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Optimal Method for Reducing Equivalent Fuel Consumption in Hybrid Electric Vehicles

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Abstract: This paper presents a Fuel Cell Consumption Minimization Strategy (FCMS) for Hybrid Electric Vehicles (HEVs) powered by a fuel cell and an energy storage system battery and super-capacitor(SC), in order to minimize the consumption of hydrogen while maintaining the State of Charge (SOC) of the battery. The proposed technique, when compared to current Energy Management Strategies (EMSs) such as SQP algorithm is used to determination of equivalency factor for Equivalent fuel consumption minimization strategy (ECMS) and classical PI controller (CPIC), improves overall vehicle energy efficiency and, as a result, reduces total hydrogen use while honoring the limitations of each energy and power source. Using the MATLAB software, a hybrid vehicle model has been created. Through numerous simulations, the performance of the suggested technique has been compared to the various approaches (SQP-ECMS and CPIC).

Keywords: fuel cells, Battery, super-capacitor, energy management strategy, Sequential quadratic (SQP) programming, and the classical PI controller.

Introduction

FCHEV a subset of new energy vehicles, have a number of benefits, including zero emissions, high efficiency, and independence from fossil fuels, which is regarded to be a good solution to the energy crisis and environmental pollution [1]. An appropriate energy management strategy (EMS) is necessary for multiple energy sources architecture in order to distribute electricity among them. Several researchers have done research on fuzzy logic [2], the Pontryagins Minimum Principle (PMP) [3], frequency-based approach [4], dynamic programming (DP) [5], and other techniques [6]. One type of real-time optimization technique that can get results that are nearly optimal and does not rely on previous drive cycle knowledge is the ECMS strategy.

Currently, fuel cell hybrid vehicles come in three different system configurations. A hybrid system made up of both batteries and fuel cells is the first kind. The second system uses a hybrid design that combines fuel cells with super-capacitor. The most recent type of system is a hybrid made up of FC, batteries, and SC. For several forms of fuel cell hybrid vehicles, the power system architecture has been examined and analyzed.

Equivalent fuel consumption minimization strategy for FC/Battery/SC is present in this work. The architecture of the vehicle and the power train model are presented in the first section. A plan for the ECMS is developed in the second section. The final section displays the simulation results and analyses.

I.POWERTRAIN MODELS

A. Vehicle Design

The vehicle is powered by three energy sources: a super-capacitor, Li-on battery, and a proton exchange membrane fuel cell (PEMFC), which serves as the primary energy source. A unidirectional DC/DC and a bidirectional DC/DC are used to connect the SC and FC to the DC bus, respectively. The vehicle model can compute the load current, battery state of charge (SOC), FC efficiency based on the selected drive cycle. EMS uses each of these variables to calculate the reference current for each source. An electric motor (Permanent Magnet Synchronous Machine) powers the vehicle.

B. Vehicle model

The longitudinal variables of the road vehicle can be used to determine the controls allocated to the steering control the vehicle by applying condition (1):

$$Pmot(t) = v\left(m_v(t)\frac{d}{dt}v(t) + F_a(t) + F_r(t) + F_g(t)\right) \qquad (1)$$

Where m_g is the propulsive force generated by gravity when moving down a slope, F_a are the streamlined contact, F_r is the rolling contact, and Vehicle component parameters used in Table I:

'TABLE I: Vehicle specifications and its parts

Parameter	**Value**
Mass(kg)	520
Front surface(m^2)	2.26
Coefficient of drag	0.334
Coefficient of rolling friction	0.009
Capacity of battery(Ah)	31
Capacity of super-capacitor	90
Power of fuel cell (KW)	7

C. Model of Fuel cell

FC which react hydrogen and oxygen, turn chemical energy into electricity [9]. A near-static fuel cell demonstration is being conducted using the 5 kW fuel cell pile. The high yield zone, where the efficiency is greater than 40% (from 15A to 50A), was chosen since it makes little sense to operate a fuel cell at the highest skill point given the variety of cell management, battery SOC, and super-capacitor SOC. The FC current, as determined by equation (2), can be described by FC hydrogen use rate.

$$m_{h2} = \int_0^t \frac{M_{h2} n_c}{2F} I_{fc}(t)dt \qquad (2)$$

where n_c is the total quantity of cells (120),M_{h2} is the hydrogen molecular mass (2g/mol), and m_{h2} refers to the hydrogen mass rate.

