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A Kind of Fault-Tolerant Strategy for Asynchronous Motor Vector Control Current Sensor Failure

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Abstract: The performance of modern motor system is more and more perfect, and the corresponding control algorithm is more and more complex, so t he inevitable various of faults will happen, when Asynchronous motor in the long running process. Its need to take certain fault-tolerant method to guarantee operators' safety, and make the asynchronous motor maintain the normal operation. The three phase current sampling of asynchronous motor vector control is very important to the motor drive system. The actual current sampled by current sensor feedback to the input, and control of motor speed and torque changes for real-time. Usually use two current sensors to sample two phase current, and the third phase current is obtained by calculation. This article will use the acquisition of DC bus current to refactoring three phase current when a current sensor failure, and adopt a certain strategy to revise the three phase current. Finally, verify the validity of the control strategy through Matlab simulation. *Copyright © 2013 IFSA.*

Keywords: Electric drive system, Fault-tolerant control, Refactoring phase current.

1. Introduction

It need to closed loop control phase current of asynchronous motor vector control, in order to obtain high precision three-phase sine wave current and ensure electromagnetic torque control rapidly and accurately. A typical PWM inverter main circuit is shown in Fig. 1. Usually, there have two phase current sensors in ac output, the third phase current calculated by addition of three phase current is zero. There is one current sensor and one voltage sensor setting on the DC bus for over current and over voltage protection.

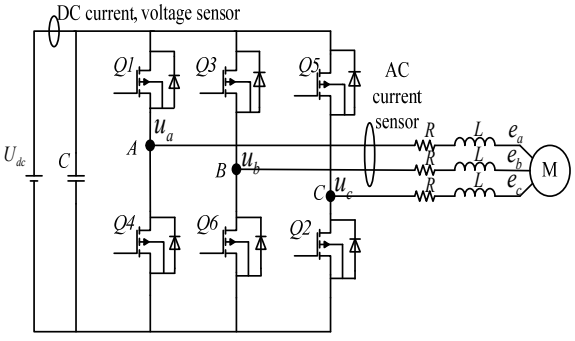

Fig. 1. The main circuit of PWM inverter.

Vector control system can't normal operation when phase current sensor failure, and to reduce the number of the current sensors for reducing equipment volume, reduce the equipment cost and improve the system reliability, recent years, inverter phase current estimation problem research took attentions. The idea of estimating inverter phase current based on the DC bus current has been put forward by Green first [1], and then the idea got continuous development. Literature [2] put up with based on DC current information to identification phase current by using the method of least squares, this method has versatility and practical value, but it requires the switching frequency is low. Literature [3, 4] put up with reconstruction based on the stator voltage space vector trajectory control method, because of the need to be close to round rotating magnetic field control, so the switch state changes frequently and the algorithm is relatively complicated. Literature [5] put forward reference model adaptive method to current reconstruction, estimate the phase current with the help of a motor model, but refactor current precision is greatly influenced by motor parameters. Literature [7-9] using a DC bus current sensor, estimate the inverter output current according to the certain relation between dc bus current and three phase current when different switch states, however, due to the two phase current sampling is not the same time in a PWM cycle, so the current caused certain error. Literature [10] put forward with the help of dc bus current sensor update of one phase current, and updated the three phase current with two phase current recently, but because of not sampling present current value, there will be some errors and control method is more complicated.

In this paper, in each PWM cycle, to estimate phase current according to the relation between three phase current with the DC current. Due to the nonzero vector function for a short time can't sampling phase current accurately, so to error compensation combining the amplitude and phase relations of three phase current, to improve the accuracy of the reconstruction method, and to validate this fault tolerant strategy's effectiveness by MATLAB simulation.

2. Refactoring Phase Current Strategy Analysis

2.1. Basic Principles of Current Reconstruction

Typical of the voltage source type inverter is shown in Fig. 1, there are eight kinds of switch mode for six power device at three bridge arms. Using S_a, S_b, S_c to mark the state of three bridge arms. Defined state of 1 when the above bridge arm power device conducting, and state of 0 when the under bridge arm power device conducting, so the eight inverter switch state corresponding to eight voltage space vector. When the three bridge arm is in a different state of conductivity, phase current and DC bus current exist a determine relationship. For different space voltage vector, phase current and DC bus current relationship as shown in Table 1.

Table 1. Relationship between the line voltage and phase voltage of motor.

