Study on Inter-turn Fault Diagnosis of the Six-Phase Interior Permanent Magnet Synchronous Motor Using d-Axis Current

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Background

In this paper, the performance of the inter-turn fault diagnosis of a six-phase interior permanent magnet synchronous motor (IPMSM) was analyzed through d-axis current using finite element analysis (FEA). The high-frequency injection method was used to perform fault diagnosis with a current response before and after a fault. To obtain the response of the current versus the applied voltage, the voltage equation of the six-phase IPMSM was obtained for the occurrence of the inter-turn fault. In addition, the dq-axis current responses in the healthy and faulty conditions were derived from the voltage equations. Furthermore, since the response of the current is a function of the magnitude and frequency of the voltage, the performance of the fault diagnosis was determined from the magnitude and frequency of the applied voltage. To verify this, the inter-turn fault diagnosis performance was analyzed through FEA and the control simulation tool. As a result, we proposed a voltage and frequency to maximize the inter-turn fault diagnosis performance of the six-phase IPMSM.

Mathematical Model for Inter-turn Fault Diagnosis

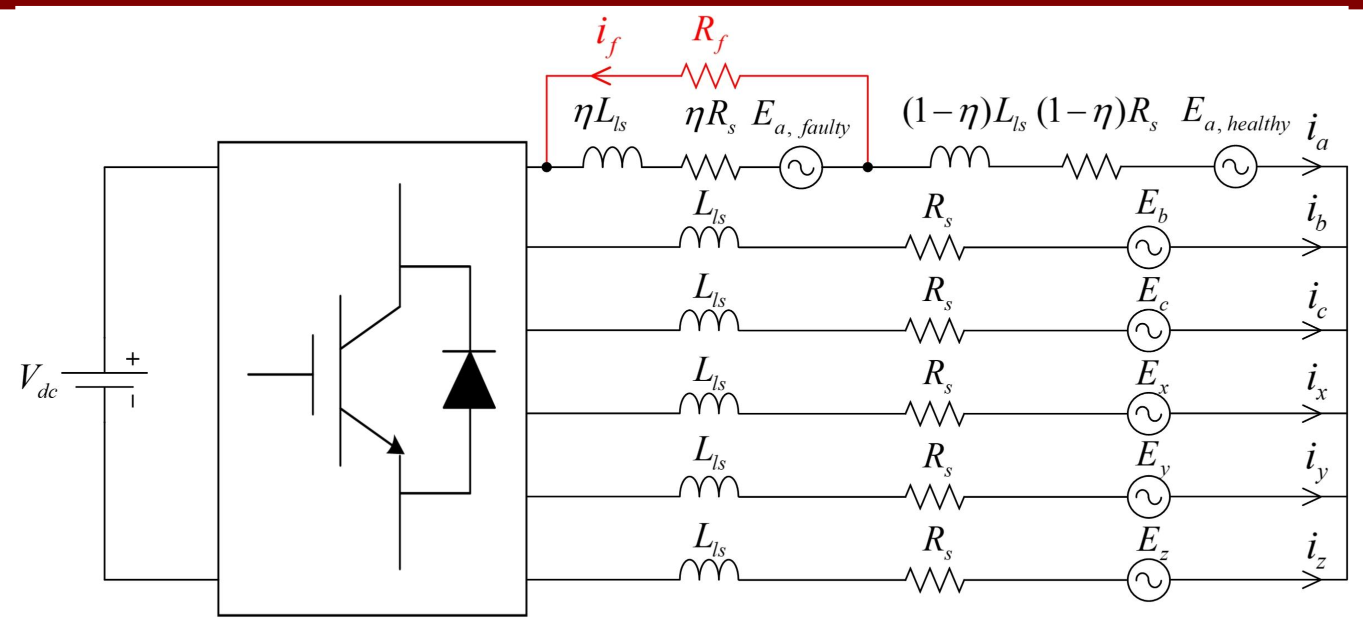