D. Model of Battery

A simple model is used by a number of battery models in the literature. These include the battery's internal capacitance and internal resistance, as well as its internal capacitance and open circuit voltage emf models.

$$SOC(t) = SOC_{init} - \frac{n_b}{c_{nom}}\int_0^t I_b(t)dt \qquad (3)$$

Where C_{nom} Speaks to the batteries ostensible capacity, SOC_{init} introductory battery SOC, n_b is charge and release efficiency.

E. Super-capacitor model

The super-capacitor model consists of a capacitor and an equivalent resistance. A DC/DC converter coupled to a super-capacitor is reduced to a simple energy converter with a fixed efficiency [13]. Equations (4) and (5) can be used to calculate the SOC and current of a super-capacitor, respectively as shown in fig 4 and 5.

$$SOC = \frac{V_{oc}-V_{min}}{V_{max}-V_{min}} \tag{4}$$

$$I = \frac{V_{oc}-\sqrt{V_{oc}^2-4RP}}{2R} \tag{5}$$

Where V_{max} and V_{min} are the maximum and minimum voltages,V_{oc} is voltage of capacitance, R is the proportional resistance, P is the super capacitor control, and SOC is SOC of super-capacitor.

II.ECMS

The purpose of the designed ECMS is to total hydrogen consumption. The hydrogen consumption of a fuel cell can be defined as a formula of electrical energy batteries and super-capacitor must be converted to equivalents hydrogen consumption. Therefore, the objective function is defined as

$$m_w(t) = k_{FC}m_{FC}(t) + k_{BA}m_{BA}(t) + k_{SC}m_{SC}(t) \tag{6}$$

Where $m_w(t)$is whole hydrogen consumption,$m_{FC}(t)$ is fuel cell hydrogen consumption,m_{BA} is battery equivalent hydrogen consumption,m_{SC} is super-capacitor equivalent hydrogen consumption,K_{FC} Operates fuel cell at high efficiency,K_{BA} andK_{SC} affect the equivalent hydrogen consumption up and down according to battery and super-capacitor SOC values at the sample time.

The equivalent hydrogen consumption of batteries and super-capacitors can be calculated in the same way as the following formulas:

$$m_{BA}(t) = P_{BA}(t) \times \frac{m_{average}}{P_{average}} * \eta \tag{7}$$

Where m_{BA} (t) is comparable hydrogen consumption to battery current, P_{BA}(t) is power of battery, $m_{average}$ is hydrogen consumption of FC, $P_{average}$ is power of FC, η is transformation efficiency.

The fuel cell efficiency penalty factor $k_{eff}$is determined (8):

$$k_{eff} = (1 - 2 * \frac{\eta-\eta_{opt}}{\eta_{max}-\eta_{min}})^2 \tag{8}$$

Where η stands for instantaneous efficiency, η_{opt} for optimal (38.5%), η_{max} for maximum (39.5%), and η_{min} for minimum efficiency.

Battery SOC Penalty coefficient K_{BA} is described by equation by

$$K_{BA} = \begin{cases} 1 - \frac{2*(\cup-B_{opt})}{B_{max}-B_{min}}^4 & B_{min} \leq \cup < B_{max} \\ 1 - \frac{2*\left(\cup-B_{opt}\right)^{20}}{B_{max}-B_{min}} & \cup < B_{min}, \cup > B_{max} \end{cases} \tag{9}$$

Where U is instantaneous SOC of battery and B_{opt} is optimal battery SOC, B_{max} Battery maximum SOC, B_{min} minimum battery SOC.

