Bat Optimization for a Dual-Source Energy Management in an Electric Vehicle Energy Storage Strategy

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ABSTRACT

This paper presents a new strategy of dual source management using Bat-optimization for an electric vehicle energy storage strategy. The power distribution between fuel cell and super-capacitor modules for obtain a good performance is an essential problem in dual-source electric vehicles. Traditional numerical optimization for energy management relies too much on the expert experience, and it's easy to get the sub-optimal performance. In order to overcome this drawback, a new intelligent method metaheuristic of Bat optimization is introduced for energy management in dual-source propelled electric vehicle. This work, based on the systemic power analysis in the energy storage strategy, the vehicle power propulsion system encounters and the constraints the energy storage strategy should obey. Then, different operation modes of dual-source systemic power analysis in energy storage strategy are presented. Finally, the results show the validity of the proposed technique.

Keywords: Dual-Source, Energy Management, Energy Storage Strategy, Bat Algorithm, Optimization Method, Electric Vehicle.

1. INTRODUCTION

The increasing concerns on energy conservation and environmental protection throughout the world result are in the revival of the electric vehicles (EVs) [1]. EVs have a number of advantages including low exhaust emissions, low operation noise and reasonably good energy efficiency. However, limited life cycle of the battery and limited range of the vehicle after each battery charge become the major obstacles for the commercialization of EVs. The power distribution between fuel cell and super-capacitor modules for obtain a good performance is an essential problem in dual-source electric vehicles. The super-capacitor is an electrochemical device that can supply a large burst of power, but cannot store much energy [2]. By connecting the two energy sources together in parallel configuration, the benefits of both can be achieved as a complete energy source. A novel electric vehicle using the dual-sources is proposed recently [3]. And the power distribution between the dual-sources becomes a tough and promising issue. Much research work has been done in recent years to design proper optimization strategy for dual-source energy management. A dynamic variable μ is defined as the power taken from the fuel cell and the power taken from the super-capacitor is the difference when μ is subtracted from the vehicle's power request [4]. Also a lookup method is used to determine the different μ value at different super-capacitor state-of-charge (SOC). The strategy is smart and easy to implement, but the set of μ value is not flexible. A Bat optimization strategy is proposed for energy management in multi-source electric vehicle. The required power, Fuel cell SOC and super-capacitor SOC are taken as minimal values and the power distribution factor as optimal value. This strategy obtains better vehicle performance than the lookup method or logic-threshold optimization method, but the set of Bat optimization is mainly dependent on the expert experience; and is easy to get the global optimum performance. In this paper, bat method is used to optimize the Fuel cell SOC and super-capacitor SOC in energy management for power distribution. Bat method is a population-based algorithm [5]. It can search automatically the optimal solutions in the vector space.

Bat algorithm (BA) is a novel metaheuristic optimization algorithm based on the echolocation behaviour of microbats, which was proposed by Yang in 2010 [5-7]. This algorithm gradually aroused people's close attention, and which is increasingly applied to different areas. Tsai (2011) proposed an improved BA to solve numerical optimization problems [8].

The rest of this paper is organized as follows: The mathematic model of dual-source energy management is set in section 2. The operation modes of energy storage system are analyzed in section 3. In section 4, the energy management optimization based BA is given. The simulation results are presented in Section 5. Finally, concluding remarks are given in Section 6.

2. DUAL-SOURCE ELECTRIC VEHICLE POWERTRAIN

The configuration of the dual-source electric vehicle powertrain with the fuel cell and super-capacitor

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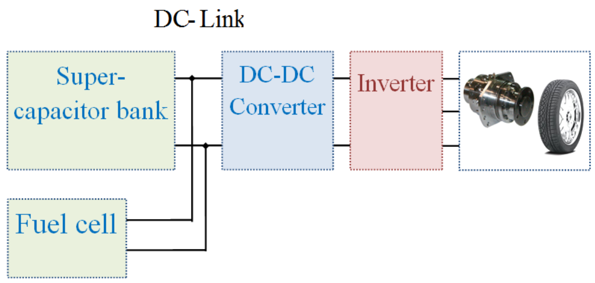

Fig.1: *Configuration of the dual-source EV powertrain.*

as the energy-storage device is shown in Fig.1. The powertrain consists of fuel cell, super-capacitor bank, a DC-DC converter, an inverter and an AC motor. The fuel cell stack is paralleled with the super-capacitor bank to make the DC-Link. The DC-DC converter regulates the DC-link voltage [9, 15]. The inverter converts the regulated DC voltage to an AC voltage to drive the AC motor [10, 16].

