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Direct Torque Control Theory of a Double Three-Phrase Permanent Magnet Synchronous Motor

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***Abstract* — This paper discusses a double three-phrase permanent magnet synchronous mathematic (DTP-PMSM) mode. Two kinds of analysis methods for DTP-PMSM Direct Torque Control theory research are provided. The first one is the flux linkage where the direct torque control (DTC) theory is similar to the three phrases PMSM。The second one is the flux linkage produced by each set of winding. The function relation of the torque and its angle can be obtained easily. Simulation shows that the torque characteristic has been researched on one or both set of windings. The simulation results have also shown that two approaches may be feasible and the motor operation may be selective in term of application occasion. The research result is a foundation of theory and application for the DTP-PMSM control system.**

***Keywords*—Permanent Magnet Synchronous Motor, Direct Torque Control, Mathematic Model, simulation analysis**

I. INTRODUCTION

In most cases, the propulsion motor is a polyphones permanent-magnet synchronous motor in the vessel power electric propulsion system. However, the Double three-phrase permanent magnet synchronous (DTP-PMSM) mode which has two sets of three phrases symmetrical winding has been used largely. There is a 30° phrase difference in corresponding phrase of two sets of winding in space. In each set of winding, the sixth time-harmonic pulse torque is equal in size and opposites in direction. This makes the total sixth time-harmonic pulse torque vanished and Magnetic Motive Force (MMF) curve is much smooth. Comparing the DTP- PMSM with PMSM in the same power, the input rating voltage of the DTP-PMSM is only half of the PMSM. That means each inverter only bears half of the total power. In this way, there are more selective in DTP-PMSM control. With these merits, the proposed approach fits better in high power and current condition such as in vessel power electric propulsion system, aviation, and electric vehicle system. Vector control and direct torque control are two popular control methods for a motor. The PMSM may be controlled better in the direct torque theory in power electric propulsion system as shown in [1]-[4]. The following describes the control of DTP-PMSM in direct torque theory.

II. DTP-PMSM MATHEMATIC MODEL AND DTC THEORY RESEARCH

The DTP-PMSM physic model is shown in Fig. 1. The rotor flux linkage may be equivalent to a flux linkage which the idea current source produces; there is an angle θ between the d-axis and *A1*-axis. From control view, there are two kinds of control methods for the DTP-PMSM; that is, the compound flux linkage control and independence flux linkage control. In order to give prominence to main problems, it is ignored such as space harmonic, magnetic saturation, hysteresis, backset and temperature when the DTP- PMSM mathematic model is built. There is an angle of 120° between each phrase winding in electric. So, the magnet motive force curve is a sine wave.

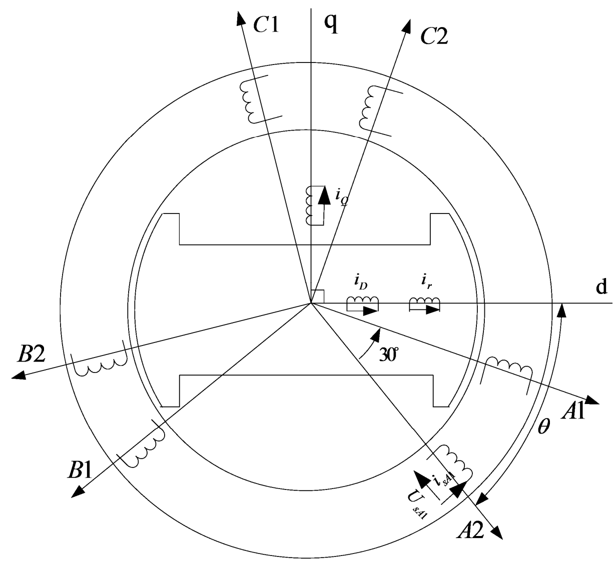

Fig. 1 The DTP- PMSM physic mode

A. Research on DTC Theory under Compounding Flux Linkage

Under static stator *ABC* coordinate system, the mathematic model is built for the DTP-PMSM. The DTP-PMSM has two sets of three-phrase winding. The center spot is independence. There is a 30° phase difference of the input voltage between the corresponding phrases of two sets winding, where u, i, ψ

