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Fault-tolerant for Electric Vehicles Drive System Sensor Failure

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Abstract

When EV failure happens, it needs to take some fault-tolerant method to ensure people's safety. When the current sensor and speed sensor are out of work, the software fault-tolerant control algorithm switching strategy can be used. This paper has done theoretical analysis of the rotor field-oriented vector control algorithm into the open loop constant V/F control algorithm, and the phase angle compensation method is used to reduce the shock of current and torque, and simulation is done in MATLAB/Simulink.

Keywords: *Drive system; Fault-tolerant; Phase angle compensation*

1. Introduction

In recent years, with the development of electric vehicle technology, the electric drive system is inevitably out of order during the long running process for each electric vehicle. In order to ensure the safety of a drive, it is necessary to control and lead the car run or limp to a safety area when the electric drive system is out of order [1]. Considering the current solution methods, the redundancy costs of hardware are costly, therefore, this paper is targeting on adjusting software strategy to make sure the stable operation of electric cars. Focusing on the particularity of the vehicle drive system, the second reference stated a method for switching among different control strategies when the electric drive system for rotor position sensor and current sensor are out of order; and hence, it pointed out that in the certain process of switching, there will be an angle difference, this rotor flux linkage angle difference will affect the torque and speed. Moreover, this reference discussed the switching improvement on the condition of a zero angle difference, and pointed out that a one-time switch generates a phase difference. However, this method should be observation to rotor flux [2]. The third reference also analyzed the possible bugs for the electric vehicle drive system. Based on modern control theories, it proposed fault detection and fault-tolerant control method [3]. The fourth reference proposed a scheme of fault-tolerant control based on data fusion aiming at the light of the transducer sensor breakdown [4]. Yet, the control precision of this method will be lower down when the current sensor and speed sensor are invalidated. This research is targeting on a fault-tolerant strategy when phase current sensor and speed sensor are broke down, which is a switching of the rotor field oriented vector control algorithm to SVPWM based modulation of the constant V/F control algorithm. Therefore, based on the switching instant voltage equations, the research will propose a method of the initial phase of voltage compensation, which can weaken the phase difference of torque and speed. As a result, the simulation results prove that this method can reduce the switching instant torque shock significantly [5].

2. Fault Tolerant Analysis

In the situation of two-phase current sensor failure, in order to ensure the normal operation of electric motor that one can sample the DC bus current, and then reconstruct the phase current [6] (shown as Figure 1). However, this is a method which requires complicate current reconstruction, high precision sampling resistance, and high costs. In practice, when the sensor is damaged, in order to ensure the basic operation of electric vehicles, one can be

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switched to constant voltage frequency ratio control, yet the quality of instant switching stability is the key point of this plan.

