SURFACE MOUNTED PMSM STATOR WINDING FAULT MODELLING

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Abstract: This paper is focused on 3-phase permanent magnet synchronous motor (PMSM) modelling with open-phase fault and inter-turn short winding fault in one phase. Open phase is often result of an inter-turn short. Presented model is suitable for surface mounted PMSM type. Model with faults is built on SimScape Matlab/Simulink toolbox. According to stator winding asymmetry (caused by winding faults) stationary abc reference frame is used inside model. This model was developed for the fault detection algorithms and the state observers used with fault isolation mechanism to satisfy fault tolerant drive operation.

Keywords: Permanent magnet synchronous motor, open phase, short winding, Simulink model, mathematical model, SimScape

1 HEALTHY PMSM MODELLING

Permanent Magnet synchronous motor (PSMS) based drives are widely used nowadays in specific applications because of their efficiency and high power-to-weight ratio. High efficiency is related to rotor with negligible electrical looses. PMSM uses sinusoidally distributed stator windings, in contrast to the electrically commutated DC motors (brush-less). This allows torque waveform without ripples caused by cogging effect. This high dynamic and precise machines are used often in high reliable applications. In this kind of applications fault tolerant operation is often required. Unhealthy model is used for developing fault detection algorithms.

Presented model enables simulations of inter-turn stator winding shorts, which is caused by insulation failure. Insulation failures are connected with over temperature in winding during overloading. Open phase failure has often origin in connection problems or in an inter-turn shorts. Early winding fault detection raises up reliability of machine.

Rorot of the PMSM in steady state rotates at the same frequency as the revolving magnetic field. PMSM is non-linear system that can be described by differential equations. PMSM can be described in different reference frame point of view.

Two types of reference frames are usually used: Stationary (abc) and Rotating rotor frame (dq). In dq coordinates, all rotating quantities can be viewed as constants from reference frame that rotates synchronously with rotor in the steady state. This is used for Field oriented closed loop controllers (or Vector control). In unhealthy phase situation the abc reference frame model is suitable because of its validity under unbalanced phase condition.

Electrical part of healthy PMSM can be described by equation (1).

$$u_{abc} = R_{abc}i_{abc} + L_{abc}\frac{di_{abc}}{dt} + \frac{d\Psi_{mabc}}{dt} = R_{abc}i_{abc} + L_{abc}\frac{di_{abc}}{dt} + e_{abc} \tag{1}$$

where:

$$u_{abc} = \begin{bmatrix} u_a & u_b & u_c \end{bmatrix}^T \qquad R_{abc} = \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix}$$

$$i_{abc} = \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^T \qquad L_{abc} = \begin{bmatrix} L_S & M & M \\ M & L_S & M \\ M & M & L_S \end{bmatrix}$$

$$e_{abc} = \omega\Psi_m \begin{bmatrix} cos(\theta) \\ cos(\theta - \frac{2\pi}{3}) \\ cos(\theta + \frac{2\pi}{3}) \end{bmatrix}$$

e_{abc} denotes back electromotive force (back-EMF) voltage, which is linearly proportional to electrical angular velocity ω and magnetic flux of permanent magnets Ψ_m. In presented model, θ denotes electrical angle between stator phase a and quadrature rotor axes q. [1]

Mechanical part of healthy PMSM can be described by following equations:

$$\frac{d\omega}{dt} = \frac{1}{J} P_P [T_E - T_L] \tag{2}$$

$$\frac{d\theta}{dt} = \omega, \tag{3}$$

where P_P is number of pole pairs, J is rotor inertia, T_L is load torque and electrical torque T_E is generated according equation

