BASED ON THE INTEGRATED FAULT DIAGNOSIS AND FAULT-TOLERANT CONTROL OF SELF-ADAPTION OBSERVER'S VFD

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ABSTRACT: Various types of troubles may occur in VFD and even result in major accidents, which would bring irretrievable loss to economy or society. Current sensor and velocity sensor are selected as research objects, and a set of plan for sensors' integrated fault diagnosis and fault-tolerant control is presented. Designs are respectively made for the fault diagnosis and fault-tolerant control unit of self-adaption observer, current sensor and velocity sensor. Finally, systematic simulation model is built and detailed analysis is made for the simulation result, which verifies this plan's currency in theory. It explains that the faults of current sensor and velocity sensor can be diagnosed simultaneously on the same system, and the system can be in normal operation with better performance after the faults happened. So the equipment maintenance can be provided enough time to avoid economic loss by the accident and improve the system reliability.
KEY WORDS: self-adaption observer; VFD; fault diagnosis; fault-tolerant control.

1 INTRODUCTION

The VFD, featured superior control performance, high efficiency, small size, low price, remarkable energy-saving effect and so on, is considered as the most optional alternating current dynamo speed control equipment at present, and is widely applied to a lot of fields like electric locomotive traction, metal smelting, elevator control, automobile, production line, chemical industry, plastic machinery, cigarette equipment, mine control system, blast furnace winch and kiln temperature control [1-3].

However, like other machinery or electric equipment, VFD also has various faults under the consequence of ageing components, improper operation, environmental disturbance or man-made sabotage. And it may cause major accidents under serious consequence and bring irretrievable loss to economy or society. The cost of these accidents is costly, but it can be avoided in advance. If some effective plans about faults diagnosis and fault-tolerant control are taken when the VFDs are being produced. The fault reason can be quickly diagnosed, and then the VFDs can be protected and repaired lest the equipment suddenly stops working. In this case, the operators have enough time to repair the equipment so as to put back on production quickly, avoid the accidents and minimize the loss.

Based on the above analysis, the most common sensor fault in variable-frequency speed control system is selected as research object. And it makes a deep analysis about failure mechanism, and then designs a set of simple, quick, accurate and plan For VFD integrated fault diagnosis. First, it maps the functional block diagram of this plan, and then makes designs for the fault diagnosis and fault-tolerant control unit of self-adaption observer, current sensor and velocity sensor respectively. Under the Matlab/Simulink's consequence, the simulation model is built and the simulation result is worked out and made a detailed analysis, which verifies the currency of this plan.

2 LITERATURE REVIEW

In recent decades, with the further research of equipment failure mechanism and increasingly improved equipment management level, the disadvantages of the traditional periodical maintenance strategy are constantly emerging. The major problem is cannot solve the contradiction between "untimely overhaul" and "more frequent overhaul", which is neither economical nor reasonable. However, the purpose of the fault diagnosis and fault-tolerant control technology is that it can currently, quickly detects the system's faults and analyzes why the faults happen. So the system can keep operating with better performance on the premise of working condition and extend the equipment operation cycle to avoid the economic loss and potential safety hazard brought by sudden machine halt with faults. Therefore, the problem in traditional periodical maintenance strategy can be well solved by adopting fault diagnosis and fault-tolerant control technology. The equipment maintenance cost can be greatly reduced and system reliability is improved.

VFD [4-6] has been widely applied to all walks of life because of its superior performance. In recent years, people have more and more demanding demand in reliability, maintainability and security.

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Thus, its fault diagnosis and fault-tolerant control technology gain more and more domestic and overseas scholars' attention, and more and more thesis about this field are published [7-9]. Researches show that [10-12], in the aspect of controller, sensor's fault is one of the common problems in industrial application, while velocity sensor and current sensor are the indispensable parts of variable-frequency speed control system. Sensor has become the most vulnerable part of variable-frequency speed control system because of the complicated and harsh working condition [13-14]. The sensor has a fault due to ageing equipment, wrong operation, environmental disturbance and other factors when the VFD is on the operational process, which would result in system down, influence the production and even cause major safety accidents if seriously. It would bring irretrievable loss to manufacturer and society. To avoid this kind of accident happening, modern fault diagnosis technology is taken to diagnose the faults of current sensor and velocity sensor on line. According to this, it can find sensor's fault in time and have a quick fault-tolerant control to the sensor, which can avoid machine halt accident. It is an important tool for improving reliability of variable-frequency speed control system.

