Study on Estimation Method for the Residual Capacity of Battery in Hybrid Devices Based on Grey Prediction

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Abstract. In order to accurately estimate the residual capacity of battery in hybrid devices, the definitions of the residual capacity in variable current and its modified formula under the actual working condition are given. The data samples of the residual capacity are obtained from the input signals which come from the power curve of a parallel hybrid excavator being scaled down to the range of a single battery. Based on the analysis of several grey prediction algorithms on the samples, a fragmentation prediction scheme is proposed that the direct grey prediction model of the cumulative- average operator is adopted at the charge stage, and the grey prediction model of the variable weight buffer factor at the discharge stage. The result shows that the proposed method can fully and effectively improve the accuracy of prediction for the residual capacity of battery in hybrid devices.

1. Introduction

For hybrid devices with battery energy storage element, obtaining the residual capacity of battery accurately can directly affect the reliability, effectiveness of the hybrid energy management system of equipment, and the service life of the battery[1]. In the process of frequent charge and discharge when the battery of hybrid power equipment works, the nonlinear factors are difficult to express accurately, and its model parameters are not accurate in the dynamic modeling process[2].

From what has been discussed above, the grey prediction method which does not rely on the mathematical model and requires only a small number of samples, has certain advantages in predicting the residual capacity of variable current charging and discharging batteries[3,4]. In this paper, a variety of grey prediction algorithms are analyzed. On this basis, a piece-wise prediction scheme is proposed, which adopts the accumulation-mean operator to directly model grey prediction $GM(1,1)$ in the charging stage and weak buffer grey prediction of variable weight in the discharge stage. This scheme can be used to compensate and modify the load disturbance independently, which can improve the accuracy of global prediction.

2. Basic principle of grey prediction

Grey prediction is a method to predict the system with uncertain factors. It looks for the law of system change by processing the original data. In this process, it generates data series with strong regularity, and then establishes the corresponding differential equation model, so as to predict the future trend of unknown system.
2.1 Accumulative - mean model of grey prediction $GM(1,1)$

$x^{(0)} = (x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n))$, is a nonnegative initial data series. $x^{(0)} = (x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n))$, is a cumulative series of $x^{(0)}$ initial data. The series $x^{(i)}$ can be given by

$$x^{(i)}(k) = \sum_{j=0}^{k} x^{(0)}(j), k = 1, 2, \ldots, n$$

(1)

$z^{(i)} = (z^{(i)}(1), z^{(i)}(2), \ldots, z^{(i)}(n))$, is the adjacent mean generation series of $x^{(0)}$. The series $z^{(i)}$ can be given by

$$z^{(i)}(k) = 0.5(x^{(i)}(k) + x^{(i)}(k - 1))$$

(2)

Where $k = 2, 3, \ldots, n$.

The basic form of grey prediction model $GM(1,1)$ is

$$x^{(0)}(k) + az^{(0)}(k) = b$$

(3)

The least square identification is carried out to identify the parameter column $\hat{a} = (a, b)^T$ of the model $GM(1,1)$ by the accumulation-mean generation operator. And the identification result is

$$\hat{a} = (a, b)^T = (B^T B)^{-1} B^T Y$$

(4)

In the formula (4), $B = -G^T$. $G$ is the cumulative mean generation matrix.

$$G = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ \frac{1}{2} & 1 & 1 & \cdots & 1 \\ 0 & \frac{1}{2} & 1 & \cdots & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \frac{1}{2} \end{bmatrix}_{n \times (n-1)}$$

Then, the prediction model of the initial data series is established as follows:

$$\hat{x}^{(i)}(k + 1) = x^{(0)}(1) - b / a e^{-ak} + b / a x^{(i)}(k) = \hat{x}^{(i)}(k + 1) - \hat{x}^{(i)}(k)$$

(5)

Where $k = 1, 2, \ldots, n$.

2.2 Variable weight weak buffer modified model $VWGM(1,1)$

$X^{(0)} = (x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n))$ is the non-negative initial disturbance series, $x(k) d$ is the variable weight weak buffer operator of the sequence $X^{(0)}$. The operator $x(k) d$ is shown as

$$x(k) d = (x(n))^\lambda \cdot (x(k))^{1-\lambda}$$

(6)

Where $\lambda$ is variable weight, $0 < \lambda < 1$, and $k = 1, 2, \ldots, n$.

Then, the correction model of variable weight weak buffer is established, and the modeling steps are as follows:

① According to formula (6), appropriate $\lambda$ value is selected to generate buffer series $X^{(0)} D$ of initial disturbance series $X^{(0)}$. The series $X^{(0)} D$ is $X^{(0)} D = (x^{(0)}(1) d, x^{(0)}(2) d, \ldots, x^{(0)}(n) d)$.

② According to the formulas (3) and (4), determine the data matrix $G, M, Y$. And take the parameter column $\hat{a}$.
charging and discharging, and

3. Employment of grey prediction model of residual capacity

The battery of hybrid power equipment is always in the conversion process of frequent charge and discharge. And the value of its residual capacity is bound to fluctuate accordingly. In this paper, a piecewise prediction scheme is proposed for charging and discharging stage modeling.

3.1 Proposal of segmented grey prediction scheme

The Classic grey prediction model is mainly suitable for the data series of single exponential growth. When the abnormal fluctuations occur in the data, its result is always not good. Grey prediction has many data processing algorithms, such as data preprocessing algorithm, buffer algorithm, and the amplitude of compression algorithm etc. These algorithms are not good at estimating the residual capacity of hybrid battery.