Super capacitors have a high power density and can be charged and discharged in comparison to batteries To extend life of fuel cells, batteries, Super-capacitors deliver peak power and break the energy first. Therefore, the super-capacitor penalty factor is K_{SC} consists of the SOC factor $S_{eff}$and the peak power factor. $S_{eff}$is the same as K_{BA} and secures the supply of super-capacitors appropriate current according to SOC value full of power regenerate brakes energy. K_{SC},S_{eff}, and S_{high} defined by equation (10) ,(11), (12) respectively:

$$K_{SC} = S_{eff} * S_{high} \tag{10}$$

$$S_{eff}=\begin{cases} \left(1-2*\frac{x-S_{opt}}{S_{max}-S_{min}}\right)^{2} 0.45 \le x \le 0.8 \\ \left(1-2*\frac{x-S_{opt}}{S_{max}-S_{min}}\right)^{8} 0.2 < x < 0.45 \\ \left(1-2*\frac{x-S_{opt}}{S_{max}-S_{min}}\right)^{20} x \le 0.2 \, , x > 0.8 \end{cases} \tag{11}$$

$$S_{high} = \begin{cases} 1 & 0 \le x \le 5000 \\ -0.00004 * P_{load} + 1 & x > 5000 \\ -0.0001 * P_{load} + 1 & x \le 0 \end{cases} \tag{12}$$

Where x is instantaneous super-capacitor SOC, S_{opt} Optimal SOC, S_{max} maximum SOC, S_{min} minimum SOC, P_{load} is load power.

Sequential quadratic Programming (SQP)

Optimization options parameters used by fmincon. MATLAb fmincon is able to be configured to run using either the "active set" or the "sqp" techniques. An Active set algorithm is a part of Sequential quadratic Programmming.The reason for using SQP algorithms were introduced due to limitation of active set i.e. inefficiency to solve highly non linear derivative expression comes from Karush –Kuhn-Tucker (KKT).

It is frequently possible to compare a nonlinearly limited problem using SQP in less time than an unconstrained problem. A Successive quadratic programming(SQP) strategy is displayed that points to overcome a few of disadvantages of dynamic set solver in ECMS calculation of Fuel cell crossover electric vehicle in which optimize the fuel utilization and to preserve the SOC in battery.

SQP is a very useful method for understanding small, medium, and large-scale related programming problems. Calculation required understanding a quadratic programming model using direct imperatives and a quadratic objective function.

A few SQP strategies utilize raised quadratic programming sub issues for the step computation utilizing quasi-newton hessian whereas other variations of the SQP show utilizing moment subordinate data. Most optimization issue can be expected to have a quadratic objective work within the neighborhood of the ideal arrangement. The use of SQP technique proves beneficial when an optimal arrangement can be achieved.

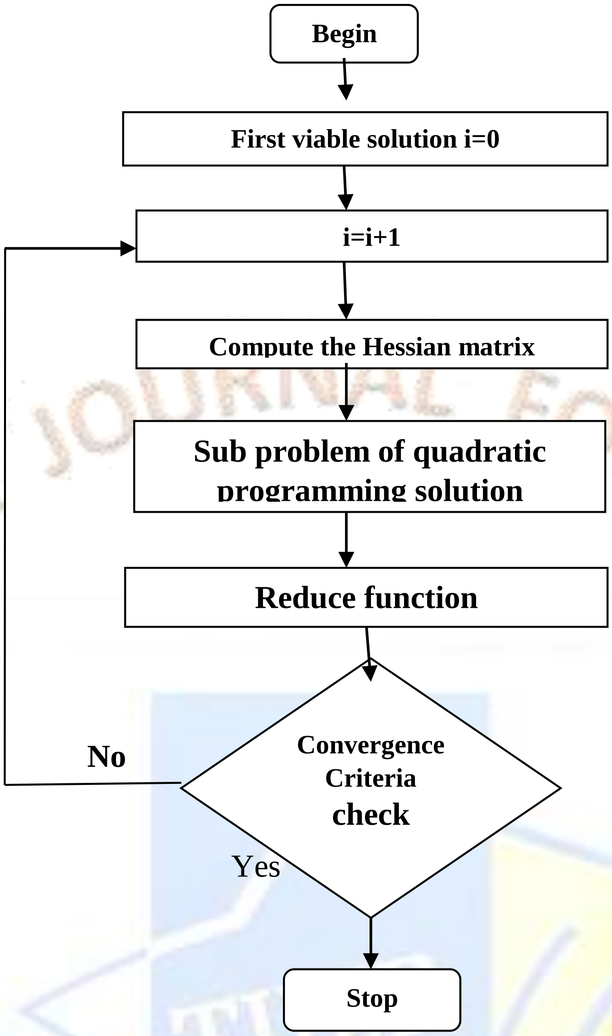


Fig 1: Flow chart of Sequential quadratic programming

The classical PI control strategy (CPCS)

