

Motor Group Aggregation of Refinery and Chemical Enterprises Based on Hierarchical Clustering Algorithm

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Keywords: Motor group aggregation; Hierarchical clustering; Load modeling

Abstract: The electric load of the refinery and chemical enterprises is mainly induction motors. When the statistical synthesis method is used to establish the load model, it is an important research content to improve the aggregation accuracy of the motor group. The clustering feature is determined by analyzing the sensitivity of each parameter of the motor model to the power trajectory. The hierarchical clustering algorithm in machine learning is applied to the classification of the motor group, and the motor aggregation is carried out according to the classification result. Through an example, the simulation results show that, compared with the equivalent of one motor group, the hierarchical clustering algorithm can improve the accuracy of motor group aggregation.

1. Introduction

The power system of a refinery and chemical enterprise is characterized by high load density and multiple voltage levels. Power system simulation analysis is an important means to study the characteristics of power systems in refining and chemical enterprises. Therefore, the accuracy of the simulation models of various equipment in the power system is related to the results of power system simulation. The induction motor load accounts for more than 80% of the power load of the refining and chemical enterprise. The motor is the most important dynamic component in the comprehensive load model, and its parameters have an important influence on the analysis of the transient stability of the power system [1-4].

Due to the large number of electric motors in refining and chemical enterprises, and the various types, it is neither possible nor necessary to model and analyze the motors one by one in simulation software. In the actual simulation process, one or more equivalent motors are usually used to simulate the dynamic characteristics of the motor group [5]. How to aggregate the motor group is an important research content. Motor parameters are different, and the dynamic characteristics shown are also different from each other. In order to make the simulation results more reflective of the actual situation, many experts and scholars have done a lot of research in this area [6-10], but these methods are not suitable for use in refining and chemical enterprises.

This article combines the actual situation of the refinery and chemical enterprises, according to the

results of the sensitivity analysis of the trajectory of the motor parameters. Taking into account the reason that the motor load is often adjusted with the changes in the processing volume of the production device, the appropriate parameters in the motor model are selected as the clustering index, the motor groups are grouped through hierarchical clustering, and then each group of motors is equivalently calculated. This method has a small amount of calculation and a simple process, while also meeting the accuracy requirements.

2. Mathematical Model of Motor

When the power system suffers a large disturbance, the active power and reactive power of the load will vary greatly with the voltage and frequency. The dynamic model of the load is to express the functional relationship between power, voltage, frequency and other electrical quantities in this state.

The most important part of the integrated load is the induction motor. Its model has many forms, among which the most widely used is the third-order electromechanical transient model. This model considers the electromagnetic transient process of the rotor winding and the mechanical dynamic process of the rotor. This model meets the requirements of higher simulation accuracy. The steady-state equivalent circuit of an induction motor is shown in Figure 1.

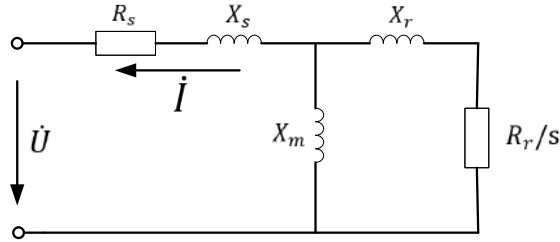


Figure 1: The steady-state equivalent circuit of induction motor

In Figure 1, R_s and X_s are the resistance and reactance of the stator winding, R_r and X_r are the resistance and reactance of the rotor winding, X_m is the excitation reactance, and s is the rotor slip. The mathematical relationship of the third-order electromechanical transient model of the motor is as follows [11].

Stator voltage equation:

$$\begin{cases} U_d = R_s I_d + X' I_q + E'_d \\ U_q = R_s I_q + X' I_d + E'_q \end{cases} \quad (1)$$

Rotor voltage equation:

$$\begin{cases} \frac{dE'_d}{dt} = -\frac{1}{T'_{d0}} [E'_d + (X - X') I_d] + s w_s E'_q \\ \frac{dE'_q}{dt} = -\frac{1}{T'_{d0}} [E'_q + (X - X') I_d] + s w_s E'_d \end{cases} \quad (2)$$

Rotor dynamic equation:

$$\begin{cases} T_J \frac{ds}{dt} = T_m - T_e \\ T_e = E'_d I_d + E'_q I_q \\ T_m = T_{m0} [A(1-s)^2 + B(1-s) + C] \\ A(1-s_0)^2 + B(1-s_0) + C = 1 \end{cases} \quad (3)$$