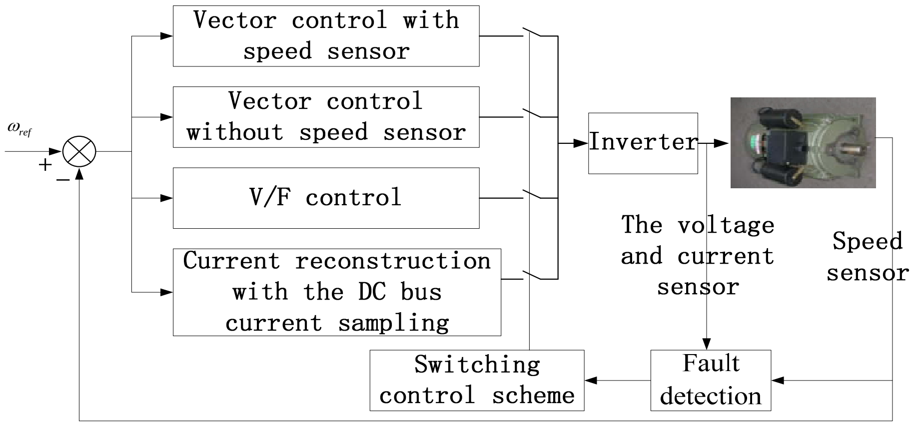

Figure 1. Fault-tolerant switching scheme

Figure 2 is the principle block diagram of the rotor field oriented vector control algorithm [7] switched to SVPWM modulation of the open-loop constant V/F control algorithm. Based on formula (1) and (2), one can conclude that in normal operation, the rotor flux position angle will be θ, it will turn to open loop after the transform. Therefore, the position angle of rotor flux will be θ_r, and the phase angle difference between them will be $\Delta\theta$. The switching process is a braking stage, the negative torque can reduce the speed of motor, and then it will back to a certain speed. Because it is an open loop, the final velocity cannot be determined. The switching transient torque angle is γ, according to formula (4), at the normal traction, Rs/s should be a positive figure. The switching transient rotor angular velocity cannot mutate. After switch to the open-loop constant V/F control, the stator given frequency is ω_r^*. Yet because this time belongs to the torque adjusted process, so that the motor rotor angular velocity is greater than the stator current angular velocity, which means ω_s is less than zero, R_s/s is negative in the work of regenerative braking zone, so the electromagnetic torque T_e is negative. In Figure 4, the switching process for S_2 is off, S_1 is on, and the quantity with an asterisk defined the value before switch.

$$\omega = \omega_r + \omega_s \tag{1}$$

$$\theta = \int \omega dt \tag{2}$$

$$\Delta\theta = \int \omega dt - \int \omega_r dt = \int \omega_s dt \tag{3}$$

$$\sin\gamma = \frac{R_s/s}{\sqrt{(R_r/s)^2 + \omega^2 L_{1r}^2}} \tag{4}$$

$$T_e = \frac{3P\psi_m I_r \sin\gamma}{2} \tag{5}$$

In the above formula, γ is the torque angle, ψ_m is air gap flux peak, and I_r is the rotor current peak.

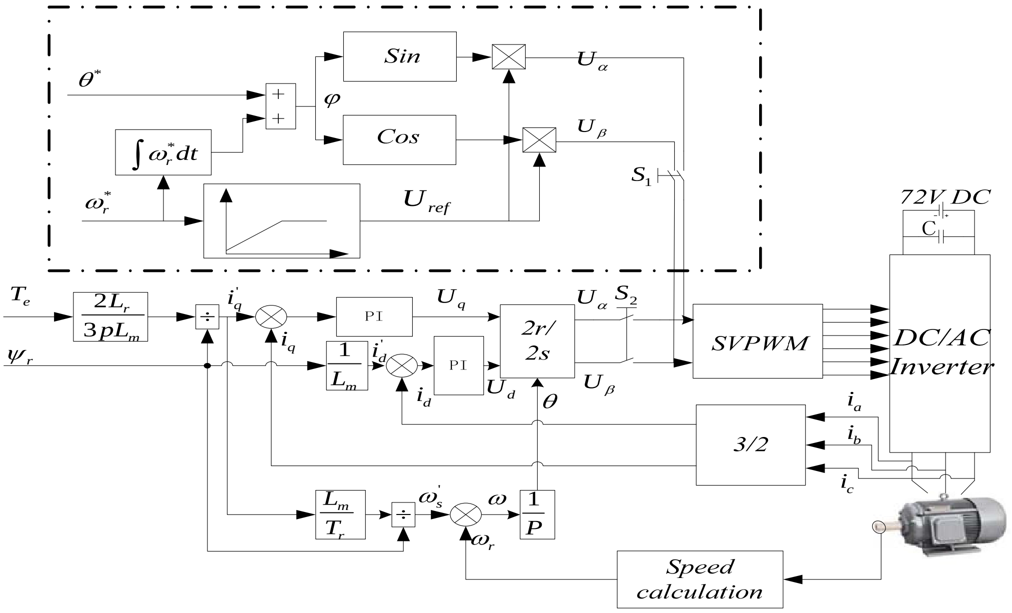

Figure 2. Rotor field-oriented vector control switch into the open-loop VVVF based on SVPWM

In Figure 3, one can learn from the position of U_{ref} in α-β coordinates system and d-q coordinates system that, in oriented control of the rotor field, U_{ref} in αβ coordinate system coordinate component respectively type (6) and type (7), synchronous coordinate rotation angular velocity isω, θ can be get from formula 2. In the control of open loop constant V/F, the actual rotor angular velocity is ω_r, in this switching process, it will introduce a phase difference as it is shown in formula 3. If one use stator current angular velocity in operation process, then the angle of U_{ref} and α is θ, however in the actual rotor field orientation angle is φ, it has a margin of angle δ. This margin is resulting from the coincide of the rotor flux orientation in dq coordinate system of the d axis and the constant V/F control, which has no flux orientation.