Fig 1. Configuration of the inter-turn fault

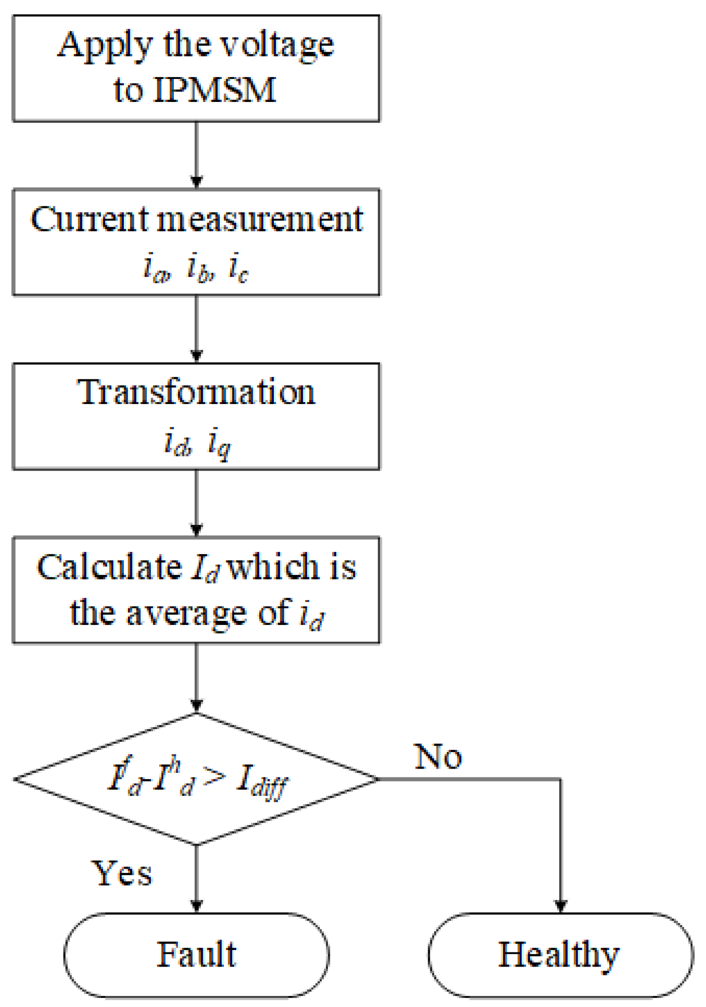

Fig 2. The algorithm of fault diagnosis using *d*-axis current

❖ The six-phase voltage equation

$$[u_{abcxyzf}]=[R_{abcxyzf}][i_{abcxyzf}]+\frac{d}{dt}\left([L_{abcxyzf}][i_{abcxyzf}]+[\lambda_{abcxyzf}]\right)$$

$$[u_{abcxyzf}]=[u_a-u_n,\ u_b-u_n,\ u_c-u_n, u_x-u_n,\ u_y-u_n,\ u_z-u_n,\ 0]^T$$

$$[i_{abcxyzf}]=[i_a,\ i_b,\ i_c, i_x, i_y, i_z, i_f]^T$$

$$[\lambda_{abcxyzf}]=[\lambda_a,\ \lambda_b,\ \lambda_c,\ \lambda_x, \lambda_y,\ \lambda_z,\ \eta\lambda_a]^T$$

$$[R_{abcf}]=\begin{bmatrix} R_s & 0 & 0 & 0 & 0 & 0 & \eta R_s \\ 0 & R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_s & 0 \\ \eta R_s & 0 & 0 & 0 & 0 & 0 & \eta R_s + R_f \end{bmatrix}$$

$$[L_{abcxyzf}]=\begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{ax} & L_{ay} & L_{az} & \eta L_{aa} \\ L_{ab} & L_{bb} & L_{bc} & L_{bx} & L_{by} & L_{bz} & \eta L_{ab} \\ L_{ac} & L_{bc} & L_{cc} & L_{cx} & L_{cy} & L_{cz} & \eta L_{ac} \\ L_{ax} & L_{bx} & L_{cx} & L_{xx} & L_{xy} & L_{xz} & \eta L_{ax} \\ L_{ay} & L_{by} & L_{cy} & L_{xy} & L_{yy} & L_{yz} & \eta L_{ay} \\ L_{az} & L_{bz} & L_{cz} & L_{xz} & L_{yz} & L_{zz} & \eta L_{az} \\ \eta L_{aa} & \eta L_{ab} & \eta L_{ac} & \eta L_{ax} & \eta L_{ay} & \eta L_{az} & \eta^2 L_{aa} \end{bmatrix}$$

