



PLUG IN HYBRID ELECTRIC VEHICLE ENERGY MANAGEMENT DESIGN USING DISCRETE BAT ALGORITHM

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ABSTRACT

This paper presents an energy management for improved battery state of charge (SOC) in Plug-In-Hybrid Electric Vehicle (PHEV). Due to the on-board charging requirement of PHEV engine and generator a means for optimal charging of the battery SOC becomes necessary. This requirement is viewed as an optimal solution of maintaining the best possible battery SOC for the hybrid electric vehicles (HEV). Inline with this, this paper presents a Discrete Bat Algorithm (DBA) based optimal battery SOC maintenance. The results obtained using the DBA was compared with that of Evolutionary Algorithms (EA). DBA recorded a computational time of 694.6767s while that of EA is 711.4752s under the same traffic data. The DBA record a fuel consumption of about 2.4182% decrease when compared to that of EA under same condition. DBA based EMS presented an average power of 25kW which is 83.33% of the battery power capacity. The SOC of the PHEV operating modes which serves as an indicator between the minimum and maximum value has a battery charge ranging from 4Ah to 10.25Ah when compared with EA with the values of 3Ah and 14Ah. The developed model outperforms the existing model in terms of battery power, SOC and fuel consumption thus making it most efficient in energy management.

1. INTRODUCTION

Efficient means of transportation is a major driver of economic growth and societal development. A large share of mobility relies on passenger car and the use of the passenger car is expected to continue increasing especially in developing countries. Today, transport is almost exclusively dominated by internal combustion vehicles with approximately 95 % of transport reliant upon liquid carbon fuels derived from crude oil [1]. There is no other sector which shows such a high level of dependence on one single source of primary energy [2]. Between 1990 and 2006, greenhouse gas (GHG) emissions from overall transport (including international aviation and marine) in European Union-27 (EU-27) has increased by 35.8% while emissions from non-transport sectors have decreased by 13.4% over the same period [3]. Road emissions in

EU-27 have actually contributed to 61% of transport emissions increase and accounted for about 71% of overall transport emissions in 2006 [4]. Besides, international aviation and marine have shown the fastest growth over the same period by 73%, and weighted 23.5% of overall transport emissions in 2006 [5]. Over the past decade, electric vehicles have emerged as a potential solution to the growing fossil fuel dependence, as well as a means of drastically reducing the man-made pollutants in the environment [6]. Plug-In Hybrid Electric Vehicles (PHEVs) contains both an internal combustion engine (ICE) and an on-board battery, designed to power the vehicle [7]. PHEVs provide a solution to pollution, there are pros and cons of switching to the contemporary technology [8]. To estimate how a fleet of PHEVs will affect the electric grid, the energy

and power requirements of PHEVs must be known. Current and ideal battery standards for PHEVs are presented as well. At the 2007 Sustainability, the Future of Transportation conference, National Renewable Energy Laboratory (NREL) gave a presentation that outlined the current and future goals for PHEV batteries [9]. The effect of PHEVs on greenhouse emissions is complex. Plug-in hybrid vehicles operating on [all-electric mode](#) do not emit harmful [tailpipe pollutants](#) from the onboard source of power. The clean air benefit is usually local because depending on the source of the electricity used to recharge the batteries, air pollutant emissions are shifted to the location of the generation plants. PHEVs do not emit [greenhouse gases](#) from the onboard source of power, but from the point of view of a [well-to-wheel assessment](#), the extent of the benefit also depends on the fuel and technology used for [electricity generation](#). From the perspective of a full [life cycle analysis](#), the electricity used to recharge the batteries must be generated from renewable or clean sources such as [wind](#), [solar](#), [hydroelectric](#), or [nuclear power](#) for PHEVs to have almost none or zero well-to-wheel emissions. However, when PHEVs are recharged from [coal](#)-fired plants, they usually produce slightly more greenhouse gas emissions than [internal combustion engine](#) vehicles. When operating in PHEV mode with assistance of the internal combustion engine, tailpipe and greenhouse emissions are lower in comparison to conventional cars. However previous research works on evolutionary algorithm based online energy management system for PHEVs did not considered the algorithm as discrete in nature, while discrete optimization (combinatorial optimization) has shown

that DBA is a promising swarm intelligence technique which can be used to optimally determine the fuel consumption of the PHEV.