In the dual-source EV powertrain, when the vehicle demands high power, the fuel cell and super-capacitor provide power to the shaft of the vehicle through the DC-DC converter, the inverter and AC motor. In this case, one can have:

$$C(P_{fc} + P_{sc}) = C_1 P_c = C_2 P_i = C_3 P_m = P_v \qquad (1)$$

where P_{fc}, P_{sc}, $_c$, P_i, P_m and P_v are the power of the fuel cell, power of the super-capacitor bank, power of the DC-DC converter, power of the inverter, power of the AC motor and the vehicle power demand, respectively. And C, C_1, C_2, C_3 are the efficiency from energy storage system, converter, inverter, AC motor, respectively.

On the other hand, when the vehicle demands low power, if the SOC of the super-capacitor is higher than the lower safe set point, the super-capacitor alone provides power to the shaft of the vehicle through the DC-DC converter, the inverter and the AC motor and charges the super-capacitor directly; otherwise, the fuel cell alone provide the power to drive the vehicle [15, 16]. When the vehicle brakes, the AC motor convert the kinetic energy of the vehicle into electricity and charges the super-capacitor through the inverter and the DC-DC converter using the generated electricity.

3. THE MATHEMATIC MODEL OF DUAL-SOURCE ENERGY MANAGEMENT IN ELECTRIC VEHICLE

According to the analysis in section 2, we can see that the goal of energy management is to attain the minimized energy consumption under the requirement of the vehicle performance through the proper assignment of the power of the fuel cell and super-capacitor [4, 18-19]. Here, energy consumption rate (ECR) is used as the performance index to evaluate the economy of electric vehicle, which denotes that the energy vehicle consumed in one hundred kilometers cycle. It is usually obtained by the following equation:

$$ECR = \frac{1.1 \times 10^{-7} \cdot E}{L} \qquad (2)$$

where, L is the drive distance in km, E is the consumed energy during the drive cycle in Joule, and can be got by power integral in time domain, 1.1×10^{-7} is the conversion factor.

In order to establish the mathematic model of dual-source energy management, the power and constraints in energy storage system should be analyzed [20-23].

3.1 Different Power in Dual-Source Electric Vehicles

As it is said in section 2, during the run, energy storage (ES) system outputs energy to the electric motor through power bus, and the motor passes energy to drive wheels to overcome the road load, denoting as F_1. According to the theory of vehicle dynamics [11], this road load F_1 consists of three main components aerodynamic drag force F_d, rolling resistance force F_r and climbing force F_c as given by:

$$F_1 = F_d + F_r + F_c \qquad (3)$$

The aerodynamic drag force is due to the drag upon the vehicle body when moving through air. Its composition is due to three aerodynamic effects the skin friction drag due to the air flow in the boundary layer, the induced drag due to the downwash of the trailing vortices behind the vehicle, and the normal pressure drag (proportional to the vehicle frontal area and speed) around the vehicle. The skin friction drag and the induced drag are usually small compared to the normal pressure drag, and are generally neglected. Thus, the aerodynamic force can be expressed as:

$$F_d = \frac{1}{2}\rho \cdot C_d \cdot S \cdot v_2 \qquad (4)$$

where, C_d is the aerodynamic drag coefficient, ρ is the air density in kg/m^3, S is the frontal area in m^2, v is the vehicle speed in km/h.

The rolling resistance force is due to the work of deformation on the wheel and road surface. The deformation on the wheel heavily dominates the rolling resistance while the deformation on the road surface is generally insignificant. This rolling resistance force is normally expressed as:

$$F_r = M \cdot g \cdot C_r \qquad (5)$$

where M is the vehicle mass in kg, g is the gravitational acceleration, C_r is the rolling resistance coefficient.

