

An Efficient Energy Management Scheme for a Hybrid FC-SC-Battery Electric Vehicle using Model Predictive Control and Multi-Objective Particle Swarm Optimization



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Abstract. This paper presents a new Design for an efficient Energy Management System (EMS) for a Plug-in Hybrid Electric Vehicle (PHEV) which is supplied by Fuel Cell/Super-capacitor/Battery sources to attain maximum energy savings and minimize the amount of the fossil fuel utilized by the transportation sector. Model Predictive Control (MPC) combined with Multi-Objective Particle Swarm Optimization (MOPSO) control strategy was proposed to manage the battery and the SC State of Charge (SOC) and decide the optimal power distribution between the Fuel Cell (FC), the Battery and the Super Capacitor (SC). The main target of the proposed EMS calculation technique is to achieve maximum energy efficiency, minimum battery current variation, minimum variation of the state of charge of the SC and minimum cumulative hydrogen consumption during the driving cycle. The proposed MOPSO based EMS methodology has been checked by the High Speed (US06) Driving Cycle utilizing the MATLAB/Simulink. Five diverse driving patterns are utilized to assess the speculation capacity of the developed technique. Simulation results and the real-time experiment demonstrate that the proposed MOPSO-Model Predictive Control based EMS technique can accomplish better energy effectiveness compared with Fuzzy Logic Rule-based EMS and GA-based EMS.

Keywords: PHEV, EMS, Energy Consumption Optimization, Fuel Cell, Battery, Super-Capacitor, MPC, MOPSO.

NOMENCLATURE

PHEVs	Plug-in Hybrid Electric Vehicle
EMS	Energy Management System
MOPSO	Multi-Objective Particle Swarm Optimization
MPC	Model-Based Predictive
ICE	Internal Combustion Engine
FC	Fuel Cell
SC	Super Capacitor
SOC	State Of Charge
GA	Genetic Algorithm
$P_{Battery}$	Generated power by the Battery
P_{SC}	Generated power by the Super-Capacitor
P_{FC}	Generated power by the FC
P_{Load}	The load power requirements
P_{Loss}	The total power loss of the system.
P_{FC_Loss}	The power loss by the FC internal resistors;
$P_{Battery_Loss}$	The power loss by the battery internal resistors;
P_{SC_Loss}	The power loss by SC internal resistors;

$P_{FC_Conv_Loss}$

$P_{Battery_Conv_Loss}$

$P_{SC_Conv_Loss}$

$Cons_{H2}$

The power loss by the FC DC/DC converter,

The loss by the Battery DC/DC converter

The power loss by the SC DC/DC converter.

The hydrogen utilization function.

I. INTRODUCTION

The PHEVs are considered as the main part of the the sustainable power source vehicles in the market because of their capacity to utilize a rechargeable battery with other sources such as Fuel Cell and/or Super-Capacitor (SC) [1-4]. The main advantage of the PHEVs is that they can be coupled to the utility grid for batteries charging process, hence expanding the utilization of power and minimizing the utilization of the fossil fuel and reducing greenhouse gas emissions resulted from non-renewable energy source consumed in transportation section [5-8]. Notwithstanding, introduced batteries in EV still have weaknesses, for example, low power density, short cycle life, etc. in addition, the installed batteries on Electric vehicles are often damaged because of the power with high-peak and rapid cycles of charge-discharge – which are happening because of frequent increase/decrease of vehicle velocity especially in urban spaces [9]. A possible solution to embedded energy and environmental problems might be to structure a hybrid energy storage scheme by choosing another energy storage component such as SC and FC to help batteries and improve the life span on the batteries [10]. Fuel cell vehicles have high potential as future most likely candidate for electric vehicles as a result of its several agreeable characteristics under every single working condition, for example, low working temperatures, low cost and fast start up, design simplicity, suitability, and high energy efficiency [11-12]. Consequently, the incorporation of the SC with the FC into vehicle drive-trains yields the benefits of FC energy density and cyclic efficiency/lifetime/power capability improvement [13] and the benefits of SC that their capacity to operate as a buffer against large volumes of power and also its oscillations [14]. The incorporation of the batteries, FC and the SC with a satisfactory EMS strategy displays an auspicious solution in short time because of the accompanying focal points of hybridization [15, 16]: i) minimizing the fuel cell stack production costs. ii) Minimizing the hydrogen consumption. iii) Improve of the vehicle self-sufficiency. iv) Maximizing the efficiency of the system.

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As a result of the intricate power demand with a high dynamics in daily driving where the required power by the EV changes broadly with various operating modes, an intelligent EMS will be needed to guarantee the effectiveness and the reliable operation of the hybrid system [17-19]. The optimal EMS is utilized to decide the optimal energy distribution among all the ICE, the FC, the SC and the battery considering the vehicle and engine operating conditions. The end goals are to derive most extreme advantage from each energy source and limit the battery current variation and enhance the vehicle range [20-22]. A wide range of EMS applications have been proposed for PHEVs with two main categories of control techniques: a) rule-based approach which depends on an arrangement of straightforward rules with no need for a priori driving conditions information [23-26]. Such procedures settle on control choices in view of moment conditions just and are effectively executed, yet their decisions are regularly a long way from being ideal because of the absence of thought of varieties driving conditions; and b) optimization based methodologies which are aimed for upgrading some predefined objective functions as indicated by the driving conditions and vehicle's dynamics [27-37]. The chosen objective functions are typically identified with the fuel utilization. In view of how the enhancement is executed, such methodologies can be additionally categorized into two classes: 1) optimization based on off-line control strategy which depends upon a whole learning of the entire driving cycle condition to attain the ideal arrangement; and 2) short-term optimal prediction control strategy which predicts the operating driving situation during a particular control horizon. Nonetheless, real disadvantages of these control systems include: 1) heavy reliance on the earlier information of forthcoming operating conditions; and 2) complex algorithm processing that are hard to execute continuously. Some studies about EMS have been proposed in light of Fuzzy Logic Controller (FLC) [38-41] for PHEVs, and demonstrate the introduced FLC procedure is successful in enhancing the efficiency while keeping the battery from over- discharging. For the most part, the FLC procedure is powerful, simple to execute, high vigorous and generally utilized online because of the low computational load necessity. Notwithstanding, the FLC methodology neglects to achieve the ideal execution because of absence of an optimization procedure. Another online accessible technique of EMS configuration is an optimization system in view of Model-based Predictive Control (MPC) [42-46]. This MPC control system depends on a time of estimated driving pattern later on and utilizes the ideal control strategy on the control time horizon. Hypothetically, the MPC can possibly accomplish a close ideal power management execution and could be actualized for real-time control if there are adequate and exact predictions of forthcoming driving situation. In any case, a large processing data capacity is requested in this sort of strategy bringing about its difficulty to be utilized on-vehicle these days. Furthermore, an exact driving condition expectation is likewise difficult to get. With a specific end goal to get the in all likelihood driving cycles later on, the off-vehicle framework, for example, cloud and GPS signs are will be needed. The global optimization approaches, using advanced optimization algorithms such as Genetic Algorithm (GA) [47-49] and Particle Swarm Optimization (PSO) [50-52] to take care of the energy management issue, have been generally

