Sensorless Control Of Dual-Three Phase PMSM Based Aircraft Electric Starter/Generator System Using Model Reference Adaptive System Method

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Abstract— This paper presents a sensorless control technique based on Model Reference Adaptive System (MRAS) for a symmetric dual three-phase permanent magnet synchronous machine (DTP-PMSM) whose sets of windings are spatially shifted by 60 degrees. The control design of starter/generator (S/G) system is studied. The analytical controller design is presented. The effectiveness of the controller is demonstrated from time-domain simulations.

Keywords—Dual Three-Phase PMSM, MRAS, starter-generator, sensorless control.

I. INTRODUCTION

Global tendency towards environmentally responsible air transportation results in significant changes to many aircraft systems technologies. The state-of-the art on-board systems are expected to be more efficient, safer, simpler in servicing and easier in maintenance [1, 2]. As a result, many existing hydraulic and pneumatic power-driven systems are being replaced by their electrical counterparts. This trend is known as a move towards the “more electric aircraft” (MEA). In recent years, multi-phase machine has been widely used in various applications such as MEA [3]. In the last two decades, a growing interest in multi-phase machines has risen due to the fact that these machines can provide notable improvements in various aspects of performance when compared with the use of their conventional three-phase counterparts [4]. The potential advantages of multiphase machines include: reduced phase current rating and torque ripple; less DC link harmonic current; smooth magneto motive force (MMF); improved efficiency [5]; excellent fault tolerant characteristics and higher reliability at system level [4-7]. In addition, reliability is greatly improved since the machine can operate continuously even if one or several phases (in some cases) are lost [3]. One of the most attractive multi-phase machines is the six-phase or dual three-phase (DTP) machine as depicted in Fig. 1. A DTP winding machine has two identical star-connected three-phase stator windings which have isolated neutral points [8]. Considering the spatially shifted angle between two sets of three-phase windings, DTP machines can be classified as symmetrical (shifted by 60 electrical degrees) machines and asymmetric (shifted by 30 electrical degrees) machines. According to [9], symmetric DTP-PMSM is preferred to satisfy the severe fault-tolerant requirements imposed by the specific aerospace application. Hence, a symmetric DTP-PMSM is investigated in this study to develop a mechatronic device for turboprop aircraft applications.

Since the space in the gear box is quite limited and not large enough to install mechanical speed/position sensors,

sensorless control is considered. One additional benefit brought by the sensorless control strategy is the improved system reliability since it reduces the vulnerable components (mechanical sensor) in entire system. Usually, sensorless control can be classified into two major groups [10]. One is based on mathematical models of machine such as the model reference adaptive system (MRAS) [11, 12] and the other one is based on the rotor saliency such as high frequency signal injection techniques [13, 14]. It has been found that sensorless control design for an aircraft electric S/G system based on multiphase machines especially for symmetric DTP-PMSM has not been studied in enough details, hence the paper addresses this gap. In this study, MRAS is developed to estimate rotor speed and position since it presents immediate advantage that the models are simple, easy to implement and have direct physical interpretation.

The paper is organized as follows: DTP-PMSM model is reviewed in section II; control design of S/G system is illustrated in section III and MRAS estimation method is presented in section IV; simulations results are included in section V, while conclusions are provided in the last section.

II. DUAL THREE-PHASE PMSM MODEL

In this section, mathematic models of DTP-PMSM in both three-phase coordinate system and dq rotating frame are developed.

A. Mathematical Model in Three-Phase Coordinate System

The voltage and flux equations in three phase coordinate system of a DTP-PMSM can be written as

$$\mathbf{u}_s = R\mathbf{i}_s + \frac{d\boldsymbol{\varphi}_s}{dt} \quad (1)$$

$$\boldsymbol{\varphi}_s = \mathbf{L}_s\mathbf{i}_s + \lambda\boldsymbol{\varphi}_m \quad (2)$$

where

$\mathbf{u}_s = [u_A \ u_A \ u_C \ u_U \ u_V \ u_W]^T$ is stator voltage;

$\mathbf{i}_s = [i_A \ i_B \ i_C \ i_U \ i_V \ i_W]^T$ is stator current;

$\boldsymbol{\varphi}_s = [\varphi_A \ \varphi_B \ \varphi_C \ \varphi_U \ \varphi_V \ \varphi_W]^T$ is stator flux;

$$\lambda = [\cos\theta_e \ \cos(\theta_e - \frac{2\pi}{3}) \ \cos(\theta_e - \frac{4\pi}{3}) \ \cos(\theta_e - \frac{\pi}{3}) \ \cos(\theta_e - \pi) \ \cos(\theta_e - \frac{5\pi}{3})]^T \text{ is flux coefficient matrix;}$$

θ_e is the electrical rotor position in radians;

R is stator resistance;

Fig. 1 DTP-PMSM drive system [15].

