Fault Diagnosis of Rotating Rectifier Based on Harmonic Features

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Abstract. Theoretical analysis of the rotating rectifier commutation process was described and the influence by the commutation reactance during commutation process was detailed. The harmonic content of the exciter current was quantitative analyzed when the rotating rectifier in the normal operating mode, the open circuit fault mode and the short circuit fault mode. Moreover, this feature is used as the basis for fault diagnosis of the rotating rectifier. The results which were verified by simulation and experiments show that the harmonic content of the exciter current can be used as a basis of the fault detection of the rotating rectifier.

1. Introduction
Rotating rectifier is an important component part of the brushless motor. The detection and diagnosis about the condition of the rotating rectifier are significant to ensure the safe operation of the brushless motor. When the brushless motor is running, the armature current of the exciter induces the harmonic current in the exciting current of the exciter through magnetic coupling. The analysis of the electromagnetic coupling process is the foundation of the rotating rectifier fault diagnosis [1-2]. The existing literature on the harmonic content of the exciter current, when rotating rectifier on fault state, is more on direct verification by simulation or experiments and few on quantitative analysis. This paper makes fast and accurate judgments on the fault diagnosis of the rotating rectifier, through the quantitative analysis on the harmonic content of the exciter current when the rotating rectifier in the normal operating mode, the open circuit fault mode and the short circuit fault mode

2. Commutation process analysis

2.1. Analysis on commutation reactance influence
The excitation system of brushless motor is equivalent to the simplified circuit in Figure 1.
The field winding of the main generator is equivalent to a high-inductive load on the DC side of the rotating rectifier. The idealized assumptions on Figure 1 are as follows [3-7]:

- The AC side of the rotating rectifier could induct three-phase symmetrical AC voltage, which is expressed as:

\[
\begin{align*}
    e_A &= \sqrt{2}V_m \cos(\omega t + \alpha) \\
    e_B &= \sqrt{2}V_m \cos(\omega t + \alpha - 2\pi/3) \\
    e_C &= \sqrt{2}V_m \cos(\omega t + \alpha + 2\pi/3)
\end{align*}
\]  

(1)

- The output current of the rotating rectifier is DC current.
- The armature winding resistance and the forward voltage drop of the diodes are ignored.

On the General operating condition, the rotating rectifier can be divided into three operating modes according to the number of the conductive diodes [8-10].

- Conduction mode: There are two conductive diodes of the rectifier bridge.
- Commutation Mode: There are three conductive diodes of the rectifier bridge.
- Short-circuit mode: There are more than three conductive diodes of the rectifier bridge and AC-side is in three-phase short-circuit state.

The commutating reactance of the rotating rectifier is expressed as: \( x_i = (x_{q_i} + x_{d_i})/2 \). Where: \( x_{q_i} \) ----the super-transient reactance of the exciter q-axis, \( x_{d_i} \) ----the super-transient reactance of the exciter d-axis. The commutation overlap angle being influenced by commutation reactance size can be calculated. The results are:

- When the commutation reactance is small, the commutation overlap angle: \( 0 < \theta \leq \pi/3 \) and commutation delay angle: \( \alpha = 0 \).
- If we increase commutation reactance, commutation overlap angle: \( \theta = \pi/3 \) and Commutation delay angle: \( 0 \leq \alpha < \pi/6 \).
- If we continue to increase the commutation reactance, commutation overlap angle: \( \pi/3 \leq \theta \leq 2\pi/3 \) and Commutation delay angle: \( \alpha = \pi/6 \).

2.2. Analysis on commutation reactance threshold

When the commutation of the rotating rectifier overlap angle: \( \theta = \pi/3 \), the three-phase armature winding current and voltage analysis are as follows:

For phase A current, when \( \omega t = 0 \), diode D1, diode D4, diode D6 are in conductive state, as shown in Figure 2 (a), the current commutation process is from phase B to phase C. When \( \omega t = \pi/3 \), phase B and phase C commutation process ends, as shown in Figure 2 (b) below.
It is calculated:  
\[ \omega t = [0, \pi / 3] : \]

\[ i_B = -[1 + \cos \omega t - \cos \alpha] I_d \sin(\alpha + \pi / 6) \]

\[ i_C = [\cos \omega t - \cos \alpha] I_d \sin(\alpha + \pi / 6) \]  \hspace{1cm} (2)