The climbing force is simply the climbing resistance or downward force for a vehicle to climb up an incline. This force is given by:

$$F_c = M \cdot g \cdot \sin\varphi \qquad (6)$$

where, φ is the angle of incline in radian or degree. So, the road load power P_{Load} can be computed by multiplying (2) by the vehicle velocity. In that case:

$$P_{Load} = \frac{v}{3600}\left(\frac{1}{2}\rho \cdot C_d \cdot S \cdot v^2 + M \cdot g(C_r + \sin\varphi)\right) \qquad (7)$$

then P_{ES} can be calculated as following:

$$P_{ES}(t) = \frac{1}{C}P_{Load}(t) \qquad (8)$$

3.2 Constraints in Energy Storage System

On one hand, to ensure that the vehicle can effectively run [21-22], ES system should provide enough energy for meeting the required vehicle power P_{req} at any time, as shown in (8). Suppose the $K_{bat}(t)$ and $K_{sc}(t)$ respectively at time t, the power assignment of the two can be expressed in the following form:

$$P_{fc}(t) = K_{fc}(t) \cdot P_{ES}(t) \qquad (9)$$

$$P_{sc}(t) = K_{sc}(t) \cdot P_{ES}(t) \qquad (10)$$

where, the sum of $K_{fc}(t)$ and $K_{sc}(t)$ is 1. So, adjusting the $K_{fc}(t)$ and $K_{sc}(t)$ consequently results in the change of $P_{fc}(t)$ and $P_{sc}(t)$.

On the other hand, as the fuel cell and super-capacitor are concerned, if their SOC is too high, the ability to recuperate braking energy would decrease, and result in the desert of the surplus energy. Conversely, if the SOC is too low, ES system may not supply enough power to meet the vehicle requirement when accelerating. In order to extend lifecycle of fuel cell and super-capacitor, their SOC should operate in proper range as much as possible, that is,

$$SOC_{fc_{min}} \leq SOC_{fc}(t) \leq SOC_{fc_{max}} \qquad (11)$$

$$SOC_{sc_{min}} \leq SOC_{sc}(t) \leq SOC_{sc_{max}} \qquad (12)$$

In this paper, the fuel cell SOC is set to vary in [0.4, 0.8], and super-capacitor SOC in [0.3, 0.8].

3.3 Mathematic Model of Dual-Source Energy Management

According to the above discussion, mathematic model of dual-source energy management can be formulated as [4]:

$$\begin{gathered} \underset{\in[0,T]}{Min}\{ECR|_{Kbat(t),K_{sc}(t)}\} \\ P_{EX}(t) = \frac{1}{C}P_{Load}(t), t \in [0,T] \end{gathered} \qquad (13)$$

4. BAT OPTIMIZATION FOR ENERGY MANAGEMENT

According to the analysis in section 3, we can see that the vital of energy management is to decide proper value for power split factor $K_{fc}(t)$ and $K_{sc}(t)$. Considering that dual-source energy management problem is virtually a nonlinear optimization problem, the traditional optimization method is unfit here. Novel metaheuristic Bat algorithm (BA) is a practical alternative for a variety of challenging optimization applications since it provides an intelligent method for constructing nonlinear optimization methods via the use of heuristic information [12-13, 17-18]. Before we start to design the energy management bat optimization, the principle of bat algorithm is presented first.

4.1 Principle of Bat Optimization Algorithm

Experimental results show that Bat algorithm (BA) outperforms all other algorithms [17]. In behavior, most of microbats have advanced capability of echolocation. These bats can emit a very loud and short sound pulse; the echo that reflects back from the surrounding objects is received by their extraordinary big auricle. Then, this feedback information of echo is analyzed in their subtle brain. They not only can discriminate direction for their own flight pathway according to the echo, but also can distinguish different insects and obstacles to hunt prey and avoid a collision effectively in the day or night [7].

First of all, let us briefly review the basics of the bat algorithm for single-objective optimization [7, 14]. In the basic BA developed by Yang in 2010, in order to propose the bat algorithm inspired by the echolocation characteristics of microbats, the following approximate:

1. All bats use echolocation to sense distance, and they also “know” the difference between food/prey and background barriers in some magical way.
2. Bats fly randomly with velocity v_i at position x_i with a fixed frequency f_{min}, varying wavelength λ, and loudness A_0 to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission $r \in [0, 1]$, depending on the proximity of their target.
3. Although the loudness can vary in many ways, we assume that the loudness varies from a large (positive) A_0 to a minimum constant value A_{min}.

