Research of Motor Energy Saving Method Based on Hybrid Search Algorithm

Song Chen1,2,3,*, Dong Feng1,2, Wenjing Li1,2, Zhongcheng Wu1
1High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei, China
2University of Science and Technology of China, Hefei, China
3College of Mechanical and Electrical Engineering, Anhui Jianzhu University, Hefei, China

*Corresponding author e-mail: gengyun97@163.com

Abstract: The motor model and control system is built based on vector control considering the iron loss, and the magnetic chain and torque observation module are designed. The system is realized by Matlab software and can run steadily. The loss model, the golden split algorithm and the hybrid algorithm are used to control the motor system and the total energy consumptions of the motor are calculated. The influence of iron loss was analyzed. The simulation results show that the energy saving operation of speed adjustment motor can be realized and enter steady state in a short time by the combination algorithm and vector control. The effect of energy saving is evident under light load.

1. Introduction

At present, the energy saving research of motor is mainly divided into two categories: one is the study of motor ontology, such as choosing efficient material, and improving the motor manufacturing process, to improve the efficiency of the operation of the machine itself. The second is the study of motor control technology, such as making the motor system operating in maximum efficiency under the certain condition through the advanced control technology.

The research of motor energy-saving running based on vector control is mainly concentrated in two aspects: one is based on the motor loss model control method, which has the advantage of high control speed, but is susceptible to the influence of the motor parameters, and control accuracy is not high. The second is the control method based on online search, which is not affected by the motor parameters. But search efficiency is not high, and the flux volatile in search process is high, which influences the stability of the system [1-4]. Some control models ignore stator leakage or rotor iron loss [5]. This design adopts hybrid search online energy-saving operation control strategy with combination of the golden online search method and the loss model, which effectively plays the advantages of two methods.

In this vector control system, model of the asynchronous motor is established considering iron losses. By studying the loss of the motor and the rotor flux under different operating conditions, hybrid energy-saving control method is adopted with the combination of motor loss model and online search. It has better efficiency compared with the simple loss model of energy-saving control method.

2. Motor model considering the iron loss

In order to make the simulation calculation results more accurate, the iron loss is considered in motor model. An equivalent pure resistance winding loss is used in place of the motor iron loss. In the static coordinate system, in addition to the original four winding of rotor and stator shaft, two iron loss equivalent winding are added at $\alpha$ and $\beta$ shaft of the stator [6-7].
The six winding voltage equation are as follows.
\[ u_{s\alpha} = R_{s\alpha} i_{s\alpha} + p\Psi_{s\alpha} \]
\[ u_{s\beta} = R_{s\beta} i_{s\beta} + p\Psi_{s\beta} \]
\[ 0 = R_{s\alpha} i_{s\alpha} + \omega\Psi_{r\beta} + p\Psi_{r\alpha} \]
\[ 0 = R_{s\beta} i_{s\beta} - \omega\Psi_{r\alpha} + p\Psi_{r\beta} \]
\[ 0 = R_{m\alpha} i_{m\alpha} - p\Psi_{m\alpha} \]
\[ 0 = R_{m\beta} i_{m\beta} - p\Psi_{m\beta} \]
(2-1)

The field current of motor are set as follows.
\[ i_{L\alpha} = i_{s\alpha} + i_{r\alpha} - i_{R\alpha} \]
\[ i_{L\beta} = i_{s\beta} + i_{r\beta} - i_{R\beta} \]
(2-2)

The field current of motor are set as follows:
- \( R_s, R_r, R_m \) —— Stator and rotor resistance and iron loss equivalent resistance;
- \( L_{s\alpha}, L_{s\beta}, L_m \) —— Leakage inductance and mutual inductance of stator and rotor;
- \( u_{s\alpha}, u_{s\beta} \) —— Stator voltage of \( \alpha \) and \( \beta \) axis;
- \( i_{s\alpha}, i_{s\beta} \) —— Stator current of \( \alpha \) and \( \beta \) axis;
- \( i_{R\alpha}, i_{R\beta} \) —— Iron loss equivalent winding current of \( \alpha \) and \( \beta \) axis;
- \( i_{L\alpha}, i_{L\beta}, i_{Lm} \) —— Field current of \( \alpha \) and \( \beta \) axis;
- \( \Psi_{r\alpha}, \Psi_{r\beta}, \Psi_{s\alpha}, \Psi_{s\beta} \) —— Stator and rotor magnetic chain of \( \alpha \) and \( \beta \) axis;
- \( \Psi_{m\alpha}, \Psi_{m\beta} \) —— Main magnetic chain of \( \alpha \) and \( \beta \) axis;

Motor running parameters are as follows: \( n_p = 2, R_s = 0.5105\,\Omega, R_r = 0.2917\,\Omega, L_r = L_s = 0.00485\,\text{H}, L_m = 0.09725\,\text{H}, R_m = 45.65\,\Omega, f = 50\,\text{Hz}. \) Rated flux: \( \Psi_e = 0.96 \, \text{Wb.} \)

3. The vector control system

![FIG3.1 structure of vector control speed regulation system.](image)

System is based on the vector control theory of rotor field oriented. Double closed loop control system is used with speed detection and current detection.