φ_m is permanent magnet flux;

$\mathbf{L}_s$ is the inductance coefficient matrix which can be presented as

$$\mathbf{L}_s = L_z \mathbf{I} + \left(\frac{L_d + L_q - 2L_z}{3}\right) \mathbf{M}_o + \left(\frac{L_d - L_q}{3}\right) \mathbf{M}_x \quad (3)$$

where L_z is stator leakage inductance, L_d and L_q are stator inductances in d -axis and q -axis respectively. $\mathbf{I}$ is a unity matrix with six columns and six rows. $\mathbf{M}_o$ and $\mathbf{M}_x$ are detailed in Appendix A. The system parameters used in this study are given in Appendix B.

The electromagnetic torque of the PMSM is obtained by taking the partial derivative of the system co-energy with respect to rotor position angle [16].

$$T_e = P_p \frac{\partial}{\partial \theta_e} \left(\frac{1}{2} \mathbf{i}_s^T \mathbf{L}_s \mathbf{i}_s + \mathbf{i}_s^T \lambda \varphi_m \right) \quad (4)$$

where P_p is the number of pole pairs.

B. Model Representation in dq Rotating Frame

By ignoring zero sequence component, DTP-PMSM can be represented as two single three-phase machines with mutual coupling through transformation matrix T_s [4, 17],

$$[f_{d1} \ f_{q1} \ f_{d2} \ f_{q2}]^T = T_s [f_A \ f_B \ f_C \ f_U \ f_V \ f_W]^T$$

f stands for variable such as voltage, current and flux (5)

$$T_s = \begin{bmatrix} T_1 & 0 \\ 0 & T_2 \end{bmatrix} \quad (6)$$

$$T_1 = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ -\sin \theta & -\sin \left(\theta - \frac{2\pi}{3} \right) & -\sin \left(\theta + \frac{2\pi}{3} \right) \end{bmatrix} \quad (7)$$

$$T_2 = \frac{2}{3} \begin{bmatrix} \cos \left(\theta - \frac{\pi}{3} \right) & \cos(\theta - \pi) & \cos \left(\theta + \frac{\pi}{3} \right) \\ -\sin \left(\theta - \frac{\pi}{3} \right) & -\sin(\theta - \pi) & -\sin \left(\theta + \frac{\pi}{3} \right) \end{bmatrix} \quad (8)$$

where θ is rotor position in electrical angle.

Fig. 2 Block diagram of load current and voltage.

The voltage and flux equations for DTP-PMSM in dq frame can be deduced as (9) and (10) by substituting (5)-(8) into (1) and (2):

$$\begin{bmatrix} u_{d1} \\ u_{q1} \\ u_{d2} \\ u_{q2} \end{bmatrix} = R \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \begin{bmatrix} \dot{\varphi}_{d1} \\ \dot{\varphi}_{q1} \\ \dot{\varphi}_{d2} \\ \dot{\varphi}_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \varphi_{d1} \\ \varphi_{q1} \\ \varphi_{d2} \\ \varphi_{q2} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} \varphi_{d1} \\ \varphi_{q1} \\ \varphi_{d2} \\ \varphi_{q2} \end{bmatrix} = \begin{bmatrix} L_d & 0 & L_{dd} & 0 \\ 0 & L_q & 0 & L_{qq} \\ L_{dd} & 0 & L_d & 0 \\ 0 & L_{qq} & 0 & L_q \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \varphi_m \quad (10)$$

where L_d and L_q are total inductances in dq frame; L_{dd} and L_{qq} are coupling inductances between two sets of windings which have the following relationships:

