2007년도 대한전기학회 하계학술대회 논문집 2007. 7. 18 - 20

매입형 영구자석 동기전동기의 고장해석 및 시뮬레이션방법

손도, 이석희, 홍정표
한양대학교 자동차공학과

Faults Analysis and Dynamic Simulation Method for Interior PM Synchronous Motor

Sun Tao, Lee Suk-Hee, Hong Jung-Pyo
Department of Automotive Engineering, Hanyang University

Abstract - This paper introduces major potential faults of IPMSM and their simulation realization methods. The faults of IPMSM, generally, contain single-phase open circuit, single-phase or 3-phase short circuit, and uncontrolled generation. When different fault occurs, the circuit of total system including motor and inverter also will be changed. Therefore, it is necessary to analyze and establish independent model for each kind of fault. In this paper, first, the drive circuit is analyzed as different fault type. Then, the corresponding simulation results solved in Simulink@MATLAB are given. The absence of experiment results leads that the veracity of simulation results can not be verified, but the tendency will be explained by theory analysis.

1. Introduction

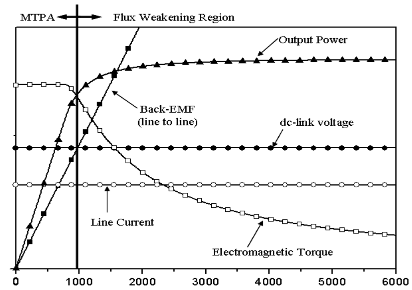
Due to high power density, excellent efficiency, and wide speed range, interior PM synchronous motor (IPMSM) has been paid much attention in various fields for these years. In the starting state of IPMSM, usually the maximum torque per current control method is used to obtain the maximum acceleration, while the motor is operating in over-base speed region, the flux weakening control strategy will be used. Fig. 1 shows the characteristic curve of each variable in a IPMSM, and it is obvious that the maximum current, maximum voltage and much great Back-EMF exist in flux weakening control condition. Hence, once some kind of fault occurs and breaks this balance state, a great pulse current may be generated, or the Back-EMF may become a great voltage source and apply the drive system, which possibly result in demagnetizing action in permanent magnets due to higher d-axis current, exploding in dc capacitor due to too great regeneration power, damage in transistors and motor coils due to higher phase current or voltage and so on.

In addition, these faults are so expensive and dangerous to do the corresponding experiments. The proper simulation model for fault prediction hence becomes meaningful. It not only can show the fault results, but also can guide the motor designer to modify deign parameters or diagnose the fault reason. Some of fault simulation studies for IPMSM have been done before this paper. In [1], the authors gave the results of several fault cases, but the simulation method was not mentioned. [2]-[4] introduced some kinds of main faults and proposed corresponding post-fault control method to reduce the damage. However, the closed-loop simulation method for post-fault control method is different with practical drive condition.

For a given motor, the different load, fault time and PWM method may produce very different results. Therefore, this paper focuses on the fault analysis and simulation method. First, according to each phase and switch states, the circuits are analyzed as different fault case. Then, the corresponding simulation results solved in Simulink@MATLAB are given. The absence of experiment results leads that the veracity of simulation can not be verified, but the tendency will be explained by theory analysis.

2. Analysis IPMSM Model

The motor analyzed in this paper is a 12KW soft-type IPMSM which is used in a parallel-type Hybrid Electric Vehicle traction system. The faultless 3-phase IPMSM generally is expressed as dq-equivalent model, the corresponding state-space equation is, where ω_e is the electrical angular velocity of rotor, R, L_d, L_q, Ψ_m stand for



<Fig. 1> Characteristics of IPMSM and their relationship

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \begin{bmatrix} R+L_qP & \omega_e L_d \\ -\omega_e L_q & R+L_dP \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_e \Psi_m \\ 0 \end{bmatrix} \quad (1)$$

phase resistance, d-axis inductance, q-axis inductance, andphase flux linkage, respectively.