proposed. The main target is to gain an ideal power for PHEVs and limit the fuel utilization and emissions for various driving cycles without giving up any progression execution. Nonetheless, dependence on the preceding driving patterns that can scarcely be acquired at continuous circumstance makes the worldwide improvement calculations based procedures hard to be executed online, which is the highest disadvantage of this class. An on-line MOPSO based EMS procedure for a Battery-FC-SC hybrid energy storage system is developed in this paper to manage the exchange off between the real-time performance and energy saving optimality for PHEVs. The developed EMS methodology in light of MOPSO can be effectively executed continuously and ready to accomplish ideal arrangements while considering the monetary elements, for example, the consequence of the high variation of charge/ discharge patterns on the battery life span, and the battery exchange cost, into the EMS procedure. The end goal of the proposed MOPSO approach based EMS to reduce the energy utilization and to get the optimal arrangement to instantaneously apply the optimal procedure in real-time control for standard driving cycles and real driving conditions. There are major advantages for the proposed control strategy: a) no need to initiate a complete process for optimization while the algorithm keeps evolving and converging to obtain an optimal solution; b) no a priori knowledge about the trip duration required; c) optimal allocating of the required between various energy units; d) no deviations from the ideal working point for every energy source. The rest of the paper is sorted out as takes after: The proposed configuration for FC-Battery-SC Powered HPEV is presented in Section 2. Section 3 introduces the proposed EMS. The Model-Based Predictive Control MPC was explained in Section 4. Section 5 presented he proposed MOPSO technique. Simulation results using MATLAB/Simulink are carried out in Section 6 while the experimental setup is given in Section 7 to validate the effectiveness of the developed EMS. Section 8 illustrated Conclusions.

II. THE PROPOSED CONFIGURATION FOR FC-BATTERY-SC POWERED HPEVS

The electrical structure of the hybrid FC/Battery/SC system is introduced in Fig. 1 to evaluate the proposed EMS based on MOPSO. The proposed hybrid system is made out of the FC, the battery and SC that contribute to fulfil the energy demand. The fundamental target of the EMS is to augment the utilization of the supply that satisfies the vehicular control request noting the driving condition and trip necessities. The proposed structure incorporates the DC bus, the battery, the FC, the SC, DC/DC converters and 3-phase induction motor which is supplied from a DC-AC inverter. The DC bus is supplied from the FC through a boost converter to actualize the proposed EMS, from the battery and the SC through buck-boost converters to maintain the DC bus voltage as close as possible to the reference voltage. The fundamental reason of utilizing this setup is on the grounds that the whole regenerative energy ought to be consumed by the SC and the battery packs.

The incorporation of the ICE in the power-train is additionally shown for the possible use as a hybrid vehicle. The charging mode for the battery and the SC can be executed from the load through the regenerative braking and/or from the FC. During the driving trip, the proposed MOPSO-EMS control strategy decides the optimal power distribution between all energy sources to satisfy the energy requirement of the driving pattern. In this paper, five different driving cycles;

a) ECE 15; b) The Urban Artemis driving pattern; c) The Rural Artemis driving pattern ; d) FTP-75cycle; e) The Highway fuel economy test (HWFET); f) WLTP Class 3 cycle g) High Speed (US06) Driving Cycle; as shown in fig. 2 have been utilized to compare and assess fuel utilization and contaminations emanations and to verify the use of different combinations of energy sources.

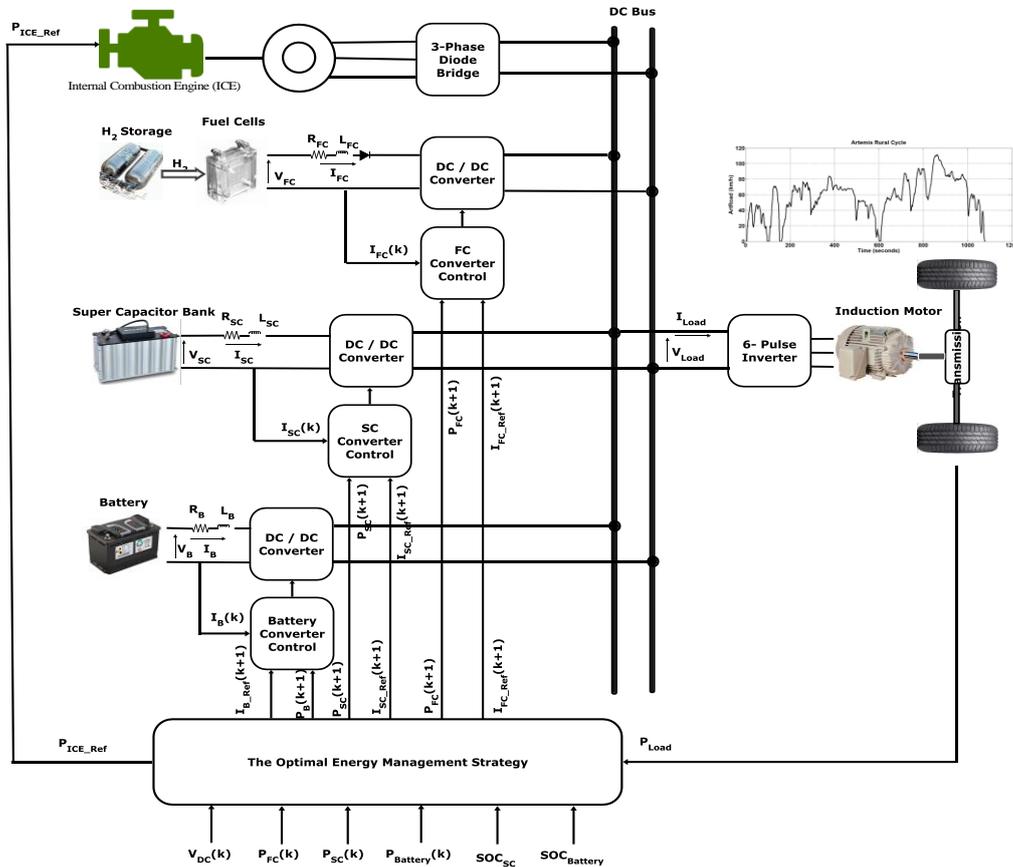
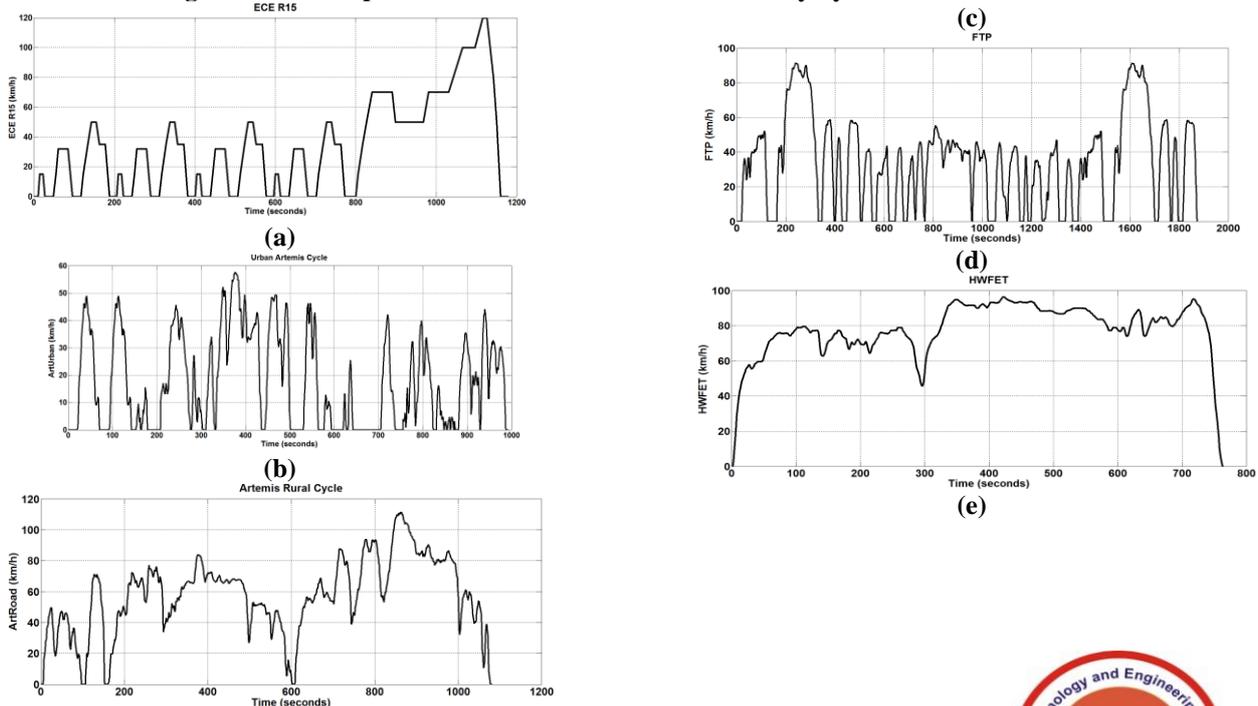


