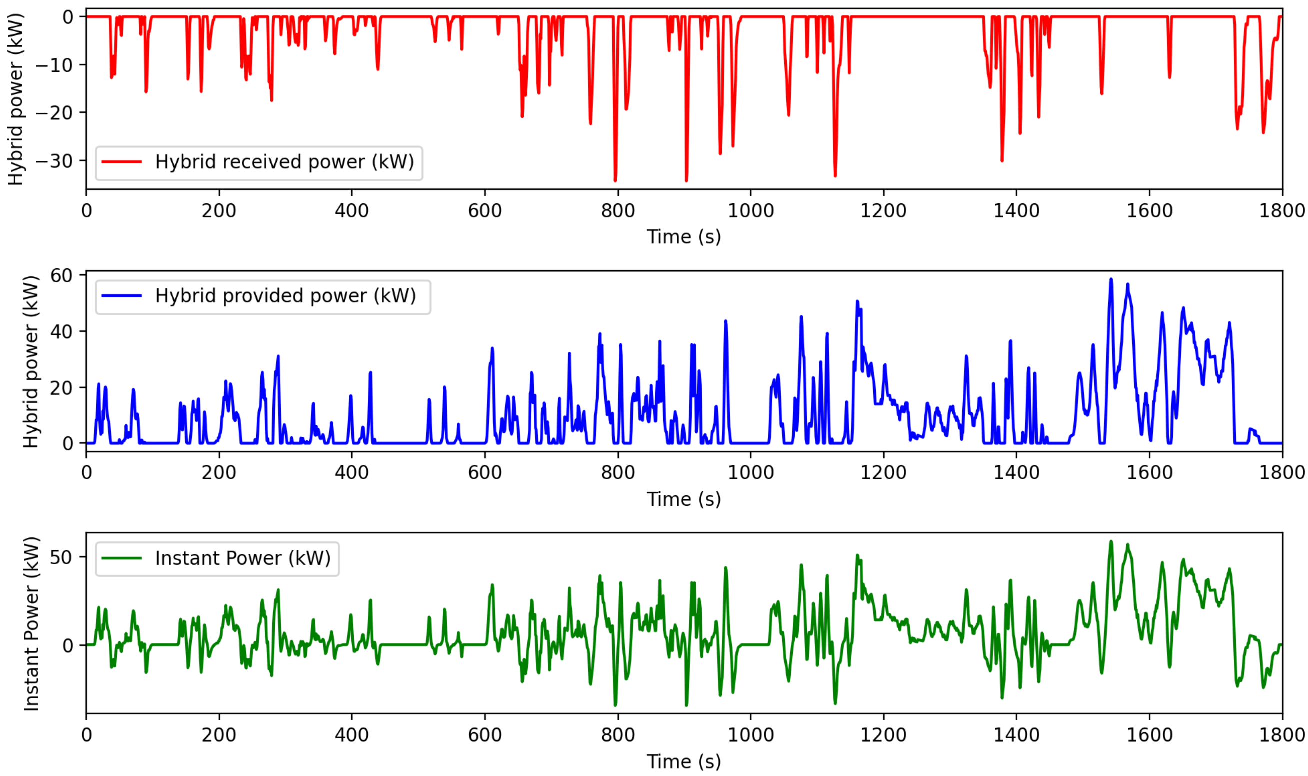


Figure 7: Hybrid working system in power transfer

To find the transfer power in the hybrid system in order to find the provided (positive) or recevied (negative), we have use instant power from pervious question as data in the Figure (5) with the efficieny of the DC/DC converter. As shown in the Figure (7): At the **first figure** had been show the **RED line graph** represented the received power (negative) to the hybrid power with the maximum received is **34.365 kW**. Moreover, as shown in the **second figure** shown the **Blue line graph** represented the provided power (positive) from the hybrid system to the motor and auxiliaries. The maximum provided power to the motor was around **58.488 kW**. According to data from the calculation, we can assumed that the vechicle mostly consum power from the hybrid and less provided power to hybrid system based on the data of speed that provided.

1.3 Calculate and Plot as a function of time : The power of the battery (kW), The power of the fuel cell system (kW), The SOC battery (%)

The energy management strategy of the hybridization between the battery and the fuel cell system is not disclosed by Tooyta.

