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A Novel Design of Hybrid Energy Storage System for Electric Vehicles

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Abstract: In order to provide long-distance endurance and ensure the minimization of a cost function for electric vehicles, a new hybrid energy storage system for an electric vehicle is designed in this paper. So far, the equivalent circuit model for Li-ion battery is common-used for its simplicity and suitability for control and estimation. For the hybrid energy storage system, the paper proposes an optimal control algorithm designed using a Li-ion battery power dynamic limitation rule-based control based on the SOC of the super-capacitor. However, among existing equivalent circuit models, it is seldom to consider the temperature effect, which has a significant influence on electric vehicle (EVs) performance. At the same time, the magnetic integration technology adding a second-order Bessel low-pass filter is introduced to DC-DC converters of electric vehicles. It is difficult to find the relationship between equivalent circuit parameters and state of charge (SOC) and temperature. As a result, the size of the battery is reduced, and the power quality of the hybrid energy storage system is optimized. In our paper, the methodology of fuzzy logic is applied to model Li-ion batteries. By using fuzzy rules, SOC and temperature effect on parameters are described simultaneously with simplicity and clarity. Simulation results show that the fuzzy logic-based model has good accuracy at different temperatures.

Keywords: Electric Vehicles, Hybrid Energy Storage System, Equivalent Circuit Model; Integrated Magnetic Structure, Fuzzy Logic, DC-DC Converter.

1. Introduction

Nowadays, embedded energy storage systems in current-generation electric vehicles are mostly based on the Li-ion batteries which, with high energy density, can provide long-distance endurance for electric vehicles. In EVs, a battery management system (BMS) controls the power flow [1]. In BMS, Li-ion battery Modeling is an important issue. Only with a model predicting the battery behaviour accurately, BMS can supervise and control the Li-ion battery's operation appropriately. While compared to the super capacitor, the response of Li-ion batteries is slower than that of super capacitors[3-4]. Therefore, in order to make electric vehicles comparable to fuel vehicles with regard to fast transient acceleration, energy, and long-distance endurance, a hybrid energy storage system(HESS) consisting of Li-ion batteries and super-capacitors is applied to electric vehicles[5]. For the development of electric vehicles, optimizing the energy storage device is critical, and it is necessary to consider increasing the capacity of the battery while reducing the size and weight of the battery to increase the charging rate[6-8]. DC-DC converters which play an important role in hybrid energy storage systems have been developed rapidly over the years. Through a series of innovations, a variety of DC-DC converters are proposed. A new zero Voltage Switch (ZVS) bidirectional DC-DC converter is proposed in [9], which has good controllability to improve conversion efficiency but is not suitable for electric vehicles due to the complex control and higher cost. It has been shown an isolated bi-directional DC-DC converter[10] with a complex structure is able to convert a large power transmission. A new zero-ripple switching DC-to-DC converter with integrated magnetic technologies is first proposed in [11-12] by S.Cuk, and the application is very successful. Isolated interleaved DC/DC converter[13] introduces the concept of three-winding coupled inductors, but it is more suitable for power transmission. It is very important for hybrid energy storage systems to select a suitable energy management strategy. Energy management strategies have been extensively reported in the literature in recent years, including neural networks, fuzzy logic, state machine control, frequency decoupling method, on/off-line optimal strategies, dynamic programming (DP), and limitation of battery power[14-17]. Most Li-ion battery equivalent circuit models are discussed at a specific temperature. However, the ambient temperature also has an obvious effect on the Li-ion battery's characteristics [9-11].

