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The Comparative Study of SOC Estimation Based on EKF and ANFIS Algorithm

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Abstract. In this paper, Two methods of SOC estimation based on Extended Kalman Filter (EKF) and Adaptive Neuro-Fuzzy Inference System (ANFIS) are studied according to the characteristic of Nickel-Metal Hydride (Ni-MH) battery pack with 120 cells in series and 8Ah capacity for HEV. Combined with the battery management system(BMS) control strategy, these two SOC estimation methods are verified by experiments. The results of EKF-based SOC estimation showed that the estimated value can solve the problem of accumulative error and inaccurate initial value, and can correct the SOC value of current integration under the condition of large current. Hardware in-the-loop simulation results showed that the ANFIS algorithm which is based on non-linear principle can better simulate the output characteristics of batteries. Compared with the EKF-based SOC estimation, the ANFIS-based SOC estimation has higher prediction accuracy for a specific condition and don't need the process of iteration.

Keywords: Hybrid electric vehicle(HEV), Nickel–metal hydride battery pack(NiMH battery pack), State of charge(SOC), Improved hybrid pulse power characterization test（Improved HPPC test）, Extended Kalman Filter(EKF), Adaptive Neuro-Fuzzy Inference System (ANFIS).

1. Introduction

Performance of BMS can evidently affect not only the drive ability and fuel economy of Hybrid Electric Vehicle(HEV), but also the life of batteries. The State of Charge (SOC) is the most difficult parameter to forecast in battery management system. In recent years, many scholars had done much work on SOC estimation in various methods[1], especially the EKF algorithm based on linear principle and the ANFIS algorithm based on nonlinear principle, But little work on the comparative study of different methods. In this thesis, The comparison of EKF and ANFIS algorithm is studied based on the data of Nickel-Metal Hydride (Ni-MH) battery pack.

2. Principle of EKF and ANFIS Methods

2.1. Principle of EKF Method

In the study of EKF-based SOC estimation, the improved Thevenin circuit model is adopted[2], and a new HPPC test is designed to identify the model parameters by using piecewise linear regression method.

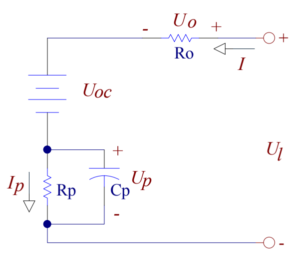

Fig. 1 Improved thevenin circuit model

The mathematical equations of the model is shown in equation (1) and (2).

$$U_L = U_{oc} + R_o I + U_p \quad (1)$$

$$\dot{U}_p = \frac{1}{C_p} I - \frac{1}{C_p R_p} U_p \quad (2)$$

The extended Kalman filtering process of non-linear discrete-time systems is shown in equation(2) to (7),[3]in which, $\hat{x}_{k/k-1}$ is the predictive value of the estimated state, $\hat{x}_{k/k}$ is the filtering value of the estimated state, K_k is the gain matrix of Kalman filter, $P_{k/k}$ is the filter error covariance matrix, $P_{k/k-1}$ is predictive error covariance matrix, I is the identity matrix.

$$\hat{x}_{0/0} = E(x_0), P_{0/0} = \mathrm{var}(x_0) \quad (2)$$

$$\hat{x}_{k/k-1} = f(\hat{x}_{k-1/k-1}, u_{k-1}) \quad (3)$$

$$P_{k/k-1} = A_{k-1} P_{k-1/k-1} A_{k-1}^T + \Gamma_{k-1} Q_{k-1} \Gamma_{k-1}^T \quad (4)$$

$$K_k = P_{k/k-1} C_k^T (C_k P_{k/k-1} C_k^T + R_k)^{-1} \quad (5)$$

$$\hat{x}_{k/k} = \hat{x}_{k/k-1} + K_k [y_k - g(\hat{x}_{k/k-1}, u_k)] \quad (6)$$

$$P_{k/k} = (I - K_k C_k) P_{k/k-1} \quad (7)$$

$$k = 1, 2, \ldots$$

The gain is obtained from the system state-space equations and observation equations. It also needs appropriate adjustment to get good filtering effect in all estimation range. Therefore, based on the basic Kalman filter gain, the filter gain matrix is optimized by importing a constant gain factor γ and a dynamic gain factor $(1+\lambda^{t_k - t_0})$. The follow K''_k is the improved gain.

$$K''_k = K'_k (1+\lambda^{t_k - t_0}) = \gamma K_k (1+\lambda^{t_k - t_0}) = \gamma (P_{k/k-1} C_k^T (C_k P_{k/k-1} C_k^T + R_k)^{-1})(1+\lambda^{t_k - t_0}) \quad (8)$$

Therefore, $$\hat{x}_{k/k} = \hat{x}_{k/k-1} + K''_k [y_k - g(\hat{x}_{k/k-1}, u_k)] \quad (9)$$

Therein, λ is a number of 0 to 1, which is set at 0.5 in this paper. t is the time of abrupt change. Every time t is cleared at the beginning of abrupt change and then re-timing. t_0 is the time of beginning of abrupt change, t_k is some time after abrupt change.