$$L_d = L_{dd} + L_z \quad (11)$$

$$L_q = L_{qq} + L_z \quad (12)$$

Substitute (10) into (9), giving

$$\begin{bmatrix} u_{d1} \\ u_{q1} \\ u_{d2} \\ u_{q2} \end{bmatrix} = \begin{bmatrix} R & -\omega_e L_q & 0 & -\omega_e L_{qq} \\ \omega_e L_d & R & \omega_e L_{dd} & 0 \\ 0 & -\omega_e L_{qq} & R & -\omega_e L_q \\ \omega_e L_{dd} & 0 & \omega_e L_d & R \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \begin{bmatrix} L_d & 0 & L_{dd} & 0 \\ 0 & L_q & 0 & L_{qq} \\ L_{dd} & 0 & L_d & 0 \\ 0 & L_{qq} & 0 & L_q \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} 0 \\ \varphi_m \\ 0 \\ \varphi_m \end{bmatrix} \quad (13)$$

One can obtain the following torque equation by transforming (4) into the dq rotating frame using (5)-(8):

$$T_e = \frac{3}{2} P_p [(L_d - L_q)(i_{d1} + i_{d2})(i_{q1} + i_{q2}) + (i_{q1} + i_{q2})\varphi_m] \quad (14)$$

In starter mode, the controlled variable is machine speed which is governed by the following equation [18]:

$$J \frac{d\omega_m}{dt} = T_e - T_L \quad (15)$$

where T_L is engine torque during start-up, J is a total inertia and ω_m is mechanical speed.

In generator mode, the controlled variable, according to the designed system requirements, is output DC current. This can be governed by the converter equation as follows [18]:

$$i_{dc} = \frac{3}{4} (m_{d1} i_{d1} + m_{q1} i_{q1} + m_{d2} i_{d2} + m_{q2} i_{q2}) \quad (16)$$

where m_d and m_q are the modulation indexes of the converter [18]:

$$m_{d1} = \frac{2u_{d1}}{u_{dc}}, m_{q1} = \frac{2u_{q1}}{u_{dc}}, m_{d2} = \frac{2u_{d2}}{u_{dc}}, m_{q2} = \frac{2u_{q2}}{u_{dc}} \quad (17)$$

Fig. 3 Block diagram of DC voltage control loop.

Fig. 4 Conceptual control scheme of S/G system.

u_{dc} is the converter output voltage (across the output capacitor C) [18]. As illustrated in Fig. 2, u_{dc} and i_{dc} has following relationship:

$$C \frac{du_{dc}}{dt} = i_{dc} - i_L \quad (18)$$

where i_L is the current drawn by the load [19].

Assuming i_L is neglected, (18) can be simplified as:

$$u_{dc} = \frac{i_{dc}}{C \cdot s} \quad (19)$$

where s is differential operator. According to (19), a PI controller is designed to control u_{dc} , which is shown in Fig. 3.

According to energy conservation law, the electrical power generated by the system is equal to the mechanical power injected into the system. Hence, electromagnetic torque can be presented as

$$T_e = \frac{u_{dc} i_{dc}}{\omega_m} \quad (20)$$

Since electromagnetic torque is proportional to q -axis current, combining (19) and (20), the reference of q -axis current can be generated by u_{dc} , as illustrated in Fig. 9.

III. CONTROL DESIGN

In this section, design of control system is investigated. Firstly, capabilities and limitations of S/G system are analysed. According to the capabilities and limitations of S/G system, a direct current flux weakening control approach is developed to avoid overmodulation. Control of starter mode and generator mode are mentioned at the end of this section.

The general control scheme for the S/G can be seen in Fig. 4. ω_m is the mechanical speed, S_{abcuvw} is six phase switching states and all variables with the * notation denote the reference value of controlled variable.

A. S/G System Capabilities and Limitations.

Control of the system is established in terms of a synchronously rotating dq frame which is aligned with the rotor. Current control has been solved in a traditional method by employing a proportional plus integral current controller

Fig. 5 ACHIEVE system voltage and current limit circles.

with standard tuning [21]. The closed-loop natural frequency is set to 500 Hz with a damping factor of 0.707. The parameters of the system are detailed in Appendix B.