❖ The *dq*-axis voltage equation

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix}=\begin{bmatrix} R_s+pL_d & -\omega L_q \\ \omega L_d & R_s+pL_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix}+\begin{bmatrix} 0 \\ \omega\lambda_f \end{bmatrix}+\frac{1}{3}\eta\begin{bmatrix} e_{df} \\ e_{qf} \end{bmatrix}$$

$$\begin{bmatrix} e_{df} \\ e_{qf} \end{bmatrix}=\begin{bmatrix} \eta R_s\cos\theta i_f+\eta L_d p(\cos\theta i_f)+\omega\eta L_q\sin\theta i_f \\ -\eta R_s\sin\theta i_f-\eta L_q p(\sin\theta i_f)+\omega\eta L_d\cos\theta i_f \end{bmatrix}$$

$$u_n=-\frac{1}{6}\eta R_s i_f-\frac{1}{6}\eta L_0\frac{di_f}{dt}+3\omega\lambda_{3h}\cos\frac{3}{2}\gamma\sin(3\theta+\frac{3}{2}\gamma)$$

❖ The d-axis current under healthy and fault condition

Average of dq-axis current is different!!

$$\begin{bmatrix} i'_{di} \\ i'_{qi} \end{bmatrix}=\begin{bmatrix} i_{di} \\ i_{qi} \end{bmatrix}+\frac{V_i}{2k_f}\begin{bmatrix} (a_f+d_f)+(a_f-d_f)\cos\omega_i t+(b_f+c_f)\sin\omega_i t \\ -(b_f-c_f)+(b_f+c_f)\cos\omega_i t-(a_f-d_f)\sin\omega_i t \end{bmatrix} \longrightarrow I^f_d-I^h_d=\frac{V_i}{2k_f}(a_f+d_f)$$

→ a_f, b_f, c_f, d_f is function of motor parameters which are **winding resistance**, ***dq*-axis inductance**, **fault resistance and input frequency**.
→ The performance of fault diagnosis is determined by motor parameters and input voltage..

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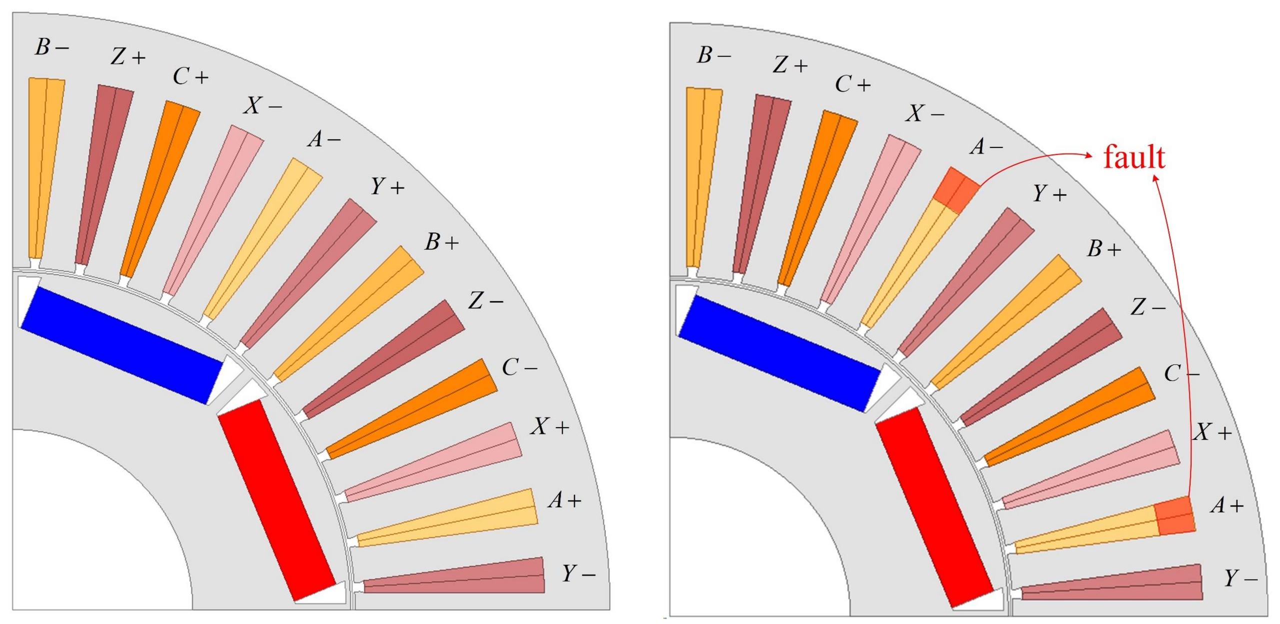
Conclusion