Ignoring the diode voltage drop, the average load DC voltage is calculated as follows:

\[ U_d = \frac{3}{\pi} \int_0^\pi U_{AB} d\omega t = \frac{9\sqrt{2}V_m}{2\pi} \cos(\alpha + \pi / 6) \]

\[ U_d = R_d I_d \]  \hspace{1cm} (3)

\[ \cos(\alpha + \pi / 6) = \frac{2\pi R_d I_d}{9\sqrt{2}V_m} \]

After simplification:

\[ I_d \approx \frac{9\sqrt{2}V_m}{2\pi} \left(\frac{1}{2\pi} \sqrt{R_d^2 + \frac{27x_i^2}{\pi^2}}\right) \]

\[ \sin(\alpha) \approx \frac{9x_i}{\pi} \frac{R_d}{\sqrt{2\pi} \left(\frac{1}{2\pi} \sqrt{R_d^2 + \frac{27x_i^2}{\pi^2}}\right)} \]  \hspace{1cm} (4)

When the commutation overlap angle  \[ \theta = \pi / 3 \], accordingly, the commutation delay angle  \[ 0 \leq \alpha < \pi / 6 \], it obtains the corresponding commutation reactance:  \[ \pi R_d / 9 \leq x \leq \pi R_d / 3 \]. Therefore, when the commutation reactance  \[ x \leq \pi R / 9 \], it can get rectifier commutation overlap angle  \[ 0 < \theta \leq \pi / 3 \] and commutation delay angle  \[ \alpha = 0 \]; when  \[ x \geq \pi R_d / 3 \], it can get rectifier commutation overlap angle  \[ \pi / 3 \leq \theta \leq 2\pi / 3 \] and the commutation delay angle  \[ \alpha = \pi / 6 \).

Because the symmetrical three-phase current, the current waveform of phase B and phase C are the same with phase A and their phases have  \[ \pi / 3 \] degrees respectively leading and lagging.

3. Analysis on harmonic content of excitation current

3.1. Analysis on the harmonic content of the excitation current in general condition

It is assumed that there is a brushless excitation generator with rated frequency of 50 Hz. It can be calculated that the commutation reactance of the rotating rectifier  \[ x_i = 0.34 \] by the exciter parameters. The main generator field winding impedance can be equivalent to a large inductance connecting the resistance of 0.77Ω in series. The effective value of the exciter output voltage  \[ V_e = 346V \]. The commutation overlap angle of the rotating rectifier  \[ \theta = \pi / 3 \]. Through the analysis, the three-phase current of the rotating rectifier is solved and the Fourier transform is performed as follows:
\[ i_A = \frac{6\sqrt{3}}{\pi^2} I_d \{ \cos \omega t - \frac{1}{25} \cos 5\omega t - \frac{1}{49} \cos 7\omega t + \frac{1}{121} \cos 11\omega t \} \]

\[ i_B = \frac{6\sqrt{3}}{\pi^2} I_d \{ \cos(\omega t - \frac{2\pi}{3}) - \frac{1}{25} \cos(5\omega t + \frac{2\pi}{3}) - \frac{1}{49} \cos(7\omega t - \frac{2\pi}{3}) + \frac{1}{121} \cos 11(\omega t + \frac{2\pi}{3}) \} \]  \( (5) \)

\[ i_C = \frac{6\sqrt{3}}{\pi^2} I_d \{ \cos(\omega t + \frac{2\pi}{3}) - \frac{1}{25} \cos(5\omega t - \frac{2\pi}{3}) - \frac{1}{49} \cos(7\omega t + \frac{2\pi}{3}) + \frac{1}{121} \cos 11(\omega t - \frac{2\pi}{3}) \} \]

According to the generator excitation voltage mathematical equation:

\[ U_{\mu} = \frac{d(M_{fda}i_A + M_{fbd}i_B + M_{fcd}i_C)}{dt} + \frac{d(L_{fda}i_{fda})}{dt} + \frac{d(M_{fda}i_{fda})}{dt} + r_{fda}i_{fda} \]  \( (6) \)

Where: \( U_{\mu} \) ---- the excitation voltage of the exciter; \( i_A \) ----the excitation current of the exciter; \( r_{fda} \) ----the field winding resistance of the exciter; \( M_{fda}, M_{fbd}, M_{fcd}, M_{fda}, L_{fda} \) respectively represent the mutual inductance of the three-phase windings of A, B and C, the mutual inductance of the field winding to the direct-axis damping winding and the self-inductance of the field winding.

