An Adaptive Fuzzy Logic Based Energy Management Strategy for Electric Vehicles

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Abstract— **one of the key issues for electric vehicle (EV) development is the energy management strategy, especially for those with hybrid energy storage systems. A fuzzy logic based energy management strategy (FEMS) is proposed in this work to determine the power split between two energy storage sources: a battery tank and an ultracapacitor tank. Fuzzy logic control is chosen because of the nonlinearity of the EV plant and real-time control issue. The FEMS is further improved to be adaptive for better control performance. The underlying principle of this adaptive fuzzy logic control is to maximize the system efficiency, to maintain ultracapacitor charge state, and to minimize the battery current variation. NetLogo is used to assess the performance of the proposed methods. Simulation results show that the proposed control method produces better and balanced performance in terms of comparison criteria.**

Keywords—Electirc Vehicle; batteries; ultracapacitors; fuzzy logic; adaptive; energy management strategy

I. INTRODUCTION

Hybrid electric vehicles (HEVs) using an internal combustion engine (ICE) as well as a battery tank as a secondary energy source are the main portion of renewable energy vehicles in the market at present. However, it is believed that such HEVs are only intermediate products between conventional vehicles and pure electric vehicles (PEVs), which use batteries as the primary energy sources. With the rapid development of battery technologies, lithium-ion batteries today have reasonable energy density but become much cheaper, which makes it possible to utilize them to supply energy to the demand of a vehicle. Except batteries, other energy storage sources such as traditional ICEs, fuel cells, fly wheels and ultracapacitors may also be selected to assist batteries, forming a hybrid energy storage system (HESS). HESS is always preferred because two or more energy storage sources allow synergy among them and this kind cooperation promises a better vehicle system performance than that with a single-energy storage source. How those energy storage sources work together becomes an energy management strategy (EMS) problem for HESS.

Researchers in various areas have proposed different EMSs for different HESS structures. Farzard [1] classified the main proposed approaches of the energy management strategies into two categories: rule-based and optimization based energy management strategies. Rule-based EMSs, which could be further classified as deterministic rule-based and fuzzy rule-based EMSs, are favored by automobile manufactures because of their simplicity and effectiveness in real-time supervisory control properties. For example, energy control on Toyota Prius and Honda Insight are both based on a deterministic rule-based management strategy, called power follower control strategy [1, 2].

In research communities, some focus on using fuzzy logic based EMSs to control the power split between an ICE and a battery-supported electric motor [3-6]. The main idea of these EMSs is to leveling the operation points of the ICE onto its high efficiency curve with the complement energy supplied by batteries to increase the ICE efficiency and decrease emission. Some also used fuzzy logic in a fuel cell-battery dual energy source system [7-8]. They use batteries to reduce transient response of fuel cells. However, only few authors make use of fuzzy logic to develop EMSs for a battery-ultracapacitor dual energy source system [9], not mention an adaptive fuzzy logic based EMS.

A fuzzy logic based energy management strategy (FEMS) is proposed in this work first and then this FEMS is further improved to be an adaptive fuzzy logic based energy management strategy (AFEMS) to provide a better performance. Fuzzy logic is chosen because vehicle driving is a non-linear process and fuzzy logic control is a convenient practical alternative for such process since it utilize heuristic information for control. Also, the fuzzy logic controller does not have real-time calculation issues, which is critical for real vehicle applications.

In Section II, the simulation system configurations including vehicle configurations, battery model, ultracapacitor model, and driving cycle are provided. In Section III, FEMS and AFMES are presented and discussed in order. Section IV defines the comparison criteria and provides simulation results with corresponding analysis. Finally, a short conclusion and discussion on further work are given in Section V.

II. SYSTEM CONFIGURATION AND BACKGROUND

First, vehicle configurations used in this work are given in this section, followed by the battery and ultracapacitor model used in this work. Finally, how to select an appropriated testing driving cycle is briefly explained as the background.

