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Energy Management System Optimization for Battery-Ultracapacitor Powered Electric Vehicle

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Energy usage and environment pollution in the transportation are major problems of today's world. Although electric vehicles are promising solutions to these problems, their energy management methods are complicated and need to be improved for the extensive usage. In this work, the heuristic optimization methods; Differential Evolution Algorithm, Genetic Algorithm and Particle Swarm Optimization, are used to provide an optimal energy management system for a battery/ultracapacitor powered electric vehicle without prior knowledge of the drive cycle. The proposed scheme has been simulated in Matlab and applied on the ECE driving cycle. The differences between optimization methods are compared with reproducible and measurable error criteria. Results and the comparisons show the effectiveness and the practicality of the applied methods for the energy management problem of the multi-source electric vehicles.

Keywords: Battery, differential evolution algorithm, electric vehicle, energy management, genetic algorithm, optimization, particle swarm optimization, ultracapacitor.

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1. INTRODUCTION

In recent years, depletion of petroleum resources, global warming and climate change has caused an increased interest about effective usage of available energy resources. Electric vehicles (EVs) are promising solutions about transportation to those problems because of high efficiency of electric motors and almost zero emission of drivetrains. Improvements on power converters and control techniques lead to increase of usability and drivability of them. However, there are some drawbacks and unresolved problem that are research subjects of many researchers. Energy management of energy sources is one of these problems because of only one type of energy source could not provide the needs of the entire drive profile. It is a common solution to use multi energy storage devices to overcome the disadvantage of each source and taking benefit of every source in an optimal way.

Batteries, fuel cells, ultracapacitors (UC) and flywheels are the most researched storage solutions for the electric vehicle energy source [1]. Energy storage systems in electric vehicles need to have high specific energy, high specific power, long cycle life and safe operation in all road conditions [2]. Fuel cells and flywheels are not sufficient yet to supply all needs of vehicles due to limited storage capability, safety and operational constraints [1]. Batteries provide a high specific energy but their specific powers are not enough to meet the vehicle instant power need most of the time. Therefore, integration of UC with batteries is an accepted solution because of the ability of UC to provide or absorb high powers [1]-[3]. Integration and management of these two sources are studied by using several methods in literature. Fuzzy logic [2], simulated annealing [4], particle swarm optimization (PSO) [1],

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model predictive control [5] methods are some of them. In addition to these methods, genetic algorithm (GA) is often used in the optimization of energy management systems for hybrid and electric vehicles [6]. Despite the difference between them, it is generally not possible to compare the effectiveness or usefulness of these methods because nearly all of the methods are applied to different drivetrains and topologies. The differential evolution algorithm (DE), proposed by Storn and Price, is also a heuristic and evolutionary optimization method such as GA and PSO [7]. Although it is not widely used in electric vehicles, it is an effective method that can be used easily wherever GA and PSO are used.

In this work, an optimization based energy management strategy is applied to the Alatay-EV whose general connection topology is shown in Fig. 1 [8].

Optimization of the energy management strategy (EMS) is achieved in two stages. The first stage is to restrict the search space of the optimization method according to conditions of storage devices and power demand of the vehicle. After determination and restriction of the search space, the power sharing optimization is implemented by using the selected optimization method.

This paper is structured as follows. The first section states the needs for this work and introduces the subject. The second section presents the structure of the EMS and the third section gives detailed information about the optimization method. Section 4 represents the results of simulations studies, and discussion of the obtained results. Finally, conclusions are given in Section 5.