Therefore, The Kalman gain matrix is optimized for EKF iterative algorithm by two ways: a constant gain is increased taking into account the entire process; a dynamic gain which increases at the beginning of mutation and decreases rapidly after mutation is set up. The improvement achieves a good tracing prediction.

2.2. Principle of ANFIS Method

In the study of ANFIS-based SOC estimation, The model structure is combined of Takagi_Sugeno fuzzy inference system and neural network[4]. A correlation analysis is used in the choice of input variables; After correlation analysis, the three main impact variables of SOC are voltage, current and the voltage change rate between two sampling time. So, there are 3 input variables in The ANFIS model established in this paper as shown in Figure 2. The Member Functions (MFs) numbers of the 3 input variables are all 6. the input variables are all trapmf type and the output variable SOC is linear type. The training error is 0.0269 after 40 epoch training of 8000 classic data groups. Fuzzy rules of the model are 252.

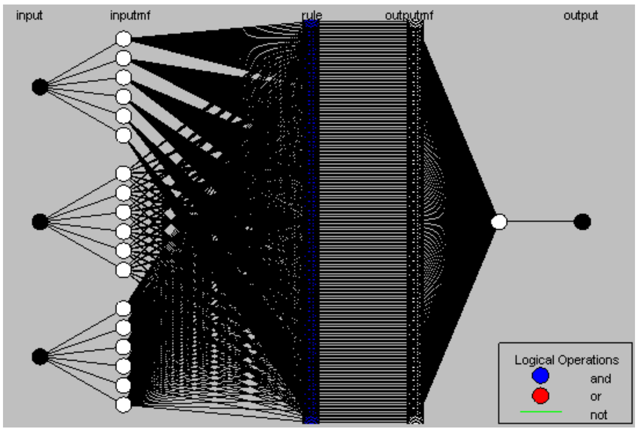

Fig.2 Structure of ANFIS model

a comprehensive algorithm is used in data training: the premise parameters are estimated by BP algorithm with momentum factor and learning rate; the consequent parameters are estimated by Least Squares Estimator (LSE) algorithm. This data training method not only can strengthen the convergence ability and optimizing capacity of the model, but also can overcome the local optimum problem of single BP algorithm to some extent. Moreover, subtractive fuzzy cluster analysis method is used to optimize the number of fuzzy sets and fuzzy rules. It has improved the convergence rate of data learning and model training with high precision; also it has reduced the complexity of the model.

3. Experimental Equipment and Experiment Method

All the current, voltage and SOC data of batteries are measured accurately by Bitrode FTN400-450 equipment Based on 8Ah NIMH batteries (120 cells).

The new hybrid pulse power characterization (HPPC) test is defined Referencing the test of the Partnership for a new Generation of Vehicles (PNGV) US[5]: Select the soc points of 0.9, 0.85,0.8,0.75…… 0.1. At first, fully charge the batteries, and then discharge them to 0.9 SOC, standing half an hour, complete a charge and discharge cycle, measuring the voltage and current of the batteries, then discharge the batteries to 0.85 SOC, standing one hour before the cycle of next SOC point.

4. Comparative Study of SOC Estimation Based on EKF and ANFIS Algorithm

Principle aspect. EKF is based on linear recursive principle, ANFIS is based on nonlinear principle. Battery is a nonlinear system, its output and input parameters are nonlinear relationship. Therefore, ANFIS can better track the nonlinear output characteristic of batteries. With the single cycle data of HPPC test and three cycles data of HPPC test used as the examples, the comparative results of the SOC theory value and SOC estimate value based on ANFIS and EKF are shown in Fig.3 and Fig.4. in Fig.3, the average estimate error of ANFIS method is 0.31693%, and the average estimate error of EKF method is 2.2084%. in Fig.4, the average estimate error of ANFIS method is 1.5749%, and the average estimate error of EKF method is 3.1423%.

Adaptive working condition aspect. The EKF estimation method is based on circuit model, as long as the battery's internal chemical properties is activated, the circuit model can simulate the battery's properties in a certain extent. Therefore, The SOC estimation algorithm based on EKF applies to more current interval; But the SOC estimation algorithm based on ANFIS is limited by the training data, only applies to similar conditions, the using range is relatively minor.