The power equation:

$$\begin{cases} P = U_d I_d + U_q I_q \\ Q = U_q I_d - U_d I_q \end{cases} \quad (4)$$

Where: U_d is d -axis component of stator voltage, U_q is q -axis component of stator voltage, E'_d is d -axis component of electromotive force after transient reactance, E'_q is q -axis component of electromotive force after transient reactance, I_d is d -axis component of stator current, I_q is q -axis component of stator current, X is rotor steady-state reactance, X' is rotor transient reactance, T_j is rotor inertia time constant, T'_{d0} is rotor loop time constant, T_m is mechanical torque, T_e is Electromagnetic torque, T_{m0} is stable mechanical torque, A , B and C is mechanical torque coefficient, s_0 is initial slip. Among them: $T'_{d0} = (X_r + X_m)/R_r$, $X = X_s + X_m$, $X' = X_s + X_m X_r / (X_m + X_r)$, $A + B + C = 1$.

3. Clustering Feature Vector of Motor

Trajectory sensitivity is a quantitative analysis of the impact of small changes in system parameters on the dynamic response of the system [12], and its expression is to establish a differential equation that changes with time according to the system. The expression of the trajectory of the induction motor parameters and its power is as follows:

$$\begin{cases} \dot{x} = f(x, y, \mu) \\ 0 = g(x, y, \mu) \\ x(0) = x_0 \\ y(0) = y_0 \end{cases} \quad (5)$$

In the formula, x is the motor state variable, $x = [P, Q]^T$; y is the algebraic variable of the motor, $y = U$; μ is the motor parameter $\mu = [R_s, X_s, X_m, R_r, X_r, T_j, A, C, L_{fm}]^T$; x_0, y_0 are the initial values of x and y respectively.

The solutions of equation (5) are respectively denoted as $x(\mu, t)$ and $y(\mu, t)$, which are expanded by Taylor series about μ , and the $\Delta\mu$ quadratic and above terms are ignored, and we get:

$$\begin{cases} x_\mu(t) = \lim_{\Delta\mu \rightarrow 0} \frac{\Delta x(t)}{\Delta\mu} \\ y_\mu(t) = \lim_{\Delta\mu \rightarrow 0} \frac{\Delta y(t)}{\Delta\mu} \end{cases} \quad (6)$$

The main methods of calculating the trajectory sensitivity are analytical method, perturbation method and convolution method. These methods have their own advantages and disadvantages. This article adopts the perturbation method. When $\Delta\mu$ approaches zero, we can get:

$$\begin{cases} x_\mu(t) \approx \frac{\Delta x(t)}{\Delta\mu} = \frac{\varphi(x_0, t, \mu + \Delta\mu) - \varphi(x_0, t, \mu)}{\Delta\mu} \\ y_\mu(t) \approx \frac{\Delta y(t)}{\Delta\mu} = \frac{\varphi(y_0, t, \mu + \Delta\mu) - \varphi(y_0, t, \mu)}{\Delta\mu} \end{cases} \quad (7)$$

Taking the State Grid II motor [13] as an example, in the case of 0.8pu excitation voltage, the change curve of the sensitivity of each parameter of the motor to the power is shown in Figure 2 and Figure 3.