A. Vehicle Configurations

Figure 1 shows the overview of the vehicle configurations used in this work. The battery and ultracapacitor tanks form a dual-energy storage system. The battery tank is connected with a unidirectional DC/DC converter while the ultracapacitor tank is connected with a bidirectional DC/DC converter. The unidirectional DC/DC converter is used to implement the proposed energy management strategy and the bidirectional

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DC/DC converter is used for voltage stabilization on the bus terminal. Solid lines in Fig. 1 represent the energy flow while the dashed lines represent the signal flow. In the driving procedure, the battery tank would supply calculated current according to the specified energy management strategies implemented in the vehicle controller and the ultracapacitor tank would supply the complement current to meet the demand of the driving cycle.

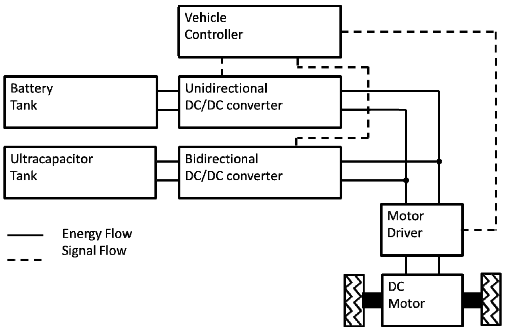


Fig. 1. Overview of vehicle configuration

B. Battery and Ultracapacitor model

The model of the battery used in this work is shown in Fig. 2(a). It is composed of an ideal DC voltage source (OCV), a series resistor (R_S), two additional resistors R_1, R_2, and two additional capacitors C_1, C_2. Each value of these six elements can be represented as a sixth-order polynomial function of the State of Charge (SOC) of the battery and all the coefficients are determined based on experimental data regression on a specific battery cell in this work (Lishen Lithium-ion Power Cell of LP2770102AC-12.5 Ah). For example:

$$R_s = 0.02 - 0.236 \cdot SOC - 1.6899 \cdot SOC^2 - 5.66 \cdot SOC^3 + 9.67 \cdot SOC^4 - 8.13 \cdot SOC^5 + 2.67 \cdot SOC^6 \quad (1)$$

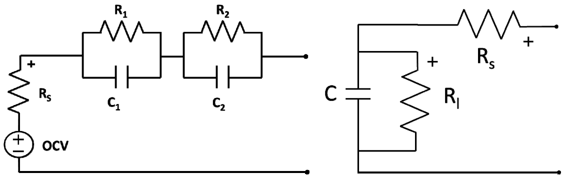
$$OCV = 2.3016 + 15.962 \cdot SOC - 99.56 \cdot SOC^2 + 295.2 \cdot SOC^3 - 446.49 \cdot SOC^4 - 331.41 \cdot SOC^5 - 95.559 \cdot SOC^6 \quad (2)$$

Coefficients of R_1, R_2, C_1 and C_2 are summarized in Table 1 for simplicity, where ai is the coefficient of the i-th order term.

TABLE 1 COEFFICIENTS OF R_1, R_2, C_1 AND C_2

	a0	a1	a2	a3	a4	a5	a6
R_1	0.3469	-3.555	13.81	-25.05	21.49	-7.028	0
C_1	-87.29	2052	-9051	18400	-17830	6635	0
R_2	0.2484	-3.991	27.3	-89.26	149	-122.3	39.08
C_2	-523.6	17740	52440	-561400	1475000	-1618000	641600

The model of the ultracapacitor used in this work (NIPPON CHEMI-CON N3ELD) in shown in Fig. 2(b), which consists of an ideal large-value capacitor, a parallel leakage resistor (R_l), and an equivalent series resistor (ESR). The values of the ESR, R_l and the nominal capacitance are set to be 1.1mΩ, 2MΩ and 2200F, respectively, according to the product manual.



(a) (b)

Fig. 2 Battery and ultracapacitor models

C. Driving Cycles

The driving cycle used in this work is a 3-in-1 driving cycle, which is a combination of three different but commonly used driving cycles [10-12]: NYCC, JC08 and WHFET. The purpose of this combination is to reform a new driving cycle that is corresponding to typical work-to-home trip in Shanghai, China in terms of trip length, average speed, speed distributions and other driving patterns. By combining the three existing driving cycles, a new driving cycle is produced and this new driving cycle is basically consistent with the such information mentioned above released by an annual report published by Chinese Academy of Sciences in 2012 [13] and a report published by Shanghai Academy of Environmental Sciences in 2005 [14].