In addition, for simplicity, they also use the following approximations: in general, the frequency f in a range $[f_{min}, f_{max}]$ corresponds to a range of wavelengths $[\lambda_{min}, \lambda_{max}]$. In fact, they just vary in the frequency while fixed in the wavelength λ and assume $f \in [0, f_{max}]$ in their implementation. This is because λ and f are related due to the fact that $\lambda f = v$ is constant. In simulations, they use virtual bats naturally to define the updated rules of their positions x_i and velocities v_i in a D-dimensional search space. The new solutions x_i^t and velocities v_i^t at time step t are given by

$$\begin{cases} f_i = f_{min} + (f_{max} - f_{min})\beta \\ v_i^t = v_i^{t-1} + (x_i^t - x*)f_i \\ x_i^t = x_i^{t-1} + v_i^t \end{cases} \tag{14}$$

where $\beta \in [0, 1]$ is a random vector drawn from a uniform distribution. Here, is the current global best location (solution) which is located after comparing all the solutions among all the n bats [5, 7, 14, 18]. For the local search part, once a solution is selected among the current best solutions, a new solution for each bat is generated locally using random walk:

$$x_{new} = x_{old} + \epsilon A_t \tag{15}$$

where $\epsilon \in [-1, +1]$ is a random number, while $A_t =< A_i^t >$ is the average loudness of all the bats at this time step. Furthermore, the loudness and the rate of pulse emission have to be updated accordingly as the iterations proceed. These formulas are

$$A_i^{t+1} = \alpha A_i^t \tag{16}$$

$$r_i^{t+1} = r_i^0(1 - \exp(-\gamma t)) \tag{17}$$

where α and γ are constants.

4.2 Energy Management Using Bat Algorithm

The BA for energy management contains the SOC_{fc} and SOC_{sc} as a values should be minimized. And the result is the power split factor of battery K_{fc}. Once K_{fc} is given at time step t, the split power P_{fc} and P_{sc} can be easily determined.

Besides defining the position and velocity of bats, the evaluate index, which is called fitness here, should also be defined. As it is mentioned above, the goal of energy management is minimizing the ECR with a satisfactory performance. So, ECR is adopted as the fitness function during the optimal process.

Due to the existence of A_i^0, r_i^0, α and γ, although encoding of position or velocity in current iteration are integers, the next position or velocity may be real number. Therefore, the new real number position should take integer operation to avoid the infeasible solutions.

$$\begin{aligned} &Objective function: \underset{\in[0,T]}{Min}\{ECR|_{Kbat(t),K_{sc}(t)}\} \\ &which: \ 0.4 \le SOC_{fc}(t) \le 0.8 \\ &\qquad\quad 0.3 \le SOC_{sc}(t) \le 0.7 \end{aligned} \tag{18}$$

Based on these approximations and idealization, the basic steps of the bat algorithm can be summarized in the Pseudo-code 1.

```
Objective function f(x), x = [x1, x2, ..., xn]^t;
Initialize the bat population xi(i = 1, 2, ..., n) and vi;
Define pulse frequency ri at xi;
Initialize pulse rates ri and the loudness Ai;
While (t < Max number of iterations)
    Generate new solutions by adjusting frequency,
    And updating velocities and locations (13);
    if (rand > ri)
      Select a solution among the best solutions,
      Generate a local solution around the selected
      best solution,
    end if
    Generate a new solution by flying randomly
    if (rand < Ai & f(xi) < f(x*))
      Accept the new solutions,
      Increase ri and reduce Ai,
    end if
    Rank the bats and find the current best x*,
end while
Post − process results and visualization.
```

Pseudo-code 1

Table 1: *The parameters set of BA.*

	n	f_{min}	f_{min}	A_i^0	r_i^0	α	γ
BA	40	0	100	(1,2)	(0,0.1)	0.86	0.92

Table 2: *Main parameters of electric vehicle.*

Vehicle parameters		**Motor parameters**	
Glider Mass	1020 Kg	Type	IM
Frontal area	2.03 m^2	Rated power	20 KW
Rolling	0.024	Peak power	60 KW
Aerodynamic	0.22	Rated speed	3600 rpm

5. SIMULATION RESULTS

The proposed BA is implemented in MATLAB R2011a, simulation platform i5-CPU Intel 2.00GHz; DDRAM-III: 4GHz. The parameter setting for BA listed in Table 1. The stopping criterion can be defined in many ways. We adopt two terminated criteria: we can use a given tolerance (10^{-5}) for a test function that has certain minimum value in theory; on the contrary, each simulation run terminates when a certain number of function evaluations have been reached. In this paper, function evaluations could be obtained by population size multiplied by the number of iteration. In our experiment, function evaluations equal 24000, BA = 200×40×2.