(subscript is $A1$, $B1$, $C1$, $A2, B2, C2$) is used to show voltage, current, and flux linkage in *d*-axis and *q*-axis for the DTP-PMSM, where p is a differential arithmetic operator symbol. So the DTP-PMSM voltage equation is expressed in the following in static reference frame.

$$\begin{bmatrix} u_{sA1} \\ u_{sB1} \\ u_{sC1} \\ u_{sA2} \\ u_{sB2} \\ u_{sC2} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 & 0 \\ 0 & 0 & R_s & 0 & 0 & 0 \\ 0 & 0 & 0 & R_s & 0 & 0 \\ 0 & 0 & 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{sA1} \\ i_{sB1} \\ i_{sC1} \\ i_{sA2} \\ i_{sB2} \\ i_{sC2} \end{bmatrix} + p \begin{bmatrix} \psi_{sA1} \\ \psi_{sB1} \\ \psi_{sC1} \\ \psi_{sA2} \\ \psi_{sB2} \\ \psi_{sC2} \end{bmatrix}$$
(1)

where R_S is each phrase stator resistance. Each phrase flux linkage is composed of self and mutual flux linkages. If we do not consider convex pole effect to influence motor and mutual inductance [5]-[7], the flux linkage can be decomposed in *d*-axis and *q*-axis. The DTP-PMSM flux linkage equation is given as follows.

$$\begin{bmatrix} \psi_{sA1} \\ \psi_{sB1} \\ \psi_{sC1} \\ \psi_{sA2} \\ \psi_{sB2} \\ \psi_{sC2} \end{bmatrix} = \begin{bmatrix} L_{A1A1} & L_{A1B1} & L_{A1C1} & L_{A1A2} & L_{A1B2} & L_{A1C2} \\ L_{B1A1} & L_{B1B1} & L_{B1C1} & L_{B1A2} & L_{B1B2} & L_{B1C2} \\ L_{C1A1} & L_{C1B1} & L_{C1C1} & L_{C1A2} & L_{C1B2} & L_{C1C2} \\ L_{A2A1} & L_{A2B1} & L_{A2C1} & L_{A2A2} & L_{A2B2} & L_{A2C2} \\ L_{B2A1} & L_{B2B1} & L_{B2C1} & L_{B2A2} & L_{B2B2} & L_{B2C2} \\ L_{C2A1} & L_{C2B1} & L_{C2C1} & L_{C2A2} & L_{C2B2} & L_{C2C2} \end{bmatrix} \begin{bmatrix} i_{sA1} \\ i_{sB1} \\ i_{sC1} \\ i_{sA2} \\ i_{sB2} \\ i_{sC2} \end{bmatrix} + \psi_r \begin{bmatrix} \cos\theta \\ \cos(\theta-120^\circ) \\ \cos(\theta+120^\circ) \\ \cos(\theta-30^\circ) \\ \cos(\theta-150^\circ) \\ \cos(\theta+90^\circ) \end{bmatrix} \quad (2)$$

$L_{A1A1} = L_s + L_m + L_t \cos(2\theta)$,
$L_{A2A2} = L_s + L_m + L_t \cos(2\theta - 60^\circ)$,
$L_{B1B1} = L_s + L_m + L_t \cos(2\theta - 120^\circ)$,
$L_{B2B2} = L_s + L_m + L_t \cos(2\theta - 180^\circ)$,
$L_{C1C1} = L_s + L_m + L_t \cos(2\theta + 120^\circ)$,
$L_{C2C2} = L_s + L_m + L_t \cos(2\theta + 60^\circ)$,
$L_{A1B1} = L_m \cos(-120^\circ) + L_t \cos(2\theta + 120^\circ)$,
$L_{A1C1} = L_m \cos(120^\circ) + L_t \cos(2\theta - 120^\circ)$,
$L_{B1C1} = L_m \cos(120^\circ) + L_t \cos(2\theta)$,
$L_{A1A2} = L_{A2A1} = L_m \cos(30^\circ) + L_t \cos(2\theta - 30^\circ)$,
$L_{A1B2} = L_{B2A1} = L_m \cos(-90^\circ) + L_t \cos(2\theta + 90^\circ)$,
$L_{A1C2} = L_{C2A1} = L_m \cos(150^\circ) + L_t \cos(2\theta - 150^\circ)$,
$L_{A2B1} = L_{B1A2} = L_m \cos(150^\circ) + L_t \cos(2\theta + 90^\circ)$,
$L_{A2C1} = L_{C1A2} = L_m \cos(-90^\circ) + L_t \cos(2\theta - 150^\circ)$,
$L_{B2B1} = L_{B1B2} = L_m \cos(30^\circ) + L_t \cos(2\theta - 150^\circ)$,
$L_{B2C1} = L_{C1B2} = L_m \cos(150^\circ) + L_t \cos(2\theta - 30^\circ)$,
$L_{C2C1} = L_{C1C2} = L_m \cos(30^\circ) + L_t \cos(2\theta + 90^\circ)$,
$L_{A2C2} = L_{C2A2} = L_m \cos(120^\circ) + L_t \cos(2\theta - 180^\circ)$,
$L_{A2B2} = L_{B2A2} = L_m \cos(-120^\circ) + L_t \cos(2\theta + 60^\circ)$,
$L_{B2C2} = L_{C2B2} = L_m \cos(120^\circ) + L_t \cos(2\theta - 60^\circ)$

