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An Effective Energy Management Strategy for Series-Parallel Hybrid Electric Vehicle using COOT bird Optimization Algorithm

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Abstract-The lack of fossil fuels and greenhouse gases effects has motivated car manufactures to introduce new generation hybrid electric vehicles. In this paper the COOT optimization algorithm is employed to search optimal controller gains in Electric Vehicles. The objective of optimization is to attain fuel economy, subjected to vehicle constraint. The Vehicle power split is done in such a way that at every moment, the net power demand on final drive is fulfilled by either the internal combustion engine alone, the motor alone or in combination. This series-parallel HEV addressed in this paper, has complex configuration. The operation modes create complications in controller design. Therefore, a MATLAB based simulation study was carried, to check the feasibility of COOT optimization in the controller design. The obtained results from 4 different drive cycles, shows that the fuel consumption of vehicle can be reduced by the optimization of controller parameters.

Keywords-Design optimization; fuel consumption; COOT optimization algorithm; hybrid electric vehicle
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1 Introduction

Presently, the new transportation medium such as Electric Vehicles (EVs), Hybrid electric vehicles (HEVs) and Plug-in Hybrid electric vehicles (PHEVs) clean, economical, efficient, and environment friendly. The HEVs offers a fuel-efficient solution that combines an electric motor-based drive train with the conventional Internal Combustion Engine (ICE) to reduce fuel consumption and vehicle emissions [1-3].

The researchers developed several mathematical and intelligent computational techniques for minimizing fuel consumption. Seshadev Debata *et.al* [4] developed Suffered Frog Leaping Algorithm (SFLA) with ANN for solution of Energy Management (EM) problem in HEV. Further, Hybrid PSO such as PSO-DE and PSO-QE [5] has been used to solve the EM problem in a HEV here fuel rate and consumption has been represented in terms of binary storage power and driving cycle of the HEV the simulation was based on a Ford 43v power net unit 2001.

The electric vehicles designed by Hajer Marzougui *et al* [6]. In this work three control strategies has been applied like fuzzy logic control, fitness control and rule based algorithm to split the energy flow between the three sources and minimizes the fuel economy. A Breath First Search (BFS) with DP algorithm [7] was been applied to reduce the fuel consumption. This was followed by PSO and Simulated Annealing (SA) [8] to provide energy organization strategy.

Adaptive equivalent minimal fuel consumption strategy has been developed for improving the capabilities of energy storage and emission minimization in a PHEV [9]. The MATLAB and cruise software are used to simulate the PHEV. The same problem was analyzed using fuzzy adaptive equivalent consumption minimization strategy [10. This approach minimizes the fuel consumption under different driving cycle. Then Type-1 and type-2 Fuzzy logic controller [11] has been applied in hybrid electric autonomous vehicles for energy management. Initially type-1 was used to determine the uncertainties of driving conditions type-2 fuzzy logic control optimize the HEV variables and determines fuel consumption management of autonomous HEVs.

A chaotic non-dominated sorting GA has been projected to solve fuzzy EM optimization problem in a parallel HEV [12]. A fuzzy logic was used to reduce the fuel consumption and manage the energy economy of parallel HEV. Non-dominated GA tuned membership functions was used to reduce the emission of HC, CO_X and NO_X of the HEV.

In Reference [13] a dynamic programming with rule based supervisory control has been applied in EM problem to reduce the fuel consumption and wheel slip simultaneously. The applied methodology reduces 16% fuel consumption and 12% wheel slip then the conventional methods. Similar to this, reference 14 compares four optimization algorithms such as DIRECT, SA, GA and PSO [14] to minimize the fuel economy of the HEV. PSAT simulation model has been considered to check the performance of projected algorithms. Among these four algorithms DIRECT and SA methods provides than the GA and PSO algorithms.

Grey wolf optimizer [15] has been introduced to reduce the CO_2 emission of the HEV. This method properly splits the power to the HEV and control the state of charge of battery. PMC controller [16] based power split HEV model has been developed to improve the Energy Management. The applied PMC controller shows a noticeable improvement in fuel consumption of HEV. The PSAT software has been considered to testing the proposed model.

Genetic Algorithm [17] was applied to optimize the HEV power train to reduce the fuel consumption. GA optimizes the power train components of super capacitors. The vehicle Quasy-Static-Simulator (QSS) combined with city highway drive cycle was considered for design purpose.

