A Reconfigure Modelling of Double Stator PMSM after Turn-to-Turn Short Circuit

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Abstract: This article presents an original modelling of a high speed double stator permanent magnet synchronous machine (DSPMSM). When a turn-to-turn short-circuit fault occurs in the stator windings, the current flowing in the short-circuited turns can be much higher than the phase current. And the unbalance between the phases caused by the fault makes the phase voltage unmeasured. For overcoming this problem, a reconfiguration modelling method is proposed. The reconfiguration is a model which input line voltage rather phase voltage that can be measured correctly even if the machine is unbalanced. This advanced model is familiar with the classical d-q model. Therefore the traditional vector control algorithm is still available, the machine can be controlled by using the same signals (measured phase currents at the inverter level and DC bus voltage). A simulation of a DSPMSM variable speed drive shows the relevance of the model.

1 INTRODUCTION

Multi-phases electrical machine have a raising prospective in many applications, such as aerospace, energy, precision manufacturing, electric vehicle and so on. In these applications, the reliability of electrical machine will be very important. Especially for multi-phase machine, the possibility of malfunction is higher because of the increasing of phases. There are many type of internal faults in electrical machines, most commons are open-circuit fault and short-circuit fault. Of course, the Statistical data shows that open-circuit fault in electrical machine is more frequent than short-circuit fault, so the research on open-circuit fault is more widespread. The fault tolerant control algorithm for open-circuit is abundant, in the contrast research on short-circuit fault is rare. Because the fault situation for short-circuit is much complex than open-circuit. The short-circuit fault happened inside of machine can be divided into phase-to-phase fault and turn-to-turn fault. The former occurs between phases, or another is in one single phase.

This article focus on turn-to-turn short-circuit fault happening in the double stator PMSM machine (double three phases machine). Figure 1 shows a kind of 6 phases double stator PMSM of EMRAX company. Figure 2 shows the electrical structure of the machine found in the user's manual of this kind of machine.

Once the short-circuit fault occurs, the machine will become asymmetry. The nutral point voltage of electrical machine will drift. As the result, phase voltage will be unmeasureable. So that the traditional park model which is most common modelling method for control algorithm will be uncorrect. The current amplitude in the short-circuit winding is extremely high. Especially in high speed condition, the short circuit current may damage the machine. In order to limit the current in the short-circuited windings. In this article, a the line voltage inputs model for PMSM has been proposed. Different from park model, this modelling method is based on line voltage and loop current instead of phase voltage and phase current. In section II, the reconfigureation model for double stator PMSM will be presented which can avoid the influence of homopolar component. This modelling method committee to overcome the unbalance caused by short circuit fault that don't have to predict the zero-sequence current or voltage as people usually does. The control system is based on flux oriented control introduced in section III. In section IV, the simulation results are presented in order to prove the effectiveness the control strategy in this article.

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Figure 1: Exterior of a kind of double stator PMSM.

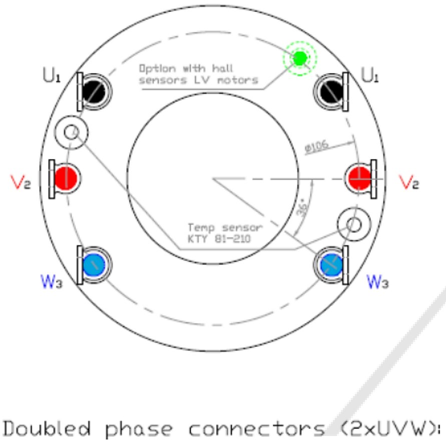


Figure 2: The electrical structure of EMRAX DSPMSM.

2 TWO-INPUTS MODEL

2.1 Turn to Turn Short Circuit Fault

What happens in windings after turn-to-turn short-circuit fault is shown in figure 3. In figure 3, the fault only occurs in phase A. In phase A, a parts of winding has been short circuited, rest of them is still in series of phase windings. As the result, the machine will become asymmetry. The asymmetry between phases cause many problem in machine operation. For example, the synthetic field will no longer be a circle, the decoupled between d axis and q axis will be affected and homopolar component will make the phase voltage unmeasurable. But it doesn't mean that the traditional vector control algorithm is ineffective. In this chapter, an advanced modelling method is proposed that such as make the line voltage as the inputting of the machine rather than phase voltage. The modelling method will be presented as follows.