Considering the different control strategies of incharging and discharging, and it’s easy to distinguish the charge and discharge state of battery in engineering, this paper puts forward a piecewise prediction scheme which adopts the accumulation-mean operator to directly model grey prediction GM(1,1) in the charging stage and weak buffer grey prediction of variable weight in the discharge stage.

3.2 Grey prediction method for residual capacity of battery

According to the principle of grey prediction modeling, the specific steps of grey prediction Piecewise modeling for battery residual capacity are as follows:

1. According to the characteristics of charging and discharging in the actual physical process, the original series \( X^{(0)} \) of the residual capacity of the battery is divided into charging series \( X^{(0)}_1 \) and discharging series \( X^{(0)}_2 \).

2. According to formula (3), (4) and (5), the model GM(1,1) of charging series \( X^{(0)}_1 \) is established, and the model VWGM(1,1) of discharging series \( X^{(0)}_2 \) is established according to formula (6) and (7).

3. Judge the battery is what kind of state, charged or discharge? In charging state perform step 4, otherwise the step 5.

4. The initial value of the residual capacity of the battery is obtained in the experiment. Using it to replace the original data by the similar principle. And the next residual capacity is estimated by the model GM(1,1) of the step 2. Then judge whether the charging process is over. If the charging process is not finished, repeat the above estimation process. That is, using the estimated result to replace the original data by the similar principle, modifying the original model, and estimating the next residual capacity value until the end of the charging process. Taken the last estimation result as the initial value of the residual capacity estimation in the discharge stage, enter into the step 5. Otherwise, the charge process is over, take the result directly to the step 5.

5. The initial value of the residual capacity of the battery is obtained in the experiment. Using it to replace the original data by the similar principle. And the next residual capacity is estimated by the
model \( VWGM_{(1,1)} \) of the step ②. Then judge whether the discharging process is over. If the discharging process is not finished, repeat the above estimation process. That is, using the estimated result to replace the original data by the similar principle, modifying the original model, and estimating the next residual capacity value until the end of the discharging process. Taken the last estimation result as the initial value of the residual capacity estimation in the charge stage, enter into the step ④. Otherwise, the discharge process is over, take the result directly to the step ④.

⑥The estimated residual capacity is cycled alternately in the charging and discharging stage until the end of the estimation process.

4. Example verification
In actual working conditions, it is different for battery of hybrid devices to the value of residual capacity in charging and discharging. But both have their own control strategies[5]. Therefore, using the information of the no-load and heavy-load working conditions as its input signal of the experiment, it is obtained that the modeling and verification data of battery residual capacity estimation, as shown in table 1 and table 2.

4.1 Modeling of piecewise grey prediction algorithm
Taken the data series of the residual capacity in the table 2 in the no-load condition as the modeling series of the charging stage, the model \( GM_{(1,1)} \) in charging stage is established according to the formula (5). It can be written

\[
\hat{x}^{11}(k + 1) = 4609.397e^{0.0135k} - 4457.397
\]  

(8)

Taken the data series of the residual capacity in the table 2 in the heavy-load condition as the modeling series of the discharging stage, the model \( VWGM_{(1,1)} \) in discharging stage is established according to the formula (7). It can be expressed

\[
\hat{x}^{11}(k + 1) = -5332.554e^{-0.0498k} + 5607.704
\]  

(9)

4.2 Predicted results

| Time(s) | 0   | 2   | 4   | 6   |
|---------|-----|-----|-----|-----|
| No-load residual capacity (Ah) | 152.00 | 156.89 | 163.72 | 170.07 |
| heavy load residual capacity (Ah) | 272.00 | 255.11 | 242.53 | 231.35 |

Using the above model formula (8) and (9), the residual capacity of hybrid battery can be predict. In this paper, it is verified by the data series in the table 1.

The first, judge the battery state of the charging and discharging. It can be judged by the direction of the current of the battery in the experiment. It can also be judged by the size of two adjacent residual capacity values. The rule is, if the latter value is larger than the former one, it can be judged as the charging state. Otherwise, is the discharging state. As shown in the table 1, the starting point 12s is
the charging state, and the next point 14s has been transformed into the discharge state. That is, the point of 14s is the end of the charging, and the start of the discharging, and so on.

Secondly, the position of the initial value in the prediction model is determined by the approximation principle. For example, in the estimate of the charging model, which is formula (8), \( \hat{x}^{0}(10) = 213.65, \hat{x}^{0}(11) = 220.31 \). The point of 12s in the table 1, which is 217.6, is closer to \( \hat{x}^{0}(11) \). Replacing \( \hat{x}^{0}(11) \) with 217.6, the formula (8) is modified to \( \hat{x}^{0}(k + 1) = 4609.397 e^{0.0338 k + 0.0004} - 4457.397 \). Where m is the difference between the initial value and the replacement. The discharge stage is similar, so it is unnecessary to repeat.

Following, according to the steps in section 2.2, the residual capacity is estimated by the above modified model. The estimated results are shown in figure 1. It can be seen that the algorithm proposed in this paper can well track the fluctuation of the original data. According to the calculation, the maximum relative error is 4.91%, which can be considered for practical application in engineering.

5. Conclusions

It is difficult to estimate the residual capacity of the battery in hybrid power equipment because of the variable in current. In this paper, the accumulating-mean operator grey prediction is used for direct modeling in charge stage, and the variable weight weak buffer grey prediction is used in discharge stage to buffer and modify the disturbance of battery residual capacity data series, which caused by load variation. And the effectiveness of the proposed scheme is verified.

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