ISSN Number: 2454-2024(Online)

IJTRS International Journal of Technical Research & Science

ADAPTIVE EQUIVALENT FUEL CONSUMPTION MINIMIZATION STRATEGIES FOR ENERGY MANAGEMENT OF ELECTRIC VEHICLE

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Abstract- Growing concerns about global warming have been sparked by the rise in the emission rate of greenhouse gases, which is mostly brought on by the transportation industry. Additionally, cost of fuels based on gasoline and diesel is rising daily. Due to this, the transportation sector must adopt hybrid and plug-in hybrid vehicles. The vehicle battery needs to be charged frequently because its range is not very great. The charging method that must be used to recharge the batteries in electric vehicles must be effective, quick, and inexpensive. Electric vehicles require between 60 and 80 minutes to recharge their battery compared to conventional gasoline vehicles, which can be refuelled in 2 to 5 minutes or less. A hybrid electric vehicle consists of two or more energy sources with energy management and power management for the better fuel economy. The main scheme of the energy management strategy (EMS) is to split energy between the sources to reduce fuel consumption.

Keywords: Electric Vehicle, Supercapacitor, Battery, Converter, Fuel cell, Genetic Algorithm, Adaptive equivalent fuel consumption minimization, Energy Management Strategy.

1. INTRODUCTION

Growing efforts are being made to reduce greenhouse emissions as a result of environmental concern over climate change brought on by global warming. The transportation industry is responsible for about 23% of all greenhouse gas emissions worldwide. Electric vehicles with zero emissions are urgently needed to reduce greenhouse gas emissions from the transportation industry. The cleanest, most effective, and most efficient mode of transportation is an electric vehicle. Additionally, the world's automakers are being encouraged to embrace the electric car technology by the continuously rising cost of fuel and the rising environmental concerns. Over the past few years, interest in electric vehicles has grown significantly. Numerous automakers have created contemporary electric car models, demonstrating the technical superiority and environmental friendliness of electric driving. Manufacturers are now concentrating on creating cars that are more powerful, have a greater range, support fast charging, and are also less expensive.

Electric motors or traction motors are used in an electric vehicle's propulsion system. A battery, solar cells, or an electric generator can turn fuel into electricity in an electric vehicle. Electricity can be utilised as a form of fuel for automobiles using batteries. But the amount of energy storage in these electric cars is constrained. As a result, they need to be recharged or refuelled by plugging into an electric source. Electric vehicles can get their energy from a variety of sources, including thermal power, nuclear power, renewable sources, or any combination of these. This sets them apart from conventional fossil fuel-powered vehicles. The generated energy from these sources is then transmitted directly by an electric cable, wirelessly over a network, or through overhead power lines to the electric car. Batteries, flywheels, supercapacitors, or fuel cells can then be employed in electric vehicles to store this energy. Electric vehicles are regarded as zero emission vehicles because their motors emit no exhaust or emissions, despite the fact that the creation of electricity may contribute to air pollution. Fig. 1.1 shows the basic block diagram of an electric vehicle.

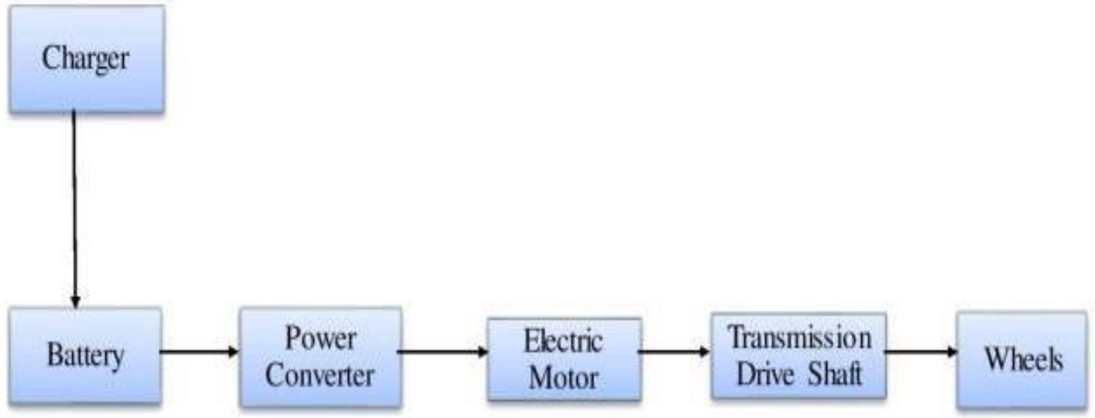

Fig. 1.1 Block diagram of Electric Vehicle system

DOI Number: https://doi.org/10.30780/IJTRS.V07.I07.002

Electric vehicles can make use of a variety of technology. Even if battery electric vehicles are very much in the public eye, hybrid automobiles are currently the most prevalent ones on the roads. There are three basic categories of electric cars, depending on how much electricity is used as their energy source:

- Battery Electric Vehicles (BEV)
- Plug-in Hybrid Electric Vehicles (PHEV)
- Hybrid Electric Vehicles (HEV)

1.1 Battery Electric Vehicles (BEV)

Fully electric vehicles with rechargeable batteries and no gasoline engines are known as battery electric vehicles. High-capacity battery packs are used in battery electric vehicles to store electricity onboard. The electric motor and other on-board electronics are powered by their batteries. These have a power source that charges them. BEVs don't produce any of the damaging emissions that conventional gasoline-powered cars do. Regenerative braking, which is used by battery electric vehicles to slow down while operating as a tiny generator to top off the battery, slows the car down. The range of the car may increase by at least 10 miles as a result. Currently, the majority of these cars have a range of about 100 miles. BEVs are distinguished by their slickness. They often only require one gear, providing smooth acceleration and deceleration. BEVs can be charged from a standard outlet, however there are a variety of charging methods available in public and residential sites to shorten recharging times.

