An On-line Diagnosis Method of Broken Rotor Bars Fault in Motor of Aerospace Surveying Vessel via Salient Characteristic Residual Signal from Dynamic Model

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Abstract. Diagnosis of broken rotor bar fault in induction motors is a hot research focus in recent years. The most common method of diagnosis of this fault is to analyse the spectral characteristics of stator current. However the characteristic frequencies are too close to both sides of power frequency and usually covered by it in early failure. To overcome this limitation, this paper presents a method by introducing a dynamic model based on field-oriented control (FOC), which was widely applied in control. The FOC technique is modified to generate an estimated stator current signal in a little computation. The residual signal of stator current is produced by comparing the measured one and the estimated one as the motor running. The result of simulation shows that power frequency component is greatly reduced and the feature of fault is more significant than the measured current signal.

1. Introduction
Squirrel-cage induction motors is applied in aerospace surveying vessel because of its simplicity and high reliability. Broken rotor bar fault is one of the most common faults of induction motor, so early fault diagnosis of broken rotor bars is significant to improve the safety and efficiency of motor. Up to now, many researches has been done in this problem with very different kinds of method by detecting various physical variable such as electromagnetic torque [1], stator current [2], vibration [3] and so on. Among these methods, spectral analysis of stator current is adopted by researchers most often since its signal is easy to get and the fault can be reflected in it by characteristic frequencies $|(1 \pm 2s)f_1|$ (where $s$ means slip and $f_1$ means power frequency). On the other hand, the characteristic frequencies is close to both sides of the power frequency and so it may be covered [4], which brings difficulty to diagnosis in early fault. To solve this issue, some researchers have tried to find out an algorithm to extract the characteristic frequencies. The method that monitoring stator startup current and finding out the characteristic frequencies changing needs to stop and restart the motor [5]. Wavelet transform is a powerful tool for extracting the feature of broken rotor bars [6] but the choice of basis function and decomposition level is not fixed.

This paper presents a method by introducing dynamic model which is a health reference to the real motor, and simulation experiment proved that the decrease of the amplitude of power frequency and other disruption brought by input voltage is significant. The field-oriented control technique is
introduced because it decouples motor’s parameter [7], so the result signal can get as the motor is running.

The paper is consists of three chapters. The first chapter introduces the broken rotor bars fault’s feature and research status. The second one is about how to utilize the dynamic model based on FOC technique to reduce power frequency interference. The third one validates the method by Simulink. The last one conclusion the whole paper.

2. The dynamic model based on field-oriented control technique

2.1 Field-Oriented Technique

The model of induction motor in three-phase stationary frame is a multivariable, high-order, nonlinear and strongly coupled system. A transformation from three-phase stationary frame to tow-phase synchronous rotation frame can simplifies the model and facilitates computation. In this paper, the direction of rotor flux was selected as d axis and the direction perpendicular to d axis was q axis. This is so-called field-oriented control (FOC). The transformation was shown in Fig 1.

\[
\begin{align*}
\text{voltage equation: } & \quad \begin{bmatrix}
    \mathbf{u}_{sd} \\
    \mathbf{u}_{sq} \\
    \mathbf{u}_{rd} \\
    \mathbf{u}_{rq}
\end{bmatrix} = \begin{bmatrix}
    R_s + L_s p & -\omega_n L_s & L_m p & -\omega_n L_m \\
    \omega_n L_s & R_s + L_s p & \omega_n L_m & L_m p \\
    L_m p & 0 & R_r + L_r p & 0 \\
    \omega_n L_m & 0 & \omega_n L_r & R_r
\end{bmatrix} \begin{bmatrix}
    i_{sd} \\
    i_{sq} \\
    i_{rd} \\
    i_{rq}
\end{bmatrix} \\
\text{flux equation: } & \quad \begin{bmatrix}
    \psi_{sd} \\
    \psi_{sq} \\
    \psi_{rd} \\
    \psi_{rq}
\end{bmatrix} = \begin{bmatrix}
    L_s & 0 & L_m & 0 \\
    0 & L_s & 0 & L_m \\
    L_m & 0 & L_r & 0 \\
    0 & L_m & 0 & L_r
\end{bmatrix} \begin{bmatrix}
    i_{sd} \\
    i_{sq} \\
    i_{rd} \\
    i_{rq}
\end{bmatrix} \\
\text{torque equation: } & \quad T_e = n_p i_{sq} \psi_{rd} L_m / L_r
\end{align*}
\]

Where \( u, i, R \) and \( L \) represent voltage, current, resistance and inductance, subscript \( s \) and \( r \) represent stator and rotor, \( d \) and \( q \) represent d axis and q axis, \( L_m \) represents mutual inductance, \( p \) represents differential operator, \( \omega_n \) an \( \omega_s \) represent the synchronous speed and slip speed.