The basic vector	U_0	U_{60}	U_{120}	U_{180}	U_{240}	U_{300}	U_{000}	U_{111}
Switch state	100	110	010	011	001	101	000	111
i_{dc}	i_a	$-i_c$	i_b	$-i_a$	i_c	$-i_b$	0	0

To analysis of the phase current and DC bus current corresponding relation through a case, as show in Fig. 2.when the reference voltage in the first sector, the order of voltage space vector is $U_{000} \rightarrow U_0 \rightarrow U_{60} \rightarrow U_{111} \rightarrow U_{60} \rightarrow U_0 \rightarrow U_{000}$. When two zero vector function, load in the stream state, current is not flowing through the bus, $i_{dc}=0$; When U0 function, $i_{dc}=i_c$; When U60 function, $i_{dc}=-i_a$. If the nonzero voltage space vector effect time is long enough, it is easy to obtain current by direct sampling.

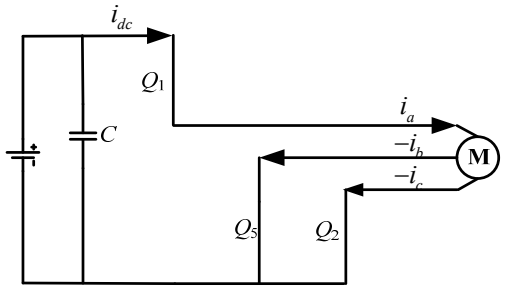

Fig. 2. The current flow of basic voltage vector U_0.

As shown in figure 3, (k-1), (k), (k+1) means the (k-1), the (k), the (k+1) times of sampling, $\tau 1$, $\tau 2$ means the adjacent dc current sampling time, T_1, T_2, $T_0/2$ means the function time of basic voltage vector U_0, U_{60}, U_{000} (U_{111}).

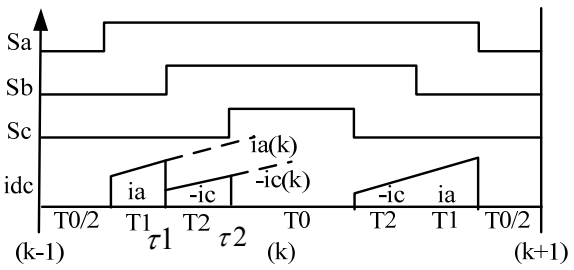

Fig. 3. The DC current sampling and phase current reconstruction of the first sector.

Specifically, (k-1) and k times of sampling, the DC current sampling values of $\tau 1$ moment and $\tau 2$

moment, and the reconstruction values of the phase current i_a , i_c , respectively is:

$$\begin{cases} i_{dc}(\tau 1) = i_a(\tau 1) \\ i_{dc}(\tau 2) = -i_c(\tau 2) \end{cases} \tag{1}$$

Considering grid three-phase balance, according to:

$$i_a + i_b + i_c = 0 \tag{2}$$

Calculate the b phase current, however, because the AC reconstruction current $i_a(\tau 1)$, $-i_c(\tau 2)$ is not the same time samples values, the b phase current calculation has error according to the type (2), hence, hoping using $i_a(\tau 1)$, $-i_c(\tau 2)$ sampled by the (k-1) and the (k) times, to prediction $i_a(k)$ and $i_c(k)$ by the (k) times through the first order linear. Is derived as follows:

From Fig. 3:

$$\begin{cases} i_a(k) = i_{dc}(\tau 1) + (T2 + T0/2)\dfrac{di_{dc}}{dt}\Big|_{t=\tau 1} \\ i_c(k) = -i_{dc}(\tau 2) - (T0/2)\dfrac{di_{dc}}{dt}\Big|_{t=\tau 2} \end{cases} \tag{3}$$

Current rate relations are as follows:

$$\begin{cases} \dfrac{di_{dc}}{dt}\Big|_{t=\tau 1} = \dfrac{di_a}{dt}\Big|_{t=\tau 1} \\ \dfrac{di_{dc}}{dt}\Big|_{t=\tau 2} = \dfrac{di_c}{dt}\Big|_{t=\tau 2} \end{cases} \tag{4}$$

From Fig. 1, according to the three phase inverter circuit calculation available:

$$\begin{cases} \dfrac{di_a}{dt}\Big|_{t=\tau 1} = \dfrac{u_a - e_a - Ri_{dc}(\tau 1)}{L} \\ \dfrac{di_{dc}}{dt}\Big|_{t=\tau 2} = \dfrac{u_c - e_c - Ri_{dc}(\tau 2)}{L} \end{cases} \tag{5}$$

