Research on model calibration method for energy consumption evaluation of cluster motor system

Qu Bo¹,², Sun Xiaofei³, Sun Ruonan³, Zhang Xinhe², Huang Wei², Su Juan⁴, Du Songhuai³, Zhai Qingzhi³, Lou Zhenyi³

¹Tianjin University, Tianjin 300072, China; ²China Electric Power Research Institute, Beijing 100192, China; ³College of Information and Electrical Engineering, China Agricultural University, Beijing 100083, China

Abstract. In practical engineering, the conventional energy consumption calculation method of the motor system is facing many problems, such as difficulty in data acquisition, deviation of model parameters and so on. In order to ensure and improve the accuracy and evaluation ability of the energy consumption model, a calibration method based on parameter identification theory is proposed in this paper. Using the Levenberg-Marquardt algorithm, the rated efficiency, rated variable loss and constant loss parameters of the single and cluster motor systems are identified, and the correction model for the calculation of motor energy consumption is established. Taking a typical three machine cluster motor system as an example, a real physical experiment platform is built to obtain real running data. The example shows that the energy consumption model correction method proposed in this paper has strong engineering practicability, which provides an effective technical means for energy consumption assessment and energy saving transformation of motor energy system.

1. Introduction

Energy conservation studies in typical energy systems seem to be conventional, but never stop. The main electrical equipment as the motor, the total electricity accounts for about 70% of electricity consumption in the industrial world. With the global energy consumption growth, environmental and energy issues have become increasingly prominent. Energy-saving motor system has become China's "12th Five-Year" and "13th Five-Year" during the focus of attention in the field of energy saving and emission reduction. In order to better assess the motor system energy consumption and energy saving in the engineering application, the energy consumption model for the calculation of the accuracy and practicability of the research can not be overlooked.

The conventional energy consumption calculation methods of motor system are mainly three kinds. One is to calculate the system energy consumption [¹] in real time by monitoring the input and output data of motor, but this method is limited to only the current energy consumption level monitoring, so the energy consumption analysis under global load rate can not be carried out; another kind is the motor nameplate system model based on energy consumption, energy consumption calculation combined with measurable data[²-⁵], but with increasing the length of the motor when in use and improper maintenance, or because of the influence of temperature, humidity and electrical aging and other factors on the motor running state, power consumption parameters of the energy consumption model in the real values are often not up to the initial value, resulting in greater calculation error;
last one is through the measurement and calculation of iron loss, copper loss, mechanical loss and stray loss, build the motor loss model, and then analyzes the situation of energy consumption, but this method requires higher data measurement capability and computational complexity, and even the need to stop the operation, in the practical application of poor usability.

In order to improve the accuracy of energy consumption assessment and calculation of motor system, many scholars at home and abroad have done a lot of research on the parameter identification and model optimization of the motor system. Literature [6] based on nameplate parameter and sequence two times programming algorithm, it presents a minimum efficiency deviation of target motor parameter identification method, the identification of the stator and rotor reactance analysis, motor efficiency, power factor and other performance parameters, but the method is based on the nameplate data and ignore the effect of iron loss, will bring about a certain error calculation; literature [7] proposes an online identification method of asynchronous motor parameters based on recursive least squares and model reference adaptive control. The method can get real-time identification values, and use equivalent circuit method to complete the dynamic evaluation of motor energy efficiency; literature [8-9] using Lyapunov theorem to construct parameter adaptive law, and based on model reference adaptive control method for multi parameter identification, this method has the advantages of simple algorithm, but how to establish the error equation of motor system energy consumption model and constructing appropriate adaptive law is the difficulty of this method; literature [10] based on the equivalent circuit of linear induction motor driven by frequency converter, according to the blocking characteristics of different frequencies, the parameters of motor resistance and leakage inductance are identified. The method is simple and feasible, but it is slightly inadequate in analyzing the energy consumption of motor. In the related research of motor energy consumption model, the equivalent circuit of induction motor rotating coordinate system considering iron loss in parallel mode is deduced and established in literature [11], and it is simplified in steady state operation; literature [12] presents an improved model of induction motor’s iron loss based on time stepping finite element.

