Research on a Novel Deadbeat Hybrid Flux Observer

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Abstract: The stability and accuracy of induction motors is seriously influenced by the flux observer. The improvement of motor is restricted by the sensitivity of traditional open-loop current and voltage flux observer to the motor parameter under low or high speed. In order to improve the accuracy and stability of flux observer, a novel close-loop flux observer is implemented, which include the current and voltage flux observer cooperated with phase-compensated transition function. The accuracy and insensitivity to motor parameter are insured in the whole speed range; what’s more, the deadbeat stator current observer is added to solve the one sample cycle delay. By the observer characteristic function being utilized to analysis flux observer, along with the simulation and experiment, the accuracy and stability are verified. Copyright © 2013 IFSA.

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1. Introduction

With the increasing requirements of industrial, the importance of high performance and high-precision drive system is growing. As the particularity of industrial production, good dynamic and stability are required not only at high speed but also at low speed, while the flux observer for vector control system directly determines the above factors. The basic flux observer can be drawn by the motor mathematical model, that are the current model and voltage model. But each of these models has some defects.

The voltage model uses the drop on the magnetizing inductance to estimate the motor flux. When the motor is running at high speed, the counter electromotive force of the stator is higher, the state of flux can be very accurately estimated using voltage model. When the motor speed is low, due to the partial pressure of the stator resistance, it becomes more difficult to measure voltage on the magnetizing inductance, so the motor flux estimation accuracy is poor. The current model can be used at full segment, but due to sensitive to the rotor time constant and changes in the magnetizing inductance for the model, thus the flux observer output is seriously affected. In summary, the voltage model and current models estimates are accurate at the high and low speed, in order to obtain accurate full paragraph flux, [1-5] have proposed closed-loop flux observer model, the full segment can get accurate flux integrating the advantages of voltage model and the current model[6].

In this paper, a new hybrid flux observer [7] is adopted, the observer characteristic function is used to unify forms of the flux observer, and with basic flux observer, the traditional flux observer and a new flux observer contrast and influence of motor parameters change, the stator current measurement
offset error and stator voltage measurement bias errors are analyzed. In order to improve the output flux observer accuracy, stator current observer is built to solve the delay problem of stator current control period due to the sampling. Usefulness and accuracy of the algorithm are verified based on Matlab simulation and experimental platform.

2. The Flux Observer Model

The control variables in motor vector control system are decomposed into two-phase coordinate system, i.e., the d-axis and q-axis, and they can be re-expressed in vector form as

\[ f^s = f^s_d + jf^s_q \]  

(1)

Among (1), the superscript is s or e, which respectively donates that the coordinate system where variables are in is the two-variable-phase stationary coordinate system and a two-phase rotating coordinate system. The subscript indicates that the variable component of the coordinate system.

2.1. The Current Model

The current model uses the stator current and rotor speed as input [1], the expression in the stationary coordinate is

\[ p\lambda_{qdr} = \frac{\hat{R}_r}{L_r} \hat{L}_m i_{qds} - (\frac{\hat{R}_r}{L_r} + j\omega - j\omega_r)\lambda_{qdr} \]  

(2)

The current model, which is not easy to converge in discrete stationary coordinate system, needs to be converted into the two-phase rotating coordinate system, as

\[ p\lambda_{qdr} = \frac{\hat{R}_r}{L_r} \hat{L}_m i_{qds} - \frac{\hat{R}_r}{L_r} \lambda_{qdr} \]  

(3)

The motor flux estimated by the current model is calculated from the above equation.

2.2. The Voltage Model

The motor speed is not needed for voltage model of rotor flux, while the stator excitation coil voltage is gotten by the use of stator voltage and current, and stator flux is obtained by integrating the voltage, as

\[ p\dot{\lambda} = v_{qds} - \dot{r}_{s1} i_{qds} \]  

(4)

Rotor flux comes from the stator flux coupling, the rotor flux is

\[ \dot{\lambda}_{qdr} = \frac{\hat{L}_m}{L_m} \dot{\lambda}_{qds} - \frac{\hat{\sigma}}{1-\hat{\sigma}} \hat{L}_m i_{qds} \]  

(5)

2.3. The Hybrid Model

By the formula (3) and (5), current model and voltage model can be constructed. If the voltage model and the current model are cascaded, and the middle link uses linear controller, hybrid flux observer based on Gopinath type can be obtained, as is shown in Fig. 1.