where L_{ij} is self-inductance in $i = j$ or mutual inductance in $i \neq j$, L_s is the stator leakage inductance, L_m is an invariable of mutual inductance, and L_t is a variable of mutual inductance.

The DTP-PMSM mathematic model is very complex in stator static coordinate system; but it may be transferred two phrases motor model in *d-q* coordinate system. The mathematic model can be predigested in orthogonal Park transform [8]. The stator static coordinate system is transformed into rotor *d-q* coordinate system through the following matrix.

$$C_{3s/2r} = N\begin{bmatrix} \cos\theta & \cos(\theta-12\theta^\circ) & \cos(\theta+12\theta^\circ) & \cos(\theta-3\theta^\circ) & \cos(\theta-15\theta^\circ) & \cos(\theta+9\theta^\circ) \\ -\sin\theta & -\sin(\theta-120^\circ) & -\sin(\theta+120^\circ) & -\sin(\theta-30^\circ) & -\sin(\theta-150^\circ) & -\sin(\theta+90^\circ) \end{bmatrix} \quad (3)$$

where $C_{3s/2r} C^T{}_{3s/2r} = E_{2\times2}$, so, $3N^2 = 1$, $n = 1/\sqrt{3}$ then:

$$C_{3s/2r} = \frac{1}{\sqrt{3}}\begin{bmatrix} \cos\theta & \cos(\theta-12\theta^\circ) & \cos(\theta+12\theta^\circ) & \cos(\theta-3\theta^\circ) & \cos(\theta-15\theta^\circ) & \cos(\theta+9\theta^\circ) \\ -\sin\theta & -\sin(\theta-120^\circ) & -\sin(\theta+120^\circ) & -\sin(\theta-30^\circ) & -\sin(\theta-150^\circ) & -\sin(\theta+90^\circ) \end{bmatrix} \quad (4)$$

Using the transformation matrix in Eq. (4), Equations (1)-(2) may be transformed from stator *ABC* to *d-q* coordinate system.

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} p & p \\ \omega_r & -\omega_r \end{bmatrix} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} \quad (5)$$

The flux linkage equation is rewritten for DTP-PMSM in *d-q* coordinate system:

$$\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \psi_r \begin{bmatrix} \sqrt{3} \\ 0 \end{bmatrix} \quad (6)$$

where $L_d = L_s + 3L_m + 3L_t$, $L_q = L_s + 3L_m - 3L_t$ other parameters are the same as (1) - (2).

We can set up the compound flux linkage in M-T coordinate system as shown in Fig. 2, where the compound flux linkage direction is the same as M axis, the torque and torque angle function can be expressed as:

$$T_e = \frac{n_p}{2L_d L_q}|\psi_s|\left[2\sqrt{3}\psi_r L_q \sin\delta - |\psi_s|(L_q - L_d)\sin 2\delta\right] \quad (7)$$

where ψ_s is the compound flux linkage. L_d and L_q are equivalent to inductance of two sets of winding in *d*-axis and *q*-axis, respectively. Under the compound flux linkage, the function of the torque and torque angle is similar to the ordinary PMSM. So, the control method of the DTP-PMSM is also similar to the ordinary PMSM; but it is noticed that the torque is produced by the compound magnet flux linkage.