This paper presents COOT bird optimization tool for the solution of energy management of series-parallel HEV. The prime objective of the work is optimally split the power and minimize the fuel consumption of the HEV and considering various standard operating constraints. The control parameters of projected COOT algorithm effectively optimize the HEV variables and highly reduce the fuel economy of the proposed model. in MATLAB and then we used a trial method to adjust the controller gains. In the next step the COOT bird algorithm is used to estimate the controller gains with the objective of fuel economy.

2 Series-Parallel HEV Modeling

The SPHEV can work in three modes like, series hybrid mode, electric mode and parallel mode. Figure 1 shows the major blocks of a SPHEV and its various states based on SOC.

As in figure 1 an external charger may power the battery when vehicle is in rest. The major simulation parameters for the vehicle and generator are given in Appendix table 8 and 9. In this investigation the mass and tire related data where assumed to constant. Perhaps, these may be altered to suit various passenger comforts and road conditions.

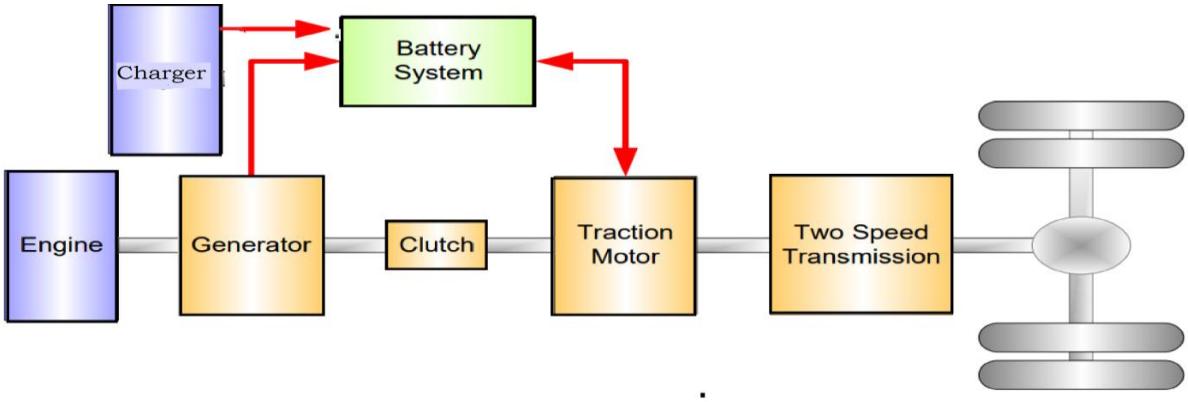

Fig. 1. Configuration of Series-parallel HEV

2.1 Mathematical Modeling

This section presents the formulas used to calculate individual force terms and the net traction effort. Perhaps, a simple MATLAB script was used to implement this task and it's described below. The Rolling resistance F_r created mainly due to the vehicle tyres and mildly from the bearing parts. The equation for this is,

$$F_r = mgC_r \tag{1}$$

The next term the aerodynamic component is given by,

$$F_d = \frac{1}{2}\,\rho\, C_d A U^2 \tag{2}$$

, Then the force needed when vehicle moves up a slope needs to the calculated. This is the called the Hill climbing force (3).

$$F_h = m\ g \sin\beta \tag{3}$$

$$F_{al} + F_{a\omega} = 1.05\ Ma \tag{4}$$

Then the overall tractive effort,

$$F_t = F_r + F_d + F_h + F_{al} + F_{a\omega} \tag{5}$$

The storage power defines as

$$P_{sm} = \frac{F_T U}{\eta} \tag{6}$$

$$P_{sreg} = F_t U \eta \tag{7}$$

$$\eta = \eta_t \eta_m \eta_i \eta_c \tag{8}$$

2.2 Drive Cycles

The Driving cycle data is an array of velocity with respect to time. In this work 4 urban cycles, combined high-way drive cycles were used to test the effectiveness of COOT optimization. Two different drive cycle patterns were used in this study; the Urban drive cycle and FTP-75(Federal Test Procedure). The objective function in equation (9), proposed by wipke et al., 2001 is used in this work.

$$\text{Composite fuel economy} = \frac{1}{\left(\frac{0.55}{\text{urban}}\right)+\left(\frac{0.45}{\text{Highway}}\right)}$$

(9)

The standard constrains are

$Pm_{min} <= Pm <= Pm_{max}$ (10)
$Pe_{min} <= Pe <= Pe_{max}$ (11)
$Pb_{min} <= Pb <= Pb_{max}$ (12)

These constraints can be translated to time-varying bounds on Ps. combining those leads to one lower and upper bound for Ps at each time instant:

$$Ps_{min} <= Ps <= Ps_{max} \tag{13}$$

The PID controller block present in the EMS of HEV is tuned to achieve minimum fuel consumption. To make it simple, diesel engine pollutant emissions are not considered in this study. As with figure 4, to achieve acceleration from (0 km/h) to (50 km/h) in 150 seconds the PI controller is used.