In the development of formula (6), it comes out formula (8), and according to formula (8), (9) and (10), it can calculate the value of δ is the value of formula (11), in the first quadrant. In order to reduce the phase difference of the torque and speed caused by mutation, one can use the phase compensate during the control moment of fault-tolerant scheme switching into constant V/F according to the above analysis. Due to the normal vector control switch to SVPWM is based on open loop modulation flux phase jump, the root cause of U_α、 U_β phase changes, therefore compensating to their initial phase angle and the compensation scheme is shown in Figure 4. The switching process for S_2 is off, S_1 is on, and an asterisk defined the value before switch.

$$U_\alpha = U_d \cos\theta - U_q \sin\theta = U_{ref} \cos\varphi \quad (6)$$

$$U_\beta = U_d \sin\theta + U_q \cos\theta = U_{ref} \sin\varphi \quad (7)$$

$$\sqrt{U_d^2 + U_q^2}\left(\frac{U_d}{\sqrt{U_d^2 + U_q^2}}\cos\theta - \frac{U_q}{\sqrt{U_d^2 + U_q^2}}\sin\theta\right) = U_{ref} \cos(\theta + \delta) \quad (8)$$

$$\cos\delta = \frac{U_d}{\sqrt{U_d^2 + U_q^2}} \quad (9)$$

$$\sin\delta = \frac{U_q}{\sqrt{U_d^2 + U_q^2}} \tag{10}$$

$$\delta = \arctan\frac{U_q}{U_d} \tag{11}$$

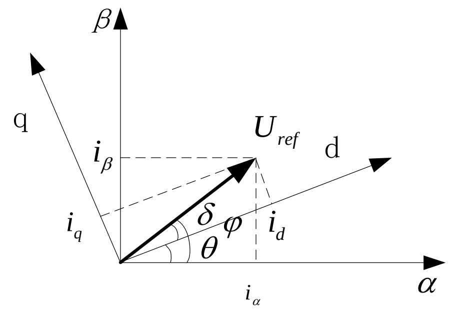

Figure 3. Position of Uref in α-β frame and d-q frame

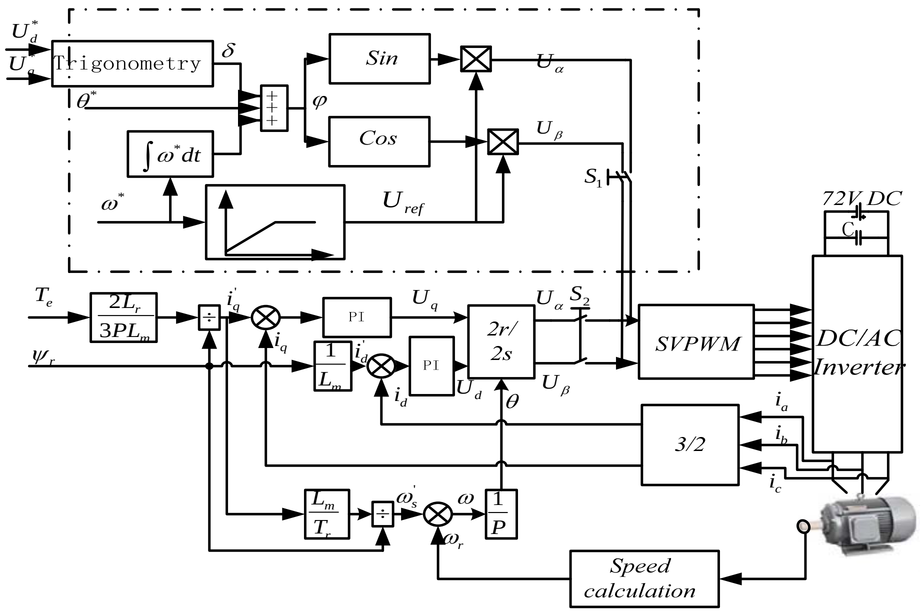

Figure 4. Rotor field-oriented vector control switching into constant V/F based on SVPWM with the phase angle compensation

