Analysis of electromagnetic force of damping winding in salient pole synchronous motor short circuit fault

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Abstract. In recent ten years, China's pumped storage power station has developed rapidly. As the core component of pumped storage unit, salient pole synchronous motor is very important to study its abnormal operation. In this paper, taking salient pole synchronous motor as the research object, the mathematical expressions of magnetomotive force for single-phase short circuit to ground, phase to phase short circuit and two-phase short circuit to ground are derived respectively, and the mathematical law of magnetomotive force for short circuit fault of salient pole synchronous motor under generating condition is revealed. It provides a basis for fault diagnosis, related research and calculation of salient pole synchronous motor.

1. Introduction
In recent years, China's pumped storage power station has developed rapidly, and its key component is salient pole synchronous motor. The research and manufacture of salient pole synchronous motor has been a key problem in the industry [1, 2]. In this paper, the magnetomotive force of the damper winding of salient pole synchronous motor is studied by taking three kinds of short-circuit states as example.

2. Calculation of magnetomotive force under short circuit fault
When the stator winding has a short-circuit fault, additional current will be generated in the stator circuit, and the additional current will generate the corresponding additional magnetic field, which is different from the magnetic field generated by the armature reaction. The additional magnetomotive force is as follows, excluding the high-order harmonics [3-6]:

\[ f_d(\alpha, t) = F_d \cos(\omega t) \cos(p\alpha) \]  

(1)

Where, \( p \) is the polar logarithm and \( \alpha \) is the circumferential mechanical angle.

The additional magnetomotive force described in formula (1) can be decomposed into a positive and a negative rotating magnetomotive force, as follows:

\[ f_d(\alpha, t) = F_{d+} \cos(\omega t - p\alpha) + F_{d-} \cos(\omega t + p\alpha) \]  

(2)
The forward rotating magnetomotive force $f_{d+}$ does not generate harmonic EMF, and rotates with the rotor at the synchronous speed. The negative rotating magnetomotive force $f_{d-}$ generates harmonic EMF of frequency $2\omega$, which turns in the opposite direction to the rotor. The excitation current is as follows:

\[ I_t = I_{t1} + I_{t2} \cos 2\omega t \]  

(3)

Where: $I_{t1}$ is the excitation current under normal operation, $I_{t2}$ is the short-circuit current generated by winding short circuit. The magnetic density caused by stator winding short circuit is as follows:

\[ B(\alpha_m, t) = f(\alpha_m, t) A_0 = 
\begin{align*}
(I_{t0} + I_{t0} \cos 2\omega t) N A_0 \cos(\omega t - \alpha_m + \frac{\pi}{2}) + F_{s1+} A_0 \cos(\omega t - \alpha_m) + \\
F_{s2+} A_0 \cos(\omega t + \alpha_m) + F_{s3+} A_0 \cos(3\omega t - \alpha_m)
\end{align*} \]  

(4)

Where: $F_{s1+}$ is the magnitude of the magnetomotive force generated by the forward rotation of the fundamental frequency, $F_{s3+}$ is the magnitude of the magnetomotive force generated by the forward rotation of three times the frequency, and $F_{s2+}$ is the magnitude of the magnetomotive force generated by the reverse rotation of the fundamental frequency.

The salient pole synchronous motor operates under rated condition, and the excitation current is DC. When the stator winding is short circuited, the excitation current fluctuates greatly, and there are components at different frequencies. In order to simplify the formula calculation, the calculation of most higher harmonics is simplified here. When the finite element method is used to analyze and calculate the motor, the influence of all harmonics should be considered. However, due to the existence of harmonics, the magnetic field will be distorted after short circuit, and the magnetic field of the whole salient pole synchronous motor will no longer be symmetrical.

2.1. Analysis of magnetomotive force in single phase to ground short circuit

According to the symmetrical component method, when the salient pole synchronous motor is in the short-circuit fault state, the operation state is asymmetric. At this time, the positive sequence current, negative sequence current and zero sequence current coexist in the stator winding. At this time, the electromagnetic field in the motor is divided into the forward and reverse rotating magnetic fields. The fundamental wave component of the magnetic field in the motor can be analyzed and calculated by the integration and difference formula.

When the salient pole synchronous motor is short circuited to ground, the magnetomotive force of stator winding is equal to that of single-phase winding. The magnetomotive force in the single-phase winding is the fundamental pulse magnetomotive force, which is composed of the forward and reverse rotating magnetic fields. For example, when the phase a winding of the motor is short circuited to ground, as shown in Fig. 1.