1.2 Plug-in Hybrid Electric Vehicle (PHEV)

A plug-in hybrid electric vehicle has a battery that can be charged by both its on-board engine and generator as well as by hooking it into an external power source. Plug-in Hybrid All Electric Range, is referred to as a PHEV (miles). For instance, the PHEV-20 can go 32 km without using its internal combustion engine. In some cases, using the grid for power is less expensive, and it also uses less petroleum than driving a traditional car. PHEVs have a gasoline engine and an electric motor that draws power from a battery.

1.3 Hybrid Electric Vehicles (HEV)

Hybrid Electric Vehicles are a subset of hybrid vehicles that combine an electric propulsion system with a traditional internal combustion engine system. When an electric power train is included, traditional vehicles' fuel efficiency is improved. Regenerative braking is a technique used by modern hybrid automobiles to convert kinetic energy into electrical energy that may be stored in a battery or a supercapacitor. Some HEVs additionally use an internal combustion engine to power an electrical generator that either directly powers the vehicle's electric drive motors or recharges the batteries; this setup is referred to as a motor-generator.

2. SYSTEM MODELING OF A-ECMS

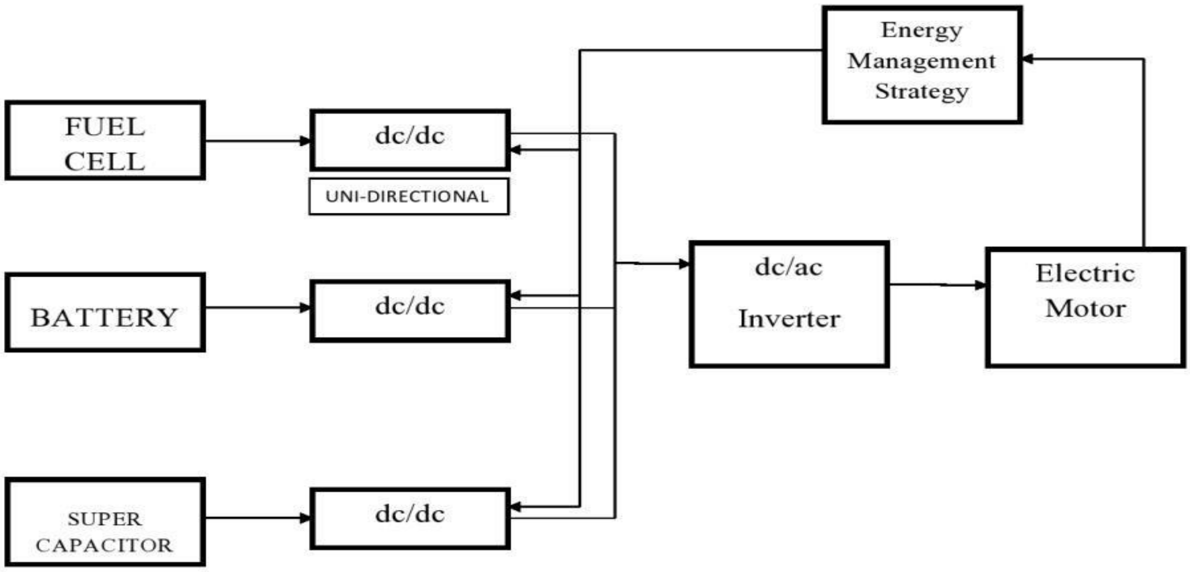

Fig. 2.1 Basic Block Diagram of the HEV

2.1 Battery Technologies for Electric Vehicles

It is an electro-chemical cell which converted the stored energy into the electricity. There are three types of the battery used in the electric vehicle which are lithium ion, nickel metal hydride, lead-acid. The only energy storage component found in modern battery-powered cars is the battery. Usually, the component with the highest price, weight, and volume in an electric vehicle is the battery. The battery in an electric car is of the utmost importance and will play a crucial role in the future revolution of the electric vehicle market since it must continuously deliver or store energy. The success of the electric vehicle will be determined by the battery, and until advancements are made in terms of higher specific energy, longer service life, and lower cost, the electric power train may only be available in certain markets. In battery electric cars, a variety of different types of batteries have been used. Table 2.1 shows the battery parameters.