The structure of hybrid flux closed loop observer model [3] is composed by the model of two open-loop flux, the first stage is the current model, the middle is the transition function, the rear stage is the voltage model. The flux for Pre-current model is estimated by stator currents and speed estimation, the corresponding flux for the latter level voltage model is estimated by stator voltage and the stator current, the output flux is determined by transition function from the current model to voltage mode. The gain of transition function determines the eigenvalues of the closed-loop flux observer model, the transition function completes the switch when the motor speed reaches the observer bandwidth.

![Fig. 1. Hybrid flux observer based on Gopinath type.](image-url)
3. The Characteristic Function and Analysis of Observer

Define the characteristic function of flux observer $F(s)$, and the flux can be obtained by the following transfer function, as

$$\hat{\lambda}_v^s = F(s)(\hat{\lambda}_v^s - \hat{\lambda}_v^c) + \hat{\lambda}_v^c$$

$$= F(s)\hat{\lambda}_v^s + (1 - F(s))\hat{\lambda}_v^c$$

(6)

Among (6), $\hat{\lambda}_v^s$ indicates the voltage output of the model, $\hat{\lambda}_v^c$ means the current output of the model.

In different models, the characteristic function has different meaning, as is shown in Table 1.

Through simplifying and finishing the transfer function of hybrid flux observer, the closed-loop transfer function expression of closed hybrid flux observer can be drawn for

$$\lambda_v^s = \frac{s^2}{s^2 + K_p s + K_i} \hat{\lambda}_v^c +$$

$$\frac{K_p s + K_i}{s^2 + K_p s + K_i} \hat{\lambda}_v^c$$

(7)

where $K_p = \frac{L_p}{L_m}$, $K_i = \frac{L_i}{L_m}$.

Among (7), the first is the transfer function of high-pass filter, it indicates that the flux estimated by the voltage model is dominant when the motor frequency is greater than the cutoff frequency of the closed-loop transfer function; the second is low-pass filter with a band pass filter, it means that the flux estimated by the current model is dominant when the motor frequency is lower than the cutoff frequency of the closed-loop transfer function.

According to Table 1, the hybrid flux observer model characteristic function is

$$F(s) = \frac{s^2}{s^2 + K_p s + K_i}$$

an expression for the steady-state characteristic function can be obtained using $s = j\omega_c$ as replacement in the steady state.

$$F(j\omega_c) = \frac{\omega_c^2 e^{(\pi - \tan^{-1}(K_p\omega_c/K_i\omega_c))}}{\sqrt{(K_i - \omega_c^2)^2 + (K_p\omega_c)^2}}$$

(8)

Draw observer frequency response curve and magnetic chain locus of the characteristic function in the complex frequency domain, as is shown in Fig. 2 and Fig. 3.

Fig. 2 shows the phase of the characteristic function of the observer is a changeable value. The output of flux will deteriorate by adding additional phase when the current and voltage flux model switches.

The optimal path that two kinds flux model switches [6] is the vector difference between the two, as is shown in Fig. 3. Meanwhile, it can be seen from Fig. 3, the output flux locus of hybrid flux model greatly offset the best path in switching from low to high speed. This seriously affects the accuracy of the output flux. If there are parameter and measurement error when we estimate flux, then flux is even inaccurate.

In order to solve the problem of the accuracy of the flux when the model is switching, the phase offset produced by the characteristic function of the observer must be compensated, and compensated flux observer characteristic function as it is shown in equation (9).
where \( \alpha \) is the phase of the characteristic function of the observer.

