초전도 동기 전동기의 단락해석과 동특성 시뮬레이션

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Short circuit fault analysis and dynamic simulation of superconducting synchronous machine

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Abstract : This paper mainly introduces the short circuit analysis of superconducting synchronous machine. Because the superconducting machine's model is similar to the permanent magnet synchronous machine (PMSM)'s model, the mathematical model of PMSM is mainly introduced. The 2-phase equivalent circuit model can commonly be used in both non-salient and salient PMSM for simplicity. So a two phase model for a PMSM is derived and the properties of the variables are discussed in relation to the physical 3-phase entities. Use the steady state model to deduce the three types fault models, and then use MATLAB software to get the simulation results.

1. Introduction

The superconducting synchronous machines expecially PMSM are very popular in industrial applications such as traction, automobiles, robotics and aerospace technology. Because the model of PMSM is also suitable to superconducting machine, how to get the model of PMSM is mainly introduced. The PMSM is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has salient permanent magnets. In this respect, the PM Synchronous motor is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PM motors.

Conventionally, a d-q model has been used to analyze PM synchronous machines[1]. Throughout the article, the following assumptions are made[2]:

(1)Stator windings produce sinusoidal mmf distribution, and space harmonics in the air-gaps are neglected.

(2) Balanced 3 phase supply voltage is considered.

(3) Although magnetic saturation is considered, eddy current and hysteretic effects are neglected.

(4) Presence of damper windings are not considered here because they are not used in PM synchronous machines in general.

P: number of poles of the motor.

i_a, i_b, i_c: phase a, b, c instantaneous current.

v_a, v_b, v_c: phase a, b, c instantaneous voltage.

i_d, i_q: d- and q-axis components of stator current.

v_d, v_q: d- and q-axis components of stator phase voltage.

r: stator resistance.

L_d, L_q: d- and q-axis stator self inductance.

λ_m: peak flux linkage due to permanent magnet.

θ: electrical angle between a- and d-axis in degrees.

ω: angular velocity of rotation in electrical.

2. The model of steady state of PMSM

2.1 The mathematical model of PMSM.

2.1.1 The PM synchronous machine.

The relationship between physical stator windings and dq-axis is shown in Fig.1 where the axis of north pole of the rotor is called the direct-axis[3]. The a, b, and c mean the three phases of the stator windings. To the PMSM, the stator carries a three-phase winding, which produces a near sinusoidal distribution of magneto motive force based on the values of stator current. The magnets have the same role as the field winding in a synchronous machine except their magnetic field is constant and there is no control on it[2].

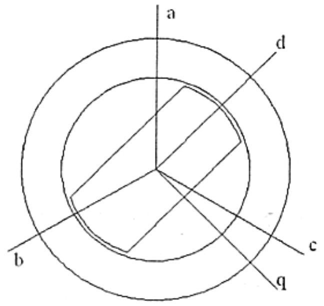

Fig. 1. The permanent magnet synchronous machine.

2.1.2 The two-axis theory.

To the PMSM, the voltage equations of 3-phase windings is shown in equation(1).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} \quad (1)$$

The flux linkages are given by equation(2).

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \lambda_{ma} \\ \lambda_{mb} \\ \lambda_{mc} \end{bmatrix} \quad (2)$$

Where $\begin{cases} \lambda_{ma} = \lambda_m \cos\theta \\ \lambda_{mb} = \lambda_m \cos(\theta - 2\pi/3) \\ \lambda_{mc} = \lambda_m \cos(\theta + 2\pi/3) \end{cases}$

Park transformation in equation(3) can be used to realize the transformation between the 2-phase (d/q-axis) model and 3-phase model.

$$P = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta - 4\pi/3) \end{bmatrix} \quad (3)$$

So the transformed *dq0* model is equation(4).

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} r & -\omega L_q \\ \omega L_d & r \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\lambda_m \end{bmatrix} \quad (4)$$

2.1.3 The parameters of a salient PMSM.

In order to establish a 2-phase model of a motor, there are four motor parameters that are to be determined. These are stator resistance r, inductances L_q and L_d, and PM flux linkage λ_m. This portion is adapted from [4]. All the parameters of a salient-PMSM introduced in this paper are shown in Table 1.