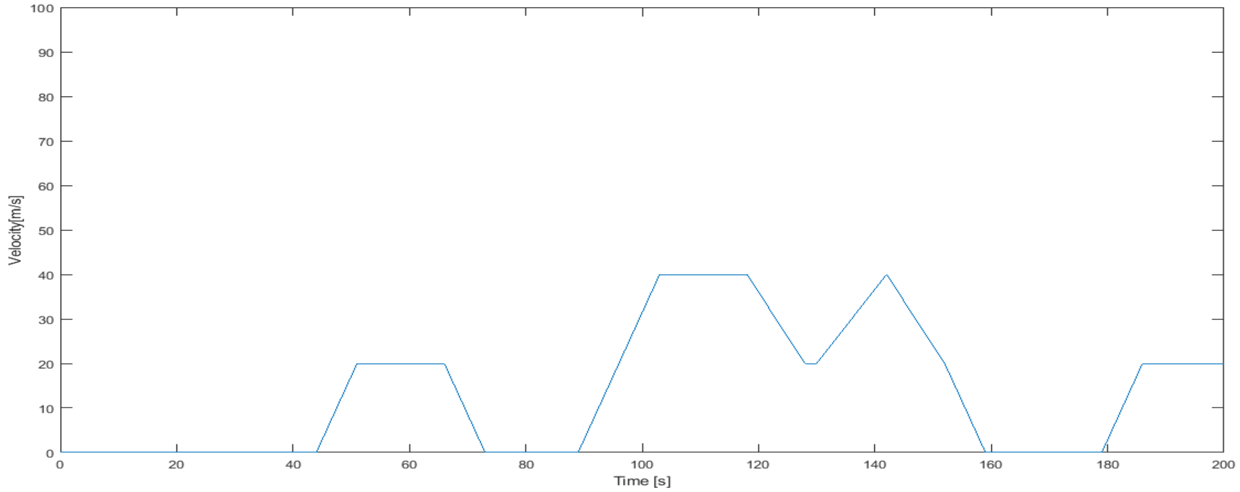

Fig. 2. Urban drive cycle

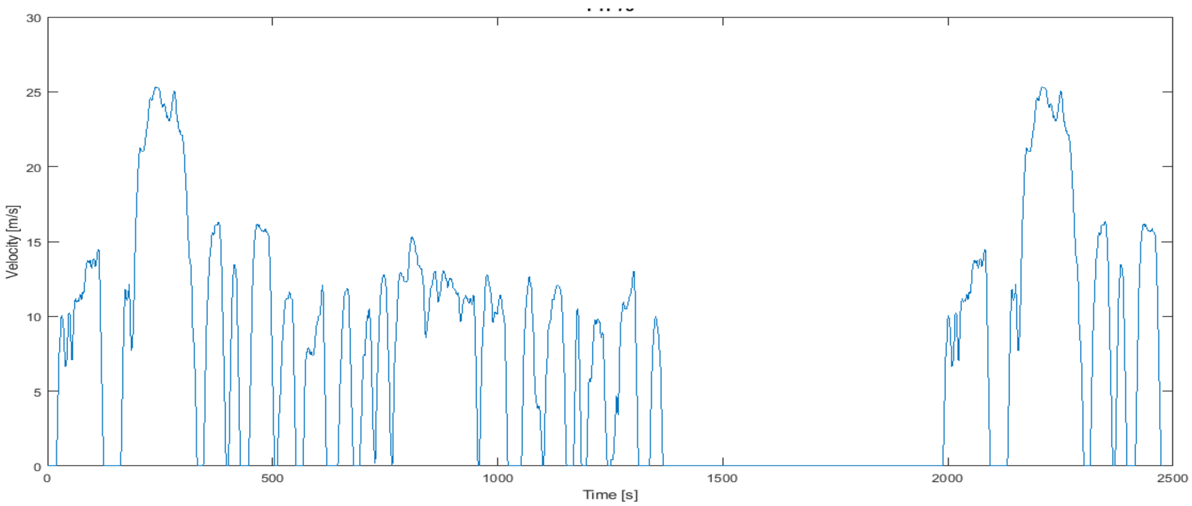

Fig. 3. FTP-75 Drive cycle

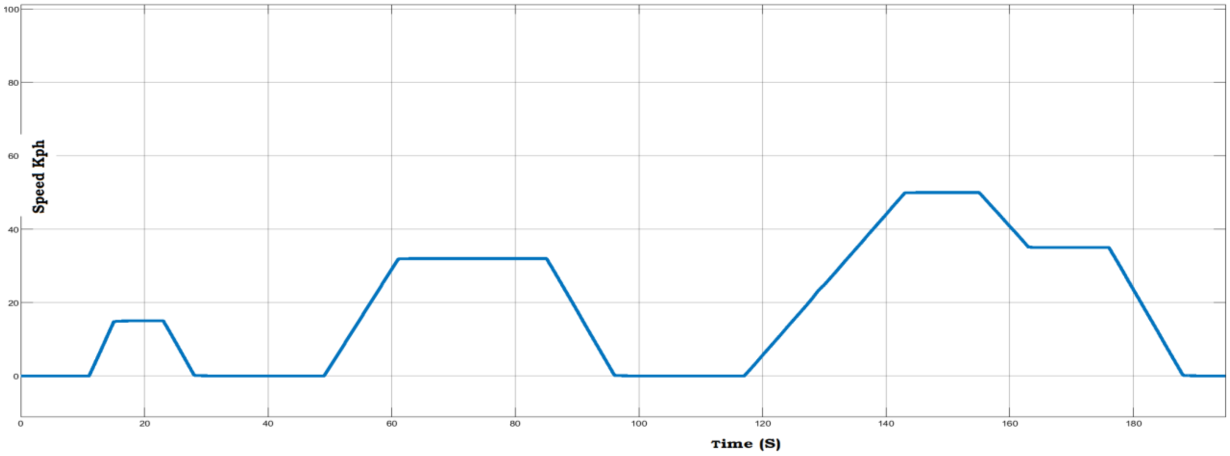

Fig. 4. Vehicle Acceleration

2.3 Series-parallel Hybrid Controller Logic

The Hybrid controller that is used is a rule-based controller. The energy management system will only use current and past vehicle states and driver commands to calculate a near optimal control signal. The design analysis starts from interpreting the driver pedal signal as a power demand. According to this power demand, the operation of this controller is divided into three modes, braking control, power split control and charging control. Further battery status monitoring assures that SOC stays within preset lower (SOC_{min}) and upper (SOC_{max}) bounds. This allows efficient battery operation as well as prevents battery depletion or damage.

The switching from IC engine to Electric Motor, generator mode and breaking mode are modeled by state machine (Figure 5). The state machine cycle carried out in MATLAB, can be directly realized in hardware. The operating modes are selected by the state machine, based on the following set of rules: The Controller state machine diagram Shone in fig. 6.

