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Energy Management of a Solar Powered Electric Vehicle with Multiple-Energy Storage via Optimized Fuzzy Controller

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Abstract
The optimum energy management is the main challenge of powered electric vehicles (EVs) with multiple energy storage systems. The solar powered EVs are enabled with multiple energy sources and storages, and so, achieving the optimum energy management schedule is a complicated optimization problem. This paper develops an optimized fuzzy controller using genetic algorithm (GA) for energy management of solar powered EV equipped with photovoltaic cells as well as two power banks including battery and super-capacitor. Design of fuzzy controllers relies too much on the expert experience and non-optimal design may lead to sub-optimal performance. To overcome this complexity, genetic algorithm (GA) is employed to optimally determine fuzzy rules and membership functions. The proposed approach is modelled in ADVISOR software. Standard driving cycle is used to simulate the proposed approach. Simulation results demonstrate the decrease on consumed power by the proposed optimal GA-Fuzzy controller in comparison with the standard fuzzy controller.

Keywords: *Electric vehicle (EV), energy management, fuzzy controller, genetic algorithm (GA), solar, ADVISOR*

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INTRODUCTION

The management and control to run the transportation system has become more necessary due to the increasing fuel consumption in recent years. Traditionally, fossil fuels were the major energy resources for transportation system. However, price uncertainties, political issues of oil provider countries and environmental problems of fossil fuels resulted in a need to find other energy resources [1–3]. The transportation system as one of the major energy sectors is changing the internal combustion engines. Electric vehicles as one of the best possible option have been developed in the last decade and new development in battery and storage devices, charge and discharge infrastructures has led to relatively high penetration of these vehicles [4, 5]. According to above mentioned issues, optimum design of EVs is an important task. Optimal modeling and simulation of EVs leads to energy consumption and cost minimization. There are lots of simulation software to model and simulate the EVs in which ADVISOR seems to be more accurate.

Recently, due to the importance of EVs there has been an augmented interest in energy and power management and control field. A control strategy to reduce the energy consumption in super capacitor and fuel cell based EVs have been developed by Azib *et al.* and Thounthong *et al.* [6, 7]. Moreover, fuel consumption optimization has been modelled by Jiang *et al.* and Azib *et al.* for super capacitor and fuel cell based EVs [8, 9]. The developed method by Jiang *et al.* has also been examined on real EVs [8]. Azib *et al.* discussed that the super capacitor's duty is to supply electric power in case of high power consumption of EV, especially in acceleration mode [9]. Adaptive control method for EVs with parallel pattern has been studied by Chasse *et al.*; the developed strategy in this article has been adapted with a driving schematic [10].

Azib *et al.* has modelled an EV system with just one convertor [11], while Dawei Gao *et al.* has used a fuzzy logic for optimum design of energy consumption in EVs [12].

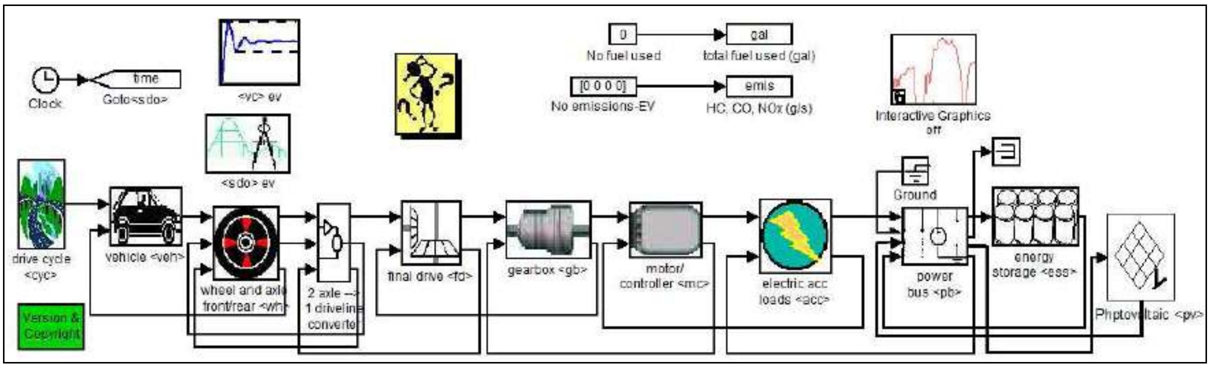

Fig. 1: *Block Diagram Solar Powered EV with Dual Energy Sources in ADVISOR Software.*

In this paper an optimum energy consumption pattern for EV enabled with super capacitor, battery and fuel cell based on fuzzy model has been developed. For efficient and optimum performance of EVs the sustain control system should be designed since storage system selection and charging pattern is a very important task. It has been shown that fuzzy controller has better performance in comparison with other linear or nonlinear controllers. The objective of this study is to design the fuzzy based controller to control and manage EVs' power sources.

In a fuzzy system membership function definition and fuzzy rules is the most important task. Hence to improve the controller operation, genetic algorithm (GA) is used to determine the membership functions of input and output parameter and variables as well as fuzzy rules. This paper is organized as follows; next part of the paper introduces the mathematical model of the solar powered EV system; then the employed mixed integer genetic algorithm is proposed followed by the development of the fuzzy controller for energy management of solar powered EV. Some simulation results for a typical solar powered EV are provided after that and finally, concluding remarks are given.

MATHEMATICAL MODEL OF SOLAR POWERED ELECTRIC VEHICLE

The schematic diagram of studied solar powered EV has been shown in Figure 1. The power transmission system contains battery, super capacitor bank, DC/DC convertor, inventor and electric motor. Battery and super capacitor have parallel structure in order to make DC link. DC/DC converter regulates DC link voltage. the controlled DC voltage converts to AC by inverter to start electric motor. Transmission system which contains a gearbox, multiplies motors torque to conversion coefficient. In case of high power need, battery, super capacitor, gearbox and electric motor produce the needed power and supplies the vehicle.