3 METHODS

3.1 The design of self-adaption observer

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The direct vector control system of induction machine used needs a magnetic flux and revolving speed modules. In order to estimate motor speed, stator current and rotorflux linkage, t a full-order state self-adaption observer based on [15-17] Lyapunov stability theory is designed to replace magnetic flux and revolving speed modules.

(1) State and output equation of induction machine

As for the mathematical model of the three-phase induction machine at two-phase static $(\alpha-\beta)$ coordinate system, stator current $i_{s\alpha,\beta}$ and rotor flux linkage $\psi_{r\alpha,\beta}$ of induction machine are chosen as systematical state variable, and stator current is taken as output variable, the state and output equation of induction machine can be expressedas formula (1) and (2).

$$\frac{d}{dt}\underbrace{\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix}}_{x} = \underbrace{\begin{bmatrix} a_1 & 0 & a_2 & a_3\omega_r \\ 0 & a_1 & -a_3\omega_r & a_2 \\ a_4 & 0 & a_5 & -\omega_r \\ 0 & a_4 & \omega_r & a_5 \end{bmatrix}}_{A(\omega_r)} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} + \underbrace{\begin{bmatrix} b & 0 \\ 0 & b \\ 0 & 0 \\ 0 & 0 \end{bmatrix}}_{B} \underbrace{\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix}}_{u_s} \quad (1)$$

$$i_s = Cx \quad (2)$$

In the equation

$$a_1 = -\frac{R_r L_m^2 + R_s L_r^2}{\sigma L_s L_r^2}, \quad a_2 = \frac{R_r L_m}{\sigma L_s L_r^2},$$

$$a_3 = \frac{L_m}{\sigma L_s L_r}, \quad a_4 = \frac{L_m R_r}{L_r}, \quad a_5 = -\frac{R_r}{L_r}, \quad b = \frac{1}{\sigma L_s},$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

σ is a magnetic flux leakage coefficient.

(2) The structure of self-adaption observer

According to above state and output equation of induction machine, the mathematical model of full-order state self-adaption observer adopted can be expressed as followed:

$$\frac{d}{dt}\hat{x} = A(\hat{\omega}_r)\hat{x} + Bu + G(\hat{i}_s - i_s) \quad (3)$$

$$G = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \\ g_5 & g_6 & g_7 & g_8 \end{bmatrix}^T \quad (4)$$

In the equation, $\hat{i}_s$ is estimated value, G is observer gain matrix, and the evaluation of intrinsic parameter $g_1 \sim g_8$ directly determines this self-adaption observer's reliability, the following text would make a design for it.

According to formula (1), (2) and (3), the structure chart of self-adaption observer can be drawn as following chart 1. The theory compares estimated value $\hat{i}_s$ of stator current to measured value i_s of stator current, and then works out the error value of stator current. It can make the observer asymptotic stable by the reasonable design of observer's gain matrix G and speed self-adaptive rule, making revolving speed estimated value $\hat{\omega}_r$ and stator current estimated value $\hat{i}_s$ converge into its actual value respectively.

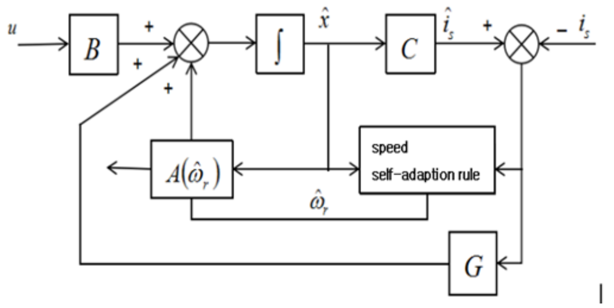

Figure 1. Structure chart of self-adaption observer

(3) Derivation of speed self-adaptive rule

Design-reasonable speed self-adaptive rule is crucial for system stability. Here, Lyapunov stability theory will be adopted to infer it. A state estimated error equation can be worked out from formula (1) subtracting formula (2):

$$\frac{d}{dt}\Delta x = \left[A(\omega_r)+GC\right]\Delta x + \Delta A\hat{x} \tag{5}$$