There are two factors that restrict the control performance in the designed system. One is the maximum current of the converter IGBTs $I_{max} = 34$ A and the other is the machine maximum phase voltage on the converter ac side $U_{max} = \frac{540}{\sqrt{3}} V = 311$ V. Thus, the following relationships exist:

$$U_{max}^2 \geq u_{d1,2}^2 + u_{q1,2}^2 \quad (21)$$

Assuming steady state operation and ignoring stator resistance, the machine electrical equations (13) can be reduced to:

$$\begin{bmatrix} u_{d1} \\ u_{q1} \\ u_{d2} \\ u_{q2} \end{bmatrix} = \begin{bmatrix} 0 & -\omega_e L_q & 0 & -\omega_e L_{qq} \\ \omega_e L_d & 0 & \omega_e L_{dd} & 0 \\ 0 & -\omega_e L_{qq} & 0 & -\omega_e L_q \\ \omega_e L_{dd} & 0 & \omega_e L_d & 0 \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} 0 \\ \varphi_m \\ 0 \\ \varphi_m \end{bmatrix} \quad (22)$$

Since the two sets of three-phase windings are exactly symmetric, if the current controllers of these two dq frames share same parameters, (22) can be expressed as:

$$\begin{bmatrix} u_{d1} \\ u_{q1} \\ u_{d2} \\ u_{q2} \end{bmatrix} = \begin{bmatrix} 0 & -\omega_e L_Q & 0 & 0 \\ \omega_e L_D & 0 & 0 & 0 \\ 0 & 0 & 0 & -\omega_e L_Q \\ 0 & 0 & \omega_e L_D & 0 \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} 0 \\ \varphi_m \\ 0 \\ \varphi_m \end{bmatrix} \quad (23)$$

where

$$L_D = L_d + L_{dd} \quad (24)$$

$$L_Q = L_q + L_{qq} \quad (25)$$

From (23), the following can be derived:

$$u_{d1,2} = -\omega_e L_Q i_{q1,2} \quad (26)$$

$$u_{q1,2} = \omega_e (L_D i_{d1,2} + \varphi_m) \quad (27)$$

The voltage limit equation can be deduced using (21), (26) and (27) [22]:

$$\left(\frac{U_{max}}{\omega_e L_Q}\right)^2 = \left(\frac{L_D}{L_Q} i_{d1,2} + \frac{\varphi_m}{L_Q}\right)^2 + i_{q1,2}^2 \quad (28)$$

The following equation represents current limit in terms of dq frame currents [22]:

$$I_{max}^2 \geq i_{d1,2}^2 + i_{q1,2}^2 \quad (29)$$

The voltage and current limit circles can be plotted according to (28) and (29) on an $i_d - i_q$ plane. The radius of the voltage ellipse decreases as the speed increases from 14 krpm to 18 krpm, as shown in Fig. 5. The black circle represents the current limit while the others are the voltage limits at different operating speeds. Theoretically, infinite speed can be achieved as the center point is within the current limit circle. The center point of this circle is the critical current at $-\frac{\varphi_m}{L_D}$ or -65.2 A.

B. Flux Weakening Control

To avoid converter overmodulation, flux weakening control is introduced. In this study, flux weakening mode is achieved by controlling the i_d current component (direct current method). Rigorous design of direct current method in both starter mode and generator mode has been investigated in [28]. As illustrated in Fig. 6, the machine voltage is controlled to U_{max} by voltage controller that produces the reference for d -axis current. And a dynamic limiter is used to limit reference of q -axis current $i_{q1,2}^*$. When $i_{q1,2}^*$ is within $[-i_{qlim}, i_{qlim}]$, where $i_{qlim} = \sqrt{I_{max}^2 - i_{d1,2}^{*2}}$, $i_{q1,2}^*$ is determined by the output of the speed controller, otherwise the dynamic limiter is active and it will be completely determined by $i_{d1,2}^*$ as shown in the following:

$$i_{q1,2}^* \leq i_{qlim} = \sqrt{I_{max}^2 - i_{d1,2}^{*2}} \quad (30)$$

C. Starter Mode Control

In starter mode, the system task is to accelerate the engine to up to 18 krpm which can be implemented by building a speed control system that facilitates smooth engine acceleration. The standard PI speed controller design procedure [21] is applied. The speed loop bandwidth is set to 5Hz with a damping factor of 0.707.

Fig. 6 Flux weakening control diagram.