In the type: u_a means inverter AC output voltage; e_a means AC phase voltage. United type (3) - (5) and simplified to:

$$\begin{cases} i_a(k) = i_{dc}(\tau 1) + \\ \dfrac{(T2 + T0/2)}{L}[u_a - e_a - Ri_{dc}(\tau 1)] \\ i_c(k) = -i_{dc}(\tau 2) - \\ \dfrac{(T0/2)}{L}[u_c - e_c - Ri_{dc}(\tau 2)] \end{cases} \tag{6}$$

To take the average of the (k-1) times and the (k) times sampling, that is:

$$\begin{cases} u_a \approx \dfrac{T1(\frac{2}{3})v_{dc} + T2(\frac{1}{3})v_{dc}}{Ts/2} \\ = \dfrac{2T1 + T2}{Ts}(\frac{2}{3}v_{dc}) \\ u_c \approx \dfrac{T1(-\frac{1}{3})v_{dc} + T2(-\frac{2}{3})v_{dc}}{Ts/2} \\ = \dfrac{T1 + 2T2}{Ts}(\frac{2}{3}v_{dc}) \end{cases} \tag{7}$$

United vertical (3) ~ (7), the reconstruction of AC phase current $i_a(k)$, $i_c(k)$ can be realized, then calculated the b phase current according to equation (2). The phase current reconstruction method represents the reference voltage vector in the case of the first sector, apply this method to other five sectors, can realize the phase current refactoring. Actually, it can improve the accuracy of current reconstruction using DSP to realize the k times sampling.

2.2. Problems Existing in the Current Reconstruction

The basic principle of reconstructing phase current is through DC side current to get the corresponding phase current when the effective vector function, In order to accurately measure DC current value in actual system, Effective vector function time must continue a minimum sampling time T_{min}, T_{min} is made up of dead zone time T_{dead}, DC current stable time T_{set} and A/D conversion time, as shown in type (8). If the vector function time duration less than effective T_{min}, it unable to complete accurate sampling of dc current during the function of vector.

$$T_{\min} = T_{dead} + T_{set} + T_{AD} \tag{8}$$

In addition to the T_{min} and the influence of different time sampling, there is a error between reconstruction of the AC current and the measured current, the causes of error are mainly: DC current oscillation error, DC current distortion error, DC current bias error, DC current amplitude errors and the sampling phase error etc. By reasonable design of hardware circuit, increase the correction and a series of processing program to reduce the error.

2.3. Current Reconstruction Scheme in Detail

This paper under the assumption that the AC three phase current is symmetrical, three phase amplitude is equal at the same sampling times, under the premise of Angle is differ 120 °, design a kind of phase current restructuring strategy based on DC bus current. When the current sensor detected failure, system detection of reference voltage vector in any sector for real-time, in a PWM cycle, to look-up table and obtain the current state of the switch first, then detect the fundamental voltage space vector function times to the corresponding switch state, and decide whether the time is greater than the minimum sampling time $T_{\min}$, in this paper the minimum sampling time is 10 μs through calculate.

1. Suppose two effective switch state detected in a PWM cycle, get two phase current value, so both phase current can be set up stably at this time, and according to the three phase current sum zero, the third phase current is calculated.

2. Suppose only one valid current value can detect in a PWM cycle, a valid current i_a is detected, and i_b can't accurate sampling because of corresponding to the voltage space vector function time is too short, according to the three phase current amplitude phase relationship:

$$\begin{cases} i_a = A\sin\theta \\ i_b = A\sin(\theta - 120°) \end{cases} \tag{9}$$

Calculated the A and θ, combining the $i_{a(k-1)}$ sampled at the moment before to amended the current, assuming steady current i_a at the moment has a amplitude error ΔA with the stable current $i_{a(k-1)}$ sampling at the moment before, so the difference of the two current value is:

$$\Delta i_a = \Delta A\sin(\theta) \tag{10}$$

To check the three phase current amplitude:

$$\begin{cases} i_{a1} = (A+\Delta A)\sin\theta \\ i_{b1} = (A+\Delta A)\sin(\theta - 120^\circ) \\ i_{c1} = (A+\Delta A)\sin(\theta - 240^\circ) \end{cases} \tag{11}$$