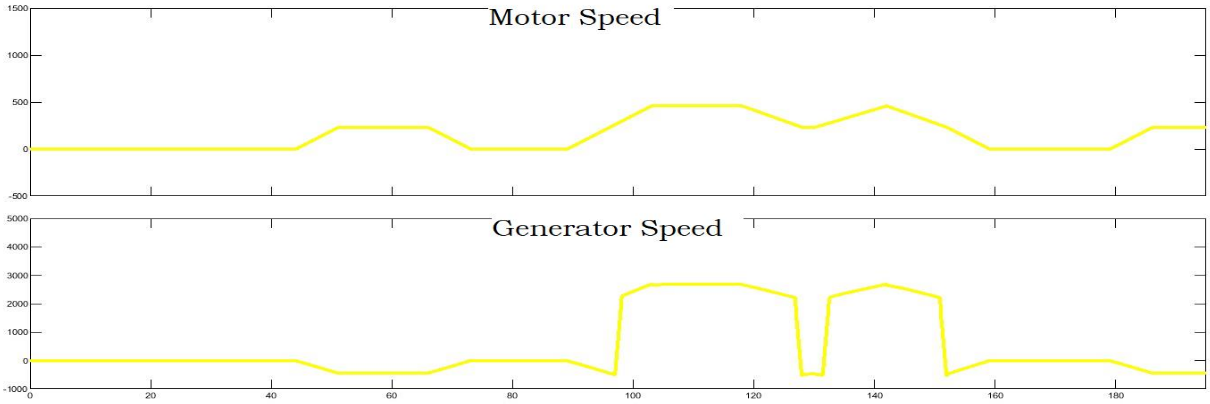

Fig. 5. Motor generator Speed Variations for Drive cycle -1

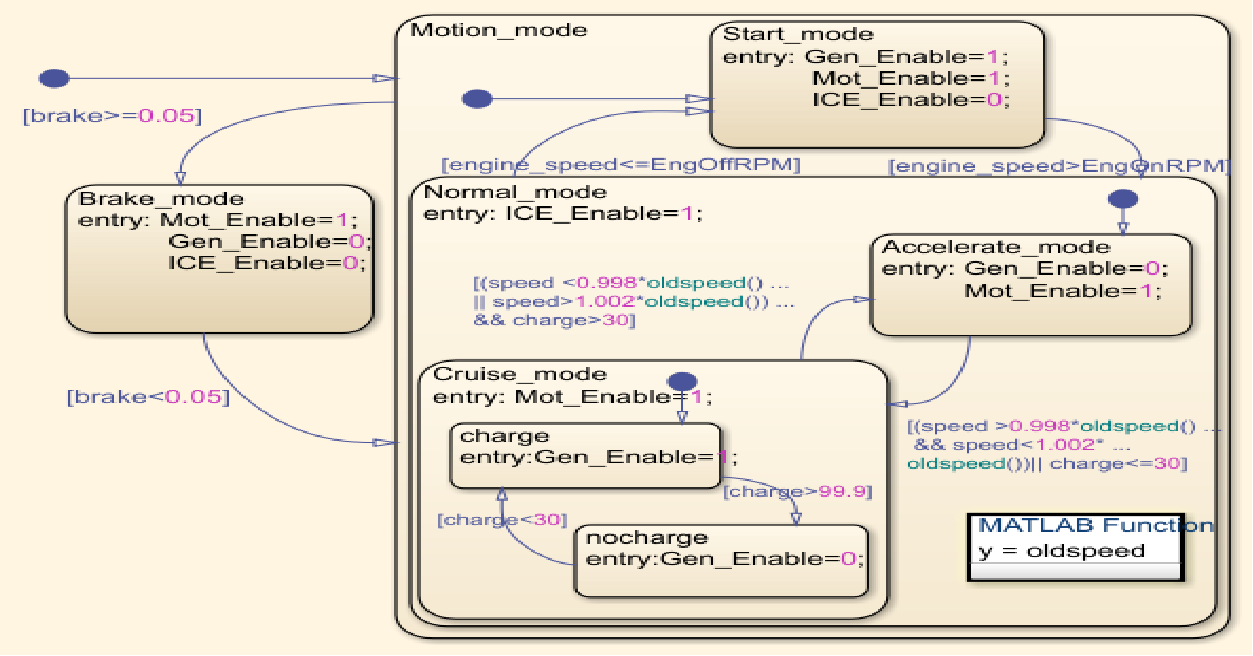

Fig. 6. Controller state machine diagram

3 COOT Bird Optimization (CBO) Algorithm

The Coot Bird Optimization (CBO) algorithm is inspired from natural behavior of different movements of coot birds on the water surface. It is a new and efficient meta-heuristic optimization algorithm and developed by Naruei I, *et.al*. in 2021..

The characteristics of the Coot birds on the water surface, which are represented as follows,

- Random movement
- Chain movement
- Adjusting the position based on the group leaders
- Leader Movement

The population of the coot is randomly generated and mathematically represented using the equation (14).

$$\mathrm{CootPos}(i) = \mathrm{rand}(1, d).* (\mathrm{ub} - \mathrm{lb}) + \mathrm{lb}$$
(14)

Where,

CootPos(i) is the coot position,
d the number of variables or problem dimensions,
lb is the lower bound of the search space and
ub is the upper bound of the search space

The lower and upper bound are defined as follows
$\mathrm{lb} = [\mathrm{lb}_1, \mathrm{lb}_2, \ldots, \mathrm{lb}_d], \mathrm{ub} = [\mathrm{ub}_1, \mathrm{ub}_2, \ldots, \mathrm{ub}_d]$
(15)

3.1 Random movement

The random movements of the coot birds at position Q are mathematically defend using equation (16).

$$Q = \mathrm{rand}(1, d).* (\mathrm{ub} - \mathrm{lb}) + \mathrm{lb} \qquad (16)$$

In order to keep away from a local optimum solution, updates the position of the coot using equation (17)

$$\mathrm{CootPos}(i) = \mathrm{CootPos}(i) + A \times R2 \times \left(Q - \mathrm{CootPos}(i)\right) \quad (17)$$

Where,
R2 is a random number in the interval [0, 1], A is determined using equation (18).

$$A = 1 - L \times \left(\frac{1}{\mathrm{iter}}\right) \qquad (18)$$

Where,
L is current iteration, Iter is maximum iteration

.