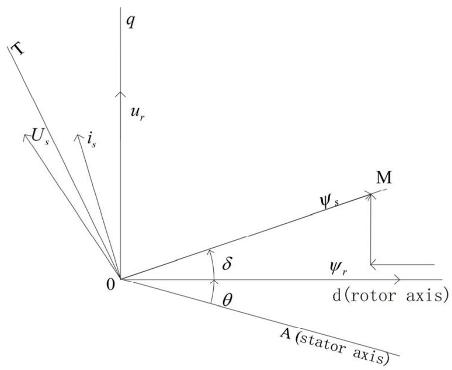

Fig. 2. The stator and rotor reference axis for the PMSM

B. Research on DTC Theory under Independent Flux Linkage Condition

Under static coordinate system, the voltage, the current, and the flux linkage equations of each set of winding are the same as three phrases PMSM. Equation (2) may be rewritten in term of its broken line in matrix.

$$\begin{bmatrix}\psi_{s1}\\ \psi_{s2}\end{bmatrix} = \begin{bmatrix}L_{s1s1} & L_{s1s2}\\ L_{s2s1} & L_{s2s2}\end{bmatrix}\begin{bmatrix}i_{s1}\\ i_{s2}\end{bmatrix} + \psi_r\begin{bmatrix}S_{\theta 1}\\ S_{\theta 2}\end{bmatrix} \quad (8)$$

where $L_{s1s2} = L^T{}_{s2s1}$. According to constant power orthogonal Park transform, each sets winding (three phrases) may be transformed into two phrases in *d*-*q* coordinate system, the transformation matrix is:

$$C_{3s1/2r} = \sqrt{\tfrac{2}{3}}\begin{bmatrix}\cos\theta & \cos(\theta-120^\circ) & \cos(\theta+120^\circ)\\ -\sin\theta & -\sin(\theta-120^\circ) & -\sin(\theta+120^\circ)\end{bmatrix} \quad (9)$$

$$C_{3s2/2r} = \sqrt{\tfrac{2}{3}}\begin{bmatrix}\cos(\theta-30^\circ) & \cos(\theta-150^\circ) & \cos(\theta+90^\circ)\\ -\sin(\theta-30^\circ) & -\sin(\theta-150^\circ) & -\sin(\theta+90^\circ)\end{bmatrix} \quad (10)$$

So, the flux linkage may be transformed shown as follows.

$$\begin{bmatrix}\psi_{sd1}\\ \psi_{sq1}\\ \psi_{sd2}\\ \psi_{sq2}\end{bmatrix} = \left[\begin{array}{c|c}C_{3s1/2r} & 0\\ \hline 0 & C_{3s2/2r}\end{array}\right]\begin{bmatrix}\psi_{sA1}\\ \psi_{sB1}\\ \psi_{sC1}\\ \psi_{sA2}\\ \psi_{sB2}\\ \psi_{sC2}\end{bmatrix} \quad (11)$$

Using Eq. (2), the flux linkage matrix equation can be written as a product of the inductance matrix multiplying the current vector of double three phrases stator. Using the inverse transformation matrix, $C_{3s1/2r}, C_{3s2/2r}$, the current vector may be transformed into two dimensional vectors in *d*-*q* coordinate system. So, Equation (11) may be rewritten as follows.

$$\begin{bmatrix}\psi_{sd1}\\ \psi_{sq1}\\ \psi_{sd2}\\ \psi_{sq2}\end{bmatrix} = \left[\begin{array}{c|c}C_{3s1/2r} & 0\\ \hline 0 & C_{3s2/2r}\end{array}\right]\left[\begin{array}{c|c}L_{s1s1} & L_{s1s2}\\ \hline L_{s2s1} & L_{s2s2}\end{array}\right]$$
$$\left[\begin{array}{c|c}C^{-1}{}_{3s1/2r} & 0\\ \hline 0 & C^{-1}{}_{3s2/2r}\end{array}\right]\begin{bmatrix}i_{sd1}\\ i_{sq1}\\ i_{sd2}\\ i_{sq2}\end{bmatrix} + \psi_r\left[\begin{array}{c|c}C_{3s1/2r} & 0\\ \hline 0 & C_{3s2/2r}\end{array}\right]\begin{bmatrix}S_{\theta 1}\\ S_{\theta 2}\end{bmatrix} \quad (12)$$

Substitute Equations (9)-(10) into (12), then Equation (12) is simplified and the flux linkage equation can be obtained in *d*-*q* coordinate system shown below.