Feedback channel is mainly used to detect the rotor speed and stator current. Current feedback is used to reflect the status of the load, make the torque component of current isq change with load, and simulate the working condition of motor. Speed feedback is used to reflect the differences between the actual speed of dragging system and a given speed, and correct the system at right speed, so as to improve the dynamic performance of the system. A, B and C phase stator current sampling values of
Ac motor can be changed to torque component and excitation component at two phase rotating coordinate system by Clarke transform and Parke transform. The rotor flux position angle can be got by rotor flux observer. The three variables are used for the control of forward channel in the system.

After calculating the deviation of a given speed signal and the actual speed with PI regulator and iron loss, we can get torque current. Difference between calculated torque current and actual torque current is sent to PI regulator, so as to get torque voltage output $U_{sq}$.

In the same way, after calculating the deviation of a given flux linkage and the actual flux linkage with PI regulator and iron loss, we can get field current. Difference between calculated field current and actual field current is sent to PI regulator, so as to get field voltage output $U_{sd}$. With $U_{sq}$ and $U_{sd}$ through the Park inverse transformation, we can get $v_{α}$ and $v_{β}$. The system uses space vector modulation to control pulse, gets switching sequence and time of inverter, and outputs trigger pulse [8-9].

4. The flux calculation

The electrical power input of induction motor is $P_1$. Part of $P_1$ will consume on the stator winding resistance and change to copper loss $P_{Cus}$. A small part due to set up a rotating magnetic field will be consumed in the stator core as iron loss $P_{Fe}$. Most of the rest is passed on to the rotor with the help of the air gap of the rotating magnetic field, and a small part of the electromagnetic power will be changed to rotor winding copper loss $P_{Cur}$.

Total controllable loss is as follow:

$$P_{loss} = P_{Cus} + P_{Cur} + P_{Fe}$$

$$= R_s(I_{d1}^2 + I_{q1}^2) + \frac{R_eT_e^2}{n_p^2}\frac{R_e}{\Psi_r^2} + \frac{\omega^2}{n_p^2}\frac{T_e^2}{\Psi_r^2} + \frac{2\omega T_eR_s}{R_{Fe}n_p}$$

$$= \frac{R_s}{I_m} + \frac{\omega^2}{R_{Fe}}\frac{T_e^2}{n_p^2}(R_s + R_e)\Psi_r^{-2} + \frac{2\omega T_eR_s}{R_{Fe}n_p}$$

$Ψ_r$ is the rotor flux linkage.

The derivation formula of rotor flux is:

$$\frac{\partial P_{loss}}{\partial Ψ_r} = 2\frac{R_s}{I_m} + \frac{\omega^2}{R_{Fe}}\frac{T_e^2}{n_p^2}(R_s + R_e)Ψ_r^{-3}$$

We can get the optimal flux that makes controllable loss minimum.

$$Ψ_m = \left(\frac{R_e}{I_m} + \frac{\omega^2}{R_{Fe}}\frac{T_e^2}{n_p^2}(R_s + R_e)\right)^{-\frac{1}{3}}$$

In this formula, $ω_r$ means motor angular velocity; $I_m$ means dc current after filtering; $T_e$ means real electromagnetic torque.

After 0.3 seconds when speed is stable, loss model is used to calculate the optimal flux. If optimal flux was calculated at the beginning, the situation that dividing by 0 to get infinite value would appear. If the given speed changes, after a period of time after the speed achieves stability, flux calculation also achieves stability. Use flux linkage calculation value of loss model to driver motor to the steady state at first, and then search optimal flux by golden section method.
5. Motor flux torque observer

![Diagram of motor flux torque observer](image)

Motor flux torque observation module is as shown in FIG.5.1. \( \phi_{\text{hrob}} \) is rotor flux observation; \( W_{\text{sob}} \) is rotor slip observations; \( T_{\text{eob}} \) is torque observation. Computation formula is as follows.

\[
T_e = \frac{n_p L_m}{L_r} i_s \psi_r
\]  
(5-1)

\[
\omega_1 - \omega_2 = \omega_s = \frac{L_m i_s}{T_r} \psi_r
\]  
(5-2)

\[
\psi_r = \frac{L_m i_{sm}}{T_r p + 1}
\]  
(5-3)

In the formula, \( T_e \) is the rotor flux observation; \( \omega_s \) is rotor slip observations; \( \psi_r^* \) is torque observation; \( p \) is the differential operator.

6. Gold segmentation algorithm

Golden section search method uses the relationship between field current and efficiency. In the range of the optimal efficiency of field current, with the golden section number for excitation current trial points, by comparing the input powers of the two trial points, the search range is narrowed. The algorithm has the characteristics of the absolute convergence, and therefore there is no oscillation near optimal efficiency. The search speed is faster.

