Model Predictive Control for A Dual Three-Phase Two-Sector Permanent Magnet Synchronous Machine

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Abstract

A novel dual three-phase permanent magnet synchronous machine is designed for taxiing motor-generator on propeller aircraft. The unique structre of machine enhances system reliability, and also brings extra merits such as reducing torque ripple when appling model predictvie control. Two possible control algorithms are proposed and performances are compared by simulation.

1   Introduction of dual three-phase two-sector PMSM

More electric aircraft (MEA) is identified as the trend for future aircraft due to its low CO2 emission, high efficiency, high availability and low noise, etc. Within the CleanSky 2 ACHIEVE project (No. 737814), a new multifunctional high-speed integrated drive system (Taxiing motor-generator system) for propeller aircraft is developed. As shown in Fig.1, the developed drive system is integrated within the engine gearbox with an ambient temperature of 130℃.

This developed taxiing motor-generator system is used as a motor, with power from batteries (main engine is off), driving the propeller for the green-taxiing application. The system will be used for power generation when the propeller engine is in the air.

A dual three-phase two-sector permanent magnet synchronous machine (PMSM) is selected for this Taxiing motor/generator system considering the redundancy requirement.

The section view of the electrical machine is shown in Fig. 2 and more details about its math model and machine parameters are revealed in [1]. Compared with traditional dual three-phase machine, the windings placement of this machine are placed separately on each half of the stator. This means the stator has two sectors: one is for ABC phase windings on one side and the other side is for UVW phase windings.

Each three-phase windings are driven by a three-phase full-bridge SiC convertor. The two converters can operate separately and each one provides half of the rated power. Even one converter or one three-phase windings is failed, the machine can still be service with half of its capacity. The overall system is shown in Fig. 3.
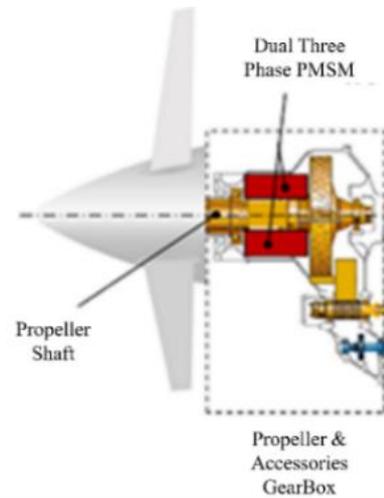

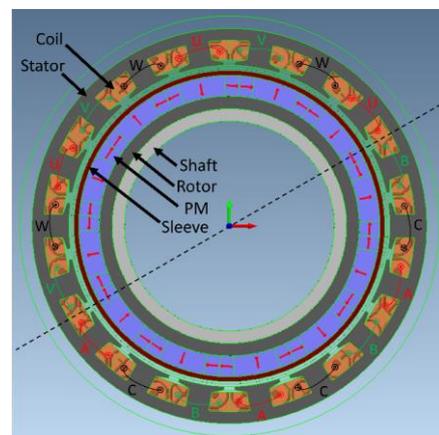Fig. 1. Taxiing Motor-Generator Installed in Propeller Shaft

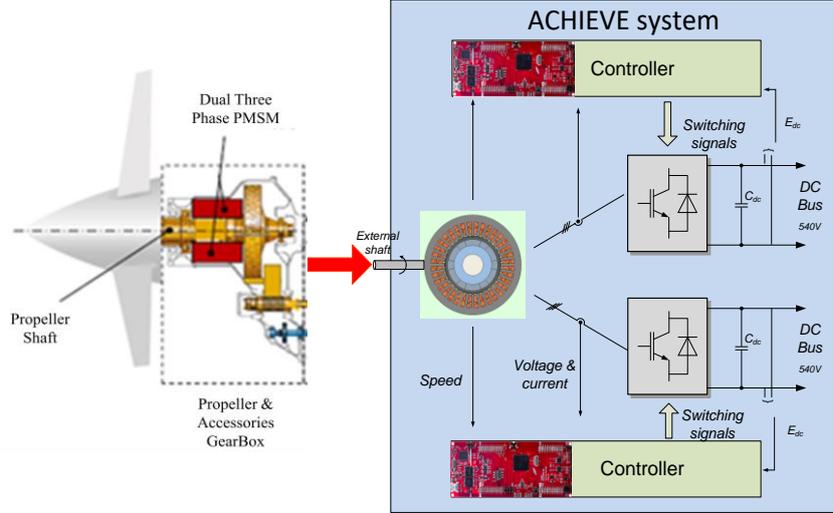

Fig. 2. Section View of The Machine

Fig. 3. Overall System View for Aircraft Application

Model Predictive Control (MPC) has been widely proposed and successfully applied in power electronics and drives for decades. It shows many advantages, such as fast dynamic response, easy inclusion of nonlinearities and constraints of system, etc [2]–[6]. Although there are many references of MPC control for PMSM applications, most of them are aimed at traditional three-phase PMSMs.