**Figure 1.** The schematic of machine single phase grounding short circuit fault.
According to the fact that the magnetomotive force of stator winding is equal to that of single winding, it can be concluded that:

\[ f_i = \frac{4}{\pi} \frac{N_{k_{u1}}}{2p} i_b \cos \theta_i \]  

(5)

It can be seen from formula (5) that the fundamental pulse magnetomotive force \( f_i \) is directly proportional to the single-phase current \( i_b \) and the number of turns in series of each pole and phase \( \frac{N_{k_{u1}}}{2p} \). For single-phase current \( i_b = \sqrt{2} I_b \cos \omega t \), the fundamental pulse magnetomotive force is as follows:

\[ f_i(\theta_i, t) = \frac{4}{\pi} \frac{N_{k_{u1}}}{2p} \sqrt{2} I_b \cos \theta_i \cos \omega t = F_{0i} \cos \theta_i \cos \omega t \]  

(6)

Where: \( F_{0i} \) is the amplitude of the fundamental pulse magnetomotive force.

\[ F_{0i} = \frac{4}{\pi} \frac{\sqrt{2} \ N_{k_{u1}}}{2p} I_b = 0.9 \frac{N_{k_{u1}}}{p} I_b \]  

(7)

It can be seen from formula (7) that the time of the fundamental pulse magnetomotive force changes with the cosine of \( t \), that is, the instantaneous value of the magnetomotive force changes with the alternating current, and the pulse is vibrated between the wave crest and the wave trough; the time of the fundamental pulse magnetomotive force changes with the cosine of \( \theta_i \) in space, that is, the axis is constant, so it is called the pulse magnetomotive force. Formula (6) is calculated according to the sum of integrations and differences, and the following results are obtained:

\[ f_i(\theta_i, t) = F_{0i} \cos \theta_i \cos \omega t = \frac{F_{0i}}{2} \cos (\theta_i - \omega t) + \frac{F_{0i}}{2} \cos (\theta_i + \omega t) \]  

(8)

Where: \( f_i(\theta_i, t) = \frac{F_{0i}}{2} \cos (\theta_i - \omega t) \) is positive sequence magnetomotive force, \( f_i(\theta_i, t) = \frac{F_{0i}}{2} \cos (\theta_i + \omega t) \) is the negative sequence magnetomotive force.

It can be seen from formula (8) that the two rotating directions are opposite, but the circular rotating magnetomotive force with the same rotating speed synthesizes the pulse magnetomotive force, and the amplitude of the pulse magnetomotive force after synthesis is twice of the original rotating pulse magnetomotive force. When the salient pole synchronous motor has a single-phase short circuit fault, the electromagnetic torque is divided into two parts: positive sequence magnetic field produces positive rotating electromagnetic torque, negative sequence magnetic field produces negative rotating electromagnetic torque. The size of the two is equal and the direction is opposite, so a prime mover is needed to pull the rotor to rotate, otherwise the motor rotor will remain static. When the stator winding of the motor is short circuited to ground, it will produce great braking torque, which will bring harm to the safe and stable operation of the motor.
2.2. Analysis of magnetomotive force in phase to phase short circuit

When phase to phase short circuit occurs in salient pole synchronous motor, the magnetomotive force in single-phase winding is fundamental pulse vibration magnetomotive force, which is composed of forward and reverse rotating magnetic fields. For example, when the phase-A and phase-B windings of the motor are in phase short circuit, the phase-C winding is in open circuit, that is:

\[ i_A = \sqrt{2}I_0 \cos \omega t, \]
\[ i_B = -i_A = -\sqrt{2}I_0 \cos \omega t, \]
\[ i_C = 0, \]

as shown in Fig. 2.

\[ \begin{aligned}
\frac{d}{dt}I &= \mathbf{F}_t \\
\mathbf{F}_t &= F_{11} \cos(\theta - 120^\circ) \cos \omega t \\
\mathbf{F}_t &= F_{12} \cos(\theta - 240^\circ) \cos \omega t \\
\mathbf{F}_t &= F_{13} \cos \theta \cos \omega t = 0
\end{aligned} \] (9)

Add the three-phase fundamental pulse magnetomotive force to get the total pulse magnetomotive force, as follows:

\[ f_1(\theta, t) = f_{1A} + f_{1B} + f_{1C} = F_{11} \cos(\theta - 120^\circ) \cos \omega t - F_{12} \cos(\theta - 240^\circ) \cos \omega t \] (10)

