Modeling and parameter identification of composite power supply for plug-in HEV

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Abstract. By analyzing the characteristics of the components of PHEV composite power supply, the voltage characteristics, temperature characteristics and capacity efficiency of batteries and supercapacitor are clarified. The dynamic voltage characteristics of batteries and supercapacitor are simulated by modeling the composite power supply. Based on the cross current discharge characteristics of lithium-ion batteries and the application conditions of batteries in PHEV, the second-order linear battery model recommended in PNGV is selected in this paper; for supercapacitor, the simplified RC branch model can be used to describe the characteristics, and the experimental data are used to identify the parameters involved in the model, and the accuracy of the model is verified.

1. Introduction
With the progress of society and the development of science and technology, hybrid electric vehicle (HEV) which has the advantages of improving fuel consumption and reducing emissions, has been widely promoted. The key technology of PHEV is to ensure the power performance of the vehicle, improve the fuel economy, reduce emissions, and maintain the balance of battery charge and discharge, and reasonable energy distribution control. In this paper, based on the cross current discharge characteristics of lithium-ion batteries and the application conditions of batteries in PHEV, the second-order linear battery model recommended in PNGV is selected; the simplified RC branch model can be used to describe the characteristics of super capacitor, and the parameters involved in the model are identified by using experimental data, and the accuracy of the model is verified.

2. Model establishment and battery parameter identification

2.1. Establishment of battery model
Based on the characteristics of constant current discharge of lithium-ion batteries and the application conditions of batteries in PHEV, the second-order linearized battery model[1] recommended in PNGV (partnership for a new generation of vehicle) is selected in this paper, as shown in Figure 1. The model can well simulate the complex internal reaction of the battery in the process of charging and discharging. In the model, $R_0$ reflects the partial resistance of the battery in the first stage. The parallel combination of $R_2$ and $C_2$ reflects the dynamic characteristics of the surface effect of the battery electrode. $C_1$ has a large capacity and reflects the storage capacity. The ideal electromotive force $E$ and large capacitance $C_1$ are combined to reflect the gentle discharge platform in the second stage.
The voltage response curve obtained by using PNGV battery model plus pulse current is shown in Figure 2. It can be seen from the figure that the real battery voltage response curve is very close to the voltage response curve obtained by using PNGV model simulation, which shows that the battery model recommended by PNGV is reasonable.

2.2. On line parameter identification based on battery second order linear model

By determining the specific values of unknown parameters $C_1$, $C_2$, $R_0$ and $R_2$, the battery model can be completely determined [2]. To identify the parameters, it is necessary to establish a mathematical model of the identification system suitable for computer operation. According to the equivalent circuit model relationship shown in Figure 3, the following relationship can be obtained:

$$U(t) = (R_0 + \frac{1}{C_1 t} + \frac{R_2}{R_2 C_2 t + 1}) I(t) + E$$

(1)

If the output is $y(t) = U(t) - E$ and the input is $I(t)$, then the transfer function of the model is:

$$y(t) = \frac{R_0 R_2 C_2 C_1}{R_2 C_2} t^2 + \left( \frac{R_0 C_1 + R_0 C_2 + R_2 C_1}{R_2 C_2} \right) t + 1 \frac{I(t)}{R_2 C_2 t^2 + C_1 t}$$

(2)
Suppose $\tau_1 = C_1, \tau_2 = R_2 C_2$, the above formula is as follows:

$$
\tau_1 \tau_2 y(t) t^2 + \tau_1 y(t) t = \tau_1 \tau_2 I(t) R_0 t^2 + (R_0 \tau_1 + R_2 \tau_1) I(t) t + I(t)
$$

(3)

Suppose $\alpha = \tau_1 \tau_2, \beta = \tau_1, \lambda = R_0 \tau_1 + \tau_2 + R_2 \tau_1$, Replace these parameters into the above equation:

$$
\alpha y(t) t^2 + \beta y(t) t = \alpha I(t) R_0 t^2 + \lambda I(t) t + I(t)
$$

(4)

