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Performance Evaluation of Battery and Super-Capacitor for Electric Vehicle with Hybrid Techniques

Nagesh B.K., B. R. LakshmiKantha

Abstract: *In recent trends, Plug-in Hybrid Electric Vehicles (PHEVs) have an excessive opportunity due to its charging facilities and charge storage system. Through appropriate design and development, Electric Vehicles (EVs) not only eliminate the pollution but also make the system more efficient over traditional vehicles. However, still it is in the progress of the investigation and has several unanswered issues. The performance of PHEV depends upon proper utilization of electric power which is solely affected by the battery State-Of-Charge (SOC). SOC determination becomes a vital problem in whole area where it comprises a battery storage; because it has several drawbacks such as weak power density, longevity, etc. one probable and favourable resolution for this issue is multi-source EV. Both the batteries and Ultra-Capacitors (UC) can reduce the aforementioned disadvantages in existing systems. This proposed work has more efficiency because of the combined design model of both battery and super-capacitor. Hence, in this work, the Particle Swarm Optimization (PSO) technique with Fuzzy Logic Controller (FLC) is implemented for optimal sharing of power between the battery and the super-capacitor.*

Index Terms: *Plug-in Hybrid Electric Vehicles (PHEVs), State-Of-Charge (SOC), Energy management system(EMS), Particle Swarm Optimization (PSO), Fuzzy Logic Controller (FLC).*

I. INTRODUCTION

Recently, the world is facing a growing challenge from global climate change which mainly associated with gas emissions that has increased the interest and demand for EVs. In the meantime, the traditional vehicles are found with Internal Combustion Engine (ICE) which is used as an extra energy-saving and eco-friendly [1], [2]. The exploration and presentation of Hybrid Energy Storage System (HESS) in areas like EVs, HEVs and distributed micro-grids is growing attractive. HESS comprises of various storage devices and that having robust energy proficiency and extensive life span [3], [4].

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*Correspondence Author(s)
Nagesh B.K., Department of Electrical and Electronics Engineering, REVA University, Bangalore, India.
Dr. B. R. LakshmiKantha, Electrical and Electronics Engineering, Dayananda Sagar Academy of Technology & Management, Bangalore, India.

Several designs have been suggested to decrease the constant worry (stress) on the battery, in that way life span is increased. The ultra-capacitor is used as equivalent to a battery to simplify the power stresses on the battery. Here, UC would absorb energy from regenerative braking and assist the battery during discharge [5]. The concept is to share peak power/current by high power battery to reduce the burden of the battery. UC can provide extreme high current as well as keep adequate energy [6]. A suitable ESS can be chosen based on different performance requirements. The frequently manipulated ESSs are separated into multiple categories: mechanical, electrical and chemical ESS [7].

Batteries can be combined with UC to create a lightweight, compact ESS that exhibits decent cooperation between energy and power densities. Batteries normally drop their efficiency once after thousand charge–discharge rotations. In conflict, UC is capable to conserve the presentation for approximately one million rotations [8]. In discussing the power capability of batteries and UC, it is necessary to specify the time of the charge or discharge and the conditions under which the energy transfer takes place [9], [10]. In [11], suggested converter works like a Zero-Voltage Transition (ZVT) buck to charge a UC or battery and acts as a ZVT boost converter to discharge a UC or battery. However once the converter changes from boost mode to buck, UC voltage increases slowly. An online joint estimation method [12] for SOC and Fractional Order Model (FOM) parameters is proposed and validated by a hardware-in-the-loop platform. However, a smaller sampling interval will increase the computational burden. There is a lot of energy storage type to be installed in MCS unit. This research discusses both battery and UC as two main ESS. [13]. Meanwhile, to predict a potential energy storage device is one of the challenging issues. Current studies on supportable equipment's for transportation sector which are extending popularity amongst the research groups from dissimilar regions. The idea of hybridization is to exploit the performance of the vehicle and minimalize the shortcomings of PHEV by suitable structure and energy control. The main contributions of this research are specified as follows:

- The efficient power distribution to PHEV is accomplished with the help of two various energy storage devices such as battery and ultra-capacitor.
- Here the PSO-FLC based controller is utilized for supporting the charging and discharging of the UC. When the battery doesn't have sufficient power to manage the load requirement of PHEV, UC is used for discharging the power to compensate.

- In this case, the effective power is given to the HEV as well as this proposed methodology gives better speed for motor, vehicle and it gives better torque too.