Solving the generator mathematical equation can get the excitation current \( i_{fda} \) containing DC component and k-th (k=6n; n=1, 2, 3...) harmonic component. The harmonic content is approximately calculated as follows: \( M_{fda}, M_{fbd}, M_{fcd}, M_{fda}, L_{fda} \)

\[ i_{fda6} \approx -\frac{6\sqrt{3}}{\pi^2} I_d M_{fda} \left( \frac{3}{50} + \frac{3}{98} \right) \cos 6\omega t / L_{fda} \]

\[ i_{fda12} \approx \frac{6\sqrt{3}}{\pi^2} I_d M_{fda} \left( \frac{3}{242} + \frac{3}{338} \right) \cos 12\omega t / L_{fda} \]  \( (7) \)

\[ i_{fda18} \approx -\frac{6\sqrt{3}}{\pi^2} I_d M_{fda} \left( \frac{3}{578} + \frac{3}{722} \right) \cos 18\omega t / L_{fda} \]

It can obtain that when the rotating rectifier operating in general conditions, the amplitude of the 6th degree harmonic is the largest in the harmonic current of the excitation current.

3.2. Analysis on the harmonic content of the exciting current in open circuit fault

If \( \text{No.1} \) diode of the rotating rectifier open circuit, it can approximate that the output voltage of exciter is still symmetrical three-phase voltage by the damper winding effect of the motor. The phase change is analysed as follows:

When \( \omega t = 0 \), rotating rectifier is equivalent to single-phase bridge rectifier circuit, and phase B, phase C current conduct short-circuit commutation. Since \( \pi / 9 \leq \theta / R_d \leq \pi / 3 \), so the commutation angle \( \theta / R_d \leq 2\pi / 3 \).

When \( \omega t = [\theta, 2\pi / 3] \), No.2 and No.3 diodes are in the conductive mode.

When \( \omega t = [2\pi / 3, \pi] \), the commutation angle \( \theta < \pi / 3 \). During \( \omega t = [2\pi / 3, 2\pi / 3 + \theta] \), Rotating rectifier operates in commutation mode; During \( \omega t = [2\pi / 3 + \theta, \pi] \), Rotating rectifier operates in the conductive mode.

When \( \omega t = [\pi, 4\pi / 3] \) and \( \omega t = [4\pi / 3, 5\pi / 3] \), the commutation process of rotating rectifier is similar to when \( \omega t = [2\pi / 3, \pi] \).

When \( \omega t = [5\pi / 3, 2\pi] \), the rectifier commutates in conductive mode.

According to analysis of a cycle of commutation process, it can obtain that:
The three-phase input current of the rotating rectifier under the open-circuit fault is Fourier-transformed. Then take the transformation results into the generator mathematical model. The harmonic content of excitation current is obtained:

\[
U = \frac{1}{2\pi} \int_0^{2\pi} U d\omega t = R_d I_d
\]

\[
I_d = \frac{5\sqrt{6}V_m}{2\pi R_d + 7x} = 588A
\]

\[
\theta_1 = \arccos(1 - \frac{4I_d x}{\sqrt{6}V_m}) \approx 87^\circ
\]

\[
\theta_2 = \arccos(1 - \frac{2I_d x}{\sqrt{6}V_m}) \approx 58^\circ
\]

The three-phase input current of the rotating rectifier under the open-circuit fault is Fourier-transformed. Then take the transformation results into the generator mathematical model. The harmonic content of excitation current is obtained:

\[
i_{d1} = 0.65 I_d M_{a/d0} \cos(\omega t) / L_{fld};
\]

\[
i_{d2} = I_d M_{a/d0} \cos(2\omega t + \pi/4) / 2L_{fbd} k_{fd};
\]

\[
i_{d3} = 0.25 I_d M_{a/d0} \cos(3\omega t + 4\pi/9) / L_{fd};
\]

\[
i_{d4} = -0.02 I_d M_{a/d0} \cos(4\omega t - 5\pi/18) / L_{fbd}
\]

Therefore, when the rotating rectifier in a single diode open case, the harmonic content of excitation current is characterized that the amplitude of the first harmonic is the largest In the harmonic current of the excitation current, and the amplitude of Second harmonic, the amplitude of third harmonic amplitude, the amplitude of fourth harmonic corresponding to the ratio of the amplitude of the first harmonic as follows: \(i_{d1} = 0.77\); \(i_{d2} = 0.39\); \(i_{d3} = 0.03\).