- The battery technology is Li-ion, with a stored energy of **1.24kWh**.
- The test results of Mirai 1 indicate that the battery State of Charge (SoC) is comprised between **50%** and **65%**
- The power delivered by the battery is often close to **5%** of the total power provided by the hybrid power source when $SoC < 55\%$ or **30%** when $SoC > 55\%$
- Discharging power of the battery is approximately **12.4 kW** (or 10C), while the charging power depends on the battery SoC: **10C** if $SoC < 55\%$ or **6C** if $SoC > 55\%$
- The battery provides $0\%, 5\%, 30\%$ of the total power depending on its SoC and in the limit of its maximum discharging power.
- The EMS avoids values of SoC below 50% and above 65%

- The fuel cell system provides the rest of the power reuqired, excpet if the power demand is too low: the power provided by the fuel cell system can't be lower than **2.5kW**

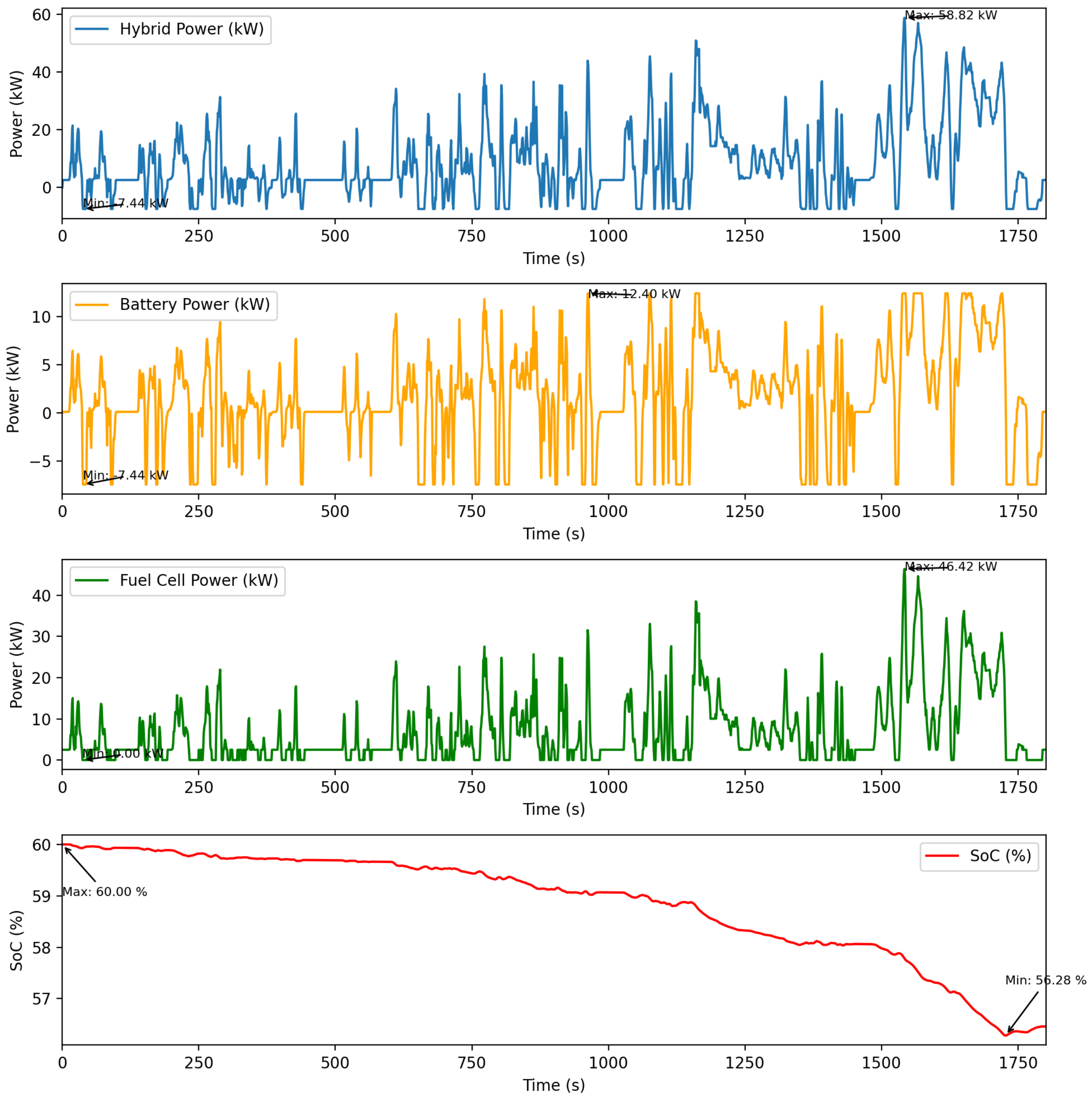


Figure 8: Hybrid system, Battery Management, Fuel Cell power and State of Charge in the Vehicle

As the result that shown in the Figure (8),

- The first plot of the Figure (8) (represented by the by blue curve) show about the **Hybrid Power** working in the system.

- The second plot of the Figure (8) (represented by the by yellow curve) show the characteristic of the charging and discharging of the Battery in the vehicle. The maximum power discharging is **12.4 kW** and the maximum power charging is **7.44 kW**. The status of charge and discharge ws depend on the time and speed per second.

- The third plot of the Figure (8) (represented by the by green curve) show the fuel cell consumption that will be use in the system. The maximum fuel cell consumption is **46.42 kW**. The consumption of the fuel cell variable depend on the time.