Figure 4 is the schematic of short circuit faults on phase A. For a PMSM, every phase in stator has N turn coils in series. When turn-to-turn short circuit occurs, Nc turn will be short circuited, only N - Nc turns coils are connected in series with phase A. For deriving the unbalanced model, set $\alpha=(N - N_c)/N=1-N_c/N$. The resistance of the short citcuited phase is αR, self-inductance is $\alpha^2 L$, mutual inductance is αM. In this section, the two inputs model is derived by supposing that the fault is happened in phase A of stator 1.

Different from traditional park model, the inputs of two-inputs model is line voltage U_{1_ab}, U_{1_bc}, U_{2_ab} and U_{2_bc} rather phase voltage. And the line current will be replaced by loop currents J_{1_1}, J_{1_2}, J_{2_1}, J_{2_2}, as figure 4 shows.

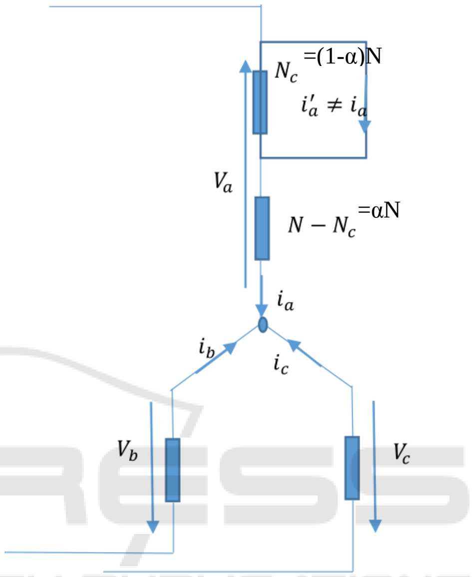


Figure 3: Turn-to-turn short circuit.

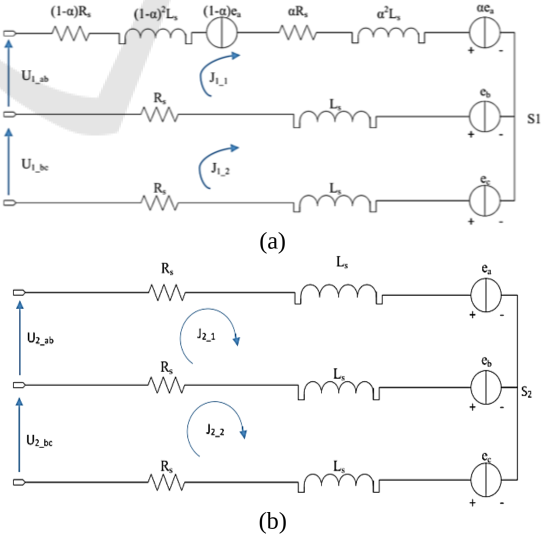


Figure 4: The equivalent circuit of line-voltage input model (a) Stator 1. (b) Stator 2.

2.2 Two-inputs Model

In this part, it is assumed that the shrot-circuit fault will happen in phase A of stator 1.The equivalent circuit has been shown in figure 4. Phase voltage U_{ab} and U_{bc} are acted as the inputs of machine model, line current is replaced by two loop current. e_a, e_b and e_c is the back EMF. The original equation of voltage and flux equation of PMSM is shown as follows:

$$\begin{cases} \mathrm{V_{1abc}} = \mathrm{R} \cdot \mathrm{i_{1abc}} + \frac{\mathrm{d}}{\mathrm{dt}} \Phi_{\mathrm{1abc}} \\ \mathrm{V_{2abc}} = \mathrm{R} \cdot \mathrm{i_{2abc}} + \frac{\mathrm{d}}{\mathrm{dt}} \Phi_{\mathrm{2abc}} \end{cases} \tag{1}$$

$$\begin{cases} \Phi_{\mathrm{1abc}} = \mathrm{L_{s1}} \cdot \mathrm{i_{1abc}} + \varphi_{\mathrm{r1}} \\ \Phi_{\mathrm{2abc}} = \mathrm{L_{s2}} \cdot \mathrm{i_{2abc}} + \varphi_{\mathrm{r2}} \end{cases} \tag{2}$$