This research paper is prepared as follows. Several recent papers on PHEV system surveyed in the section II. Detailed explanation about the proposed system in PHEV is given in section III. The results and analysis of proposed system are discussed in section IV. Conclusion of research work is made in section V.

II. LITERATURE REVIEW

Hajer Marzougui *et al.* [14] demonstrated an energy management algorithm for an electrical hybrid vehicle. The proposed hybrid vehicle presents a fuel cell as the main energy source and the storage system, comprises of a battery and a Super-Capacitor (SC) as the secondary energy source. The addition of battery and SC in fuel cell-based vehicles has excessive prospective since it permits a substantial decrease of the hydrogen ingestion and an enhancement of the vehicle efficiency. But some chemical reactions are mixed with the fuel cell, so their responding time is high.

Kursad Gokce and Ayhan Ozdemir [15] presented an efficient rule based controller scheme to the combined battery/UC ESS. The SOC level of energy sources is formulated the weighting parameters of rule table. The charging/discharging are defined by both the weighting parameters and states of energy sources. The battery and UC present in the electric vehicles are protected from high temperature rise and high current pulses. In this rule based control scheme, the battery is less exposed to the rapid current changes.

Rui Xiong *et al.* [16] proposed Battery and ultra-capacitor in-the-loop approach to validate a real-time energy controlling technique for an all-climate electric vehicle. Dynamic programming scheme can decrease the ratio of charge/discharge in the battery pack, which prolongs the life span and increases the effectiveness of the structure. But for a suitable strategy, more importantly, the real-time application performance is also very important. However, yet there is a certain gap between the simulation and practical application.

Akif Demircal *et al.* [17] presented temperature dependent models for the battery/ultra-capacitor powered EV to manage storage components as well as the drive train components. The energy management of the vehicle is achieved in two stages. The primary stage is to control the search space of the technique conferring to situations of ESS and energy request of the vehicle. After determination and limitation of the search space, energy distribution method is executed with PSO. However, these studies aimed to decreasing the usage of fuel only, does not consider certain parameters and equipments.

Hui Peng *et al.* [18] proposed a compound control framework for energy management of hybrid ultra-capacitor-battery electric drive system. The topology guarantees that the ultra-capacitor current and the battery current can be controlled individually. In calculation, the management of the hybrid source is connected through electrical drives. The advantages of the proposed compound control are that ultra-capacitor supplies peak and ripple current while battery supplies smooth and steady current. The main current is supplied by the battery, but the ultra-capacitor cannot supply enough current to reject disturbance.

III. PROBLEM STATEMENT

- There is an essential requirement to discover a cost-effective, long-lasting and environmental friendly technique to save the energy that attained from a various array of resources.
- Regularly the batteries do not initiate at zero voltage and even if they ensure only a small amount of charge is essential to get them to a huge fraction of the open circuit voltage.
- The load requirements of the EV is investigated in this paper which is restricted to the propulsion load type. Even though the non-propulsion load requirements have been considered as part of this study.

IV. PROPOSED METHOD

At first, the Energy Management System (EMS) is optimized then the search space is restricted according to the parameters and the conditions of the energy sources and the power demand of the vehicle. After the search space has been defined the PSO algorithm will be implemented. Meanwhile, the total power demand was designed according to the data corresponding to the drive cycle. As power be determined by velocity, at each interval of time the power request varies as the velocity varies. To compare the constraints of the model the power request has been reduced. The battery and UC power were established by computing the optimal values at every time interval through PSO. One practical substitute to both analytical and experiential method that is robust and more precise. FLC for the battery has been generated by considering the output attained from the PSO algorithm like battery voltage, battery power demand, battery internal resistance and charge capacity of the battery. This state of charge decides the propulsion of vehicle and control strategy to meet the load demand, sustain the battery and SC charge, improve the HESS efficiency and extend the battery lifetime.

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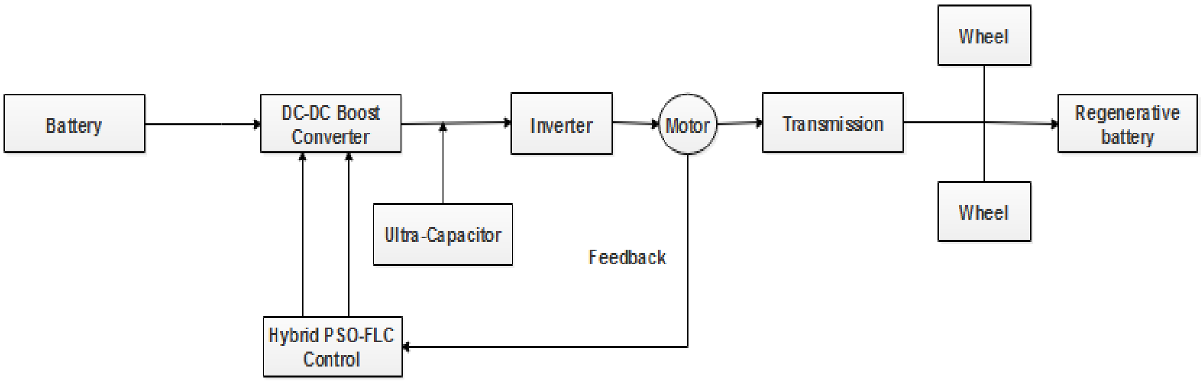