In the equation,

$\Delta x = x - \hat{x}$,

$\Delta\omega_r = \omega_r - \hat{\omega}_r$,

$$\Delta A = A(\omega_r) - A(\hat{\omega}_r) = \begin{bmatrix} 0 & 0 & 0 & a_3\Delta\omega_r \\ 0 & 0 & -a_3\Delta\omega_r & 0 \\ 0 & 0 & 0 & -\Delta\omega_r \\ 0 & 0 & \Delta\omega_r & 0 \end{bmatrix}$$

The following Lyapunov function is selected:

$$V = \Delta x^T \Delta x + \xi\Delta\omega_r^2 \tag{6}$$

In the equation, ξ is a positive constant.

So the Lyapunov function can be derived:

$$\frac{d}{dt}V = \Delta x^T D\Delta x + 2\Delta\omega_r\varepsilon - 2\xi\Delta\omega_r\frac{d}{dt}\hat{\omega}_r \tag{7}$$

In the equation,

$$D = \left[A(\omega_r)+GC\right]^T + \left[A(\omega_r)+GC\right] \tag{8}$$

$$\varepsilon = a_3\left(i_{sa}-\hat{i}_{sa}\right)\psi_{r\beta} - a_3\left(i_{s\beta}-\hat{i}_{s\beta}\right)\hat{\psi}_{r\alpha} + \varepsilon_\psi \tag{9}$$

$$\varepsilon_\psi = \psi_{r\beta}\hat{\psi}_{r\alpha} - \psi_{r\alpha}\hat{\psi}_{r\beta} \tag{10}$$

If self-adaptive rule is selected like formula (11), the second and third item of the formula (7) can be cancelled out, and the Lyapunov function can be simplified like formula (12). According to Lyapunov stability theory, observer gain matrix G selected properly can make the function of formula (12) negative semidefinite. That is to say, it can make the designed self-adaption observer stable.

$$\frac{d}{dt}\hat{\omega}_r = \varepsilon / \xi \tag{11}$$

$$\frac{d}{dt}V = \Delta x^T D\Delta x \tag{12}$$

In the formula (10), ε_ψ contains actual value $\left(\psi_{r\alpha,\beta}\right)$ of rotor flux linkage. Because the actual value of rotor flux linkage is hard to measure, we assume the estimated value and its actual value are equal. In this case, ε_ψ is equal to zero, which can be neglected from formula (9). Besides, in order to work out motor speed quickly, the following PI self-adaptive rule is adopted to replace the formula (11)'s.

$$\omega_r = \left(K_P + \frac{K_I}{s}\right)\left[\left(i_{sa}-\hat{i}_{sa}\right)\hat{\psi}_{r\beta} - \left(i_{s\beta}-\hat{i}_{s\beta}\right)\hat{\psi}_{r\alpha}\right] \tag{13}$$

In the equation, K_P and K_I are positive gain.

(4) The design of observer gain matrix G

Because the three-phase induction machine is a nonlinear time-varying system and the observer pole changes with the rotate speed, the pole assignment of linear time-invariant system in modern control theory is not suitable for the design of observer gain matrix and it makes the design of matrix G more complicated. In order to solve this problem, $\Delta\omega_r = 0$ is assumed here according to mathematical model of induction machine, so the state estimated error equation (5) can be equal to formula(14)

$$\frac{d}{dt}\begin{bmatrix}\Delta i_{s\alpha}\\ \Delta i_{s\beta}\\ \Delta\psi_{r\alpha}\\ \Delta\psi_{r\beta}\end{bmatrix} = \begin{bmatrix} a_1+g_1 & g_5 & a_2 & a_3\omega_r \\ g_2 & a_1+g_6 & -a_3\omega_r & a_2 \\ a_4+g_3 & g_7 & a_5 & -\omega_r \\ g_4 & a_4+g_8 & \omega_r & a_5 \end{bmatrix}\begin{bmatrix}\Delta i_{s\alpha}\\ \Delta i_{s\beta}\\ \Delta\psi_{r\alpha}\\ \Delta\psi_{r\beta}\end{bmatrix} \tag{14}$$

