Transient analysis of the fault process of double Y-type three-phase asynchronous motor during open phase operation

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Abstract. In order to reduce the loss caused by the failure of large motors, it is of great significance to accurately detect and predict the state of the motor during operation. Based on the theory of motor asymmetry, combined with the influence of temperature on the winding resistance in the actual operation of the motor, with the help of ANSYS finite element analysis software, a simulation model of a large three-phase asynchronous motor with double Y windings is established. This article uses the Maxwell circuit editor module to build an external circuit. First, verify the abnormal characteristics of the three-phase current when the phase is missing through simulation, and then analyze the influence of the resistance asymmetry on the motor operating characteristics. The simulation results show that the abnormality of the three-phase current caused by the winding asymmetry is regularly and cyclically amplified, that is, in the actual motor operation, the first phase of the abnormal winding can be determined by real-time observation of the three-phase current. In this way, we can avoid the burning of the motor.

1. Introduction
Asynchronous motor stator coil failure is one of the main reasons for motor failure. 30%~40% of motor failures are caused by stator failure, so early fault detection and diagnosis of the motor stator is beneficial to personal safety and economic benefits. Both have important meanings. However, the working environment of large asynchronous motors is relatively complicated, the conditions for diagnosis and repair are limited, and it is difficult to quickly locate motor faults. Therefore, it is necessary to quickly locate the fault point of the motor and stop the loss in time when the motor fails.

At present, the research on the stator winding lack phase fault is mainly based on the establishment of the fault model. The phase failure analysis mainly uses the symmetrical component method. When one phase of the motor is disconnected for some reason, the winding changes from three phases to two phases asymmetrical. At this time, the motor can still run, but long-term operation will cause the motor windings to burn out, so it is very necessary to determine the lack of phase operation status of the motor in time. Literature [3] uses a multi-loop model to analyze the influence of the asymmetry of stator winding resistance and inductance on the operating characteristics of the motor, but ignores the influence of temperature on the winding resistance. Literature [4] uses the phase difference of the stator three-phase current Determine whether the stator winding is faulty, and further determine the degree of fault. Literature [5~6] analyzes the stator negative sequence impedance, stator negative sequence current, power, and magnetic flux caused by asymmetric stator winding faults. The literature [7~8] used the multi-loop mathematical model finite element method and the Park model finite element method to model the inter-turn short circuit faults when the stator windings of the three-phase induction motor were symmetrical and asymmetrical. The parameters of the electromagnetic field in the motor are...
calculated and analyzed in detail. This paper uses ANSYS software to build the motor body model and external circuit model, and simulates the three-phase winding current of the double Y-type three-phase asynchronous motor before the phase failure occurs. According to the relative magnitude of the three-phase winding current, the fault point is judged and repaired in time to avoid the failure of winding burnt.

2. Mathematical model of three-phase asynchronous motor

Three-phase asynchronous motors mostly use the symmetrical component method to analyze the lack of phase faults. Assuming that the A phase is disconnected, the voltage is decomposed into positive sequence components and negative sequence components. The stator winding is Y-connected, and there is no neutral wire, and the stator is zero. The sequence current is equal to zero. The positive sequence voltage produces a three-phase positive sequence current in the stator winding, while the negative sequence voltage produces a negative sequence current in the stator winding. The positive sequence and negative sequence equivalent circuit diagrams are shown in Figure 1.

Figure 1. Positive sequence and negative sequence equivalent circuit diagram of asynchronous motor when phase is missing

The relationship of the three-phase current is: \( I_B^0 = 0, \quad I_C^0 = -I_A^0 \), obtain the current of phase B and C by symmetrical component method:

\[
I_B^0 = \frac{R_2}{Z_2} + \frac{R_{2a}^0 + jX_{2a}^0}{Z_2} \left( I_A^0 + \frac{R_{2a} + jX_{2a}}{Z_2} \right)
\]

(1)

\[
I_C^0 = -\frac{R_2}{Z_2} - \frac{R_{2a}^0 + jX_{2a}^0}{Z_2} \left( I_A^0 + \frac{R_{2a} + jX_{2a}}{Z_2} \right)
\]

(2)

\[
U_{BC} = U_B^0 - U_C^0 = (I_A^0 + I_B^0 + I_C^0) = (\frac{R_{2a}}{Z_2} + \frac{R_{2a}^0 + jX_{2a}^0}{Z_2} + \frac{R_{2a} + jX_{2a}}{Z_2})
\]

(3)