For simplify the analysis, magnetic saturation, eddy current, skin effect etc. will all be ignored. For the sake of fault tolerant ability, the mutual inductance between two stators are eliminated. V_{1abc} and V_{2abc} are the line voltage of the stator. Φ_{1abc} and Φ_{2abc} are the flux linkage. R and L_{s1} and L_{s2} are line resistance and inductance of both stator respectively. φ_{r1} and φ_{r2} are the magnetic flux of rotor which is generate by Permanent magnetic material. The relationship between phase voltage&loop current and line voltage&current is as follows:

$$\begin{bmatrix} \mathrm{i_a} \\ \mathrm{i_b} \\ \mathrm{i_c} \end{bmatrix} = \begin{pmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{pmatrix} \cdot \begin{bmatrix} \mathrm{J_1} \\ \mathrm{J_2} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} U_{ab} \\ U_{bc} \end{bmatrix} = \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{pmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4}$$

Extracting the transition matrix C=$\begin{pmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{pmatrix}$ to transfer the machine model from three-inputs model (1) and (2) to the new two-inputs model:

$$C^t V_{1abc} = C^t RC \cdot J_{1\_12} + \frac{d}{dt} C^t \Phi_{1abc} \tag{5}$$

$$C^t V_{2abc} = C^t RC \cdot J_{2\_12} + \frac{d}{dt} C^t \Phi_{\mathrm{2abc}} \tag{6}$$

Then the two equations above can be written as follows:

$$\begin{cases} \mathrm{V_{1\_12}} = \mathrm{C^tRC} \cdot \mathrm{J_{1\_12}} + \frac{\mathrm{d}}{\mathrm{dt}} \Phi_{12} \\ \mathrm{V_{2\_12}} = \mathrm{C^tRC} \cdot \mathrm{J_{2\_12}} + \frac{\mathrm{d}}{\mathrm{dt}} \Phi_{22} \end{cases} \tag{7}$$

$$\begin{cases} \Phi_{1\_12} = \mathrm{C^tL_{s1}C} \cdot \mathrm{J_{1\_12}} + \mathrm{C^t} \varphi_{\mathrm{r1}} \\ \Phi_{2\_12} = \mathrm{C^tL_{s2}C} \cdot \mathrm{J_{2\_12}} + \mathrm{C^t} \varphi_{\mathrm{r2}} \end{cases} \tag{8}$$

Considering short-circuit fault, a fault matrix should using the parameter α be introduced as follows:

$$F_1 = \begin{bmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_3 \end{bmatrix} \quad F_2 = \begin{bmatrix} \alpha_4 & 0 & 0 \\ 0 & \alpha_5 & 0 \\ 0 & 0 & \alpha_6 \end{bmatrix} \tag{9}$$

The inductance matrix $\mathrm{L_{s1}}$, resistance matrix R and magnetic flux of rotor which encompass permanent magnetic material of unbalanced PMSM (stator 1) embedding the fault matrix will become as follows:

$$L_{s1} \rightarrow F \cdot L_{s1} \cdot F \tag{10}$$

$$R \rightarrow \mathrm{F} \cdot R \tag{11}$$

$$\varphi_r \rightarrow F \cdot \varphi_r \tag{12}$$

Because the purpose of this model is that can use the same control algorithm, so the machine model should to be orthogonal and decoupled which is similar with park model based on d-q frame. The furthering transformation matrix has been found as follows:

$$T = \begin{pmatrix} -\frac{\sqrt{2}}{2} & -\frac{\sqrt{6}}{6} \\ 0 & \frac{\sqrt{6}}{3} \\ \frac{\sqrt{2}}{2} & -\frac{\sqrt{6}}{6} \end{pmatrix} \tag{13}$$

The transformation is shown as equation (14)-(15):

$$\begin{cases} V_{1\_\alpha\beta} = T'C^t \mathrm{FRCT} \cdot \mathrm{J_{1\_\alpha\beta}} + \frac{d}{dt} \Phi_{1\_\alpha\beta} \\ V_{2\_\alpha\beta} = T'C^t \mathrm{RCT} \cdot \mathrm{J_{2\_\alpha\beta}} + \frac{d}{dt} \Phi_{2\_\alpha\beta} \end{cases} \tag{14}$$

$$\begin{cases} \Phi_{1\_\alpha\beta} = T'\mathrm{C^t} F \mathrm{L_{s1}FCT} \cdot \mathrm{J_{1\_\alpha\beta}} + T'\mathrm{C^t} F \varphi_{\mathrm{r1}} \\ \Phi_{2\_\alpha\beta} = T'\mathrm{C^tL_{s2}CT} \cdot \mathrm{J_{2\_\alpha\beta}} + T'\mathrm{C^t} F \varphi_{\mathrm{r2}} \end{cases} \tag{15}$$