Table 1. The parameters of a salient-PMSM.

The parameters of PMSM	Values
Synchronous speed/frequency	3600(rpm)/60(Hz)
Phase resistance	0.084(Ohm)
Linkage flux magnitude-max of phaseA	6.315(Wb)
d-axis inductance	1.645(mH)
q-axis inductance	1.645(mH)
No. of pole and slot	2pole/36slots

2.2 Short circuit analysis.

Fault models can be derived from the steady state model. In this paper two types of short circuit will be analyzed, and they are short circuit between all three terminals of the machine and short circuit between two terminals of the machine.

In both fault cases it is assumed that the switching of the valves in the output inverter is stopped immediately when the fault occurs. To simplify the simulations, it is also assumed that the PM machine was running at no-load, driving a friction-less load with an infinite inertia. This implies that the PM machine changes from motor operation to generator operation without any change of speed, and will continue to run at that speed. Due to the loss-less no-load operation, it is also assumed that all three stator currents are equal to zero when the different short circuits appear[5].

2.2.1 Three phases short circuit.

At the moment of three phases short circuit happened, the synchronous machine operates at synchronous speed with constant excitation. So the initial values of currents and voltages are as shown[6] in equation (5).

$$\begin{cases} i_a(0^+) = i_b(0^+) = i_c(0^+) = 0 \\ i_0(0^+) = i_d(0^+) = i_q(0^+) = 0 \\ v_a = v_b = v_c = 0 \\ v_0 = v_d = v_q = 0 \end{cases} \quad (5)$$

To salient permanent magnet synchronous machine, The current and torque models are equation (6) and equation (7).

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = -\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}^{-1} \begin{bmatrix} r & -\omega L_q \\ \omega L_d & r \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ \omega\lambda_m \end{bmatrix} \quad (6)$$

$$T = P/2\lambda_m I_q, \quad L_d = L_q, \quad (7)$$

The simulation results of currents are shown in Fig.2 -Fig.5. Fig.6 shows the torque waveform. The peak value of phase current is about 4200 (A), and the peak value of torque is about 22000 (Nm). The current waveforms consist of three part, a fundamental frequency component, a *dc* component and a double-frequency component. The superposition of the fundamental component and dc component will give an unsymmetrical waveform at the transient time of short circuit.

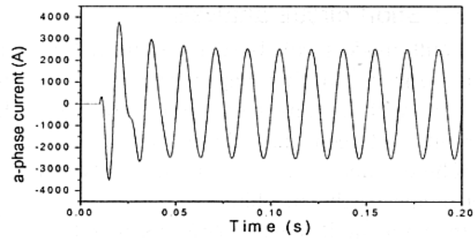

Fig. 2. The a-phase current of three-phase short circuit.

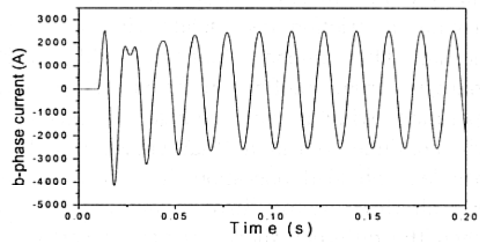

Fig. 3. The b-phase current of three-phase short circuit.

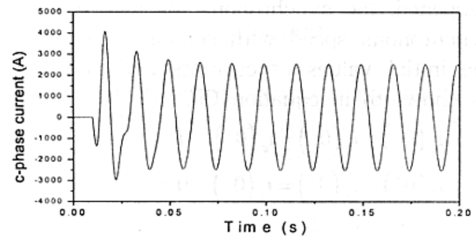

Fig. 4. The c-phase current of three-phase short circuit.

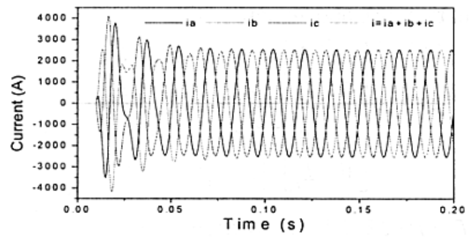

Fig. 5. The phase currents of three-phase short circuit.