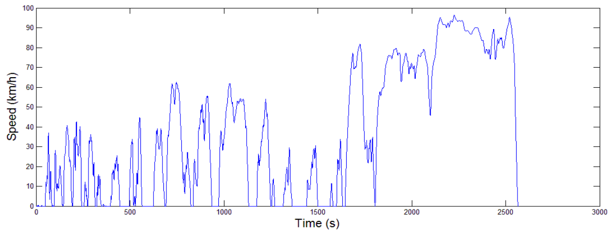


Fig. 3 Combined driving cycle

III. AN ADAPTIVE FUZZY LOGIC BASED ENERGY MANAGEMENT METHOD

This section consists of three sub-sections. First, the underlying principles of the proposed EMS are presented. Next, we describe this fuzzy logic based energy management strategy (FEMS) according to the underlying principles. Finally, an adaptive fuzzy logic based energy management strategy (AFEMS) is further developed in the last sub-section.

A. Underlying principles

There are three basic principles under consideration during the development of the proposed energy management strategy.

Principle No.1: The power demand of the driving cycle should be satisfied consistently. Even though the usage scenario might be different, EVs are supposed to replace conventional vehicles when being used. Therefore, driving an EV should at least not 'feel' different from driving a conventional vehicle [15]. So an energy management strategy should be able to be applicable without compromising consumer expectations with respect to vehicle performance.

Principle No. 2: Battery lifetime, efficiency and state of health (SOH) are largely dependent on the absolute value of the current and current dynamics of batteries. It is easy to show that larger discharging current would significantly increase energy loss on the battery internal resistor, which leads to lower battery efficiency and this result has been validated by experiments [16]. Also, larger variation in the discharging current would lead to damage to batteries resulting in shorter battery lifetime and poorer state of health. In [17], the author shows that the pulse load, even with the same average current, leads to higher temperature increasing compared to a constant average load. Therefore, the battery current should be kept in a low absolute level and unchanged as much as possible. That is why ultracapacitors are taken into consideration to form a hybrid energy storage system (HESS).

<u>*Principle No. 3*</u>: Batteries are the only real 'energy' sources on the vehicle. The energy demanded by the driving cycle should be supplied by the energy from batteries only, and ultracapacitors are only used as energy buffers. The purpose of involving ultracapacitors in this dual-energy storage system is to lower and guarantee a much smoother load profile for the battery tank. Ideally, the SOC of the ultracapacitors at the end of a trip is expected to be the same as that at the beginning of the trip.

B. Fuzzy logic based energy management strategy (FEMS)

A general fuzzy logic controller (FLC) is shown in Fig. 4. The proposed EMS has two inputs and one output. The inputs are instant power demand from the driving cycle and the instant ultracapacitor tank voltage; the output is the current which the battery tank would supply at that moment.

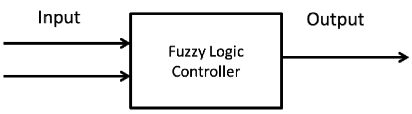


Fig. 4 A general fuzzy logic controller

The FLC in this work contains three steps: fuzzification, finding rules, and defuzzification, as shown in Fig. 5. They are discussed in detail as follows.

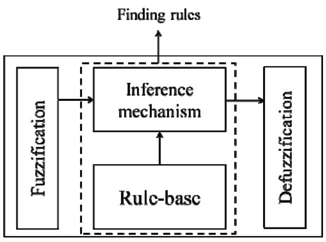


Fig. 5 Three steps of a FLC

STEP 1 FUZZIFICATION: In fuzzy logic, the membership function is used to convert crisp inputs into fuzzified inputs. Figure 6 shows the membership function of the power demand.