Formula (10) is calculated according to the sum difference of integrations, and the following results are obtained:

\[ f_1(\theta, t) = \frac{\sqrt{3}}{2} F_{11}[-\sin(\omega t - \theta) + \sin(\omega t + \theta)] = f_1(\theta, t) \] (11)

It can be seen from formula (11) that when phase to phase short circuit fault occurs in salient pole synchronous motor, the total resultant magnetomotive force can be divided into the sum of positive and negative rotating magnetomotive force. Compared with the single-phase short-circuit fault, the amplitude of the positive sequence rotating magnetomotive force and the negative sequence rotating magnetomotive force is larger than that of the single-phase ground short-circuit fault. Phase to phase short-circuit fault can be regarded as one of the single-phase ground short-circuit faults. The reason is that the axis of the winding is different from a certain angle. When the number of closed windings changes in multiples, the physical quantities will change in multiples.
2.3. Analysis of magnetomotive force in two phase grounding short circuit

When two-phase ground short circuit occurs to salient pole synchronous motor, its fundamental pulse magnetomotive force can be regarded as the synthesis of two single-phase ground short circuits. When the short circuit occurs, the current of each fundamental frequency phase in stator winding changes cosine with time, as shown in Fig. 3.

![Figure 3](image)

Figure 3. The schematic of machine two phase grounding short circuit fault.

Let \( i_a = \sqrt{2} I_a \cos(\omega t - 120^\circ) \), \( i_b = \sqrt{2} I_b \cos(\omega t - 240^\circ) \), \( i_c = 0 \), at this time, the fundamental pulse magnetomotive force of each phase is as follows:

\[
\begin{align*}
    f_{a1} &= F_{\psi a} \cos(\theta_a - 120^\circ) \cos(\omega t - 120^\circ) \\
    f_{b1} &= F_{\psi b} \cos(\theta_b - 240^\circ) \cos(\omega t - 240^\circ) \\
    f_{c1} &= F_{\psi c} \cos \theta_c \cos \omega t = 0
\end{align*}
\]  

(12)

Add the three-phase fundamental pulse magnetomotive force to get the total pulse magnetomotive force, as follows:

\[
\begin{align*}
    f_1(\theta_a, t) &= f_{a1} + f_{b1} + f_{c1} = \\
    &= F_{\psi a} \cos(\theta_a - 120^\circ) \cos(\omega t - 120^\circ) + \\
    &= F_{\psi b} \cos(\theta_b - 240^\circ) \cos(\omega t - 240^\circ)
\end{align*}
\]  

(13)

Formula (13) is calculated according to the sum difference of integrations, and the following results are obtained:

\[
\begin{align*}
    f_1(\theta_a, t) &= F_{\psi a} \cos(\omega t - \theta_a) - \frac{1}{2} F_{\psi a} \cos(\omega t + \theta_a)
\end{align*}
\]  

(14)

Where: \( f_1(\theta_a, t) = F_{\psi a} \cos(\omega t - \theta_a) \) is positive sequence magnetomotive force, \( f_1(\theta_a, t) = -\frac{1}{2} F_{\psi a} \cos(\omega t + \theta_a) \) is the negative sequence magnetomotive force.

It can be seen from the above formula that the amplitude of negative sequence magnetomotive force is only half of that of positive sequence magnetomotive force in the case of two-phase short circuit to ground fault.
3. Conclusion
This paper analyzes the theoretical derivation of the mathematical formula of the magnetomotive force in the case of three kinds of short-circuit faults of salient pole synchronous motor, and obtains the mathematical rules under the single-phase short-circuit, phase to phase short-circuit and two-phase short-circuit faults. The conclusion is as follows:

1. When the salient pole synchronous motor has a single-phase ground short circuit fault, the magnitude of the forward rotating electromagnetic torque and the reverse rotating electromagnetic torque are equal, which will produce great braking torque, and bring harm to the safe and stable operation of the motor.

2. In case of phase to phase short-circuit fault, the amplitude of positive sequence rotating magnetomotive force and negative sequence rotating magnetomotive force is larger than that of single-phase ground short-circuit fault. The number of closed windings changes exponentially, so do the physical quantities.

3. When two-phase ground fault occurs, the amplitude of negative sequence magnetomotive force is only half of that of positive sequence magnetomotive force.

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