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Modelling and Simulation of the Fuel Cell/Battery Hybrid Electric Vehicle Drive Train

John Malata and Sam Sichilalu
Department of Mechanical Engineering, University of Zambia, Zambia

Abstract:-

- ***Background***

This paper has analysed the different types of dive trains published by different authors on fuel cell/battery hybrid electric vehicles. The fuel cell/battery hybrid electric vehicle has been optimised in this paper to increase the driving range of the electric vehicle by improving the state of charge (SOC) of the battery pack by using the fuel cell. Methondology used: MATLAB/SIMLINK (2020) is used to simulate the optimum parameters from components of the hybrid electric vehicle drive train and their energy sources. Simulation results:1. The simulation results show that with optimum parameters from the vehicle body, curb weight 300kg, drag coefficient 0.25 and air density 1.18kg/m^{3}and from the traction motor, no-load speed 14000rpm and rated speed 12000rpm.It is proved that with these optimum parameters the hybrid electric vehicle is able to follow smoothly the reference speed from the signal builder block.2. The fuel cell through the booster converter is able to charge and maintain the state of charge (SOC) of the battery pack from 95% to 70% for the entire simulation period. Conclusion:In conclusion, from the simulation results, as long as the fuel cell is able to supply 140V to charge the 120V battery pack, the traction motor will be able to propel the vehicle to the pre-determined destination.

***Keywords*:-** *Fuel Cell, Battery Pack, Hybrid, Simulation, Traction Motor.*

I. INTRODUCTION

The need for the Government of the Republic of Zambia to reduce dependence on imported crude oil to power the transport sector and to hide on global climate change challenges and green solutions has necessitated this research on fuel cell/ battery hybrid electric vehicle in Zambia [1].

This study is sought to come up with the optimised parameters of the fuel cell/battery hybrid electric drive train to have sufficient energy to power the traction motor to cover the entire journey of the vehicle.

The components of the drive train for the fuel cell/battery hybrid electric vehicle (FCHEV) consists of the motor controller, traction motor, transmission, differential unit, the driving wheels, vehicle body, the energy sources include battery pack and fuel cell. [2,3]

The drive trains used in fuel cell hybrid salon cars are basically three types, combination of fuel cell and ultra capacitors this has the merit of high power density and demerit of low energy density which is required to extend the driving range. This causes increase in size of the fuel cell and the weight of the vehicle. The second one is the combination of the fuel cell and the batteries this has the merit of high energy density required to extend the driving range of the vehicle. However, it has the demerit of low power density required during high power demand of the vehicle. [4,5]

Ehsani et al [6,], investigated that fuel cell/battery hybrid electric vehicles (FCHEVs) have a better power performance, however, it is the research difficulty to make the power source power distribution more reasonable and better improve the economy.

Ahmadi et al. [7], also investigated that the drive train of the (FCHEVs) is affected by the working conditions which have an impact on the power source performance and economy of (FCHEVs) and as result that could cause the degradation of a fuel cell and the performance of the vehicle in general.

Hybridisation of fuel cell has to overcome the vehicular challenges of the fuel cell as an energy source by improving its shortcomings of inability to recover braking energy, soft output characteristics and slow start speed. The fuel cell/battery hybrid electric vehicle has resolved this problem; however, the gaps still exist in balancing fuel cell/battery energy sources in energy and power density for hybrid electric vehicle applications [8], the average cost of the fuel cell/battery electric vehicle is still high compared to the internal combustion engines (ICE) vehicles, this has posed as challenge to grow the market for the renewable energy source hybrid electric vehicles [9,10,11]and according to Bossel [12,] ,the hydrogen infrastructure of refuelling stations is still under developed in many countries which has posed a challenge for development of fuel cell hybrid electric vehicles in world.

Hybridisation of fuel cell electric vehicle has brought about optimisation of the drive train, which has improved manufacturing of electric motors with high power ratings to withstand difficult driving terrains. Improved technology on production of Lithium Batteries with high energy and moderate power densities capable of meeting the demand of the modern electric vehicle [13,14,]. The fuel cell also has been reduced in size to reduce the weight of the vehicle but efficient enough to continue to supply power to the traction motors and batteries in order to extend the driving range. The motor controllers have been improved to vary the speed of the traction motors in different driving conditions [15,16,17]. The research shows that as long as hydrogen is continued supplied to the fuel cell, the battery pack will maintain the state of charge to continue supplying the traction motor with enough voltage to propel the vehicle.

However, with the latest technology on production of lithium batteries, which has improved the low power density, reduced the size and weight of the battery pack. This has caused in the reduction in weight of the fuel cell and generally the weight of the vehicle [18,19].

Therefore, the drive train adopted in this electric vehicle will be powered by the fuel cell /battery energy system which will have high energy and moderate power density to withstand the conditions in Zambia. This electric vehicle will use improved Lithium Ion batteries and high performance fuel cell with reduced size and weight, which will drastically reduce the mass of the vehicle.

This paper is addressing the degradation of the fuel cell and the limited driving range the of the battery pack by complimenting each other’s energy strength by coming up with the hybrid energy source which will combine the battery pack and fuel cell energy to propel the traction motor. The model was constructed and simulated in MATLAB Simulink (2020) using the vehicle components and the two energy sources battery pack and fuel cell. The reference speed is generated using the signal builder block in Simulink. The two energy sources are linked using the control switch connecting the battery pack and fuel cell through the booster converter. The battery pack is 120V, Lithium batteries and fuel cell is 1.26Kw,24V DC, connected to the circuit through the booster converter. The main power source for the hybrid electric vehicle is the Lithium battery pack with the state of charge (SOC) of 95% and the fuel cell is the additional energy used to charge the battery pack and maintain the state of charge. When the vehicle is operating and the state of charge drops to 75% the control switch will open the fuel cell is used to charge the battery pack with 140V through the booster converter and maintain the state of charge to 70% through the remaining simulation time. The control algorithms controls the switch which connects the battery pack and the fuel cell and it set at 75% SOC, which means when the state of charge reaches 75% it commands the switch to open, to connect the fuel cell through the booster converter to charge the battery pack and maintain the state of charge.

This paper also is proposing to use the local minerals which are mined in Zambia such copper, cobalt, and other minerals to manufacture vehicle components like fuel cell, batteries, transmission, traction motors, cables and other electronic components to lower the cost production of the fuel cell/battery hybrid electric vehicles so that the market could afford them.

The hydrogen will be produced from the abundant natural resources in Zambia, like water to produce hydro electricity which could be used to produce hydrogen during industrial electrolysis.

MATLAB/Simulink is used to simulate the components of the fuel cell/battery electric vehicle and the operational parameters are optimised for the better performance of the hybrid electric vehicle.

The block diagram shown in figure 1, consists of the tires connected to the vehicle body, the input power to the tires is received from the differential unit, through the gearbox and the traction motor. The motor controller will vary the traction motor speed through the input signal from the driver. The battery will be the main energy source of energy which is supplemented and charged by the fuel cell through the booster converter.