2. LITERATURE REVIEW

This section discourse some of the previous effort made by researchers on HEV energy management. Lin, et al. [10] developed an Optimal Energy Management Scheme for a PHEV Real-time controller. A specific model was established which contains most of the powertrain properties and partly vehicle dynamics, an optimal control problem with inequality constraints is analyzed and formulated mathematically, then the particle swarm optimization (PSO) is applied to search for global near-optimum at each time interval. The neural network is designed to get sub-optimal real-time controller by employing the near-optimal results obtained from aforementioned PSO. The results were obtained from Powertrain System Analysis Toolkit (PSAT). Moura, et al. [11] proposed a stochastic optimal approach for power management in PHEV to optimally split the driver power demand among different actuators. The work used stochastic dynamic programming to optimize PHEV power management over distribution of driving cycle. It also adds an explicit made off fuel and electric usage in PHEV. Finally, the work examines the impact of variation on relative fuel-to-electricity pricing on optimal PHEV power management. Wirasingha and Emadi [12] proposed a Classification and Review of Control Strategies for PHEVs to reduce fuel consumption and emissions. The work employed the use of rule base control strategy and shows a systematic process of optimization when designing a controller for PHEVs.

Tribioli and Onori [13], analysed the energy management strategies in PHEVs: application to the GM Chevrolet Volt was presented. The work also compared the performances of fuel economy in two energy management strategies developed for the GM Chevrolet Volt vehicle. First, an optimal control strategy based on Pontryagin's Minimum Principle (PMP) was developed and implemented on the first PHEV in the mainstream market. A benchmark for fuel consumption evaluation to assess the Charge Depleting-Charge Sustaining (CD-CS) model used today on-board of the vehicle. However, a comparison was also made based on the powertrain modes of operation under the optimal and CDCS scenarios. This showed a significant difference in the use of the powertrain in the two cases and analysis of the operating points. Vajedi, et al. [14] presented a comparative analysis of route-based power management strategies for real-time application in plug-in hybrid electric vehicles. The works compared two outstanding optimal route-based control approaches: model predictive control (MPC) and adaptive equivalent consumption minimization strategy (A-ECMS), for different levels of trip information and evaluated the performance of the two strategies by using Toyota Prius Plug-in Hybrid high fidelity model in Autonomies software. The simulations were done for different levels of trip information. However, it was concluded that the result obtained from MPC and A-ECMS strategies are close with each level of trip information or without any information about the future driving condition, manual CDCS strategy has the less performance and the fuel efficiency is not close to near optimal which cause more emission.

In view of the problems associated with the influence of air pollution and climate changes which associated with the fossils have given a fundamental reason for the electrification of transport system. Energy Management System (EMS) for Plug-in Hybrid Electric Vehicle (PHEV) are employed. Due to high depletion rate of PHEV energy, there is need to develop an EMS to control the state of charge of the battery in order to maintain its optimality. This paper employed a discrete bat algorithm for this purpose.

3. METHODOLOGY

This section presents the detail method used in implementing the idea presented in this paper.

3.1 Battery Modelling

The battery was modeled using a controlled voltage source (CVS) in series with a constant internal resistor R_b and open circuit voltage source V_{oc} as shown in Figure.1

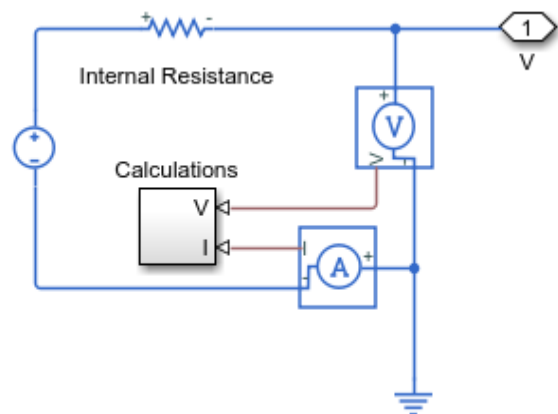


Figure 1 : Simulink Diagram Model of Battery

The model assumes the same characteristic for the charge and the discharge cycles that produce

electrical energy. The open circuit voltage was calculated with nonlinear equation based on the actual state of charge (SOC) of the battery.