Fig. 1. Converter parallel structure for a FC/SCs/Battery hybrid Electric Vehicle.



An Efficient Energy Management Scheme for a Hybrid FC-SC-Battery Electric Vehicle Using Model Predictive Control and Multi-Objective Particle Swarm Optimization

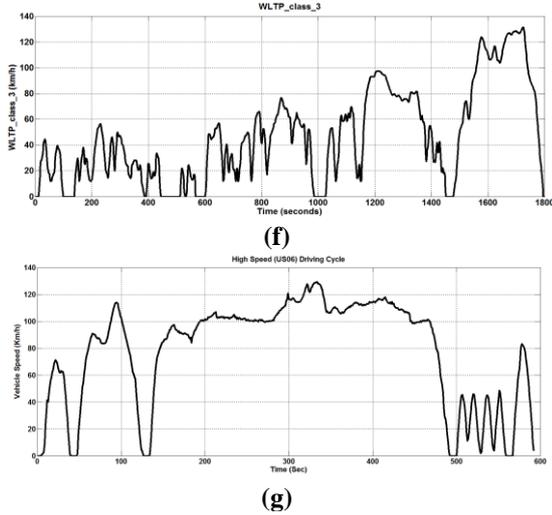


Figure 2. Driving cycle speed versus time: a) ECE 15; b) The Urban Artemis driving cycle; c) The Rural Artemis driving cycle ; d) FTP-75cycle; e) The Highway fuel economy test (HWFET); f) WLT Class 3 cycle g) High Speed (US06) Driving Cycle

II. THE PROPOSED ENERGY MANAGEMENT PROCEDURE

The main idea of the suggested EMS is to distribute the energy requirement through the driving cycle for the PHEV among the various energy sources, keeping in mind the end goal to improve the efficiency of all energy sources, limit the peak of the battery current, reduce the fluctuations of the battery charge and discharge therefore increase the lifetime of the battery. At the beginning of the driving cycle, the proposed control strategy decides the FC capacity, the SC SOC, the battery capacity and the pedal acceleration. At that point, in view of the control calculation, the EMS figures out which energy sources ought to be initiated. The battery and the SC likewise work as storage devices that get charges from the FC or through the load during the regenerative braking operating mode. The FC is utilized as an auxiliary power supply for the PHEV. The FC begins providing power to the load and, in the meantime, energizes the battery and the SC when the SOC limit is less than 50% which is considered as enough energy until FC can surpass the battery and the SC. Two feedback signals, the battery SOC and the vehicle driving speed, are utilized to estimate the power demand. The battery energy is utilized until the SOC reaches 50%. When the battery SOC becomes below 50%, the FC is activated to recharge the battery until it reaches full SOC, then the FC is cut off. The energy generated by the SC is utilized when both the battery and FC still not satisfactory to provide energy to high power demands. In order to evaluate the validity of the suggested MOPSO-EMS, a set of objective functions is utilized to compare different EMS strategies. The most imperative aspect that ought to dependably be considered is the efficiency of all energy sources and the overall system efficiency. Therefore, the first objective function J_1 will be adopted in this paper is to maximize the equivalent system efficiency which is characterized as:

$$J_1 = \frac{P_{Load}}{P_{FC} + P_{Battery} + P_{SC}} \quad (1)$$

$$P_{Load} = (P_{FC} + P_{Battery} + P_{SC}) - P_{Loss} \quad (2)$$

$$P_{Loss} = P_{FC_Loss} + P_{Battery_Loss} + P_{SC_Loss} + P_{FC_Conv_Loss} + P_{Battery_Conv_Loss} + P_{SC_Conv_Loss} \quad (3)$$

The second adopted objective function J_2 is to lessen the fluctuation of the battery current as the incessant battery current fluctuation could drastically decrease the life span of the battery. For each calculation step, the present distinction between nearby calculation steps is measured and stored then at the end of the driving pattern; the following objective function is computed;

$$J_2 = \sqrt{\sum_{k=1}^n (I_B(k+1) - I_B(k))^2} \quad (4)$$

The third objective function J_3 is to minimize the consumed energy from or transposed into the SC pack to improve the energy self-sustainability of the Energy management system. This objective function can be obtained by observing the SOC variation of the SC between the initial state $SOC_{SC}(t_0)$ and final state $SOC_{SC}(t_f)$.

$$J_3 = |SOC_{SC}(t_0) - SOC_{SC}(t_f)| \quad (5)$$

The last goal is to limit the hydrogen utilization amid the driving cycle that working the FC proficiently and exploiting the energy gotten from regenerative braking. In this manner, the fourth objective function J_4 of the EMS that measures the amount of hydrogen devoured in the FC is defined as follows:

$$J_4 = \sum_{k=1}^n Cons_{H_2}(P_{FC}(k))P_{FC}(k)\Delta T \quad (6)$$

Since the scopes of the distinctive amounts are restricted by driving requirements or by the vehicular design, the control system at each iteration will be planned as a complicated optimization case subject to imperatives considering the intend to expand the battery life span, the SC and the FC, the accompanying disparity limitations should be forced:

$$P_{FC_min} \leq P_{FC_min}(k) \leq P_{FC_max} \quad (7)$$

$$P_{Battery_min} \leq P_{Battery_min}(k) \leq P_{Battery_max} \quad (8)$$

$$P_{SC_min} \leq P_{SC_min}(k) \leq P_{SC_max} \quad (9)$$

$$SOC_{Battery_min} \leq SOC_{Battery_min}(k) \leq SOC_{Battery_max} \quad (10)$$

$$SOC_{SC_min} \leq SOC_{SC_min}(k) \leq SOC_{SC_max} \quad (11)$$

IV. MODEL-BASED PREDICTIVE CONTROL MPC

The new efficient on-line EMS system utilizes the retreating horizon control technique as shown in Fig. 3. It comprises of data securing from external model information, driving cycle predictor, optimization algorithm, and energy distribution control. With the retreating horizon control, the whole driving pattern is partitioned into fragments of time. The control horizon of M sampling calculation steps should be shorter than the prediction horizon of N sampling calculation steps and both continue pushing ahead while the system is working. The estimation model is utilized in each iteration to predict the power demand then the optimal power distribution among all energy sources is calculated with this anticipated data.