Suppose stable current i_{a1} at the moment has no amplitude error with stable current $i_{a(k-1)}$ sampling before the moment, but the phase angle error is δ, so the difference of the two current value is

$$\Delta i_{a1} = (A+\Delta A)\sin(\theta+\delta) \tag{12}$$

Work out δ, phase Angle adjustment for the three phase current:

$$\begin{cases} i_{a2} = (A+\Delta A)\sin(\theta+\delta) \\ i_{b2} = (A+\Delta A)\sin(\theta+\delta-120^\circ) \\ i_{c2} = (A+\Delta A)\sin(\theta+\delta-240^\circ) \end{cases} \tag{13}$$

If the reference voltage vector located in other sectors, detected the i_a, i_c or i_b, i_c at the same time, detected the accurate current value at this moment and the corresponding current value sampling before the moment to fixed phase current, correction method is same as above.

3. Suppose detected the two phase current value are both not accurate in a PWM cycle, then give up current sampling points at this moment, use the current amplitude error ΔA at the creating current time before and the phase angle error, to build current combined with the previous moment calculated accurate current value. Assume that accurate current amplitude and phase Angle are respectively $A_{\text{k-1}}$, θ_{k-1}, at the time before sampling time at this moment, the error of amplitude and phase Angle error is respectively ΔA_{k-1}, δ_{k-1}, at the time before this sampling time, the three phase current at this time as follows:

$$\begin{cases} i_{ak} = (A_{\text{k-1}} + \Delta A_{k-1})\sin(\theta_{k-1} + \delta_{k-1}) \\ i_{bk} = (A_{\text{k-1}} + \Delta A_{k-1})\sin(\theta_{k-1} + \delta_{k-1} - 120^\circ) \\ i_{ck} = (A_{\text{k-1}} + \Delta A_{k-1})\sin(\theta_{k-1} + \delta_{k-1} - 240^\circ) \end{cases} \tag{14}$$

Correction of phase Angle can reduce the reconstruction process of the torque ripple, in the process of simulation, using the trigger module to keep the sampling value before switching. In addition, in the process of frequent switching devices, there is a high dv/dt, it will cause electromagnetic interference in the dc current sensor, as shown in Fig. 4, to weaken its influence on the reconstruction of the phase current, design a second order digital filter module *IIR* using FDATool module of Simulink, it can overcome the effects of measurement noise and improve the quality of reconstructed phase current. Fig. 5 is the principle block diagram of phase current reconstruction.

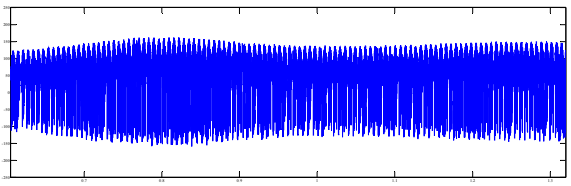

Fig. 4. The electromagnetic interference of direct current i_{dc}.

3. Modeling and Simulation to Reconstruct the Current

To simulate the current reconstruction strategy in MATLAB/Simulink, the simulation is shown in Fig. 6.

The switch state judgment simulation model as shown in Fig. 7.

It's mainly relies on the S function module in the MATLAB/Simulink. When realize the simulation of current reconstruction, It is equivalent to a Simulink built-in module library for augmented, and can be customized by the user, by writing code to realize the expected requirements. Completing the reasonable function variables setting, initialization. Selecting the simulation phase, etc, then can use C language for programming to realize the function. This current refactoring is mainly used the if/end structure in the design of sector judgment, PWM switch state judgment, phase current assignment, and so on, ultimately achieve current refactoring.

The motor simulation under three conditions: at low speed, medium speed and high speed. Analysis the waveform of the refactor current and the measured current and refactoring current. Fig. 8(a)~Fig. 8(c) is the A phase current simulation waveforms when the motor speed is 300 rad/min, Fig. 8(a) is reconstruction without the digital filter current, the current waveform after a *IIR* digital filter is shown in Fig. 8(b), Fig. 8(c) is the A phase current and reconstruction phase current comparison chart.

Fig. 9 (a)~Fig. 9 (c) is the A phase current simulation waveforms when the motor speed is 1000 rad/min.

Fig. 10 (a)~Fig. 10 (c) is the A phase current simulation waveforms when the motor speed is 1500 rad/min.