To sum up, based on the existing research theory, considering the engineering application conditions and taking the data observability as the premise, a correction method of energy consumption model of trunking motor system based on LM parameter identification is proposed. By analyzing the main energy consumption factors of the cluster motor system, the parameters to be identified will be determined; meter based on the measured data, and combined with the LM algorithm to identify the parameters of the energy consumption of the system, and then establish the calibration model of cluster motor system energy consumption, provide effective technical means for motor performance assessment and energy consumption analysis.

2 Energy consumption model of cluster motor system

2.1 Energy consumption model for single machine

Based on the principle of power balance, the energy consumption of the motor can be expressed as:

\[ P_1 = \Delta p_a + \Delta p_b + P_2 \]  

(1)

In the type, \( P_1 \) is the input power of the motor; \( \Delta p_a \) is the variable loss of the motor; \( \Delta p_b \) is the constant loss of the motor, and the \( P_2 \) is the output power of the motor.

For the further analysis of the motor loss, the variable loss is composed of copper loss and stray loss. The constant loss is composed of iron loss and mechanical loss. The following is the following:

\[ \left\{ \begin{array}{l}
\Delta p_a = p_{cu1} + p_{cu2} + p_s \\
\Delta p_b = p_{fe} + p_{fw}
\end{array} \right. \]  

(2)

In the formula, \( p_{cu1} \) is stator copper loss; \( p_{cu2} \) is rotor copper loss; \( p_{fe} \) is iron loss; \( p_{fw} \) is mechanical loss; \( p_s \) is stray loss.

The variable loss of the motor is related to the load rate and the rated variable loss, and there is a formula[4]:
\[
\begin{align*}
\Delta p_a &= \beta^2 \Delta p_{aN} \\
\Delta p_{aN} &= \frac{P_N}{\eta_N} - P_N - \Delta p_b
\end{align*}
\] (3)

In the form, \( \beta \) is motor load rate; \( \Delta p_{aN} \) is rated variable loss for motor; \( P_N \) is motor rated power; \( \eta_N \) is motor rated efficiency.

The energy consumption model of single machine can be obtained by formulae (1) and (3):

\[
P_{\lambda} = \beta^2 \left( \frac{P_N}{\eta_N} - P_N - \Delta p_b \right) + \Delta p_b + P_2
\] (4)

According to the formula (4), the main energy consumption parameters of a single machine are defined as the load rate, the rated efficiency and the constant loss.

2.2 Energy consumption model of cluster motor system

For a multi motor parallel operation of the cluster motor system, the main measuring point is the total input end of all motors under the same voltage level, often the two terminal of the transformer, so the energy consumption of the system can be expressed as:

\[
P_T = \sum_{j=1}^{n} P_{j1}
\] (5)

In the form, \( P_T \) is the total input power of the cluster motor system; \( n \) is the total number of the system motor; \( j \) is the system motor number; \( P_{j1} \) is the input power of the \( j \) motor in the system.

Considering the energy consumption of each platform in the system, the formula (4) and (5) can be obtained:

\[
P_T = \sum_{j=1}^{n} \left[ \beta_j^2 \left( \frac{P_{jN}}{\eta_{jN}} - P_{jN} - \Delta p_{jM} \right) + \Delta p_{jM} + P_{j2} \right]
\] (6)

\( \beta_j \) is the load rate of \( j \) motor in the system, \( P_{jN} \) is the rated power of the \( j \) motor in the system, \( \eta_{jN} \) is the rated efficiency of the \( j \) motor in the system, \( \Delta p_{jM} \) is the constant loss of the \( j \) motor in the system, \( P_{j2} \) is the output power of the \( j \) motor in the system.