Table-2.1 Battery Specifications

Block Parameter	
Nominal Voltage (V)	48
Rated Capacity (Ah)	40
Initial State of Charge (%)	65
Battery Response Time (s)	20

2.2 Ultra-Capacitor

An Ultra capacitor or super capacitor is simply a capacitor but with high capacitance. This capacitor stores the energy 10 to 100 times compared to normal capacitor. It can absorb and supply the charge way faster than the batteries. It has very high density which includes metal plates and also laminated with activated carbon. They are present in the vehicle along with regenerative braking system. Capacitance of the super capacitor can be up to 5000 farads. Density available in the market of this capacitor is 30 Wh/kg. Cell voltage of the super capacitor is quite low (2.7V). The reason behind this is to ignore the electrolysis. Super capacitor helps maintain the vehicle without reducing its life cycle or damaging the vehicle. Table 2.2 & 2.3 shows the major difference between the battery(Lithium Ion)and ultra-capacitor. Table 2.3 shows the super capacitor parameters.

Table-2.2 Comparisons between Battery

Property	LIB	UC
Cycle Life(Sec.)	90 -1000	100,000Millions
Energy Density(Wh/L)	200 -600	2 -5
Operating Voltage(V)	Max:4.5, Typical:3.8 Min:3.0	Max:2.7 Min:0.0
Peak Power Density @Discharge(kW/L)	Low<<0.1	Very High >>10
Self Discharge(mA)	Very Low<2	Very High

Table-2.3 Super-Capacitor Block Parameter

Block Parameter	
Rated Capacitance(F)	15.6
Rated Voltage(V)	291.6

2.3 Fuel Cell

A fuel cell is the device in which the chemical energy changes into the electricity. It is an electrochemical cell. Hydrogen and oxygen are the fuel and oxidizing agent of the cell respectively. The conversion happens in the form of redox reaction. Redox is the term used in the chemistry in which the atoms oxidation states are converted. Fuel cell is completely differing from a battery as it requires oxygen and hydrogen for chemical reaction to happen. As long as oxygen and hydrogen are supplying a fuel cell can generate the electricity. This helps in the electric vehicle. Fuel cell does not require any recharging unlike the battery. In fuel cell an anode and a cathode is present, in between this anelectrolyte is there. For example, in hydrogen-based fuel cell, H2molecules divide intoelectrons (e-) and protons. These electrons and protons further take separate path. Later in the process, protons form a bond with oxygen and electron which generate heat and water fuel cell system contains some parts which are as follows-power conditioners, fuel cell stack, humidifiers, fuel processor, air compressors. The Fuel Cell are also known as the electrochemical cell which converted the chemical energy to electricity. The fuel cell different from the battery because it required the oxygen and hydrogen for chemical reaction to happen, and the oxygen and hydrogen are supply the fuel cell for generate the electricity. Table 2.4 shows the fuel cell parameter.

Table-2.4 Fuel Cell Specifications

Block Parameters	
Voltage @0A and @1A	52.5,52.46
Nominal Operating Point	250,41.15
Maximum Operating Point	320,39.2
Operating Temperature	45
Nominal Stack Efficiency (%)	50

2.4 Converter

Converter which are used to change the voltage from one magnitude to another magnitude. DC-DC converters are used for converting the fixed dc voltage to variable dc voltage. DC-DC boost converters with an output voltage are greater than the source voltage and it is also called step up voltage. DC-DC buck converter with an output voltage is less than the input voltage because the inductor always bucks and act against the input voltage and it is also a step-down voltage.

Table 2.5 shows the parameter of DC-DC Boost Converter for fuel cell.

Table-2.5 FC DC-DC Boost Converter Specifications

Block Parameter	
Full Load Current	45
Efficiency @Full and @10% Load	85,10
Response Time (s)	0.1
Load Capacitance	15.6

Table 2.6 shows the parameter for DC-DC Boost Converter for battery.

Table-2.6 DC-DC Boost Converter Specifications

Block Parameter	
Full Load Current	45
Efficiency @Full and @10% Load	85,10
Response Time	0.1
Load Capacitance	15.6

Table 2.7 shows the parameters for DC-DC Buck Converter for battery.

Table-2.7 DC-DC Buck Converter Specifications

Block Parameter	
Full Load Current	20
Efficiency @Full and @10% Load	80,88
Response Time	0.1
Load Capacitance	$100e^{-3}$

Table 2.8 shows the DC-AC Converter.

Table-2.8 DC-AC Converter Specifications

Block Parameter	
Output Line Voltage (Vrms)	200
Output Frequency (Hz)	400
Nominal Efficiency (%)	97

3. ENERGY MANAGEMENT STRATEGY (EMS)

Hybrid Electric Vehicle is the best solution for improving the environment issues. By combining several energy sources HEVs can be designed. For improving the performance and fuel economy of the HEVs, developing appropriate EMS is essential. Without affecting the vehicle speed, fuel consumption can be minimized by splitting power between the power sources. HEVs are to ensure that the vehicle's energy issued and recycled efficiently. Developing the EMS is the most important part of designing the HEV. Various power splitting techniques have been adopted in recent years. These strategies may differ in terms of global or local optimization, computation time, prior information of the driving pattern; structural complexity and algorithm effectiveness. There are two basic strategies for the energy management for the vehicle-Rule Based Strategy, Optimization Based Strategy.

Rule based strategy depends on modes of operation. For a particular drive cycle, rule-based control strategies (RBCS) are aimed at improving fuel economy, productivity, performance, and emissions. RBCS determines individual component output. To break the power demand between different power sources, RBCS requires rules or fuzzy rules. It is easy to build and monitor in real-time. The static controller is rule-based. The operating point of the elements is determined by using rule tables to reach the driver's demand. Optimization-based control strategies (OBCS) are used to achieve one or more objectives such as minimize cost, maximize driving distance, reduce fuel consumption, improve battery SOC level etc. It considers the best outcomes. They can be used to generate a real-time control strategy based on an instantaneous objective function.