In order to implement the MPC, the prediction model should be discretized where the last information will be incorporated into the discrete-time state space variable model as follows [53]:

$$x(k+1) = Ax(k) + Bu(k) \tag{12}$$

$$y(k) = Cx(k) + Du(k) \tag{13}$$

$$x(k+1) = \begin{bmatrix} V_{FC}(k+1) \\ V_{Battery}(k+1) \\ V_{SC}(k+1) \\ I_{FC_ref}(k) \\ I_{Battery_ref}(k) \\ I_{SC_ref}(k) \end{bmatrix} \quad y(k) = \begin{bmatrix} V_{FC}(k) \\ V_{Battery}(k) \\ V_{SC}(k) \\ I_{DC_Bus}(k) \\ \Delta I_{FC}(k) \\ \Delta I_{Battery}(k) \\ \Delta I_{SC}(k) \end{bmatrix}$$

$$u(k) = \begin{bmatrix} I_{FC_ref}(k) \\ I_{Battery_ref}(k) \\ I_{SC_ref}(k) \end{bmatrix} \quad A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -\frac{V_{DC_Bus_ref} t_s}{V_{FC_ref} C_{FC}} & 0 & 0 \\ 0 & -\frac{V_{DC_Bus_ref} t_s}{V_{Battery_ref} C_{Battery}} & 0 \\ 0 & 0 & -\frac{V_{DC_Bus_ref} t_s}{V_{SC_ref} C_{SC}} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{t_s} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{t_s} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{t_s} \end{bmatrix}, \quad D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{1}{t_s} & 1 & 1 \\ \frac{1}{t_s} & 0 & 0 \\ 0 & \frac{1}{t_s} & 0 \\ 0 & 0 & \frac{1}{t_s} \end{bmatrix}$$

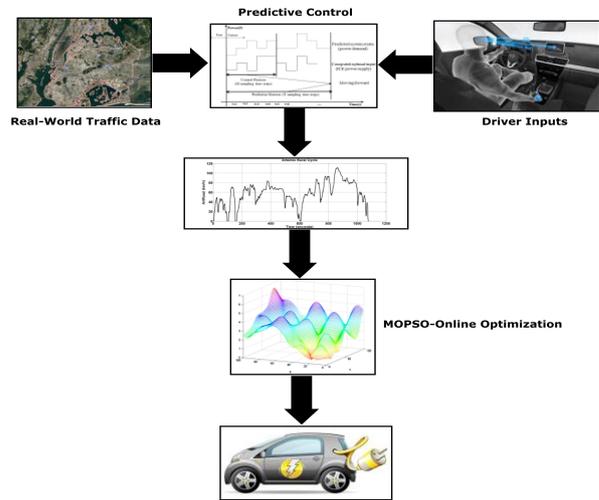


Fig. 3 the main procedure of the suggested on-line EMS

V. THE PROPOSED MULTI OBJECTIVE PARTICLE SWARM OPTIMIZATION (MOPSO) ALGORITHM

In the developed MOPSO-MPC based EMS control technique, the value of $P_{Battery}$, P_{SC} and P_{FC} will be symbolized as the possible position or solution for the particles array. Each particle represents a specific configuration and will be considered as a possible solution of the EMS problem. A vector of the four objective functions which are functions of the encoded values of $P_{Battery}$, P_{SC} and P_{FC} will be produced using the encoded value of each particle. The optimal objective functions vector and the associated best particle will be determined by comparing the different objective function values. The main algorithm of the developed MOPSO-based EMS procedure is presented in Fig. 4. The general procedure of the MOPSO calculation and optimization exercise is described as follows [54]:

1. Assign the maximum and minimum limits of $P_{Battery}$, P_{SC} and P_{FC} ;
2. Arbitrarily produce a populace of particles. The acceleration and the location of all particles are instated as indicated by the limitations of step1;
3. The assessment of the objective functions is executed on the vector of the produced particles and will be saved in $pbest$ vector structure.
4. Ascertain the multi-objective functions of each particle and all "non-dominated" arrangements are saved in the "Pareto Archive".
5. The acceleration of all particle is refreshed, utilizing the following formula:

$$\begin{bmatrix} v_{i1}(t+1) \\ v_{i2}(t+1) \\ v_{i3}(t+1) \end{bmatrix} = \omega \times \begin{bmatrix} v_{i1}(t) \\ v_{i2}(t) \\ v_{i3}(t) \end{bmatrix} + c_1 \times r_1(\cdot) \times \begin{bmatrix} P_{p1}(t) - P_{FC_i}(t) \\ P_{p2}(t) - P_{Battery_i}(t) \\ P_{p3}(t) - P_{SC_i}(t) \end{bmatrix} \tag{14}$$

$$+ c_2 \times r_2(\cdot) \times \begin{bmatrix} P_{r1}(t) - P_{FC_i}(t) \\ P_{r2}(t) - P_{Battery_i}(t) \\ P_{r3}(t) - P_{SC_i}(t) \end{bmatrix}$$

Where $\begin{bmatrix} P_{p1} \\ P_{p2} \\ P_{p3} \end{bmatrix}$, $\begin{bmatrix} P_{r1} \\ P_{r2} \\ P_{r3} \end{bmatrix}$ are randomly chosen from the

An Efficient Energy Management Scheme for a Hybrid FC-SC-Battery Electric Vehicle Using Model Predictive Control and Multi-Objective Particle Swarm Optimization

Pareto archive, The lower and upper bounds of the acceleration of each particle are verified utilizing the following constrains:

$$\begin{aligned} \text{if } v_{id}(t+1) &\geq v_d^{max} & \text{then } v_{id}(t+1) &= v_d^{max} \\ \text{if } v_{id}(t+1) &\leq v_d^{min} & \text{then } v_{id}(t+1) &= v_d^{min} \end{aligned} \quad (15)$$

- The arrangement of every particle is updated utilizing the following equation. The particles are kept into the passable range esteems.

$$\begin{bmatrix} P_{FCi}(t+1) \\ P_{Battery_i}(t+1) \\ P_{SCi}(t+1) \end{bmatrix} = \begin{bmatrix} P_{FCi}(t) \\ P_{Battery_i}(t) \\ P_{SCi}(t) \end{bmatrix} + \begin{bmatrix} v_{i1}(t+1) \\ v_{i2}(t+1) \\ v_{i3}(t+1) \end{bmatrix} \quad (16)$$

- Assess and compare all objective function values of all particles and the “non-dominated particles” are saved in the “Pareto Archive”.
- Then, two particles arrangements are chosen arbitrarily from the Pareto file for $\begin{bmatrix} P_{p1} \\ P_{p2} \\ P_{p3} \end{bmatrix}$, $\begin{bmatrix} P_{r1} \\ P_{r2} \\ P_{r3} \end{bmatrix}$.
- Redo the same calculations from (4) to (8), until the convergence criteria are met.