Fig. 1. Block Diagram Of The Proposed System

A control scheme for the HESS is introduced using the SOC of battery and UC to balance the energy in HESS. Furthermore, the HEV requires regulated EMS to manage higher efficiency motor and maintain the real-time charging/discharging capability of HESS. The main components of the proposed system are the battery, Ultra-capacitor, DC-DC buck/boost converter, motor, PSO-FLC controller, wheel and regenerative braking. Fig. 1 shows the block diagram for the proposed system. Here, the battery is connected as a primary energy source and UC works as a buffer in contrast to substantial magnitudes and fast fluctuations in power, whereas the battery connected to DC/DC is sheltered and its energy flow can be controlled effectively. The battery is working as the main source which supplies to the whole system. Whereas, DC-DC converter maintain the power balance between battery and UC. The motor is used as a load to evaluate the performance of the complete system. The working condition of the system is stable by providing chemical energy via motor speed. The operating condition of UC is defined by the feedback from the motor and the control strategy maintain the charging/discharging capability of UC in HESS.

In PHEVs, State-of-charge determination develops a progressively vital problem in whole regions that contain a battery. Earlier process having voltage range limitations only to protect the battery in contradiction of profound overcharge and discharge. To get enhanced results, SOC of battery is used as a key feature and its operating mode of battery is also varying which relatively called battery management. The other problem is how to divide the power between the battery and the super-capacitor. The division must be optimal and efficient. Energy management between different energy sources is an essential part of this research as presently no energy source can power the entire electric vehicle efficiently.

A. Hybrid PSO-FLC Methodology

PSO is a multi-agent search technique and an excellent tool for optimization problem in power system. And also it is very powerful and well established meta-heuristic optimization algorithm; it has robust principle, less number of constraints and it is easy to be executed with fast convergence rate; it is frequently applied to optimize the FLC, which is able to balance the energy trading with the PHEV, while the EMS is completely based on FLC. PSO is used to resolve the profitable and environmental related problems, so in this work it is selected to execute an efficient optimization algorithm which increases the exploitation of generation and reduces the operating cost of the power system. And also used to attain the economical load assignment with minimal value to enhance the utilization of energy resources. From this PSO it is used to optimize the effectiveness of uncertainties of the input variable forecasting, so, the EMS selects the PSO strategy to resolve the optimization issues in EV, which reduces the computing time and enhanced the proficiency of the system.

Consider swarm with size of K along with N-dimensional search space. Initially the velocity and position of the particles are created randomly within the N-dimensional search space. The position and velocity of each particle get updated at each iteration using next Eq. (1) and Eq. (2) respectively.

$$V_i^{(k+1)} = V_i^k + C_1 \times rand_1 \times (pbest_i - x_i^k) + C_2 \times rand_2 \times (gbest_i - x_i^k) \quad (1)$$

$$x_i^{(k+1)} = x_i^k + V_i^{(k+1)} \quad (2)$$

Where the value of k indicates the current iteration number and C_1 *and* C_2 represents the constant weighting factor of the stochastic acceleration terms, which makes the particle towards the p_{best} *and* g_{best} position and the two random values are indicated by $rand_1$ *and* $rand_2$ in the range of 0 to 1. The design of FLC can provide appropriate both large signal and small signal active performance at similar time, which is not imaginable with linear control system. In this paper, FLC theory is deliberated for the hybrid structure to attain the development of the system. This design standard requires that both the battery and UC should produce energy at same operating point. The difference between the entire generated power and the actual load is taken into account for battery in charge and discharge modes. To enhance the life span of the battery by controlling and maintaining the SOC of battery with fuzzy based control technique.

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To achieve the preferred SOC value, FLC is calculated to be in either charging or discharging mode for the hybrid structure. The fuzzy control activities are calculated by the controller through two real valued constraints within the limits [0, 1].