Add the improved characteristic function to basic hybrid flux observer based on Gopinath type, the improved hybrid flux observer block diagram is shown in Fig. 4.

In steady state, the optimization characteristic function of observer will be obtained through substituting \( s = j \omega_e \), the improved steady-state characteristics function expression is

\[
F(s) = \frac{s^2}{s^2 + K_p s + K_i} e^{-j \alpha},
\]

(9)

\[
F(s) = \frac{\omega_e^2}{\sqrt{(K_i - \omega_e^2)^2 + (K_p \omega_e)^2}} e^{j \alpha}
\]

(10)

Drawn frequency response curves and flux trajectory of the optimized characteristic function of observer in the complex frequency domain. As are shown in Fig. 5 and Fig. 6.

4. Sampling Error and Parameter Sensitivity Analysis

4.1. Analysis for Voltage and Current Bias Impact on the Observer

In PWM inverter system, the bias voltages and currents affect the output and stability of flux observer. In order to study the bias effect for the closed-loop flux observer, the observer features are analyzed using the characteristic function.

The closed-loop flux observer contains the current model and voltage model, which respectively is sensitive to current bias and voltage bias, and error expressions of observer model is respectively written in steady state, such as formula (11) and (12).

\[
\Delta \psi_{vm} = \frac{\dot{L}}{L_m}, \Delta u_s = \frac{\Delta L}{L_m} - r \frac{\Delta i}{s^2} - \sigma L_s \frac{\Delta i}{s}
\]

(11)
\[ \Delta \psi_{cm}^s = \frac{r_i L_m}{L_r} \left( s + \left( \frac{r_i}{L_r} - j \omega_t \right) \right) \Delta i + \frac{1}{s}, \]  

(12)

where \( \Delta \psi_{cm}^s \) and \( \Delta \psi_{cm}^v \) represent steady state error generated by the bias voltage and current to the current and voltage flux the model. According to the above formula, the steady-state error expressions of closed-loop flux model can be obtained, such as formula (13).

\[ \Delta \psi_{i}^s = \lim_{s \to 0} s(F(s)\Delta \psi_{cm}^s + (1 - F(s))\Delta \psi_{cm}^v) \]  

(13)

Substitute the formula (11), (12) into (13), the error expression of closed-loop flux observer for the steady-state can be gotten through simplifying.

\[ \Delta \psi_{i}^s = \left( \frac{r_i L_m}{L_r} / \left( \frac{r_i}{L_r} - j \omega_t \right) \right) \Delta i \]  

(14)

Seen from the above equation, only the bias current affects the closed-loop flux observer and the bias voltage doesn’t affect the output.

4.2. Sensitivity Analysis on the Motor Parameters for the Observer

When the motor is running, a number of factors that will inevitably cause the parameter changes, such as the motor temperature, speed and magnetic fields. In order to ensure the stability and accuracy of the motor, flux observer for parameter variables must have strong immunity. Study the robustness of observer at different frequencies using the frequency response function and contrast with the basic model of mixed flux. The frequency response function of linear flux Observer of available is shown in formula (15).

\[ \frac{\hat{\lambda}_{qdr}}{\lambda_{qdr}} = F(s) \text{FRF}_{cm} + (1 - F(s)) \text{FRF}_{cm} \]  

(15)

5. The Observer of Stator Current

Stator current, which not only is inner control volume, but also is the flux observer's input, is an important controlled variable in the motor vector control system. The accuracy of the stator current directly affects the output accuracy of the flux observer. However, due to the impact of the control algorithm, the control system of the stator current always lags behind the actual stator current control cycle, which affects the control precision and the accuracy of the flux observer. Let the stator current and rotor flux as state variables, write the state equation of the motor, construct the complex vector mathematical models of the motor [4].
By the formula (19) and (20), the block diagram of the motor model that stator current and the rotor flux is the state variable can be drawn, as is shown in Fig. 8.

From the formula (19), it contains a derivative of the stator current, differential predictive and forward Euler method can be used to predict the next cycle stator current, the equation of state that stator current is the state variable will be discrete firstly.