Adaptive Equivalent Fuel Consumption Minimization Strategy(A-ECMS) can be applied on the hybrid (fuel cell, battery and super capacitor) system. A-ECMS is a method which can minimize the fuel economy with the computation method. It can divide the energy between the source very efficiently. A-ECMS can deliver power to the fuel cell with the low frequency as well as to battery. In this manner, hydrogen usage can be minimized. In ECMS, battery power or energy transforms into the equivalent fuel energy and this transformation can reduce the total fuel consumption. Optimal power distribution can be identified instantaneously. To obtain equivalent fuel power, it required to determine the conversion factor for the effectiveness of the strategy. The ECMS determines the target of the ICE as well as EMs, which can reduce fuel power and also determine the power demand of the vehicle.

3.1 Genetic Algorithm

Genetic Algorithm is one of the methods in Optimization Based Strategy. The Genetic Algorithm are solving both constrained and unconstrained optimization problems that is based on natural selection. This algorithm repeatedly modifies a population of individual solution. In this Genetic Algorithm five steps are included which are-

- Determine the initial Population
- Crossover
- Mutation
- Selection
- Find Fitness Function

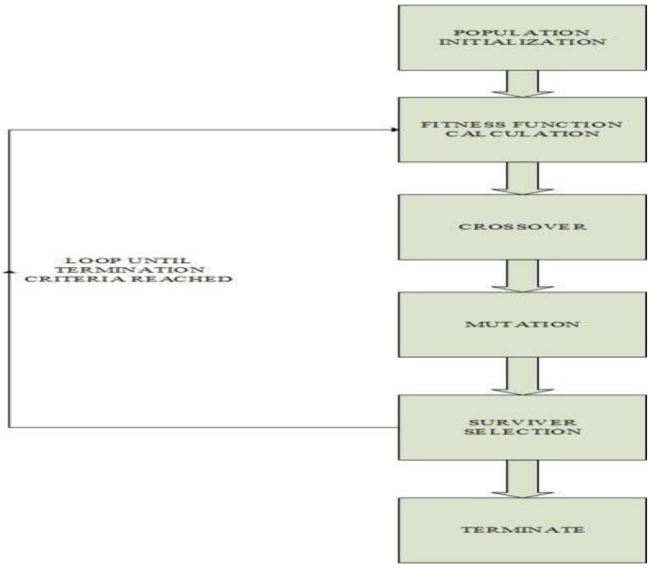

Fig. 3.1 Basic Flow Chart of Genetic Algorithm (AG)