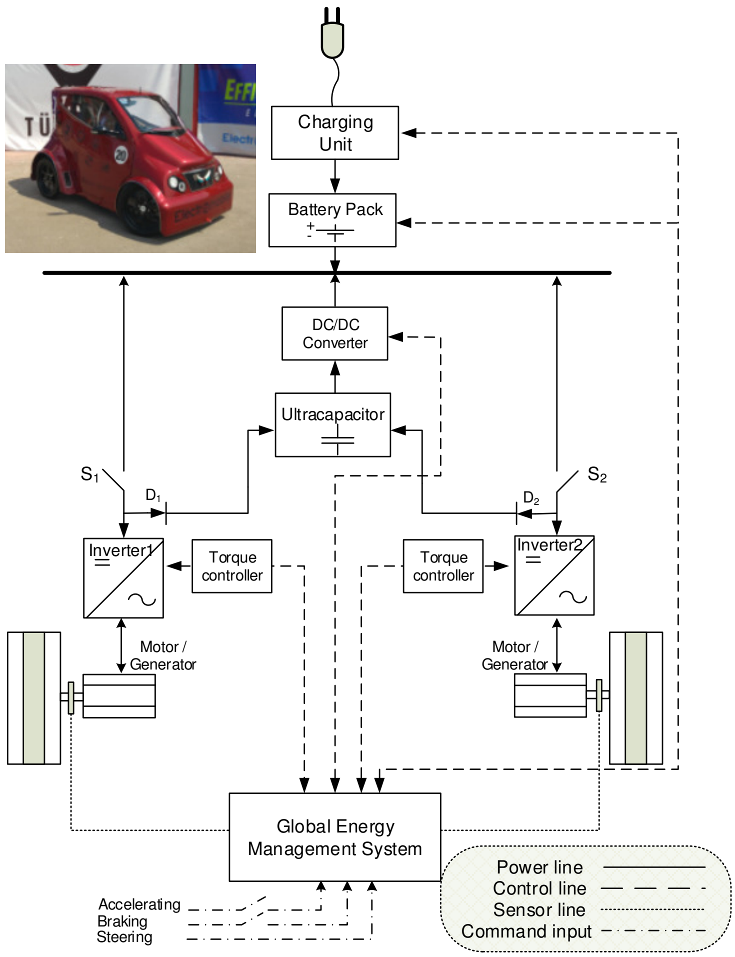


Fig. 1. General connection topology of Alatay-EV

2. ENERGY MANAGEMENT STRATEGY

In this work, power losses are neglected to provide simplicity. Only power sharing is considered as illustrated in Fig. 2 [3]. Here, the battery provides the continuous power while the UC provides peak powers. For accepting high regenerative powers and sometimes to provide high power to accelerate the vehicle, there is a power exchange between battery and UC. This exchange results in a more efficient use of energy storage devices and by consequence longer the driving range. The energy exchange is implemented according to some rules. These rules are formed by considering the minimum and maximum capacities of storage devices, demanded power and maximum obtainable power of battery. These rules and relevant actions are described in details in [4]. Forming the rules is implemented according to working constraints and operational needs of the vehicle and storage devices.

In electric vehicles, demanded power and supplied powers from battery and UC must be in equilibrium in any case and in the whole time interval as described in (1).

$$P_{dem}(t) = P_{bat}(t) + P_{UC}(t) \quad \forall t \tag{1}$$

where the demanded power is calculated according to (2), and the constants and parameters used in this equation are given in Table I.

$$P_{dem} = m.a.V + \frac{1}{2}.C_d.\rho.V^3 + K_r.m.V + m.g.\sin(\theta).V \tag{2}$$

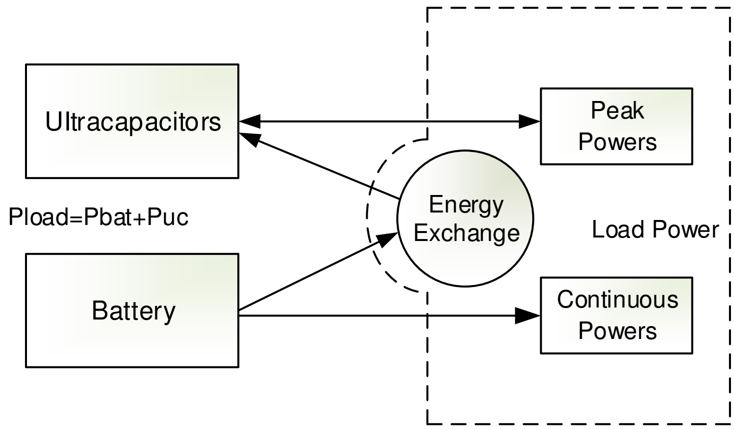


Fig. 2. General power sharing scheme [3]

This power equilibrium is subject to certain restrictions in terms of minimum and maximum charging/discharging powers as (3).