A PI controller used in the methodology regulates the battery SOC [20]. The FC vitality is obtained by subtracting the battery control from the stack control, which is the PI controller's output. The FC power is limited when the battery SOC exceeds over the reference level, and the battery takes over management. Fuel cell provides virtually charging control when SOC is below reference. Compared to ECMS technique, this scheme is easier to carry out, and the PI pick down is put up online for much better responsiveness. The fuel cell then seeks to provide charge controls and comes back the energy storage device as the battery releases more quickly to get to the SOC reference. The SC and FC controls are inactive when the device first turns on.

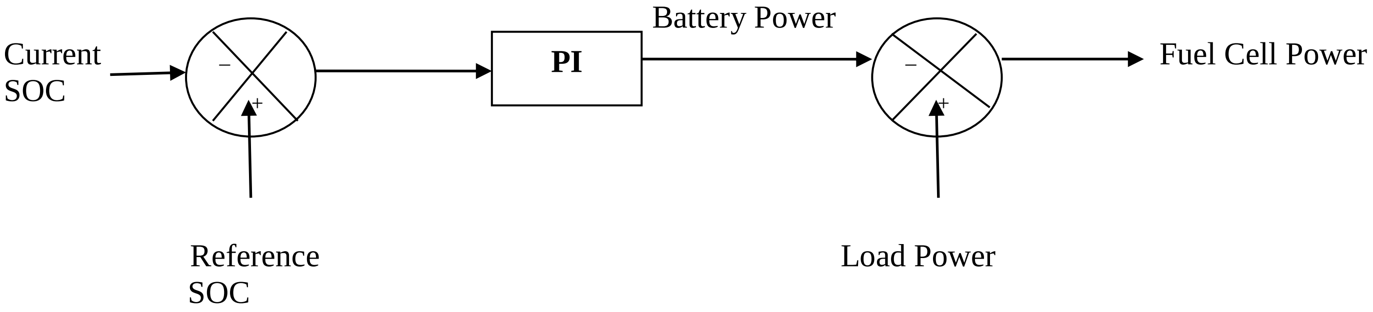


Fig 2: Classical PI control energy management strategy

A. Results

The performance of the EMS compared using simulations SQP based ECMS energy management strategy and classical PI control EMS. Figure 3 shows the load power and power demand shared by FC, Battery, SC to meet the load demand.