were used in the simulation study; ECE 15, the Urban Artemis driving cycle, the Rural Artemis driving cycle, FTP-75cycle, the Highway fuel economy test (HWFET), WLTP Class 3 cycle and High Speed (US06) Driving Cycle. The proposed vehicular system incorporates the FC, the SC, the battery, the uni-directional and bi-directional dc-dc converters and the control strategy based on MOPSO-MPC. The parameters of each component of the proposed scheme are presented in Table I. The control calculations are executed in a PC for SC side, the battery’s side, and FC’s side converters. The DC bus power will be assumed as a positive if the power streams from the DC bus to the storage arrangement; and will be assumed as a negative if the power streams from the storage arrangement to the DC bus. The SC bank is thought to be an ideal capacitor because its internal resistance is much smaller than that of the batteries and the FC. The control technique of the dc-dc converters is utilized to assign the power between the FC, the SC bank and the battery bank. The simulation results corresponding to the three strategies: Fuzzy Logic Rule-based EMS; MOPSO-based EMS and GA-based EMS are shown in Figure 4 to Figure 8 for the High Speed (US06) Driving Cycle Speed then a comparative between the corresponding performances for the different driving cycles is carried out.

Table 1. The specifications of the proposed system

Fuel Cell	220 V, 76 KW
Super Capacitor	150 F, 400 V
Battery	Lead-acid, 70 Ah, 500 V
Unidirectional DC/DC Converter	Input voltage: 100-300 V, output voltage:400-600 V
Bidirectional DC/DC Converter	Input voltage: 200-400 V, output voltage:400-600 V

Fig. 4 shows variations of the FC Fuel Consumption during High Speed (US06) Driving Cycle Speed; Hydrogen Consumption (gal) and the Rate of Hydrogen Consumption (gal/sec.). As can be seen in this figure, as the FC power rises, it is expected that the FC current increases in order to provide requested power. FC current is proportional to the fuel consumption i.e. sudden increase of the current leads to fuel starvation and also having a negative impact on FC membrane. Therefore, the fuel cell lifetime can be increased by the proposed strategy. Additionally, the SOC of the battery during High Speed (US06) Driving Cycle Speed is presented together with the SOC of the SC in Fig. 5. the battery and the SC SOC are kept more stable using the MOPSO-EMS strategy than that in the other EMS strategies. Fig. 6 shows the DC bus/FC/Battery/SC voltage plots with the proposed MOPSO-EMS during High Speed (US06) Driving Cycle Speed. To assess the effectiveness of the DC-bus voltage control strategy, the reference value of the DC-bus voltage is set constant at 50 Volt. The figure demonstrates that the developed DC bus-voltage control strategy is adequate and the actual value of the DC-bus voltage is very close to the reference value. Load current profile, the FC/Battery/SC pack current are presented in Fig. 7. These plots affirm the conclusion that the proposed EMS strategy provides minimum variation of the battery current. The battery current covers an excessive number of dynamic parts which prompt a bigger battery current variety.

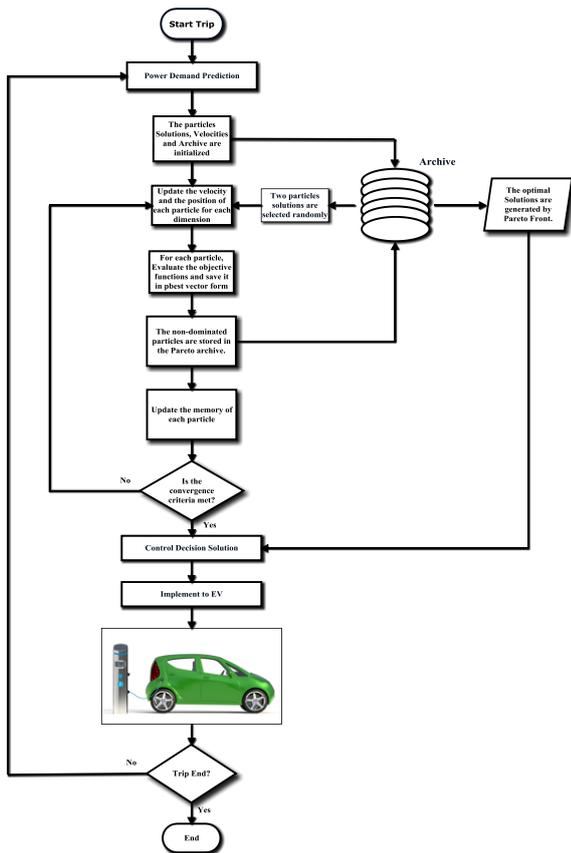


Fig. 4 MOPSO-based EMS procedure

VI. SIMULATION RESULTS

In order to verify and compare the effectiveness and the performance of the developed MOPSO-MPC based EMS in different driving cycles with several proposed EMSs in the literature, the proposed MOPSO-EMS was modelled in the Simulink and the SimPowerSystem toolbox are employed as simulation software. The following testing driving cycles

Obviously when MOPSO-EMS is implemented, the battery pack current is kept as low as conceivable with constrained current varieties and the dynamic parts are all most secured by the SC pack. It is conceivable to presume that the all changes of the current are moderated by the SC, and this arrangement empowers to lessen the cycle number of the battery to enhance their live time. These outcomes demonstrate that the fundamental commitment of the storage gadgets is guaranteed by the SC. The simulation results of the EMS during High Speed (US06) Driving Cycle Speed are shown in Figure 8. It is obvious that the controller is keeping the DC bus voltage stabilized and maintained on the same value even with the high amplitude variations on the DC bus power. The performance demonstrates a decent choice from the MOPSO, as the SCs consumed the power from the DC bus, also, the batteries were made a request to add to the SCs charging in the meantime.

The composite power supply EMS in view of FLC is compelling, and it can sensibly convey the power between the battery, the FC and the SC in the composite power supply. The battery gives the essential energy to the driving framework and the FC and the SC gives the supplement to the pinnacle control. The vast majority of braking criticism power is consumed by the SC. For better assessment for the effectiveness of the proposed MOPSO-based EMS, four other driving speed profiles are utilized to analyze the effectiveness of various EMS procedures. In Tables 2-7 some performance Criteria are listed that are studied in different control strategies; Fuzzy Logic Rule-based EMS, GA-based EMS and the proposed MOPSO-based EMS for different driving cycles. Table 2 shows the simulation results of the system efficiency performance analyzing. It is obvious in Table 2 that the proposed MOPSO-based EMS gives the highest system efficiency among the three EMSs for all driving cycles. The Battery Current Variation simulation results are shown in Tables 3. Compared to Fuzzy Logic Rule-based EMS, GA-based EMS strategies, it is clear that the battery current variation is vastly improved with the MOPSO algorithm. The comparison of the fluctuation of the battery SOC is shown in Table 4. In general, the battery SOC fluctuation is within the limitation for all energy management strategies and its performances in all techniques are very close to those of the developed MOPSO and most importantly no driving pattern will be required. Table 5 compares the results of SOC deviations, it is clear that, the SOC deviation of the proposed MOPSO-EMS strategy is less than other strategies. One of the evaluation criteria for energy management strategies is their capability to maintain the SOC of energy storage devices. Tables 6-7 demonstrate the comparison between the behaviours of the three EMS techniques, as far as hydrogen utilization per kilometer. The comparison is carried out between the behaviour of the three procedures concerning the relating to the ideal situation where the utilization in least; the qualities in rates demonstrate the addition in utilization regarding the ideal case. The behaviour of the ideal case is evaluated expecting that the totally cycle is known from the earlier. In this way, it is conceivable to work the FC amid the completely cycle at its purpose of most extreme productivity. The results affirm that the proposed control technique is for sure viable in Hydrogen fuel economy under all driving cycles.