Assuming stator voltage in a sampling period remains unchanged [8], the actual stator current value of the k-th cycle is $i_{qds}^s(k)$, the current output value of the current observer is $i_{qds}^e(k)$, the error of the estimation and the actual stator current is

$$i_{qds}^e(k)_{error} = i_{qds}^e(k) - i_{qds}^s(k)$$

If a linear controller is used to adjust between the estimated value and the actual value of the stator current [9], so that the estimated value of the k-th cycle approaches to the true value, the predictive value $i_{qds}^e(k+1)$ of the next cycle approaches to the true value of the next sampling period, the rotor flux values with the high accuracy can be output through substituting the predicted value of the next cycle into the control system. Join linear controller [10], predict the next cycle stator voltage value, as is shown in formula (21).

$$V_{sun}(k) = (K_1 + TK_2)i_{qds}^s(k)_{error} - K_1i_{qds}^s(k-1)_{error} + V_{qds}^s(k)$$

$$-\frac{\hat{L}_m}{L_y} + \frac{\hat{R}_s}{L_y} - j\omega_1(k)\hat{i}_{qds}^e(k)$$

Order

$$R_{eq} = R_s + \frac{L_y}{L_y} R_y, \ \tau_{eq} = \frac{\sigma L_y}{R_s + \frac{L_y}{L_y} R_y}$$

Substitute the predicted value of the stator voltage [11] into formula (21), the predicted value of the
stator current of the next cycle can be obtained, as is shown in the formula (22).
\[
\hat{i}_{qs}(k+1) = \hat{i}_{qs}(k)e^{-T_s} + \\
V_{sum}(k) \frac{1}{R_{eq}} (1 - e^{-T_s})
\]

(22)

The stator current observer can be shown as Fig. 9 using structure diagram.

The accuracy and timeliness can be greatly enhanced through adding the stator current observer into improved hybrid flux observer.

6. Experiments

In order to verify the correctness of the algorithm, the experimental platform is established for algorithm verification. The direct connection between asynchronous motor and magnetic brake is used for experimental platform. The drive control system uses Infineon's XE164 chip in the chip to achieve motor control algorithms. Import the data into first bit machine, draw and analyze waveforms.

Fig. 10 and Fig. 11 are waveforms when speed instructions sudden. When the speed commands sudden, the speed based on improved hybrid motor control system has good track, and the output of flux observer essentially unchanged. But for the basic hybrid flux model based control system, the motor speed does not perform the tracking speed command, the output speed of the motor is poor, and flux fluctuations is great, the output characteristics of the motor is deteriorating.

Fig. 12 and Fig. 13 are the torque of current command of the torque axis and the actual torque current waveform when the magnetic brake reduces load suddenly. Use an improved hybrid flux model and stator current observer control system fast track torque current command, and overshoot is small, the steady-state error is very small in the steady state. And use the basic hybrid flux model system, it can be seen obviously that response speed is slower than that of improved system, and the overshoot is large, it is difficult to meet the system requirements for accuracy and stability.

7. Conclusions

This article analyzes the flux observer of asynchronous motor using the observer characteristic function, the unified function expression is used to represent for flux observer. Use the frequency response function method in the complex frequency domain to analyze flux observer based on Gopinath type and find the shortcomings of flux trajectory deterioration when two models switch. By improving characteristic function of the observer, so that flux switching tracks approach the ideal flux paths to get improved hybrid flux observer. Parameters sensitivity and the sampling error of two models are analyzed in the full frequency range. In order to improve the accuracy of the observer output, build stator current observer, the problem of the delay control system solved, and the output characteristics of induction motor is improved greatly. Analysis and experimental verify validity and practicality of the new hybrid flux model and the stator current observer.
Fig. 10. Improved speed command is triangular ramp waveform.

Fig. 11. Basic speed command is triangular ramp waveform.

Fig. 12. Iq response waveform of improved model when load changes suddenly.

Fig. 13. Iq response waveform of basic model when load changes suddenly.

References