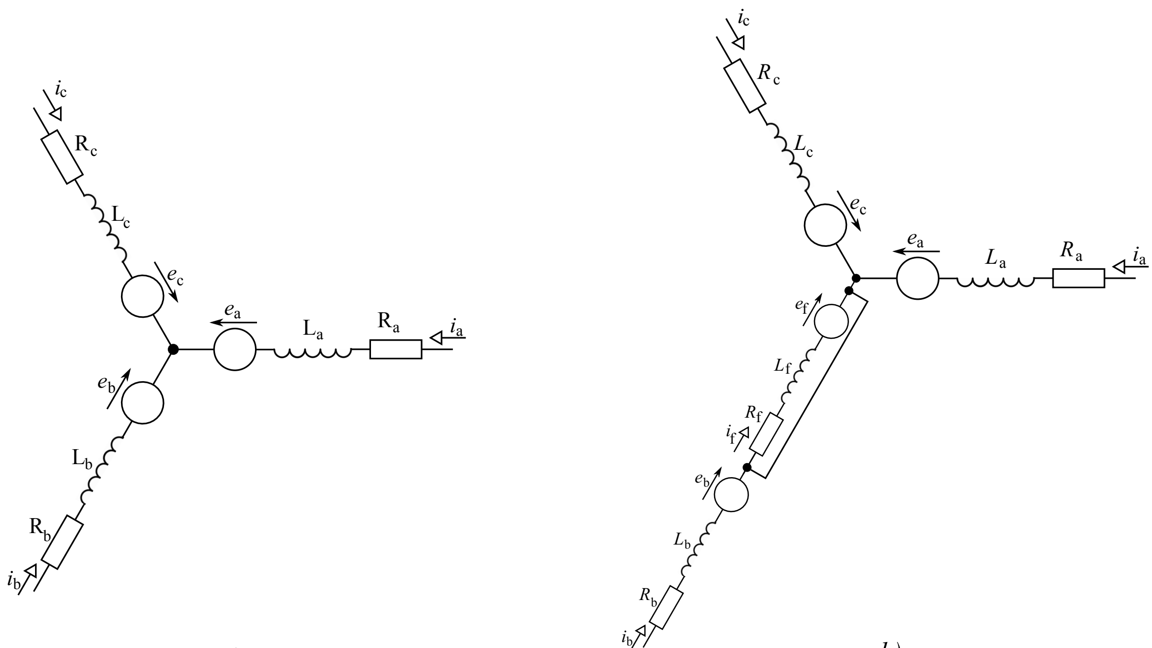
$$T_E = P_P \frac{{i_{abc}}^T e_{abc}}{\omega} = P_P {i_{abc}}^T \Psi_m \begin{bmatrix} cos(\theta) \\ cos(\theta - \frac{2\pi}{3}) \\ cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \tag{4}$$

It should be also mentioned, that rotor velocity corresponds to $\omega_{mech} = \omega / P_P$ and rotor orientation corresponds to $\theta_{mech} = \theta / P_P$.

2 WINDING INTER-TURN SHORT AND OPEN PHASE MODELLING

Principle of inter-turn short winding model was described in [1] and [2]. Both of these thesis are based on analogy to transformer inter-turn faults. There is situation, when unhealthy phase is divided into couple of windings as is on figure 1 b). Ratio of shorted turns to total number of turns per phase is marked as σ, that denotes severity of inter-turn fault. Faulty phase have to be included into healthy model mentioned in introduction. So vectors in equation (1) have to be extended by u_f, i_f and e_f. In relation to inter-turn short we expect that $u_f = 0$. In the PMSM model presented in this paper all faults occur in phase b. Because back-EMF voltage is proportional to number of turns, back-EMF e_{abcf} vector and electrical torque T_E have to be extended according to σ parameter as follows [1]:

$$e_{abc} = \omega\Psi_m \begin{bmatrix} cos(\theta) \\ (1-\sigma)cos(\theta - \frac{2\pi}{3}) \\ cos(\theta + \frac{2\pi}{3}) \\ \sigma cos(\theta - \frac{2\pi}{3}) \end{bmatrix}, \qquad T_E = P_P {i_{abcf}}^T \Psi_m \begin{bmatrix} cos(\theta) \\ (1-\sigma)cos(\theta - \frac{2\pi}{3}) \\ cos(\theta + \frac{2\pi}{3}) \\ \sigma cos(\theta - \frac{2\pi}{3}) \end{bmatrix}$$



a) *b)*

Figure 1: Healthy PMSM stator model *a)* and stator with short winding fault *b)*

Key thing is, how L_{abcf} and R_{abcf} matrices are changed. If PMSM has only $P_P = 1$, it is valid to change phase inductance only by turn change. Relation between inductance and turns is quadratic. Relation between equivalent serial resistance of inductor is linear with turns. For these simple conditions we can construct R_{abcf} and L_{abcf} matrices[1]:

$$L_{abcf} = \begin{bmatrix} L_S & (1-\sigma)M & M & \sigma M \\ (1-\sigma)M & (1-\sigma)^2 L_S & (1-\sigma)M & (1-\sigma)\sigma M \\ M & (1-\sigma)M & L_S & \sigma M \\ \sigma M & (1-\sigma)\sigma M & \sigma M & \sigma^2 L_S \end{bmatrix}, \ R_{abc} = \begin{bmatrix} R_S & 0 & 0 & 0 \\ 0 & (1-\sigma)R_S & 0 & 0 \\ 0 & 0 & R_S & 0 \\ 0 & 0 & 0 & \sigma R_S \end{bmatrix}$$