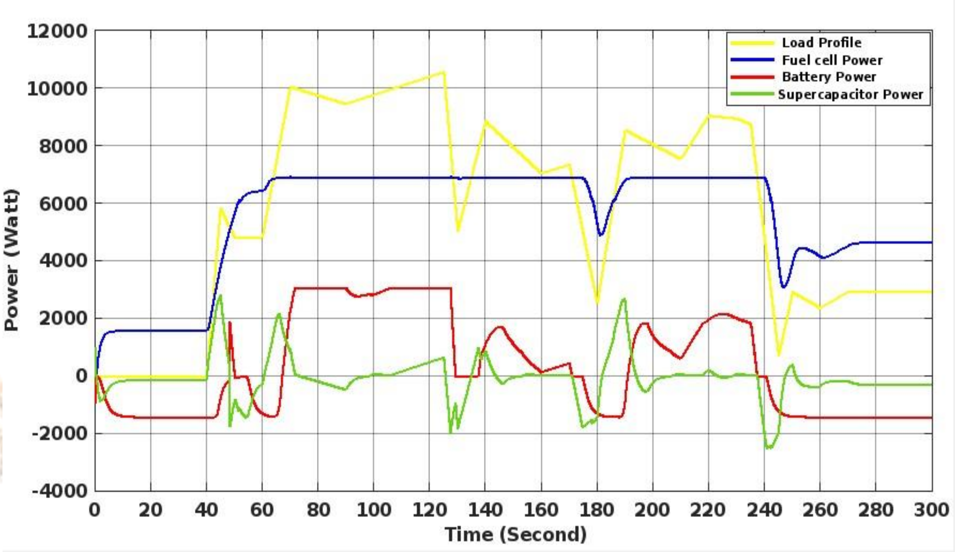
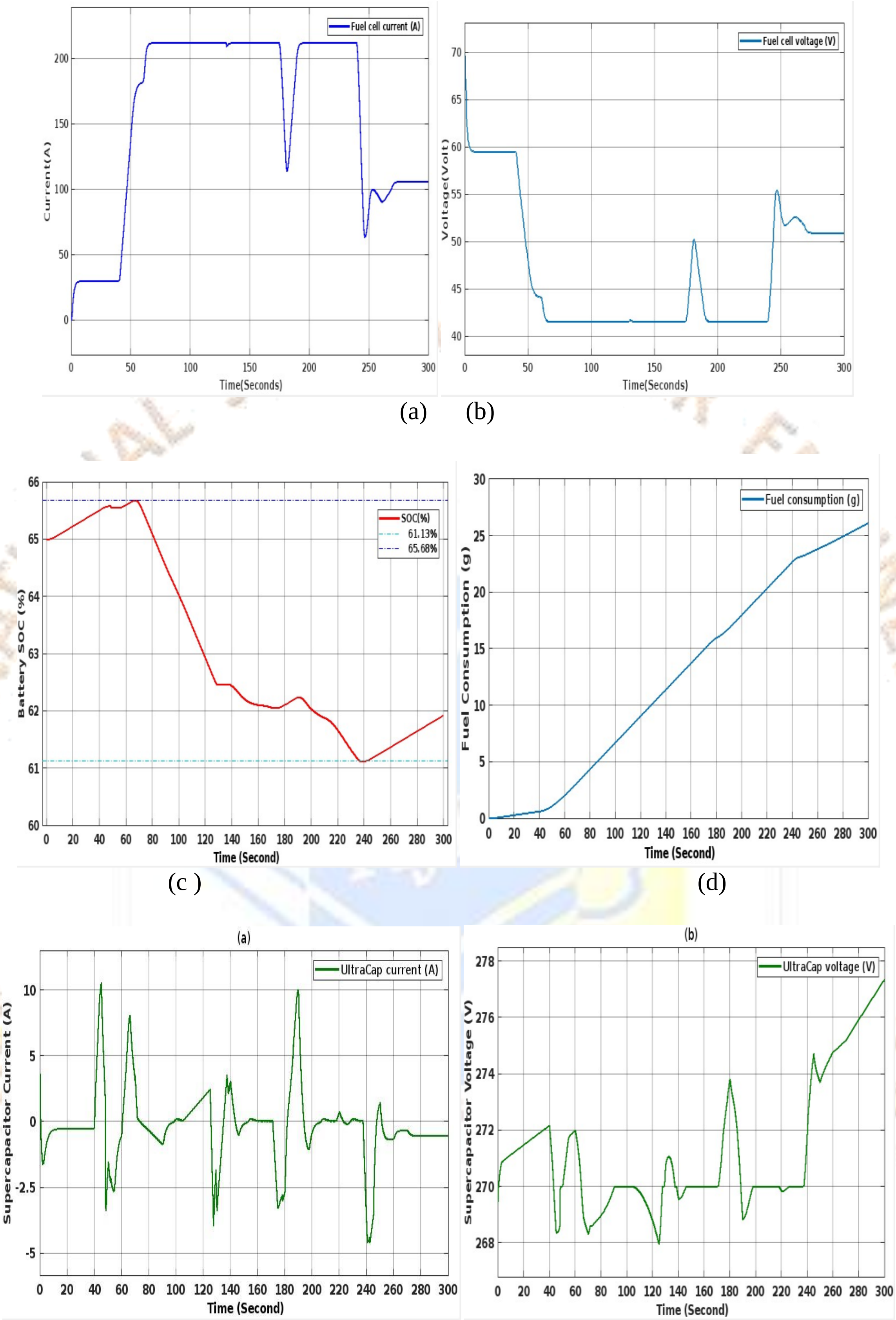