The $V_{1\_\alpha\beta}$, $V_{2\_\alpha\beta}$, $\Phi_{1\_\alpha\beta}$ and $\Phi_{2\_\alpha\beta}$ are voltage and magnetic linkage at static orthogonal coordinate frame just like αβ frame in Park model. Then the model need to be transferred to a rotating coordinate frame. This procession is similar with park rotation is park transformation. Park matrix is required: P=$\begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}$:

$$\begin{cases} V_{1\_dq} = p(-\theta)R_{1\_\alpha\beta}p(-\theta) + \dfrac{d}{dt}p(-\theta)\Phi_{1\_\alpha\beta} \\ V_{2\_dq} = p(-\theta)R_{2\_\alpha\beta}p(\theta) + p(-\theta)\dfrac{d}{dt}\Phi_{\_\alpha\beta} \end{cases} \tag{16}$$

$$\begin{cases} \Phi_{1\_dq} = p(-\theta)L_{1s}p(\theta)\cdot \mathrm{J}_{1\_dq} + \varphi_{r1s} \\ \Phi_{2\_dq} = p(-\theta)L_{2s}p(\theta)\cdot \mathrm{J}_{2\_dq} + \varphi_{r2s} \end{cases} \tag{17}$$

In the above equations, $R_{1\_\alpha\beta} = T'C^t\mathrm{FRCT}$, $R_{2\_\alpha\beta} = T'C^t\mathrm{RCT}$, $L_{1s} = T'\mathrm{C}^tF\mathrm{L}_{s1}\mathrm{FCT}$, $L_{2s} = T'\mathrm{C}^t\mathrm{L}_{s2}\mathrm{CT}$, $\varphi_{r1s} = T'\mathrm{C}^tF\varphi_{r1}$, $\varphi_{r2s} = T'\mathrm{C}^tF\varphi_{r2}$.

Besides, the torque equation and mechanical equation are as equation (18) and (19):

$$\Gamma_{em} = p\cdot\left(\Phi_{1\_d}\cdot J_{1\_q} + \Phi_{2\_d}\cdot J_{2\_q}\right) \tag{18}$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(\Gamma_{em} - T_L - f_v\cdot\omega_m\right) \tag{19}$$

3 CONTROL SYSTEM

There are several kinds of control strategy for PMSM, including vector control, direct torque control (DTC), model perspective control and so on. In this article the line voltage input model is expected to work on traditional control algorithm, so the flux oriented control system is chosen. Field Oriented Control (FOC) is a kind of vector control (Senjyu et al., 2001). This control algorithm is dedicated to control the AC machine just like the DC machine. Usually the park transformation is used to achieve this idea that park model is the equivalent DC machine model for AC electrical machine. Chapter 2 have introduced a new modelling method that similar with park model, so the FOC control strategy is still available.

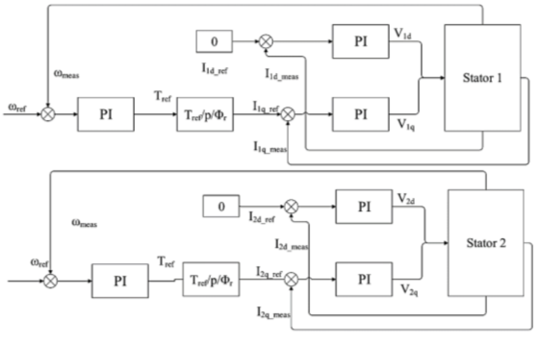


Figure 5: Control system of doubly stator PMSM.

The field oriented control divides the stator current into two part: excitation component and torque generation component. In d-q coordinate frame, d axis current is acted as excitation current, and q axis current is acted as torque generating current. In order to get highest electrical torque, we want to the current is engaged in generating the torque, so the reference of d-axis current will be set to 0, the reference of q-axis current is based on load torque as figure 5 shows. Actually, the real control system should modulate PWM capitalized on the output of controller that limit the output voltage of converters. But in this article, machine will be built in s-function as a math model, so the voltage reference can effect on the machine directly that don't have to convert the signal to energy.