$$\begin{aligned} P_{bat,\min} \le P_{bat}(t) \le P_{bat,\max}, \quad \forall t \\ P_{UC,\min} \le P_{UC}(t) \le P_{UC,\max}, \quad \forall t \end{aligned} \tag{3}$$

where minimum and maximum powers are as described in (4). Here, minimum power represents the maximum charging power, while the maximum power is the maximum discharging power from the storage units.

$$P_{i,\min} \le 0 \le P_{i,\max}, \quad i \in \{bat, UC\} \tag{4}$$

The objective function to be minimized can be expressed as in (5) as described in [3], [4].

$$J = \min \sum_{k=1}^{t=N} \{ P_{dem}(t) - (w_{Bat}(t) * P_{bat,\max}(t) + w_{UC}(t) * P_{UC,\max}(t)) \} \tag{5}$$

where N is the time interval of the chosen drive profile and w_{Bat} and w_{UC} is the weighting factors of battery and UC, respectively. Also the weighting factors have restrictions as in (6).

$$\begin{aligned} & w_{Bat}, w_{UC} \in [-1,1] \\ & P_{bat}(t) = w_{Bat}(t) * P_{bat,\max}(t) \\ & P_{UC}(t) = w_{UC}(t) * P_{UC,\max}(t) \end{aligned} \tag{6}$$

Here, the objective is to provide optimal sharing of power among battery and UC by determining the weighting factors of them. The determination and optimization of these factors achieved with the optimization methods. Details of the methods are given in the next section.

As already mentioned, measurable and objective error criteria must be established in order to compare the suitability of the applied optimization methods. For this purpose, we get the following equation if the target function in equation (5) is re-expressed in terms of error;

$$\begin{aligned} & P_{supply}(t) = P_{bat}(t) + P_{UC}(t) \\ & E(t) = P_{dem}(t) - P_{supply}(t) \end{aligned} \tag{7}$$

Here, $P_{supply}(t)$ represents the power supplied by the battery and the ultracapacitor and $E(t)$ represents the difference between the demanded power and supplied power. In equation (8), mean absolute error (MAE) is obtained by dividing the sum of the absolute values of these errors by the total number of elements.

$$MAE = \frac{1}{N} \sum_{t=1}^{N} \left| E(t) \right| \tag{8}$$

Equation (9) also shows the correlation coefficient, which measures the correlation between $P_{dem}(t)$ and $P_{supply}(t)$.

$$R = \frac{N * \sum_{t=1}^{N} (P_{dem}(t) * P_{supply}(t)) - \left[\sum_{t=1}^{N} P_{dem}(t) * \sum_{t=1}^{N} P_{supply}(t) \right]}{\sqrt{N * \sum_{t=1}^{N} (P_{dem}(t))^2 - (\sum_{t=1}^{N} P_{dem}(t))^2} * \sqrt{N * \sum_{t=1}^{N} (P_{supply}(t))^2 - (\sum_{t=1}^{N} P_{supply}(t))^2}} \tag{9}$$

Optimization methods have been compared in terms of these criteria that measure the similarities and differences between any two sets of values.

In the implementation phase some threshold values for battery and UC must be determined to avoid damage of the storage devices. For this purpose, the battery state of charge (SOC) level is restricted between 35% and 95%. In a same way, UC minimum and maximum SOC are limited between 30% and 95% to show effective operation of the algorithm. Also, the operating voltages of battery and UC cells are (2.8-3.7) and (0-2.85) respectively. Detailed specifications and some constants about vehicle, battery and UC are given in Table I.

TABLE I: Assumptions and constants used in the simulation

Name	**Value**	**Unit**
Mass (*m*)	400	Kg
G	9.81	m/s^2
Kr	0.012	
Θ	20	Degree
P	1.2	kg/m^3
cd	0.3	
Front Area (*A*)	1.64	m^2
Number of Battery Cell	32	
Battery Cell Nominal Voltage	3.2	V
Battery Cell Nominal Capacity	36	Ah
Battery Nominal Discharge Current	21.6	A
Number of UC Cell	30	
UC Cell Nominal Voltage	2.7	V
UC Cell Nominal Capacity	0.244	Ah

3. Optimization Methods

There are many optimization methods in the literature for optimizing the energy management systems of electric and hybrid electric vehicles [1]-[6]. In this study, differential evolution algorithm [7], genetic algorithm [9] and particle swarm optimization [10] methods are used from these optimization methods.