As a result $t = [x(k) - x(k-1)]/T, \ t^2 = [x(k) - 2x(k-1) + x(k-2)]/T^2$, the difference equation is:

$$
y(k) = [(2\alpha + \beta T) y(k-1) - \alpha y (k-2) + (\alpha R_0 + \lambda T + T^2) I(k) + (-2\alpha R_0 - \lambda T) I(k-1) + \alpha R_0 I(k-2)]/(\alpha + \beta T)
$$

(5)

Suppose the parameter $n_1, n_2, n_3, n_4, n_5$, simplify the above formula is:

$$
y(k) = n_1 y(k-1) + n_2 y(k-2) + n_3 I(k) + n_4 I(k-1) + n_5 I(k-2)
$$

(6)

According to $\alpha = \tau_1 \tau_2, \beta = \tau_1, \lambda = R_0 \tau_1 + \tau_2 + R_2 \tau_1$, get the result $\tau_1 = \beta, \tau_2 = \alpha/\beta, R_2 = (\lambda R_0 - \tau_1 - \tau_2)$

The parameters $C_1, C_2, R_0, R_2$ in the model can be obtained from the above formula. In the identification of model parameters, the known parameters are terminal voltage $y(k)$, terminal current $I(k)$, terminal voltage $y(k-1)$, terminal current $I(k-1)$, SOC (k-1), terminal voltage $y(K-2)$ and terminal current $I(K-2)$ of the first two beats.

In the field of parameter identification, the least square method is the most basic and important estimation method, and many estimation algorithms used for system identification can also be interpreted as the least square method [3]. On the other hand, considering the realization of adaptive control and tracking time-varying parameters, recursive algorithm must be used for online identification. In this paper, recursive least square algorithm is used as the parameter identification algorithm [4].

Suppose that the difference equation corresponding to the mathematical model of the identified system is as follows:

$$
y(k) = \psi^T (k) \theta^0
$$

(7)

In the formula $\psi = [y(k-1) y(k-2) \ldots y(k-n) I(k) I(k-1) I(k-2)]$, $\theta^0 = [n_1 n_2 n_3 n_4 n_5]^T$

Calculation formula of recursive least square method:

$$
\dot{\theta}(N+1) = \dot{\theta}(N) + I(N+1) [y(N+1) - \psi^T (N+1) \dot{\theta}(N)]
$$

$$
I(N+1) = P(N+1) \psi(N+1)
$$

$$
P(N+1) = P(N) - \frac{P(N) \psi(N+1) \psi^T (N+1) P(N)}{I + \psi^T (N+1) P(N) \psi(N+1)}
$$

(8)
In the formula, \( \theta (N) \) is the last parameter estimation value, \( y^{T}(N+1) \) is the prediction of the current observation value, \( y(N+1) \) is the actual observation value, after subtracting the two, it is the prediction error. After multiplying the prediction error and the gain term \( l(N+1) \), it is the correction term of the current prediction value. Using it to correct the predicted value, the estimated value \( \theta (N+1) \) is obtained.

Then programming in MATLAB, according to the function relationship between sampling time \( T \), nominal capacity \( Q_n \), initial \( U(0) \), SOC \( (0) \) and end voltage and SOC of battery state of charge, the terminal voltage \( U(k) \) is calculated; \( \theta (0) \) and \( P \) \((0) \) are initialized to start recursive least squares, the initial set value of \( \theta (0) \) is used as the initial setting value of \( \theta (0) \) According to the recursive least square method with limited memory, the coefficient \( n_1, n_2, n_3, n_4, n_5 \) in the system description equation is calculated by formula (7) and (8); the parameter \( C_1, C_2, R_0, R_2 \) is obtained by using equation (6).