In the equation,

$\Delta i_{sa} = i_{sa} - \hat{i}_{sa}$, $\Delta i_{s\beta} = i_{s\beta} - \hat{i}_{s\beta}$,

$\Delta\psi_{ra} = \psi_{ra} - \hat{\psi}_{ra}$, $\Delta\psi_{r\beta} = \psi_{r\beta} - \hat{\psi}_{r\beta}$

In the formula (14), both the stator current i_{sa} and $i_{s\beta}$ as well as the actual value of rotor flux linkage ψ_{ra} and $\psi_{r\beta}$ need to be known. However, because the actual value of rotor flux linkage is hard to measure, $\Delta\psi_{ra}=0$, $\psi_{r\beta}=0$ is assumed, and then an error differential equation can be got as formula (15) shows.

$$\begin{cases} \frac{d}{dt}\Delta i_{s\alpha} = (a_1+g_1)\Delta i_{s\alpha} + g_5\Delta i_{s\beta} \\ \frac{d}{dt}\Delta i_{s\beta} = g_2\Delta i_{s\alpha} + (a_1+g_6)\Delta i_{s\beta} \\ \frac{d}{dt}\Delta \psi_{r\alpha} = (a_4+g_3)\Delta i_{s\alpha} + g_7\Delta i_{s\beta} \\ \frac{d}{dt}\Delta \psi_{r\beta} = g_4\Delta i_{s\alpha} + (a_4+g_8)\Delta i_{s\beta} \end{cases} \tag{15}$$

In order to make the result of the error differential equation be zero, the unknown parameter is selected from formula (15): $g_1=g_6=-a_1$, $g_3=g_8=-a_4$, $g_2=g_5=g_4=g_7=0$. Therefore, it can design the observer gain matrix G , like formula (16) shows.

$$G=\begin{bmatrix} -a_1 & 0 & -a_4 & 0 \\ 0 & -a_1 & 0 & -a_4 \end{bmatrix}^T \tag{16}$$

In conclusion, state observer adopted in sensor's fault diagnosis and fault-tolerant control unit consists of formula (3-3) and (3-13). Using this observer can work out the stator current estimated value $(\hat{i}_{s\alpha}、\hat{i}_{s\beta})$ and rotor flux linkage estimated value $(\hat{\psi}_{r\alpha}、\hat{\psi}_{r\beta})$ of induction machine.

3.2 Current sensor's fault diagnosis and fault-tolerant control unit

Input signal $(\lambda_i, i=1,2,3)$ of current sensor's fault diagnosis and fault-tolerant control unit is provided by three self-adaption observers. Internal structures of the three observersare completely identical, the difference among them is that their input current $i_{s\alpha,n}$ and $i_{s\beta,n}(1,2,3)$ are different.

$$i_{sa}+i_{sb}+i_{sc}=0 \tag{17}$$

Because of phase current, its two items can work out the sum of i_{sa}, i_{sb} and i_{sc} are zero like formula (17) shows. Any phase current can be worked out by other two items, for example:

$$\hat{i}_{sc}=-i_{sa}-i_{sb} \tag{18}$$

In the equation, $\hat{i}_{sc}$ is i_{sc}'s calculated value.