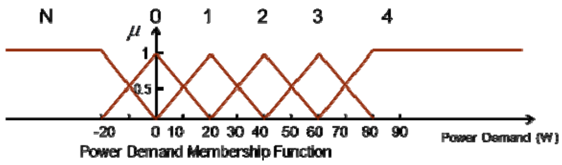


Fig. 6 Membership function of power demand

The power demand of the driving cycle is divided into five categories: 'N', '0', '1', '2', '3', '4', respectively; each one has its own μ value. For example, when the power demand is 30 watts, the μ values of 'N', '0', '3' and '4' are all 0, and the μ values of '2' and '3' are both 0.5. Similarly, the membership function of another input – ultracapacitor (UC) tank voltage, is shown in Fig. 7.

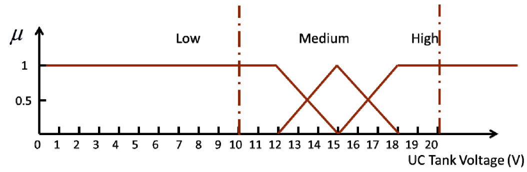


Fig. 7 Membership function of UC tank voltage

The ultracapacitor tank voltage is divided into three categories: 'low', 'medium' and 'high', respectively; each one has its own μ value too. For example, when the supercapacitor voltage is 13.5 volts, then the μ value of 'low' is 0.5, the μ value of 'medium' is 0.5 and the μ value of 'high' is 0.

STEP 2 FINDING RULES: After the fuzzified inputs are obtained, rule-base is used to find out the fuzzy conclusions. This part is more like an expert system, experience and heuristic information are used for control decision making. Before the rule-base is set up, in the proposed EMS, we divide vehicle speeds into four categories in order to make a single big rule-base into four parallel sub-rule-bases.

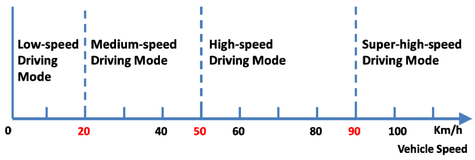


Fig. 6 Drivng Mode classification

As shown in Fig. 6, we define four driving modes: low-speed, medium-speed, high-speed and super-high-speed according to different vehicle speeds. Then the four sub-rule-bases are defined for each of the four driving modes as shown in TABLE 2.

TABLE 2 FOUR SUB-RULE-BASES

Low-speed Mode Rule-base

I_BatTDC Level		Power Demand Level				
		N	0	1	2	3
UC LV	L	1	2	2	3	3
	M	1	1	2	2	3
	H	0	1	1	2	2

Medium-speed Mode Rule-base

I_BatTDC Level		Power Demand Level				
		N	0	1	2	3
UC LV	L	2	2	3	3	4
	M	1	2	2	3	3
	H	1	1	2	2	3

High-speed Mode Rule-base

I_BatTDC Level		Power Demand Level				
		N	0	1	2	3
UC LV	L	2	3	3	4	4
	M	2	2	3	3	4
	H	1	2	2	3	3

Super-high-speed Mode Rule-base

I_BatTDC Level		Power Demand Level				
		N	0	1	2	3
UC LV	L	3	3	4	4	5
	M	2	3	3	4	4
	H	2	2	3	3	4

The conclusions drawn from these rule-bases are the fuzzified battery tank current, which is represented by six levels '0', '1', '2', '3', '4', '5', respectively. For example, when the vehicle speed is 40 km/h, which means it is in medium-speed mode, the second table is picked up as the rule-base. If the μ values of ‘low’, ‘medium’ and ‘high’ are 0.5, 0.5, and 0, respectively, for the ultracapacitor tank voltage level and the μ values of ‘N’,’0’, ‘1’, ‘2’, ‘3’, ‘4’ for power demand level are 0, 0.5, 0.5, 0, 0 and 0 respectively, then for the fuzzified conclusion, the μ values of ‘0’, ‘1’, ‘2’, ‘3’, ‘4’, ‘5’ are 0, 0, 0, 0.5, 0.5 and 0 respectively.

STEP 3 DEFUZZIFICATION: In Fig. 7, the output membership function is defined for converting the fuzzified outputs to crisp outputs. Many methods could be used for defuzzification. The center of gravity (COG) method is used in this work.