$$\begin{bmatrix}\psi_{sd1}\\ \psi_{sq1}\\ \psi_{sd2}\\ \psi_{sq2}\end{bmatrix} = \begin{bmatrix}L_d & 0 & L_{d1d2} & 0\\ 0 & L_q & 0 & L_{q1q2}\\ L_{d2d1} & 0 & L_d & 0\\ 0 & L_{q2q1} & 0 & L_q\end{bmatrix}\begin{bmatrix}i_{sd1}\\ i_{sq1}\\ i_{sd2}\\ i_{sq2}\end{bmatrix} + \psi_r\begin{bmatrix}\sqrt{\frac{3}{2}}\\ 0\\ \sqrt{\frac{3}{2}}\\ 0\end{bmatrix} \quad (13)$$

where $L_d = L_{ls} + \frac{3}{2}L_m + \frac{3}{2}L_t$, $L_q = L_{ls} + \frac{3}{2}L_m - \frac{3}{2}L_t$, $L_{d1d2} = L_{d2d1} = \frac{3}{2}L_m + L_t \stackrel{\Delta}{=} l_d, L_{q1q2} = L_{q2q1} = \frac{3}{2}L_m - L_t \stackrel{\Delta}{=} l_q$.

Suppose proper control method is adapted. We can make an angle of ψ_{s1} in *d*-axis equal to one of ψ_{s2} in *d*-axis. That is $\delta_1 = \delta_2 = \delta$ [9]-[10]. We can express it as in Eq. (14):

$$\begin{bmatrix}F_{d1}\\ F_{q1}\\ F_{d2}\\ F_{q2}\end{bmatrix} = \begin{bmatrix}\cos\delta & -\sin\delta & 0 & 0\\ \sin\delta & \cos\delta & 0 & 0\\ 0 & 0 & \cos\delta & -\sin\delta\\ 0 & 0 & \sin\delta & \cos\delta\end{bmatrix}\begin{bmatrix}F_{M1}\\ F_{T1}\\ F_{M2}\\ F_{T2}\end{bmatrix} \quad (14)$$

where, "F" may denote the voltage, current, or flux linkage. The flux linkage equations have been deduced in M-T coordinate system.

$$\begin{bmatrix}\psi_{M1}\\ \psi_{T1}\\ \psi_{M2}\\ \psi_{T2}\end{bmatrix}=\begin{bmatrix}L_d\cos^2\delta+L_q\sin^2\delta & \frac{1}{2}(L_q-L_d)\sin 2\delta & l_d\cos^2\delta+l_d\sin^2\delta & \frac{1}{2}(l_q-l_d)\sin 2\delta\\ \frac{1}{2}(L_q-L_d)\sin 2\delta & L_d\sin^2\delta+L_q\cos^2\delta & \frac{1}{2}(l_q-l_d)\sin 2\delta & l_d\cos^2\delta+l_d\sin^2\delta\\ l_d\cos^2\delta+l_d\sin^2\delta & \frac{1}{2}(L_q-L_d)\sin 2\delta & L_d\cos^2\delta+L_q\sin^2\delta & \frac{1}{2}(l_q-l_d)\sin 2\delta\\ \frac{1}{2}(L_q-L_d)\sin 2\delta & L_d\sin^2\delta+L_q\cos^2\delta & \frac{1}{2}(l_q-l_d)\sin 2\delta & L_d\sin^2\delta+L_q\cos^2\delta\end{bmatrix}\begin{bmatrix}i_{sM1}\\ i_{sT1}\\ i_{sM2}\\ i_{sT2}\end{bmatrix}+\sqrt{\frac{3}{2}}\psi_r\begin{bmatrix}\cos\delta\\ -\sin\delta\\ \cos\delta\\ -\sin\delta\end{bmatrix} \tag{15}$$