B. Battery Model

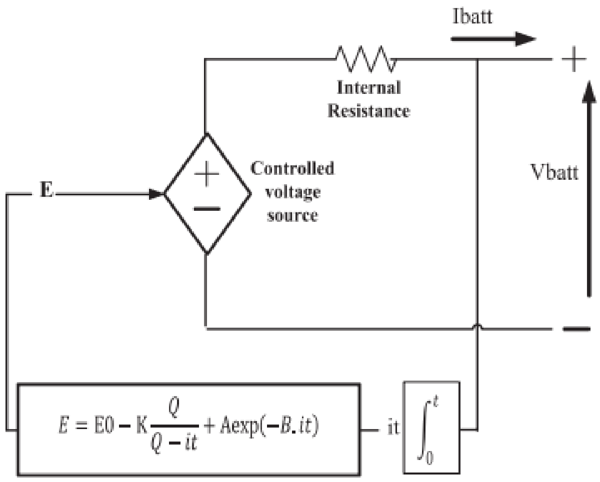

Fig. 2. Equivalent Model for Battery

The battery is demonstrated with controlled voltage source in series with a constant resistance as illustrated in fig 2. The battery voltage V_{bat} is described by Eq. (3).

$$V_{bat} = E - R_{bat} I_{bat} \tag{3}$$

The controlled voltage source is given in Eq. (4).

$$E = E_o - K\frac{Q}{Q_D - \int i.dt} + A.\exp\left(-B\int i.dt\right) \tag{4}$$

E : is the no load voltage (V)

E_0 : is the battery constant voltage (V)

K : is the polarization voltage (V)

Q : is the battery capacity (Ah)

A = exponential zone amplitude (V)

B = exponential zone time constant inverse (Ah)-1.

C. Ultra-Capacitor Model

Ultra-capacitors are one of the latest innovations for storing energy especially for embedded systems. The UC electrical model is given in following Fig. 3. The model consists of a capacitance C_{UC} in series with an equivalent series resistance R_{UC} . UC voltage V_{UC} is given, as function of SC current I_{UC} by the following Eq. (5):

$$V_{UC} = V_1 - R_{UC} * I_{UC} = \frac{Q_{UC}}{C_{UC}} - R_{UC} * I_{UC} \tag{5}$$

Where Q_{UC} is the electricity quantity stored in a cell. Ultra-capacitor power is given by the Eq. (6).

$$P_{UC} = \frac{Q_{UC}}{C_{UC}} * I_{UC} - R_{UC} * I_{UC^2} \tag{6}$$

Using UC as a storage element which consisting of several cells which N_s cells are connected in series and N_p cells are connected in parallel. The capacity and the resistance of UC stack are defined respectively by Eq. (7) and (8).

$$C_{UC} = C_{elem}\frac{N_p}{N_s} \tag{7}$$

$$R_{UC} = R_{elem}\frac{N_s}{N_p} \tag{8}$$

The voltage and current of the stack are given, as function of the element voltage and the element current, by the following Eq. (9) and (10).

$$V_{UC} = N_S.V_{elem} \tag{9}$$

$$I_{UC} = N_p.I_{elem} \tag{10}$$

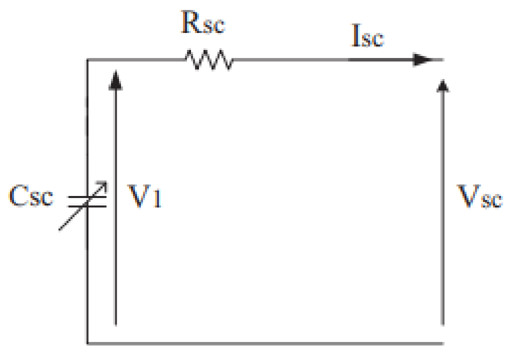

Fig. 3. Equivalent Model for Ultra-Capacitor

D. Vector Control of PMSM

Electric vehicles with the advantage of no pollution, low noise, zero-emission, high energy conversion efficiency, have become the trend of the automotive industry. The PMSM with its straightforward structure, little size, lightweight, little inactivity, high power thickness, is truly appropriate for the constrained space of EV; its high effectiveness, high power factor, torque to latency, solid over-burden limit, high yield torque particularly at low speed, which implies that the PMSM is likewise truly reasonable for the necessities of acceleration and starting. Hence i_d is normally zero in the constant torque mode. Consider three-phase currents which are mentioned in Eq. (11), (12) and (13).