This paper is aimed to develop a MPC algorithm for this green taxiing/generator system. There are some references before appling MPC to dual three-phase machine control [7], [8], but the machines they use are different with our machine. As the machine in this paper has different stator windings placement and is asymmetric compared with those traditional dual three-phase machine, the model developed for conventional control will not be valid. This paper starts from modelling of this dual three-phase asymmetric two-sector machine in six-phase coordinate. A mathematic way will be developed to transform the six-phase model to two sets of dq rotating models. An advanced MPC method will be proposed based on the derived model followed by simulation results.

2 Model predictive control (MPC) for dual three-phase two sector PMSM

The math model of this machine is shown like (1) and $[\boldsymbol{L_s}]_{6\times6}$ is the inductance matrix for all 6 windings which shown in Table I. If the first 3 rows and second 3 rows of (1) are applied with Clarke-Park transform separately, math models of ABC phase and UVW phase in d-q frame can be obtained like (2) and (3). $\boldsymbol{d}$ is the coupled item between two three-phases shown in (4), which can be ignored as $\boldsymbol{M}$ is much smaller than L and $i_{d1} \approx i_{d2}$, $i_{q1} \approx i_{q2}$.

To be used by model predictive control, the discrete predictive model (5) is obtained from (2) and (3). Because the machine in this paper has two three-phase windings, it is easy to come out with two different MPC method: one is controlling each

three-phase windings separately, the other is combining them together, which are shown in Fig. 4 and Fig. 5 respectively.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \\ u_u \\ u_v \\ u_w \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_u \\ i_v \\ i_w \end{bmatrix} + [\boldsymbol{L_s}]_{6\times6} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_u \\ i_v \\ i_w \end{bmatrix}' - \begin{bmatrix} \sin\theta \\ \sin(\theta - 120°) \\ \sin(\theta + 120°) \\ \sin(\theta - 180°) \\ \sin(\theta + 60°) \\ \sin(\theta - 60°) \end{bmatrix} \omega_e \phi_m \quad (1)$$

$$\begin{bmatrix} u_{d1} \\ u_{q1} \end{bmatrix} = L \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix}' + R \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} + \omega_e \begin{bmatrix} -Li_{q1} \\ Li_{d1} + \phi_m \end{bmatrix} + \boldsymbol{d} \quad (2)$$

$$\begin{bmatrix} u_{d2} \\ u_{q2} \end{bmatrix} = L \begin{bmatrix} i_{d2} \\ i_{q2} \end{bmatrix}' + R \begin{bmatrix} i_{d2} \\ i_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} -Li_{q2} \\ Li_{d2} + \phi_m \end{bmatrix} - \boldsymbol{d} \quad (3)$$

$$\boldsymbol{d} = \boldsymbol{M} \left\{ \begin{bmatrix} i_{d1} - i_{d2} \\ i_{q1} - i_{q2} \end{bmatrix}' - \omega_e \begin{bmatrix} i_{q1} - i_{q2} \\ i_{d2} - i_{d1} \end{bmatrix} \right\} \quad (4)$$

$$\begin{bmatrix} \hat{i}_{d,k+1} \\ \hat{i}_{q,k+1} \end{bmatrix} = \begin{bmatrix} i_{d,k} \\ i_{q,k} \end{bmatrix} + \frac{T_s}{L} \begin{bmatrix} u_{d,k}^* - Ri_{d,k} + \omega_e Li_{q,k} \\ u_{q,k}^* - Ri_{q,k} - \omega_e(Li_{d,k} + \phi_m) \end{bmatrix} \quad (5)$$

$$g_1 = \left(\hat{i}_{d,k+1} - i_d^* \right)^2 + \left(\hat{i}_{q,k+1} - i_q^* \right)^2 \quad (6)$$

$$\begin{cases} g_{21} = \left[\frac{\hat{i}_{d1,k+1} + \hat{i}_{d2,k+1}}{2} - i_d^* \right]^2 + \left[\frac{\hat{i}_{q1,k+1} + \hat{i}_{q2,k+1}}{2} - i_q^* \right]^2 \\ g_{22} = \left(\hat{i}_{d1,k+1} - \hat{i}_{d2,k+1} \right)^2 + \left(\hat{i}_{q1,k+1} - \hat{i}_{q2,k+1} \right)^2 \\ \qquad g_2 = g_{21} + Ag_{22} \end{cases} \quad (7)$$