According to Figure 1, the corresponding positive sequence impedance and negative sequence impedance can be calculated:

\[
Z^+ = Z_i + \frac{R_{2a}^0 + jX_{2a}^0}{Z_2}, \quad Z^- = Z_i + \frac{R_{2a}^0 + jX_{2a}^0}{Z_2} \left( \frac{R'_{2a}^0 + jX'_{2a}^0}{2 - S} \right)
\]

(4)

From the above formula, the current of phase B can be obtained:

\[
I_B^0 = \frac{U_{BC}}{Z^+ + Z^-} = \frac{U_{BC}}{Z_i + \frac{R_{2a}^0 + jX_{2a}^0}{Z_2} + Z_i + \frac{R_{2a}^0 + jX_{2a}^0}{Z_2} \left( \frac{R'_{2a}^0 + jX'_{2a}^0}{2 - S} \right)}
\]

(5)

The same is true for phase C current.
3. Modeling of Double Y Type Asynchronous Motor

3.1. Main parameters of motor

For a large-capacity asynchronous motor, when it is designed for normal three-phase connection, the voltage is higher, so the main insulation requirement of the stator coil is higher. A large slot current will cause the stator coil to be subjected to strong alternating electromagnetic, so the slot of the coil The parts and ends need to have a reliable fixing method to prevent damage to the motor caused by electromagnetic vibration. The use of double Y type is one of the effective methods to solve this problem.

![Double Y winding connection](image)

In this paper, a 10000KW three-phase asynchronous motor is studied. The main structural parameters of the motor are shown in Table 1.

| Parameter               | Value | Parameter               | Value |
|-------------------------|-------|-------------------------|-------|
| Rated voltage/KV        | 6.6   | Rated current/A         | 1006  |
| Rated power/KW          | 10000 | Rated speed/(r/min)     | 1493  |
| Power factor            | 0.89  | Motor efficiency        | 0.977 |
| Number of stator slots  | 84    | Stator diameter/mm      | 940   |
| Axial height/mm         | 863   | Winding connection      | 2Y    |

3.2. Simulation model establishment

According to the basic parameters and rated data of the motor, the motor body is geometrically modeled with ANSYS software, as shown in Figure 3. It consists of a stator core, a stator winding, a rotor core, a rotor squirrel cage bar and a non-magnetic shaft.

![Motor 2D model](image)
4. Finite element simulation experiment and analysis

4.1. Analysis of three-phase current characteristics when stator resistance is asymmetry

According to the above theory, the simulation analysis using ANSYS software assumes that the contact resistance under normal conditions is 0.0001 Ω, and the failure of the motor appears as an increase in contact resistance.

Suppose the contact resistance of phase C increases due to a certain fault, and the three-phase current waveforms when the other two phases are normal are as follows:

![Three-phase current waveform when the C-phase resistance is maximum](image)

The lack of phase operation of a three-phase induction motor is actually the extreme case of asymmetrical operation of the motor. For the state before the phase failure of the three-phase asynchronous motor, the contact resistance of the faulty branch changes continuously with temperature changes, and the resistance of the stator winding is not Symmetrical, so it cannot be analyzed by the symmetrical component method.

In order to facilitate the analysis, the external circuit diagram is simplified as the following figure 5:

![Simplified diagram of external circuit](image)

It is assumed (for some reason) that the phase B resistance is relatively large. Set a three-phase symmetric power supply:

\[
\begin{align*}
\mathbf{t}_A^* &= U \angle 0^\circ \\
\mathbf{t}_B^* &= U \angle 120^\circ \\
\mathbf{t}_C^* &= U \angle -120^\circ 
\end{align*}
\]

Three-phase asymmetric load impedance:

\[
\begin{align*}
Z_A &= a_A + jb_A \\
Z_B &= a_B + jb_B \\
Z_C &= a_C + jb_C
\end{align*}
\]

among them, \( a_A = a_C < a_B, b_A = b_B = b_C \). Because the motor power factor \( \lambda = \cos \phi = 0.89 \), So suppose:

\[
\frac{b_A}{a_A} = \tan \phi = 0.51, \phi = 27.13^\circ 
\]

The equation can be listed according to the node voltage method:
\[
\left( \frac{1}{Z_A} + \frac{1}{Z_B} + \frac{1}{Z_C} \right) t_{AN'} = \frac{t_{AN}}{Z_A} + \frac{t_{BN}}{Z_B} + \frac{t_{CN}}{Z_C}
\]

From Figure 5:

\[
\begin{align*}
t_{AN'} &= t_{AN} + t_{AN'} = U \angle 0^\circ \\
t_{BN'} &= t_{BN} + t_{BN'} = U \angle 120^\circ \\
t_{CN'} &= t_{CN} + t_{CN'} = U \angle -120^\circ
\end{align*}
\]

So three-phase current can be obtained:

\[
\begin{align*}
&\frac{t_{AN}}{Z_A} = \frac{t_{AN}}{Z_A} = a + jb_A \\
&\frac{t_{BN}}{Z_B} = \frac{t_{BN}}{Z_B} = a + jb_B \\
&\frac{t_{CN}}{Z_C} = \frac{t_{CN}}{Z_C} = a + jb_C
\end{align*}
\]

According to the parallelogram method as figure 6, the phase range is \( t_{AN'} \in (-150^\circ + \varphi, -60^\circ - \varphi + \varphi_1) \).