- ❖ The inter-turn fault diagnosis performance of the six-phase is analyzed through the d-axis current using co-analysis
- ❖ The d-axis current is analyzed through the mathematical model of six-phase IPMSM.
- ❖ The dc component d-axis current of healthy and faulty condition is different according input voltage.
- ❖ The magnitude and frequency of input voltage is determined the inter-turn fault diagnosis performance
- ❖ Therefore, we must select the ratio of magnitude and frequency of input voltage for inter-turn fault diagnosis.

Inter-turn Fault Diagnosis Using Co-analysis

- ❖ Figure 3 show the six-phase IPMSM model to perform the inter-turn fault diagnosis
- ❖ The input voltage is applied through the inverter model in Figure 4.
- ❖ The ratio of magnitude and frequency of input voltage is determined the inter-turn fault diagnosis performance in Figure 5.



(a) (b)

Fig 3. The FEA model (a) healthy condition (b) faulty condition

Content	Value	Unit
Pole/Slot combination	8/48	-
Stator diameter	254	mm
Rotor diameter	150	mm
Stack length	180	mm
Winding resistance	4.02	mΩ
d-axis inductance	1.22	mH
q-axis inductance	2	mH

Table 1. Specification of six-phase motor

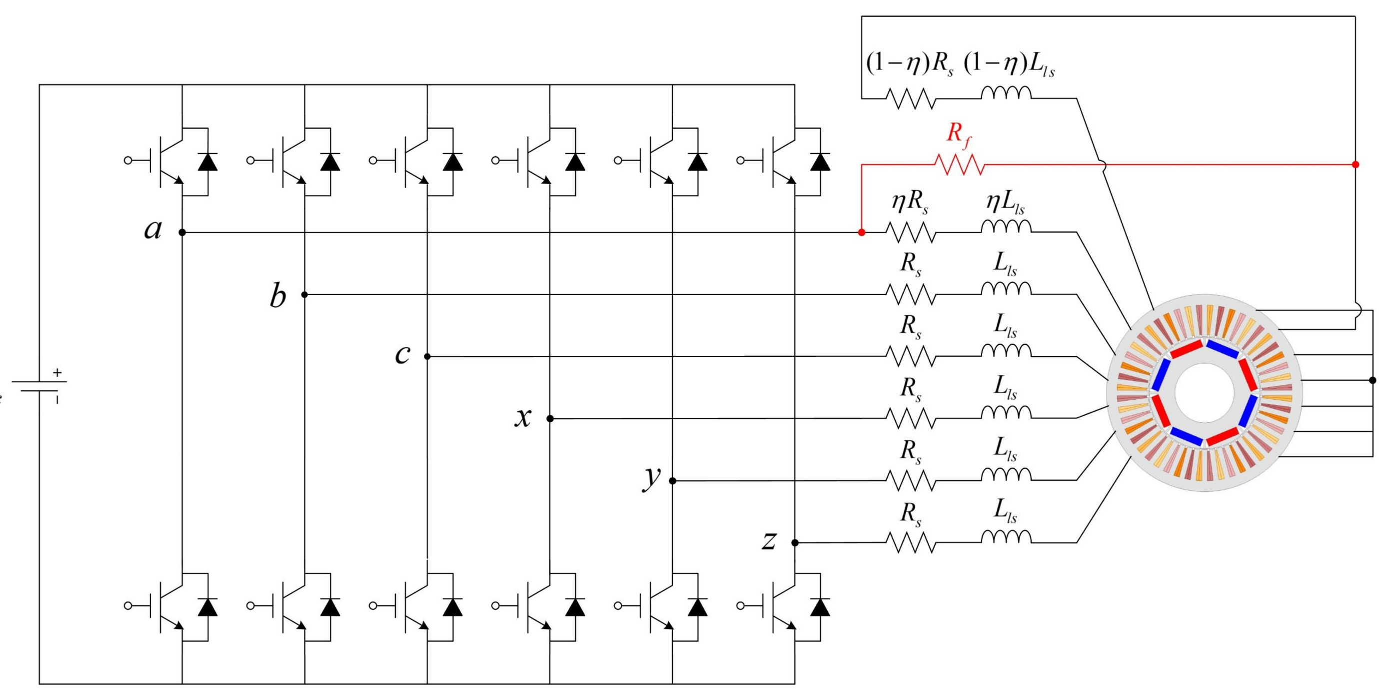


Fig 4. The Inverter model for co-analysis

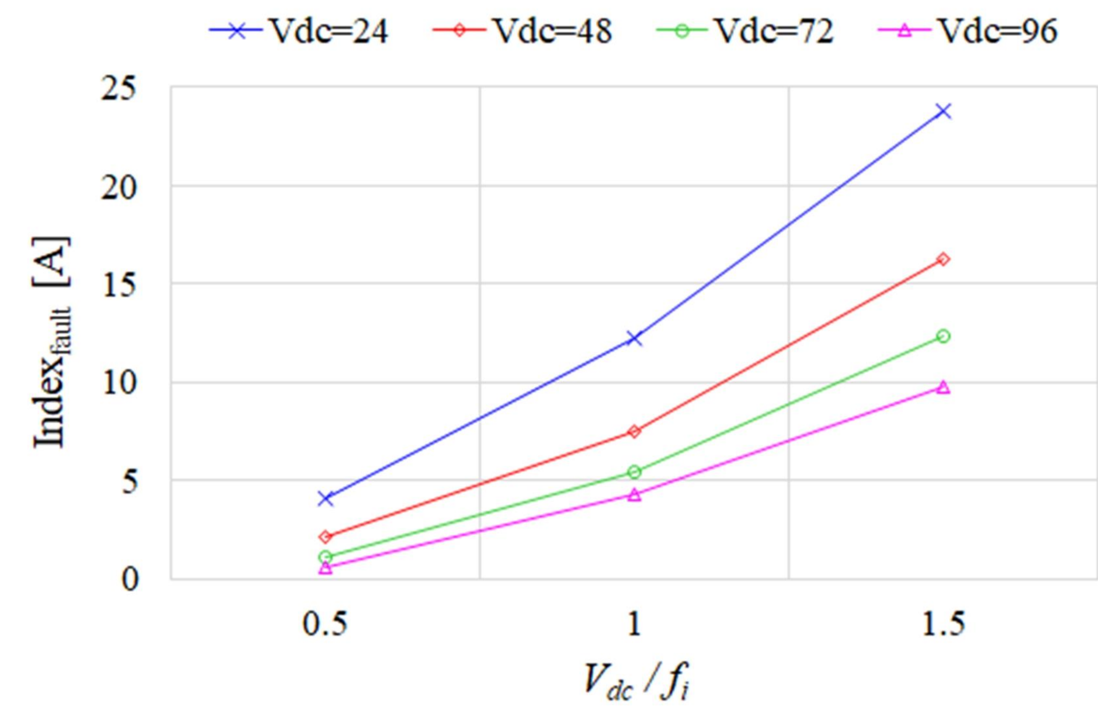


Fig 5. Analysis of $index_{fault}$ using co-analysis according to the ratio of dc-link voltage to the frequency of the applied voltage.

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