3.3. Analysis on the harmonic content of the excitation current in short circuit fault

When the No. 1 diode of rotating rectifier is short-circuit, the effect of the armature resistance can be ignored because the commutation reactance is much larger than the armature resistance. To highlight the main contradiction, when one diode short-circuit, it approximate that the waveform of armature winding current is the three-phase sine wave. On the basis of neglecting the armature resistance and the DC side current of the rotating rectifier. It Consider that phase A winding has only negative current flowing, and phase B, phase C winding have only forward current. The simplified circuit is shown in Figure 3.

\[\text{Figure 3. The simplified circuit of rotating rectifier under short fault mode} \]

The AC components \(i'_A, i'_B, i'_C\) of Three-phase current meet:
\[
\begin{align*}
\left\{ \begin{array}{l}
e_B - e_A &= x_i \frac{di_A'}{dt} - x_i \frac{di_B'}{dt} \\
e_C - e_A &= x_i \frac{di_A'}{dt} - x_i \frac{di_C'}{dt} \\
e_C - e_B &= x_i \frac{di_B'}{dt} - x_i \frac{di_C'}{dt} 
\end{array} \right. \\
\end{align*}
\]

(10)

Obtained:

\[
\begin{align*}
i_A' &= \frac{\sqrt{2}V \cos \omega t}{x_i} \\
i_B' &= \frac{\sqrt{2}V \cos(\omega t - 2\pi/3)}{x_i} \\
i_C' &= \frac{\sqrt{2}V \cos(\omega t + 2\pi/3)}{x_i}
\end{align*}
\]

(11)

And the DC component of the three-phase current are obtained:

\[
i''_A = \frac{-2\sqrt{2}V_m}{x_i} ; \quad i''_B = \frac{\sqrt{2}V_m}{x_i} ; \quad i''_C = \frac{\sqrt{2}V_m}{x_i}
\]

The obtained three-phase current expression is substituted into the mathematical equation of motor, and it can get that the excitation current of the exciter is mainly composed of the DC component \(i_{fd0}\) and the first harmonic component \(i_{fd1}\) as follows:

\[
\begin{align*}
i_{fd0} &= I_{dc} = \frac{U_{ald}k_{ald}}{r_{ald}k_{ald}} \\
i_{fd1} &\approx \frac{3\sqrt{2}M_{ald0}V_m}{x_iL_f k_{ald}} \sin(\omega t)
\end{align*}
\]

(12)

It can considere that the excitation current of the exciter mainly contains the DC component and the first harmonic content when the rotating rectifier in a short-circuit fault.

4. Verification by simulation and experiment

The simulation model brushless excitation generator is built in the Matlab shown in Figure 4.

Figure 4. Simulation model of the exciting system
The rotating rectifier under general operating condition, open circuit condition and short circuit condition is researched by simulation and experiment, and the corresponding excitation current is acquired. The harmonic analysis and contrast on the excitation current waveform of Simulation and experiment are shown in Figure 5.

(a) Excitation current waveforms of simulation and experiment under general operating condition
(b) Excitation current waveforms of simulation and experiment under open circuit condition
(c) Excitation current waveforms of simulation and experimental under short circuit condition

Figure 5. The excitation current comparison of simulation and experiment

The results of simulation and experiment on the harmonic content of excitation current Under different conditions have little difference with the theoretical analysis, which can prove that the quantitative analysis on the harmonic content of the excitation current of the exciter was correct, and the feasibility of using harmonic content of the excitation current as a basis for fault diagnosis of rotating rectifier is also verified.
5. Conclusion
In this paper, the commutation process of rotating rectifier under general operating condition, open circuit condition and short circuit condition are analysed, and the different harmonic content of the exciting current of the exciter under these three conditions are obtained quantitatively by theoretical analysis, simulation and experiment. It can get that the harmonic content of the exciting current have corresponding characteristics when the rotating rectifier in different conditions. Therefore, the harmonic content of excitation current of the exciter can be used as the fault diagnosis basis, which can improve the rapidity and accuracy of the fault diagnosis of the rotating rectifier.

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