In driving stage, energy storage system (ESS) supplies power needed to run the car. Considering the drag the car in road, mechanical force as much as F1 is needed, with respect to vehicle dynamic theory, F1 includes four terms: air resistance (F_d), wheel friction (F_r), upward drag force (F_c) and accelerating force (F_a) as:

$$F1 = F_d + F_r + F_c + F_a \qquad (1)$$

Aerodynamic force (F_d) is resulted by interaction between vehicle body and air by car movement. This force itself has three terms each of which created by an aerodynamic phenomena: shell traction friction, induced force created behind the vehicle and finally natural pressure force that is rational to front of car and driving speed. The third term is greater than two other terms, and so aerodynamic power could rewritten as:

$$F_d = 0.5\rho \times C_d \times A \times V^{2} \qquad (2)$$

Where, C_d is aerodynamic traction coefficient ρ is air density, A is car front area and V is the current speed. Rotational resistance force that is because of while deformation can be explained as:

$$F_r = M \times g \times C \qquad (3)$$

Where, M is mass of car, g is gravity and C is rotational resistance coefficient. The upward drag force is simple and obeys:

$$F_c = M \times g \times \sin(\alpha) \quad (4)$$

Where, α is ramp degree. The acceleration force to drive the car can be derived form:

$$F_a = M \times \frac{dV}{dt} \quad (5)$$

Hence, total force can be rewritten as:

$$F_1 = \frac{0.5\rho \times C_d \times A \times V^2 + M \times g \times C + M \times g \times \sin(\alpha) + M \times dV}{dt} \quad (6)$$

Multiplying this force to velocity, needed power to drive the car is calculated by:

$$P_{Load} = \frac{(0.5\rho \times C_d \times A \times V^2) \times \mathrm{V}}{3600} + \frac{(M \times g \times C + M \times g \times \sin(\alpha) + M \times dV) \times \mathrm{V}}{3600} \quad (7)$$

Considering efficiency of studied electric vehicle electric, power demand to drive the car is obtained by:

$$P_{\mathrm{Req}} = (P_{Load} \times \eta) - P_{PV} \quad (8)$$

In the above equation, P_{PV} is the power produced by the photovoltaic cells and P_{Req} is the power required that should be supplied by batteries and supercapacitors.

To have enough power at all time reliably, ESS should have enough power and on the other hand considering $K_{Bat}(t)$ and $K_{sc}(t)$ as battery and super capacitor power factors, the amount of power that is extracted from each power sources can be calculated from:

$$P_{Bat} = K_{Bat}(\mathrm{t}) \times P_{\mathrm{Req}}(\mathrm{t})$$
$$P_{SC} = K_{SC}(\mathrm{t}) \times P_{\mathrm{Req}}(\mathrm{t}) \quad (9)$$

Also sum of power factors for battery and super capacitor should be unit at all time. Moreover, if SOC of battery and super capacitor rich to more than selected amount, their ability to absorb regenerative breaking power will reduce. On the other hand if SOC become very low, ESS may have lower power than the needed amount in acceleration stage. To increase the life of battery and super capacitor, the stored energy should be in predefined range. Energy resource of solar powered EVs charging constrains are as following.

$$SOC_{Bat}^{Min} \le SOC_{Bat}(\mathrm{t}) \le SOC_{Bat}^{Max}$$
$$SOC_{SC}^{Min} \le SOC_{SC}(\mathrm{t}) \le SOC_{SC}^{Max} \quad (10)$$

In this paper, the lower and upper level of capacitor and battery storage limits are 0.2 and 0.8 respectively. Considering all the above mentioned notes, mathematical model to manage energy of these to sources can be formulated as following:

$$Min \quad Energy_{\mathrm{Req}} \; |K_{Bat}(\mathrm{t}), K_{SC}(\mathrm{t})$$
$$St.$$
$$P_{\mathrm{Req}} = (P_{Load} \times \eta) - P_{PV}$$
$$SOC_{Bat}^{Min} \le SOC_{Bat}(\mathrm{t}) \le SOC_{Bat}^{Max}$$
$$SOC_{SC}^{Min} \le SOC_{SC}(\mathrm{t}) \le SOC_{SC}^{Max} \quad (11)$$

MIXED INTEGER GENETIC ALGORITHM

MIGA is an optimization technique for solving the integer and mixed integer constrained optimizations. Here, this technique is modified to find a stable solution of the protection coordination problem using FCLs. Different functions of the basic GA, including the power mutation and Laplace crossover functions have been modified and an especial truncation procedure has been used to cope with the integrality constraints. A parameter free penalty approach is used to handle the problem constraints. In the following formulation, *n* is the number of variables indexed by *i*.

The modifications with respect to the original GA algorithm are presented here. The Laplace crossover function that was originally proposed by Deep and Thakur, is the first function that is modified here [13]. According to Deep and Thakur, two offspring y^1 and y^2 are generated from two parents x^1 and x^2 based on Eq. (12), where β_i is a random number that satisfies the Laplace distribution based on Eq. (13) [13]. In Eq. (13), u_i and r_i, both between 0 and 1, are two uniformly distributed random variables and *a* and *b*>0 are location and scaling parameters, respectively. For the continuous variables $b=b_{real}$ and for the integer variables $b=b_{int}$.

$$y_i^1 = x_i^1 + \beta_i . \left| x_i^1 - x_i^2 \right|$$
$$y_i^2 = x_i^2 + \beta_i . \left| x_i^1 - x_i^2 \right| \quad (12)$$

$$\beta_i = \begin{cases} a - b.\log(u_i), & r_i \le 0.5 \\ a + b.\log(u_i), & r_i > 0.5 \end{cases} \quad (13)$$

Deep and Thakur proposed a power distribution for mutation process [14].