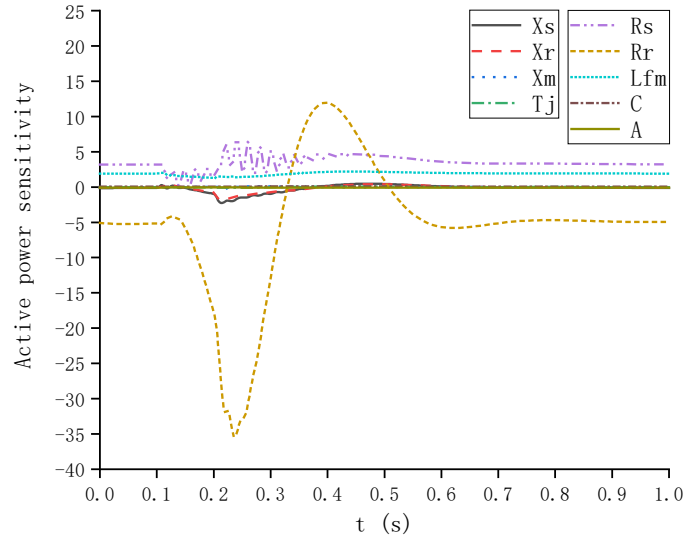


Figure 2: Sensitivity of motor parameters to active power

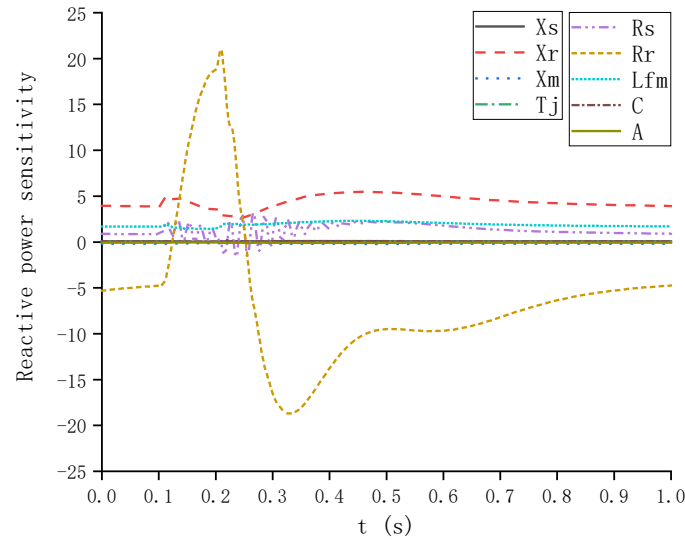


Figure 3: Sensitivity of motor parameters to reactive power

It can be seen from Figure 2 and Figure 3 that the sensitivity values of the motor parameters R_r, X_s, X_r, R_s and L_{fm} are relatively large, indicating that these parameters have a greater impact on the motor power when the motor is disturbed, while the parameters X_m, T_j, A and C sensitivity value is relatively small, indicating that these parameters have a relatively small impact on the motor power when the motor is disturbed. In refining and chemical enterprises, because the load factor L_{fm} will change with the adjustment of production, such as the increase in equipment processing volume, etc., therefore, in order to make the clustering results more applicable, use R_r, X_s, X_r and R_s As the feature vector of the cluster.

4. Hierarchical Clustering

The main idea of hierarchical clustering is to divide the data set at different levels, and finally form a tree-like clustering structure. The algorithm's realization process is based on the similarity to

measure the categories, each time the two categories with the closest similarity are selected for merging, this process is repeated continuously, and the result is returned when the termination condition is reached [14].

Agglomerated hierarchical clustering is also called AGNES (Agglomerative Nesting) algorithm. This algorithm uses a "bottom-up" aggregation strategy for the division of the data set. At the beginning, each element in the data set is seen as a class, and each time it is merged The most similar elements until the number of preset classes is reached.

In this paper, the AGNES algorithm is used to cluster the motors, and the algorithm is shown in Figure 4:

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input: sample set  $D = \{x_1, x_2, \dots, x_m\}$ ;
cluster distance measurement function  $d$ ;
number of clusters  $k$ .
process:
1: for  $j = 1, 2, \dots, m$  do
2:    $C_j = \{x_j\}$ 
3: end for
4: for  $i = 1, 2, \dots, m$  do
5:   for  $j = 1, 2, \dots, m$  do
6:      $M(i, j) = d(C_i, C_j)$ ;
7:      $M(j, i) = M(i, j)$ ;
8:   end for
9: end for
10: set the current number of clusters:  $q = m$ 
11: while  $q > k$  do
12: find the two closest clusters  $C_{i^*}$  and  $C_{j^*}$ ;
13: combine  $C_{i^*}$  and  $C_{j^*}$ :  $C_{i^*} = C_{i^*} \cup C_{j^*}$ ;
14: for  $j = j^* + 1, j^* + 2, \dots, q$  do
15: renumber the cluster  $C_j$  as  $C_{j-1}$ 
16: end for
17: delete  $j^*$  row and  $j^*$  column of the matrix  $M$ ;
18: for  $j = 1, 2, \dots, q - 1$  do
19:  $M(i^*, j) = d(C_{i^*}, C_j)$ ;
20:  $M(j, i^*) = M(i^*, j)$ ;
21: end for
22:  $q = q - 1$ 
23: end while
output: cluster division  $C = \{C_1, C_2, \dots, C_k\}$ 

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Figure 4: AGNES algorithm

5. Motor Equivalent Calculation

The purpose of motor synthesis is to replace the motor before synthesis with one or more motor equivalents. The equivalent value here means that the external response characteristics of the integrated motor and the multiple motors before synthesis are the same or close.

