Analysis of short circuit electromagnetic force of salient pole synchronous motor winding

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Abstract. China's pumped storage power station has a broad prospect, in which salient pole synchronous motor plays an important role. In this paper, the mathematical expression of electromagnetic force in the case of short circuit of the excitation winding of salient pole synchronous motor is derived, and the variation law of electromagnetic force density in the case of fault corresponding to the electromagnetic force of damping winding is calculated. The mathematical law of electromagnetic force in the case of short circuit fault of salient pole synchronous motor is revealed, which has practical reference significance.

1. Introduction

Scholars at home and abroad have carried out a lot of research work on the calculation of electromagnetic force of synchronous generator and induction motor and achieved remarkable results, but for the salient pole synchronous motor in the short circuit state of excitation winding, the related calculation of electromagnetic force of damping winding is less. In this paper, the electromagnetic force, electromagnetic field and magnetic density of damping winding of salient pole synchronous motor are studied in depth to study the development of similar motor. The electromagnetic force after short circuit fault is generated provides reference.

2. Calculation of electromagnetic force in case of short circuit fault

1) When the object under force is only a current carrying conductor, the force is calculated by Lorentz force method, and the calculation formula for two-dimensional magnetic field is as follows [1-3]:

\[ F_e = lS_e J_e \times B_e \]  

Where: \( F_e \) is the Lorentz force vector of the unit, \( l \) is the axial length of the guide bar, \( S_e \) is the area of the unit, \( J_e \) is the electric density vector of the unit, and \( B_e \) is the magnetic density vector of the unit.

Force on current carrying conductor in magnetic field:
\[ F = \int J \times B \, dV \]  

Where:  \( J \) is the current density of the conductor;  \( B \) is the magnetic flux density of the conductor. The force density  \( f \) is determined by the following formula:

\[ f = J \times B \]

If the current carrying conductor is a linear conductor with small cross section, the electromagnetic force  \( df \) acting on the length  \( dl \) is:

\[ df = idl \times B \]

The force  \( F \) applied to the whole conductor is:

\[ F = \int idl \times B \]

2) Force on ferromagnetic medium in magnetic field:

If there is no permanent magnet, the density of electromagnetic force can be obtained from the expression of magnetic field energy by virtual displacement method as follows:

\[ f = J \times B + f' + f'' \]

In the formula, the first item  \( J \times B \) at the right end is the density generated by the conduction current of the magnetic medium, the second item  \( f' \) is caused by the uneven permeability inside or at the junction of the magnetic medium, and the direction of the force is from the place where the permeability value is large to the place where the permeability value is small.

The third item  \( f'' \) is the density of the magnetostrictive force, which is caused by the change of permeability in each direction caused by the deformation of the magnetic medium due to the stress collected in the magnetic field. This item can be ignored in the motor.

When considering the electromagnetic force at the interface of two media, the Maxwell stress method should be used for calculation. Let the permeability of two different mediums be  \( \mu_1, \mu_2 \); the magnetic field intensity is  \( H_1, H_2 \); the magnetic induction intensity is  \( B_1, B_2 \); the normal component of each quantity is expressed by subscript n, the tangential component is expressed by subscript t, and the electromagnetic stress on unit area element is as follows by Maxwell stress method [4-6]:

\[
\begin{align*}
\sigma_{tt} = & -\frac{1}{\mu_1} (B_{tt}^2 - B_{tn}^2) + \frac{1}{2\mu_1} (B_{tn}^2 - B_{tt}^2) \\
\sigma_{tn} = & \frac{1}{\mu_1} B_{tn} B_{tt} - \frac{1}{\mu_2} B_{tn} B_{2tt}
\end{align*}
\]

The boundary conditions for stress calculation by Maxwell stress method are as follows:

\[
\begin{align*}
B_{tn} = & B_{2tn} = B_n \\
H_{tn} = & H_{2tn} = H_t
\end{align*}
\]

There is no current at the junction of the two mediums. Substituting equation (8) into equation (7), we can get:
At this time, the magnitude of normal electromagnetic force on the cogging of salient pole synchronous motor is as shown in the above formula, and its electromagnetic stress direction is from the iron core to the air.

By using the Maxwell tensor method, the bulk density of the electromagnetic force of the object to be studied can be converted into the calculation of the electromagnetic force of the surface density of the object, and then the area of the surface density is divided to obtain the magnitude of the electromagnetic force. The calculation method is as follows:

$$f_i = 0$$
$$f_n = \frac{\mu_2 - \mu_1}{2\mu_1\mu_2}(B_n^2 + \mu_1\mu_2H_i^2)$$

(9)

Where, $B_1$, $B_2$ is the tangential flux density of different media at the interface; $B_{m1}$, $B_{m2}$ is the normal flux density of different media at the interface; and $\mu_1$, $\mu_2$ is the permeability of different media at the interface.

When the Maxwell tensor method is used to calculate the electromagnetic force, its physical meaning is very clear, but its calculation accuracy is closely related to the number of sectioning elements, the regularity of sectioning grid, the selection of integration path and other factors. When there is no current sheet at the interface of different media, the magnetic field strength $H$ at the interface of different media can not ensure its value to be equal. When using this method, many conditions should be satisfied to ensure the accuracy of the calculation results.