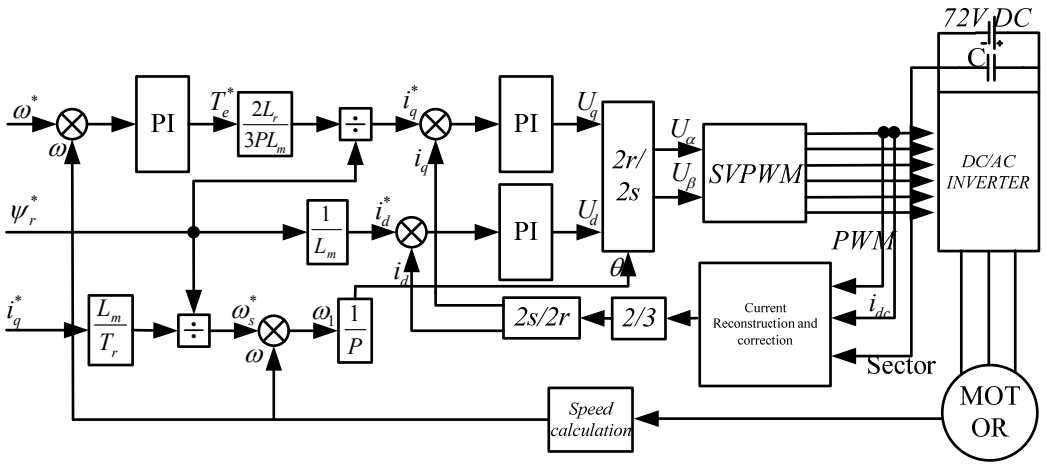

Fig. 5. The principle diagram of the PWM inverter circuit phase current reconstruction.

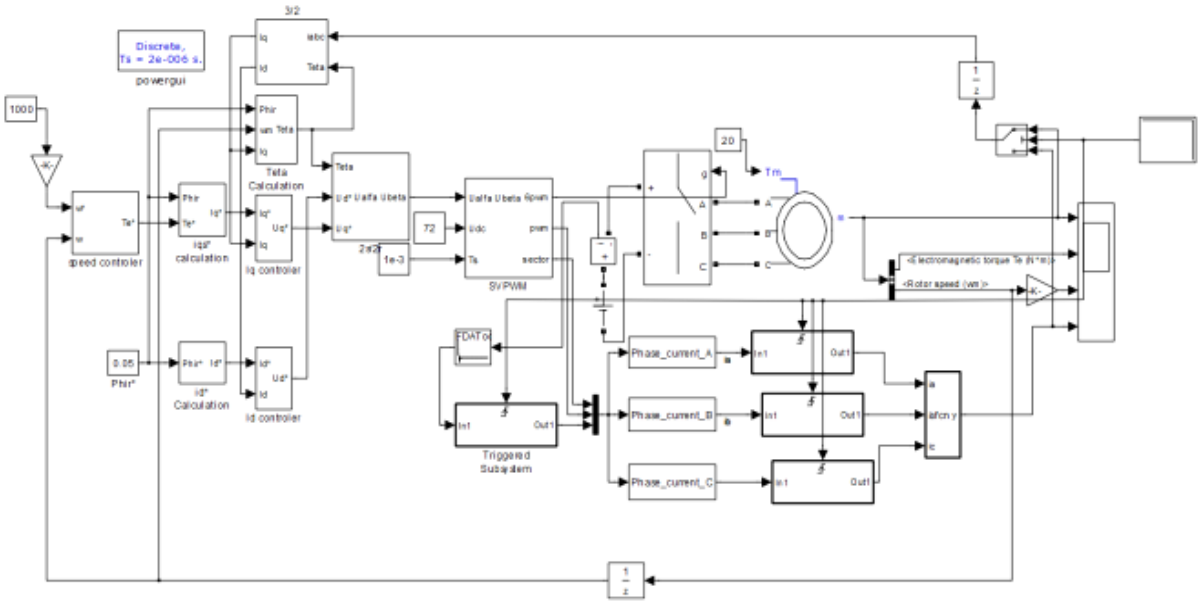

Fig. 6. The diagram of three phase current reconstruction simulation.