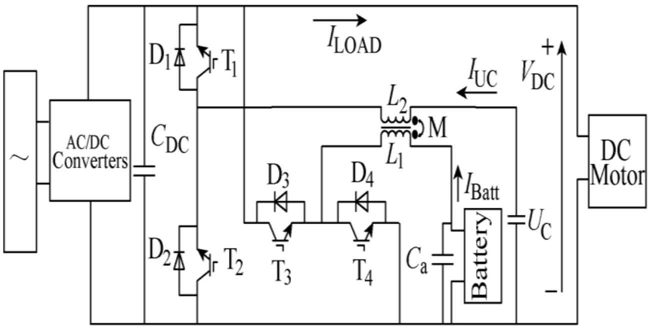
Recently, some researchers begin to describe this effect. In [9], the temperature effect on model parameters is described. In [10], the model parameters are represented by nonlinear functions of SOC and temperature. However, the model parameters are complex with the functions. These strategies can be divided into offline global optimization and online local optimization. For off-line global optimization, it is necessary to acquire the best power distribution between different sources. At the same time, for online local optimization, accurate prediction of driving conditions is necessary[18-20]. In this work, a new integrated magnetic structure of DC-DC converter is proposed and applied toa hybrid energy storage system for electric vehicles. The proposed DC-DC converter gives the specific topology and operating modes, as well as Li-ion battery and supercapacitor control.

With regards to energy management strategy, the paper proposes an optimization control algorithm designed using a Li-ion battery power dynamic limitation rule-based control based on the state of charge(SOC) of the super-capacitor.

An equivalent circuit model based on fuzzy logic for Li-ion batteries is proposed in this paper. Fuzzy systems can model dynamics using a fuzzy rule base consisting of a set of fuzzy rules, instead of complex mathematical expressions [12]. Hence, fuzzy logic [13, 14] is utilized here to describe both SOC and temperature's effect on model parameters. In this paper, a fuzzy logic-based Li-ion battery model considering SOC and temperature effect is established. The SOC and temperature effect on model parameters are represented by fuzzy rules clearly and efficiently. From simulations, it is verified that this new model has good accuracy and flexibility in the entire SOC and temperature range.

2. Related Work

Fig.1 is a proposed hybrid energy storage system composed of a DC/DC converter, supercapacitors, and the Li-ion battery. DC/DC converters consist of four IGBT switches T1~T4 and its corresponding diode (added battery) tube D1~D4, and an integrated magnetic structure self-inductance L1, L2, and mutual inductance M, which share a core inductor. The battery pack provides power to the smooth DC motor. The supercapacitor deals with the instantaneous state of peak power supply. The power management system of electric vehicles determines the electrical energy flow according to the load demand. The converter has five main operating modes (mode due to the additional battery pack change). Table 1 shows the specific operation mode of the hybrid energy storage system corresponding to energy flows and the operating mode DC-DC converter.



ig.1 Topology of the hybrid energy storage system

Design of the DC/DC converter with integrated magnetic structure

Magnetic elements such as inductors are the main components of energy conversion, filtering, electrical isolation, and energy storage. The size of the magnetic element is a major factor in determining the size and weight of the converter. To achieve the integration of magnetic elements, an E-type magnetic core is used in this paper. Herein, a coupling inductance (L1 and L2) is used.

As shown in Fig.2, L2 is the output filter inductor, L1 is the external inductance, and Ca as the additional capacitance. In the steady-state, the voltage of Ca is equal to the output voltage of L2 and L1 without regard to the capacitor voltage ripple. The DC/DC converter of Fig.1 consists of 4 IGBT switches (T1~T4) and 4 diodes (D1~D4). As a boost converter, there are two operational modes (consisting of L1, T4, D4 or L2, T2, D1); and as a buck converter, there also are three operational modes (consisting of L1, T3, D4 or L2, T1, D2). It can be seen from

Table 1 The operation mode of the hybrid energy storage system

Working mode	Power source	Power flow	Operation mode
Parking charging mode	AC power	Battery and super capacitor	Buck
Constant speed mode	Battery	DC	Boost
Acceleration mode	Super capacitor	DC motor	Boost
Braking mode	Braking energy	Battery and super capacitor	Buck
Super-capacitor charging mode	Battery	Super capacitors and DC motors	Boost or buck

Table 2, thata comparison of two structures of DC/DC converter illustrates that the volume and weight of the DC/DC converter with the integrated magnetic structure are reduced. In the electric vehicle, the application of the DC/DC converter with an integrated magnetic structure can reduce the overall size and weight of the energy storage system. Moreover, the integrated magnetic structure can reduce the output current ripple. In section 4, the effectiveness of the integrated magnetic structure is validated by simulation and experiment.