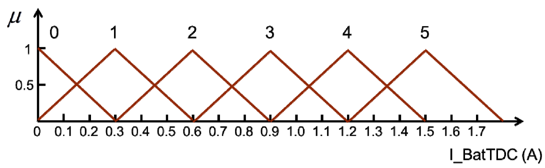


Fig. 7 Membership function of battery tank current

The COG method computes the crisp output as:

$$u^{crisp} = \frac{\sum_i b_i \int u_i}{\sum_i \int u_i} \tag{3}$$

This is a classical formula for computing the center of gravity. Here, b_i denotes the center of the membership function of the consequent of rule.

In terms of implementation, it has been shown in the literature that the frequency response of a fuzzy algorithm in a general purpose microcontroller is blow 1 kHz [18]. Therefore, a fuzzy controller is appropriate considering the dynamics of the EV system.

C. Adaptive fuzzy logic based energy management strategy (AFEMS)

In order to obtain a better control performance, the defuzzification process mentioned above is improved by considering the current occurrence number (CON). For example, we consider the combined 3-in-1 driving cycle mentioned in Section II. First, it is assumed that the battery tank is directly associated to the driving cycle load. This is reasonable because the ultracapacitor tank is ideally an energy buffer of the EV, i.e., it does not absorb or provide any energy to the EV. It is presumed that the terminal voltage of the battery tank is 20 V (in the simulation model) and we could get a driving cycle in terms of the current. Then we consider the domain where the current is greater than zero, dividing that domain into pieces of equal-length ranges and finally counting how many times each range counts, as shown on Fig. 8. As an example, the range near 0 counts about 50 times. We could find that most frequent current demands happened in the range of [0A, 2A] and this information could be used to help us form the output membership function. Thus, we redefine the output membership function to be an adaptive one as shown in Fig. 9. Here, r on the adaptive membership function of the battery tank current is associated to the range in which the current demand happens frequently. In the simulation model, the value of r is initially set to be 2 according to what we found in the analysis of the combined 3-in-1 driving cycle. As the vehicle begins to run, this r value would be altered by conducting the same analysis based on the past driving cycle information recorded. That is, the value of r is adaptively changing according to the past driving cycle patterns.

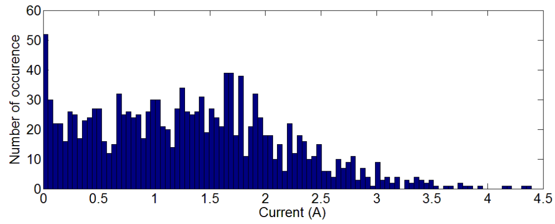


Fig. 8 CON of the combined 3-in-1 driving cycle

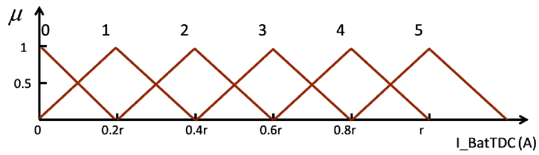


Fig. 9 Adaptive membership function of battery tank current

The next question here is the control frequency. Frequency control interrupts would cause frequent battery current changes, which should be avoided as much as possible. So once the energy management strategy decides the battery current, we would like this value to be stable as least for a while. On the other hand, if the battery current is a constant value for a too long period, it may cause the ultracapacitor tank over-charging or over-discharging. Therefore, how frequent the energy management strategy should act is a critical issue. Since a constant control frequency is apparently not appropriate, Fast Fourier Transform (FFT) is applied here to determine the control frequency. Again, take the combined 3-in-1 driving cycle as an example, its FFT result is shown in Fig. 10.

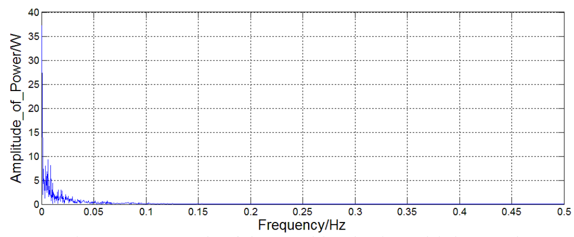


Fig. 10 FFT result of the combined 3-in-1 driving cycle

By analyzing where the main positive amplitude is located, we can identify the main frequency of the driving cycle f to decide the control frequency T.