3. Fault Tolerant Control Modeling and Simulation

The simulation model in this paper is used to simulate the current sensor and the speed sensor failure, and then switching to the open-loop constant V/F control. Before expiring, the research was using the rotor field oriented vector control algorithm. While after the sensor is failure, according to the rotor flux position calculation formula one can conclude that it cannot have real time calculation of angle values. This is the moment that cannot be controlled in switching process.

Simulation in 1.5s current sensor failure, at this moment, the load torque is 30N.m, then switching to the open-loop constant V/F control algorithm, the simulation results are as follow:

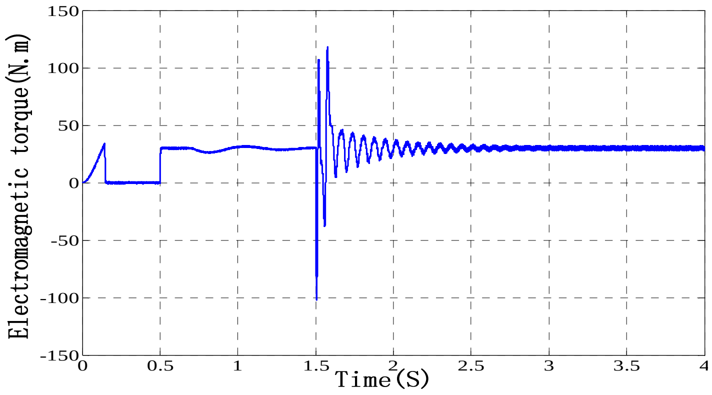

Figure 5. Torque curve of rotor field-oriented control switch into the open-loop constant V/F control

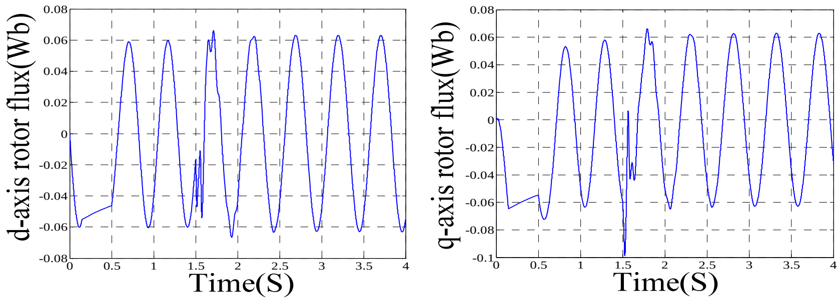

Figure 6. d-axis and q- axis rotor flux

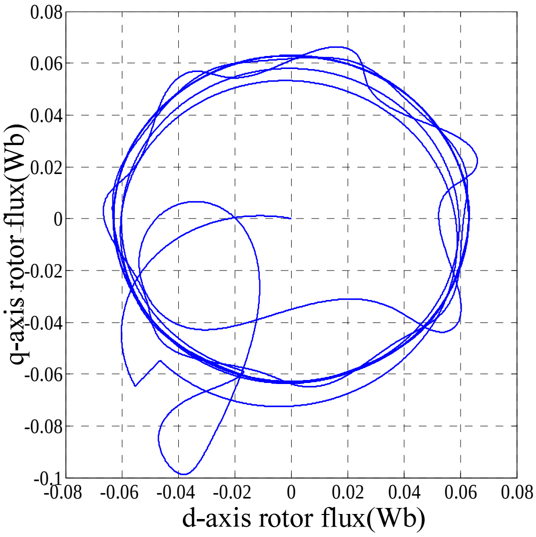

Figure 7. Rotor flux

As we can see from Figure 5, in the switching moment, because the electromagnetic torque reversed, reversed-torque is high, resulting in constant speed concussion, this is easy to cause the damage of the motor.