4. HYBRID ELECTRIC VEHICLE SIMULINK MODEL

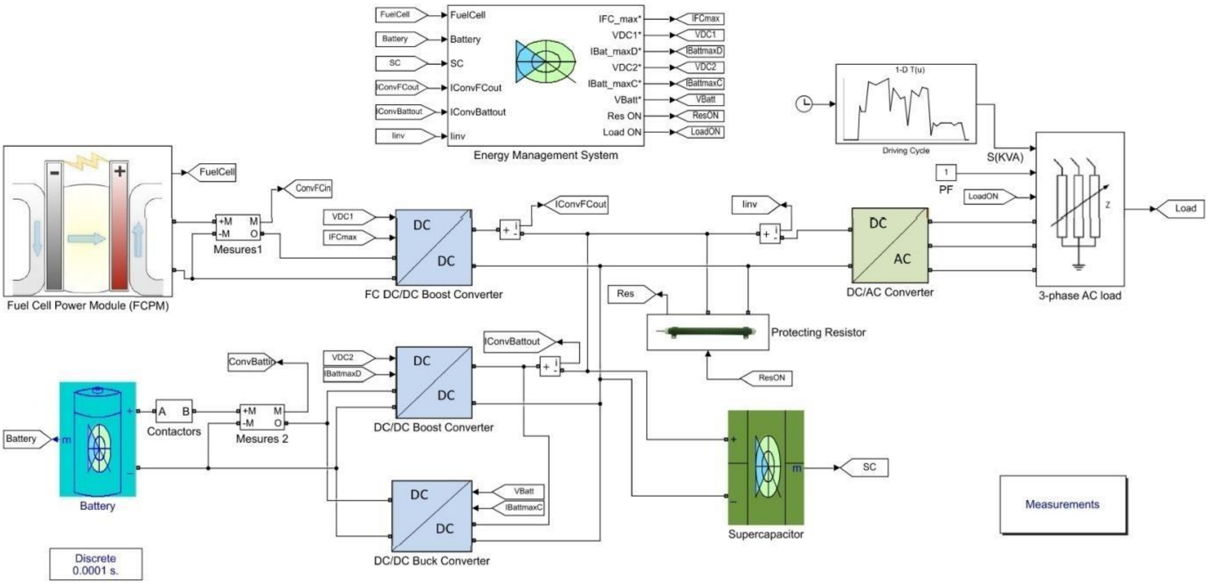

Fig. 4.1 Simulation Model of HEV

5. SIMULATION RESULT

The model of hybrid electric vehicle has three energy sources namely battery, supercapacitor and fuel cell. this shows the Simulink model of the Hybrid Electric Vehicle. DC-DC converters are used to stepping up or stepping down the voltage when necessary. DC-AC converters are used here to convert the DC voltage into AC voltage to supply. To minimize the fuel consumption in electric vehicle, two different energy management strategies have been applied on the model and compared. To design the energy management system for the HEV, SOC level of the battery is set to 65%. The battery gives the charging/discharging current at DC-DC converter .FC DC-DC converter gives the maximum current flow of fuel cell. The strategy applied here is Equivalent Consumption Minimization Strategy (ECMS). In this system, the load conditions are variable to match the practical conditions. The optimization-based strategy applied here. To obtain the maximum efficiency from the battery, DC-DC converter adjusts the duty cycle. To keep the system balance, fixed value of DC voltage is given to the system. To generate the pulse width modulation signal in DC-DC Boost converter, a PI controller is connected to the system. Supercapacitor voltage helps in finding the fuel cell power and DC voltage.

When strategy applied to this model, fuel cell voltage gives the minimum value that is 42.1132 V. the maximum value of the fuel cell voltage is 55.802V. about 48 sec, the fuel cell voltage gives the constant voltage. After this time, the voltage starts to decrease. For about 75se, the voltage again become constant and then the voltage starts to increase for the remaining time. Fig 4.1(a) shows the fuel cell voltage. For fuel sell current value, the minimum value is -30.86A and the maximum value for the fuel cell current is 214.91A at 75sec, the current remains constant and at 249sec, the current decrease for the remaining time. Fig 4.1(b) shows the fuel cell current.

The minimum and maximum value of fuel consumption is -11.13 lmp and 93.1932 lmp respectively. The negative value shows the amount of fuel used in water vaporization during the operation. Fig. 4.1(c) shows the fuel consumption of the vehicle in Liter per Minute.

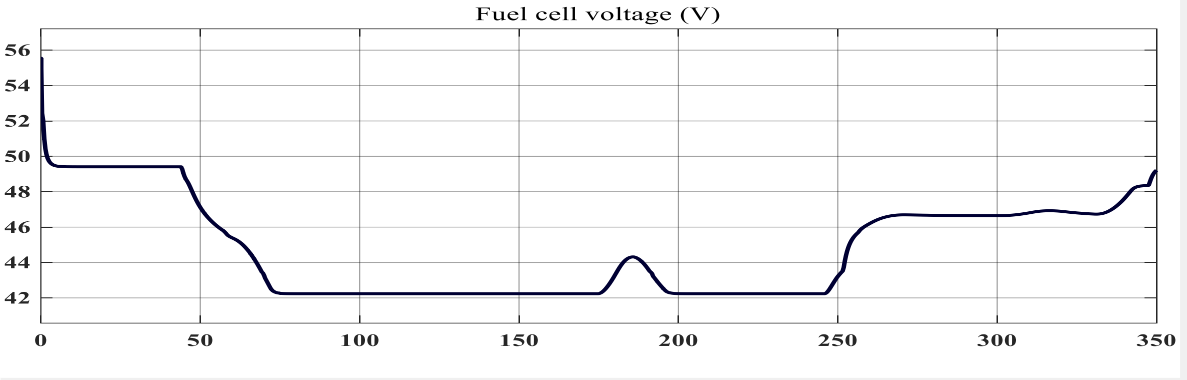

Fig. 4.1 (a) Fuel Cell Voltage(V)

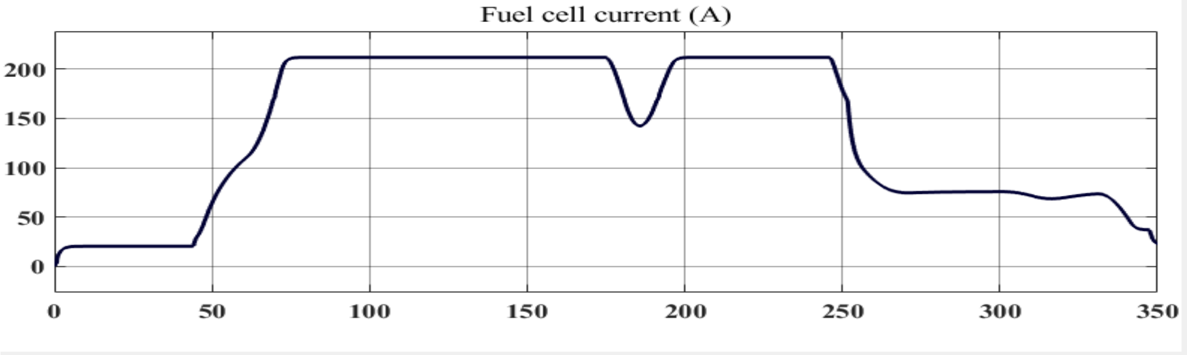

Fig. 4.1 (b) Fuel Cell Current(A)