VII. EXPERIMENTAL RESULTS

In order to validate the developed MOPSO-MPC based EMS control strategy, the experimental setup is carried out and includes a module of a 50 V SC, a 50 V battery, buck and buck-boost DC/DC converters, and a computer to host the EMS control algorithm. The MOPSO-EMS control algorithm was utilized to establish the power distribution between the FC, the battery and the SC. The aim of the DC bus control loop is to maintain the DC-bus voltage fixed at 50 V. A 6-pulse inverter was utilized to drive a 3-HP, 120-V, 3-phase IM to copy the behaviour of the traction mechanism. Fig. 9 shows the Hydrogen Consumption (gal) and the Rate of Hydrogen Consumption (gal/sec.). Additionally, the SOC of the battery is presented together with the SOC of the SC in Fig. 10. As shown in this figure the battery and the SC SOC are kept more stable using the MOPSO-EMS strategy than that in the other EMS strategies. Fig. 11 introduces the experimental results for the DC-bus voltage. It is clear from the figure that the proposed MOPSO-MPC EMS control strategy is adequate for the DC-bus voltage control. The DC bus, the FC, the SC and the battery currents experimental measurements are plotted in Fig. 12. while the FC, the SC and the battery power contributions on the DC-bus are presented in Fig. 13. It is very obvious from these experimental results that the developed MOPSO-MPC EMS control algorithm is adequate for load current and power sharing between FC, SC and battery for hybrid electric vehicles.

VIII. CONCLUSION

The paper has introduced the implementation of the MOPSO algorithm with the MPC technique for EMS of FC-Battery-SC PHEV. In order to validate the effectiveness of the developed MOPSO-MPC based EMS, a set of objective functions is utilized to compare different EMS strategies for different driving cycles. The first aspect that ought to dependably be considered is the efficiency of all energy sources and the overall system efficiency. The second optimization objective is to reduce the variation of the battery current as the incessant battery current variation would drastically decrease the lifetime of the battery. The third aspect that ought to be considered is to minimize the consumed energy from or transposed into the SC pack to improve the energy self-sustainability of the Energy management system. The last optimization goal is to reduce the hydrogen utilization during the driving cycle. Simulation results demonstrate that the developed MOPSO-MPC based EMS strategy can accomplish higher efficiency compared with traditional EMS procedures. In addition, it can minimize the variations of the battery currents and improve vehicle stored energy utilization, driving eventually to lessen part costs and enhanced vehicle range. The real-world driving cycle information is utilized with the offline optimization results, which demonstrate that in a real-world control circumstance the developed MOPSO-MPC based EMS can act as well as in a real-time domain. At the point when the actual driving pattern contrasts from the cycle utilized as a part of the optimization procedure, the EMS will accomplish a close ideal control execution.

An Efficient Energy Management Scheme for a Hybrid FC-SC-Battery Electric Vehicle Using Model Predictive Control and Multi-Objective Particle Swarm Optimization

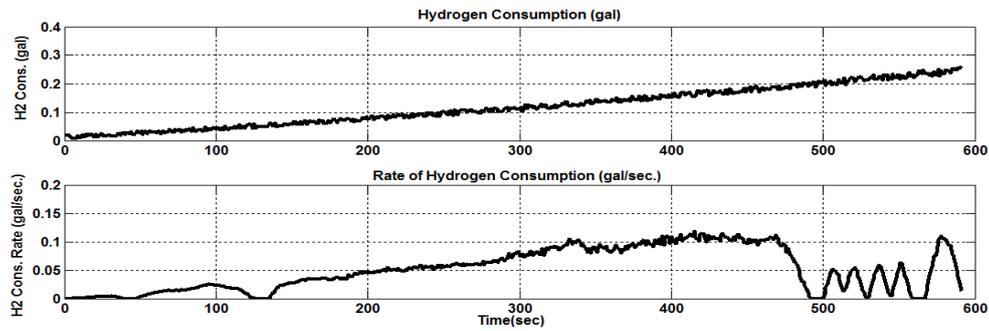


Fig. 4 FC Fuel Consumption during High Speed (US06) Driving Cycle Speed (a) Hydrogen Consumption (gal) (b) Rate of Hydrogen Consumption (gal/sec.)

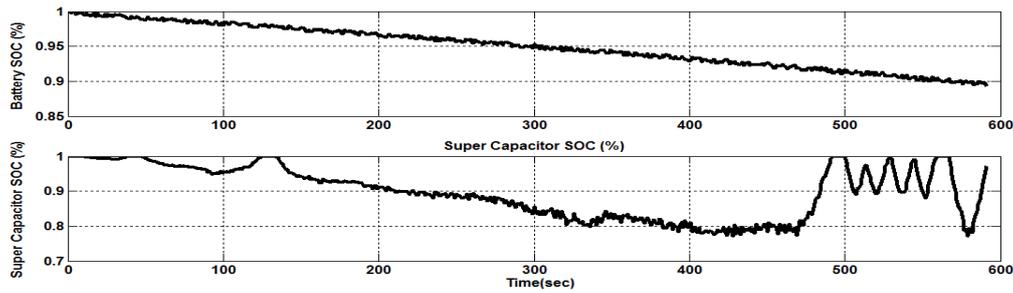


Fig. 5 SOC of the battery and the SC during High Speed (US06) Driving Cycle Speed (a) Battery SOC (%) (b) Super-Capacitor SOC (%)

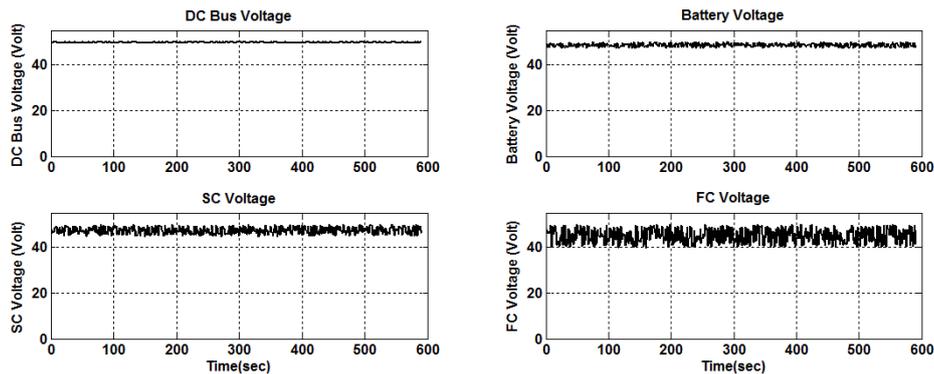


Fig. 6 DC voltage variation during High Speed (US06) Driving Cycle Speed (a) DC Bus Voltage (b) Battery Voltage (c) SC Voltage (d) FC Voltage