From the Figure 6 we can see that the flux phase angle jumps greatly after the 1.5s switch. As it is shown in Figure 7, the size of the rotor flux experiences a drastic change.

If it compensates the flux phase during the switching instant, according to the above analysis method, therefore, it can reduce the impact of phase-angle mutation.

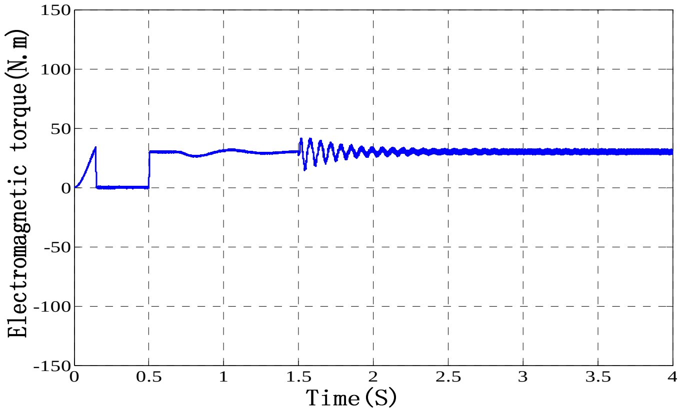

Figure 8. Torque curve of rotor field-oriented control switch into the open-loop constant V/F control with the phase angle compensation

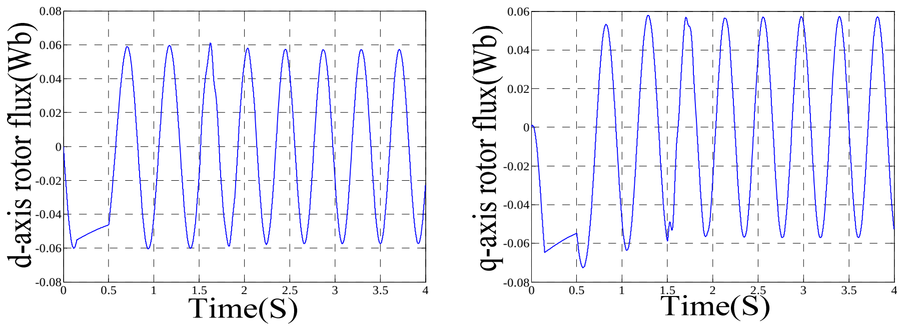

Figure 9. d-axis and q- axis rotor flux

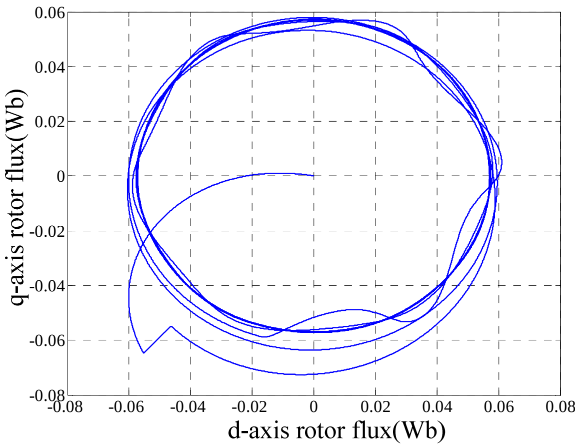

Figure 10. Rotor flux

As it is shown in Figure 8, after the phase compensation, reverse torque is obviously reduced, and the vibration is negligible, so that the effect is extremely obvious. Figure 9 states that the change of flux phase angle is very negligible, and Figure 10 shows the switching process flux change is negligible too. After stabilized, the rotor flux is all shaped round.

4. Conclusion

This paper analyzes theoretically when the current sensor and speed sensor are failure, the feasible control strategy of switching control algorithm software fault-tolerant, and analyzes the switching instants in details. In order to avoid significant shock during switching transient torque, this research applies the phase compensation method. This method can effectively reduce the switching moment of torque and rotational speed impacts. Finally, this paper proves the possibility of the method through the MATLAB/Simulink building simulation models.

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