The initial control frequency is set according to the analysis of the combined 3-in-1 driving cycle. After the vehicle begins to run, the baseline driving cycle referred would be the past driving cycle which is recorded in place of the combined 3-in-1 driving cycle. Thus the control frequency is also adaptively changing according to the past driving cycle patterns.

IV. SIMULATION RESULTS AND ANALYSIS

The simulation environment is introduced first in this section. Then five compassion criteria used for validation are discussed. Next, simulation results of the proposed FEMS, AFEMS, and other benchmark rule-based EMSs are presented and analyzed.

A. Simulation environment

In this work, the battery tank and the UC tank have different properties and according to the principles discussed previously, they will function in a different but synergetic manner together in this work. Obviously the performance of one will affect another one's performance. Furthermore, even though every battery cell (or UC cell) is supposed to be identical to each other, the parameters of one cell are always slightly different from the nominal value. In this regard, a multi-agent based simulation tool, Netlogo [19], is used in this work to demonstrate different behaviors of different components, or even cells. The battery tank, UC tank, DCDC converters, and the load are treated as independent agents who follow the rules that have been set up individually. Part of the interface of the simulation environment is shown in Fig. 11. R-language is linked with NetLogo in the form of extension to deal with Fourier Transformation.

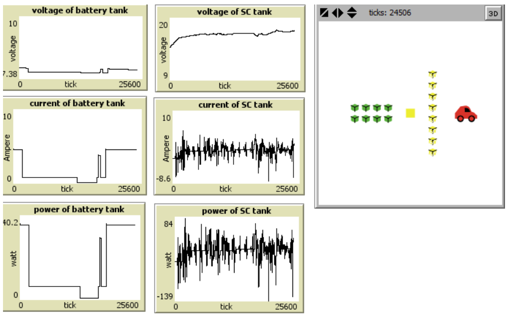


Fig. 11 Parts of the interface of NetLogo

B. Comparision criteria

We use five criteria to evaluate the performance of different energy management strategies. The first is the battery current variation. It has been shown that frequent current variation would dramatically reduce the lifetime of a lithium-ion battery [14]. For this reason, the amount of battery current variation is first considered in the evaluation. For simplicity, we consider the current from the battery tank, instead of a single battery cell, denoted as *I_BatT*. At each instant, the current difference between adjacent time steps would be recorded in an array. At the end of a driving cycle, we take the square root of this *n*-dimension array to obtain an L-2 normed value, denoted as *C*1.

$$C1 = \sqrt{\sum_{i=1}^{n} (I\_BatT_i - I\_BatT_{i-1})^2} \quad (4)$$

The second criterion shares the same idea with *C*1. In this case the value interested is the SOC variation of a typical battery cell.

$$C2 = \sqrt{\sum_{i=1}^{n} (SOC_i - SOC_{i-1})^2} \quad (5)$$

In the third criterion, we consider the energy loss in a specific battery cell by calculating the heat loss due to the internal resistance, R_S, of that battery cell, which is denoted as *C*3. The definition of *C*3 in *n* seconds is given in:

$$C3_n = R_S \times \sum_{i=0}^{n} \left(\frac{I\_BatT_i}{\#SeriesBatteryCell}\right)^2 \quad (6)$$

The forth criterion, denoted as *C*4, is another heat loss by summing the energy produced by regenerative braking when the ultracapacitor tank is already full. In that case, the energy would be dissipated in the form of heat.