D. Generator Mode Control

In generator mode, the speed of the engine is controlled externally, and control of the DC link bus power is the primary objective. The S/G is designed to provide up to 20 kW of electrical power to the 540 V DC bus and should also be capable of operation in parallel with other power sources connected to the common DC bus. The control of DC generator is designed to supply constant DC voltage even with variable engine speed (14 krpm to 18 krpm) and electrical loads. Besides, DC voltage is designed to satisfy aircraft standards (refer to MIL-STD-704F [23]) in order to ensure compatibility between the aircraft electrical power system and other loads.

IV. MODEL REFERENCE ADAPTIVE SYSTEM

As illustrated in Fig. 7 [24], the MRAS estimator in this paper uses two models to calculate stator current of the machine. One model is a reference model and the other is an adaptive model. The error between the outputs from these two models are used to drive a suitable adaptation mechanism which generates the estimated rotor speed.

To simplify analysis, stator voltage equation (13) is converted to stator current equation:

$$\frac{d}{dt} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} = A \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + B \begin{bmatrix} u_{d1} \\ u_{q1} - \omega_e \varphi_m \\ u_{d2} \\ u_{q2} - \omega_e \varphi_m \end{bmatrix} \quad (31)$$

where A and B are state matrixes that are detailed in Appendix A.

(31) can be regulated as:

$$\frac{d}{dt} \begin{bmatrix} i_{d1} + \frac{\varphi_m}{L_d + L_{dd}} \\ i_{q1} \\ i_{d2} + \frac{\varphi_m}{L_d + L_{dd}} \\ i_{q2} \end{bmatrix} = A \begin{bmatrix} i_{d1} + \frac{\varphi_m}{L_d + L_{dd}} \\ i_{q1} \\ i_{d2} + \frac{\varphi_m}{L_d + L_{dd}} \\ i_{q2} \end{bmatrix} + B \begin{bmatrix} u_{d1} + \frac{R\varphi_m}{L_d + L_{dd}} \\ u_{q1} \\ u_{d2} + \frac{R\varphi_m}{L_d + L_{dd}} \\ u_{q2} \end{bmatrix} \quad (32)$$

Define

$$\begin{cases} i'_{d1} = i_{d1} + \frac{\varphi_m}{L_d + L_{dd}} \\ i'_{q1} = i_{q1} \\ u'_{d1} = u_{d1} + \frac{R\varphi_m}{L_d + L_{dd}} \\ u'_{q1} = u_{q1} \end{cases} \quad \begin{cases} i'_{d2} = i_{d2} + \frac{\varphi_m}{L_d + L_{dd}} \\ i'_{q2} = i_{q2} \\ u'_{d2} = u_{d2} + \frac{R\varphi_m}{L_d + L_{dd}} \\ u'_{q2} = u_{q2} \end{cases} \quad (33)$$

Fig. 7 Block diagram of MRAS.

$$\frac{d}{dt} \begin{bmatrix} i'_{d1} \\ i'_{q1} \\ i'_{d2} \\ i'_{q2} \end{bmatrix} = A \begin{bmatrix} i'_{d1} \\ i'_{q1} \\ i'_{d2} \\ i'_{q2} \end{bmatrix} + B \begin{bmatrix} u'_{d1} \\ u'_{q1} \\ u'_{d2} \\ u'_{q2} \end{bmatrix} \quad (34)$$
$$\frac{d}{dt}i' = Ai' + Bu' \quad (35)$$

The Adjustable Model in Fig. 7 is obtained by replacing actual variables in (35) with estimated variables:

$$\hat{t}' = \begin{bmatrix} \hat{i}'_{d1} \\ \hat{i}'_{q1} \\ \hat{i}'_{d2} \\ \hat{i}'_{q2} \end{bmatrix} = \begin{bmatrix} \hat{i}_{d1} + \frac{\varphi_m}{L_d + L_{dd}} \\ \hat{i}_{q1} \\ \hat{i}_{d2} + \frac{\varphi_m}{L_d + L_{dd}} \\ \hat{i}_{q2} \end{bmatrix} \quad (37)$$