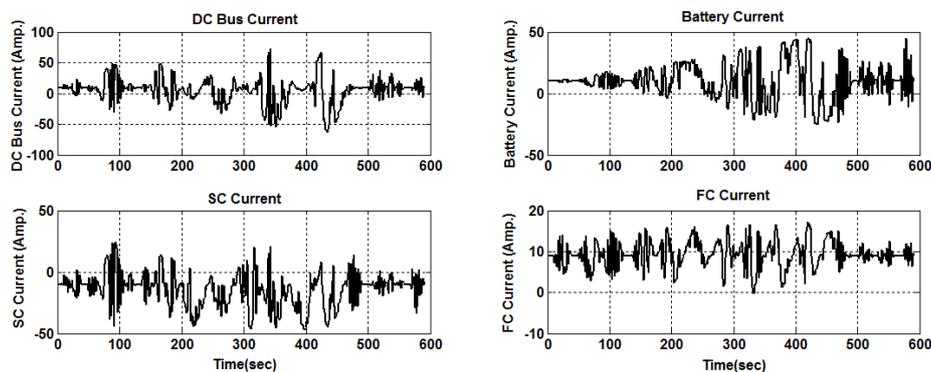


Fig. 7 DC Current variation during High Speed (US06) Driving Cycle Speed (a) DC Bus Current (b) Battery Current (c) SC Current (d) FC Current

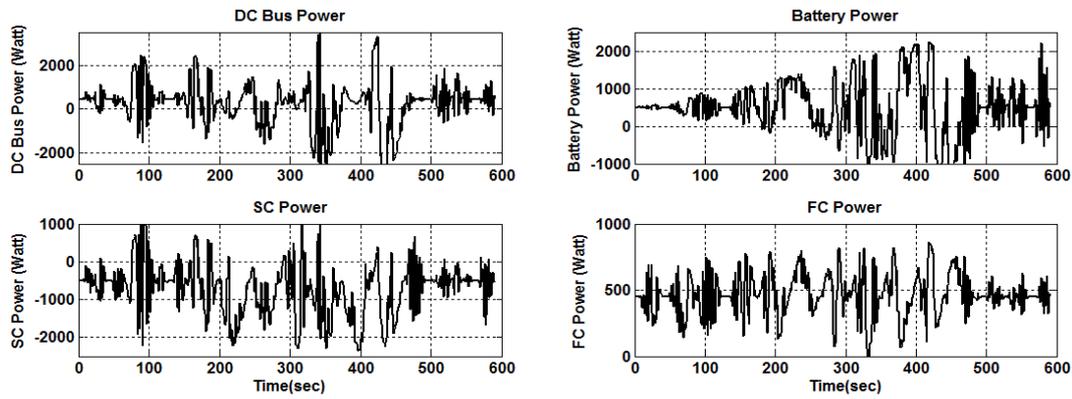


Fig. 8 DC Power variation during High Speed (US06) Driving Cycle Speed (a) DC Bus Power (b) Battery Power (c) SC Power (d) FC Power

Table 2. System Efficiency performance comparison in different control strategies for different driving cycles

	ECE 15	The Urban Artemis	The Rural Artemis	FTP-75cycle	HWFET	WLTP Class 3	High Speed (US06)
Fuzzy Logic Rule-based EMS	77.16	76.84	76.96	75.73	76.25	73.69	74.24
GA-based EMS	82.78	81.65	82.09	83.23	81.54	82.74	83.83
MOPSO-based EMS	88.45	86.23	88.67	85.78	86.32	86.38	87.09

Table 3. Battery Current Variation performance comparison in different control strategies for different driving cycles

	ECE 15	The Urban Artemis	The Rural Artemis	FTP-75cycle	HWFET	WLTP Class 3	High Speed (US06)
Fuzzy Logic Rule-based EMS	31.95	34.84	33.38	32.49	31.28	36.06	34.70
GA-based EMS	27.14	29.14	26.14	28.14	27.14	28.14	27.14
MOPSO-based EMS	24.14	25.14	24.14	25.14	23.14	24.14	23.14

Table 4. Battery SOC Fluctuation performance comparison in different control strategies for different driving cycles

	ECE 15	The Urban Artemis	The Rural Artemis	FTP-75cycle	HWFET	WLTP Class 3	High Speed (US06)
Fuzzy Logic Rule-based EMS	0.1387	0.1275	0.1193	0.1239	0.1199	0.1527	0.1408
GA-based EMS	0.0901	0.0859	0.0951	0.0889	0.0806	0.0941	0.0982
MOPSO-based EMS	0.0510	0.0498	0.0409	0.0510	0.0509	0.0622	0.0577

Table 5. SC SOC Fluctuation performance comparison in different control strategies for different driving cycles

	ECE 15	The Urban Artemis	The Rural Artemis	FTP-75cycle	HWFET	WLTP Class 3	High Speed (US06)
Fuzzy Logic Rule-based EMS	0.1289	0.1196	0.1057	0.1126	0.1301	0.1407	0.1317
GA-based EMS	0.0813	0.0747	0.0890	0.0816	0.0771	0.0790	0.0889
MOPSO-based EMS	0.0389	0.0399	0.0379	0.0403	0.0299	0.0392	0.0418

Table 6. Hydrogen Consumption (g/km) performance comparison in different control strategies for different driving cycles

An Efficient Energy Management Scheme for a Hybrid FC-SC-Battery Electric Vehicle Using Model Predictive Control and Multi-Objective Particle Swarm Optimization

	ECE 15	The Urban Artemis	The Rural Artemis	FTP-75cycle	HWFET	WLTP Class 3	High Speed (US06)
Fuzzy Logic Rule-based EMS	9.3	9.1	9.5	9.4	8.3	9.2	9.7
GA-based EMS	7.1	6.9	7.2	6.8	6.7	7.4	7.2
MOPSO-based EMS	5.1	5.6	5.2	4.9	5.3	5.5	5.6

Table 7. Hydrogen Savings (%) performance comparison in different control strategies for different driving cycles

	ECE 15	The Urban Artemis	The Rural Artemis	FTP-75cycle	HWFET	WLTP Class 3	High Speed (US06)
Fuzzy Logic Rule-based EMS	15.6	14.3	15.2	16.1	17.8	16.4	15.8
GA-based EMS	20.6	21.8	22.3	22.0	23.4	21.6	22.9
MOPSO-based EMS	25.5	26.8	26.8	28.4	29.9	29.2	28.7

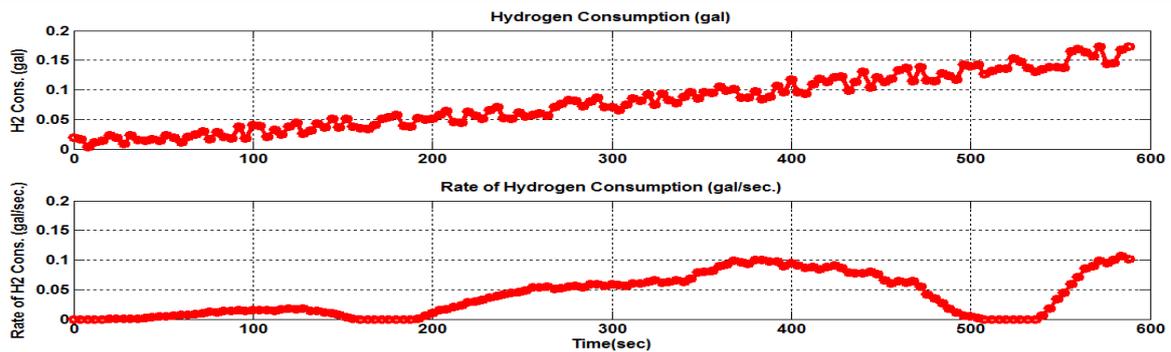


Fig. 9 FC Fuel Consumption during High Speed (US06) Driving Cycle Speed (a) Hydrogen Consumption (gal) (b) Rate of Hydrogen Consumption (gal/sec.)