$$C4 = \sum HeatLoss_{UCfull} \quad (7)$$

The fifth criterion is the system efficiency. For the whole system, we have the following equation:

$$E\_Bat + E\_SC = E\_DC + E\_Loss \quad (8)$$

where E_Bat represents the energy that the battery tank provides; E_SC represents the energy difference of the ultracapacitor tank between the beginning and the end of the driving cycle; E_DC represents the energy consumed by the load during the driving cycle; E_Loss represents the energy loss of the whole system. Thus, the definition of efficiency is given as:

$$\eta = \frac{E\_DC}{E\_DC + E\_Loss} \quad (9)$$

C. Simulation result and analysis

Three published rule-based energy management strategies are used as benchmarks to validate the proposed FEMS and AFEMS. LTM is a limited tolerance method introduced in [20]; TM is the thermostat control method presented in [21]; and ACM [22] is average current control method which sets the battery current to be a constant value in the entire driving process and ensures the initial and the terminal voltages of the ultracapacitor tank to be the same. The battery current could be calculated in the following formulation:

$$I_{dc} = \frac{\int P_{dc}(t)dt}{T \cdot U_{UC}} \quad (10)$$

where $P_{dc}(t)$ is the power demand at time *t*, *T* is the total trip length, and U_{uc} is the initial voltage of the ultracapacitor tank.

TABLE 3 shows the simulation results of the proposed FEMS, AFEMS, and the benchmark energy management strategies as well. It can be seen that AFEMS gives the best result in terms of *C*4, the second best result in terms of *C*2, *C*3 and *C*5, and the third best result in terms of *C*1. Furthermore, it should be noticed that the simulation results of AFEMS in all five comparison criteria are very close to the best simulation results from benchmark energy management strategies, which means AFEMS does provide good and balanced performance in all perspectives considered in the comparison. Even the FEMS just gives slightly worse performance compared to the AFEMS. Also notice that, unlike the ACM approach, the proposed AFEMS and FEMS does not apply any 'future' information of the driving cycle after the vehicle starts to run.

Instead, the proposed approach uses more past information recorded for the adaption.

TABLE 3 SIMULATION RESULTS

	C1. Current Variation	C2. SOC Variation	C3. Heat Loss 1	C4. Heat Loss 2	C5. System Efficiency
LTM	42.2121	0.0034	3453 J	0 J	89.6%
TM	6.3	0.0043	5789 J	0 J	83.7%
ACM	0.223	0.0091	22938 J	61958 J	56.5%
FEMS	4.6848	0.0028	4021 J	0 J	88.1 %
AFEMS	4.9	0.0025	3589 J	0 J	89.2%

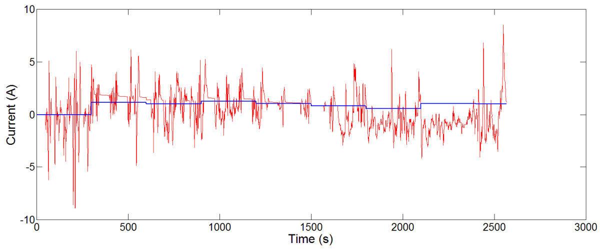


Fig 12 Current plot of FEMS

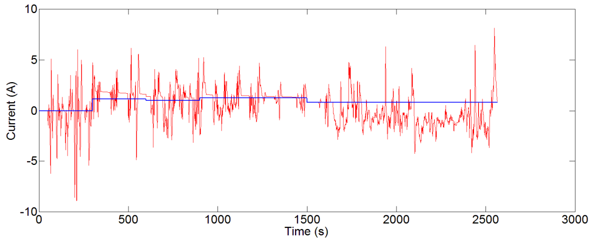


Fig. 13 Current plot of AFEMS

Figures 12 and 13 show the current in FEMS and AFEMS, respectively. The red curve is the ultracapacitor tank current curve while the blue curve is the battery tank current curve. It is clear that in both cases, the battery tank current is kept as low as possible with limited current variations. In addition, the dynamic components are all most covered by the ultracapacitor tank.

V. CONCLUSION

In this work, simulation model and energy storage source models are first introduced. Then a combined driving cycle is presented for purpose of appropriate simulations. A general fuzzy logic based energy management strategy (FEMS) is proposed to manage the power split between two energy storage sources: batteries and ultracapacitors. This FEMS is further improved to be an adaptive fuzzy logic based energy management strategy (AFEMS) to provide better and balanced performance compared with other benchmark EMSs. Simulation results showed that the proposed strategies provide a very well overall performance. More test driving cycles would be taken into the simulation to validate the proposed control method in the further work and more improvement would be done in terms of adaptive control.

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