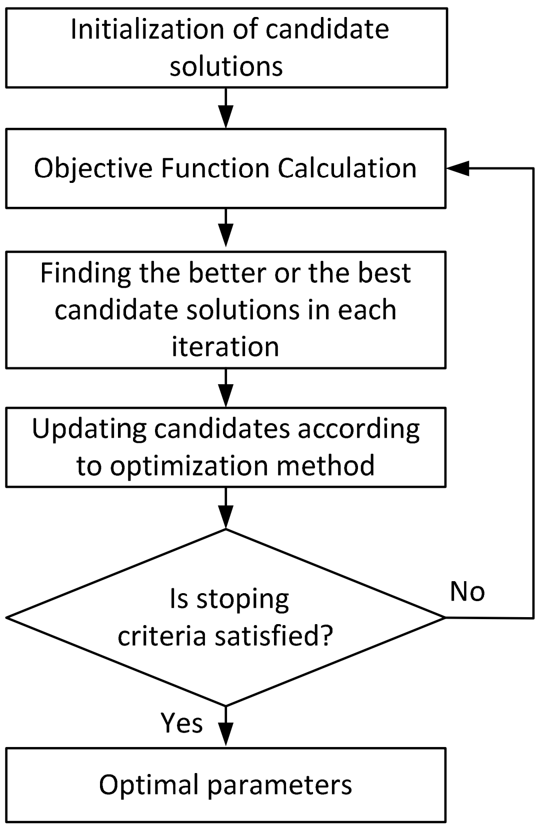


Fig. 3. Flow chart of the general optimization algorithm.

Each of the three optimization methods starts with a solution set that is a solution candidate and targets to reach the most appropriate solution in such a short time by updating these solution candidates according to specified rules at each iteration.

In the PSO and DE method, the candidate solution set is constructed using the real solution values, and in the GA method, the set is constructed using the corresponding binary values of real values in the specified length.

Each created solution candidate is tested in the object function and the fitness value is obtained for each candidate. Candidates in the solution set are updated according to the obtained these fitness values. This update depends on the specified rules, and the rules and details of the methods used in this work are described in detail in the reference [11].

In all three methods, the algorithm continues until to reach the desired fitness value or the maximum number of iterations.

The overall optimization scheme is shown as a flow chart in Fig. 3.

4. Results and Discussions

The proposed energy management strategy is applied on ECE driving cycle shown in Fig. 4 [12]. Drive cycle data gives information of the speed of the vehicle. The demanded power according to this drive profile is calculated according to (2).

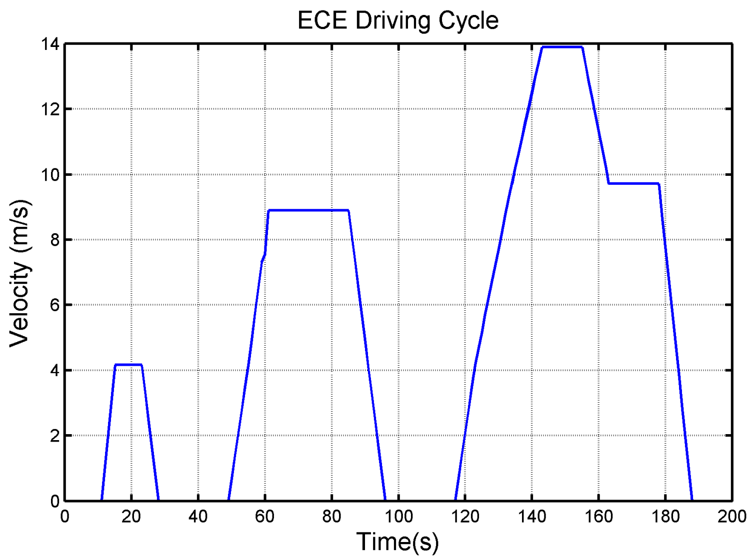
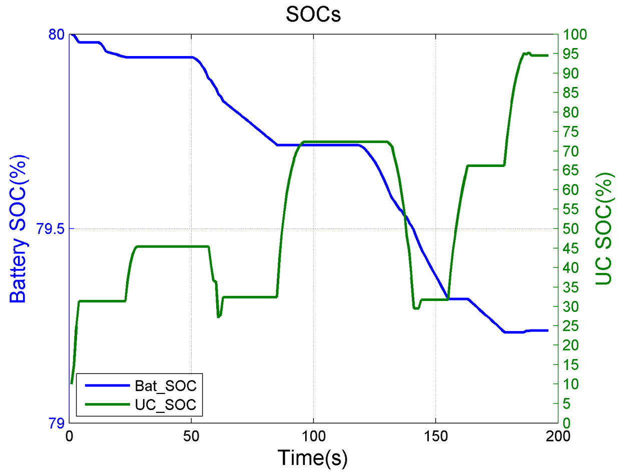