- The fourth plot in Figure (8) (represented by the by red curve) illustrates the State of Charge (SoC) of the battery system. It starts with an initial SoC of approximately **60%** and gradually decreases to **56.28%** over time, depending on the driving characteristics. The SoC can fluctuate, increasing or decreasing based on the motor's operation and the dynamics of the hybrid system.m

1.4 Make the same analysis with the road cycle "130 kmh". Consider two different cases : $\alpha = 0°$ and $\alpha = 2°$

1.4.1 Analysis $\alpha = 0°$

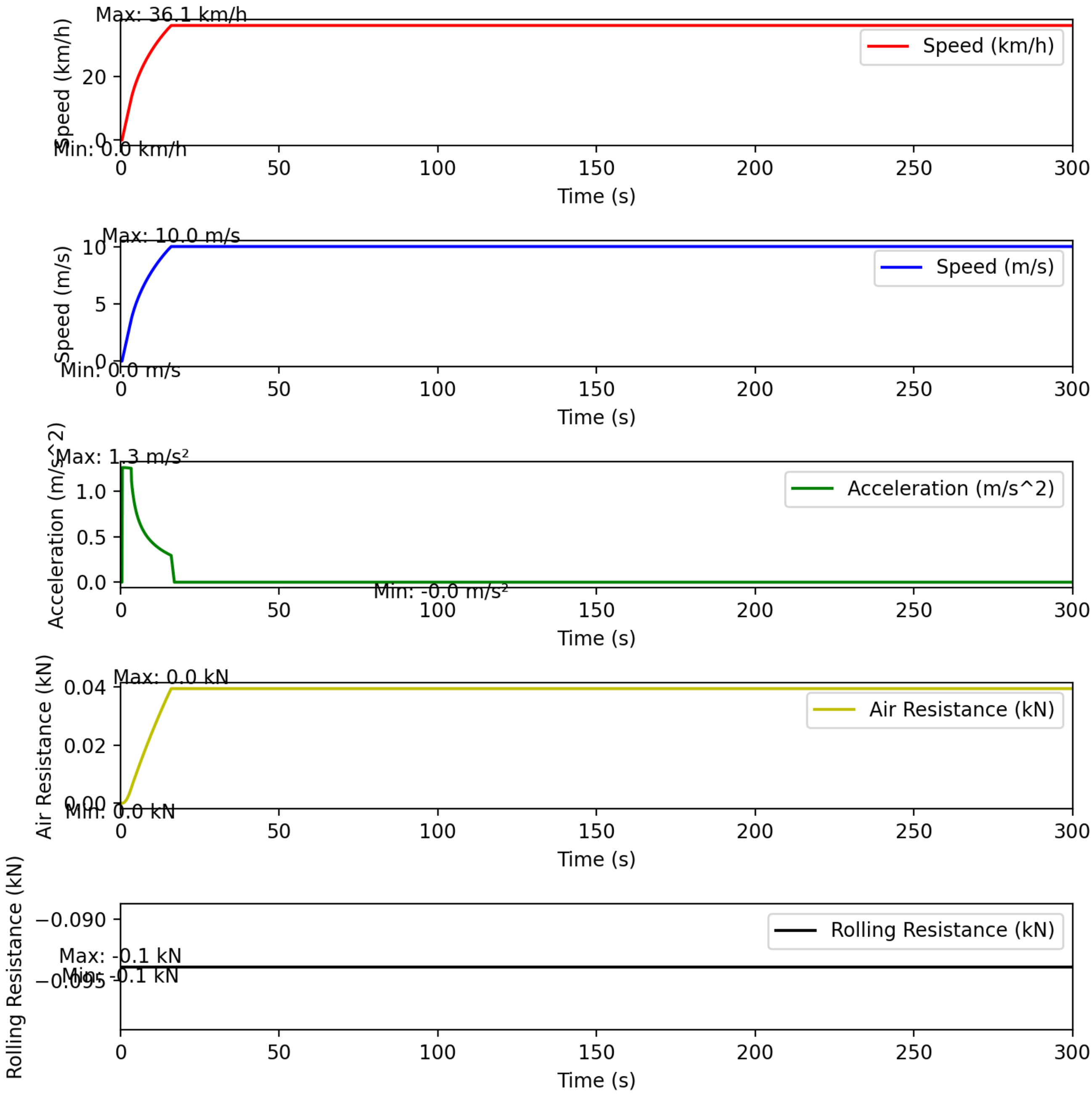


Figure 9: Plots related to Speed, acceleration, air resistance, and rolling resistance over time

In the Figure (9), it was shown the data curve about the speed within km/h and m/s, acceleration in m/s^2, Air Resistance and Rolling Resistance.

- The first red curve in the Figure (9)

1.4.2 Analysis $\alpha = 2^\circ$