For MPC method 1, d and q-axis currents of each sector are predicted separately with 7 different voltage vectors. Cost function (6) is used to find the best predictive current which has minimum error with current reference. However, MPC method 2 combines the two sectors together and only one cost function (7) is used. Because each convertor has 7 different voltage vectors, there will be 49(7*7) different voltage vectors for method 2.
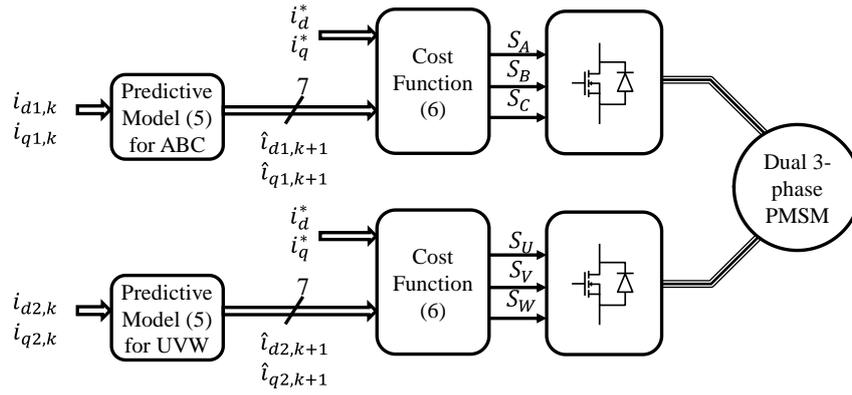
Fig. 4. Model Predictive Control Algorithm 1 for Dual Three-Phase Two-Sector PMSM
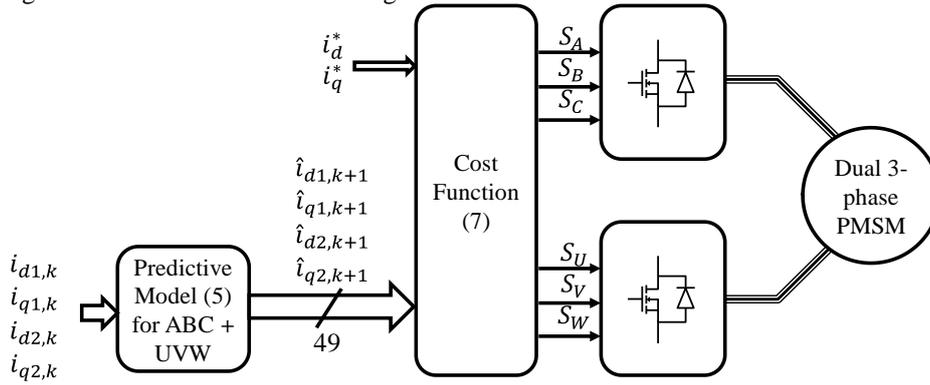

Fig. 5. Model Predictive Control Algorithm 2 for Dual Three-Phase Two-Sector PMSM

	A	B	C	U	V	W
A	326	-81	-111	20	50	20
B	-81	326	-111	50	20	20
C	-111	-111	326	20	20	20
U	20	50	20	326	-81	-111
V	50	20	20	-81	326	-111
W	20	20	20	-111	-111	326

The cost function (7) contains two parts, g_{21} makes the mean of i_{d1} and i_{d2} (also i_{q1} and i_{q2}) converge to i_d^* (i_q^*), g_{22} makes i_{d1} close to i_{d2} and i_{q1} close to i_{q2}. The function of g_{22} is to make sure the amplitude of currents for the two sectors don't have much difference, and prevent radial force unbalance and electrical power unbalance of the two sectors. Changing the value of A in (7) can adjust the importance of g_{22}. The following simulation result reveals even very small value of A can prevent the unbalance of two sectors, but $A = 0$ will cause unbalance of the two sectors.

3   Simulation validation

In order to compare the control performance of the two MPC methods, simulation of current close loop control is built and the machine parameters are listed in Table II. The simulation assumes the machine is running at a constant speed and a step current reference of $i_d^* = 0$A, $i_q^* = -25$A is applied at 0s.

TABLE II. PARAMETERS OF MACHINE

Parameter	Mark	Value
Phase Resistance	R	0.035Ω
Peak No-load Flux Linkage per channel	ϕ_m	0.033Vs
d-/q-axis Inductance for each sector	L	437μH
Pole numbers	P	12
Runing speed	n	12.4krpm

Fig. 6 and Fig. 7 show the current tracking performance of the two methods. Fig. 6 shows the d and q-axis currents of the two sectors are identical for MPC method 1, which due to the two sectors use the same discrete predictive model (5) and same cost function (6). Therefore the selected voltage vector of the two sectors are always the same. However, Fig. 7 shows d and q-axis currents of the two sectors don't same for MPC method

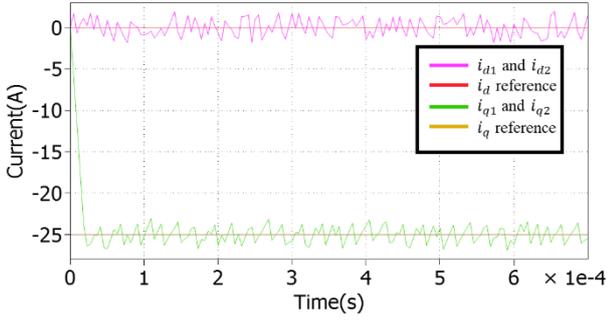2. This means the selected voltage vectors of the two sectors are different.