3.2 DC-DC Converter

The DC-DC Converter was modelled using ideal dc-dc voltage converter as shown in the Simulink diagram shown in Figure 2.

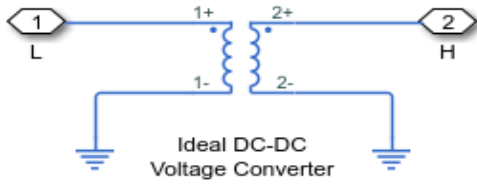


Figure 2: Simulink Diagram of the DC-DC Converter

Figure 2 shows the Simulink block of the DC-DC Converter. It is seen that as the supercapacitor's module to the DC-link. This converts the direct current from one voltage to another, by storing the input energy temporarily then releasing that energy to the output at a different voltage.

3.3 Vehicle Body

The Simulink representation of the vehicle body was modelled with different sub modelled tire of the PHEV, and this is shown in Figure 3.

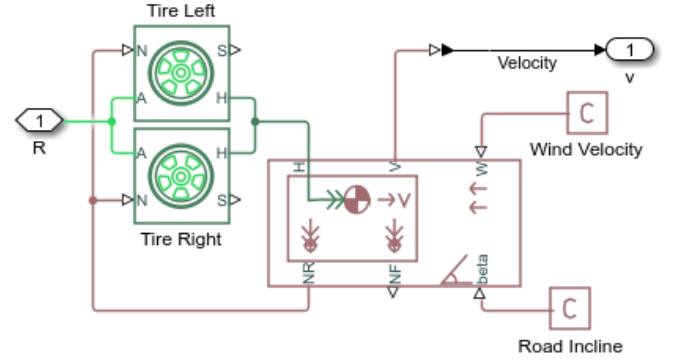


Figure 3: Simulink Model of the Vehicle Body

From Figure 3, it shows that the vehicle model is composed of two left and right tires, which are fed to the input of the vehicle stirring, and an input of wind velocity and road inclination. Finally, an output is being sensed as the velocity, which is been read at the speedometer of the vehicle.

3.4 Determination of SOC Constraint

The SOC constraint was determined from minimum to maximum level at 3Ah and 14Ah, respectively. The engine power was discretized and reformulate the optimization problem as given in equation (1)

$$\left\{ \begin{array}{l} \min \left\{ \int_0^T h(\omega_e, q_e, t) dt \right\} \\ \text{subject to :} \\ \text{soc} = f(\text{SOC}, \omega_{MG1}, \omega_{MG2}, q_{MG2}) \\ (\omega_e, q_e) = g(\omega_{MG1}, q_{MG1}, \omega_{MG2}, q_{MG2}) \\ \text{SOC}_{\min} \leq \text{SOC} \leq \text{SOC}_{\max} \\ \omega_{\min} \leq \omega_e \leq \omega_{\max} \\ q_{\min} \leq q_e \leq q_{\max} \end{array} \right\} \quad (1)$$

where T is the trip duration; ω_e , q_e are the engine's angular velocity and engine's torque, respectively; $h_{\omega_e, T q_e}$ is ICE fuel consumption model; ω_{MG1} , q_{MG1} are the first motor/generator's angular velocity and torque, respectively; ω_{MG2} , q_{MG2} are the second motor/generator's angular velocity and torque, respectively; $f(SOC, \omega_{MG1}, q_{MG1}, \omega_{MG2}, q_{MG2})$ is the battery power consumption model;