The equivalent circuit of each motor is shown in Figure 1. The parameters in the figure are based on the unit value of the motor's own rated value. Now the synthesis of N motors is essentially equivalent to simplifying the N parallel circuits into an equivalent circuit. In order to facilitate the application in engineering practice, the internal nodes of each motor are connected. This approximate equipotential treatment is simple and practical. The equivalent simplified circuit of multiple motors is shown in Figure 5.

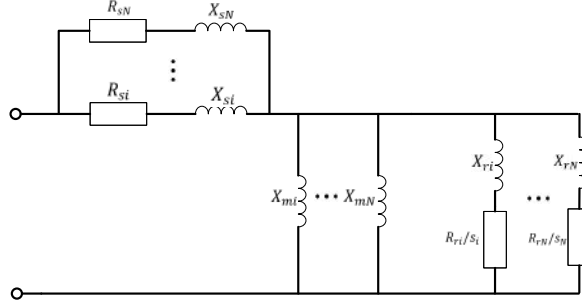


Figure 5: Equivalent circuit of multiple motors

For N motors, the rated capacity is S_{Ni} , and the sum of the rated capacities of each motor is the equivalent motor rated capacity S_{NM} . The weight of each motor capacity in the total motor capacity is defined as ρ_i :

$$\rho_i = \frac{S_{Ni}}{S_{NM}} \quad (8)$$

It can be seen from Figure 5 that the equivalent stator impedance, excitation reactance, and rotor impedance are the parallel values of the stator branch, excitation branch, and rotor branch of N motors. According to the definition of parallel circuit:

$$\frac{1}{Z_M} = \sum_{i=1}^N \frac{\rho_i}{Z_i} \quad (9)$$

The excitation reactance can be obtained:

$$\frac{1}{X_{mM}} = \sum_{i=1}^N \frac{\rho_i}{X_{mi}} \quad (10)$$

The rotor impedance can be obtained:

$$\frac{1}{\frac{R_{rM}}{s_M} + jX_{mM}} = \sum_{i=1}^N \frac{\rho_i}{\frac{R_{ri}}{s_i} + jX_{mi}} \quad (11)$$

Where R_{ri} , X_{mi} and s_i are the rotor resistance, excitation reactance, and slip of the i -th motor, respectively; R_{rM} , X_{mM} and s_M are the equivalent motor rotor resistance, excitation reactance, and slip, respectively.

Obviously, when $s_i=1$, equation (11) should also be established, then:

$$R_{rM} = \frac{a}{a^2+b^2}, X_{mM} = \frac{b}{a^2+b^2} \quad (12)$$

Where $a = \sum_{i=1}^N \frac{\rho_i R_{ri}}{R_{ri}^2 + X_{mi}^2}$, $b = \sum_{i=1}^N \frac{\rho_i X_{mi}}{R_{ri}^2 + X_{mi}^2}$

The definition of the inertial time constant is twice the kinetic energy at the synchronous speed divided by its own capacity, the formula is:

$$T_J = \frac{2W}{S_N} \quad (13)$$

At the synchronous speed, the sum of the kinetic energy of the equivalent motors is equal to the sum of the kinetic energy of the motors. therefore:

$$T_{JM} S_{NM} = \sum_{i=1}^N T_{Ji} S_{Ni} \quad (14)$$

$$T_{JM} = \sum_{i=1}^N \rho_i T_{Ji} \quad (15)$$

In the formula, T_{Ji} and S_{Ni} are the inertia time constant and rated capacity of the i -th motor respectively; T_{JM} and S_{NM} are the inertia time constant and rated capacity of the equivalent motor respectively.

6. Example Analysis

This paper uses an IEEE9 example system to simulate the method proposed. The system is shown in Figure 6. Take a P-xylene (PX) unit 6kV high-voltage motor group of a refinery and chemical enterprise as an example. The motor model parameters are shown in Table 1. A transformer is connected to bus 6 with a voltage of 6kV on the secondary side of the transformer, and the motor load is connected to the bus on the secondary side of the transformer.