$$e = i' - \hat{i}' = \begin{bmatrix} i'_{d1} - \hat{i}'_{d1} \\ i'_{q1} - \hat{i}'_{q1} \\ i'_{d2} - \hat{i}'_{d2} \\ i'_{q2} - \hat{i}'_{q2} \end{bmatrix} \quad (38)$$
$$W = (\hat{\omega}_e - \omega_e)Y \begin{bmatrix} \hat{l}'_{d1} \\ \hat{l}'_{q1} \\ \hat{l}'_{d2} \\ \hat{l}'_{q2} \end{bmatrix} \quad (41)$$
$$Y = \begin{bmatrix} 0 & \frac{L_d L_q - L_{dd} L_{qq}}{L_d^2 - L_{dd}^2} & 0 & \frac{L_d L_{qq} - L_{dd} L_q}{L_d^2 - L_{dd}^2} \\ \frac{L_{dd} L_{qq} - L_d L_q}{L_q^2 - L_{qq}^2} & 0 & \frac{L_d L_{qq} - L_{dd} L_q}{L_q^2 - L_{qq}^2} & 0 \\ 0 & \frac{L_d L_{qq} - L_{dd} L_q}{L_d^2 - L_{dd}^2} & 0 & \frac{L_d L_q - L_{dd} L_{qq}}{L_d^2 - L_{dd}^2} \\ \frac{L_d L_{qq} - L_{dd} L_q}{L_q^2 - L_{qq}^2} & 0 & \frac{L_{dd} L_{qq} - L_d L_q}{L_q^2 - L_{qq}^2} & 0 \end{bmatrix}$$
$$\hat{\omega}_e = \left(K_p + \frac{K_i}{s}\right) \varepsilon \quad (42)$$
$$\varepsilon = i'_{d1}\hat{l}'_{q1} - \hat{l}'_{d1}i'_{q1} + i'_{d2}\hat{l}'_{q2} - \hat{l}'_{d2}i'_{q2} \quad (43)$$
$$\begin{aligned} \hat{\omega}_e = & \left(K_p + \frac{K_i}{s}\right) [i_{d1}\hat{i}_{q1} - \hat{i}_{d1}i_{q1} + i_{d2}\hat{i}_{q2} - \hat{i}_{d2}i_{q2} - \\ & \frac{\varphi_m}{L_d}(i_{q1} - \hat{i}_{q1} + i_{q2} - \hat{i}_{q2})] \end{aligned} \quad (44)$$
$$\hat{\theta}_e = \int \hat{\omega}_e d\tau \quad (45)$$

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Fig. 9 Block diagram of sensorless system in generator mode.

Fig. 10 Simulation results of DC voltage in generator mode.

Fig. 11 Simulation results of system (a) starter mode (b) generator mode.

Fig. 12 Comparison of actual and estimated rotor position (a) starter mode (b) generator mode.

V. SIMULATION RESULTS

Performance of designed sensorless S/G system has been verified through time-domain simulation using system models (Fig. 8 and Fig. 9) build in MATLAB/SimPower. Simulations of starter mode operation are given in Fig. 11(a)

and Fig. 12(a). In starter mode, there are two stages. The first stage covers from beginning to 2.5 s while the second stage lasts from 2.5 s to 4 s. In the first stage, there is no load torque and rotor speed increases steadily from 0 rpm to 18 krpm during the first two seconds and retains at 18 krpm afterwards.

Based on speed response characteristic, the response of electromagnetic torque can be verified by applying parameters in Table. 1 to (14). By plotting dq axis current responses in the voltage and current limit circle, the current trajectory during this period moves along the green locus from point O to point A and then point B as shown in Fig. 5. In the second stage, a torque load is applied which grows steadily from 0 N.m to 100% rated load -14.8 N.m between 2.5 s and 3.5 s and keeps constant to the end of simulation. It can be observed immediately that electromagnetic torque and voltages in dq frame have good responses. The current trajectory during this interval moves along the voltage limit ellipse of 18 krpm as the green locus from point B to point C in Fig. 5. In both stages, the current trajectory of starter mode is always within current limit circle, which is an identification of system capabilities and limitations discussed in section III. Besides, in both stages, the dq frame voltage response figure, $u_{d1,2}$, $u_{q1,2}$ and their square root $|u|$ are always within voltage limit range $[-U_{max}, +U_{max}]$. Hence, good flux weakening control performance is confirmed. In Fig. 12 (a), the estimated rotor position is compared with the actual position. The maximum position error between them is less than $3.5 \times 10^{-5} \text{ rad}$, indicating the satisfactory robustness of this estimation method.