Iterative convergence aspect. the SOC estimation algorithm based on ANFIS realize expert system in rules form at last, the decision is similar to man's judgement. SOC estimate value of every moment the battery parameters only relevant to the battery parameters of that moment, no iterative convergence process. when there's a slight difference between the working condition data and model training data, the model have certain adaptability. EKF algorithm has the process of iteratively convergence, there's a relationship between the current value and the value of last moment, SOC estimate error of EKF algorithm will be relatively larger under the condition of the battery laying aside for a long time or discharging with low current, SOC estimate error of EKF algorithm will be relatively accurate with frequent high-current charging or discharging.

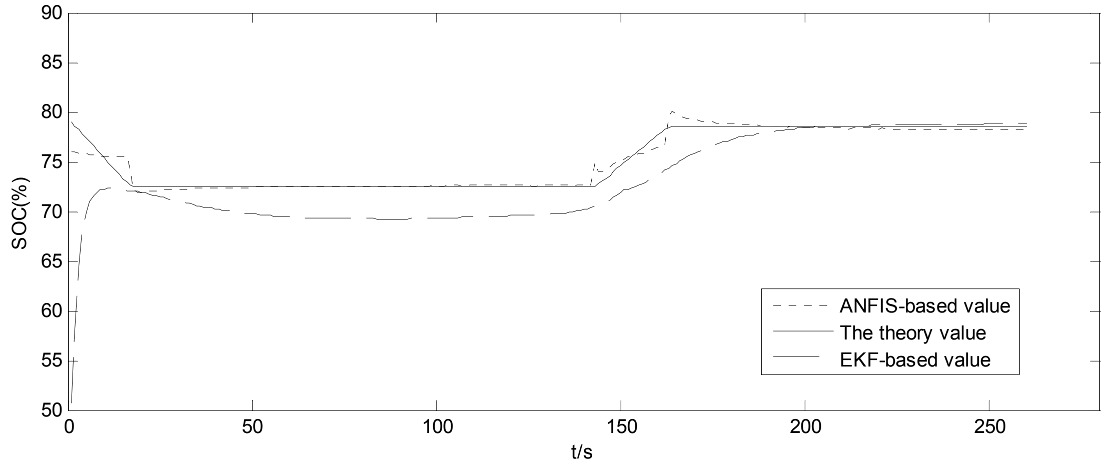

Fig.3 The comparative results of the single cycle data

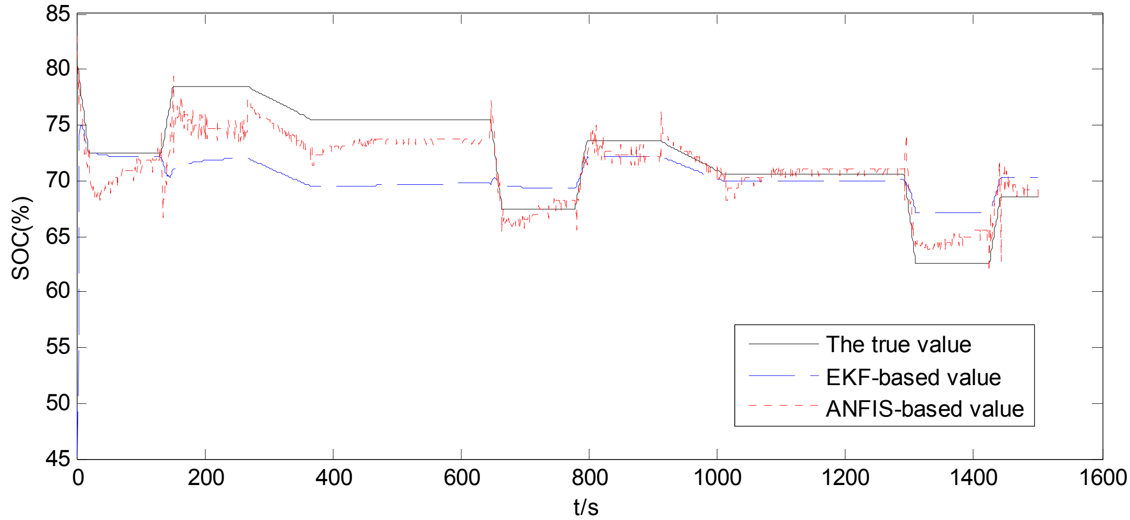

Fig.4 The comparative results of three cycles data

5. Acknowledgment

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