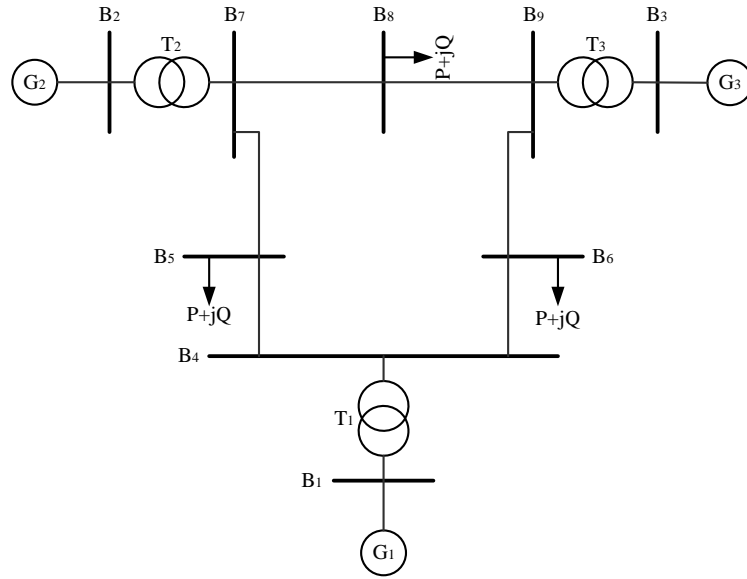


Figure 6: IEEE9 example system

Table 1: 6kV motor model parameters of PX unit

NO	R_s /pu	X_s /pu	R_r /pu	X_r /pu	X_m /pu	H /s
M1	0.0273	0.0892	0.0228	0.0892	5.9368	4.0407
M2	0.0307	0.0806	0.0273	0.0806	5.9067	4.6316
M3	0.0298	0.1156	0.0296	0.1156	4.6000	2.5390
M4	0.0300	0.0974	0.0163	0.0974	5.0462	2.7218
M5	0.0216	0.1009	0.0229	0.1009	6.3594	3.2492
M6	0.0298	0.1156	0.0208	0.1156	4.6000	2.5390
M7	0.0324	0.1029	0.0247	0.1029	3.6218	1.0400
M8	0.0239	0.0981	0.0341	0.0981	4.8292	1.6835
M9	0.0019	0.1293	0.0164	0.1293	3.2717	0.4990
M10	0.0338	0.1133	0.0351	0.1133	2.8578	0.4205
M11	0.0409	0.0926	0.0472	0.0926	5.1725	2.1006
M12	0.0381	0.0859	0.0345	0.0859	4.5153	1.9174

The results of the classification by hierarchical clustering are shown in Figure 7 and Table 2.

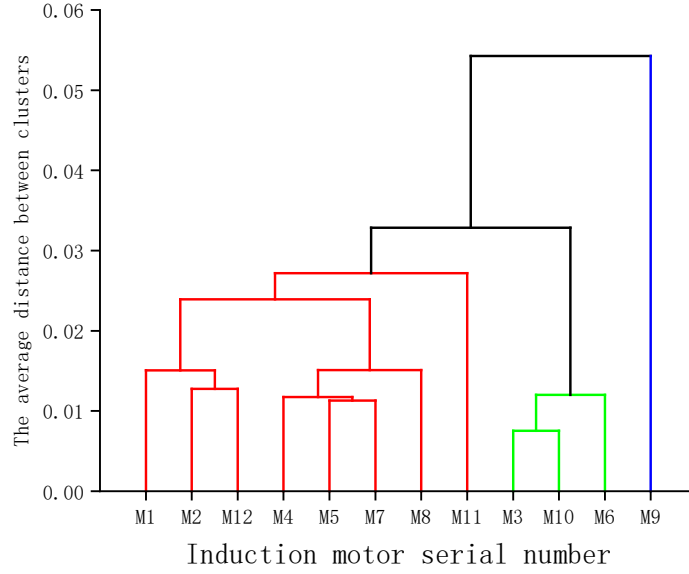


Figure 7: 6kV motor classification of PX unit

Table 2: PX unit motor classification

Area	Number of motors
I	M1, M2, M4, M5, M7, M8, M11, M12
II	M3, M6, M10
III	M9

According to the classification results in Table 2, the motors are integrated, and the results are shown in Table 3.