The stator flux linkage ψ_{T1}, ψ_{T2} is 0 in M-axis. So, the current of the stator winding may be obtained in M-T:

$$i_{sM1}=\frac{1}{(L_d+l_d)(L_q+l_q)}\Big[(L_d\sin^2\delta+L_q\cos^2\delta)|\psi_{s1}|+ (l_d\sin^2\delta+l_q\cos^2\delta)|\psi_{s2}|-\sqrt{\tfrac{3}{2}}\psi_r(L_d+l_q)\cos\delta\Big] \tag{16}$$

$$i_{sT1}=\frac{1}{(L_d+l_d)(L_q+l_q)}\Big[(L_d-L_q)\sin\delta\cos\delta|\psi_{s1}|+ [(l_d-l_q)\sin\delta\cos\delta]|\psi_{s2}|+\sqrt{\tfrac{3}{2}}\psi_r(L_d+l_q)\sin\delta\Big] \tag{17}$$

$$i_{sM2}=\frac{1}{(L_d+l_d)(L_q+l_q)}\Big[(L_d\sin^2\delta+L_q\cos^2\delta)|\psi_{s2}|+ (l_d\sin^2\delta+l_q\cos^2\delta)|\psi_{s1}|-\sqrt{\tfrac{3}{2}}\psi_r(L_d+l_q)\cos\delta\Big] \tag{18}$$

$$i_{sT2}=\frac{1}{(L_d+l_d)(L_q+l_q)}\Big[[(L_d-L_q)\sin\delta\cos\delta]|\psi_{s2}|+ [(l_d-l_q)\sin\delta\cos\delta]|\psi_{s1}|+\sqrt{\tfrac{3}{2}}\psi_r(L_d+l_q)\sin\delta\Big] \tag{19}$$

Where $|\psi_{M1}|=\sqrt{\psi_{sd1}^2+\psi_{sq1}^2}=|\psi_{s1}|$,

$|\psi_{M2}|=\sqrt{\psi_{sd2}^2+\psi_{sq2}^2}=|\psi_{s2}|$

Referring to the relation of torque angle and the flux linkage shown in Fig. 2, the following equation can be obtained:

$$\begin{aligned}\sin\delta&=\psi_{q1}/|\psi_{s1}|=\psi_{q2}/|\psi_{s2}|\\ \cos\delta&=\psi_{d1}/|\psi_{s1}|=\psi_{d2}/|\psi_{s2}|\end{aligned} \tag{20}$$

Substitute Eq. (20) to Eq. (7); the torque equation in M-T is:

$$T_{e1}=n_p\begin{bmatrix}\psi_{sd1}(i_{sM1}\sin\delta+i_{sT1}\cos\delta)-\\ \psi_{sq1}(i_{sM1}\cos\delta+i_{sT1}\sin\delta)\end{bmatrix} \tag{21}$$

$$T_{e2}=n_p\begin{bmatrix}\psi_{sd2}(i_{sM2}\sin\delta+i_{sT2}\cos\delta)-\\ \psi_{sq2}(i_{sM2}\cos\delta+i_{sT2}\sin\delta)\end{bmatrix} \tag{22}$$

Substitute Eqs. (16) - (19) to Eqs. (21) - (22); then, the torque equations are:

$$T_{e1}=\frac{n_p|\psi_{s1}|}{2(L_d+l_d)(L_q+l_q)}\Big[(\sqrt{2}\psi_r L_q\sin\delta-|\psi_{s1}|(L_q-L_d)\sin 2\delta)+ (\sqrt{2}\psi_r l_q\sin\delta-|\psi_{s2}|(l_q-l_d)\sin 2\delta\Big] \tag{23}$$

$$T_{e2}=\frac{n_p|\psi_{s2}|}{2(L_d+l_d)(L_q+l_q)}\Big[(\sqrt{2}\psi_r L_q\sin\delta-|\psi_{s2}|(L_q-L_d)\sin 2\delta)+ (\sqrt{2}\psi_r l_q\sin\delta-|\psi_{s1}|(l_q-l_d)\sin 2\delta\Big] \tag{24}$$

Comparing (7), (23), and (24), we find that the coefficient in the first bracket of (23)-(24) is different from one of (7). This is because the double three-phrase winding influences each other. The second item of (23)-(24) is the torque part of mutual induction. So, the DTC theory is suitable for the DTP-PMSM. The difference between DTP-PMSM and MSM in the DTC theory application lies in that the mutual inductance must be considered in the DTP-PMSM. It is very important for us to design control method.

III. SIMULATION OF DIFFERENT RUNNING MODE OF THE DTP-PMSM

The paper addresses on the torque control rules for the DTP-PMSM and establishes mathematic model in term of rotor orientation theory. The DTP-PMSM parameters are given in Table 1.