This formulation is quite suitable for traditional mathematical optimization methods which has good computational complexity. In order to facilitate on-line optimization, the engine power is discretized and reformulate the optimization problem represented by:

$$\min \sum_{k=1}^T \sum_{i=1}^N x(k, i) p_i^{mg} \quad (2)$$

subject to:

$$\sum_{k=1}^i f \left(p_k - \sum_{i=1}^N x(k, i) P_i^{mg} \right) \leq C \quad \forall j = 1, \dots, T \quad (3)$$

$$\sum_{i=1}^N x(k, i) = 1 \quad \forall k \quad (4)$$

$$x(k, i) = \{0, 1\} \quad \forall k, i \quad (5)$$

where N is the number of discretized power level for the engine; k is the time step index; i is the engine power level index; C is the gap of the battery pack's SOC between the initial and the minimum; P_i^{mg} is the i -th discretized level for the engine power and η_i^{eng} is the associated engine efficiency; and P_k is the driving power demand at time step k .

However, if the change in SOC for each possible engine power level at each time step is pre-calculated given the (predicted) power demand, then constraint in equation (2) can be replaced by:

$$\begin{aligned} SOC^{\min} - SOC^{\max} &\leq \sum_{k=1}^i x(k, i) \Delta SOC(k, i) \\ &\leq SOC^{ini} - SOC^{\min} \\ &\quad \forall j = 1, \dots, T \end{aligned} \quad (6)$$

The fitness function can be defined as the summation of total ICE fuel consumption for the trip segment. The objective of fitness function is minimizing the fuel consumption and is given by equation (7). (Qi *et al.*, 2014).

$$f(s) = C_{fuel} - P \quad (7)$$

Where: s is a candidate solution; C_{fuel} is fuel consumption;

and P is imposed penalty that is the largest possible amount of energy that can be consumed in this trip segment

3.4.1 PHEV model parameter

The major parameters and the associated values of the PHEV's parameters used in this research are shown in the Table 1.

Table 1: Parameters of PHEV[15]

Parameters	Value	Unit
Vehicle curb weight	1718	Kg
Final drive ratio	3.93	/
Vehicle equivalent mass	1853	Kg
Tire radius	0.317	M
No. of teeth on sun gear	30	/
No. of teeth on ring gear	78	/

Gravitational acceleration	9.81	m/s ²
Rolling resistance coefficient (constant term)	0.008	
Rolling resistance coefficient (linear term)	0.00012	s/rad
Air density	1.2041	Kg/m ³
Projected frontal area	2.2508	m ²
Aerodynamic drag coefficient	0.26	
Maximum engine power	60	Kwatt
Moment of inertia for engine	0.1598	Kg*m ²
Maximum motor power	50	Kwatt
Moment of inertia for generator	0.0302	Kg*watt
Maximum generator power	30	Kwatt
Maximum brake torque	2000	N*m
No. of battery cells per module	12	/
No. of battery module	6	/
Nominal open-circuit voltage	3.6	Volt
Battery capacity	17	Ah
Maximum state of charge	0,2	/

3.4.2 Modeling of PHEV

The model of PHEV is of three types of powertrain architecture: series, parallel and power split (series parallel). In this research, the power split model was adopted due to; the power split has three sub-systems: ICE, PGS, and Motor/battery. A simplified block diagram was developed in MATLAB/Simulink environment, which is shown in the Figure 4.

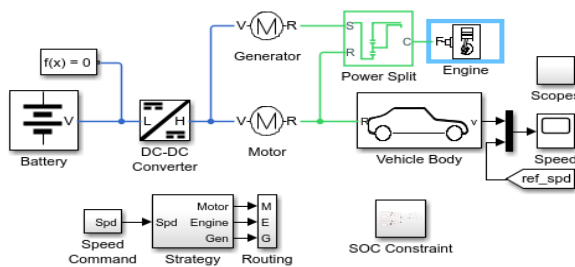


Figure 4. Power Split Hybrid Transmission Model

The component of the PHEV model given in Figure 4 were individually modelled initially. This model were then integrated together to achieve Figure 4.

The SOC of the model is optimized using Discrete Bat Algorithms (DBA) for real time energy management system for PHEVs SOC. The parameters settings of the DBA is as tabulated in Table.