3.2 Chain movement

The chain movement may be represented by average position of two coot birds which is represented as

$$\mathrm{CootPos}(i) = 0.5 \times \left(\mathrm{CootPos}(i-1) + \mathrm{CootPos}(i)\right) \quad (19)$$

.

3.3 Adjusting the position based on the group leaders

. The leader is selected using equation (20).

$$K = 1 + (i\mathrm{MOD}\ NL) \qquad (20)$$

The next position of the coot based on the selected leader is premeditated using the equation (22)

$$\mathrm{CootPos}(i) = \mathrm{LeaderPos}(k) + 2 \times R1 \times \cos(2R\pi) \times \left(\mathrm{LeaderPos}(k) - \mathrm{CootPos}(i)\right) \quad (21)$$

3.4 Leader Movement

The leader must mathematically defines as

$$\mathrm{LeaderPos}(i) = \begin{cases} B \times R3 \times \cos\left(2R\pi \times \left(\mathrm{gBest} - \mathrm{LeaderPos}(i)\right) + \mathrm{gBest} & R4 < 0.5 \\ B \times R3 \times \cos\left(2R\pi \times \left(\mathrm{gBest} - \mathrm{LeaderPos}(i)\right) - \mathrm{gBest} & R4 \geq 0.5 \end{cases} \quad (22)$$

B is calculated using the equation (23)

$$B = 2 - L \times \left(\frac{1}{\mathrm{Iter}}\right) \qquad (23)$$

4 Electric Vehicle System Simulations

4.1 Battery Modeling

In this research a generic battery model is simulated as in fig 7. The parameters for the same are presented in table 1. In these batteries, it can be observed that the energy storage system charging lies between 90% and 100% and discharging efficiency lies between 80% and 90% all the time except the idle time of the driving cycle

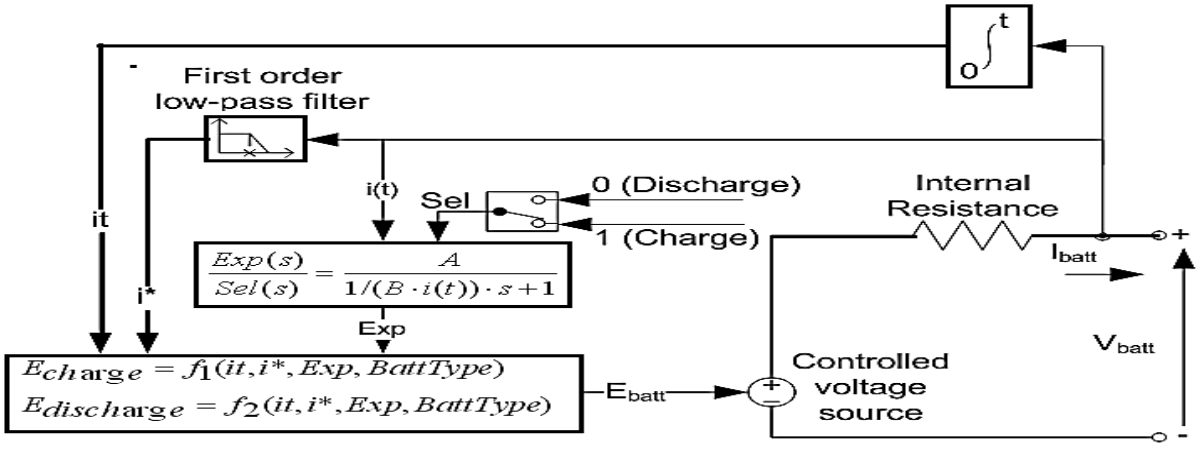

Fig. 7. Generic Battery Model

Table 1. Battery parameters

S.No	Battery parameters	Value
1	Nominal Voltage (V)	217
2	Internal Resistance (ohms)	0.2461
3	Rated Capacity (Ampere-hours)	6.9
4	Initial Charge	6.9
5	Expn Voltage (V)	215
6	Expn Charge	2.3
7	C1 Capacitance	2500
8	C1 Initial Voltage	19
9	C1 series resistance (ohms)	1e-6
10	R2 (ohms)	0.3
11	R1 (ohms)	1.8
12	Rated capacity	6.9