Since the d axis is the direction of rotor flux, so:

\[
\begin{align*}
\psi_{rd} &= L_m i_{rd} + L_r i_{rd} = \psi_r \\
\end{align*}
\]

From the equation (1) and (2), the following equations can be extracted:

\[
R_r i_{rd} + p(L_m i_{rd} + L_r i_{rd}) = 0
\]

Substituted equation (5) into equation (6):

\[
i_{rd} = - \frac{p \psi_r}{R_r}
\]

Substituted equation (7) into equation (6):
Where $\tau_c = \frac{L_r}{R_c}$. 

The equation (8) shows that the rotor flux $\psi_r$ is only associated to the d axis component of stator current $i_{sd}$. And from equation (3), if the rotor flux was fixed, the electromagnetic torque is only associated to q axis component of stator current. This technique decouples the induction motor and reduce the number of control objects to two, which is similar to synchronous motor.

### 2.2 Dynamic Model Based On FOC

The FOC technique uses desired stator current to calculate the stator voltage and control the motor. In this paper, the technique was used reversely by building a dynamic model. In another word, the dynamic model calculates the stator current utilizing the stator voltage.

From equation (1), the following equations can be extracted:

$$
\begin{align*}
\mathbf{u}_d &= R_s i_{sd} + (L_s p i_{sd} + L_m p i_{rq}) - \omega_m (L_s i_{sq} + L_m i_{rq}) \\
\mathbf{u}_q &= R_s i_{sq} + (L_s p i_{sq} + L_m p i_{rd}) + \omega_m (L_s i_{sd} + L_m i_{rd})
\end{align*}
$$

(9)

Substituted equation (4), (5) and (7) into equation (9):

$$
\begin{align*}
\sigma L_s (d i_{sd}/dt) + R_s i_{sd} &= \omega_m \sigma L_s i_{sq} + \psi_r, \quad R_s/L_r i_{rd}^2 + u_{sd} \\
\sigma L_s (d i_{sq}/dt) + R_s i_{sq} &= -\omega_m \sigma L_s i_{sd} - \psi_r, \quad R_s/L_r i_{rd}^2 + u_{sq}
\end{align*}
$$

(10)

Where $\sigma = 1 - L_m^2/L_s L_r$, and $\omega_m$ represents rotor angular speed.

From equation (10), the voltage is input, the current is output, and other variables are all state variables.

If the discrete time is $T_s$ and the equation (10) can be described in time $k$ as following:

$$
\begin{align*}
\begin{bmatrix} i_{sd}(k) \\ i_{sq}(k) \end{bmatrix} &= \begin{bmatrix} 1 - T_s/\tau_r & \omega_m/T_s \\ -\omega_m/T_s & 1 - T_s/\tau_r \end{bmatrix} \begin{bmatrix} i_{sd}(k-1) \\ i_{sq}(k-1) \end{bmatrix} + \frac{T_s}{\sigma L_s} \begin{bmatrix} u_{sd}(k) \\ u_{sq}(k) \end{bmatrix} + \frac{L_m T_s}{L_s L_r - L_m^2} \frac{R_s/L_r}{-\omega_m} \psi_r(k)
\end{align*}
$$

(11)

Where $\tau_r = \sigma L_s^2 L_m/(L_s^2 R_s + L_m^2 R_c)$.

In equation (11), the variables $\hat{i}_{sd}(k)$ and $\hat{i}_{sq}(k)$ are the estimated stator currents at time $k$, the variables $i_{sd}(k-1)$ and $i_{sq}(k-1)$ are the measured stator currents at time $k-1$, the variables $u_{sd}(k)$ and $u_{sq}(k)$ is the measured voltages at time $k$, and they are also the input of the motor. The variable $\psi_r$ can calculate from equation (8) by measured stator current. So the estimated stator current can be calculated.