From the formula (3) and (6), the energy consumption model of the cluster motor system can be obtained as follows:

\[
P_T = \sum_{j=1}^{n} \left( \beta_j^2 \Delta p_{jAN} + P_{j2} \right) + \Delta p_{total}
\] (7)

In the system, \( \Delta p_{jAN} \) is the rated variable loss of the \( j \) motor in the system; \( \Delta p_{total} \) is the total constant loss of the system.

According to the formula (7), the main energy consumption parameters of the cluster motor system are defined as the load rate, the rated variable loss and the total constant loss.

In the actual operation of the system, the parameters of the motor energy consumption are often deviated from the parameters of the factory, which is shown on the rated efficiency and loss parameters. In the calculation of the energy consumption of the cluster motor system, the calculation error of the energy consumption of each motor in the system is reflected in the whole cluster motor system.

3 Energy consumption model correction of cluster motor system based on LM method

3.1 LM parameter identification method

On the basis of Gauss Newton method, the concept of damping factor is introduced by the LM method, for the nonlinear equation:

\[
y=f(x,c)
\] (8)

In the formula, \( x \) is a variable; \( c \) is a parameter to be identified.

Based on the thought of the least square method, the sum of square sum of the calculated residual is minimized, and the optimal solution\[13\] is obtained. There are formulas:

\[
\begin{align*}
\tilde{y}_i &= f(x_i, \hat{c}) - y_i \\
R_{\text{min}} &= \sum_{i=1}^{n} \tilde{y}_i^2 = \sum_{i=1}^{n} [f(x_i, \hat{c}) - y_i]^2
\end{align*}
\] (9)
In the formula, \( i \) is data number, \( r \) is residuals, \( R_{\text{min}} \) is the minimum sum of residuals, \( l \) is the number of data, and \( \hat{c} \) is the best solution.

The first order Taylor expansion of \( y = f(x, c) \) is carried out at \( c^{(k)} \), and the results are as follows:

\[
y \approx f(x, c^{(k)}) + \sum_{j=1}^{l} \frac{\partial f(x, c^{(k)})}{\partial c_j} \Delta c_j \quad (10)
\]

In the formula, \( J \) is the Jacobi matrix.

The relation matrix is obtained as follows:

\[
Y = F + J\Delta c \quad (11)
\]

In order to prevent the singularity of \( J^T J \) and cause the fitting and divergence, the LM method introduces the damping factor \( \lambda (\lambda > 0) \), which has the equation:

\[
(J^T J + \lambda I)\Delta c = J^T(Y - F) \quad (12)
\]

In the formula, \( I \) is a unit matrix.

The final iteration formula is as follows:

\[
c^{(k+1)} = c^{(k)} + (J^T J + \lambda I)^{-1}J^T r(c^{(k)}) \quad (13)
\]

### 3.2 Energy consumption model correction of cluster motor system

In the analysis of the cluster motor system, the energy consumption model is set up according to the formula (7):

\[
\Delta p_T = f(\beta_j, \Delta p_{jAN}, \Delta p_{b\text{total}}) \quad (14)
\]

In the formula, \( \Delta p_T \) is the total loss of the cluster motor system; the data parameters are \( \Delta p_T \) and \( \beta_j \); the parameters to be identified are \( \Delta p_{jAN} \) and \( \Delta p_{b\text{total}} \). The data type is the output power and the total input power of each motor at different load rates when the rated voltage is run in the cluster motor system.