Solution x is generated in the vicinity of a parent solution $\bar{x}$ using Eq. (14). The variable s follows the power distribution ($s=w^p$). Variable w is a uniformly distributed random variable between 0 and 1. The index of mutation is denoted by p. The values of this index for integer and continuous variables are p_{int} and p_{real}, respectively. In Eq. (14), r is a random variable with uniform distribution. Notations x^l and x^u are used for the lower and upper bounds of the decision variable x, respectively.

$$x = \begin{cases} \bar{x} - s(\bar{x} - x^l), & t < r \\ \bar{x} + s(x^u - \bar{x}), & t \geq r \end{cases}$$

$$t = \frac{(\bar{x} - x^l)}{(x^u - \bar{x})} \tag{14}$$

In order to select the individuals from the population to be inserted into the mating pool, the same selection technique as proposed by Goldberg and Deb is also used here [15]. To ensure that after crossover and mutation operations, the integrality constraints are satisfied, a truncation procedure is adopted. If variable x_i does not have an integer value after these operations, the value of this variable is changed to $[x_i]$ or $[x_i]+1$ each with the probability of 0.5, where $[x_i]$ is the correct part of x_i.

In order to find a solution that satisfies the problem constraints, a parameter free penalty function approach is adopted [16]. The fitness value for jth solution is calculated using Eq. (15), where f_w is the value of objective function for the worst feasible solution available in the current population. Under such setup, the fitness value of a solution depends on the degree of constraint violation and also the population in hand. In the case where there is no feasible solution so far, f_w is set to zero.

Based on Deb's work, such constraint handling technique pushes the infeasible solutions towards the problem feasible region [16]. k^{th} inequality constraint and the penalty function regarding to this constraint is shown in Eq. (16) for solution j. In order to satisfy the equality constraints in the final solution these constraints are managed to be changed into two inequality constraints using a constraint satisfaction tolerance.

$$fit(X_j) = \begin{cases} f(X_j), & \text{if } X_j \text{ is a feasible solution} \\ f_w + \sum_{k=1}^{K} \left|\phi_k(X_j)\right|, & \text{otherwise} \end{cases} \tag{15}$$

$$g_k(X) \leq G_k$$
$$\phi_k(X_j) = G_k - g_k(X_j) \tag{16}$$

FUZZY CONTROLLER DESIGN

In order to manage the energy stored in battery and super capacitor sustainably, in each time step, a sustainable decision for power factors should be made. According to energy management rules and constraints between two energy storage sources, the optimization problem is nonlinear, and therefore conventional optimization approaches cannot be employed. Fuzzy control is one of best approaches to tackle this optimization problem. Fuzzy control can be easily used for nonlinear problems [17].

Fuzzy Systems

A simple block diagram of energy management fuzzy control is illustrated in Figure 2. Battery and super capacitor charging state are input of this control system and output is battery power factor. Once battery power factor is determined, the super capacitor power factor could be easily determined, since the sum of these factors is unit at all times. Inputs and output membership functions are illustrated in Figure 3.

Proposed Optimized Fuzzy Controller based on Genetic Algorithm

In spite of the capability of fuzzy systems, the design of fuzzy systems need to knowledge of expert human that may not be available. To solve this problem, in this paper, genetic algorithm is used to optimize the design of fuzzy controller. As shown in Figure 3, the membership function of the required power is symmetrical around zero.

This membership function can be determined individually by three parameters. These parameters are named z_1, z_2 and z_3 as shown in Figure 4. Similarly, to determine membership function of battery and super capacitor, parameters z_4 and z_5 are needed. Also, output membership function should be determined by z_6 and z_7. In fact, these seven parameters are the optimization variables.

There are three states for battery SOC and three states for super capacitor SOC and seven states for required power state. Hence there are 63 if and then rules in the fuzzy system. These 63 rules introduce 63 decision variables; these variables are integers. Moreover, there are five state variables for the output. As mentioned earlier GA is employed to optimally determine the fuzzy rules and fuzzy membership of inputs and output. There are continuous and integer variables in this optimization problem. GA is used to properly handle these variables and determine these variables such that the fuzzy system has the best performance. Once the variables are determined, the fuzzy system can be used to optimally determine the battery and super capacitor power factor in different times in the driving cycle.

