Analysis of Permanent Magnet Synchronous Machine Tooth Flux
Under Eccentricity Fault

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Abstract. Eccentricity fault is a common fault of permanent magnet synchronous machines. It is hard to repair the fault efficiently if it is not diagnosed accurately. This paper presents a quantitative analysis of tooth flux with eccentricity fault based on co-simulation. Moreover, set up an experiment platform to validate the analysis. The analysis result reflects quantitative relationship of the eccentricity ratio and the tooth fluxes. It is helpful for improving the accuracy of the eccentricity diagnosis based on the tooth flux and the reliability of PMSMs.

Introduction

Permanent magnet synchronous machines (PMSMs) are widely used because of their advantages, which include small volume, lightweight, high efficiency, and high reliability [1, 2]. Eccentricity fault is a common fault of PMSMs. Generally, an eccentricity fault is caused by an unbalanced load, coupling misalignment, inappropriate assembly, and bent rotor shaft [3]. Eccentricity causes mechanical and electromagnetic vibration sources because of the increased unbalance in the air gap [4, 5]. If a PMSM operates with eccentricity for a long time, then it may cause bearing fault, short circuit, or demagnetization fault [6, 7] and eventually shutdown the entire driving system. Analysis of the tooth flux reveals the quantitative relationship between tooth flux and eccentricity. It is helpful for improving the accuracy of the eccentricity diagnosis based on the tooth flux and the reliability of PMSMs.

Basics of Eccentricity Fault

For a healthy PMSM, the geometric center of the stator and rotor must be at the same position. If not, an eccentricity exists in the PMSM. The eccentricity can be static, which means the rotation center of the rotor is fixed; and it also can be dynamic, which means the rotation center of the rotor also rotates around the stator center.

The eccentricity ratio can be defined as follow [13]; it describes the eccentricity fault quantitatively.
\[ \vec{E} = \frac{\vec{\varepsilon}}{l_{g0}}, \]  

(1)

where \( \vec{\varepsilon} \) is the vector form of stator center to rotor center and \( l_{g0} \) is the uniform air gap length.

The air gap length with eccentricity fault can be calculated as [9]

\[ l_{ge}(\theta) = r_s - l_{g0} \left| \frac{\vec{E}}{l_{g0}} \right| \cos(\theta - \varphi) - \sqrt{r_r^2 - \left| \frac{\vec{E}}{l_{g0}} \right|^2 r_s^2 \sin^2(\theta - \varphi)}, \]  

(2)

where \( \theta \) is the angular position around the air gap, \( r_s \) is the stator inner radius, \( r_r \) is the rotor outer radius, and \( \varphi \) is the orientation angle of \( \vec{E} \).

For PMSM, \( r_s \) and \( r_r \) are much larger than \( l_{g0} \). Therefore, Equation (2) can be approximated as

\[ l_{ge}(\theta) \approx r_s - l_{g0} \left| \frac{\vec{E}}{l_{g0}} \right| \cos(\theta - \varphi) - r_r \left[ 1 - \left( \frac{\vec{E}}{l_{g0}} \right) \cos(\theta - \varphi) \right]. \]  

(3)

The above equation shows that the air gap length distribution is almost a sine wave.

Co-simulation Model of Eccentricity Fault

In order to calculate the tooth flux accurately, the magnetic field distribution, material nonlinearity and controller must be considered in the simulation. A co-simulation of Maxwell, Simplorer and Simulink is adopted. The connections between the softwares and the model of each software are shown in Fig.1 and Fig2.

![Connections between softwares](image)

**Figure 1.** The connections between the softwares.

![Simulation models](image)

**Figure 2.** The simulation models, (a) the FE model of the adopted motor in Maxwell, (b) the model of the motor circuit and the inverter in Simplorer, (c) the model of the controller in Simulink.

The eccentricity fault must be set in the co-simulation to calculate the tooth flux with eccentricity. The rotation condition in Maxwell in shown in Fig.3 (a). The region within the rotation boundary rotates. According to the principle of rotation condition, the eccentricity can be set as follows:

1) Static eccentricity: keep the rotor and the rotation center, move the stator, as shown in Fig.3 (b).
2) Dynamic eccentricity: keep the stator and the rotation center, move the rotor, as shown in Fig.3 (c).