For dynamic modelling of inter-turn short fault R_{abcf} and L_{abcf} became a functions of σ. In situation $P_P > 1$ more precise approximation of inductance matrix have to be used. This is described in [1] based on transformer winding faults presented in [3]. Also [2] describes inductance matrix change in $P_P > 1$ situation on Flux2D FEM based model results. This will be verified in future work.

SimScape is used to create model of PMSM. Classical electrical diagram, with components connected by wires can be simulated there. So simulation of open phase fault is developed embedding the Circuit breaker component form SimScape toolbox into phase b circuit.

2.1 Custom SimScape component implementation

SimScape and Foundation library was used to develop model of faulty PMSM machine. SimScape component contains equations between the nodes and their signals. Also some mathematical definitions can be added on the top of equations. There is an possibility to define effort and flow between nodes like in bond graphs. Complete PMSM model was divided into two components. The first, variable mutual inductor, implements part of equation (1). The second, block back-EMF and mechanical part, implements equations (2) and (3) extended to faulty model, where σ is time variable.

Parameter	Symbol	Value
Permanent magnet flux	Ψ_m	$0.1546\,Vs$
Rotor inertia	J	$60 \cdot 10^{-6}\ kgm^2$
Stator inductance	L_S	$0.73\ mH$
Stator mutual inductance	M	$73\ \mu H$
Stator resistance	R_S	$1.4\ \Omega$
Number of pole pairs	P_P	1
Load Torque (step at 0.15 s)	T_L	$5\ Nm$

Table 1: PMSM parameters

3 SIMULATION RESULTS

There is simulation of faulty PMSM controlled by vector control scheme. Diagram of vector control is on figure 2. Parameters of modelled PMSM are summarized in table 1.

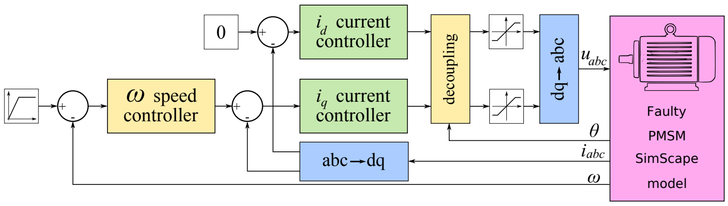


Figure 2: Closed loop simulation diagram

In following simulations, speed ramp until time $0.1\,s$ ends with speed $\omega_{mech} = 314.16\,rad/s$. There is also torque step in time $0.15\,s$. Faults occurs in time $0.3\,s$. Waveforms under inter-turn short winding is on figure 3, there is 20 % of turns of phase b winding shorted ($\sigma = 0.2$). As result, currents into phases are increased. There is also a visible ripple on torque and on ω_{mech} waveform during fault.