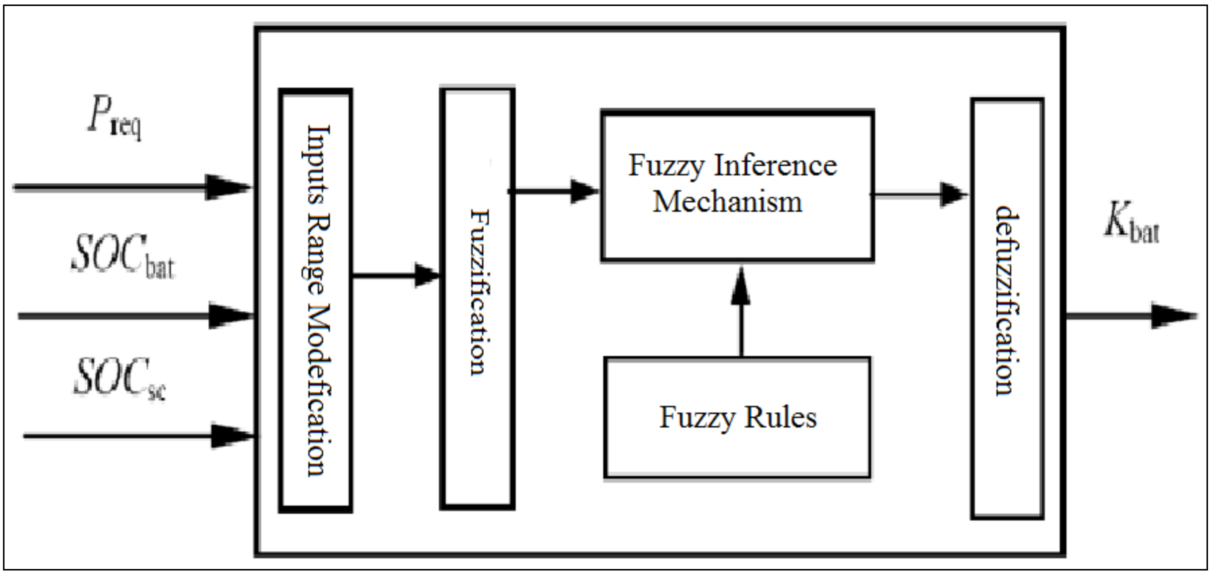

Fig. 2: *Fuzzy Control System Block Diagram.*

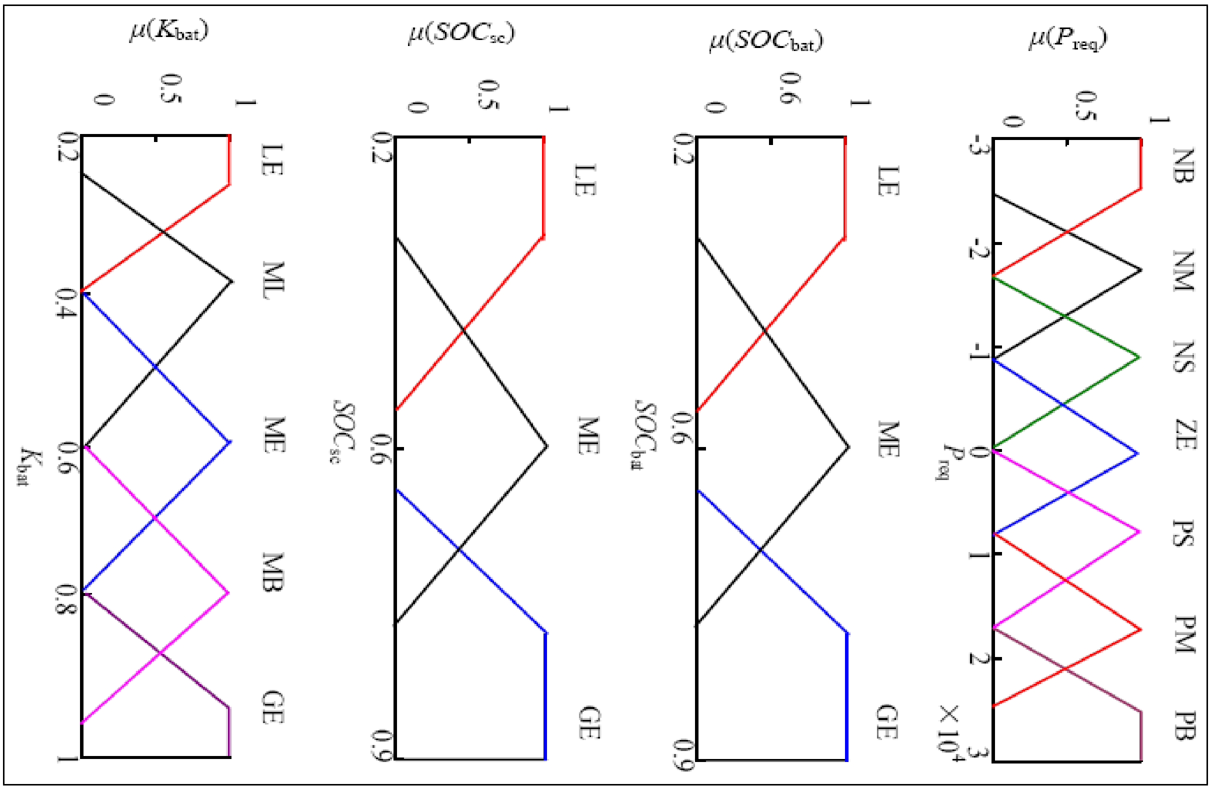

Fig. 3: *Input and Output Membership Functions.*

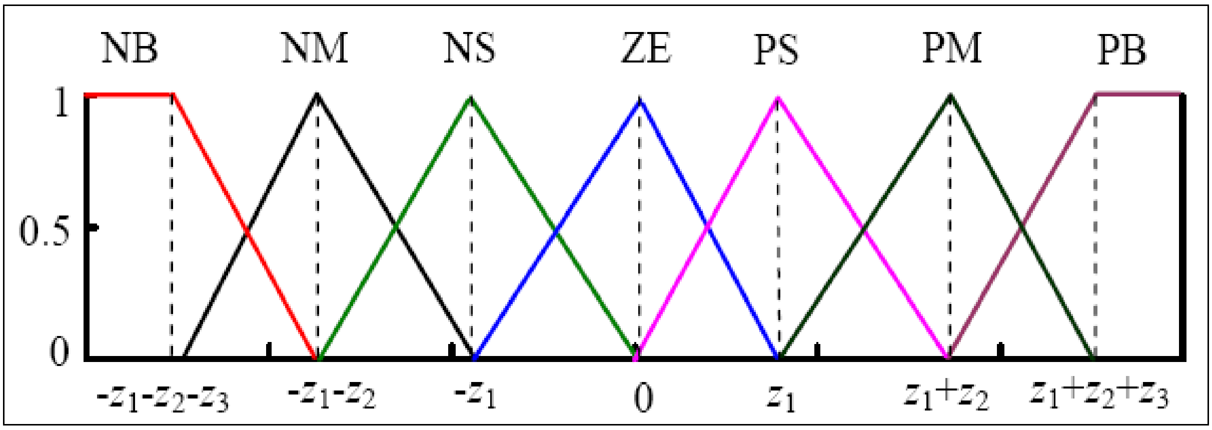

Fig. 4: *Parameters of Required Membership Function.*

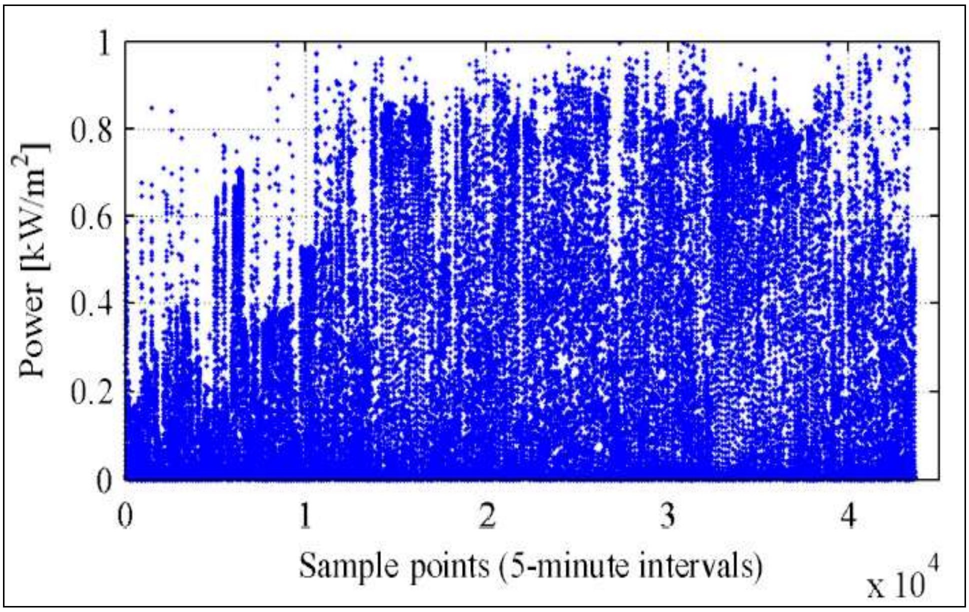

Fig. 5: *Solar Radiation in a Five Months Period.*

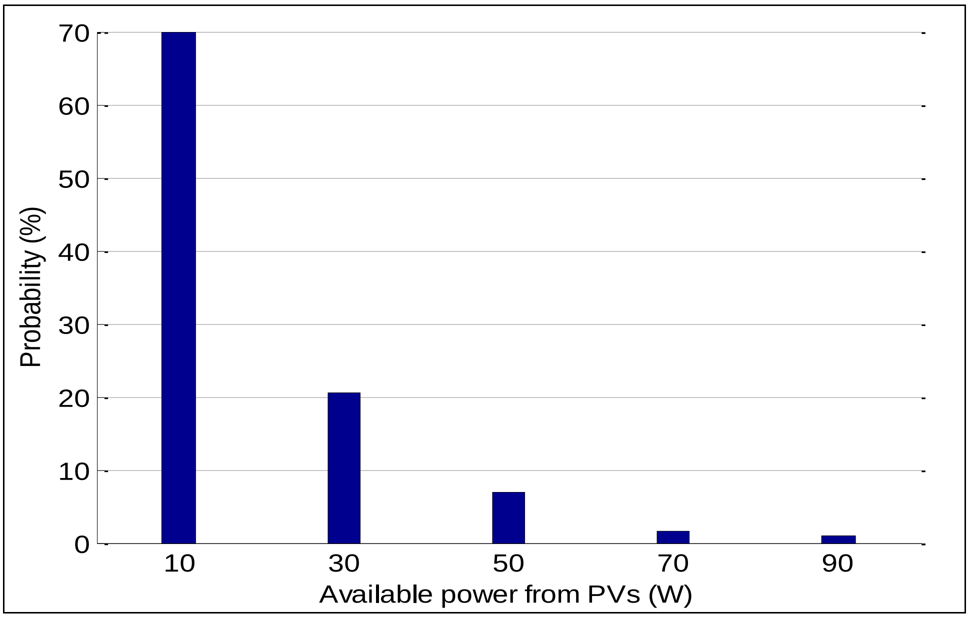

Fig. 6: *Available Power from PVs and the Associated Probability.*

CASE STUDY

Developed optimal fuzzy controller is employed to control the battery and super capacitor SOC in solar powered EV. Some simulation results are provided and compared with ordinary fuzzy controller results. To generate the driving force, solar powered EV uses photovoltaic cells, battery and capacitor.

The solar radiation in a 5 months period is presented in Figure 5. Using the above figure, the available power from the PVs with the associated probability is extracted and shown in Figure 6.

To evaluate suggested method, a standard driving cycle has been used. Figure 7 shows the characteristics of this cycle.

By simulating this driving cycle in ADVISOR, total and time frame amount of required power can be excluded. The required motor power in each second is shown in Figure 8. In order to evaluate the developed method in this paper, first energy management results by ordinary fuzzy controller have been calculated and then the results of developed fuzzy control method is presented.

Ordinary Fuzzy Control

Using ordinary fuzzy control and simulation of driving cycle second by second, with respect to required power, SOC of super capacitor and battery can be calculated. Figure 8 shows the battery quota of generated power. Hence super capacitor quota simply can be calculated.

Figures 8 and 9 show the super capacitor and battery SOCs. Primitive value of SOCs are considered to be 80% of maximum capacity. It can be seen from Figures 9 and 10 that the minimum power charge constrains are not met. The total supplied power by battery and capacitor is 6.71 MJ.