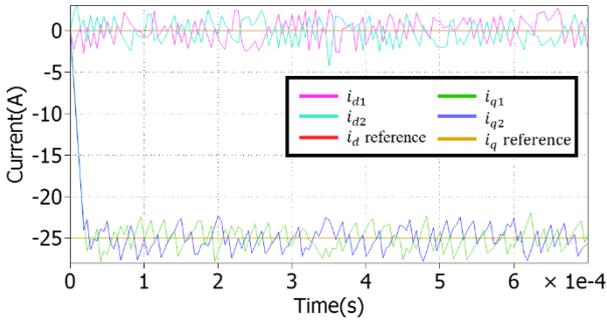Fig. 6. i_d and i_q for Model Predictive Control Method 1

Fig. 7. i_d and i_q for Model Predictive Control Method 2 with $A = 1\text{x}10^{-4}$

Fig. 8 shows the torque waveform of the two MPC methods and it's quite obvious method 2 has smaller ripple. Table III lists the details of torque ripple and it reveals MPC 2 can have a very good impact on torque ripple suppression, which makes torque ripple decrease from 15.32% to 7.47%.

Table IV compares the torque ripple with different g_{22} Coefficient (A). It shows $A = 1$ will make MPC 2 have similar torque ripple with MPC 1. When A is smaller than 0.01, the ripple is stable at a low range. That means the selection of A is very robust. However, if $A = 0$, the d and q-axis currents will fluctuate heavily shown like Fig. 9. Therefore, the part of g_{22} is very essential for the stable operation of MPC method 2, even its coefficient A is very small.

4   Conclusion

This paper introduces model predictive control (MPC) method for dual three-phase two sector permanent magnet synchronous machine. Two kinds of MPC methods are compared, one is controlling two sector separately, and the other is combining them together. Simulation result shows the second method has much smaller torque ripple than the first method.

TABLE III. TORQUE RIPPLE COMPARISON IN STABLE STATE

Method	Mean Torque(Nm)	Max-Min (Nm)	Torque Ripple
MPC 1	-14.83	2.27	-15.32%
MPC 2	-14.83	1.11	-7.47%

TABLE IV. TORQUE RIPPLE WITH DIFFERENT g_{22} COEFFICIENT (A)

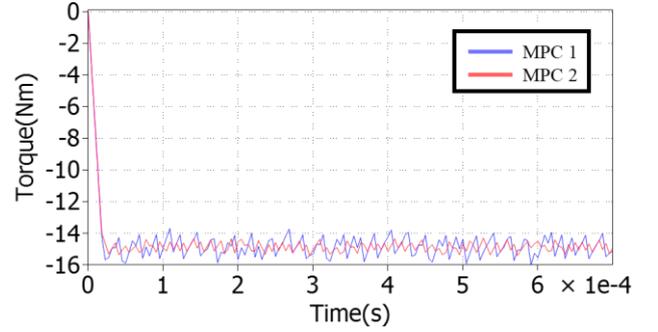| A	Mean Torque(Nm)	Max-Min (Nm)	Torque Ripple
1	-14.83	2.26	-15.25%
0.1	-14.87	1.43	-9.61%
0.01	-14.84	1.11	-7.47%
0.001	-14.84	1.11	-7.46%
0.0001	-14.83	1.11	-7.47%
0	-14.83	1.11	-7.47%

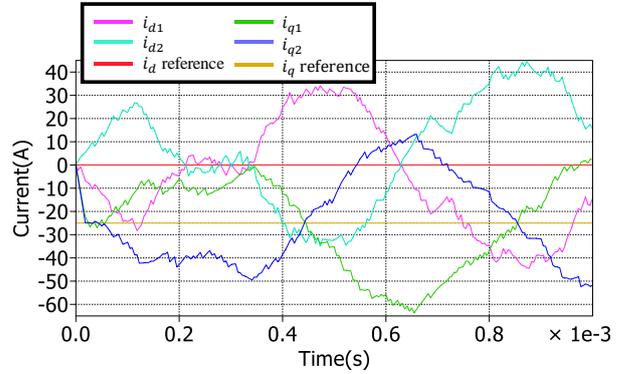Fig. 8. Torque Comparison of Model Predictive Control (MPC) Method 1 and 2

Fig. 9. i_d and i_q for Model Predictive Control Method 2 with $A = 0$

5   Acknowledgement

6 Reference

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