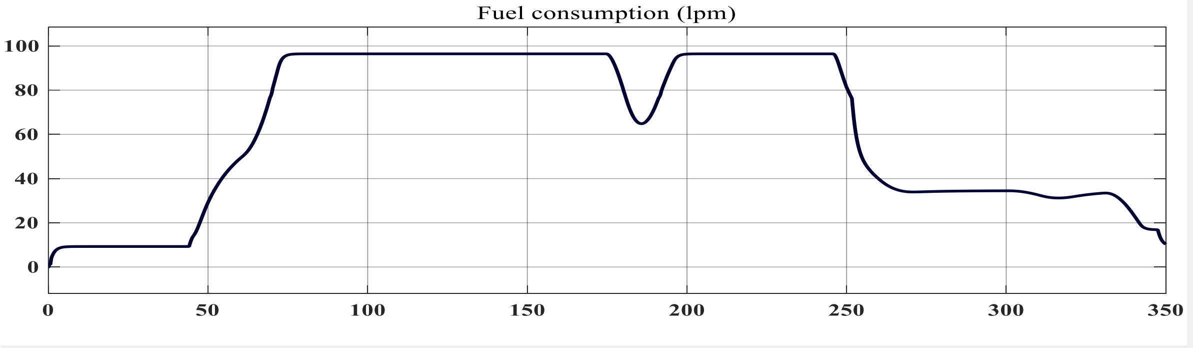

Fig. 4.1 (c) Fuel Consumption (lpm)

When strategy is applied on the model, battery current gives the minimum value that is -20.1010 A. The maximum value of the battery current is 80.72A. For about 46 sec., the current gives negative component to the vehicle. After this time, there are some variations that imply the discharging of the battery. For time period 125-250 sec, the current is variable for some period and then constant. Fig. 4.2(a) shows the battery current. For battery voltage value, the minimum value is 50.1735V and the maximum value for the battery voltage is 52.817V. Battery voltage depends on the SOC of the battery. Fig 4.2(b) shows the battery voltage. In the SOC, the maximum value of the battery is 61.217% and the minimum value of the SOC is 65.72%. The continuous decrement in the battery SOC is obtained when the current value is constant. Fig 4.2(c) shows the battery SOC for the strategy.

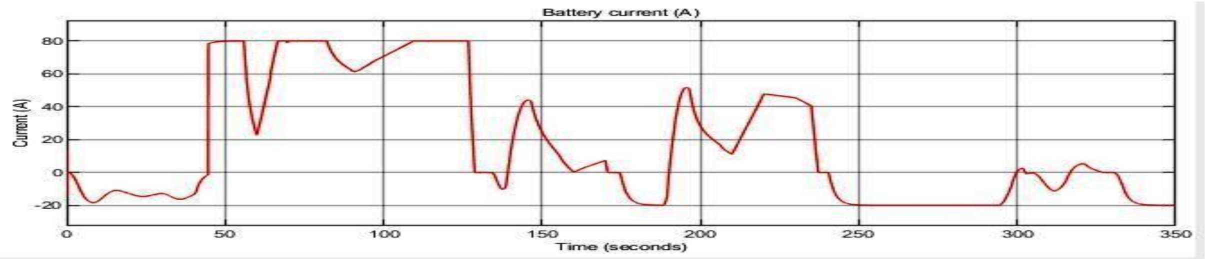

Fig. 4.2 (a) Battery Current(A)

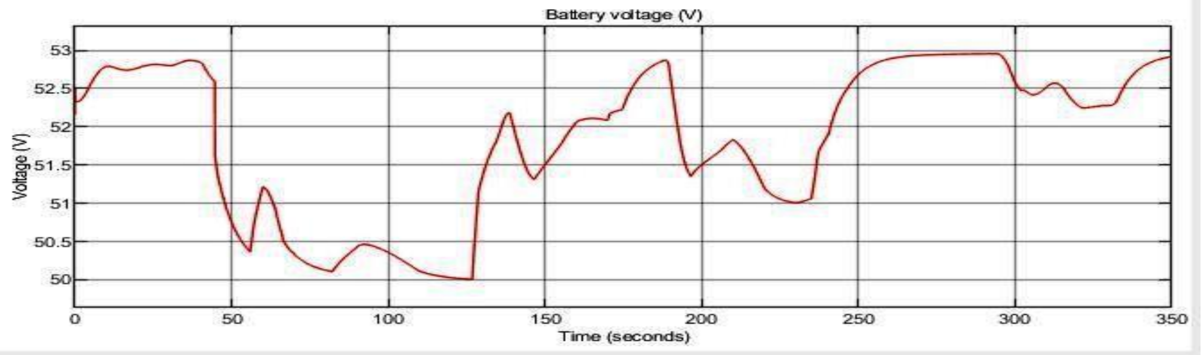

Fig. 4.2 (b) Battery Voltage (V)