The parameter identification process of a cluster motor system is similar to that of a single motor device. The energy consumption solution model is shown by the one Taylor expansion of parameters and the Jacobi matrix, such as formula (15) and (16).

\[
F = \sum_{j=1}^{n}(\beta_j^2 \Delta p_{jAN}^{(0)} + \Delta p_{b\text{total}}^{(0)}) + \sum_{j=1}^{n} \left[ \frac{\partial f(\beta_j, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{jAN}} \right]_{\Delta p_{jAN}=\Delta p_{jAN}^{(0)}} \Delta (\Delta p_{jAN}) + \sum_{j=1}^{n} \left[ \frac{\partial f(\beta_j, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{b\text{total}}} \right]_{\Delta p_{b\text{total}}=\Delta p_{b\text{total}}^{(0)}} \Delta (\Delta p_{b\text{total}})
\]

\[
J = \begin{bmatrix}
\frac{\partial f(\beta_1, \Delta p_{1AN}, \Delta p_{b\text{total}})}{\partial \Delta p_{1AN}} & \frac{\partial f(\beta_1, \Delta p_{1AN}, \Delta p_{b\text{total}})}{\partial \Delta p_{2AN}} & \cdots & \frac{\partial f(\beta_1, \Delta p_{1AN}, \Delta p_{b\text{total}})}{\partial \Delta p_{jAN}} & \frac{\partial f(\beta_1, \Delta p_{1AN}, \Delta p_{b\text{total}})}{\partial \Delta p_{b\text{total}}} \\
\frac{\partial f(\beta_1, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{1AN}} & \frac{\partial f(\beta_2, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{2AN}} & \cdots & \frac{\partial f(\beta_2, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{jAN}} & \frac{\partial f(\beta_2, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{b\text{total}}} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
\frac{\partial f(\beta_1, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{1AN}} & \frac{\partial f(\beta_1, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{2AN}} & \cdots & \frac{\partial f(\beta_1, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{jAN}} & \frac{\partial f(\beta_1, \Delta p_{jAN}, \Delta p_{b\text{total}})}{\partial \Delta p_{b\text{total}}}
\end{bmatrix}
\]

(16)

The iterative calculation is carried out according to the formula (13) until the iteration is convergent, and the residual difference is within a reasonable range, and the optimal solution \( \Delta p_{jAN} \) and \( \Delta p_{b\text{total}} \) are obtained. Finally, based on the identification parameters, the energy consumption model of the cluster motor system is corrected, and the correction model is obtained.

\[
\hat{p}_T = \sum_{j=1}^{n}(\beta_j^2 \Delta p_{jAN} + p_{j2}) + \Delta p_{b\text{total}} \quad (17)
\]

Energy consumption, calibration model can accurately calculate the single motor and motor system in cluster based on global load rate and the energy consumption of the system can be analyzed through energy level parameter identification results, reference[14] standards, is not up to the level of energy consumption, equipment maintenance or elimination, operation adjustment or energy-saving motor system energy consumption of cluster the level of difference.
4. Example analysis
Calibration models for energy consumption of cluster motor system, now the choice of three models of the same nameplate value, rated voltage $U_N = 220\, V$, rated current $I_N = 0.5\, A$, rated frequency $f_N = 50\, Hertz$, rated power $P_N = 100\, W$ and rated speed $n_N = 1400\, r/min$ three-phase squirrel cage asynchronous motor, experimental analysis of motor based on the experimental platform of China Agricultural University. Under the load experiment and the load experiment, the rated parameters of three motors are measured respectively. The motor is set to operate at rated voltage and frequency, and the no load loss is approximated to constant loss. The average value of the ten measurement is taken as the real energy consumption parameter of the motor, as shown in Table 1.

Table 1. Motors energy consumption real parameters.

| Motor  | Motor2 | Motor 3 | Motor group |
|--------|--------|---------|-------------|
| Rated efficiency(%) | 57.13  | 58.36   | 45.18       | --          |
| Rated variable loss(W) | 27.48  | 25.23   | 57.37       | 110.08      |
| Constant loss(W) | 47.56  | 46.12   | 63.97       | 157.65      |

Based on the cluster motor system composed of the three motors, the energy consumption correction model is studied. At the rated voltage, the output power and the total input power of the motor in the cluster motor system at different load rates are measured. Based on the measured data, the rated variable loss and the total invariable loss parameters of the cluster motor system are identified and the error analysis is made, as shown in Table 2.