Fig. 4. ECE Driving cycle.

Setup results of the management strategy is given in Fig. 5 to Fig. 7 to show the optimization process. In this setup, battery and UC initial SOCs are determined as 80% and 10% respectively. From Fig. 5, small differences and similarities between battery SOC and UC SOC can be seen as well as energy exchange between battery and UC. It can be seen that all three methods hold battery and UC between the specified SOC limits. Although the UC SOC starts at 10%, it has been brought to a safe range in a short period of time, exceeding the specified critical value of 30%. Looking at the interval between 95 and 140 seconds, it is seen that UC SOC has different levels in each optimization method. This level is higher in DE and PSO than in GA. Similarly, it can be noticed from the end of the driving profile that the PSO keeps the battery and UC at higher SOC levels.

In Fig. 6, demanded power and supplied power from each source are illustrated according to optimization method. Power exchanges between sources can be seen clearly in this figure. For example, in the first 8 seconds power demand is zero and UC SOC is below the threshold value. So, battery charges the UC in this case. This increment provides to rise

UC SOC for the later use to accelerate the vehicle.



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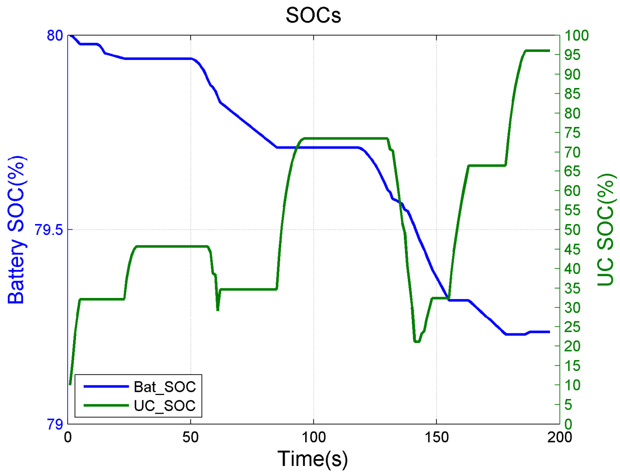

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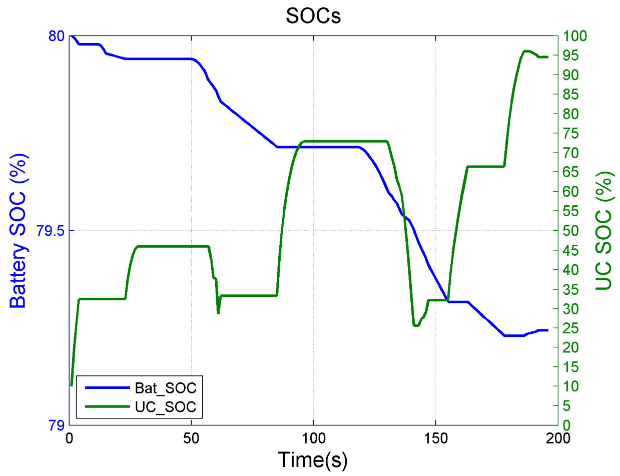