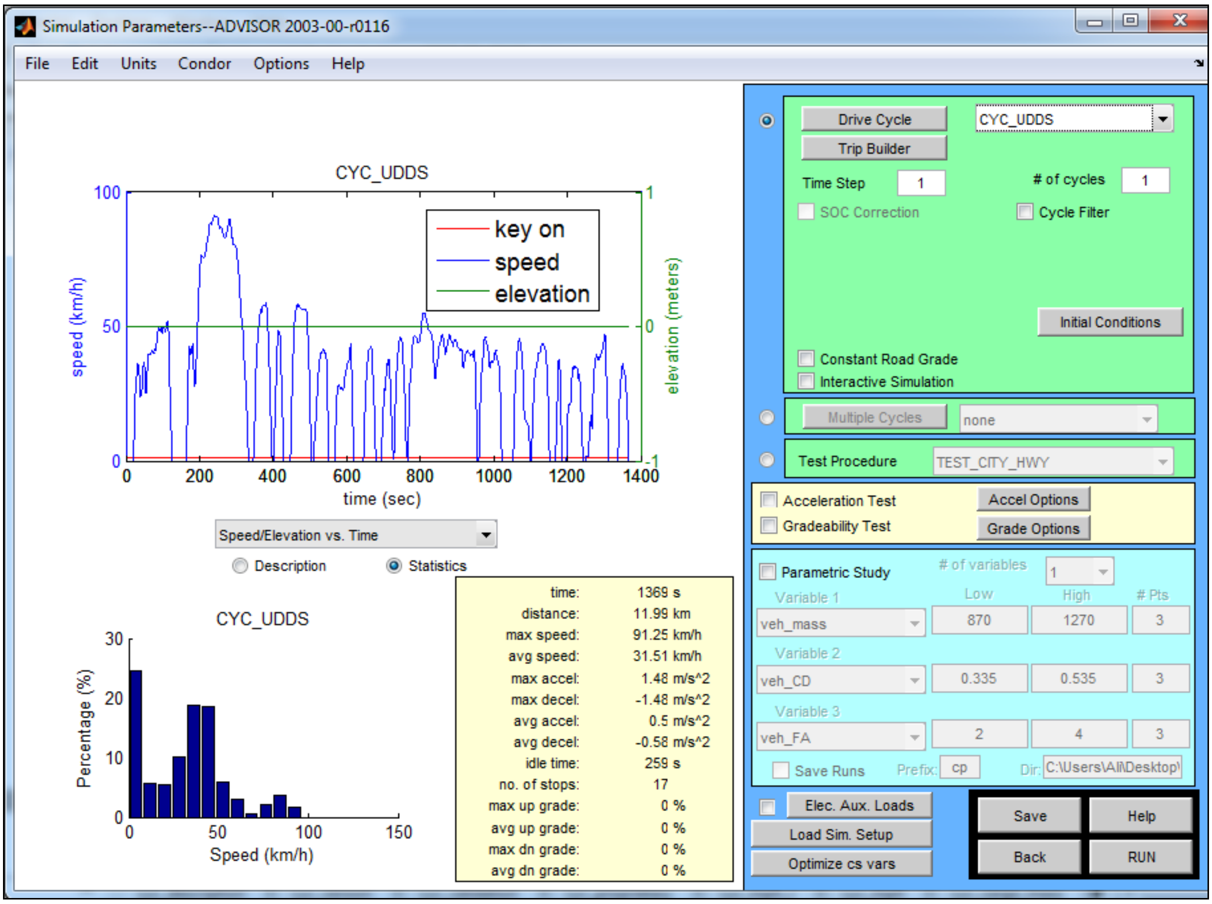

Fig. 7: *Driving Cycle in ADVISOR Software.*

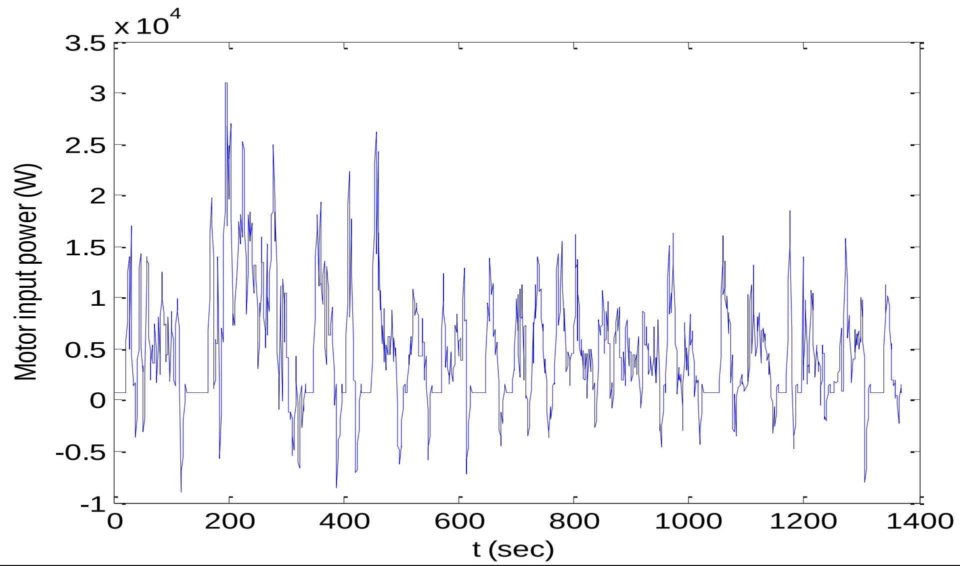

Fig. 8: *Required Power with Respect to Time.*

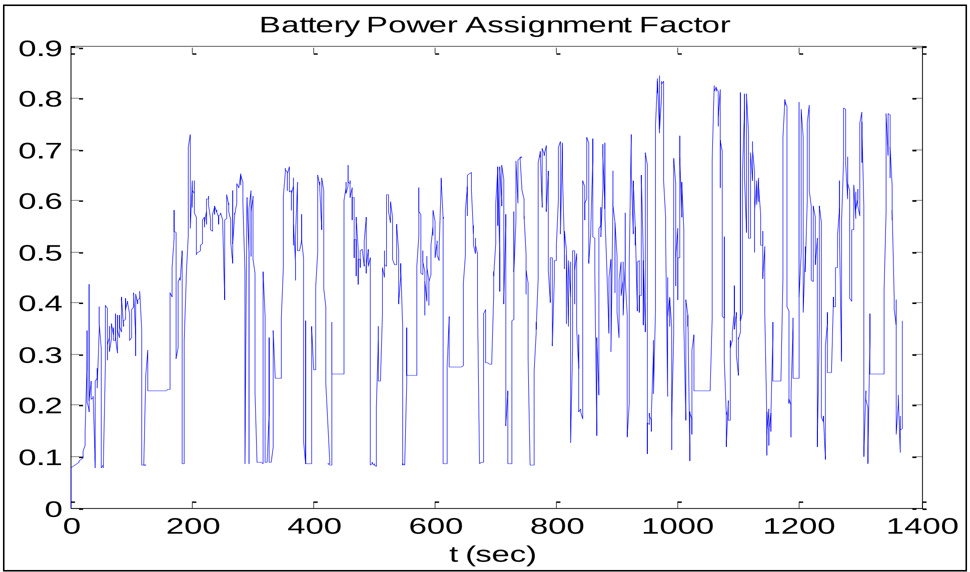

Fig. 9: *Battery Quota of Required Power Resulted from Ordinary Fuzzy Control.*

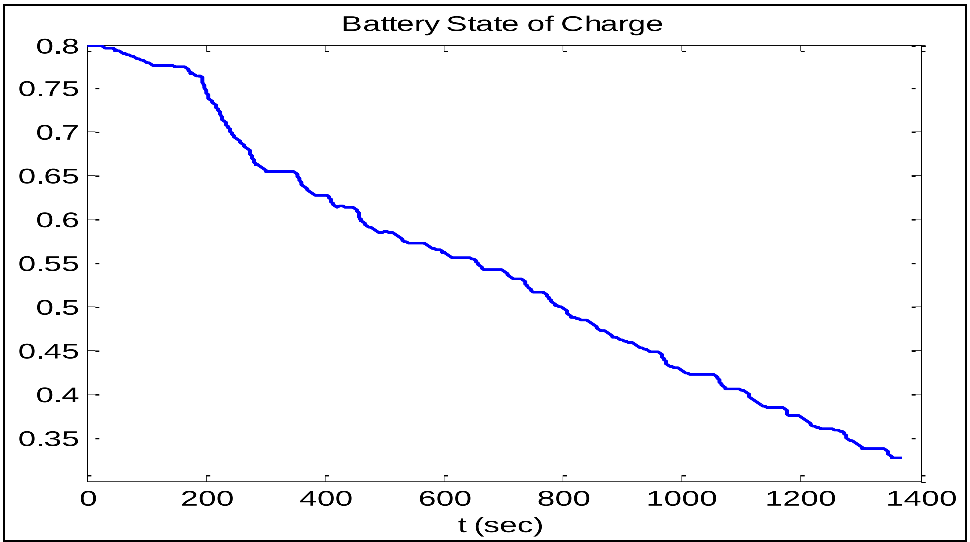

Fig. 10: *Battery SOC Resulted by Ordinary Fuzzy Control.*

Optimal Fuzzy Control

Using optimal input and output membership function and if and then rules and simulating driving cycle second by second SOC of super capacitor and battery can be extracted. Figure 12 shows batteries portion of required power. Figures 13 and 14 show the super capacitor and battery SOC in driving cycle. It is shown that minimum stored energy constraint cannot be met by ordinary fuzzy control. By optimal control the minimum energy constraint has been met. Also, total energy consumption by optimal fuzzy control is 6.52 MJ.