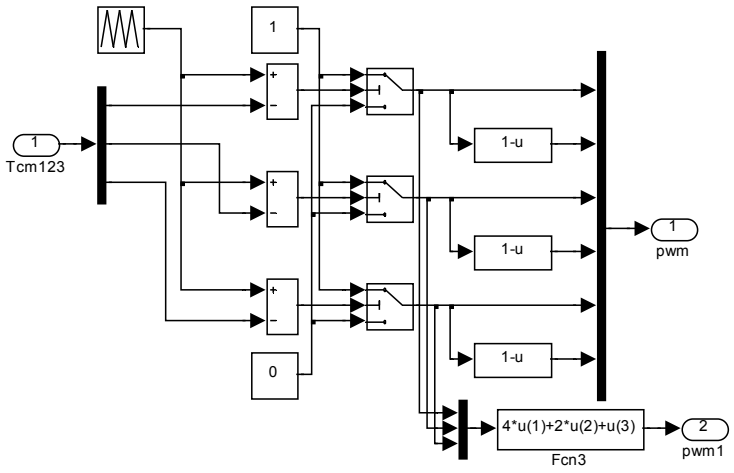

Fig. 7. The model of PWM switch state judging simulation.

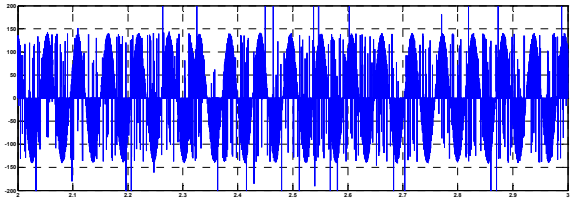

Fig. 8 (a). The reconstruction of A phase current before filter ($n = 300 rad / \min$).

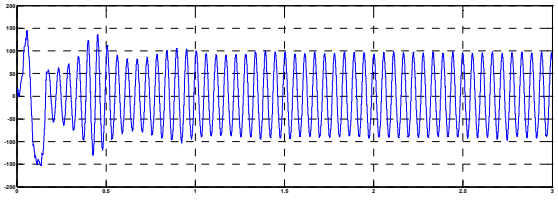

Fig. 8 (b). The reconstruction of A phase current after filter ($n = 300 rad / \min$).

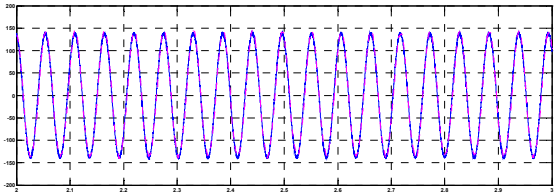

Fig. 8 (c). The measured current and reconstruction current of A phase current ($n = 300 rad / \min$).

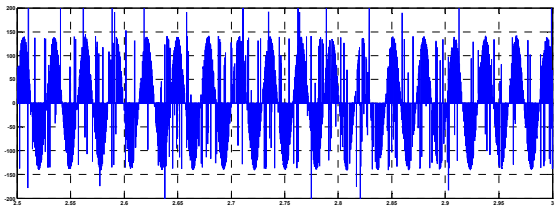

Fig. 9 (a). The reconstruction of A phase current before filter ($n = 1000 rad / \min$).

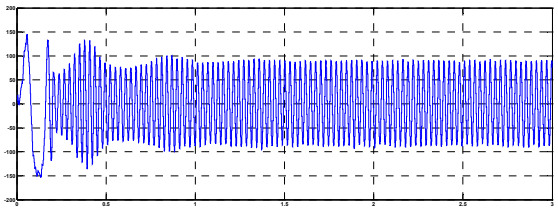

Fig. 9 (b). The reconstruction of A phase current after filter ($n = 1000 rad / \min$).

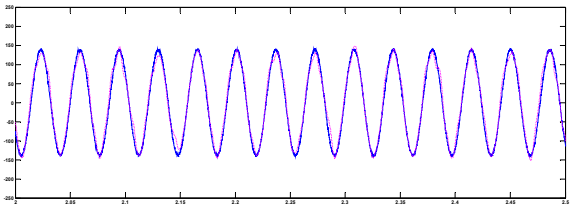

Fig. 9 (c). The measured current and reconstruction current of A phase current ($n = 1000 rad / \min$).

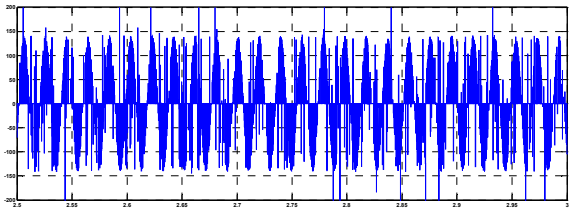

Fig. 10 (a). The reconstruction of A phase current before filter ($n = 1500 rad / \min$).