In this case, input current of self-adaption observer1 can be worked out by i_{sa}, i_{sb} and $\hat{i}_{sc}$ using formula (19):

$$\begin{cases} i_{sa,1}=(1/3)(2i_{sa}-i_{sb}-\hat{i}_{sc}) \\ i_{s\beta,1}=(\sqrt{3}/3)(i_{sb}-\hat{i}_{sc}) \end{cases} \tag{19}$$

Similarly, input current $(i_{s\alpha,2}, i_{s\beta,2})$ of observer2 can be worked out by i_{sa}, i_{sc} and $\hat{i}_{sb}$; and input current $(i_{s\alpha,3}, i_{s\beta,3})$ of observer3 can be worked out by i_{sb}, i_{sc} and $\hat{i}_{sa}$. Output quantity of every observer is expressed as follows:

$$\lambda_j=\begin{bmatrix} i_{s\alpha,j} & i_{s\beta,j} & \hat{\psi}_{r\alpha,j} & \hat{\psi}_{r\beta,j} & \hat{\omega}_{r,j} \end{bmatrix}^T, j=1,2,3 \tag{20}$$

In order to make a fault diagnosis for current sensor, the followingresidual variable can be defined:

$$E_j=\overline{\left|\overline{\hat{\psi}^2_{r,j}}-(\psi^*_r)^2\right|+\left|\overline{\hat{\omega}_{r,j}}-\omega^*_r\right|}, j=1,2,3 \tag{21}$$

In the equation, $\hat{\psi}_{r,j}$ is the estimated value of rotor magnetic flux, ψ^*_r is set value of rotor magnetic flux, $\hat{\omega}_{r,j}$ is estimated value of motor speed, ω^*_r is set value of motor speed, and $\hat{\psi}^2_{r,j}=\hat{\psi}^2_{r\alpha,j}+\hat{\psi}^2_{r\beta,j}$. Transverse line striping on the signal means that they have reached the value after low pass filter's smoothing, the filter's transfer function is expressed as follows:

$$H_n(s)=\frac{1}{\tau_n s+1}, \quad n=1,2,3 \tag{22}$$

In this equation, $H_1(s)$ refers to $\hat{\psi}^2_{r,j}$'s filter, $H_2(s)$ refers to $\hat{\omega}_{r,j}$'s filter and $H_3(s)$ refers to E_j's filter.

When system keeps stable, E_j's value is approximately zero. As previously mentioned, observer's input current $\left(i_{s\alpha,2}, i_{s\beta,2}\right)$ is worked out by i_{sa} and i_{sc}. So if b phase current sensor has a fault, the output current (λ_2) of observer2 would not be influenced, and $E_2 \approx 0$. However, the value of E_1 and E_3 would be greatly increased. The faults of a phase and c phase current are similar to this. Therefore, the fault diagnosis plan of current sensor can be put forward as follows:

(1) If $E_1 > E_3$ and $E_2 > E_3$, and $\iota = 3$. On this premise, if $E_1 - E_3 > F_\iota$, and $I_{Flag} = 1$. If not, $I_{Flag} = 0$.

(2) If $E_1 > E_2$ and $E_3 > E_3$, and $\iota = 2$. On this premise, if $E_1 - E_2 > F_\iota$, and $I_{Flag} = 1$. If not, $I_{Flag} = 0$.

(3) If $E_2 > E_1$ and $E_3 > E_1$, and $\iota = 1$. On this premise, if $E_2 - E_1 > F_\iota$, and $I_{Flag} = 1$. If not, $I_{Flag} = 0$.

(4) At last, in every sampling period, fault diagnosis and fault-tolerant control unit of current sensor output $\hat{\theta}$, $\hat{\omega}_{r,\iota}$, $i_{s\alpha,\iota}$ and $i_{s\beta,\iota}$ to the controller.

In this equation, F_ι is the threshold value of current sensor fault, and I_{Flag} is the marking signal of the current sensor fault. If $I_{Flag} = 0$, it means that current sensor has no fault. If $I_{Flag} = 1$, it means that current sensor has faults.

$$\theta = \arctan\left(\frac{\hat{\psi}_{r\beta,\iota}}{\hat{\psi}_{r\alpha,\iota}}\right) \tag{23}$$

3.3 Fault diagnosis and fault-tolerant control unit of velocity sensor

In order to diagnose the velocity sensor's fault, the following error variable should be considered:

$$\pi = i_{sd} - i_{sd}^* \tag{24}$$

i_{sd} is worked out by $i_{s\alpha}$, $i_{s\beta}$ and $\hat{\theta}$. And i_{sd}^* is i_{sd}'s set value. So when the system keeps stable, π average value is approximately zero. However, if velocity sensor has a fault, systematic balance would be broken and π's value will be influenced. Similarly, π's value is also influenced by load change and velocity sensor faults. Therefore, it should adopt a low pass filter to extract useful signals. The transfer function is as follows:

$$H_4(S) = \frac{1}{\tau_4 S + 1} \tag{25}$$

In this equation, it needs to select proper time constant τ_4 to effectively filter π's harmonic component.