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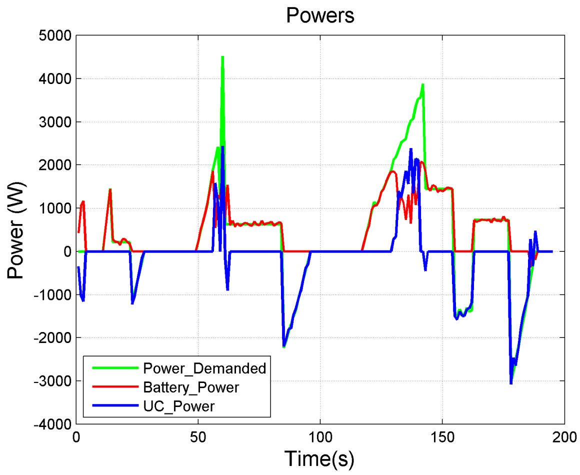
Fig. 5. Battery and UC SOC values a) GA, b) DE, c) PSO (Battery initial SOC: %80, UC initial SOC: %10).



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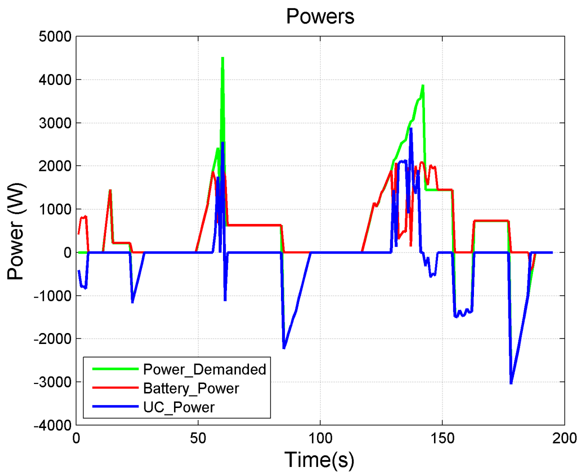

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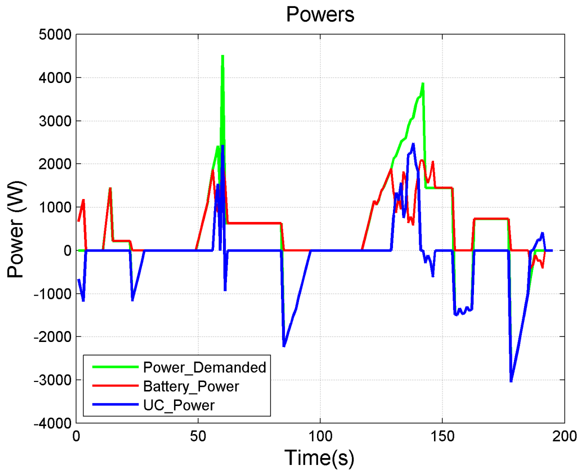
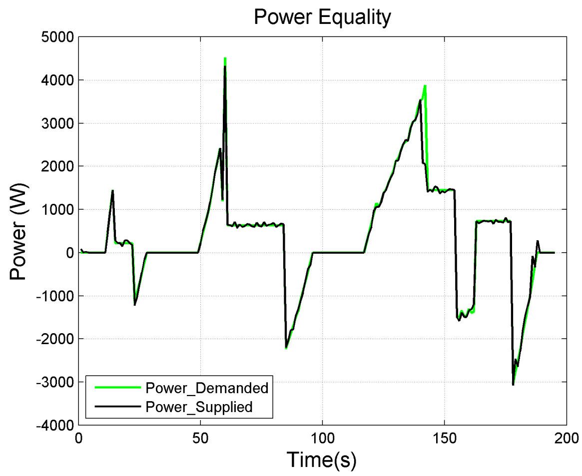


(c)

Fig. 6. Battery, UC and demanded powers a) GA, b) DE, c) PSO (Battery initial SOC: %80, UC initial SOC: %10).



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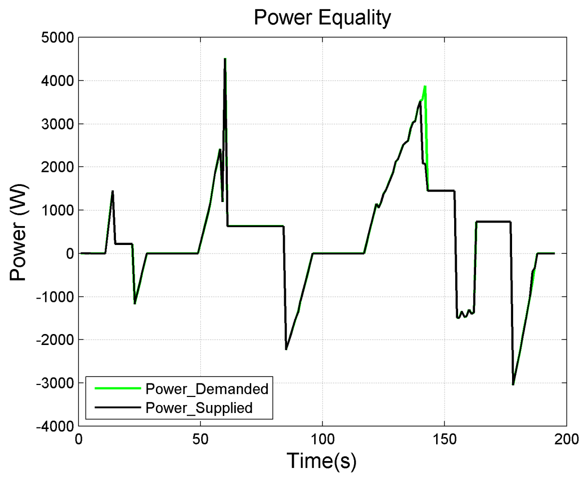