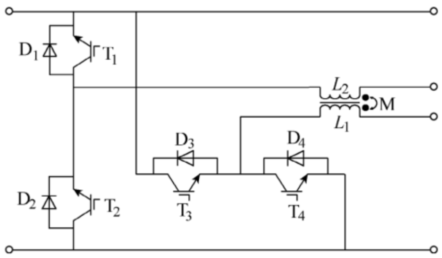


Fig.2 Topology of DC/DC converter with integrated magnetic structure

The Fuzzy Logic-Based Model For Li-Ion Battery

The above section shows that the equivalent circuit model parameters are influenced by SOC and temperature. In this section, a global fuzzy logic-based model considering the parameters' variation to SOC and temperature is established. Fuzzy logic can describe several antecedents in one rule and approximate nonlinear dynamic properties with high accuracy. Therefore, the model parameters' variation to SOC and temperature represented by fuzzy rules could model the battery dynamics accurately. In our model, the parameter values around some partition points of SOC and temperature are taken as the fuzzy rule consequents.

Fuzzy Rules Describing the Battery Capacity It has been stated that the battery capacity is almost constant around or above room temperature. When the temperature is below room temperature, the capacity decreases. To describe this variation trend, the fuzzy rule base of temperature for battery capacity Cn is determined by the following form:

$Rule^1$: IF T is ($T \geq 23$ ℃), THEN $C_n = C_{n1}$;

$Rule^2$: IF T is ($T \leq 15$ ℃), THEN $C_n = C_{n2}$,

where Cn1 and Cn2 have been obtained from the battery test. The methodology to determine the fuzzy rules for model parameters within low temperature range is similar to the temperature scope described in this section. Here, the battery capacity within the interpolate interval 15 23 << T °C is represented by a combination of these two rules with the membership function μ( ) T . Hence, the battery capacity varying with temperature is determined by:

$$C_n(T) = \sum_{m=1}^{M} \mu_m(T) \cdot C_{nm} ,$$

where $\mu_m(T)$ represents the membership functions associating to the fuzzy rules. Here,

$0 \leq \mu_m(T) \leq 1$ and $\sum_{m=1}^{M} \mu_m = 1$ The trapezoidal membership function is utilized as Fig. 12 shows.

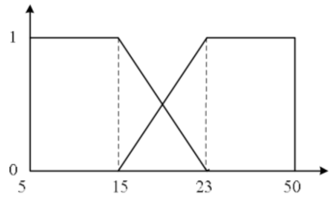


Fig. 12. The membership functions of temperature for Cn.

Fuzzy Rules Describing the Model Parameters

For the resistors in the model, the variation pattern of 2 effecting factors should be established. Firstly, the two effecting factors, SOC and temperature, are considered separately. The effect of SOC on the model parameters is analyzed based on the parameter variation trend at specific temperature. As Fig. 7 shows, the variation trend of Rs to SOC at each temperature is similar. The Rs value varies little within the region SOC > 0.2 at each temperature. In the region SOC <0.2 ,Rs begins to increase. Rs increases drastically in the rough interval SOC ∈(0,0.1) .

To describe this variation trend by fuzzy rules, the partition points and the membership functions are selected according to the Rs value over the SOC range. Then, the rules can be optimized and verified by existing fuzzy identification algorithms [15]. The partition points are amended to optimum subspace divisions to achieve high Modeling accuracy over the entire range of the antecedent SOC. In this case, considering both the model accuracy and simplicity, the partitioning points of (0.04, 0.06, 0.09, 0.2) of SOC are selected and the trapezoidal and triangular membership functions are utilized.