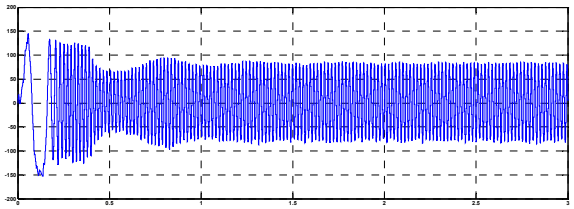

Fig. 10 (b). The reconstruction of A phase current after filter ($n = 1500 rad / \min$).

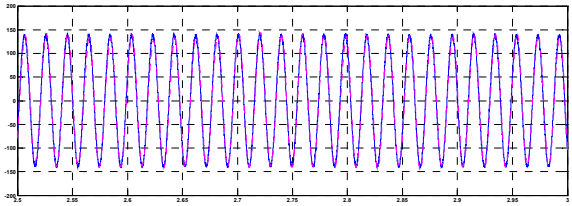

Fig. 10 (c). The measured current and reconstruction current of A phase current ($n = 1500 rad / \min$).

It can be seen from the simulation waveform that the reconstruction of the motor stator winding current waveform is the basic sine wave, the simulation waveform of Fig. 8(c), Fig. 9(c) and Fig. 10(c) displays that the error of the reconstruction current and the measured current is small; Contrast Fig. 8(a) and Fig. 8(b), Fig. 9(a) and Fig. 9(b), Fig. 10(a) and Fig. 10(b), it can be seen *IIR* digital filter design is reasonable, it weakened the direct current electromagnetic noise's influence on the reconstruction of current effectively and improve the quality of the reconstructed phase current greatly.

Switching algorithm to the fault-tolerant algorithm when the fault detection system detects current sensor failure, and the switching process simulation waveform is shown in Fig. 11 and Fig. 12 and Fig. 13. Simulated current sensor failure at 1.5 s, the load torque is 20 N.m at this time, then switching the normal operation of current sensor to DC current refactoring phase current control strategy, get the following simulation results, Fig. 11 is three phase stator current waveform, Fig. 12 is the variation of torque when switching, Fig. 13 is the speed waveform.

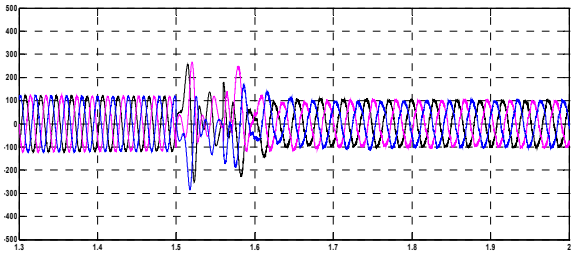

Fig. 11. The three phase current waveform of the current sensor normal work switch to DC current reconfiguration phase current.

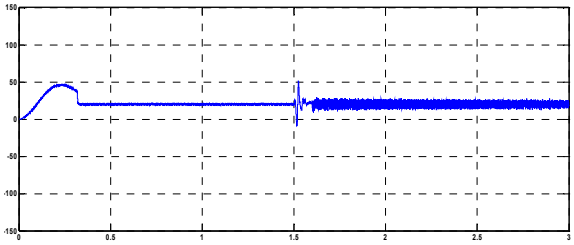

Fig. 12. The electromagnetic torque waveform of the current sensor normal work switch to DC current reconfiguration phase current.

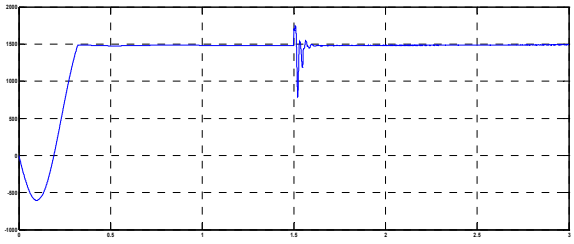

Fig. 13. The speed waveform of the current sensor normal work switch to DC current reconfiguration phase current.

It can be seen from Fig. 11 that at the instant of switching, the three phase current with transient instability of 1 s, so it shall ensure the maximum current under the IGBT inverter support scope, and long flow may lead to motor damage. Electromagnetic torque in the switching moment has small amplitude oscillations for 1 s, in the case of security can cause temporary discomfort to the operator, also brief wobble of speed, but the stable duration of switching process is short, it will not affect the safety.