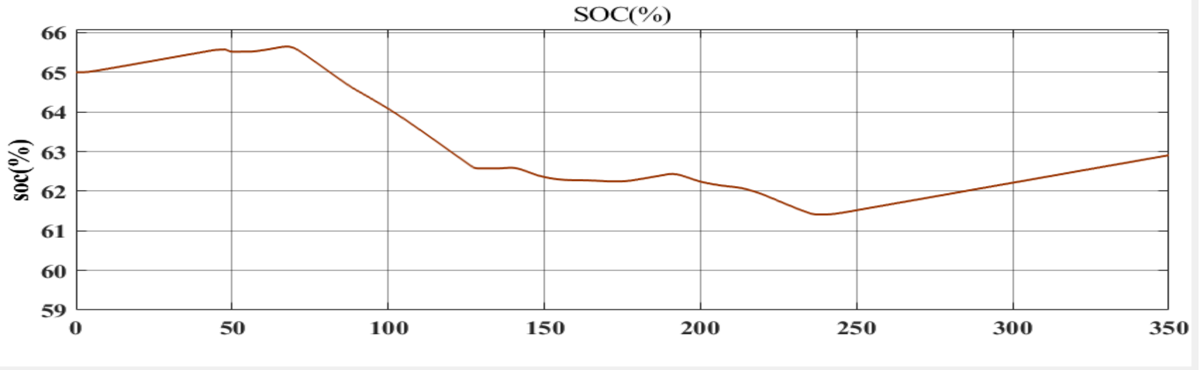

Fig. 4.2 (c) SOC%

When Strategy is applied on the model, super capacitor current gives the minimum value that is -23.1714A. The maximum value of the super capacitor current is 16.5413A. For about 48sec., SC supplies small amount of current. Then it goes to peak instantaneously. After this instant, fluctuation in the current is observed. Fig. 4.3(a)shows the Supercapacitor current. The minimum value of the supercapacitor voltage is 268.80 and the maximum value of the supercapacitor is 281.109. Fig. 4.3(b)shows the supercapacitor voltage.

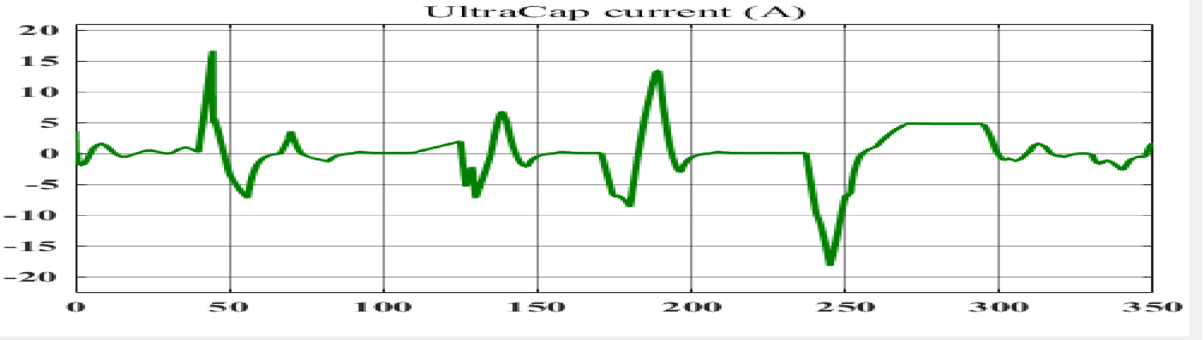

Fig. 4.3 (a) Super Capacitor Current (A)

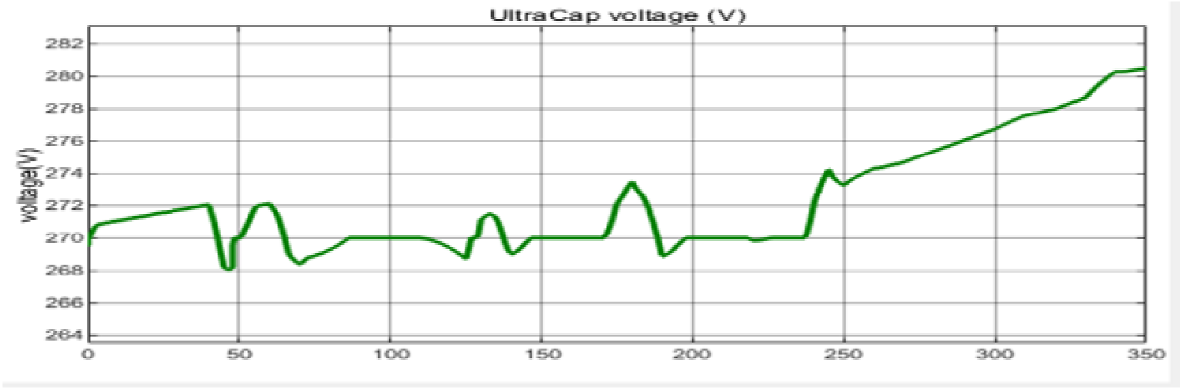

Fig. 4.3 (b) Super Capacitor Voltage (V)

When strategy applied to the model, Fc converter has the minimum value is 38.124Vand the maximum value is 55.138V this remain constant up to 48 sec. After, it gives variable value, Fig 4.4(a) shows the input voltage of FC DC-DC converter. When strategy applied on the model, battery converter gives the minimum value is 46.12V and the maximum value is 56.65V. Fig 4.4(b) shows the input voltage of battery DC-DC converter.