3. Potential Faults and Circuit Analysis

3.1 Single-phase Open Circuit Fault

The single-phase open circuit may be because of switch-on failure of both the transistors of a leg in inverter, or a rupture between one phase winding terminal and periphery supply line. In this case, the motor in fact is operated by the rest 2 phases, because no current flow in the fault phase winding. This asymmetrical structure is not suit for abc-dq transform, hence the motor mathematical model should be modified for simulation. [2] proposed a modified mathematical model for thiscase. The key point is the absent of current in fault phase (a-phase is assumed as fault phase here). Hence, the d- and q-axis currents actually are produced by the normal phases totally. According to dq-$\alpha\beta$ transform, a equation only including β-axis voltage and d- and q-axis voltage variables is established.

$$\begin{aligned} \frac{1}{\sqrt{3}}(v_{co}-v_{bo}) &= v_\beta = -\sin\theta_e v_q + \cos\theta_e v_d \\ &= -Ri_q\sin\theta - L_q\sin\theta - \omega_e\Psi_m\sin\theta_e \\ &\quad -\omega_e L_d i_d\sin\theta_e + Ri_d\cos\theta_e + L_d\frac{di_d}{dt}cos\theta - \omega_e L_q i_q\cos\theta_e \end{aligned} \quad (2)$$

It is obvious that this is a singularity equation due to the existent trigonometric functions. Thanks to the null a-phase current, the other simultaneous equation may be obtained.

$$i_\alpha = i_q\cos\theta_e + i_d\sin\theta_e = i_a = 0 \quad (3)$$

On the other hand, the available legs of inverter become 2. Assume the controller does not reflect to the open circuit fault, and keep switching each phase every 120^o electrical angle. In this paper, a SVPWM current control strategy is considered. Especially, the b- and c-phase voltages are null when the their switch state are the same.

3.2 Single-phase Short Circuit Fault

A transistor cannot switch off, which results in the complementary one is switched off by a transistor protection circuit. The other potential reason is a phase terminal rupture and ground.

For a faultless system, the 0 sequence component in abc-dq0 transform could be ignored because its voltage is 0.

$$v_0 = \frac{1}{3}(v_a + v_b + v_c) = 0 \quad (4)$$

However, in the case of single-phase short circuit fault, the v_0 is 0 no more. Thus, the 0 sequence component voltage equation should be considered in the simulation of this case.
Unlike the case of single-phase open circuit fault, the dq-model of IPMSM is still available to this fault because the existent Back-EMF and phase current. The Back-EMF has same frequency with the other faultless phase Back-EMFs, which means the phase impedance is the same to those of faultless phases. In addition, because the 3 phases still share a same neutral voltage, as long as the switch signals are known, the each phase voltage can be obtained.

3.3 Single-phase Short Circuit Fault

The 3-phase short circuit fault possibly happens when 3 legs of inverter are switched to the same side simultaneously, the dc link voltage is short, or the 3-phase terminals ground. 3-phase short circuit also is called symmetrical short circuit because the balance phase voltage, current and impedance remain. Therefore, the mathematical model does not need to modify. It can be realized by switching 3-phase terminal voltages to 0 when the fault starts.

3.4 Uncontrolled Generation Fault

The base speed of IPMSM may be expressed as

$$\omega_b = \frac{V_{om}}{\Psi_o} \quad (5)$$

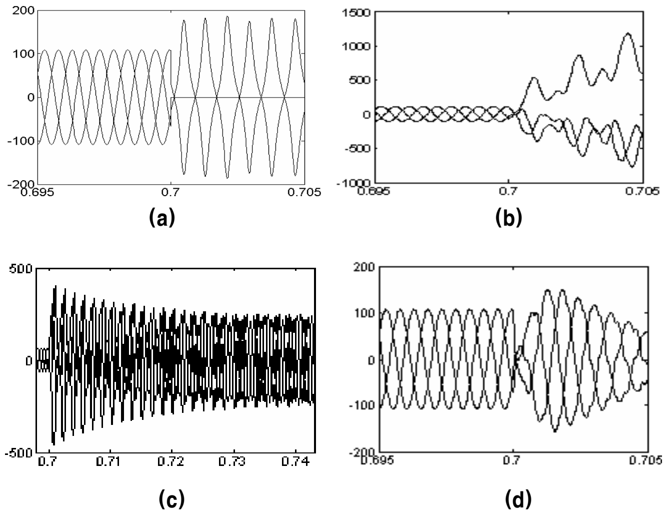
where $\Psi_o = \sqrt{(\Psi_m + L_d i_d)^2 + (L_q i_q)^2}$ and $V_{om} = V_{am} - RI_{am}$. Ignore the phase resistance R, the line-to-line Back-EMF will equal to line-to-line voltage. The line-to-line voltage in theory is the dc link voltage. Hence, in over-base speed, the peak value of line-to-line Back-EMF will beyond the dc-link voltage. If there is no flux weakening control, this case is impossible to happen in motoring mode of IPMSM. However, the flux weakening control apply a more negative d-axis current to the motor, which weakens the d-axis magnetic field and hence limits the line-to-line voltage to dc link voltage value. Thus, once the flux weakening control suddenly disappear, the great line-to-line Back-EMF immediately becomes a voltage source and feedback power to dc source through antiparallel diodes. This fault usually is caused by the controller problem, such as damage of DSP or position sensor, and accidental shutdown of controller power source.