As this article says before, FOC control system is in order to control the AC motor resembles controlling the DC machine that have good effect on both Static and dynamic performance. It is better that make the effect point of flux disturbance in the torque loop (inner loop), so we can repress the disturbance via torque feedback rather speed loop (outer loop) which has some Hysteresis. The torque regulator will be connected between the rotating speed regulator and torque current (q-axis current) component regulator. When flux fluctuates, we can regulate the reference of torque current component through torque regulator in time, as to remediate the influence of the change of flux.

It is important to tune the parameter of control system via some generic tuning method when debugging a new control system. So we are going to compute the parameters of controller by analytical formulas. In the following, some tuning equations will be presented.

The expression of PI controller is as follows:

$$U_o = K_pU_i + k_i\int_0^t U_i\,dt \tag{20}$$

The transfer function of PI controller is as follows:

$$G_i = K_p + \frac{K_i}{s} \tag{21}$$

The proportional parameter K_P and integral parameter K_I is the function of damping factor ζ, natural frequency ω_0 and time constant τ. The PMSM is seems as a one order actuator:

$$G_a = \frac{K_s}{1+T_s s} \tag{22}$$

The transfer function of the whole system can be written in this form:

$$\mathrm{H} = \frac{s+C}{\left(\frac{s}{\omega_0}\right)^2 + 2\zeta\left(\frac{s}{\omega_0}\right)+1} \tag{23}$$

The parameter of PI controller can be determined by damping factor ζ, natural frequency ω_0 and time constant τ.

The PI controller will be used in the d-q axis current close loop control system. The speed loop with PI controller will output the torque reference. The current reference can be calculated through torque regulator. Then the PI controller in current loop will output the voltage setting of two stators.

4 SIMULATION RESULTS

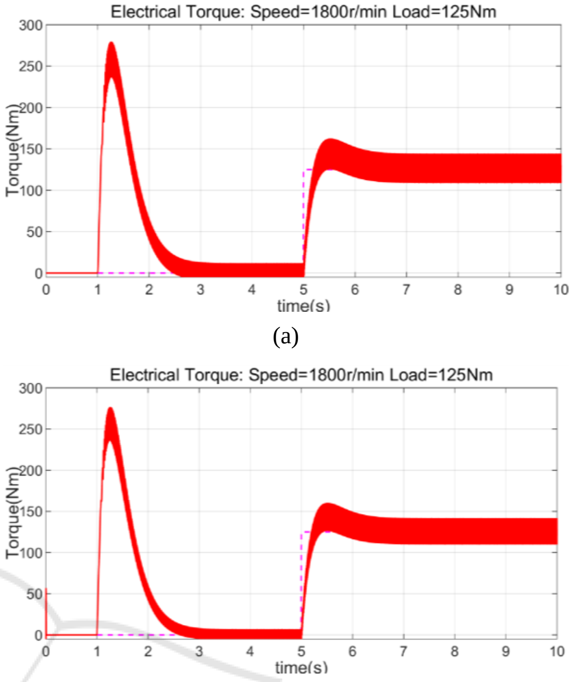
Simulation results are conducted to investigate the fault remediation effect of line voltage input model. A motor which max power is 100kw is the prototype of the simulation. The motor has 6 phases (two three phases stators), Y-connection stator, and the permanent magnetic material is on the rotor. The parameter of the motor in this simulation is shown as table 1 which is from UMAAFSMG, 2017.

Table 1: Parameter.

R_s	$8\times 10^{-3}\Omega$
L_d	76μH
L_q	79μH
M_d	18μH
M_q	20μH
Ψ_r	0.0350T
P (pole pairs)	10
J (Rotor inertia)	421kg$\cdot cm^2$
f_v (friction of rotor and load)	1×10^{-3}
Specific idle speed (no load RPM)	14 RPM/1Vdc
Specific load speed	11 – 14 RPM/1Vdc

Firstly, it is necessary to compare the difference on control effect between based on traditional park model and line voltage input model that using the same control strategy. This simulation is lasting 10s. The rotating speed is set to 1800rpm at 1s, then a 125Nm load will be connected to machine at 5s. Figure 6-7 is the simulation result with α=0.8 that the fault happens in phase A of stator 1. Figure 6 is the result of electrical torque. Figure 7 is the comparison of rotating speed between two kinds of model.