Table 3: PX unit 6kV motor aggregation model parameters

Area	R_s /pu	X_s /pu	X_m /pu	R_r /pu	X_r /pu	T_j /s
I	0.0288	0.0958	5.2055	0.0264	0.0960	5.4913
II	0.0316	0.1146	3.6364	0.0295	0.1149	3.2344
III	0.0019	0.1293	3.2717	0.0164	0.1293	1.0000

The fault is set to be near the bus 4 between the bus 4 and the bus 6. The fault type is a three-phase grounding short-circuit, the short-circuit time starts from 0.3s, and the fault disappears after 5 cycles. The simulation waveforms are shown in Figure 8 and Figure 9.

The one marked as "Original models" in the simulation waveform is to model the motors one by one; the one marked as "Single equivalent model" in the simulation waveform is the equivalent of one motor group; in the simulation waveform, it is marked as "Equivalent model of this paper" is a model of equivalence after clustering the motor group according to the hierarchy.

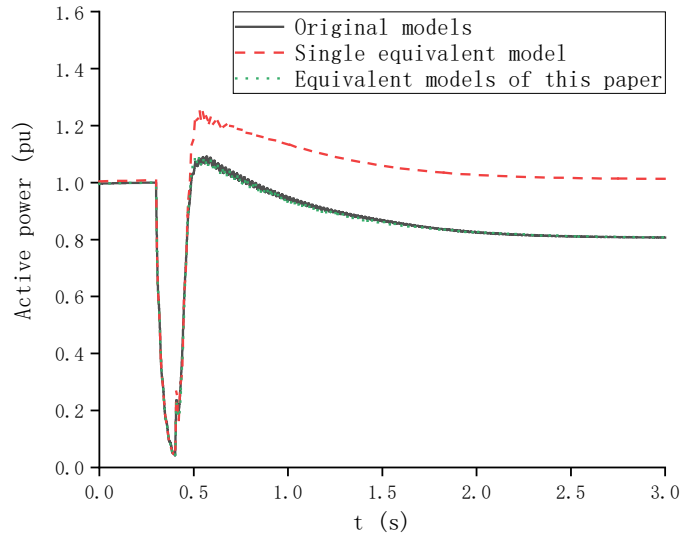


Figure 8: Bus active power change curve after fault removal

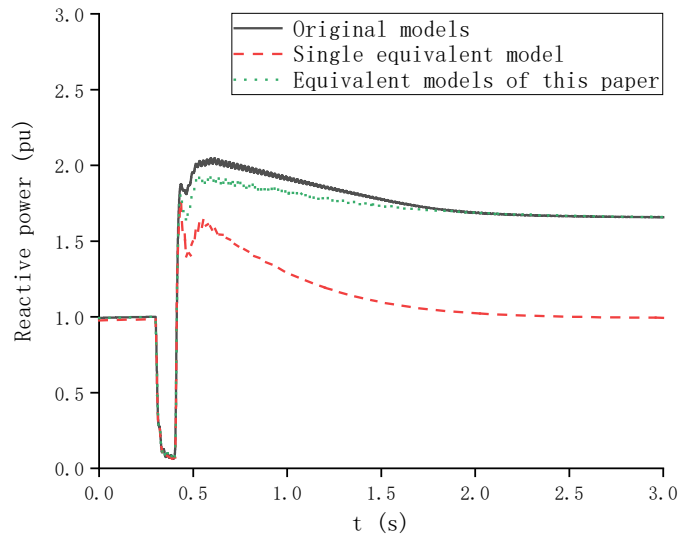


Figure 9: Bus reactive power change curve after fault removal

Figures 8 and 9 are the change curves of active power and reactive power of the busbar after 0.3s fault removal. For changes in active power and reactive power, the equivalent value after clustering of the motor group can reflect the actual situation better than the direct equivalent value.

Comparing the active and reactive power curves under different processing methods for the motor group, it can be found that when the characteristics of the motors in the motor group are quite different, the equivalent value is that the error of one motor is relatively large.

7. Conclusions and Discussion

Based on the characteristics of the power system of the refining and chemical enterprise, combined with the results of the sensitivity analysis of the power trajectory of the various parameters of the motor, the appropriate amount of motor model parameters are selected as the characteristic quantities of the hierarchical clustering, and the hierarchical clustering algorithm is used to aggregate the motors.

The simulation results show that, In this paper, the use of hierarchical clustering algorithm to aggregate the motor groups of refining and chemical enterprises is effective and convenient, and it has guiding significance for the relevant work of refining and chemical enterprises.

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