TABLE I
PARAMETERS OF THE DTP- PMSM

Symbol	Quantity	Value
P_N(kw)	Rated power	2.2
η_N	Efficiency	0.86
$\cos\varphi$	Power factor	0.88
$I_N(A)$	Current	3
$L_{sq1}(mH)$	Inductance in q-axis	54.69
$L_{sq2}(mH)$		
$L_{sd1}(mH)$	Inductance in d-axis	32.05
$L_{sd2}(mH)$		
$R_s(\Omega)$	Stator resistance	1.3972
n_p	Number of poles	3
$J_m(kgm^2)$	Rotating Inertia	0.009
$\psi_r(V/r/s)$	Permanent flux link	0.712
$L_s(mH)$	Leakage inductance	2.74
$L_m(mH)$	Mutual inductance	28.02
$L_t(mH)$	Bulge pole inductance	6.55

During the simulation, the input value is the quality of the single or double three phrases in the static coordinate system.

The input is, first, transformed into the value in *d-q* axis accordingly; second, it is substituted into a state equation in *d-q*; and third, the state variable is resolved by Runge-Kutta method. The input voltage is a fundamental wave or a fundamental wave plus 5 and 7 times of harmonious wave (it is 1/5, 1/7 of the fundamental wave, respectively) or a 6 ladder wave. The simulation is performed when DTP-PMSM is started in load directly for double three phrases or the three phrases. We set the voltage fundamental wave reference 311V in each phrase, frequency is set as 20Hz, the load torque T_L is set as 20 Nm as shown in Fig. 3-Fig. 5, and the load torque T_L is set as 10 Nm as shown in Fig. 6-Fig. 8.

It is shown in Fig. 6-Fig.8 that the harmonious wave has great influence to motor when the input phrase voltage contains 5 and 7 times of harmonious wave or a 6 ladder wave in single three phrases mode. The torque and the rotate speed produce a pulsation in stable state. At the same time, there is a distortion greatly in stator current. However, there is no any influence for motor in the double three phrases mode when the input phrase voltage concludes 5 and 7 times of harmonious wave. The motor rotate speed, torque, and stator current wave have the same wave curve like the input phrase voltage. When the input phrase voltage is 6 ladder waves, the rotate speed, the torque pulsation and the stator current distortion is smaller than in the single three phrases mode.

When the input phrase voltage is a fundamental wave, the simulation indicates that the stator phrase current is only half in compare the double three phrases mode with the single three phrases mode; so total power can be raised one times in the double three phrases mode .

From the above analysis, the DTP-PMSM may reduce 5 and 7 times of harmonious wave in the rotate speed, the torque pulsation, and the stator current harmonious wave. So, the designed structure can improve electric energy quality in vessel power network; can increase the reliability of propulsion motor power and the stabilization of the vessel.

IV. CONCLUSION

The paper has established DTP-PMSM mathematic model in *d-q* coordinate system. In compound flux linkage, the function relation between the torque and torque angle has been obtained; it is similar to a common PMSM characteristics. So, the compound flux linkage control method may be applied in the DTP-PMSM. When the flux linkage of each set winding is considered respectively, the function relation between the torque and torque angle is also obtained, respectively. We find that the DTC theory is also suitable to the independence flux linkage method. Because the influence between two sets of winding affects each other, it must be considered carefully. The simulation result indicates that the mathematic model is correct. The DTP-PMSM performance is superior to the single three phrases PMSM. This research provides a foundation of theory and application for the DTP-PMSM control system.

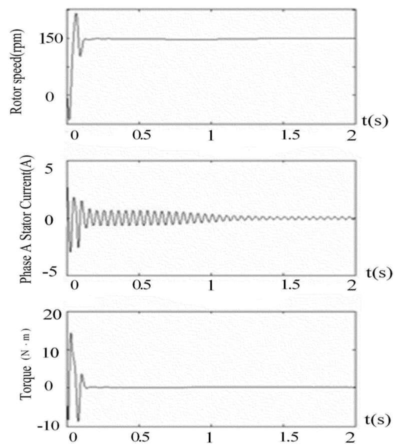

Fig. 3. The stator phrase current, the torque dynamic curves when the input phrase voltage is a fundamental wave in the double three phrases mode.