Table 2: Algorithm Parameters

SN	Parameters	Values	Symbol
1	Population	10-25	nPop
2	Dimension	1801	nVar
3	Loudness	1,0.7	Amax,Amin
4	Pulse Rate	0,0.4	rMin,rMax
5	Alpha	0.98	A
6	Gamma	0.98	0.98

The implementation flow for the proposed method is give in Figure 5.

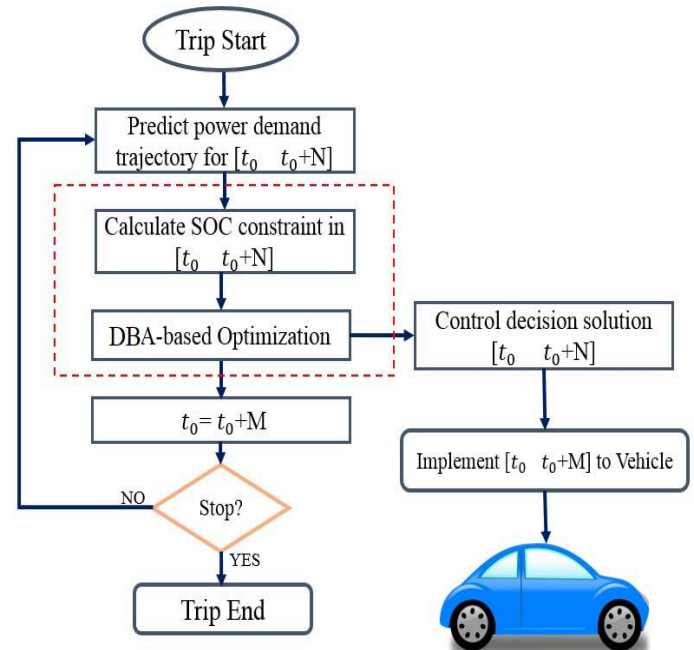


Figure 5: Flowchart of the DBA based Approach [16]

4. RESULTS AND DISCUSSION

This section presented the results and discussion of the optimized energy management scheme developed in this paper.

4.1 Engine and Battery Power Comparison

The performance of the PHEV system under the adopted DBA was first evaluated using the behavior of the battery and engine of the vehicle. Figure 6 shows the superimposed behavior of both vehicle engine and the battery

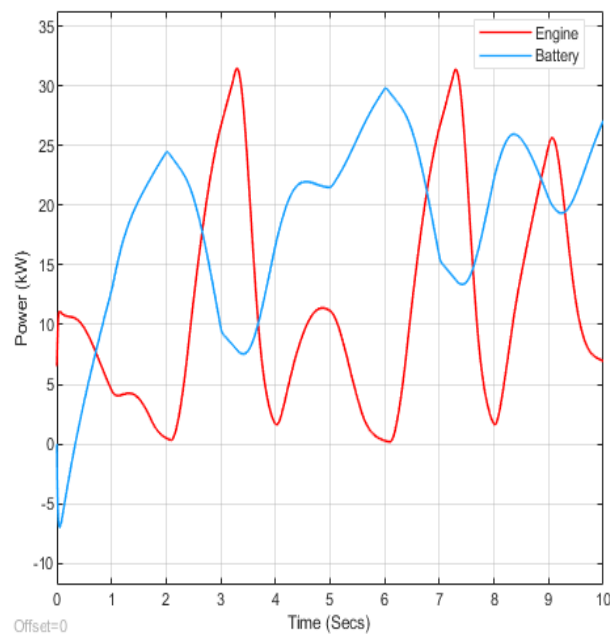


Fig 6: Engine and Battery Power

From Figure 6, it can be observed that both the battery powered engine and the motor-powered engine worked together to ensure efficient operation of PHEV. Though, the motor and the battery power vary with time, they are operating in such a manner to ensure stable operation of the PHEV which gives a better SOC and fuel economy.

4.5 Engine Power Analysis

The power analysis of the PHEV obtained by both EA and DBA is discussed in this subsection. Figure 7 shows the superimposed engine power of PHEV obtained by DBA and EA.