To validate the performance of the dual-source energy management using BA, we compared this technique in the energy management without optimization; simulations are taken for an electric vehicle energy storage strategy. The electric vehicle with the main parameters listed in Table 2. Table 3 illustrates the main parameters of duel-source.

Figure 2 and figure 3 show the SOC trends of fuel cell and super-capacitor using BA method during the specific cycle. From the figure 2, we can see that, because the regenerative energy is small, it is charged only to the super-capacitor. So, as the main source,

Table 3: *Main parameters of duel-source.*

Fuel cell		Super-capacitor	
Type	PEM	Type	Maxwell
Stack's number	3×2	Rated voltage	2.5 V
Cell's number	125	Cell's number	180
Cell's power	64 W	Current range	±225

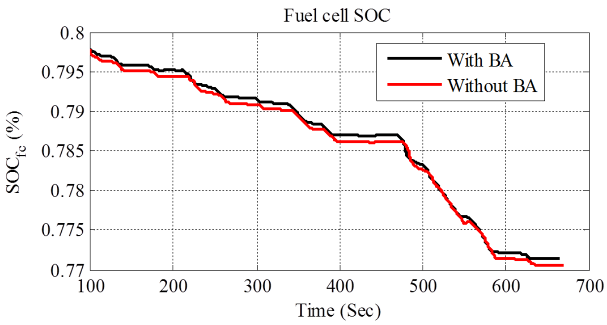

Fig.2: *Fuel cell SOC_{fc} trend.*

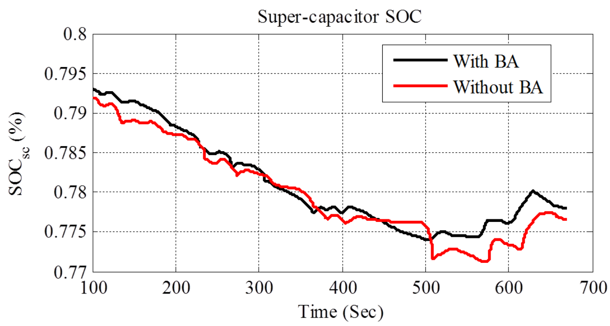

Fig.3: *Super-capacitor SOC_{sc} trend.*

Table 4: *ECR and computation time comparison.*

	***ECR* (kWh)**	***Computation time*(Sec)**
With BA optimization	12.9	3.4
Without BA optimization	11.7	7.6

fuel cell's SOC decreases along with time. The SOC trend using BA method decreases slower than the case without optimization. It is shown in figure 3 that, super-capacitor discharges or charges frequently during the run, and the SOC trend of super-capacitor using BA method varies more frequently than the case without optimization.

To evaluate the validity of the proposed strategy more clearly, the dual-source energy storage in terms of ECR is compared. From Table 4, we can see that the electric vehicle without BA optimization method has an ECR value of 12.9 kWh, while ECR using BA is 11.7 kWh, which is adopting the optimization strategy of the ECR, value is improved by 9.7 percent. Figure 4 show the convergence curve of the function, from a particular run of BA, which end at 200 generations.

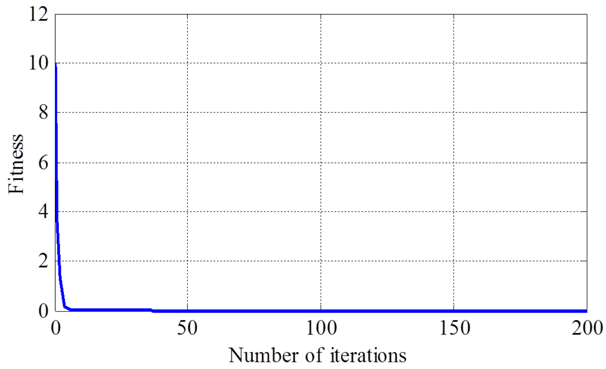

Fig.4: *Convergence curve of the function.*

6. CONCLUSION

In this paper, dual-source energy management modeling and energy storage system optimization are discussed in detail. After the systematic analysis of objective function and constraints in ES system, the energy management model is established. From the model, we get that how to distribute the power between fuel cell and super-capacitor modules to obtain good performance is the vital to applied optimization method of energy management. Bat algorithm is the method to handle this problem. The simulation results show that the electric vehicle using BA have a best fuel economy performance for a dual-source energy management.

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