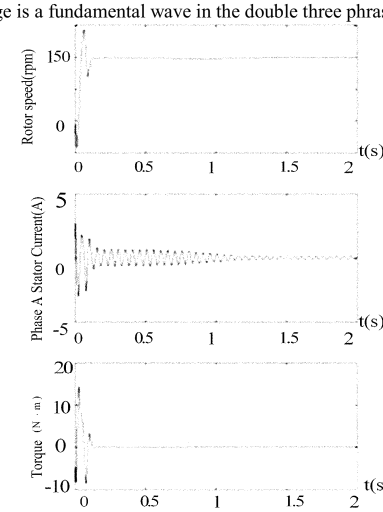

Fig. 4. The rotate speed, the stator, a phrase current and the torque wave plus 5, and 7 time harmonious dynamic curves when the input phrase voltage is fundamental in the double three phrases mode.

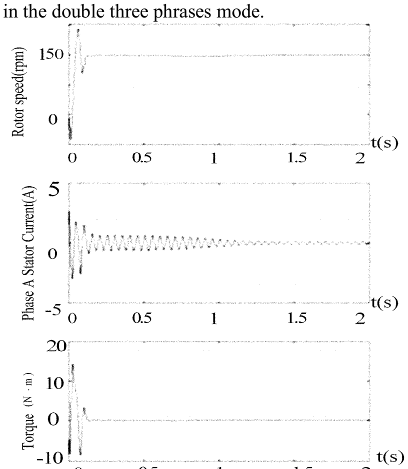

Fig. 5. The rotate speed, the stator, a phrase current and the torque dynamic curves when the input phrase voltage is 6 ladder wave in the double three phrases mode.

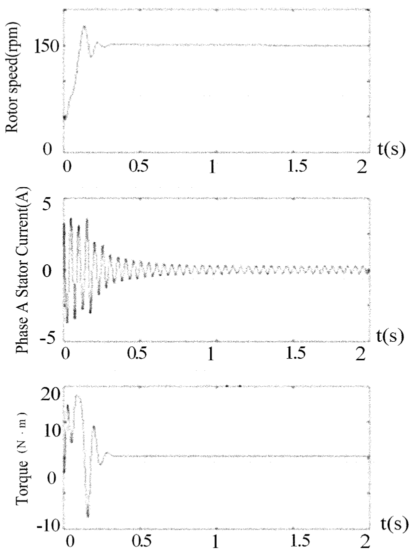

Fig. 6. The rotate speed, the stator, a phrase current and the torque dynamic curves when the input phrase voltage is fundamental wave in the single three phrases mode.

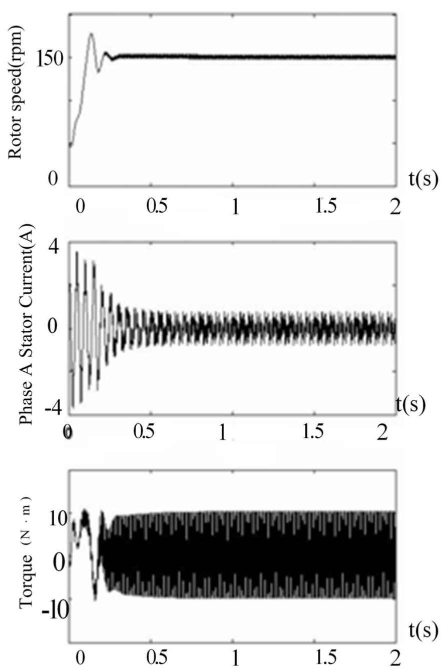

Fig. 7. The rotate speed, the stator, a phrase current and the torque dynamic curves when the input phrase voltage is fundamental wave plus 5, 7 times harmonious wave the single three phrases mode.

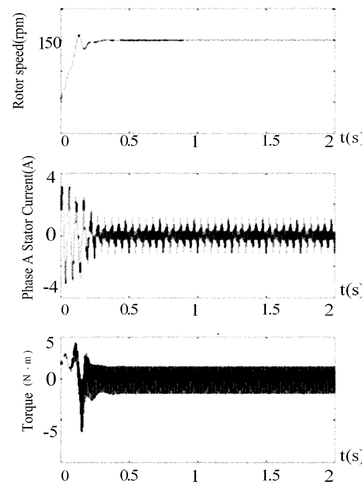

Fig. 8. The rotate speed, the stator, a phrase current and the torque dynamic curves when the input phrase voltage is 6 ladder wave in the single three phrases mode.

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