Figure 6. Stator three-phase current under impedance asymmetry fault.

The phase resistance of A phase is increased, the other two phases are normal, and the phase resistance of B phase is increased. The normal current analysis of the other two phases is the same as above.
Figure 7. Three-phase current waveform when the resistance of phase A and phase B is the largest
It can be seen from this that the current abnormality is a process of mutual influence and cyclic amplification. The above calculation can deduce that phase B resistance is large → phase C current is large → (caused by heating) phase C resistance is large → phase A current is large → (caused by heating) B phase resistance is large → next round.

4.2. The influence of stator resistance asymmetry rate on current
Taking "A phase resistance is the largest, B phase second, and C phase normal" as an example, the influence of the asymmetry rate of the stator resistance on the current is introduced, and the asymmetry rate $\gamma_R$ of the stator resistance is defined, and its expression is: $\gamma_R = R / R_s$

R is the phase resistance of the faulty phase, and $R_s$ is the phase resistance in the normal state. Here, taking the stator winding A phase and B phase failure, C phase is normal as an example, according to the definition, the asymmetry rate of the A-phase resistance and the asymmetry rate of the B-phase resistance:

$$\gamma_{R,A} = R_A / R_s \quad \gamma_{R,B} = R_B / R_s$$  \hspace{1cm} (11)

Through simulation, the above results are expressed in vectors:

$$\gamma_{R,A} = 25, \gamma_{R,B} = 5 \quad \gamma_{R,A} = 100, \gamma_{R,B} = 10 \quad \gamma_{R,A} = 400, \gamma_{R,B} = 20$$

Figure 8. Stator three-phase current in case of asymmetric resistance

The above simulation experiment can intuitively draw the following conclusions: when the three-phase stator resistance is asymmetrical, the phase angle and amplitude of the three-phase current are asymmetrical, and as the stator resistance asymmetry rate increases, the phase angle of the three-phase current The degree of asymmetry with amplitude will increase accordingly. In the actual production of the motor, when the fault situation is unknown, the fault situation can be judged by measuring the effective value of the three-phase current and its change trend.

References
[1] Fang Fang, Yang Shi yuan, Hou Xinguo, Wu Zhengguo. Application of Parker Vector Rotation Transformation in Induction Motor Stator Fault Diagnosis[J]. Proceedings of the Chinese Society of Electrical Engineering, 2009, 29(12): 99-103.
[2] Pang Shi qiu. Three-phase asynchronous motor open circuit fault and its detection[J]. Shandong Coal Science and Technology, 2009(03): 57-58.

[3] Li Li, Li Ping, Jin Fu jiang, Peng Yan. Fault model of asymmetric stator impedance of three-phase asynchronous motor with no load[J]. Journal of Huaqiao University (Natural Science Edition), 2018, 39(01): 139-145.

[4] Sun Li ling, Li Heming, Xu Boqiang, Internal Fault Transient Process of Asynchronous Motor Based on Multi-loop Mathematical Model[J]. Automation of Electric Power Systems, 2004(23): 35-40+75.

[5] Ma Hongzhong, Zhang Zhiyan, Zhang Zhixin, Qian Yayun. Research on Fault Diagnosis of Stator Interturn Short Circuit of Doubly-fed Asynchronous Generator[J]. Journal of Electrical Machines and Control, 2011, 15(11): 50-54.

[6] Q. Wu and S. Nandi, "Fast Single-Turn Sensitive Stator Inter-Turn Fault Detection of Induction Machines Based on Positive and Negative Sequence Third Harmonic Components of Line Currents," 2008 IEEE Industry Applications Society Annual Meeting, Edmonton, AB, 2008, pp. 1-8, doi: 10.1109/08IAS.2008.25.

[7] M. Arkan, D. Kostic-Perovic, P. J. Unsworth. Modeling and simulation of induction motors with inter-turn faults for diagnostics[J]. Electric Power Systems Research, 2015, 75(1): 57-66

[8] V. Devanneaux, B. Dagues, J. Faucher, et al. An accurate model of squirrel cage induction machines under stator faults[J]. Mathematics and Computers in Simulation, 2003, 63(3): 377-391