Starting winding matching analysis of dual three phase permanent magnet synchronous starter-generator

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Abstract
In view of the double three-phase high and low voltage winding permanent magnet synchronous starter-generator (PMSSG) starting winding selection problem. First of all, the double three-phase PMSSG state space mathematical model was set up. Then, using the method of comparative analysis, taking into account the compatible system and reliability factors, demonstrates the winding start matching scheme, and gives the best start scheme. In addition, the high and low voltage winding in series on the physical implementation was analyzed, and the solution was given. Based on state space mathematical model, using Matlab/Simulink software, motor speed control system model have been established, and the simulation, verify the optimum winding matching start scheme.
Key words: PERMANENT MAGNET SYNCHRONOUS, STARTER-GENERATOR, DUAL THREE-PHASE, STARTING WINDING, OPTIMUM WINDING MATCHING.

1. Introduction

Dual three-phase PMSSG also called dual three-phase permanent magnet synchronous motor(PMSM), it is the further development of ordinary three-phase PMSM, it is relative to the ordinary three-phase PMSM has many advantages. As in electric propulsion system can realize low-voltage high-power, space harmonic minimum number is higher than ordinary three-phase motor, System is still reliable operation under the condition of lack of phase failure. So it has been applied in the area of ship propulsion and aviation aircraft, etc. [1]-[3]

This paper introduces the dual three-phase permanent magnet synchronous Starter-generator, Stator winding adopts double three-phase asymmetric coupling method, it is composed of 30 electric angle displacement of dual three-phase symmetrical star winding. Starter-generator is motor in the starting process, after starting, it realize the generator function in the engine driven. Literature [4] - [7], this paper introduces the control method of the double three-phase PMSSG, in this paper, coordinate transformation process is simplified through synthesis of multi space coordinates, and the mathematical model of dual three-phase PMSM is completed in rotating coordinate according to the coordinate transformation. If you want to use the ordinary three-phase PMSM control circuit to achieve control of dual three-phase PMSSG, because this article research the starter generator uses two sets of three-phase windings are high and low voltage, so it is necessary to consider what a start winding, is adopted to realize starting. In the actual starting process, designers should not only to achieve effective starting motor, but also consider the physical implementation of start-up circuit. Therefore, through the analysis of the high and low voltage winding starting plan, establish simulation model, and verified for winding starting solution.

2. The mathematical model of PMSSG

For convenience of analysis, the required precision to meet the engineering practice, it can make the following assumptions:

1) Two sets of stator windings $A_1\ B_1\ C_1$ and $A_2\ B_2\ C_2$ in the space staggered 30 electric angle, each three-phase windings symmetrical on the space, it is the same number of turns per phase winding, the difference of 120 electric angle space. Regardless of iron saturation, magnetic hysteresis, eddy current effect and the conductor skin effect.

2) Damping winding is equivalent to two phase winding are perpendicular to each other, which located in d axis and q axis.

3) The air gap magnetic field sinusoidal distribution, ignoring the effect of magnetic field harmonics.

4) The rotor magnetic pole position and A_1 phase winding of the stator axis Angle for θ.

The coordinate space vector arrangement relationship is shown in figure 1.

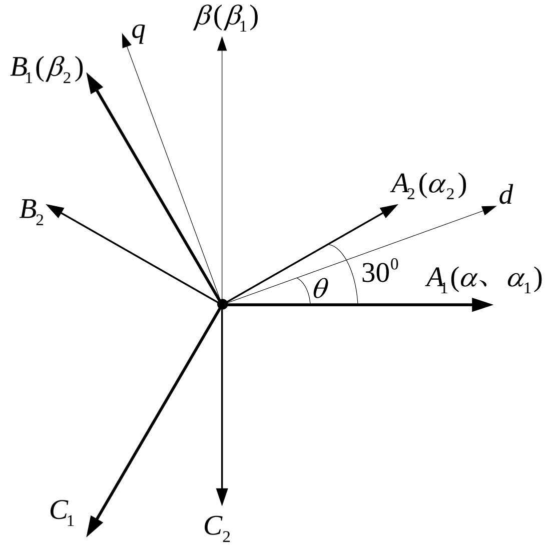

Figure 1. The synthetic diagram of Static coordinate vector and the rotating coordinate vector

2.1. Spatial decoupling transformation of dual three phase PMSSG.

Reference [1], [5], [8]-[10] are involved in using the coordinate transformation method, the realization of the motor vector control. Usually, takes two phase rotating coordinate system not only can be used to analyze the steady state performance of PMSM, but also can analyze the transient performance. The coordinate system rotation is synchronous with the stator magnetic field, conducive to the realization of motor control. Vector composition diagram shown in Figure 1 in this paper, transformation of the double three-phase static coordinate system to a two-phase rotating coordinate system is obtained directly. Application of three phase coordinate system to the two-phase coordinate system equivalent transformation rules, such as the vector relation in Figure 1, can achieve dual three-phase static coordinate system to the two-phase rotating coordinate transformation.