Results of generator mode are shown in Fig. 11(b) and Fig. 12(b). In generator mode, there are also two stages. The first stage lasts from beginning to 0.01 s and then the second stage starts until the end of simulation. In the first stage, the power system is not subjected to any load. The current trajectory of this stage is the red straight line from point O to point B shown in Fig. 5. At the beginning of second stage, a full load (20 KW) is applied to the system in the form of a step function. The electromagnetic torque in steady state is observed as -10.9 N.m in Fig. 11(b). Since the rotor speed is a constant value (18 krpm), the value of electromagnetic torque can be verified by (20). The current trajectory of this stage moves along the voltage limit ellipse of 18 krpm from point B to point D as depicted in Fig. 5. The negative sign of both electromagnetic torque and q -axis current confirm that the machine operates as a generator. As observed in Fig. 10, DC voltage response is within limitation boundaries. Hence, the effectiveness of DC voltage control can be verified. In Fig. 12(b), the estimated rotor position is compared with the actual position. The maximum position error between them is larger than that of starter mode but still tiny, less than $3.5 \times 10^{-3} \text{ rad}$, which proves good performance of estimator.

VI. CONCLUSIONS

A robust speed estimator based on an MRAS structure has been proposed for a sensorless symmetric DTP-PMSM. The proposed MRAS approach can be applied both in starter mode and generator mode for MEA. It has been shown that the rotor speed and position can be accurately tracked in both modes. The robustness of the proposed system is confirmed in the case of load torque variation and the effectiveness of the proposed algorithm is verified by simulation results.

ACKNOWLEDGEMENT

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020

research and innovation program under grant agreement No 737814.

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APPENDIX A

M_o and M_x are matrixs in inductance equation (3):

$$M_o = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & -1 & \frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ -\frac{1}{2} & -\frac{1}{2} & 1 & -1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & -1 & 1 & -\frac{1}{2} & -\frac{1}{2} \\ -1 & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & 1 & -\frac{1}{2} \\ \frac{1}{2} & -1 & \frac{1}{2} & -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix}$$

A , $\hat{A}$ and B are matrixs in current equation (35) and (36):

$$M_x = \begin{bmatrix} \cos 2\theta & \cos\left(2\theta - \frac{2\pi}{3}\right) & \cos\left(2\theta + \frac{2\pi}{3}\right) & \cos\left(2\theta - \frac{\pi}{3}\right) & \cos(2\theta - \pi) & \cos\left(2\theta + \frac{\pi}{3}\right) \\ \cos\left(2\theta - \frac{2\pi}{3}\right) & \cos\left(2\theta + \frac{2\pi}{3}\right) & \cos 2\theta & \cos(2\theta - \pi) & \cos\left(2\theta + \frac{\pi}{3}\right) & \cos\left(2\theta - \frac{\pi}{3}\right) \\ \cos\left(2\theta + \frac{2\pi}{3}\right) & \cos 2\theta & \cos\left(2\theta - \frac{2\pi}{3}\right) & \cos\left(2\theta + \frac{\pi}{3}\right) & \cos\left(2\theta - \frac{\pi}{3}\right) & \cos(2\theta - \pi) \\ \cos\left(2\theta - \frac{\pi}{3}\right) & \cos(2\theta - \pi) & \cos\left(2\theta + \frac{\pi}{3}\right) & \cos\left(2\theta - \frac{2\pi}{3}\right) & \cos\left(2\theta - \frac{4\pi}{3}\right) & \cos 2\theta \\ \cos(2\theta - \pi) & \cos\left(2\theta + \frac{\pi}{3}\right) & \cos\left(2\theta - \frac{\pi}{3}\right) & \cos\left(2\theta - \frac{4\pi}{3}\right) & \cos 2\theta & \cos\left(2\theta - \frac{2\pi}{3}\right) \\ \cos\left(2\theta + \frac{\pi}{3}\right) & \cos\left(2\theta - \frac{\pi}{3}\right) & \cos(2\theta - \pi) & \cos 2\theta & \cos\left(2\theta - \frac{2\pi}{3}\right) & \cos\left(2\theta - \frac{4\pi}{3}\right) \end{bmatrix}$$