Table 2. The results and errors of cluster motor system parameters identification.

| Motor  | Motor2 | Motor 3 | Motor group |
|--------|--------|---------|-------------|
| Rated variable loss(W) | 21.28  | 31.95   | 56.22       | 109.45      |
| Rated variable loss error (W) | -6.20 | 6.72    | -1.15       | -0.63       |
| Error rate (%) | 22.58  | 26.64   | 2.00        | 0.57        |
| Constant loss(W) | --     | --      | --          | 154.03      |
| Constant loss error(W) | --     | --      | --          | 3.62        |
| Error rate (%) | --     | --      | --          | 2.29        |

In the analysis of the identification results of clustered motor system, the maximum error is second devices, the error rate is 26.64%, the error is the smallest of third devices, the error rate is 2%, the total constant loss calculation error rate is 2.29%. The identification error rate of the variable loss $\sum_{j=1}^{n}\Delta p_{j\omega\omega}$ for the total system total variable loss is only 0.57%, although there is a large error in the rated variable loss identification of the single machine. In the analysis of the overall energy consumption of the cluster motor system, the energy consumption level can be evaluated through the total rated variable loss and the total constant loss parameters. If the energy consumption analysis of the single motor in the system is needed, the energy consumption parameters of the selected motor are identified and calculated.

Based on the identification results, the energy consumption model of the cluster motor system is corrected. According to the formula (7), the energy consumption model of the system is constructed.

$$P_{T(leave)} = \sum_{j=1}^{n}(p_j^2 \Delta p_{j\omega\omega} + p_j^2) + \Delta p_{btotal} = 31.45\beta_1^2 + 31.45\beta_2^2 + 31.45\beta_3^2 + 100\beta_1 + 100\beta_2 + 100\beta_3 + 62.91(W)$$

From Table 1, the energy consumption model of the cluster motor system is constructed based on the experimental parameters:
\[ P_T(\text{real}) = 27.48\beta_1^2 + 25.23\beta_2^2 + 57.37\beta_3^2 + 100\beta_1 + 100\beta_2 + 100\beta_3 + 157.65(W) \]  \hspace{1cm} (19)

From Table 2, the energy consumption correction model of the cluster motor system based on the identification results is as follows:
\[ P_T(\text{check}) = \sum_{i=1}^{n}(\beta_i^2\Delta p_\text{ta} + p_{f2}) + \Delta p_\text{ptotal} = 21.28\beta_1^2 + 31.95\beta_2^2 + 56.22\beta_3^2 + 100\beta_1 + 100\beta_2 + 100\beta_3 + 154.03(W) \]  \hspace{1cm} (20)

Based on the above models, the energy consumption curves of a single motor and a cluster motor system under the global load rate are constructed, and the energy consumption calculation error of the correction model is analyzed, as shown in Figure 1.

![Figure 1. Comparison on system energy consumption](image)

Analysis shows that the factory system energy consumption curve substantially lower than the actual energy consumption curve of the measured motor parameters, the energy consumption of the equipment has greatly changed, the factory model can not accurately calculate the energy consumption of energy consumption; but the energy consumption curve after correction and the real energy consumption curve coincide, energy consumption calculation error correction model is far less than the energy consumption of a plant model, indicating that energy consumption the correction model can accurately calculate the situation of single motor and motor system in cluster under the global load rate. For example, when the load rate is 1, the calculated factory energy consumption model based on the energy consumption of cluster motor system was 457.26W, the correction model to calculate the energy consumption of 563.48W, and the real energy consumption is 567.73W; the calculation error reached 110.47W factory energy consumption model, the error rate is 19.46%, and the calculation error correction model is only 4.25W. The error rate of 0.75%. In addition, the system completes the model calibration through less measurable data. The energy consumption calculation requires only running the load rate parameters, which solves the problems and difficulties of the conventional energy consumption calculation method in practical application, and has strong practicability.