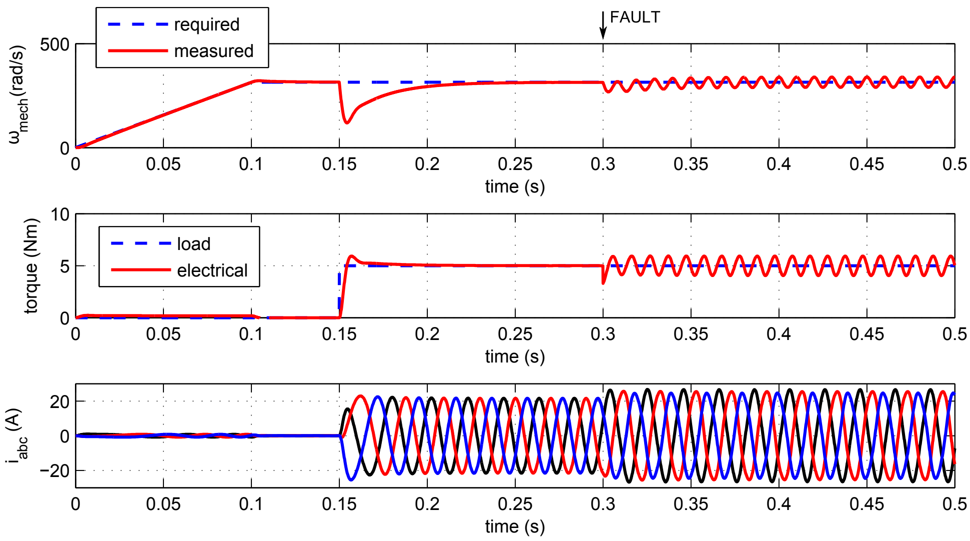


Figure 3: 20% inter-turn winding short simulation result

In open phase simulation, phase b is disconnected in time $0.3\,s$. Waveforms under open phase fault are on figure 4. As you can see current i_b is zero during fault. From high amplitude ripples on speed response and torque response during fault we can conclude that PMSM under open phase fault is unusable.

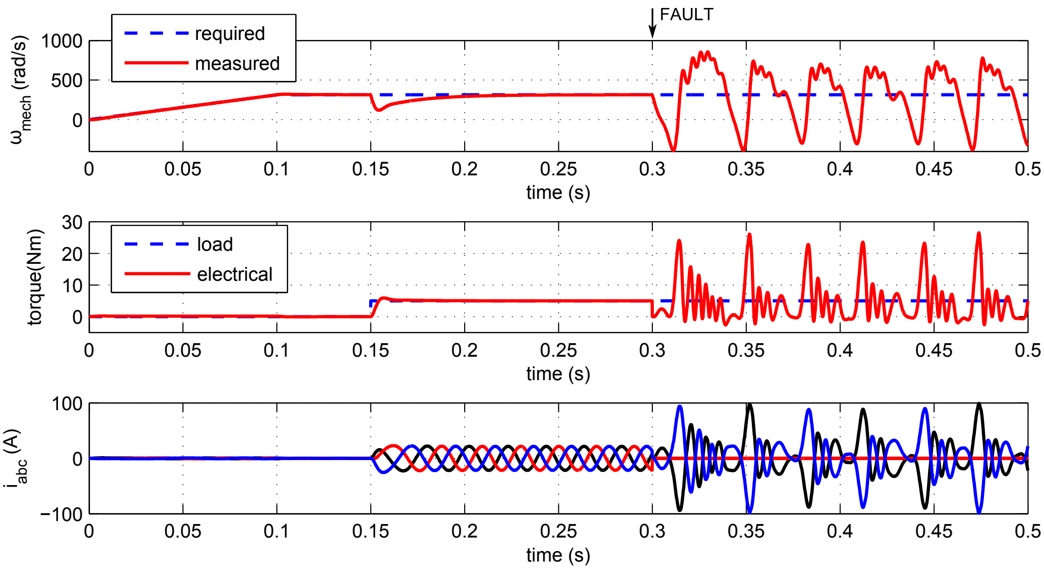


Figure 4: Open phase simulation result

4 CONCLUSION

Description and simulation results of the PMSM model with winding faults are presented in this paper. Open phase model and inter-turn short winding model of PMSM was constructed using SimScape toolbox with two custom SimScape components.

Inter-turn short winding simulation shows increased ripple in rotor speed and output torque, but PMSM is still usable but with increased power consumption and with high danger. Open phase simulation shows, that PMSM is unusable under this fault, as expected. Complete verification of presented model can be done by FEM model as presented in [2]. Another verification can be made on real machine. This model is exactly valid only for machines with $P_P = 1$. Complete verification of model with $P_P > 1$ is in progress.

This model will be used for testing state observers and fault detection algorithms based on stator resistance estimation. On time fault diagnosis helps to made more reliable PMSM based drives.

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REFERENCES

[1] Liu Li. *Robust Fault Detection and Diagnosis for Permanent Magnet Synchronous Motors*. [doctoral thesis]. Florida State University.

[2] Vaseng B. *Modeling of Non-Salient PM Synchronous Machines under Stator Winding Inter-turn Fault Condition: Dynamic Model - FEM Model*. IEEE Trans. on Industry Application, 2007.

[3] Bastard P., Bertrand P., Meunier M. *A Transformer Model for Winding Fault Studies*. IEEE Trans. on Power Delivery, 1994.