Fig 3: Power of load profile, FC, battery and SC

The highest load power is provided by the fuel cell itself, as can be shown in Fig. 3.When a fuel cell by itself is unable to supply enough power to the load, a battery is used. As was previously mentioned, since the battery converters regulate the dc bus voltage, the power of the super-capacitors is not taken into account when solving the optimization problem. The same energy from the battery system is used to recharge the SC as soon as they have finished discharging. Thus, during a certain load cycle, the fuel cell and the battery are the only ones to share the whole load energy. But when load demand changes suddenly, SC produce power effectively. The FC voltage and current changes during the simulated load scenario are shown in Fig. 4(a) and (b). It has been noted that when fuel cell power output increases, voltage decreases proportionally to ohmic losses in the fuel cell stack. The battery SOC fluctuation over time is shown in Fig. 4(c). Here, the penalty coefficient of the battery power is applied to regulate battery SOC. when a result, the battery's SOC rises initially when fuel cell power is used to charge it. The SOC then decreases as a result of the battery sharing the load when the fuel cell is unable to match the load demand on its own. With the FC, it can only meet a certain limit, it is constant.



(a) (b)

(c) (d)

(e) (f)

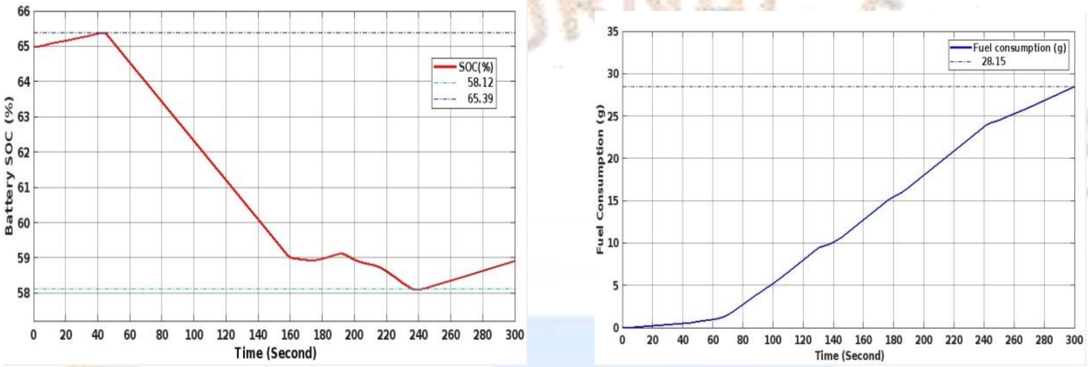
Fig 4 (a) FC current (b)FC Voltage (c) Battery SOC (d) Hydrogen consumption
Super-capacitor (e) Current (f) Voltage

In Fig. 4, the voltage and current of the supercapacitors are displayed. The power output of the supercapacitor, which is dependent on the fast change in load power, determines the supercapacitor current.

The supercapacitor's charging and discharging change the voltage, which furthercontrolled to 270 volts by the battery being charged and discharged.

Performance of the EMS in comparison between ECMS and classical PI controller FC hydrogen consumption and battery SOC levels is shown in Figures 4 and 5. Table 2 represents the total hydrogen consumption and SOC scope for ECMS and CPIC strategies for simulation. .

The comparison of the SQP-based ECMS strategy to reduce the hydrogen consumption by about 4% compared with the classical PI controller. Although some load on the battery results in a 2% less SOC than the CPIC method.



(a) (b)

Fig 5 : The classical PI controller (a) Battery SOC (b) Fuel consumption

Table 2: Performance comparison between SQPECMS and CPIC

	SQPECMS	CPIC
H_2 Consumption (g)	30.58	31.52
State of Charge (SOC)	56.21-60.72	55.15-60.45

III.Conclusion

The outcomes of the performance evaluation between hydrogen usage and battery SOC are shown. Equivalent fuel consumption minimization strategy for FC/Battery/SC HEV is presented in this work.SQP algorithm is used for determination of equivalency factor for ECMS EMS. Comparison of SQP-ECMS EMS with CPICS EMS shows that fuel consumption reduces by 8%.SOC level of battery is SQP-ECMS EMS is maintained 56.21-60.72% compare to CPIC EMS between 55.15-60.45%.

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