![Rotation conditions](image)

**Figure 3.** The rotation conditions, (a) healthy, (b) static eccentricity, (c) dynamic eccentricity.
Analysis of the Simulation Results

The time variation of tooth flux at healthy and eccentricity conditions are shown in Fig.4. Because the time variation of each tooth is almost the same, only flux on one tooth is analyzed. Fig.4 shows that the tooth flux at healthy condition is a sine wave with a constant amplitude. Tooth flux with static eccentric is also a sine wave with a constant amplitude but its amplitude is changed because of the fault. Tooth flux with dynamic eccentric is a sine wave but its amplitude varies with time. The analysis shows that the time variation of tooth flux can distinguish the type of the eccentricity.

![Figure 4. Time variation of tooth flux, (a) healthy, (b) static eccentricity, (c) dynamic eccentricity.](image)

The distribution of tooth flux amplitude differences is shown in Fig.5. The results are the difference of tooth flux amplitude between healthy motor and eccentricity motor. Fig.5. shows that the tooth flux difference is almost a sine wave with an eccentricity fault. This is because the eccentricity makes the air gap distribution like a sine wave. The relationship between the magnitude of $\bar{E}$ ($|\bar{E}|$) and the amplitude of the tooth flux differences (ATFD) are shown in Fig.6.

![Figure 5. The distribution of tooth flux amplitude differences](image)  Figure 6. The relationship between $|\bar{E}|$ and ATFD.

When $|\bar{E}|$ increases from 0.2 to 0.8, ATFD of the static eccentricity increases from 5.0×10^{-5}Wb to 1.93×10^{-4}Wb and ATFD of the dynamic eccentricity increases from 4.8×10^{-5}Wb to 1.89×10^{-4}Wb. ATFD of the static eccentricity and the dynamic eccentricity is almost the same with same $|\bar{E}|$. ATFD increases with $|\bar{E}|$ linearly. The ratio of ATFD to $|\bar{E}|$ ($R_{ATFD}$) is a constant and $R_{ATFD} = 2.5×10^{-4}$ for the adopted motor. The analysis shows that the ATFD can reflect $|\bar{E}|$, and the tooth flux can be used to identify the severity of the eccentricity fault.

Experiment Validation

An experimental platform is established to verify the analysis (Fig.7(a)). Search coils are used to monitor the tooth fluxes. Two Art-control USB-2881 DAQs are adopted for searching coil-induced voltage measuring. The eccentricity faults are set by installing the end cover eccentrically. The longest and shortest air gaps are shown in Fig. 7(b).
Figure 7. The eccentricity experiment, (a) the experimental platform, (b) air gap with the experimental eccentricity.

The experiment result of tooth flux amplitude differences is shown in Fig.9, the relationship between ATFD and $E$ are shown in Table 1. Fig.9 shows that the distributions of tooth flux amplitude differences are almost sine waves. Table 1 shows $R_{ATFD}$ for the both fault is $2.62 \times 10^{-4}$ and $2.58 \times 10^{-4}$, the relative error between the experiment results and the simulation result is about 5% and 3%. The error is reasonable and the experiment validates the correctness of simulation analysis.

![Figure 8. The experiment result of tooth flux amplitude differences.](image)

Table 1. Table headings.

| Fault No. | Set value of $E$ (Wb) | ATFD (Wb) | $R_{ATFD}$ |
|-----------|-----------------------|-----------|------------|
| 1         | 0.35                  | 9.16×$10^{-5}$ | 2.62×$10^{-4}$ |
| 2         | 0.4                   | 1.03×$10^{-4}$ | 2.58×$10^{-4}$ |

Conclusions

This paper set up a co-simulation for a PMSM and its control system with eccentricity fault. The tooth flux of the PMSM is analyzed by simulation. An experiment platform is set up and validates the analysis results. The analysis shows that the time variation and the distribution of the tooth flux can reflect the type of the eccentricity. Besides, the influence of the eccentricity on the tooth flux increases with the eccentricity ratio linearly. In addition, the ratio of them is a constant. By applying the analysis result, the diagnosis methods based on too flux can be more effective to identify the type and the severity of eccentricity fault.

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