$\bar{\pi}$ is used to show π's value after smoothing. If the system keeps stable, $\bar{\pi} \approx 0$. When velocity sensor has a fault, $\bar{\pi}$'s value would be greatly increased. If $\bar{\pi} > F_s$, the velocity sensor has a fault. And of that, F_s is the threshold value of velocity sensor's fault. The plan of velocity sensor's fault diagnosis and fault-tolerant control is very simple:

(1) If $\bar{\pi} > F_s$, $S_{Flag} = 1$ and $\omega_F = \hat{\omega}_r$.

(2) If $\bar{\pi} \leq F_s$, $S_{Flag} = 0$ and $\omega_F = c_1\omega_r + c_2\hat{\omega}_r$.

In that equation, ω_F is the output value of velocity sensor's fault diagnosis and fault-tolerant control unit, which is fed back to the controller. c_1 and c_2 are positive factors, and $c_1 + c_2 = 1$. S_{Flag} is marking signal of velocity sensor fault. $S_{Flag} = 0$, which means that velocity sensor has no fault. While if $S_{Flag} = 1$, which means velocity sensor has a fault.

According to the above analysis, a unified criterion for sensor fault is concluded like following figure1. This criterion can be used to judge which sensor has a fault, and then some maintenance measures are taken.

Type of sensor fault	Velocity sensor	a-phase current sensor	b-phase current sensor	c-phase current sensor	No fault
criterion	$S_{Flag}=1$	$\iota=3$ and $I_{Flag}=1$	$\iota=2$ and $I_{Flag}=1$	$\iota=1$ and $I_{Flag}=1$	$S_{Flag}=0$ and $I_{Flag}=0$

Figure 1. Sensor fault's criterion

4 RESULT AND ANALYSIS OF SIMULATION

In order to verify the plan's validity, feasibility and accuracy, a real-time oriented vector control system model is built for induction machine's direct magnetic field under the Matlab/Simulink consequence. This model includes an induction machine module, a inverter module, a controller module, a SVPWM module and so on [18-20].

In this experiment, simulation step size is 10 μs, set values of systematic signal are $i_d^*=1.9A$, $\psi_r^*=L_m i_d^*=0.7398Wb$. Yield value of the three state observers is completely same: $K_P=6$, $K_I=800$. Besides, filter parameter and fault threshold value are selected as follows: $\tau_1=0.001$, $\tau_2=0.001$, $\tau_3=0.05$, $\tau_4=0.015$, $F_s=0.15$, $F_t=4$. Nominal parameter of induction machine is selected as follows: rated power 1.1kw, rated speed 1400rpm, nominal voltage 380v, rated current 2.8A, stator resistance (R_s) 6.4985 Ω, rotor resistance (R_r) 3.4289 Ω, stator self-induction (L_s) 411.3467mH, rotor self-induction (L_r) 11.3467mH, common reactance (L_m) 89.3467mH, and number of pole-pairs is 2.

In order to evaluate the effect of the above mentioned plan in all respects, several groups of experiments are made under different consequences. First, researches are made for rotate speed effect of self-adaption observer and its speed control performance when the system is in normal operation. In the experiment1, electromechanical rotate speed is adapted from 0rpm to 1400rpm, and then fallen down to 0rpm at 2s. Next, the rotate speed is reversely speeded up to -1400 rpm, and then fallen down to 0rpm at 4s. The experiment waveform is shown like figure2. Seen from the figure, the electromechanical rotate speed can be accurately and quickly estimated by the designed self-adaption observers, and the systematical speed control has a good performance.