$$i_a = i_s \sin\left(w_r t + \delta\right) \tag{11}$$

$$i_b = i_s \sin\left(w_r t + \delta - 2\pi/3\right) \tag{12}$$

$$i_c = i_s \sin\left(w_r t + \delta - 2\pi/3\right) \tag{13}$$

Where, $\theta_r = \omega_r t$, from phasor diagram we get Eq. (14) as:

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = i_s \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix} \tag{14}$$

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Where, i_q = Torque-producing component of stator current = i_T i_d = Flux-producing component of stator current = i_f , If we make $i_d = 0$ by δ = 90º then the electric torque Eq. (15) becomes:

$$T_e = \left(3/2\right)\left(P/2\right)\lambda_m i_q \quad (15)$$

From the Eq. (15), torque based on the quadrature axis current and constant torque is attainable by ensuring that i_d is constant. Vector control is in this way just conceivable when exact learning of the quick rotor transition is accessible. Henceforth it is essentially simpler in the PMSM than induction motor because the situation of the rotor motion is remarkably dictated by the locus of the PMSM.

V. RESULTS AND DISCUSSION

The simulation results of the proposed PSO-FLC methodology is performed using the MATLAB/SIMULINK. The analysis of hybrid sources in PHEV is made by two storage devices such as battery and ultra-capacitor. The type of battery used in this proposed methodology is Nickel Metal Hydride battery and PMSM is used as the HEV load. EV is a forthcoming solution to the issue of transportation and pollution. The proposed controller is utilized to perform charging/ discharging of the UC, it depends on battery's SOC. The specifications of the battery, UC and PMSM are given in Table 1, 2 and 3 respectively. HESS is simulated for a fixed load (i.e., PMSM motor) with the time duration of 200 seconds. The implementation of the proposed methodology is analysed in terms of SOC of the battery, torque and speed of the motor.

Table I. Specifications of the battery

Maximum capacity (Ah)	8.7231
Cut off voltage (V)	150
Fully Charged Voltage (V)	235.5932
Nominal discharge current (A)	1.62
Initial State of Charge (%)	100
Internal resistance (Ohms)	0.24691
Energy Capacity (Ah) at nominal voltage	7.7885
Exponential zone [Voltage (V), Capacity (Ah)]	216.9492, 1.62
Discharging current [i1, i2] (A)	50, 100
Volumetric energy density (Wh /L)	200 - 250

Table II. Specifications of the Ultra-capacitor

Resistances (Ohms) $\left[R_1, R_2, R_3\right]$	0.2, 90,100
Capacitances (F)	2.5, 1.5, 4
Voltage dependent capacitor gain	0.95
Initial Voltage (V)	16

Table III. Specifications of the PMSM motor of HEV

Voltage (V)	500
Power rating (KW)	50
Speed (rpm)	3500
Number of pole pairs	4
Stator phase resistance (ohm)	0.18
Armature inductance (H)	0.000835
Flux linkage	0.175666

While related with the existing system, this combination having very low cost and compact size with other operating features like better speed and voltage limit. Energy density, power density and efficiency increases with the help of above-mentioned ESS; similarly, inclusive price is also very less. The protection of battery and its cost is more significant since it directly comparative to the price of development and proficiency. If the vehicles weight rises at that time efficiency is reduced which increases the cost. The charging/discharging process has increased by using ultra-capacitor.

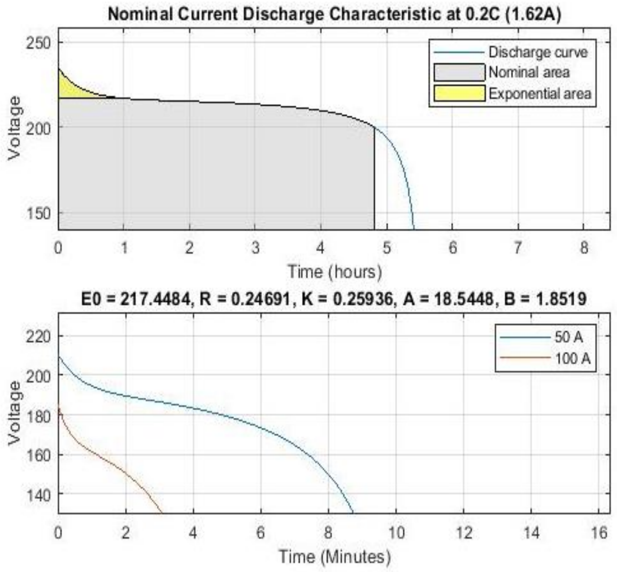

Fig. 4. Nominal current discharge characteristics

Fig. 4 shows the NiMH battery discharge characteristics of nominal current. Where, the constant voltage is E_o , the internal resistance is R; polarization current is K ; exponential voltage is A ; exponential capacity is B . The values of the E_0, R, K, A doubled as nominal voltage, when the B depends on the type of the battery.