4.2 Electric Motor

The PMSM is selected in this article, due to its popularity in EV applications. The PMSM (Table 2) offers a high density, efficiency and provides a sinusoidal EMF. The electrical motor is a 500V DC, 40 kW interior PMSM with the related drive. This motor has 8 pole and the magnets are buried, i.e., salient rotor's type. The Control part of PMSM is a vector controller, wherein the torque demand was defined based on difference between reference and actual speed of rotor. The torque demand was transformed into set values for *d* and *q* currents using vector control. The current commands, torque, and other variables were controlled to stay at realistic levels. For the PMSM a PI loop controls the motor speed. With reference to figure 8, the maximum value for V_w_{ref} is 5 volts, which is equivalent to a speed demand of 6500rpm.

In a Synchronous PM drive requires a control algorithm, when flux-weakening is needed. This is achieved by making the d-axis component as zero. Again, for speeds above the field weakening, the maximum q-axis current was limited to constant power output. Perhaps, some recent issue of the rare-earth magnets price volatility has seriously questioned the adoption of Permanent Magnet motor drives [18].

Table 2. Motor parameters

S.No	Parameter	Value
1	Nominal Voltage	500 V
2	Rated capacity	40KW
3	Series Resistance	0.02
4	Internal Resistance	0.246
5	Speed	6500rpm

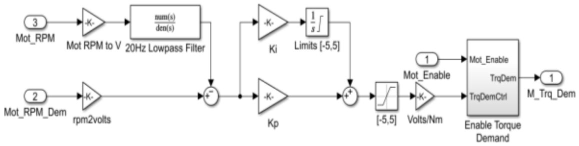

Fig. 8. Motor PI control loop

From Table 3 to 6 it’s obvious, that the four parameters optimized by coot optimization provide reduced fuel consumption. Again, the algorithm also searches the gain values within the stability limits of the control

Table 3. Fuel Consumption

S.No	Test Case 1 urban drive cycle 1	Value
1	Fuel Consumption in Liters - Without Optimization	3.29
2	Fuel Consumption in Liters - With Optimization	2.77
3	D.C to D.C converter Kp	1.2
4	D.C to D.C converter KI	0.11

5	Vehicle Speed Controller Kp	1.68
6	Vehicle Speed Controller Ki	1.85

Table 4. fuel Consumption

S.No	Test Case 2 urban drive cycle 2	Value
1	Fuel Consumption in Liters - Without Optimization	3.83
2	Fuel Consumption in Liters - With Optimization	3.19
3	D.C to D.C converter Kp	1.510
4	D.C to D.C converter KI	0.335
5	Vehicle Speed Controller Kp	1.217
6	Vehicle Speed Controller Ki	0.01

Table 5. Fuel Consumption

S.No	Test Case 3 urban drive cycle 3	Value
1	Fuel Consumption in Liters Without Optimization	3.83
2	Fuel Consumption in Liters With Optimization	3.12
3	D.C to D.C converter Kp	1.37
4	D.C to D.C converter Ki	0.6040
5	Vehicle Speed Controller Kp	1.3183
6	Vehicle Speed Controller Ki	0.3219

Table 6. Fuel Consumption

S.No	Test Case 4 urban drive cycle 4	Value
1	Fuel Consumption in Liters Without Optimization	3.0
2	Fuel Consumption in Liters with Optimization	2.56
3	D.C to D.C converter Kp	0.01
4	D.C to D.C converter Ki	0.560
5	Vehicle Speed Controller Kp	0.01
6	Vehicle Speed Controller Ki	0.01

4.3 D.C to D.C converter Temperature Rise

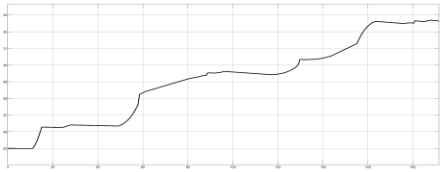

Fig. 9. Temperature in D.C to D.C converter

Table 7. IC Engine parameters

S.No	Parameter	Value
1	Shaft Inertia	0.25
2	Power	112 Hp
3	Rated Engine RPM	5000
4	IC engine speed sensor constant	0.2079