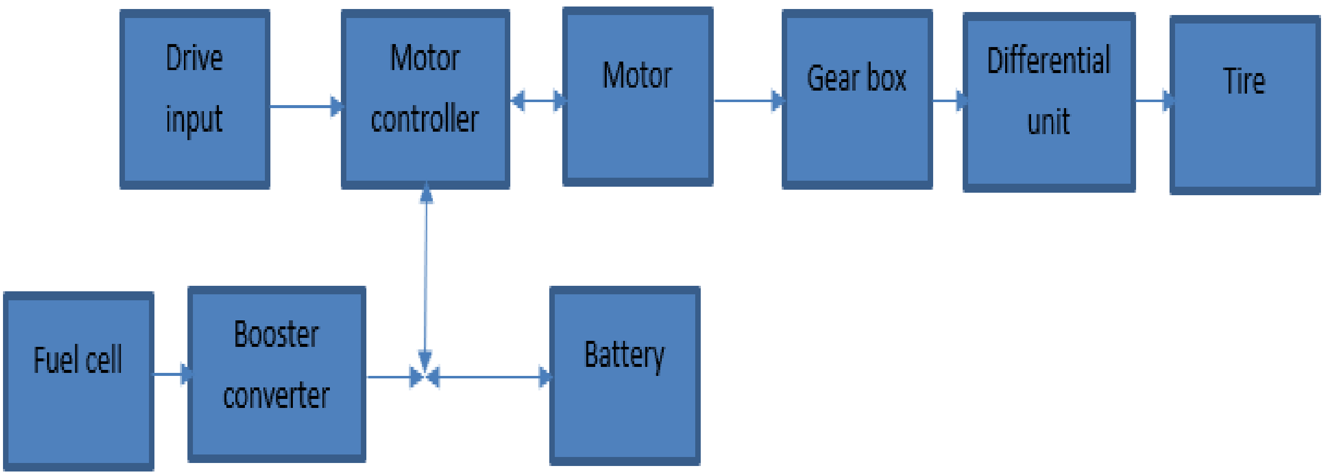

Fig 1 Shows Simulation Block Diagram.
Source: Author

II. MATHEMATICAL MODELS OF THE DRIVE TRAIN COMPONENTS USED IN THE FUEL CELL /BATTERY HYBRID ELECTRIC VEHICLE

➢ *Force model*

The electric motor must overcome the forces which act on the electric vehicle, which includes forces due to wind, gravity, inertial effect and rolling resistance. Figure 2 shows the forces acting on the vehicle.

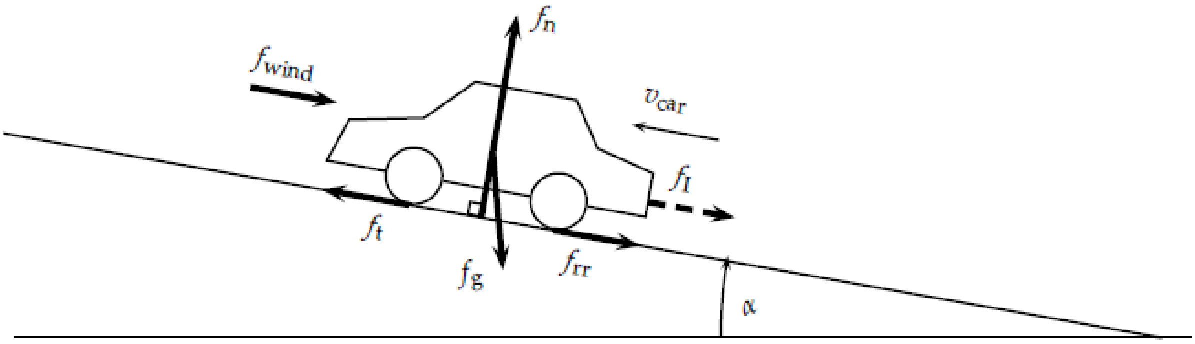

Fig 2 Shows forces acting on the electric vehicle.
Source: [20]

The traction force of the electric vehicle can be calculated using the following equation, [20].

$$f_t = \underbrace{M_{car}\dot{v}_{car}}_{f_I} + \underbrace{M_{car}}_{f_g}.g.\sin(\alpha) + \text{sign}\,(v_{car})\underbrace{\overbrace{M_{car}.g.\cos(\alpha)}^{f_n}.}_{f_{rr}}\underbrace{c_{rr}} + \text{sign}\,(v_{car}+v_{wind})\,\underbrace{\tfrac{1}{2}\rho_{air}C_{drag}(v_{car}+v_{wind})^2}_{f_{wind}} \quad (1)$$

$$c_{rr} = 0.01\left(1 + \frac{3.6}{100}\,v_{car}\right) \quad (2)$$

Given that,

f_t [N]-Traction force of the vehicle
f_I [N] -Inertial force of the vehicle
f_{rr} [N] -Rolling resistance force of the wheels
f_g [N] -Gravitational force of the vehicle
f_n [N] -Normal force of the vehicle
f_{wind} [N] -Force due to wind resistance
α [rad] -Angle of the driving surface
M_{car} [kg]- Mass of the vehicle
v_{car} [m/s]-Velocity of the vehicle
$\dot{v}_{car}$ $[m/s^2]$-Acceleration of the vehicle
g = 9.81 $[m/s^2]$-Free fall acceleration
ρ_{air}= 1.2041$[kg/m^3]$-Air density of dry air at 20℃
c_{rr} $[-]$ -Tire rolling resistance coefficient
C_{drag} $[-]$- Aerodynamic drag coefficient
A_{front} $[m^2]$ – Front area
v_{wind} [m/s] -Headwind speed

➢ *Inverter Model*

The function of the inverter is to transmit power between the electric machine (with phase voltages v_A, v_B *and* v_C,) and the battery by turning on and off the switches $Q_{A+}, Q_{A-}, Q_{B+}, Q_{B-}, Q_{C+},$ *and* Q_{C-} as demonstrated in figure 3.

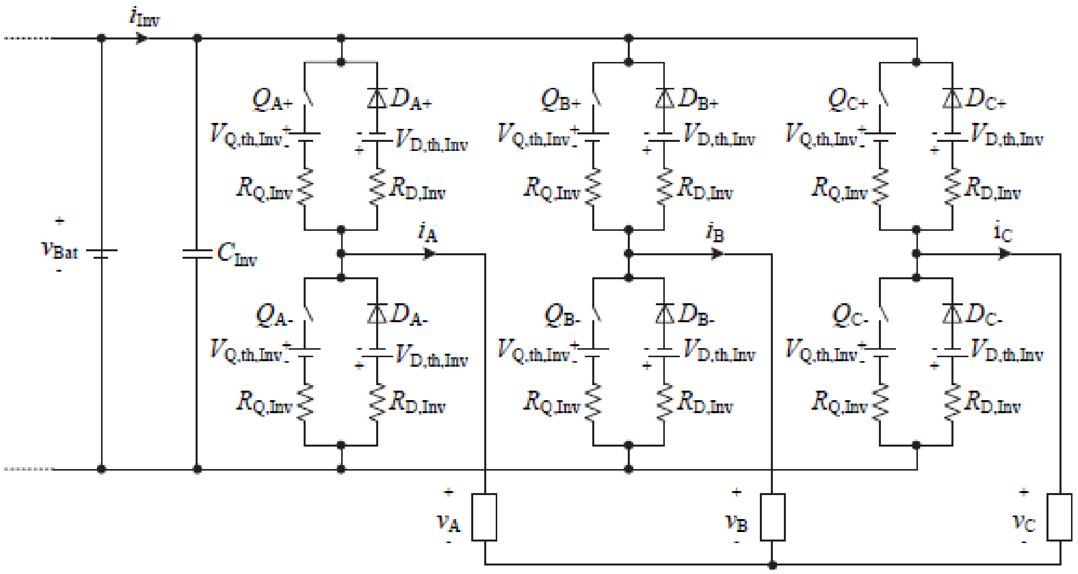

Fig 3 Shows the circuit diagram for the inverter.
Source [21]

The inverter switches have an on-resistance $R_{Q,Inv}$ and the diodes are connected parallel to each switch creating a path for the motor currents during the dead time, that is, the time when both switches in one branch are not conducting in order to avoid a shoot-through.