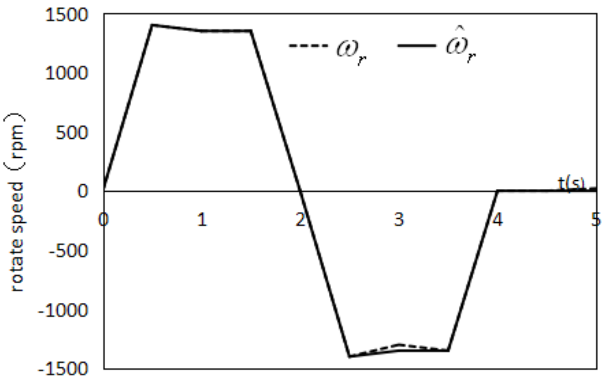

Figure 2 Induction machine's tachometric survey value and observers' estimated rotate speed value when in normal operation

In experiment2, electromechanical rotate speed is speeded up to 1400rpm at 0.5 s and put rated load to electrical machine at 1.5s. The electrical machine's load is subtracted to zero at 2.5 s. Like figure 3 shows, the observers can be in good running both in uploading and deloading process.

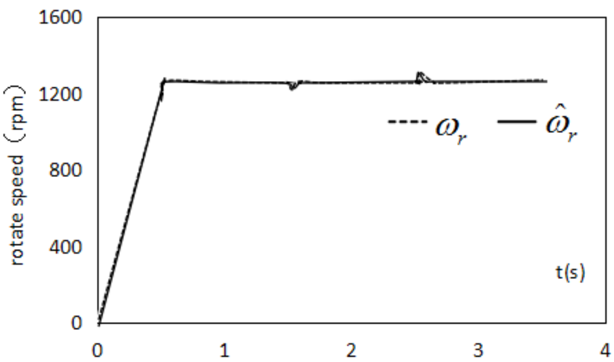

Figure 3 Systematic tachometric survey value and estimated value

Next, the system performance is researched only when current sensor has a fault. Because the current sensors are identical when they have faults, only b-phase current sensor is studied. In the experiment 3, output value of b-phase current sensor is multiplied by 0 at 1.5s so as to simulate current sensor's fault. It shows like figure 4. And after 1.5s, $\iota = 2$, $I_{Flag} = 1$ and $S_{Flag} = 0$. B-phase current sensor is diagnosed with a fault according to figure 1' criterion. At the same time, speed measured value and estimated value are not influenced by current sensor's fault.

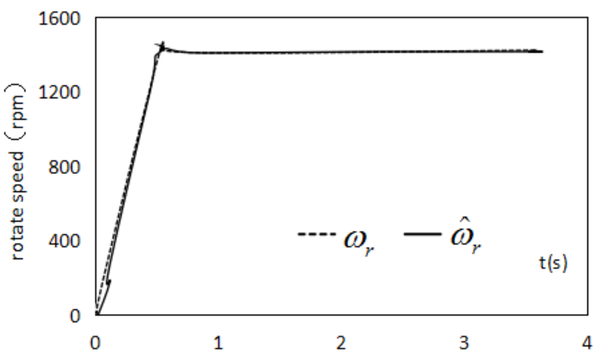

Figure 4 Tachometric measured value and estimated value when b-phase current sensor has a fault

In the experiment 4, only when velocity sensor has a fault is researched. In order to simulate velocity sensor's fault, the sensor's output value is multiplied by 0 at 1.5s and the result shows that all values of E_1, E_2, E_3 and π are largely increased at 1.5s. Because of E_1, E_2 and E_3 having close value, the current sensor has no fault when I_{Flag} is 0. However, when π is greater than F_s at 1.5s and $S_{Flag} = 1$, the velocity sensor is diagnoses with a fault by the system. From figure5, speed estimated value is slightly decreased at 1.5s, but quickly increased to 1400 rpm.

Next, researches are made for two sensors having faults at the same time, which can be classified into two situations: (1) first, current sensor has a fault is faster than velocity sensor; (2) velocity sensor has a fault is faster than current sensor. In the experiment 5, research is made for current sensor first having a fault. Output value of b-phase current sensor is multiplied by 0 at 1.5s like figure6 shows. And then output value of velocity sensor is multiplied by 0 at 2.5s. At 1.5s, because $\iota = 2$, $I_{Flag} = 1$ and $S_{Flag} = 0$, b-phase current sensor is diagnosed with a fault. At 2.5s, because $\iota = 2$ and $S_{Flag} = 1$, velocity sensor is diagnosed with a fault.