APPENDIX B

Table 1 Parameters of machine

Parameter	Mark	Value	Unit
Phase Resistance	R	0.41	Ohm
D-axis Inductance	L_d	365	μH
Q-axis Inductance	L_q	410	μH
Leakage Inductance	L_z	291	μH
Rotational Inertia	J	0.00263	$\text{kg}\cdot\text{m}^2$
Peak No-load Flux Linkage per Channel	φ_m	0.0287	$\text{V}\cdot\text{s}$
Pole Pairs number	P_p	6	/
Phase Peak Current	I_{max}	34	A
Phase Peak Voltage	U_{max}	311	V
Base Speed/Max Speed	/	1400/1800	Hz

$$B = \begin{bmatrix} \frac{L_d}{L_d^2 - L_{dd}^2} & 0 & -\frac{L_{dd}}{L_d^2 - L_{dd}^2} & 0 \\ 0 & \frac{L_q}{L_q^2 - L_{qq}^2} & 0 & -\frac{L_{qq}}{L_q^2 - L_{qq}^2} \\ -\frac{L_{dd}}{L_d^2 - L_{dd}^2} & 0 & \frac{L_d}{L_d^2 - L_{dd}^2} & 0 \\ 0 & -\frac{L_{qq}}{L_q^2 - L_{qq}^2} & 0 & \frac{L_q}{L_q^2 - L_{qq}^2} \end{bmatrix}$$

$$A = \begin{bmatrix} -\frac{L_d R}{L_d^2 - L_{dd}^2} & \frac{\omega_e(L_d L_q - L_{dd} L_{qq})}{L_d^2 - L_{dd}^2} & \frac{L_{dd} R}{L_d^2 - L_{dd}^2} & \frac{\omega_e(L_d L_{qq} - L_{dd} L_q)}{L_d^2 - L_{dd}^2} \\ \frac{\omega_e(L_{dd} L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & -\frac{L_q R}{L_q^2 - L_{qq}^2} & \frac{\omega_e(L_d L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & \frac{L_{qq} R}{L_q^2 - L_{qq}^2} \\ \frac{L_{dd} R}{L_d^2 - L_{dd}^2} & \frac{\omega_e(L_d L_{qq} - L_{dd} L_q)}{L_d^2 - L_{dd}^2} & -\frac{L_d R}{L_d^2 - L_{dd}^2} & \frac{\omega_e(L_d L_q - L_{dd} L_{qq})}{L_d^2 - L_{dd}^2} \\ \frac{\omega_e(L_d L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & \frac{L_{qq} R}{L_q^2 - L_{qq}^2} & \frac{\omega_e(L_{dd} L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & -\frac{L_q R}{L_q^2 - L_{qq}^2} \end{bmatrix}$$

$$\hat{A} = \begin{bmatrix} -\frac{L_d R}{L_d^2 - L_{dd}^2} & \frac{\hat{\omega}_e(L_d L_q - L_{dd} L_{qq})}{L_d^2 - L_{dd}^2} & \frac{L_{dd} R}{L_d^2 - L_{dd}^2} & \frac{\hat{\omega}_e(L_d L_{qq} - L_{dd} L_q)}{L_d^2 - L_{dd}^2} \\ \frac{\hat{\omega}_e(L_{dd} L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & -\frac{L_q R}{L_q^2 - L_{qq}^2} & \frac{\hat{\omega}_e(L_d L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & \frac{L_{qq} R}{L_q^2 - L_{qq}^2} \\ \frac{L_{dd} R}{L_d^2 - L_{dd}^2} & \frac{\hat{\omega}_e(L_d L_{qq} - L_{dd} L_q)}{L_d^2 - L_{dd}^2} & -\frac{L_d R}{L_d^2 - L_{dd}^2} & \frac{\hat{\omega}_e(L_d L_q - L_{dd} L_{qq})}{L_d^2 - L_{dd}^2} \\ \frac{\hat{\omega}_e(L_d L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & \frac{L_{qq} R}{L_q^2 - L_{qq}^2} & \frac{\hat{\omega}_e(L_{dd} L_{qq} - L_{dd} L_q)}{L_q^2 - L_{qq}^2} & -\frac{L_q R}{L_q^2 - L_{qq}^2} \end{bmatrix}$$