4. Experimental Verification

In this paper, using 7.5 kW asynchronous motor made in Halla company as the research object, the author designs the hardware circuit based on DSP TMS320F28335, programs software to realize the normal operation of asynchronous motor vector control and researches a fault-tolerant strategy for asynchronous motor phase current sensor failure. Motor main parameters refer to Table 2. In the process of asynchronous motor running, real-time sampling of dc current, calculate three phase current according to the relationship of dc bus current and phase current, and with the condition of three phase current sum to zero. When the ac current sensor fault is detected, then taking the reconstruction of the phase current fault-tolerant strategy continues to run. Using the fault-tolerant software implementation, the program flow as shown in Fig. 14.

Table 2. Halla 7.5 kW induction motor parameters.

Rated power	7.5 kW	Stator resistance	0.00627738 Ω
Rated voltage	51 V	Stator inductance	0.02313 mH
Rated frequency	118 Hz	Rotor resistance	0.00489315 Ω
Logarithmic	2	Rotor inductance	0.03898 mH
The moment of inertia	0.0195367 $Kg^2.m^2$	Mutual inductance	1.8271 mH

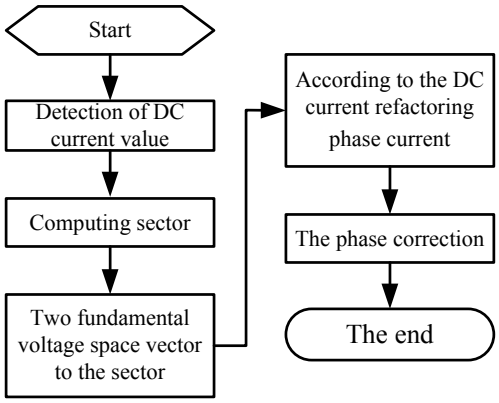

Fig. 14. The flow chart of fault-tolerant module.

Fig. 15 show is A phase current waveform of the stator when speed is 1000 rad/min, Observe the DC current refactoring A phase current waveform using the CCS4.2.4 graphics observation window as shown in Fig. 16.

As shown in Fig. 15 is actual value of reconstructing current, the peak of current is approximately equal to the peak current with the observation using the oscilloscope, but because the DC current sensor sampling range is selected at $\pm 500V$, the sampling precision is not high, and there will be inevitably produce errors in DC current refactoring phase current, so there is a small amplitude oscillation in refactoring phase current, the waveform is approximate symmetrical sine wave overall, achieved the reconstruction of the three phase current to a certain extent.

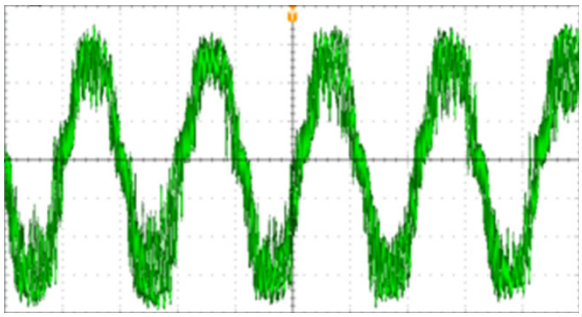

Fig. 15. Stator current waveform of A phase ($n = 1000 rad / \min$).

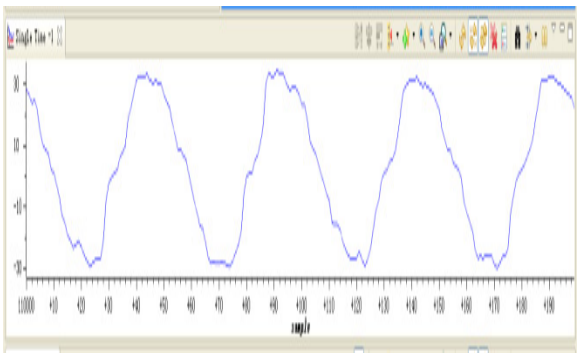

Fig. 16. The waveform of refactoring A phase currents.

5. Conclusion

This paper research a refactoring phase current strategy countering to the asynchronous motor vector control phase current sensor failure problem, taking the thought of dc current refactoring phase current, in view of the problem that dc current sample has errors when basic voltage vector acting time less than the minimum sampling time, making proper correction to improve the performance of fault tolerant strategy. Taking simulation in MATLAB/Similink, and analyzing of the simulation waveform, verification by experimental, concluded the feasibility of this strategy.

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