Online optimization process is as follows. First of all, the optimal flux value \( \Psi_e \) is estimated through the model formula of the optimal loss, under the condition of the given speed and load torque, and then to \( [\Psi_m - 30\% \Psi_m, \Psi_m + 30\% \Psi_m] \) as golden section method search range of upper limit and lower limit. If \( (\Psi_m - 30\% \Psi_m) \) is less than 0.1\( \Psi_e \), 0.1\( \Psi_e \) is set as a minimum; if \( (\Psi_m + 30\% \Psi_m) \) is greater than \( \Psi_e \), \( \Psi_e \) is set as upper limit.

Then \( \Psi 1, \Psi 2 \) are inserted into search range. According to the result of comparing two input powers at the two points, delete the corresponding search interval, repeat the above steps, insert another point in the range of left, once again to be computed. Termination conditions set in this paper is 0.05 Wb. Determine the length of the search range. When the absolute value of two inserted points is less than 0.05 Wb, stop search optimization, and we get the optimal flux values \( \Psi^* = (\Psi 1 + \Psi 2) / 2 \) [5]. The algorithm specific flow diagram is as shown in FIG. 6.1.
Set \( \epsilon \) and space \([a, b]\)

Update: \( k = k + 1 \)
\( P_1 = P_2, P_2 = P_{in}(k) \)

Update: \( k = k + 1 \)
\( P_2 = P_1, P_1 = P_{in}(k) \)

Update: \( k = k + 1 \)
\( P_2 = P_1, P_1 = P_{in}(k) \)

**FIG. 6.1** Flow chart of golden segmentation algorithm program

### 7. Energy consumption calculation and simulation results

Input datas are torque, motor speed, the total power loss, and the output data is the input power in the energy consumption calculation module.

\[
P_m + P_{loss} = P_1 \tag{7-1}
\]

In the formula (7-1), \( P_m \) is mechanical power; \( P_{loss} \) is total power loss; \( P_1 \) is the input power.

**FIG.7.1** Total energy consumption corresponding to different methods

Using the hybrid algorithm, energy consumption is low, and energy saving is obvious, at the speed of 155 rad/s, as shown in FIG.7.1 and FIG.7.2. Using loss model, the optimal flux calculated depends on the motor system parameters. Using golden section algorithm, energy consumption is higher, and
it's time-consuming, as shown in FIG.7.3.

FIG.7.2 Total energy consumption using the hybrid algorithm

FIG.7.3 Total energy consumption using golden segmentation algorithm

8. Conclusion
Motor model considering the iron loss and control system based on vector control are established, and flux and torque observation module is designed in this project. After changing the speed or torque, the system can still operate stably. Loss model, the golden section algorithm, and the hybrid algorithm to control motor system are used respectively. Motor iron loss, copper loss, total loss, and the total energy consumption are calculated. The simulation results show that using this control strategy, the vector control asynchronous motor can achieve energy saving operation with high efficiency. Effect is most obvious in the light load at high-speed, but the effect is limited when the load torque is bigger.

Acknowledgments
This work was financially supported by Anhui university natural science research project funding (Project No.KJ2016A156) and national natural science foundation of China (Project No.61273323).

References
[1] Waheedabeevi, M., A. Sukeshkumar, and N. S. Nair. "New online loss-minimization-based control of scalar and vector-controlled induction motor drives." IEEE International Conference on Power Electronics, Drives and Energy Systems IEEE, 2013:1-7.
[2] Shu, Yamamoto, et al. "Maximum Efficiency Drives of Synchronous Reluctance Motors by a Novel Loss Minimization Controller with Inductance Estimator." IEEE Transactions on Industry Applications 49.6(2013):2543-2551.

[3] Nam, K., H. Fujimoto, and Y. Hori. "Design of an adaptive sliding mode controller for robust yaw stabilisation of in-wheel-motor-driven electric vehicles." International Journal of Vehicle Design 67.1(2015):98-113.

[4] Beevi, M. Waheeda, A. S. Kumar, and H. S. Sibin. "Loss minimization of vector controlled induction motor drive using genetic Algorithm." International Conference on Green Technologies IEEE, 2013:251-257.

[5] Li Jian-jian, Liu Xin-zheng. "The research of asynchronous motor energy-saving operation based on vector control." Journal of micromotor, 3(2010) : 14-17.

[6] Karttunen, Jussi, et al. "Decoupled Vector Control Scheme for Dual Three-Phase Permanent Magnet Synchronous Machines." IEEE Transactions on Industrial Electronics 61.5(2014):2185-2196.

[7] Sun, Xiaodong, et al. "Speed-Sensorless Vector Control of a Bearingless Induction Motor With Artificial Neural Network Inverse Speed Observer." IEEE/ASME Transactions on Mechatronics 18.4(2013):1357-1366.

[8] Chen, Cai Xue, Y. X. Xie, and Y. H. Lan. "Backstepping Control of Speed Sensorless Permanent Magnet Synchronous Motor Based on Slide Model Observer." International Journal of Automation and Computing 12.2(2015):149-155.

[9] Zheng, S., et al. "Stable adaptive PI control for permanent magnet synchronous motor drive based on improved JITL technique." Isa Transactions 52.4(2013):539.