To simplify the equation (11), $G_i$, $G_u$ and $G_\psi$ represent the matrix coefficients of $i_s$, $u_s$ and $\psi_r$:

$$
\hat{i}_s(k) = G_i \hat{i}_s(k-1) + G_u u_s + G_\psi \psi_r(k)
$$

(12)

The dynamic model is set based on an assumption that the motor is healthy. When the broken rotor bar fault happens on the motor, there would be $|(1 \pm 2.5\ f)|$ frequencies on the signal of motor stator current, but the model’s stator current wouldn’t change. To subtract the model’s stator current signal from the motor’s stator current signal would exclude the power frequency and other interference brought by input voltage and highlight the difference made by the fault.

The residual signal of current is generated by the equation (13):

$$
\begin{align*}
\tau_d(k) &= i_{sd}(k) - \hat{i}_{sd}(k) \\
\tau_q(k) &= i_{sq}(k) - \hat{i}_{sq}(k)
\end{align*}
$$

(13)

Now, the residual signal of stator current has been got in dq domain, and then transform the residual signal to three-phase stationary frame to precisely diagnose which phase has a fault, the transformation formula is shown in equation (14):

$$
\begin{align*}
\begin{bmatrix} r_d(k) \\ r_q(k) \\ r_c(k) \end{bmatrix} &= \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) \end{bmatrix} \begin{bmatrix} r_{sd}(k) \\ r_{sq}(k) \end{bmatrix}
\end{align*}
$$

(14)

The variables $r_d$, $r_q$ and $r_c$ are the residual value of each phase and can be generated every $T_s$.

The algorithm flow of the method is:
1): the control part outputs the command voltage to both dynamic model and motor.
2): dynamic model calculates the estimated stator current in time $k$ as equation (11).
3): the estimated stator current compares with the measured stator current from motor to generate and output the residual signal of stator current as the motor running.

3. **The validation of the method**

This simulation model is carried out on Simulink as shown in Fig 2.

![Simulation Model](image)

**Figure 2. The simulation model**

This simulation consists of three parts, induction motor block, control block and dynamic model block. Control and dynamic model block both contains the FOC technique so that some parameter can be used commonly. In this simulation, the control block outputs command three-phase voltage to motor block and dynamic model block according to the control target and the state of the motor. Then the dynamic model and motor calculate stator current respectively and compare them.

The broken rotor bar fault is resistance unbalance of rotor winding in essence. To simulate the fault, a wound induction motor was chosen and add on another resistance in rotor winding.

The motor’s parameter is: 380V, 50Hp, 50Hz and 2 pole pairs. The resistance of stator and rotor in a phase are 0.087Ω and 0.228Ω. The leakage inductance of stator and rotor are both 8e-4H, and the mutual inductance is 3.47e-2H. The fault resistance is set as 5% of stator resistance, which is 0.0114Ω.

The Fig 3 shows the motor’s stator current of a fault phase in both time domain and frequency domain.

![Stator Current](image)

**Figure 3. The motor’s stator current**

From Fig 3, the power frequency is 42Hz and it is too big to recognize the characteristic frequency. The Fig 4 shows the residual signal of stator current in both time domain and frequency domain.

![Residual Signal](image)

**Figure 4. The residual signal**
From Fig 4, the amplitude of the residual signal of stator current decreases dramatically, the power frequency is only about 0.5% of the value in Fig 3, and the characteristic frequency as the arrow points becomes more obvious than before. It proofs that even in the early fault, this method can reduce the interference of power frequency and diagnose the fault. In addition, this method’s calculation don’t need too much computation and output the residual signal as motor running since most of its parameters and inputs can be obtained from the control block. From the above, this method can diagnose broken rotor bars fault efficiently and precisely. But this result deeply depend on the accuracy of dynamic model, and the further research should focus on how to build a more accurate model.

4. Conclusion
This paper presents a method to diagnose induction motor broken rotor bar fault based on FOC technique. A simulation is carried out in Simulink and the result shows the method can diagnose broken rotor bars fault efficiently and precisely. In engineer, the parameter of motor would slowly vary with time, temperature and other reasons. So recognizing the change is important for the accuracy of this method.

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