The local Jacobian derivative method is derived from the virtual displacement method. When the local Jacobian derivative method is used to calculate the electromagnetic force, the calculation process is intuitive and the error of the calculation result is small. However, it is required that the surrounding of the object to be studied should be surrounded by air, and the object to be studied should be regarded as a whole. This method can be used to study the force or calculate the electromagnetic torque. The calculation method is as follows:

$$F_n = \frac{1}{2} \sum_{e_n=1}^{\infty} \left[ \frac{B^T}{\mu_0} - \frac{B_{m1}^2}{2\mu_0} \right] (\partial G / \partial S) \left[ G^{-1} \frac{\partial G}{\partial S} \right] V_e$$

(10)

Where: $B$ is the element flux density matrix; $N$ is the number of air elements around the rotor; $G$ is the Jacobian matrix under coordinate transformation; $V_e$ is the unit volume; $e_n$ is the unit serial number; $\mu_0$ is the permeability in vacuum.

When considering the electromagnetic stress of solid objects, such as stator and rotor core, the stress situation will change. When salient pole synchronous motor operates under rated condition, the electromagnetic force of stator on unit area is as follows:

$$q(\alpha_m, t) = \frac{B(t)^2}{2\mu_0} = \frac{[F_1 \cos(\omega t - \alpha_m - \beta) \Lambda_b^2 + F_2^2 \Lambda_b^2]}{4\mu_0} [1 + \cos(2\omega t - 2\alpha_m - 2\beta)]$$

(12)

From the above formula, it can be concluded that when salient pole synchronous motor operates under rated working conditions, the electromagnetic force on unit area of stator inner circle is divided
into two parts, \( F^2 / 4\mu_0 \) is the amplitude of constant force, and the magnitude of this component force is not constant, changes, and does not cause vibration of motor, but it will cause core deformation over time; \( F^2 / 4\mu_0 \) is also the amplitude of alternating force, this component will change with time, and cause the stator to vibrate with it at twice the frequency of power frequency, which leads to stator failure, there is a serious security risk.

After the stator winding of salient pole synchronous motor is short circuited, a magnetic field is generated on the stator winding and a second harmonic electromotive force is induced on the excitation winding. In turn, a third harmonic electromotive force is induced on the stator winding side again. Due to the occurrence of the fault, the air gap magnetic field changes. Compared with the fundamental wave, the induced second and third harmonics have larger amplitude of the fundamental wave magnetic density, and the electromagnetic force generated by the fundamental wave magnetic density changes greatly before and after the short-circuit fault.

After the excitation winding of salient pole synchronous motor is short circuited, the electromagnetic force on the stator winding is as follows:

\[
q(\alpha_m, t) = \frac{B^2(t)}{2\mu_0} = \frac{\Lambda_0^2}{2\mu_0} \left[ F_c \cos(\omega t - \alpha_m - \beta_1) - F_{d2} \cos(2\omega t - \alpha_m - \varphi_2) \right]^2 = \\
\frac{\Lambda_0^2}{4\mu_0} \left[ F_c^2 + F_{d2}^2 - 2F_cF_{d2} \cos(\omega t - \alpha_m + \beta_1 - 2\varphi_2) + F_c^2 \cos(2\omega t - \alpha_m - \beta_1) \right] - 2F_cF_{d2} \cos(3\omega t - 3\alpha_m - \beta_1 - 2\varphi_2) + F_{d2}^2 \cos(4\omega t - \alpha_m - \varphi_2) \tag{13}
\]

It can be seen from the above formula that when the excitation winding is short circuited, there will be an electromagnetic force of one to four times the fundamental frequency in the motor; when the degree of short circuit is intensified, \( F_{d1}, F_{d2} \) will continue to increase, \( F_c \) will decrease, at this time, the electromagnetic force of two times the fundamental frequency will decrease, and the electromagnetic force of four times the fundamental frequency will increase. At this time, the radial electromagnetic force of the motor presents periodic fluctuations, which will aggravate the vibration of the motor and pose a serious threat to the safe and stable operation of the motor.

3. Conclusion
In this paper, the theory of electromagnetic force is deduced when the salient pole synchronous motor has a short circuit fault of excitation winding. The conclusion is as follows:

1. After the stator winding is short circuited, the air gap magnetic field changes. The amplitude of the fundamental magnetic density is larger than the secondary and third harmonics. The electromagnetic force produced by the fundamental magnetic density changes greatly before and after the short circuit fault.

2. After the excitation winding is short circuited, there will be one to four times the fundamental frequency electromagnetic force in the motor. With the increase of short circuit, the electromagnetic force of twice the fundamental frequency decreases and that of four times the fundamental frequency increases. At this time, the radial electromagnetic force of the motor fluctuates periodically, which will aggravate the vibration of the motor and pose a serious threat to the safe and stable operation of the motor.

References
[1] Bi D, Wang X, Wang W, et al. Improved transient simulation of salient-pole synchronous generators with internal and ground faults in the stator winding[J]. IEEE Transactions on Energy Conversion, 2005, 20(1): 128-134.
[2] Wang X, Chen S, Wang W, et al. A study of armature winding internal faults for turbogenerators[J]. IEEE Transactions on Industry Applications, 2002, 38(3): 625-631.
[3] Megahed A I, Malik O P. Synchronous generator internal fault computation and experimental verification[J]. Generation, Transmission and Distribution, IEE Proceedings-, 1998, 145(5): 604-610.

[4] Kovanen T, Tarhasaari T, Kettunen L. Localization of Electromagnetic Force Based on Material Models[J]. IEEE Transactions on Magnetics, 2012, 48(1): 13-17.

[5] Morais A P, Bratas A S, Meyn S. Adaptive Mho Relay for Synchronous Generator Loss-of-excitation Protection: ACapability Curve Limit-based Approach[J]. IET Generation, Transmission & Distribution, 2016, 10(14): 49-57.

[6] Abedini M, Sanaye-Pasand M, Davarpanah M. An Analytical Approach to Detect Generator Loss of Excitation Based on Internal Voltage Calculation[J]. IEEE Transactions on Power Delivery, 2016, PP(99): 1-6.