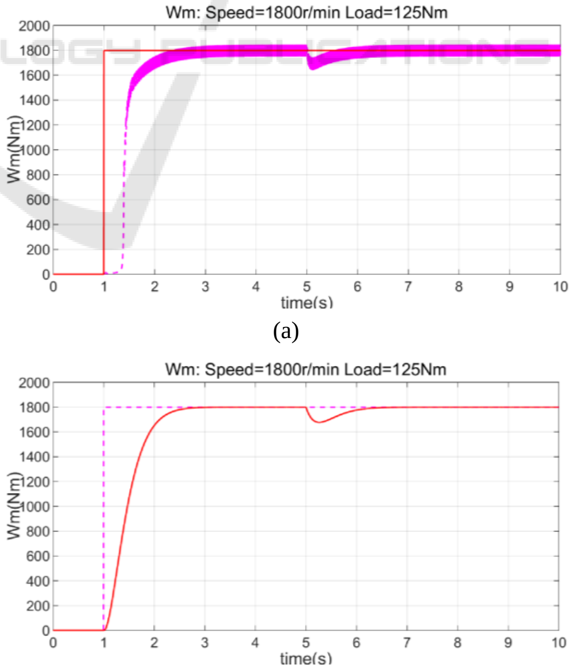
The peak to peak value of electrical torque oscillation in steady state are 35.52Nm and 31.78Nm. The reconfiguration model remediate the 10.52% torque oscillation with the same double close loop control system. As for rotating speed, it is obvious that line voltage input model have manifest effect on remediating the instability of mechanical speed as figure 8 shows. Figure 8 are simulation results of α=0.5. The oscillation are 87.54Nm and 71.34Nm, the improved model remediate the 18.51% torque oscillation.



(a)

(b)

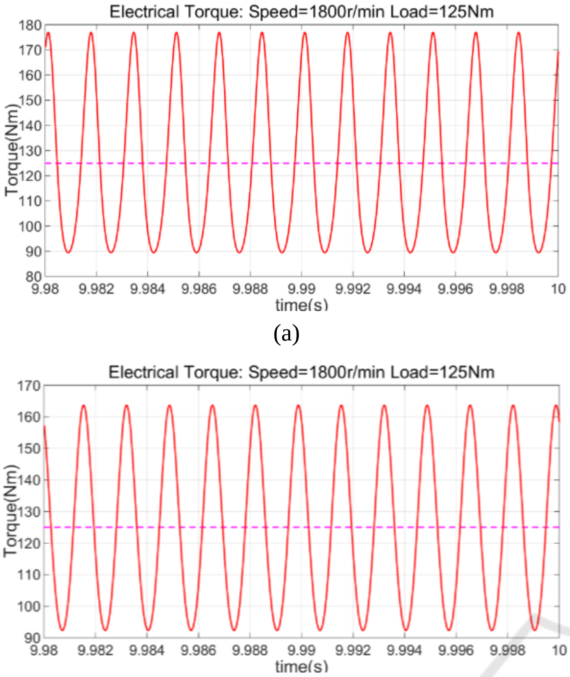
Figure 6: Electrical torque. (a) Traditional park model (b) Two-inputs model. α=0.8.



(a)

(b)

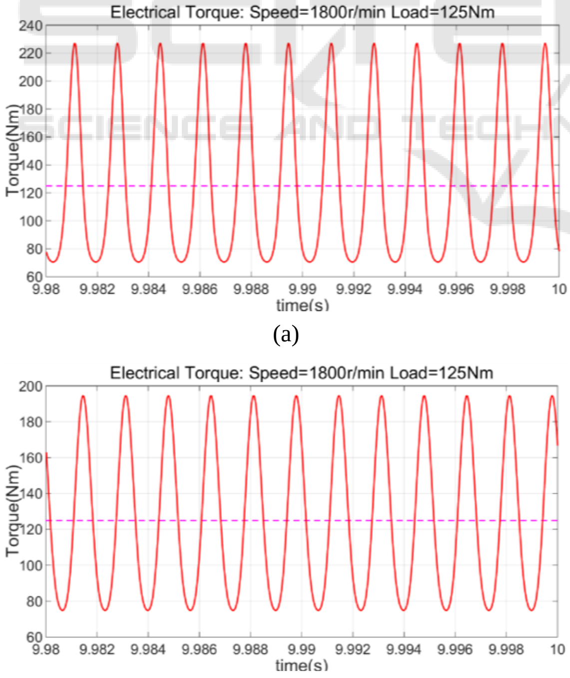
Figure 7: Rotating Speed. (a) Traditional park model (b) two-inputs model. α=0.8.