The fuzzy rule base is established by:

$Rule^1$: IF SOC is ($SOC \leq 0.04$), THEN $R_s = R_{s1(soc)}$;

$Rule^2$: IF SOC is ($SOC = 0.06$), THEN $R_s = R_{s2(soc)}$;

$Rule^3$: IF SOC is ($SOC = 0.09$), THEN $R_s = R_{s3(soc)}$;

$Rule^4$: IF SOC is ($SOC \geq 0.2$), THEN $R_s = R_{s4(soc)}$.

The membership functions over the entire SOC range for Rs are shown in Fig. 13.

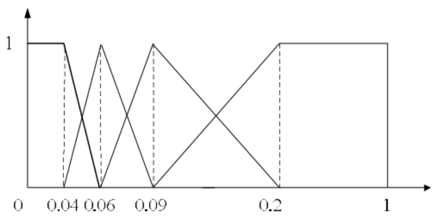


Fig. 13. The membership functions of SOC for Rs.

In Fig. 8, the variation trend for R1 at specific temperature is similar to Rs . Hence, R1's variation to SOC is represented by similar fuzzy rule base. The membership functions of SOC associating to the fuzzy rules are shown in Fig. 14. Here, the same fuzzy rule base is taken for R2.

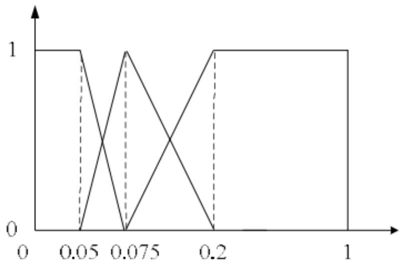


Fig. 14. The membership functions of SOC for R1 and R2.

After obtaining the fuzzy rules representing model parameters' variation to SOC, the temperature effect is considered. The Rs values within the region SOC > 0.2 at different temperatures are shown in Fig. 15. It indicates that Rs increases when the temperature decreases. When the temperature is above 35°C, Rs varies little, implying that the effect on Rs is not obvious in the high temperature region. To describe this trend, it is supposed that above a specific temperature higher than 35°C, Rs keeps constant. The Rs value difference between 15°C and 25°C is much larger than the difference between 25°C and 35°C, indicating that Rs changes more drastically when the temperature is lower than room temperature. To describe this variation, it is supposed that Rs varies continuously over the interval between 15°C and room temperature.

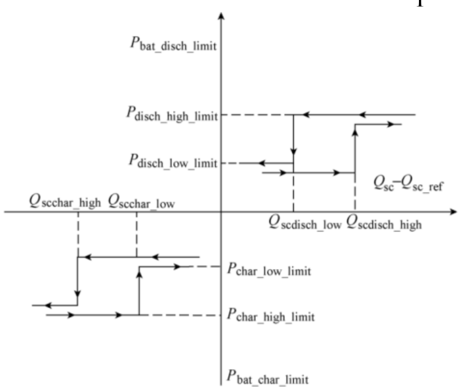


Fig.5 The diagram of Li-ion battery power dynamic limitation

if the SOC of super-capacitor is lower than the lower limitation Qsc_char_low, the limitation of Li-ion power is reduced to Pchar_low_limit. The dynamic limitation of the Li-ion battery can be written as:

$$\text{If } Q_{sc} - Q_{scref} \geqslant Q_{scchar\_high}, \quad P_{bat\_char\_limit} = P_{char\_high\_limit}$$

$$\text{If } Q_{sc} - Q_{scref} < Q_{scchar\_low}, \quad P_{bat\_char\_limit} = P_{char\_high\_limit}$$