During one fundamental period the average power losses of one switch $p_{Q.Inv}$ *and diode* p_{DInv} is calculated as follows, [21].

$$p_{Q,Inv} = \left(\frac{1}{8} + \frac{m_i}{3\pi}\right) R_{Q,Inv} I_p^2 + \left(\frac{1}{2\pi} + \frac{m_i}{8}\cos(\Phi_{EM})\right) V_{Q,th,Inv} I_p \qquad (3)$$

$$p_{D,Inv} = \left(\frac{1}{8} - \frac{m_i}{3\pi}\right) R_{D,Inv} I_p^2 + \left(\frac{1}{2\pi} - \frac{m_i}{8}\cos(\Phi_{EM})\right) V_{D,th,Inv} I_p \qquad (4)$$

$$m_i = \frac{2\hat{V}_P}{V_{Bat}} \qquad (5)$$

Whereas,

$p_{Q,Inv}$ − [W] Power loss of one switch
$p_{D,Inv}$ − [W] Power loss of one diode
Φ_{EM} −[rad] Power factor angle
I_p − [A] Peak phase current
$\hat{V}_P$ − [V] Peak phase voltage
m_i − [−] Modulation index
V_{Bat} − [V] Battery voltage
$R_{Q,Inv}$ − [Ω] Inverter switch resistance
$R_{D,Inv}$ − [Ω] Inverter diode resistance
$V_{Q,th,Inv}$ − [V] Inverter switch threshold voltage
$V_{D,th,Inv}$ − [V] Inverter diode threshold voltage

When it assumed that the voltage drop of the switches and the diodes are equal, meaning,$V_{th,Inv} = V_{Q,th,Inv} = V_{D,th,Inv}$ and that includes the resistance of switches and the diodes are also equal, meaning, $R_{Inv} = R_{Q,Inv}$=$R_{D,Inv}$,then the total power loss of the inverter is given by;

$$P_{Inv,loss} = 6\left(P_{Q,Inv} + P_{D,Inv}\right) = \frac{3}{2} Inv I_p^2 + \frac{6}{\pi} V_{th,Inv} I_p \qquad (6)$$

The output power of the inverter is equal to the input power of the motor P_{EM} and the inverter input power and efficiency is given as follows;

$$P_{Inv} = v_{Bat} i_{Inv} = P_{EM} + p_{Inv,loss} \quad (7)$$

$$\eta_{Inv} = \begin{cases} \frac{P_{EM}}{P_{Inv}}, P_{EM} \geq 0 \\ \frac{P_{Inv}}{P_{EM}}, P_{EM} < 0 \end{cases} \quad (8)$$

Whereas,

i_{Inv} − [A] Inverter input current
P_{Inv} − [W] Inverter input power
η_{Inv} − [−] Inverter efficiency

➢ *Electric machine (motor) model*

The electric vehicles normally use the induction machine (IM), permanent magnet synchronous machine (PMSM), and switched reluctance machine (SRM) for propulsion. The choice of the motor to be used depends on the trade-off between cost, mass, reliability, maintenance, volume, efficiency, etc. However, PMSM has been considered in this paper due to its high power density and high efficiency, [22]

The electric motor is divided into an electric part and mechanic part. The electric part of the PMSM is modelled in the DQ-frame, as follows:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \quad (9)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_{pm} \quad (10)$$

$$p_{EM} = \frac{3}{2}(v_d i_d + v_q i_q) \quad (11)$$

Given that,

v_d −[V] D-axis voltage
v_q −[V] Q-axis voltage
i_d −[A] D-axis current
i_q −[A] Q-axis current
R_s −[Ω] Stator phase resistance
L_d −[H] D-axis inductance
L_q −[H] Q-axis inductance
λ_{pm} −[Wb] Permanent magnet flux linkage
ω_e −[rad/s] Angular frequency of the stator
p_{EM} −[W] Electric input power

And the mechanical part of the PMSM can be modelled as follows:

$$\tau_e = j_s \frac{d\omega_s}{dt} + B_v \omega_s + \tau_c + \tau_s \quad (12)$$

$$p_s = \tau_s \omega_s \quad (13)$$

$J_s - [kgm^2]$ Shaft moment of inertia
τ_e −[Nm] Electromechanical torque
τ_c −[Nm] Coulomb torque
B_v −[Nms/rad] Viscous friction coefficient

While the coupling between the electric and mechanic part is given by

$$\tau_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{pm} i_q + \left(L_d - L_q\right) i_d i_q\right) \quad (14)$$

$$\omega_e = \frac{P}{2}\omega_s \quad (15)$$

Given that P [−] Number of poles.

➢ *Transmission Model*

It has been established that the torque, power and angular velocity of the transmission system are given by the following equations as shown.

$$\tau_t = f_t r_w \quad (16)$$

$$\tau_w = \frac{\tau_t}{2} \quad (17)$$

$$\omega_w = \frac{v_{car}}{r_w} \quad (18)$$

$$p_t = f_t v_{car} \quad (19)$$

Given that

τ_t-[Nm] Traction torque
τ_w -[Nm] Torque of each driving wheel
r_w -[m] Wheel radius
ω_w-[rad/s] Angular velocity of the wheels
p_t-[W] Traction power

There is an assumption that the power from the shaft of the electric machine to the two driving wheels has a constant efficiency of η_{TS}= 0.95, [23]. Therefore, the shaft torque, angular velocity, and power of the electric machine are as follows:

$$\tau_s = \begin{cases} \eta_{TS}\frac{\tau_t}{G}, p_t < 0 \\ \frac{\tau_t}{\eta_{TS} G}, p_t \geq 0 \end{cases} \quad (20)$$

$$\omega_s = G\omega_w \quad (21)$$

$$p_s = \tau_s \omega_s \quad (22)$$

Whereas,

τ_s- [Nm] Shaft torque of electric machine
p_s-[W] Shaft power of electric machine
ω_s- [rad/s] Shaft angular velocity of electric machine
G- [−] Gear ratio of differential

III. CASE STUDY: SIMULATION OF THE FUEL CELL /BATTERY HYBRID ELECTRIC VEHICLE

➢ *Matlab /Simulink Software*

MATLAB /Simulink is the software used to analyse and optimised the parameters of the components of the fuel cell battery hybrid electric vehicle. Simulink is the Model-Based Design which is a block diagram environment for multidomain simulation. It is used for simulation, continuous test, automatic code generation and verification of embedded systems. It provides customisable block libraries, a graphical editor, simulating dynamic systems and solvers for modelling. Simulink is incorporated in MATLAB, in order to integrate MATLAB algorithms into models and this makes it possible to export simulation results to MATLAB for further analysis. It numerically approximates the solutions from mathematical models which we are unable to, or don't wish to, solve "by hand." Therefore, the mathematical equations representing a given system serves as the basis for a Simulink model this could be derived from physical laws [24].

The simulation of the fuel cell/battery hybrid electric vehicle is done in MATLAB/Simulink (2020) [25]. The simulation components of the drive train included the vehicle body, wheels, differential unit, transmission, traction motor, motor controller, fuel booster converter, the energy sources included the battery and the fuel cell. The control inputs included the driver and the signal builder block.