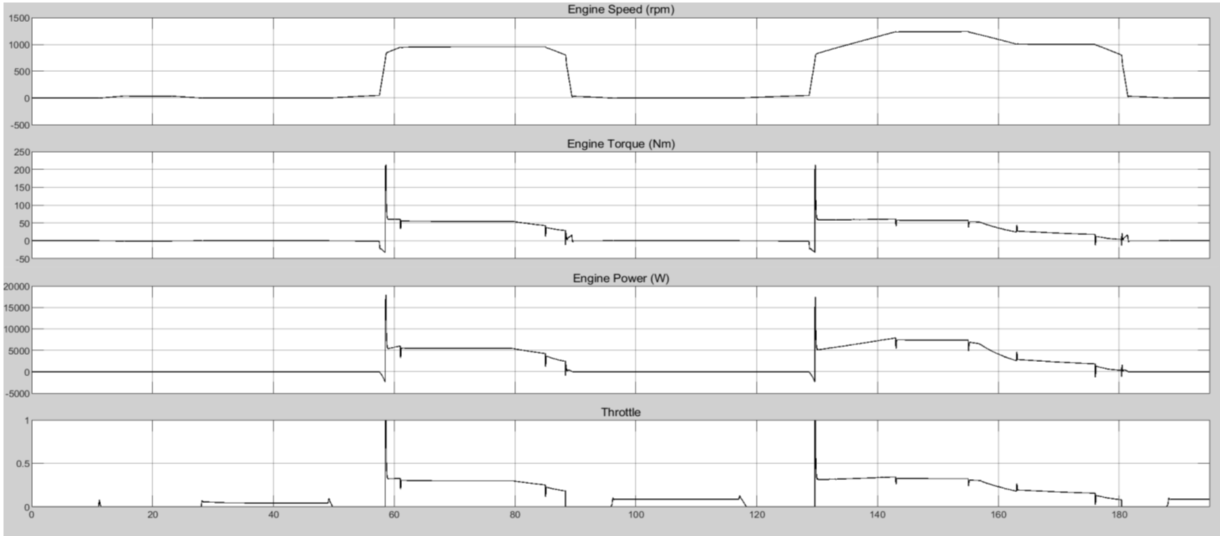

Fig. 10. IC Engine Plots for urban drive cycle

The Battery management system maintains State-Of-Charge (SOC) between 40 and 80%. Also, it prevents against voltage collapse by controlling the power required from the battery. The charging of the battery is achieved by the D.C to D.C converter and its efficiency is assumed to be 90 percent. The switching frequency of step-down converter fs was constant at 10 KHz. The safe working of power converter can be assured by measurement of its temperature raise. As in figure 9, the temperature of the converter circuit is maintained below 35 degree, for the complete cycle, to ensure safe operation. To achieve this output ripple needs to be adjusted by the proper selection of external compensation. In this work the external capacitor was selected as 1000 Micro farad. Again, the converter duty cycle can be varied between 20 to 40 percentage from their reference, their by the battery charging voltage can be adjusted.

The major element of HEV is the ICE engine, very similar to those of a traditional engine (Table 7). Perhaps, engines used in an HEV are typically smaller than a conventional vehicle of the same size. The size selected will depend on the total power needs of the vehicle. In figure 10, the throttle input signal lies between zero and one. This gives the torque demanded from engine as a fraction of the maximum possible torque. This signal also indirectly controls the engine speed; this model does not include air-fuel combustion dynamics.

5 Conclusion

The electric vehicles are pollution free and silent, and hence prove to be pure eco-friendly vehicles. This article introduced a method for optimizing a series-parallel HEV controller used in power management. The power demand from the pedal position is split between two power sources to obtain better fuel economy. Using the Optimized controller parameters, we have demonstrated that a HEV can make a good fuel economy compared to manual controller tuning. Further research in this topic will be to append the motor loss models and emission constraints.

Appendix A

Table 8. Generator parameters

S.No	Parameter	Value
1	Stator Resistance	0.005
2	Inductance	0.0006
3	Shaft Inertia	0.02
4	Series Resistance	0.01

Table 9. Vehicle parameters

S.No	Parameter	Value
1	Mass (kg)	1200
2	Radius (m)	0.3
3	Wheel Inertia	0.1

4	Aero Drag Co-efficient	0.26
5	Engine Vehicle gear ratio	1:3
6	Tire Rated Vertical Load (N)	3000
7	Rated Peak Long Force (N)	3500
8	Slip %	6

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