2.3. Simulation model of battery

![Figure 3. Battery model in composite power supply](image)

3. Modeling and parameter identification of supercapacitor

3.1. Equivalent circuit of supercapacitor

According to the characteristics of supercapacitor, there are many factors influencing the modeling of supercapacitor, but the more important factors are capacity and internal resistance. In reference [5], different physical models of supercapacitor and identification methods of model parameters are introduced in detail. At present, the equivalent models of supercapacitor include classical RC model and three branch model. However, the three branch model is more complex, and the model parameters can only be identified through complex tests, while the classical RC supercapacitor model model is simple and easy to calculate.
The equivalent circuit model of supercapacitor is shown in Figure 4, which mainly includes three parts: \( R_0 \) represents the leakage of capacitance, which can be ignored in the process of rapid charge and discharge; \( R_1C_1 \) represents the fast change branch, which is used to represent the change of capacitance energy during the charging and discharging process; \( R_2C_2 \) branch represents the slow variation branch. In the hybrid power supply, the supercapacitor is the battery peak shaving and valley filling, mainly for fast charging and discharging. The model can be equivalent to the form of \( R_1C_1 \) fast changing branch. The two RC branches have different time constants \( \tau_1 = R_1C_1 \) and \( \tau_2 = R_2C_2 \).

![Supercapacitor equivalent circuit](image)

**Figure 4.** Supercapacitor equivalent circuit

Then the current flowing into the super capacitor system \( I \) :

\[
I = I_1 + \frac{1}{R_1C_1} \int_{0}^{t} I_1 dt
\]  
(9)

Super capacitor terminal voltage \( U_c \) :

\[
U_c = R_0I + \frac{1}{C_1} \int_{0}^{t} I_1 dt
\]  
(10)

Super capacitor output energy \( E \) :

\[
E = \frac{1}{2} CU_{max}^2 - \frac{1}{2} CU_{min}^2
\]  
(11)

The state of charge value of super capacitor is linear with the capacitor terminal voltage, and the calculation equation is as follows:

\[
SOC = \frac{Q_{soc}}{Q_{to}} = \frac{C(U_{oc} - U_{min})}{C(U_{max} - U_{min})} = \frac{(U_{oc} - U_{min})}{(U_{max} - U_{min})}
\]  
(12)
In the formula, \( U_0 \) is the super capacitor terminal voltage; \( U_{\text{max}} \) is the super capacitor maximum voltage; \( U_{\text{min}} \) is the super capacitor minimum voltage; \( I \) is the current flowing into the super capacitor system; \( I_1 \) is the net current stored in the super capacitor system.

### 3.2. Parameter identification of super capacitor model

Assuming that the supercapacitor starts to charge with constant current \( I \), when the charging current rises from 0 to the set value \( I \), the terminal voltage of the super capacitor increases by \( \Delta U \) from the initial value \( U_0 \); the electric energy flowing into the circuit is completely stored in the \( R_1C_1 \) branch, and the sudden voltage \( \Delta U \) is completely determined by the \( R_1C_1 \) branch.

\( R_1C_1 \) Branch \( R_1 \) reflects the equivalent internal resistance of supercapacitor, with parameter \( \frac{I}{U} \).

The capacitance parameter \( C_1 \) of \( R_1C_1 \) branch is composed of constant capacity \( C_0 \) and dynamic capacity \( C_v \) which varies linearly with voltage. The initial capacity \( C_0 = I/(\Delta U_0/\Delta t_0) \) (\( \Delta U_0 \) is the increment of terminal voltage \( U_0 + \Delta U \) in period \( \Delta t_0 \)) is obtained from the relationship between capacity and voltage, current and charge discharge time.

Another dynamic capacity, \( C_v \) is that the increment of capacitance charge is linearly related to the terminal voltage of super capacitor, \( Q = C_1U = C_0\Delta U_1 + 1/2C_v\Delta U_1^2 \) (\( \Delta U_1 \) is the increment of terminal voltage), and the capacity can be expressed by \( Q = I\Delta t_1 \), so the parameter \( C_v = (2/\Delta U_1^2)(I\Delta t_1 - C_0\Delta U_1) \).