➢ *Fuel Cell/Battery Hybrid Electric Vehicle Simulation Parameters.*

The following parameters in table 1 are used during the simulation of the Fuel cell/Battery hybrid electric vehicle as a case study, MATLAB/Simulink is used for simulation.

Table 1 Shows Simulation Parameters for Fuel Cell/Battery Hybrid Electric Vehicle MAT/Simulink2020.

Simulation Parameters	
Parameter Description	**Measurements**
Vehicle Body	
Curb weight	300kg
Number of wheels per axle	2
Horizontal distance from CG to front axle	1.4m
Horizontal distance from CG to rear axle	1.6m
CG height above ground	0.5m
Externally-defined additional mass	off
Gravitational acceleration	$9.81 m/s^2$
Negative normal force warning	off
Frontal area	$2m^2$
Drag coefficient	0.25
Air density	$1.18 kg/m^3$
Tire (Magic formula)	
Rated vertical load	3000N
Peak longitudinal force at rated load	3500N
Slip at peak force at rated load (percent)	10
Rolling radius	0.3m
Differential unit	
Crown gear located	To the right of the centreline
Carrier (C) to driveshaft (D) teeth ratio (NC/ND)	4
Gearbox	
Follower (F) to base (B) teeth ratio (NF/NB)	2
Output shaft rotates	In the same direction of the input shaft
Electric motor	
Field type	Permanent magnet
Model parameterization	by rated load and speed
Armature inductance	12e-6H
No-load speed	14000rpm
Rated speed (at rated load)	12000rpm
Rated load (mechanical power)	120kW
Rated DC supply voltage	120V
Rotor damping parameterization	By damping value
Rotor inertia	$0.01g\ cm^2$
Rotor damping	0Nm/(rad/s)
Initial rotor speed	0rpm
H-Bridge (Motor controller)	
Power supply	Internal
Simulation mode	Averaged

Regenerative braking	Depends on REV flag and current sign
Load current characteristics	Smoothed
Enable threshold voltage	0.001V
PWM signal amplitude	1
Reverse threshold voltage	0.0001V
Braking threshold voltage	0.0001V
Output voltage amplitude	120V
Total bridge on resistance	0.1Ohm
Freewheeling diode on resistance	0.05Ohm
Freewheeling diode off-state conductance	1e-6S
Battery	
Battery type	Lithium Battery
Nominal voltage	120V
Initial state-of-charge	95%
Battery response time	30s
Fuel cell stack	
Pre-set model: PEMFC	1.26kW-24Vdc
Atomic mass units Hydrogen	1.36908036
Atomic mass units Oxygen	5.89420573
Fuel cell booster converter	
Inductance	400e-6(H)
Capacitance	1000e-6(F)
Resistance	100 (Ohms)

Source: Author

➢ *Simulation Input Signal*

The simulation inputs signal is generated by the signal builder block which determined the reference speed of the fuel cell/battery electric vehicle and with the optimum parameters of the components of the drive train the electric vehicle is supposed to accurately follow the reference speed without diverting. The driver must control the speed and the movement of the vehicle at all times. The signal shows the reference speed accelerating from 0km/h to 100km/h in 400s, then travel at constant speed at 100km/h for 200s before sharply decelerating from 100k/h to 60km/h and finally moves with the constant speed of 60km/h for 400s.The reference speed is on the scale of 1:100km/h as could be seen from figure 4 below.

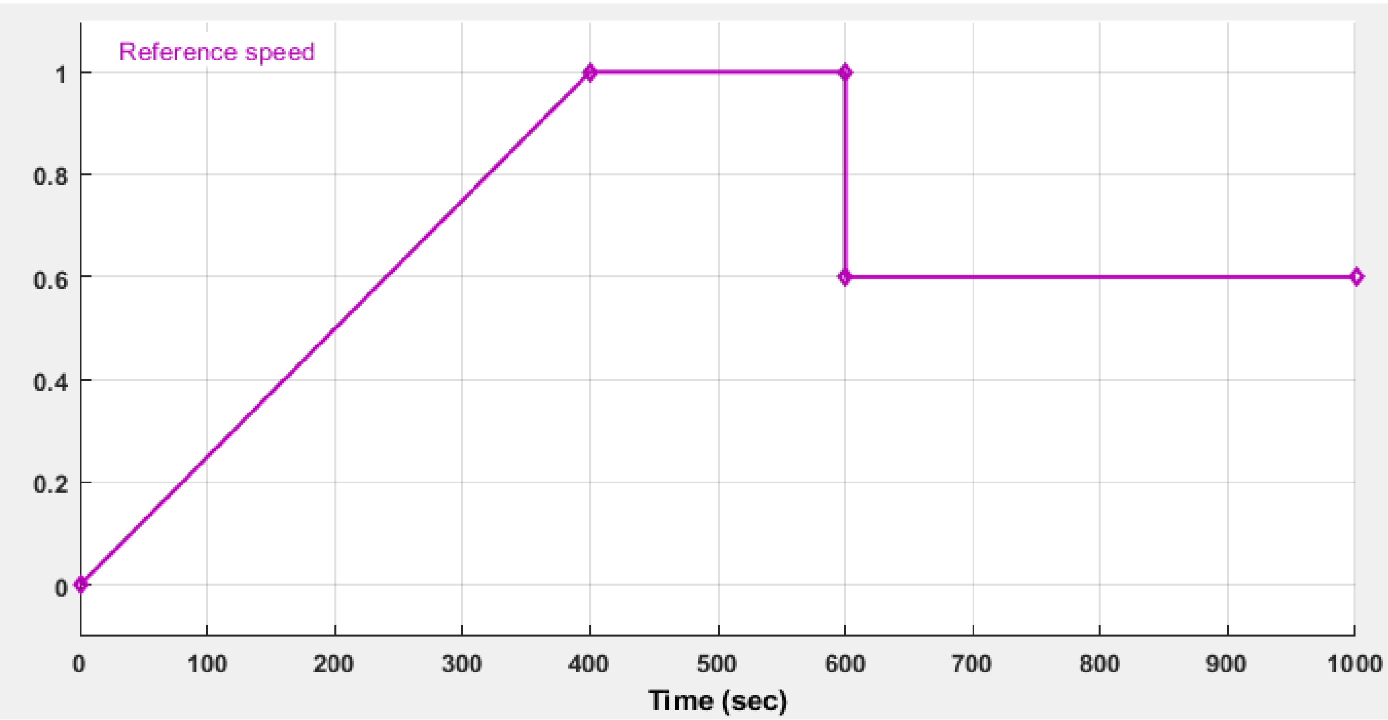

Fig 4 Shows the simulation reference speed from the signal builder block in 1000 seconds
Source: Author

The simulation diagram consists of the following components; the vehicle body, tires, differential unit, gearbox, traction motor, H-bridge (motor controller), driver, signal builder block, fuel cell, booster converter, battery pack and control logic as shown below in figure 5.