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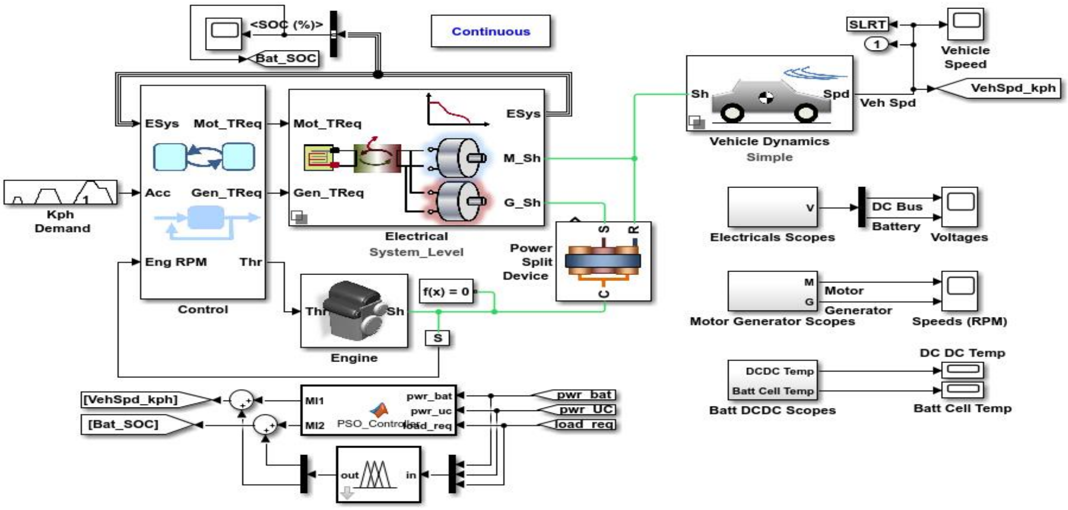

Fig. 5. Simulink model for the proposed methodology.

The Simulink model of the proposed methodology is given in Fig. 5. The major components of this model are Ni-MH battery, ultra-capacitor, HEV, and PSO-FLC controller. Initially, NiMH battery provides the essential energy to the HEV, because this NiMH battery is used as the main source.

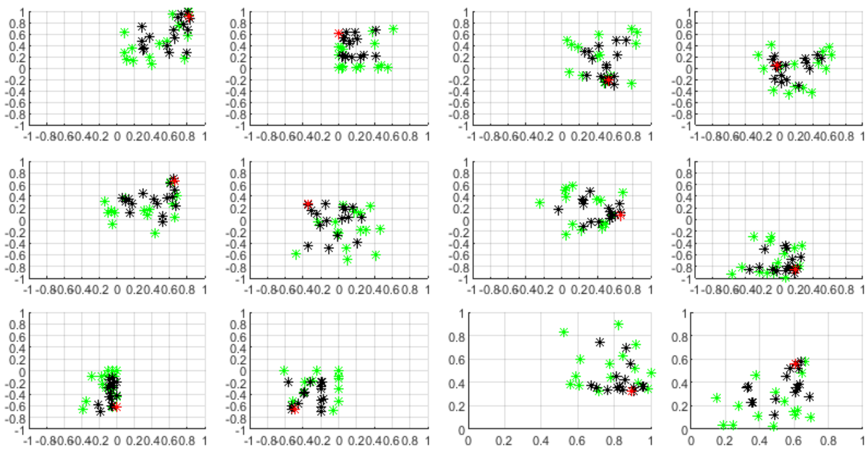

Fig. 6. Position of swarm particles.

From the Fig. 6, it is observed that the swarm particles are moved randomly accordingly with their number of iterations. If the particles find the best position and velocity until the iteration reaches its maximum count.