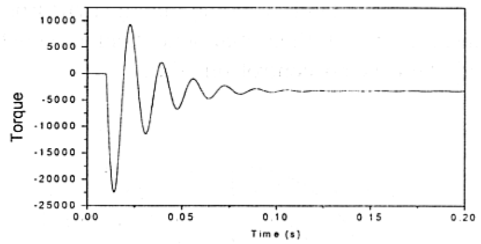

Fig. 6. The torque of three-phase short circuit.

2.2.2 The phase-to-phase short circuit.

Due to the asymmetrical characteristic of two-phase short circuit, it 's hard to be analyzed. Assuming that the short circuit happened between b- and c-phase, so the initial values are given as equation (8)-(9).

$$v_b = v_c = 0$$
$$v_d \sin\theta + v_q \cos\theta = 0 \qquad (8)$$

$$i_a = 0, \quad i_b = -i_c$$
$$i_0 = i_a + i_b + i_c = 0$$
$$\begin{cases} i_d = \sqrt{2} i_b \sin\theta \\ i_q = \sqrt{2} i_b \cos\theta \end{cases} \qquad (9)$$

So the phase-to-phase model is

$$\frac{di_b}{dt} = -\frac{r}{L_d} i_b - \frac{\omega \lambda_m \cos\theta}{\sqrt{2} L_d} \qquad (10)$$

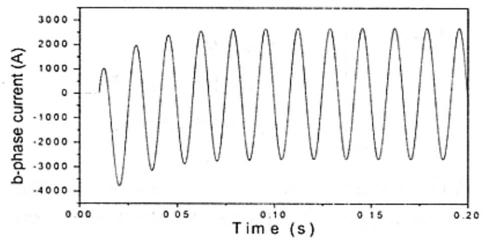

Fig. 7. The b-phase current of phase-to-phase short circuit.

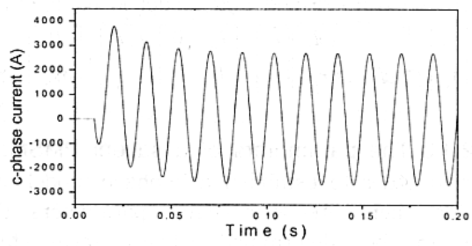

Fig. 8. The c-phase current of phase-to-phase short circuit.

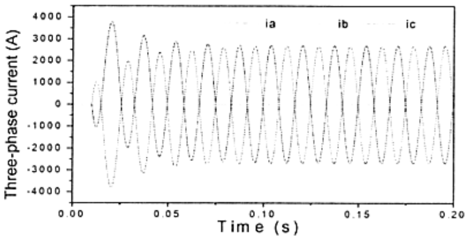

Fig. 9. The three-phase currents of phase-to-phase short circuit.

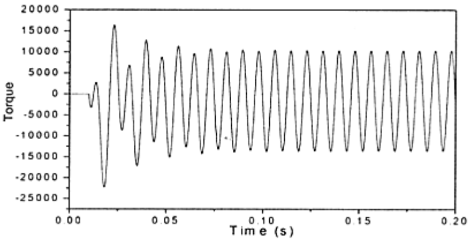

Fig. 10. The torque of phase-to-phase short circuit.

Use MATLAB to realize the simulation, and the results are shown in Fig.7-Fig.10. The peak value of phase current is about 3800 (A), and the peak value of torque is about 22500 (Nm).

3. Conclusions

In this paper short circuit fault models can be derived using Park's transformation from the physical three-phase model. Then the simulation results are gotten by MATLAB software. From the results, we can see that due to the effect of the magnet, all the currents under two conditions will come into fault steady state at last. The faults results can be used to avoid magnetic unbalance or thermal damage to the machines. The faults of a salient-PMSM will cause extensive damage and are expensive to repair. The understanding of the machine behavior during short circuit faults is very important for the full protection of the machine. To superconducting synchronous machine, the models of PMSM can also be used.