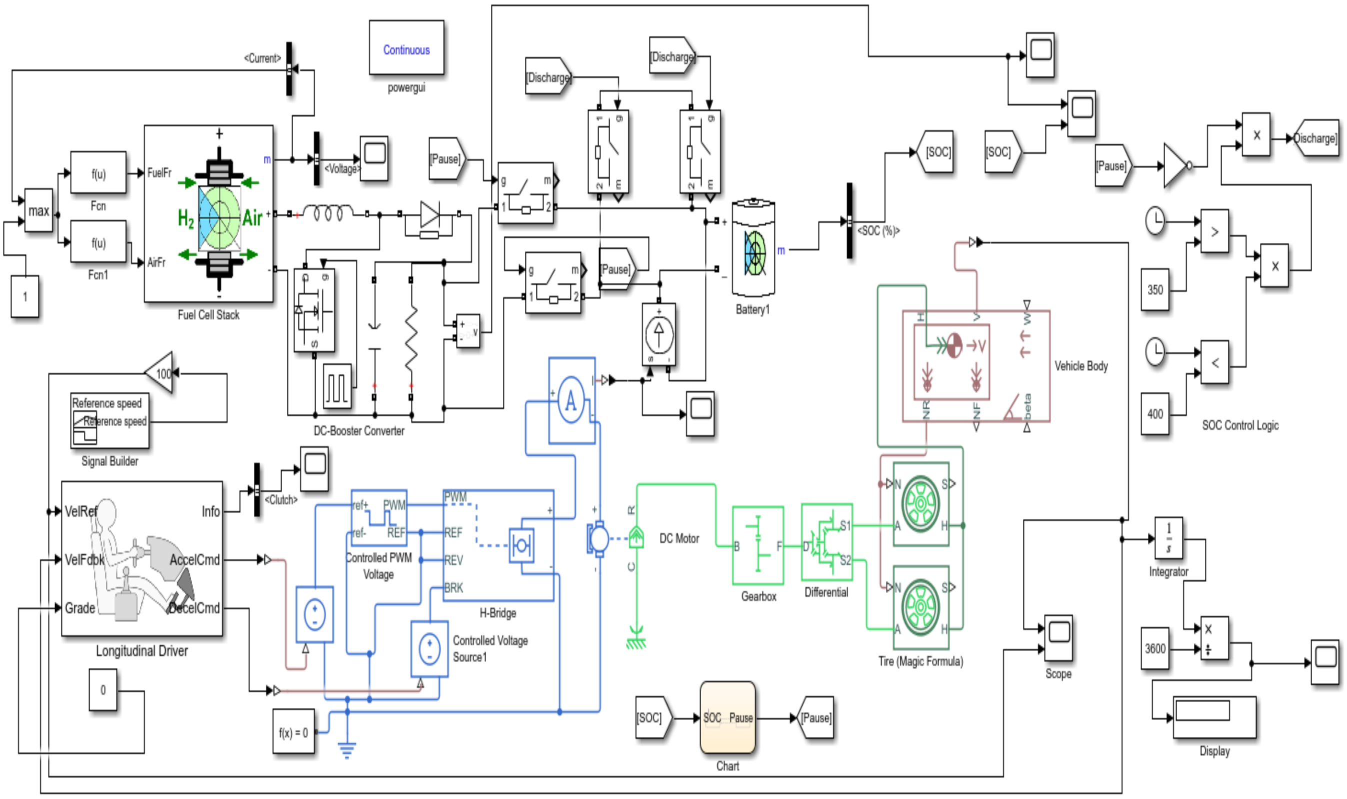

Fig 5 Shows MATLAB/Simulink Simulation Diagram for Fuel Cell/Battery Hybrid Electric Vehicle
Source: Author

➢ *State of Charge (SOC) Control Logic*

The state of charge (SOC) has been control controlled by the control logic. When the SOC of the battery pack is 95% and the vehicle is being operated the battery pack would be discharging until it reaches 75% SOC.

According to this control logic this will happen between 350 and 400 seconds simulation time. This logic will be triggered when SOC reaches the 75% and at this point the charging switch which connects the battery pack and the fuel cell through the booster converter will be switch on to allow the fuel cell to charge the battery pack as shown in in figure 6.

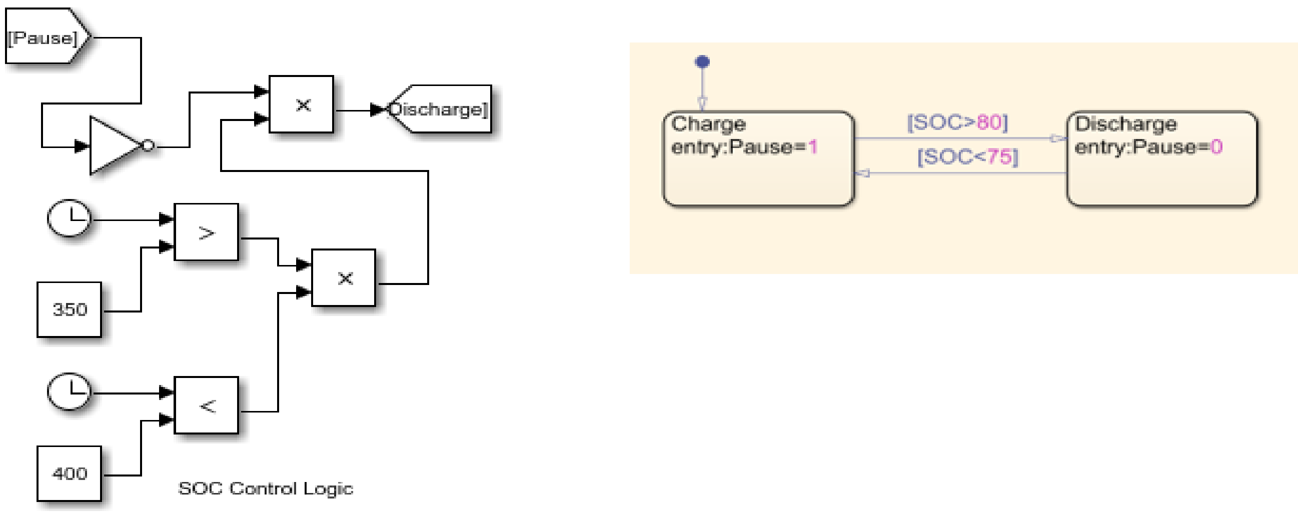

Fig 6 State of Charge Control logic for Fuel Cell/Battery Hybrid Electric vehicle.
Source: Author

IV. SIMULATION RESULTS AND DISCUSSION

The optimisation of the Fuel Cell/Battery hybrid electric vehicle drive train is done by maintaining the state of charge (SOC) of the battery pack within optimum range for the simulation distance covered and the vehicle to religiously follow the reference speed of the signal builder block, this is done by playing around with the simulation parameters.

The design of this Fuel Cell/Battery hybrid electric vehicle is that the main energy source for the vehicle is battery which is use to propel the electric vehicle through the traction motor. The nominal voltage of the Lithium battery is 120 volts and fuel cell voltage through the booster converter is about 140 volts. The operating range of the Lithium Battery state of charge (SOC) is between 95% to 65% depending on the load and speed of the vehicle. During the operation of the Fuel Cell/Battery hybrid electric vehicle, it will discharge from 95% to the predetermined level of SOC, after that the fuel cell switch connected through the booster converter will open and start charging the battery to maintain the SOC depending on the speed and the load of the vehicle as long as hydrogen is supplied to the fuel cell. It is important to note that the Lithium Battery is not recommended to be fully charged to 100% and discharged below 50% for efficient operation and to avoid damaging the individual cells in the battery pack.

The signal builder block was used to generated the reference speed from figure 7 below.

This was the reference speed which was followed by the Fuel Cell/Battery hybrid electric vehicle with optimum parameters from the vehicle body, curb weight 300kg, drag coefficient 0.25 and air density 1.18kg/m^{3}and from the traction motor, no-load speed 14000rpm and rated speed(at rated load)12000rpm.