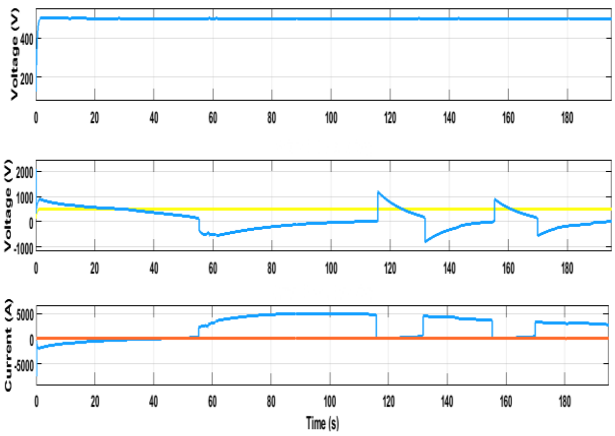

Fig. 7. Voltage and current of PMSM motor

Fig. 7 shows the voltage and current characteristics of motor and generation. From this figure, voltage level of boost converter is presented with a value of 500v. Also the current variations for the motor and generation mode is shown in the above figure.

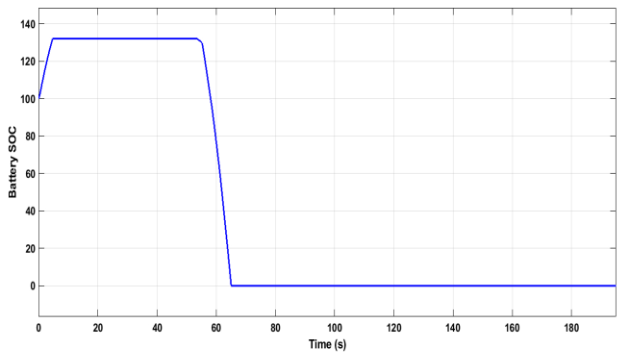

Fig. 8. SOC of Battery

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Fig. 8 shows the SOC of battery, when the EV with proposed PSO-FLC controller. The SOC estimation of the battery avoids unpredicted system interruption and prevent the batteries from being over charged and discharged, which may cause permanent damage to the internal arrangement of batteries. From Fig. 8, it concluded that battery SOC is improved when the controlled strategy managed the charging/discharging features of the UC. The lifetime of the proposed methodology is high compared to another controller. Fig. 8 shows battery's SOC goes to zero after 60 Sec. At that time, the ultra-capacitor is turned on by the PSO-FLC controller to provide the essential power to the EV. Ultra-capacitor's SOC is shown in the below Fig. 9.

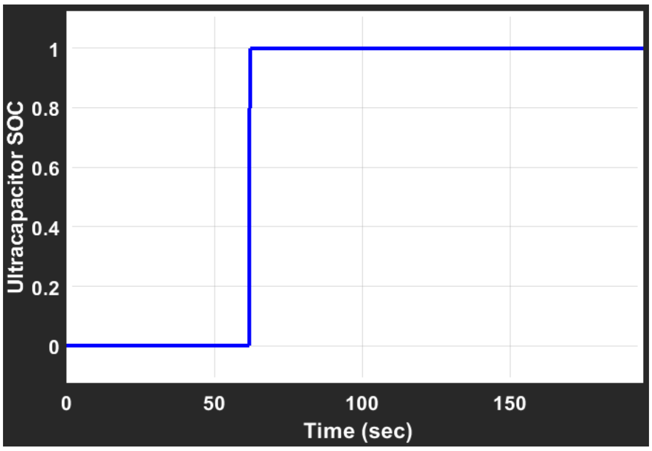

Fig. 9. SOC of Ultra-Capacitor

Fig. 10 shows the comparison of HEV motor speed with and without PSO-FLC controller. This motor speed describes the amount of the speed in RPM obtained from the engine of the PMSM motor. The value of the motor speed without control strategy is less compared to the HEV with proposed controller.

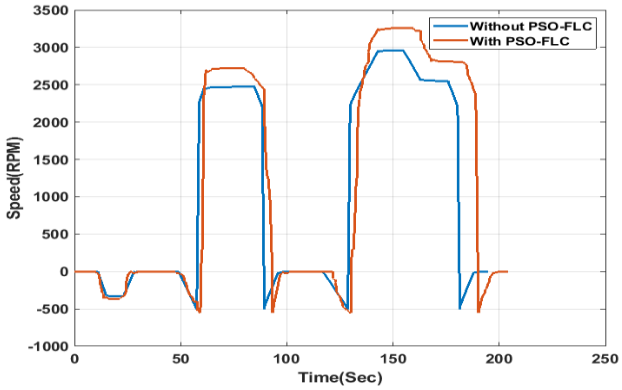

Fig. 10. Comparison of motor speed

Fig. 11 presents the vehicle's speed of HEV proposed PSO-FLC controller. The vehicle's speed describes the overall speed of the HEV which moves in real time. The vehicle's speed of the HEV with PSO-FLC controller is maximized when compared to the HEV with other techniques.