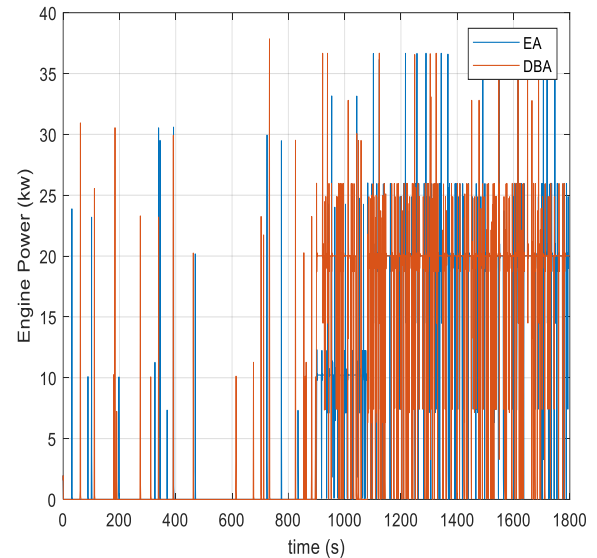


Figure 7: Engine Power of PHEV using DBA and EA

From Figure 7, it shows that the PHEV engine condition when the vehicle is in operating mode for about 1800 seconds. Also, it can be observed that the PHEV system has poor engine power at the early stage of its operating state. This is attributed to the state of charge of the PHEV battery and the battery power. After about 1000 seconds, when the battery has been charged to almost full capacity with maximum power output, the PHEV engine begins full operation as can be seen from Figure 7.

4.6 Battery Power

This section compares the results obtained by DBA and EA using the output power of the battery as a performance metrics. Figure 8 shows the

superimposed response of the power results obtained by DBA and EA.

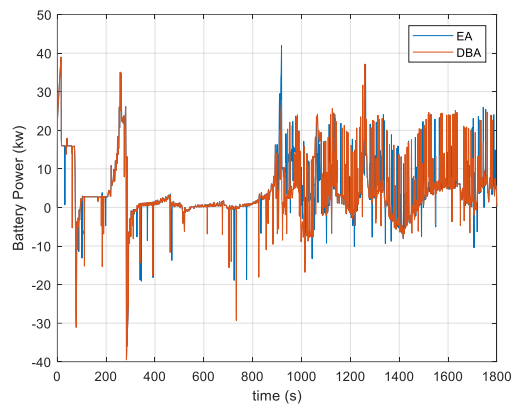


Figure 8: PHEV Battery Power

Taking comparison with the case of PHEV engine power, the output power of the battery using both EA and DBA varies as the operating time of the PHEV varies. At the early stage of the vehicle operation, when the battery is still charging the output power fluctuate between 0 and 10kW averagely. After over 800s of operation, the output power of the battery from both algorithms, attain an average of about 25kW which is about 83.33% of the battery capacity.

5. CONCLUSION

This paper presents the real time energy management system for Plug-in Hybrid Electric Vehicles (PHEVs). The State of Charge (SOC) has been modelled in MATLAB/Simulink, and the control of the vehicle SOC was formulated as a combinatorial optimization problem using Discrete Bat Algorithm (DBA) due to its simplicity, efficiency and robustness. The developed energy management system was comprehensively evaluated by number of trips (n=10) profile extracted from real world traffic data. In this research, DBA was used to solve

the problem. The PHEV battery output power of about 25kW was recorded which gives 83.33% of the battery capacity using DBA as against EA. The battery charge has a maximum and minimum value of 3Ah and 14Ah respectively. Between 4Ah to 10.25Ah, EA showed faster energy depletion when compared with DBA at 800 seconds to 1400 seconds. As a recommendation for future research works, researchers should consider implementing the proposed solution on real-time traffic data rather than predictive data traffic information in further research. Other discrete metaheuristic algorithms such as in discrete firefly algorithm and should be used to evaluate more options for better performance of energy management system of PHEVs.

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