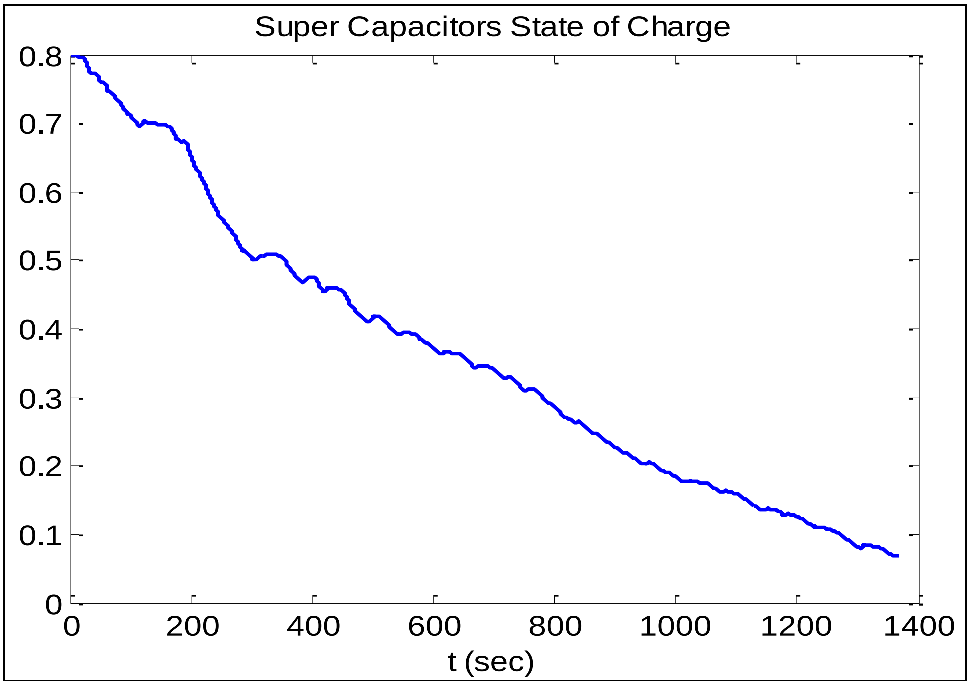

Fig. 11: *Super Capacitor SOC Resulted by Fuzzy Control.*

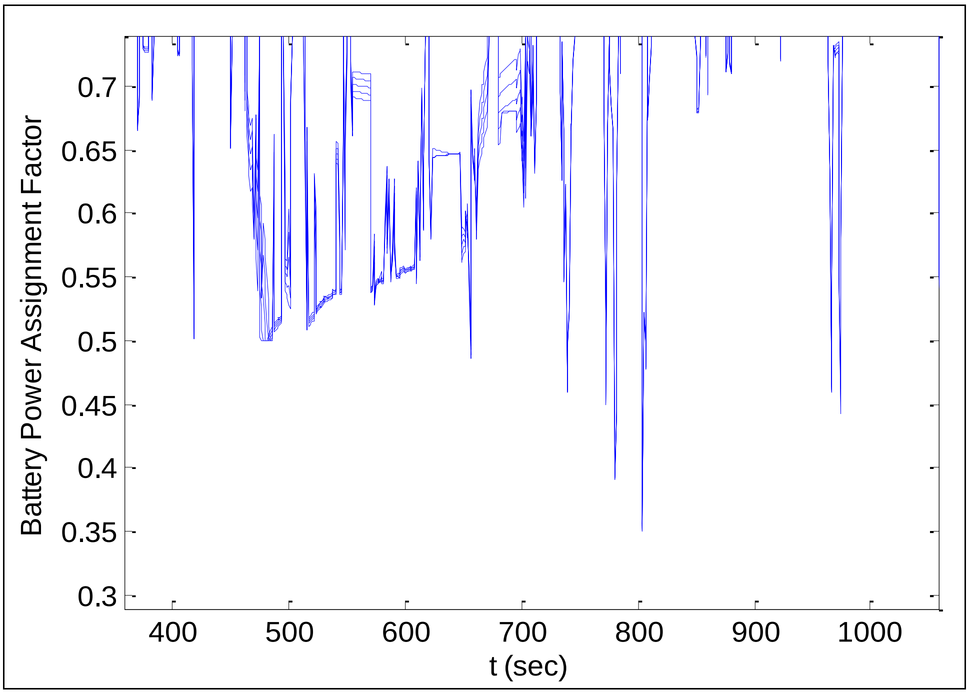

Fig. 12: *Battery Portion of Consumed Power.*

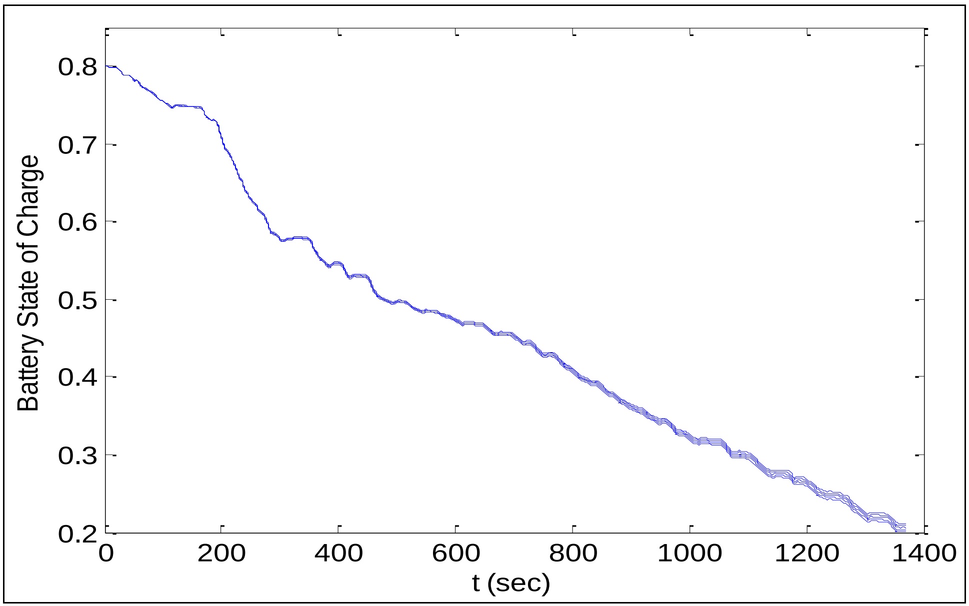

Fig. 13: *SOC of Battery in Driving Cycle Resulted by Optimal Fuzzy Controller.*

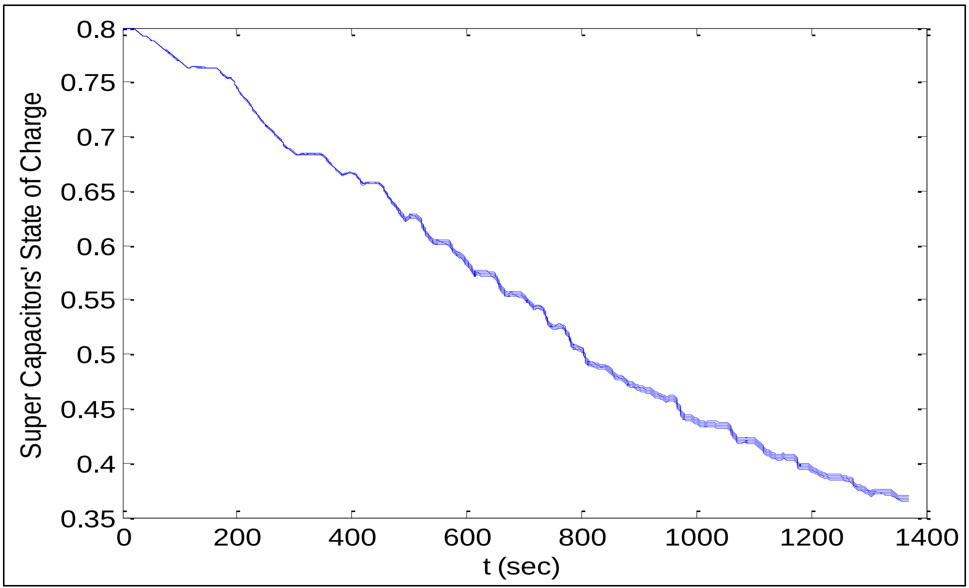

Fig. 14: *SOC of Super Capacitor in Driving Cycle Resulted by Optimal Fuzzy Controller*.

CONCLUSION

Conventional and GA-based fuzzy controllers have been used in this paper for optimal energy management of solar powered EVs. Standard driving cycle was used to evaluate the effectiveness of the proposed approach. Results demonstrated that the conventional fuzzy controller is not as effective as GA-based fuzzy controller since the minimum SOC constraints of battery and supercapacitor are violated in conventional fuzzy controller. Moreover, 2.6% reduction was observed in total energy consumption in the proposed GA-based fuzzy controller in comparison with the conventional fuzzy controller. Furthermore, the importance of optimal fuzzy membership functions and fuzzy rules was shown in the simulations.

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