Mode 2:When the HESS is discharging, if the SOC of super-capacitor exceeds the upper limitation Qsc_disch_high, the limitation of Li-ion power is increased to Pdisch_high_limit; if the SOC of super-capacitor is lower than the lower limitation Qsc_disch _low, the limitation of Li-ion power is reduced to Pdisch_low_limit. The dynamic limitation of the Li-ion battery can be written as:

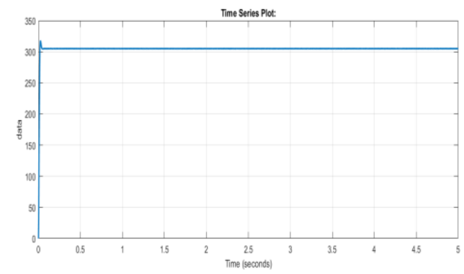
$$\text{If } Q_{sc} - Q_{scref} \geqslant Q_{scdisch\_high}, \quad P_{bat\_dischlimit} = P_{disch\_highlimit}$$

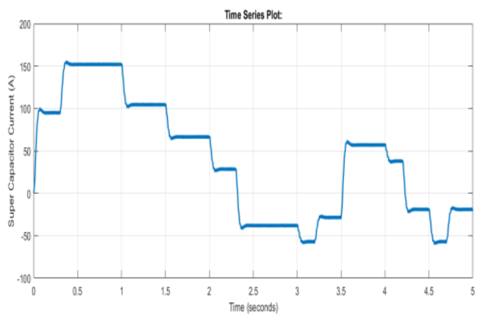
$$\text{If } Q_{sc} - Q_{scref} < Q_{scdisch\_low}, \quad P_{bat\_dischlimit} = P_{disch\_highlimit}$$

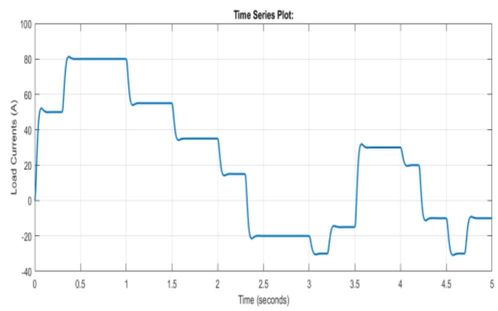
The above control parameters can be acquired by a hybrid algorithm based on particle swarm optimization and Nelder-Mead simplex approach.

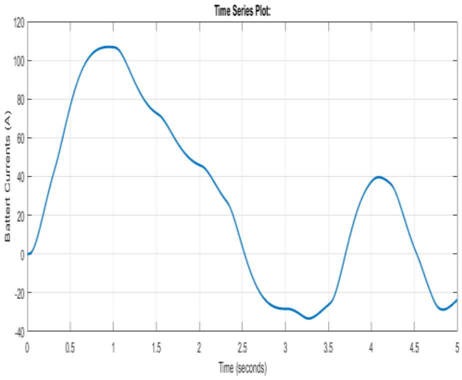
3. Results

Simulation analysis using MATLAB/Simulink is executed in favour to calculate the maximum power of the resistive load. Hybrid renewable energy system has been simulated and evaluated. simulation results of input power and input voltage before boost converter without fuzzy logic controller-based MPPT, and of input power and input voltage after boost converter with FLC and ANN-based MPPT using MATLAB/Simulink.









4. Conclusion and Future Scope

In this paper, a new model of Li-ion battery based on fuzzy logic considering SOC and temperature effect is established and improved. A new hybrid energy storage system for electric vehicles is designed based on a Li-ion battery power dynamic limitation rule-based HESS energy management and a new bi-directional DC/DC converter. The SOC and temperature effect on Li-ion battery model parameters are considered simultaneously by global fuzzy rule bases. Moreover, the ripple of output current is reduced and the life of the battery is improved. It is verified that the new model has high accuracy in various conditions. Thus, the new model based on fuzzy logic has good performance for Li-ion batteries.

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