5. Conclusion
In view of the needs of actual calculation and evaluation, this paper proposes a method of calibration for energy consumption model of cluster motor system based on LM algorithm. Through the analysis of the motor system energy consumption model, the selected single motor and motor system cluster rated efficiency and rated variable loss and constant loss parameters, using the measured data and to identify the parameters using the LM parameter identification method, according to the identification results correction model of a motor system energy consumption calculation. A real physical experiment platform is built, and three typical asynchronous motors with the same capacity and
capacity of 100W are selected to build a typical trunking motor system. The real experimental data are collected to verify the simulation work. This method according to the actual evaluation of the condition, through the observation data, can accurately identify the single motor and motor system cluster rated efficiency and rated variable loss and constant loss parameters, parameter identification can be used to assess the level of overall energy consumption of motor performance and motor system based on cluster, to meet the requirements of the energy consumption of the motor repair or eliminated. Retrofit of cluster motor system on the low power level or the potential for energy saving.

Acknowledgment
Fund Project: National Power Grid Corp headquarters science and technology project funding "energy efficiency benchmark database data validation service technical service contract" (YDB51201701973)

References
[1] Zhang H, Yin Q, Dongmei M A. Research on Efficiency Testing Technology of Motors[J]. Electric Machines & Control Application, 2012
[2] LEI Nai-hua, WEN Yun-guang, YE De-zhu, et al. Research on Efficiency Test of Variable Frequency Motor[J]. Mechanical Research & Application, 2014, 27(6): 182-184
[3] Bai Lianping, Xu Guangjiao, Zheng Shouyin. Field test and analysis of the load rate and operation efficiency of asynchronous motors[J]. Electrical Machinery Technology, 2015, 1: 29-32
[4] Chen L. Analysis of the Wear and Tear, Efficiency and Load Factor of Three-phase Asynchronous Motors[J]. Metallurgical Power, 2014
[5] Zhang Zhihua, Li Shengyong, Chen Weihua, et al. Research and design of energy efficiency testing system with 112B method for high efficiency motor[J]. Small & Special Electrical Machines, 2015, 43(12): 49-54
[6] Mao Xiaoming, Liao Weiping. Induction motor model parameter identification based on motor nameplate data and sequential quadratic programming[J]. Electric Power Automation Equipment, 2016, 36(12): 89-94
[7] Ge Suan, Paerhati. Abudukelimu, Zhao Haisen, et al. Research on the method of motor parameter identification for dynamic estimation on the efficiency of motor systems[J]. Journal of North China Electric Power University, 2014, 41(5): 62-67
[8] JIN Hai, HUANG Jin. Adaptive Flux Estimation and Parameters Identification of Induction Motors Based on Model Reference Approach[J]. Transactions of China Electrotechnical Society, 2006, 21(1): 65-69
[9] JIN Hai, HUANG Jin, YANG Jia-qiang. Adaptive rotor flux estimation and parameter identification for induction motor[J]. Journal of Zhejiang University(Engineering Science), 2006, 40(2): 339-343
[10] He Jinwei, Shi Liming. An identification method for linear induction motor parameter based on static characteristics[J]. Advanced Technology of Electrical Engineering and Energy, 2009, 28(4): 50-53
[11] Li Yaoheng, Diao Lijun. Series-parallel motor model considering iron loss and its impact on vector control[J]. Advanced Technology of Electrical Engineering and Energy, 2016, 35(1): 13-18
[12] YANG G Q, CUI Z Z, SONG L W. Analysis of iron losses in induction motor with an improved iron-loss model[A]. 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)[C]. Beijing: IEEE, 2014: 1-4
[13] Li Fahai, Zhu Dongqi. Motor Science[M]. Beijing: Science Press, 2007: 10-380
[14] GB/T 2013—2006/IEC 61972: 2002, Determination of loss and efficiency of three phase cage asynchronous motor[S]