(a)

(b)

Figure 8: Electrical torque. (a) Traditional park model (b) Two-inputs model. α=0.5.



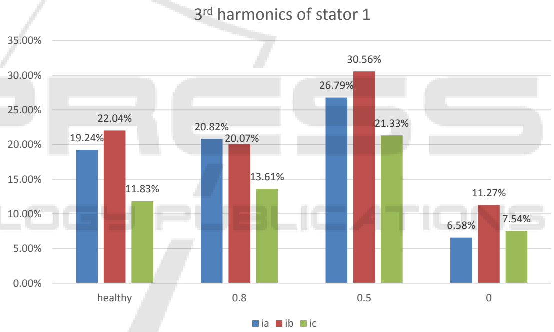
(a)

(b)

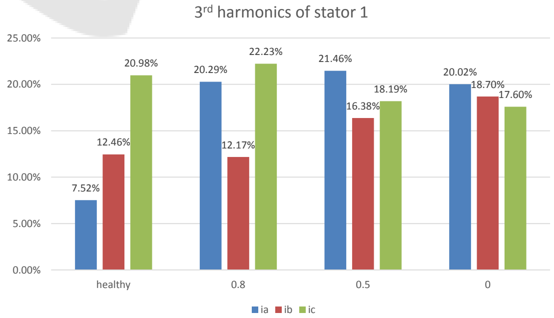
Figure 9: Oscillation of electrical torque α=0. (a) Traditional park model. (b) Two-inputs model.

In case of serious fault, such as α=0, which means the all coils of faulty phase has been short circuited, so that the torque ripple will be dramatic. Figure 9 is the waveform of electrical torque when phase A of stator 1 has been totally short circuited. We can see that the oscillation of control system with traditional model is quite high. As the figure 9 (a) shows, the oscillation is 156.53Nm. This huge oscillation will make the motor operated unstable even in large inertia application. The electrical torque oscillation of line voltage input model is 119.63Nm. The torque ripple has been reduced 23.57% without any optimal algorithm.

There are some other problems the turn-to-turn short circuit may cause, such as high order odd harmonics of phase current, especially the 3rd harmonic. These harmonics could increase the losses of motor. Figure 10 is the comparison of 3rd harmonic of current of phase A in stator 1 under the healthy condition, α_1=0.8, 0.5 and 0 fault respectively. We can see that the line voltage input model can't remediate the harmonics of phase current. So that other optimal method for harmonics is necessary.



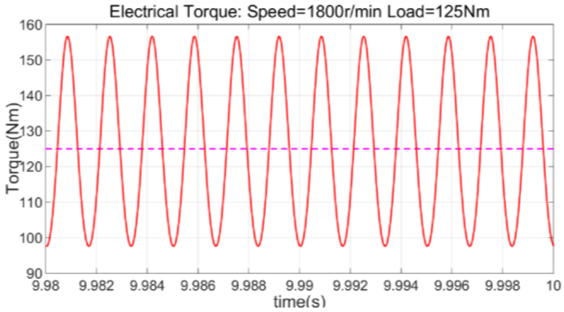
(a) Traditional Park Model



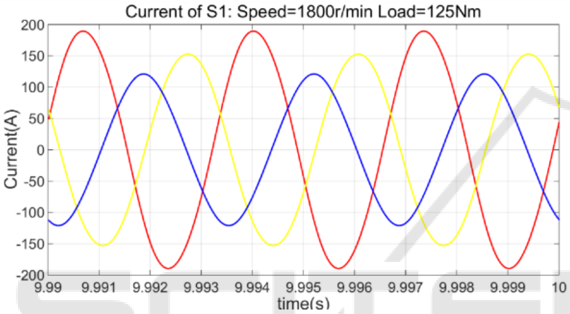
(b) Line Voltage Input Model

Figure 10: Comparison of 3rd harmonic.