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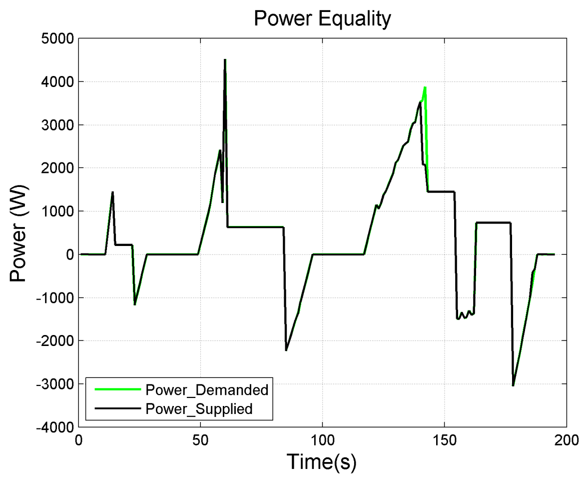

(c)

Fig. 7. Demanded and supplied powers a) GA, b) DE, c) PSO (Battery initial SOC: %80, UC initial SOC: %10).

As a result, power equality is given in Fig. 7. This figure shows good matching of demanded and supplied powers.

In Alatay-EV vehicle batteries have much more power density. It results to demand power is met by battery power most of the time. Used batteries can supply approximately 2 kW (21.6 A continuous discharge current and 96 V nominal voltage). However maximum demanded power about 3 kW for the ECE driving cycle.

The data of the Fig. 7 are compared according to error criteria stated in equations (8) and (9) and by the means of optimization time and the results are given in Table II.

TABLE II

Comparisons of optimization methods (Battery initial SOC: %80, UC initial SOC: %10).

Optimization Method	**Time (s)**	***MAE***	***R***
Rule-Based	0.0168	1.62*10^3	0.5459
GA	30.6297	48.7219	0.9886
DE	5.0827	18.2590	0.9901
PSO	0.1846	18.1885	0.9901

In the other simulation setup battery and UC initial SOCs are determined as 80% and 100% respectively, and the results are given in Table III.

TABLE III

Comparisons of optimization methods (Battery initial SOC: %80, UC initial SOC: %100).

Optimization Method	**Time (s)**	***MAE***	***R***
Rule-Based	0.0165	1.76*10^3	0.4972
GA	34.1124	76.5321	0.9817
DE	6.3678	43.9724	0.9872
PSO	0.2025	37.6321	0.9896

When we examine the tables, it can be said that the optimization methods perform energy management very successfully compared to the non-optimized rule-based energy management system. Compared according to time, GA seems to be a little slower than other optimization methods. The reason for this is that in this method, time is lost in the conversion processes because the transactions are performed on the basis of the binary values rather than the actual values.

Due to the structural characteristics of the optimization methods, it can be said that PSO is faster in solving and getting better results than others in the optimization of energy management system. Thereby, this have importance in terms of real-time implementation.

In this work, the power losses of gear box, motors and inverters are neglected to provide simplicity and avoid from the computational effort. Demanded power from the drive cycle is considered as demanded power from energy storage devices. Also the DC-DC converter between battery and UC must be included for realistic and correct results. Every energy exchange between these devices cannot be efficient in every time.

5. Conclusion

Electric vehicle technology is a growing issue with the concerns about future of the petroleum resources and climate change. One of the major components of these technology is the energy management of used storage devices in vehicle because of none of the current energy storage devices is enough the entire need of the vehicle. For this purpose, optimal power sharing and energy management of a battery/UC powered electric vehicle is studied in this work. Optimization of power sharing is achieved with several effective optimization techniques such as GA, DE, PSO. It is concluded that these optimization techniques can be used effectively for the energy management problem of the multi-source electric vehicles with the less energy usage. PSO algorithm has the best accuracy and requires less computational time when compared to the other methods. Therefore, PSO technique can be used effectively for the energy management problem of the multi-source electric vehicles in real-time applications.

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