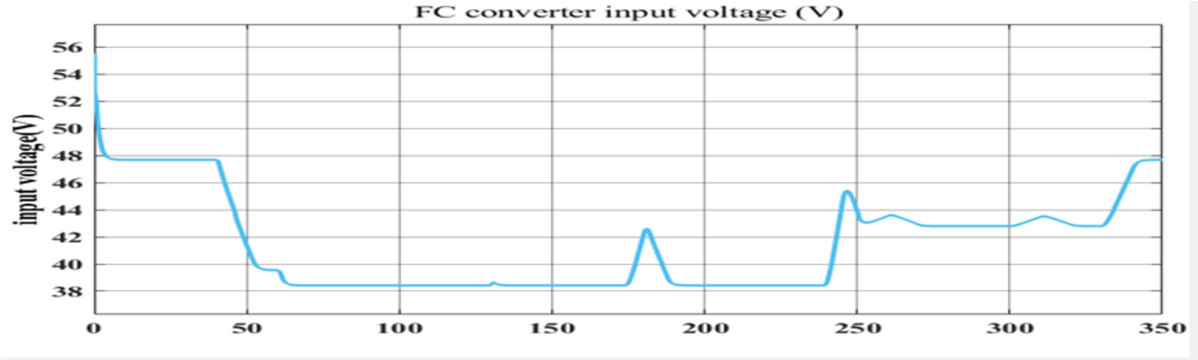

Fig. 4.4 (a) FC Converter Input Voltage (V)

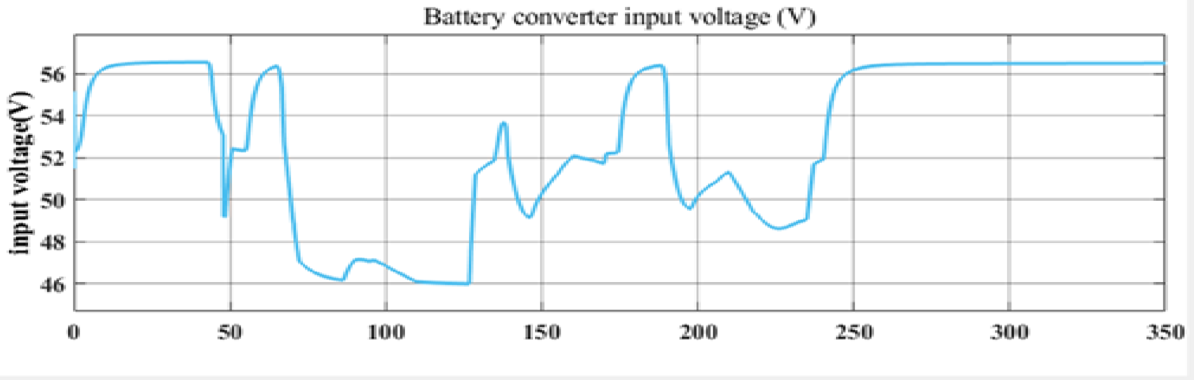

Fig. 4.4 (b) Battery Converter Input Voltage

The power output is shown in Fig 4.5 the maximum value battery power is 3492W. The maximum supercapacitor power is 11518W. The maximum power of fuel cell is 3923W. Total fuel consumption in the vehicle in GA-ECMS is 88.245 lmp. It is observed that by applying GA-ECMS, the total fuel consumption is minimized up to 10lmp. From the simulation it is clear that a supercapacitor is best energy storage device for a vehicle as it stores higher amount of energy compared to battery and fuel cell.

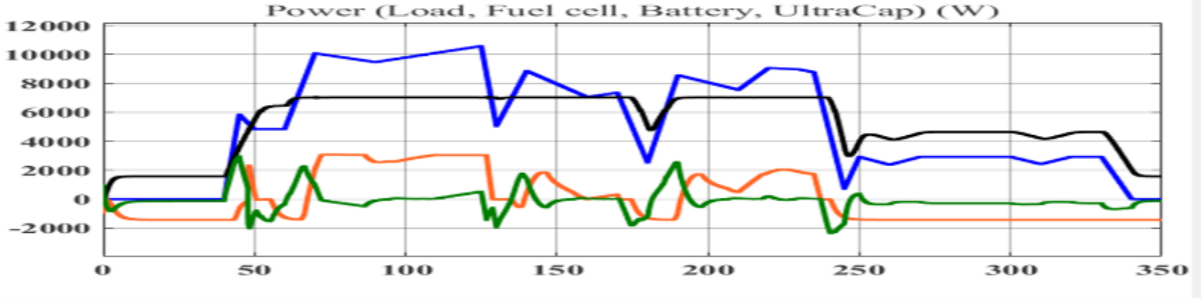

Fig. 4.5 Load Power Demand and Power share by Fuel Cell, Battery and Supercapacitor

CONCLUSIONS

The dynamic model of the Hybrid Electric Vehicle with rule based and optimization-based energy management system has been developed. The rule-based control strategy and optimization-based control strategy for the energy management has been applied to this simulation model. The main objective of the simulation is to reduce the overall fuel consumption of the electric vehicle which can be achieved by using the genetic algorithm. The comparison between these strategies shows that the total fuel consumption is minimized from 98.5211 lpm to 90.1721 lpm in ECMS based strategy. Supercapacitor provided the instantaneous power to the vehicle in transient load conditions while maintaining the SOC level of the battery. By comparing the battery SOC level in rule-based strategy and optimization-based strategy, ECMS maintained the SOC level more than the rule-based strategy with in the set limit which is 65.7272%. Fuel cell provided the extra required energy to the battery and helped to improve the fuel consumption of the vehicle. By Comparing the strategies, it can be seen that the GA-ECMS give the better performance for the fuel consumption minimization purpose and also improved the equivalent factor of the ECMS.

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