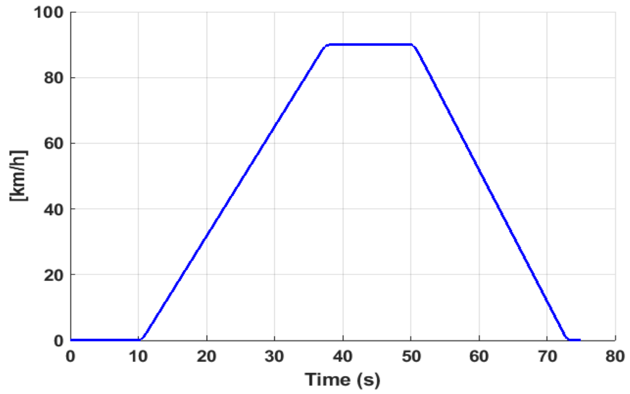

Fig. 11. Vehicle speed of PSO-FLC method

Table IV. Comparative analysis of vehicle speed

Methods	Vehicle's max speed (km/h)
Proposed PSO-FLC	85
ANN based HESS	64
Manhattan cycle [15]	40
UDDS cycle [15]	32

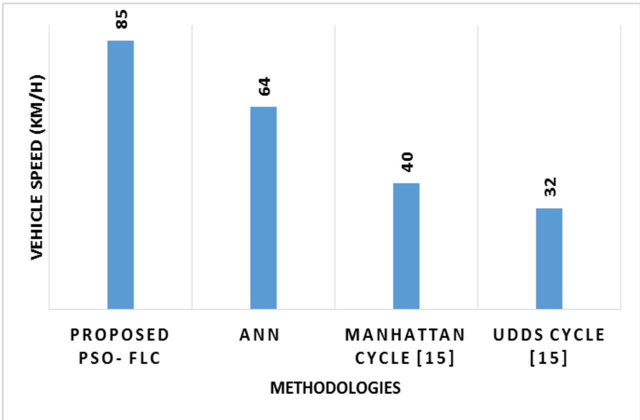

Fig. 12. Comparison Graph for Vehicle Speed

The vehicle speed of ANN-based HESS is compared with rule-based scheme [15]. It has analysed in two different cycles such as Manhattan cycle, UDDS cycle. The comparative analysis of ANN based HESS is given in the following Table 4 and Fig. 11. The proposed system is very small size equates with the existing method. Also this project having cost is very less and scope is more. From the above Fig. 12, it clearly shows that the proposed method attains the maximum vehicle speed of 85 (km/h) when compared with other existing techniques.

VI. CONCLUSION

This paper proposed an effective Energy Management System based on PSO-FLC algorithm for hybrid energy storage devices like battery and ultra-capacitor. In proposed EMS, the FLC is executed with the appropriate rule inference and the PSO algorithm is used for enhancing the membership functions of the FLC.

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This proposed methodology implemented in MATLAB Simulink and it attains the maximum speed of 85 km/hr. which is much better than existing methods. The obtained results from various analysis designate that the proposed EMS helps to produce more electric energy than the required energy to satisfy the load demand under different time variations and environmental conditions. Similarly, same process is utilized to the regenerating breaking mode to save the energy at the instance of vehicles slowdown where the energy will decrease. The battery lifetime increase by using ultra capacitor. In future work, the design of HRES will be improved by adding the additional backup system for storing the excess energy to avoid power losses.

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AUTHORS PROFILE

Mr. Nagesh B. K. completed B.E. from UBDT, Davangere, KUVEMPU University Karnataka . M.E from UVCE, Bangalore, BANGALORE University, Karnataka. Presently working as Associate Professor in the school of Electrical and Electronics Engineering, "REVA University", Bangalore Karnataka and persuing PhD., from VISVESVARAYA TECHNOLOGICAL UNIVERSITY, (VTU) Belagavi Karnataka.. His area of interests are Power Electronics, Electrical Machines, Electrical Vehicle Power Management and Control Engineering.

Dr. B. R. LakshmiKantha completed B.E and M.E. from Bangalore University, Bangalore, Karnataka State India. Ph.D. from VISVESVARAYA TECHNOLOGICAL UNIVERSITY (VTU), Belagavi Karnataka India. Presently working as Principal & Director at "Dayananda Sagar Academy of Technology & Management" since 2011.His area of interests includes FACTS controllers, application of FACTS controllers in Renewable Energy Systems, Power Electronics, Electrical Machines, and Electrical Vehicle Power Management System.

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