Therefore, the capacitance parameter \( C_1 \) of \( R_1C_1 \) branch is:

\[
C_1 = C_0 + C_v = \frac{I \Delta t_0}{\Delta U_0} (1 - \frac{2}{\Delta U_1}) + \frac{2I \Delta t_1}{U_1^2} \quad (13)
\]

After the charging process of time \( \Delta t_0 \), the \( R_1C_1 \) branch which dominates the fast response starts to discharge to \( R_2C_2 \) branch. Suppose that the discharge current of \( R_1C_1 \) branch to \( R_2C_2 \) branch is \( I_2 \), and the terminal voltage drop \( \Delta U_2 \) after time \( T_2 \), the expressions of parameters \( C_2 \) and \( R_2 \) of \( R_2C_2 \) branch are [6]:

\[
R_2 = \frac{U_2 - (\Delta U_2^2/2)}{C_1} \frac{\Delta t_2}{\Delta U_2} \quad (14)
\]

\[
C_2 = \frac{I\Delta t_1}{U_3} - (C_0 - 1/2C_vU_3)
\]

### 3.3. Simulation model of supercapacitor

According to the above mathematical model, the MATLAB / Simulink model of supercapacitor is established, as shown in Figure 5. The model takes charge discharge power and temperature as input and voltage, current and SOC as output.
Figure 5. Supercapacitor model in composite power supply

4. Composite power supply model
According to the simulation model of battery, super capacitor and DC / DC converter, combined with the control strategy of composite power supply and power bus module, the simulation model of composite power supply system is composed, as shown in Fig 6.

Figure 6. Composite power supply model

The core of the composite power supply model is the control strategy part, which mainly determines the charging and discharging conditions of the battery and the super capacitor according to the power demand and the SOC value of the battery and the super capacitor. The power bus module in the composite power supply is mainly connected with super capacitor, DC/DC converter and battery pack to distribute the current flowing to battery pack and super capacitor. The power bus model is shown in Fig.7. The power bus module transfers the required power to the control strategy module. The control
strategy outputs the requested power to the battery and super capacitor through the calculation of the control algorithm. The actual output power is calculated by the battery and super capacitor according to their respective power state parameters.

Figure 7. Composite power bus model

4.1. High power pulse charging and discharging simulation
According to the simulation model of the composite power supply, the high-power pulse is used to simulate the charge and discharge of the composite power supply system and the single battery auxiliary system, and the comparison is made. Figure 8 shows that when 2000W pulse current is working, the discharge is 10 seconds, the interval is 10 seconds, the charging is 10 seconds, and the cycle is 150 seconds in turn to complete the cycle requirements.

Figure 9 shows that single battery cannot meet the requirements of high-power charging and discharging due to the limitation of its maximum charging and discharging current. Figure 10 shows that in the case of high power charging and discharging, the composite power supply system can meet the demand of high power, and the battery in the composite power supply works in an appropriate working range. Figure 11 shows the charging and discharging power of the capacitor in the composite system. The power of the capacitor can provide instantaneous power to supplement the insufficient part of the battery.

Figure 8. Power requirements for high power pulse charging and discharging
Figure 9. Power variation of battery used alone under high power requirement

Figure 10. Battery power variation under high power requirement in composite power supply system

Figure 11. Power variation of capacitance in composite power supply system under high power requirement

Fig. 12 the current of the battery is at the maximum value under the condition of single battery working alone and charging and discharging with high power. Fig. 13 the current value diagram of the battery in the composite system. When the pulse power requirement is met, the current of the battery in the composite system changes at a better value. When the current limit of the battery is exceeded, it is absorbed or supplemented by the capacitor, which can improve the efficiency of the system and the service life of the battery.

Figure 12. Current variation of battery used alone under high power requirement
Through the analysis of simulation results, it is concluded that the composite power supply system composed of battery and super capacitor can not only better meet the power demand, but also play the role of "peak shaving and valley filling". Compared with the single application of battery, the composite power system has a great improvement in energy utilization and service life. Therefore, the hybrid system is very good in the hybrid electric vehicle power system Application of.

5. Conclusion

Combined with the application conditions of battery in PHEV, this paper selects the second-order linear battery model recommended in PNGV, and verifies the rationality of the established battery model, identifies the model parameters; analyzes the characteristics of super capacitor, models the super capacitor according to the internal resistance model, and identifies the model parameters; determines the DC / DC structure, and reduces it according to the literature test data. The DC / DC model is established. After analyzing the models of each part, the simulation model of the composite power supply is combined. The superiority of the composite power supply is verified by the high-power pulse charging and discharging experiment.

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