In this case, the fault motor also is symmetrical, hence only the drive model should be modified. The equivalent circuit becomes a 3-phase rectifier and the Back-EMFs are the voltage source. According to the principle of rectifier, the relationship of the phase terminal voltage, line-to-line Back-EMF and phase current is obtained. There are two cases for this state, one is discontinuous phase current, the other is continuous phase current.

For phase a (the other two are the same to it), when Vdc>Eab (or -Vdc<-Eab), and no current flows in this phase winding, the phase voltage is float and uncertain. Here, the 2-phase model which is presented for solving the single-phase open circuit fault can be employed. When Vdc<Eab (or -Vdc>-Eab), a negative (or positiv e) current starts flow in phase a. Synchronously, the upper (or lower) antiparallel diode of phase a gets bias, and the terminal voltage is clamped to Vdc/2 (or -Vdc/2). After Eab gets lower than Vdc, due to the flowing current in phase inductance, the diode is going on bias. If the line-to-lin Back-EMF is great enough, before phase current vanishes, -Vdc>-Eab (or Vdc<Eab) appears, which not only keep the diode bias, but also increase the phase current. If the next -Vdc>-Eac (or Vdc<Eac) can appear before this phase current produced by Eca vanishes, the phase current will be continuous, otherwise be discontinuous.

4. Simulation Results and Discussion

A dynamic simulation model of the IPMSM system based on the analysis are established in Simulink@MATLAB. The fault starting time is assume to 0.7 s, and the system has achieved steady state in 3 times base-speed (4800rpm), and 50% of maximum torque in that speed (23Nm) before fault happens. The results are shown in



<Fig. 2> Simulation results: (a) current of single-phase open circuit; (b) current of single-phase short circuit; (c) current of 3-phase short circuit; (d) current of uncontrolled generation

fig. 2 (a), (b), (c), and (d) respectively.
The fig. 2 (a) shows 3-phase currents since steady state to single-phase open circuit fault state. It is can be seen the currents become 2 phases with 180o electrical position difference after fault happens. In fig. 2 (b), the current of fault phase gets dominantly positive after 0.7s, and the polarities of other two phase current are negative. This accords with the wye connection of 3-phase windings, and the sum of phase currents always is zero. Due to the dominant dc component, the fault phase current is limited by the phase resistance. The time axis of fig. 2 (c) is extended to get through the transient state of phase currents. This transient state exists in initialization of any 3-phase voltage source circuit. The gradually decreasing currents in fig. 2 (d) is because the Back-EMFs decrease with speed. It is obvious that there is a phase shift process in the beginning of fault. This is because the voltage source which generates phase current swaps from dc supply to Back-EMFs.

5. Conclusions

This paper introduces the potential faults and corresponding dynamic simulation for IPMSM which is used in HEV traction system. Due to the large power, high torque and high speed, the IPMSM used for HEV traction has more risks if some fault happen in controller, inverter or inside of motor. For different fault, a pertinent simulation model is necessary. This paper proposes the simulation method for each case of fault. Finally, according to the proposed method, the simulation is implemented in Simulink@MATLAB. And analysis for the simulation results justify the validity of these simulation methods.

[Reference]

[1] N. Bianchi, S. Bolognani, and M. Zigliotto, "Analysis of PM synchronous motor drive failures during flux weakening operation," Power Electron. Specialists Conf., vol. 2, pp. 1542-1548, Jun. 1966

[2] B. A. Welchko, T. M. Jahns, and S. Hiti, "IPM synchronous machine drive response to a single-phase open circuit fault," IEEE Trans. Power Electron, vol. 17, pp.764 - 771, Sept. 2002.

[3] B. A. Welchko, T. M. Jahns, Wen.L. Soong, and James M. Nagashima, "IPM synchronous machine drive response to symmetrical and asymmetrical short circuit faults," IEEE Trans. Energy Conversion, vol. 18, pp. 291- 298, Jun. 2003.

[4] T. M. Jahns, and Vahe Caliskan, "Uncontrolled Generator Operation of Interior PM Synchronous Machines Following High-Speed Inverter Shutdown" IEEE Trans. Industry Application, vol. 35, pp. 1347- 1357, Nov/Dec. 1999.