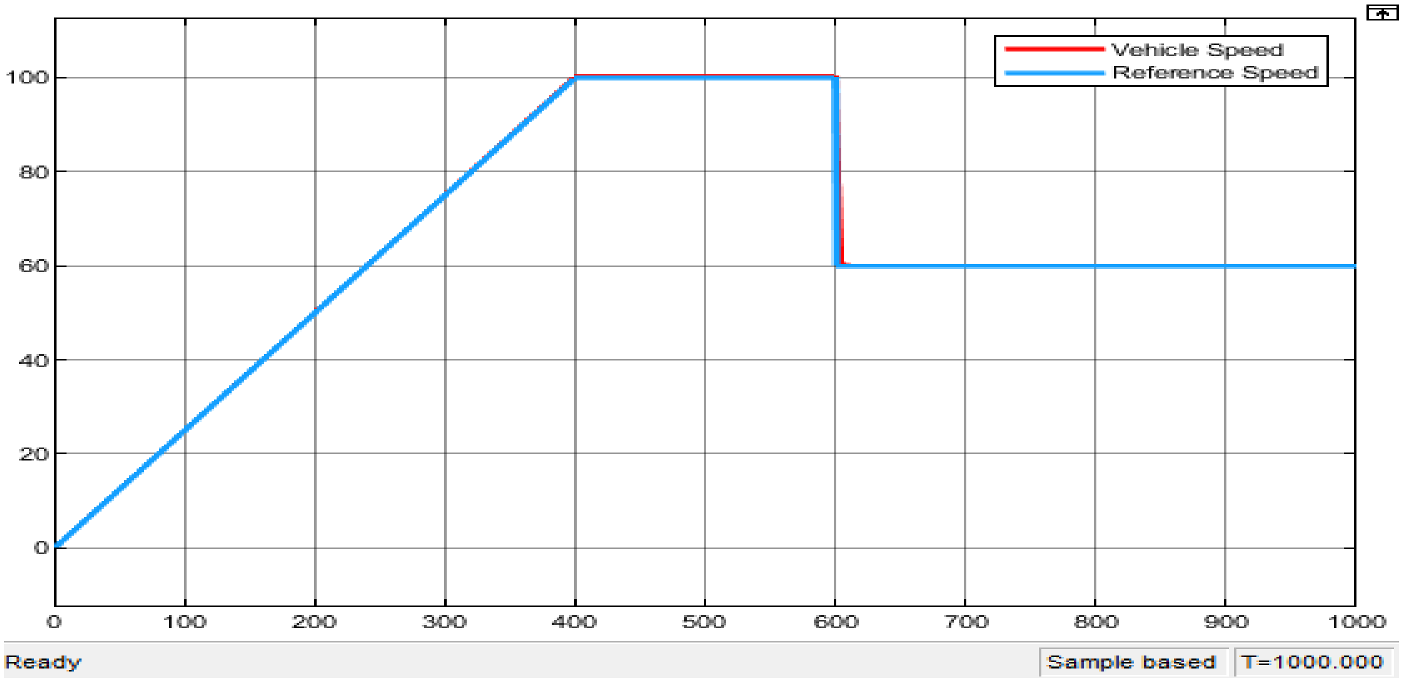

Fig 7 Shows the Fuel Cell/Battery Hybrid Electric Vehicle Matching the Reference Speed from the Signal Builder Block.
Source: Author

It is proved that with these optimum parameters the hybrid electric vehicle is able to follow smoothly the reference speed from the signal builder block.

The vehicle accelerated from 0km/hr to 100km/hr in 400s, and moved with the constant speed of 100km/hr for 200s, after that emergency brakes are applied and the vehicle decelerated from 100km/hr to 60km/hr and the vehicle moved with the constant speed of 60km/h for 400s.

Figure 1.8. shows the relationship between the fuel cell booster converter voltage and the battery pack state of charge (SOC.)

This diagram shows the relationship between the fuel cell booster converter voltage and the state of charge during simulation time of 1000 seconds.

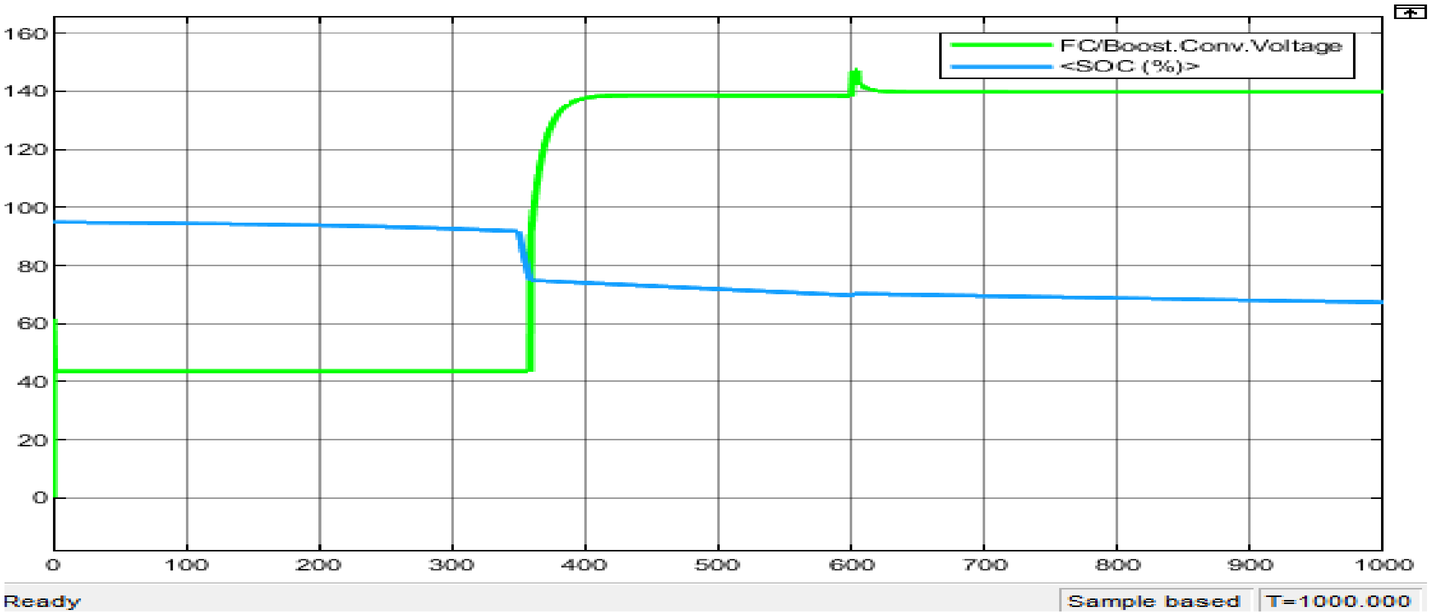

Fig 8 Shows the Relationship between SOC of the Battery Pack and Fuel Cell/Booster Converter Voltage During Simulation for 1000s.
Source: Author

Therefore, as the vehicle is accelerating from 0km/hr to 100km/hr the SOC of the Lithium Battery started decreasing from 95% due to increase in speed as per reference speed from the signal builder block and vehicle load, until it reaches 75%,the predetermined control algorithms is triggered to open the switch from the fuel cell through the booster converter and gradually the fuel cell starts charging the battery pack for 250s and additional voltage is degenerated during emergency braking ,which is called the regenerative braking for 10s,this reverse braking sends additional current to the motor, the motor during this period would act as the generator to charge the battery pack for 10s and the fuel cell booster converter continued to produce enough voltage of 140V to maintain the SOC to 70% for the remaining 400s simulation time. During the regenerative braking the fuel cell booster voltage increases to 148V because the reverse current which is being generated to charge the battery pack.