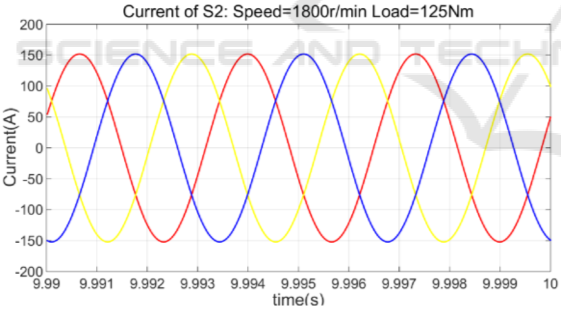
In addition, the more complicated fault condition should be concentrated. For example, phase A of both stators occur inter turn short circuit fault, and two phases on one stator go wrong. Following simulation present the fault occurs in two phases. In first one the two phases is in one stator, α_1=0.8 and α_2=0.5. The second is in both stators, α_1=0.8 and α_5=0.5. The simulation result have been shown in figure 11 and 12. Load torque has been set to 125Nm, rotating speed is 1800r/min.



(a) Electrical Torque

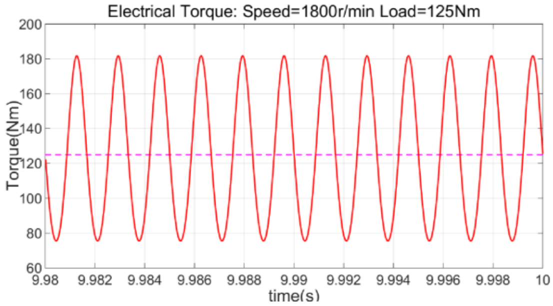


(b) Phase Current of Stator 1

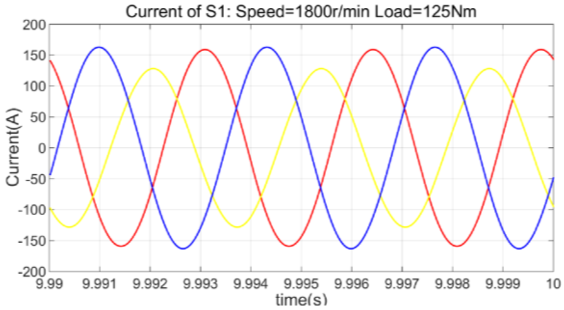


(c) Phase Current of Stator 2

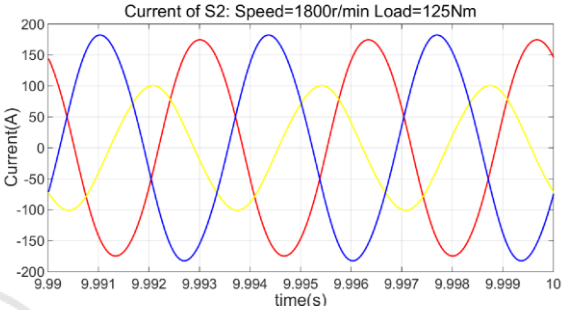
Figure 11: Simulation result of α=0.8 and 0.5 at phase A and B of stator 1.



(a) Electrical Torque



(b) Phase Current of Stator 1



(c) Phase Current of Stator 2

Figure 12: Simulation result of α=0.8 and 0.5 at phase A and B of stator 1.

In these simulation, the torque oscillation of two kinds of fault are 58.99Nm and 106.10Nm. We can see that if the fault occurs in both stator, the torque ripple will be more serious than only occurs in one stator.

5 CONCLUSION

This article has introduced an original modelling method called line voltage input model for double stator PMSM. This modelling method is dedicated to overcome the unbalance caused by short-circuit fault. The control system this article focused on is field oriented control which is a classical vector control algorithm. The simulation result validate that the modified two-inputs model have positive effect on remediate the oscillation of electrical torque and rotating speed. But the side-effect of this modelling method is that the high order harmonics will increasing which may pollute the grid. So the following work of this subject is that the high order harmonic, extremely 3^{rd} harmonic should be reduced.

Furthermore, this modelling method can be used in some other kinds of control system, such as DTC, model predictive control and sensorless control.

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