감사의 글

본 연구는 프론티어 연구개발사업인 차세대초전도응용기술개발 사업단의 연구비 지원에 의해 수행되었습니다.

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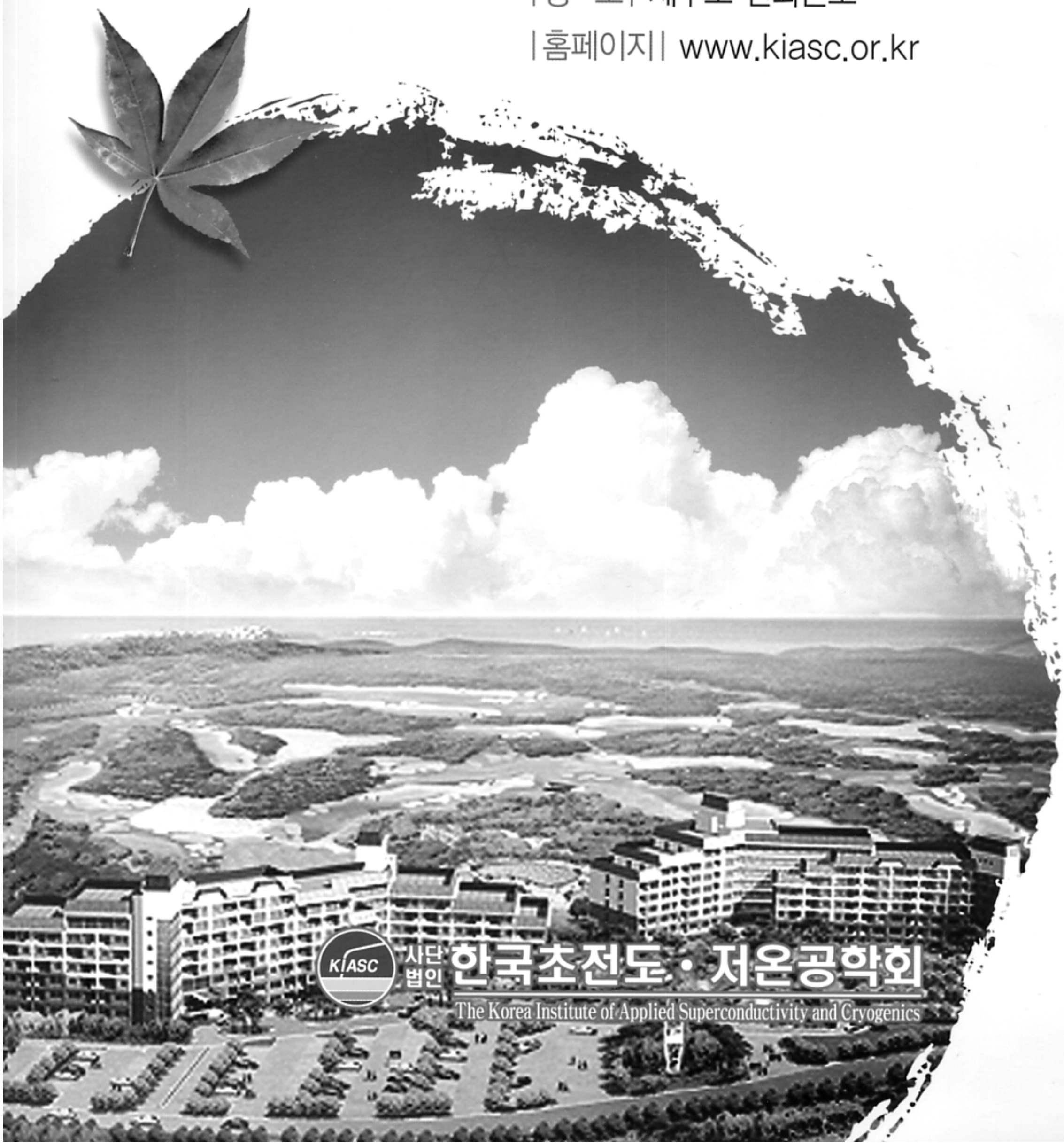

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