The current produced in figure 9 below depends on the reference speed from the signal builder block and the load of the vehicle. Therefore, during acceleration the current of the battery pack increases to about 100A in 400s, when the vehicle is moving with constant speed, the constant current of 100A is maintained for 200s.During emergency braking, the current changes the polarity because the traction motor changes the rotation direction and starts rotating in the opposite direction and the current reaches -700A. The traction motor is producing current as the generator to charge the battery pack. This is the process called regenerative braking and as the motor is slowing down during emergency braking more current is produced to increase the SOC of the battery pack.When the vehicle is moving with constant speed of 60km/h in 400s the current stabilised to about 40A.

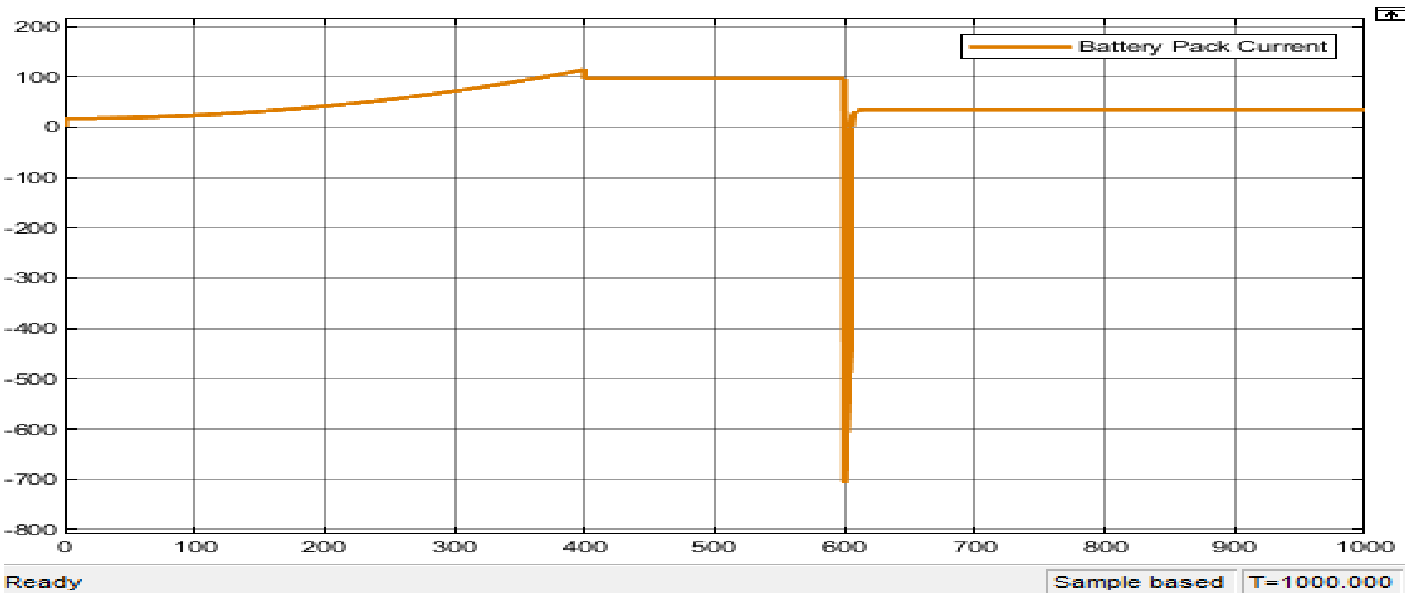

Fig 9 The Graph Shows the Current Produced by the Fuel Cell/Battery Hybrid Electric Vehicle.
Source: Author

The pre-set model, PEMFC 1.26Kw-24Vdc fuel cell is able to produce voltage of 38V,shown in figure 10 below, with the atomic mass units of hydrogen 1.36908036 and oxygen 5.89420573 respectively for 350 seconds before the fuel cell booster converter is switched on. However, when the booster converter is switched on the voltage on the fuel cell side increased to 46V for the entire simulation period of 650 seconds. From the control algorithm for the state of charge (SOC) figure 6, when the SOC is greater than 80% the battery pack was discharging and when the SOC reached 75% the battery pack was charging. This is predetermined between 350 and 400 seconds of simulation time. The fuel cell booster converter is able to booster the fuel cell voltage of 46V to 140V.This happens when the control switch detects that the SOC has dropped to 75% which means that the battery pack needs to be charged and the fuel cell through the booster converter is able to charge the 120V battery pack.

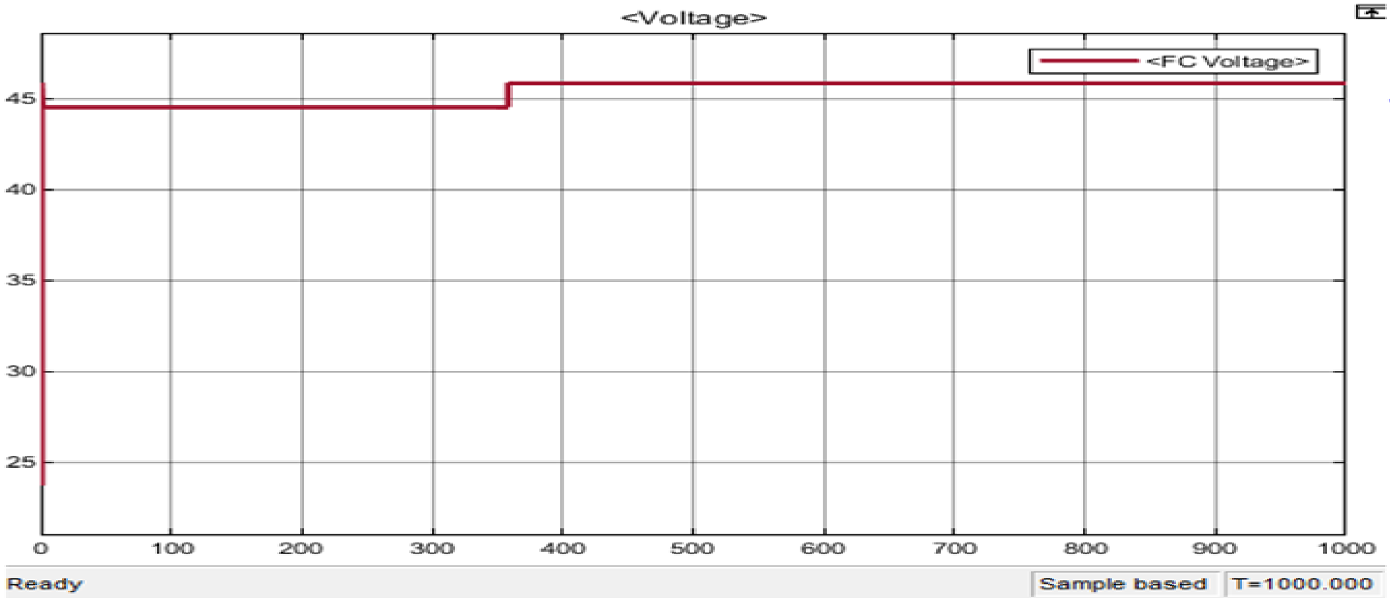

Fig 10 Shows Fuel Cell Voltage.
Source: Author

The total distance cover during the entire simulation of 1000seconds is 17.8 km as could be seen from the figure 11.