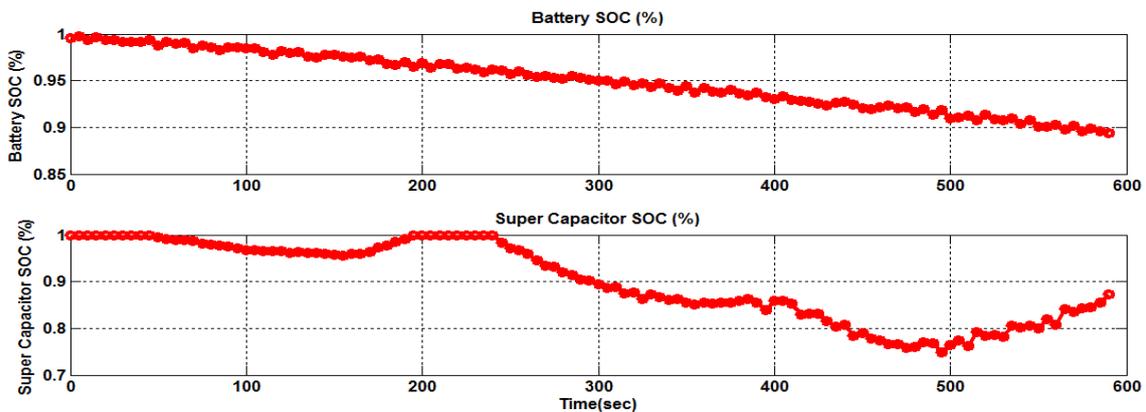


Fig. 10 SOC of the battery and the SC during High Speed (US06) Driving Cycle Speed (a) Battery SOC (%) (b) Super-Capacitor SOC (%)

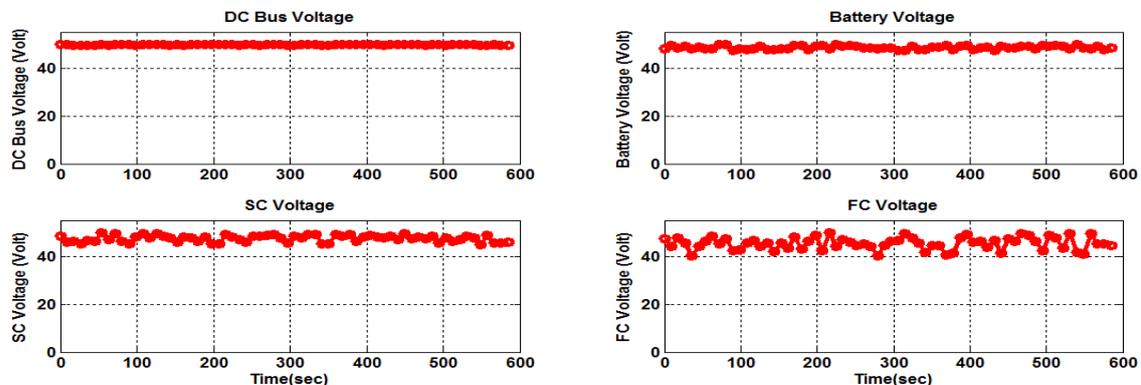


Fig. 11 DC voltage variation during High Speed (US06) Driving Cycle Speed (a) DC Bus Voltage (b) Battery Voltage (c) SC Voltage (d) FC Voltage

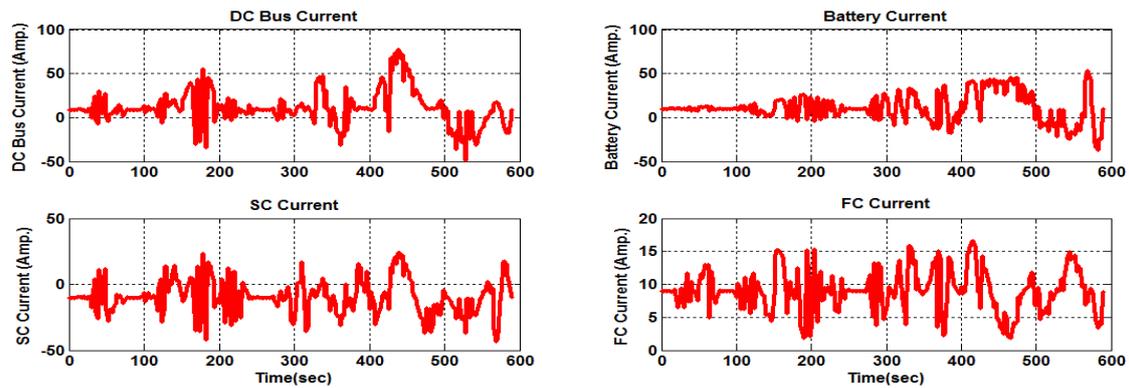


Fig. 12 DC Current variation during High Speed (US06) Driving Cycle Speed (a) DC Bus Current (b) Battery Current (c) SC Current (d) FC Current

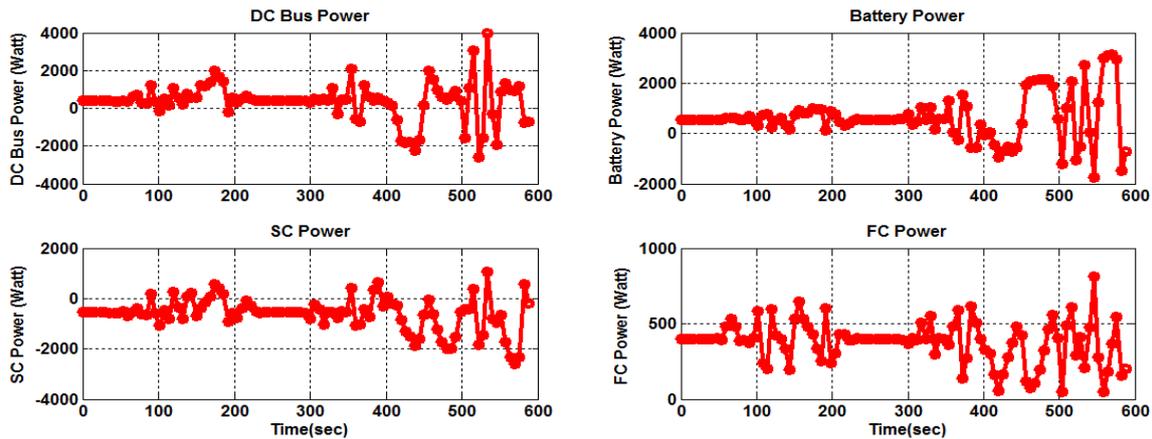


Fig. 13 DC Power variation during High Speed (US06) Driving Cycle Speed (a) DC Bus Power (b) Battery Power (c) SC Power (d) FC Power

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