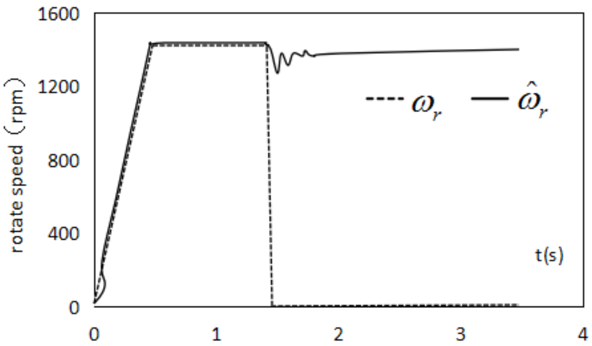

Figure 5 Tachometric measured value and estimated value when velocity sensor has a fault

In the experiment 6, research is made for velocity sensor first having a fault. Output value of velocity sensor is multiplied by 0 at 1.5s, and b-phase sensor's output value is multiplied by 0 at 2.5s like figure7 shows. At 1.5s, because $I_{Flag} = 0$ and $S_{Flag} = 1$, velocity sensor is diagnosed with a fault. At2.5s, because $\iota = 2$, $I_{Flag} = 1$ and $S_{Flag} = 1$, b-phase current sensor is diagnosed with a fault.

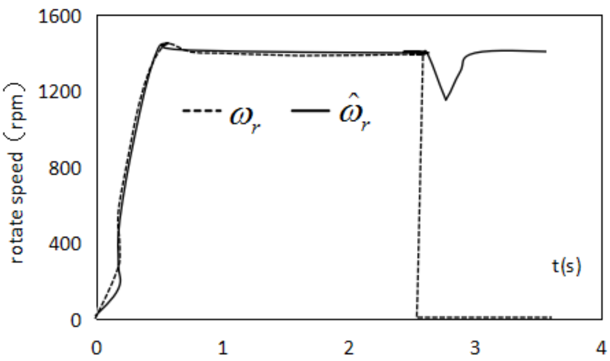

Figure 6 Tachometric measured value and estimated value when b-phase having a fault is faster than velocity sensor

The results of the experiment 5 and 6 show: when two kinds of sensors have faults at same time, the type of faults can be accurately diagnosed by system. It can keep a stable operation, and won't stop. What's more, experimental results would not be influenced by the sequence of the two sensors. And there is no wrong diagnosis in the experiment.

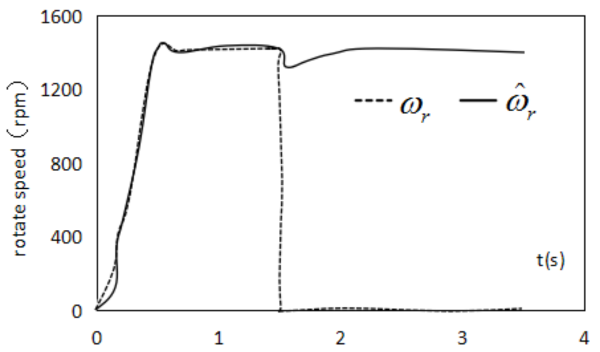

Figure 7 Tachometric Measured Value and Estimated Value when Velocity Sensor having a fault is faster than b-phase Current Sensor

5 CONCLUSION

A set of plan about integrated fault diagnosis of current sensor and velocity sensor is set up for the problem of sensor's fault diagnosis in VFD. Simulation models are built under Matlab/Simulink's consequence. From the six simulation experiments, the plan for self-adaption and sensors' fault diagnosis and fault-tolerant control is feasible in theory with a high efficiency. This plan not only can diagnose a kind of sensor's fault, but also can diagnose two kinds of sensors' faults. One kind of sensor's fault would not affect another and well avoid wrong diagnosis. And systematic fault-tolerant control has a good performance, which can fulfill the demand of practical need.

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