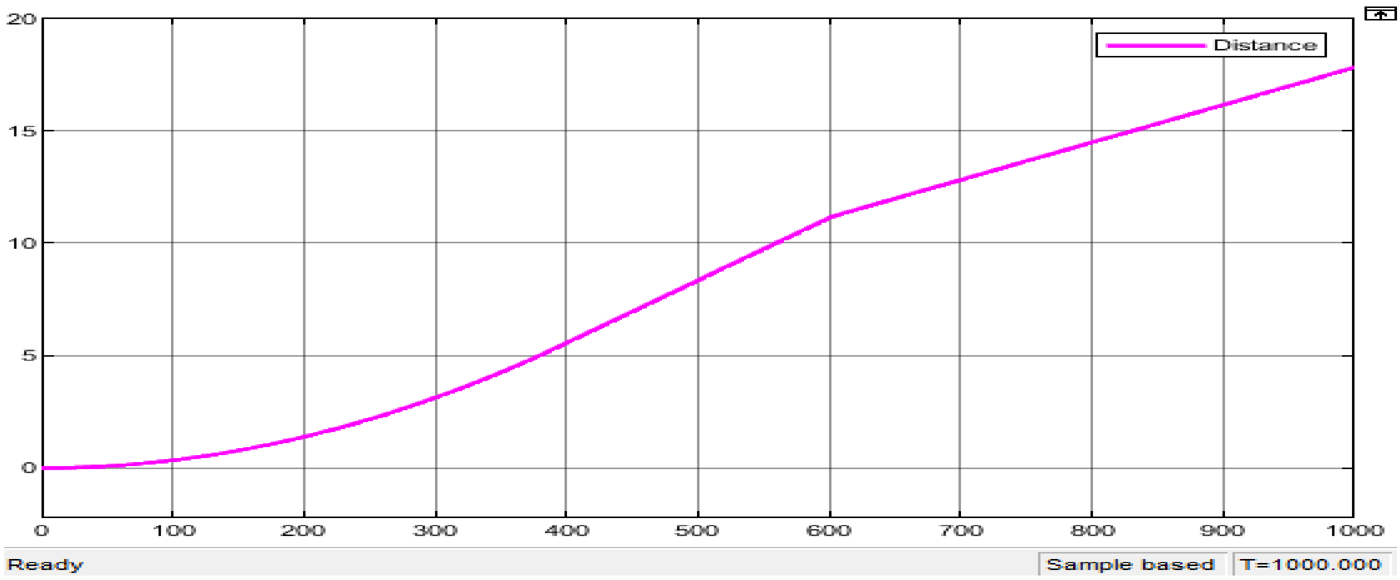

Fig 11 Shows the Distance Travelled by the Fuel Cell/Battery Hybrid Electrical Vehicle in 1000s
Source: Author

The optimum curb weight of the fuel cell/battery hybrid electric vehicle is 300kg and the vehicle is designed to carry maximum weight of 300kg.This would make the total of 600kg when the vehicle is loaded, therefore, it will carry four passengers with the average weight of 75kg per person. If the total weight of the fuel cell/battery hybrid electric vehicle goes beyond 600kg, the vehicle will be over loaded it will strangle to follow the trajectory of the reference speed. The more the weight of the vehicle the more the vehicle will divert from the reference speed from the signal builder block. Hence, the optimum maximum weight of this vehicle is 600kg, this could be seen from the diagram below in figure12.

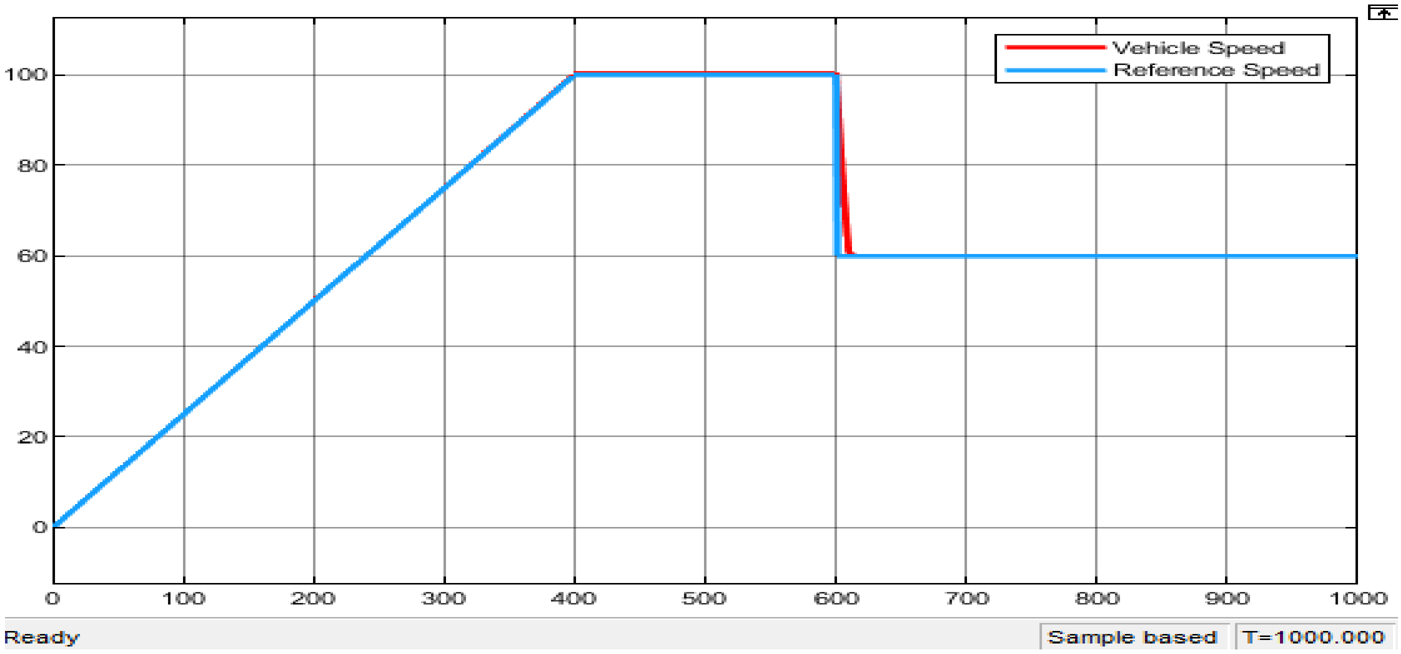

Fig 12 Shows the Fuel Cell /Battery Electric Hybrid Electric Vehicle Over Loaded and Missing the Trajectory of the Reference Speed.
Source: Author

V. CONCLUSION

The observation from this Fuel Cell/Battery hybrid electric vehicle simulation is that the total distance travelled by the vehicle is only limited by the amount of hydrogen supplied to the fuel cell to produce 140V to charge the 120V battery pack, the traction motor is able to propel the vehicle to the pre-determined destination.

As the weight of the weight exceeds the optimum weight of 600kg the vehicle speed is struggling to follow the reference speed from the signal builder block, hence missing the reference speed trajectory.

Therefore, as long as the fuel cell is producing the voltage to charge the battery pack, it would maintain the SOC between 70%-95% depending on the speed and the load of the electric vehicle. The Fuel Cell/Battery hybrid electric vehicle is able to cover any distance in Zambia as long as hydrogen is on board.

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