Under the condition of the magnetomotive force and power unchanged, in order to make the two phase winding transformation and double three-phase winding is equivalent, the magnetomotive force relation must satisfy the formula (1).

Where N2 and N6 are each phase of effective coil number in series of two phase winding and double three-phase winding. Assuming R and T are respectively the transformation matrix of dual three-phase static coordinate system to the two-phase static coordinate system and two-phase stationary coordinate system to the double three-phase static coordinate system, to prove the turns ratio $N_6 : N_2 = 1 : \sqrt{3}$.

$$\begin{cases} N_2 F_\alpha = N_6 (F_{A1}\cos 0^0 + F_{B1}\cos 120^0 + F_{C1}\cos 240^0 + F_{A2}\cos 30^0 + F_{B2}\cos 150^0 + F_{C2}\cos 270^0) \\ N_2 F_\beta = N_6 (F_{A1}\sin 0^0 + F_{B1}\sin 120^0 + F_{C1}\sin 240^0 + F_{A2}\sin 30^0 + F_{B2}\sin 150^0 + F_{C2}\sin 270^0) \end{cases} \quad (1)$$

$$C_{6s/2s} = \frac{1}{\sqrt{3}} \begin{bmatrix} \cos 0^0 & \cos 120^0 & \cos 240^0 & \cos 30^0 & \cos 150^0 & \cos 270^0 \\ \sin 0^0 & \sin 120^0 & \sin 240^0 & \sin 30^0 & \sin 150^0 & \sin 270^0 \end{bmatrix} \quad (2)$$

Where $C_{2s/6s} = \left[C_{6s/2s}\right]^T$ (3)

The transformation matrix at the same time, to meet the flux, voltage and current in double three-phase static coordinate to double two-phase static coordinate transformation. Dual three-phase stationary winding can be converted two-phase rotation of the winding by rotation transformation, the axis of which is located in d-axis and q-axis. Transform matrix and inverse transform matrix are $C_{6s/2r}$ and $C_{2r/6s}$.

$$C_{6s/2r} = \frac{1}{\sqrt{3}}\begin{bmatrix} \cos\theta & \cos(\theta-\frac{4\pi}{6}) & \cos(\theta-\frac{8\pi}{6}) & \cos(\theta-\frac{\pi}{6}) & \cos(\theta-\frac{5\pi}{6}) & \cos(\theta-\frac{9\pi}{6}) \\ -\sin\theta & -\sin(\theta-\frac{4\pi}{6}) & -\sin(\theta-\frac{8\pi}{6}) & -\sin(\theta-\frac{\pi}{6}) & -\sin(\theta-\frac{5\pi}{6}) & -\sin(\theta-\frac{9\pi}{6}) \end{bmatrix} \quad (4)$$

$$C_{2s/6s} = \left[C_{6s/2s}\right]^T \quad (5)$$

2.2. Dual-phase PMSSG mathematical model.

After double three-phase static coordinate system to the coordinates of the two-phase synchronous rotating coordinate system transform, double three-phase PMSSG to achieve the d-q axial decoupling, its attribute model is as follows:

$$\begin{cases} u_d = R_s \cdot i_d + p\psi_d - \omega \cdot \psi_q \\ u_q = R_s \cdot i_q + p\psi_q - \omega \cdot \psi_d \end{cases} \quad (6)$$

$$\begin{cases} \psi_d = L_{sd} \cdot i_d + \sqrt{3}\psi_f \\ \psi_q = L_{sq} \cdot i_{sq} \end{cases} \quad (7)$$

$$\begin{cases} T_e = n_p\left[\sqrt{3}\psi_f \cdot i_d + (L_{sd} - L_{sq})i_q \cdot i_d\right] \\ T_e = T_L + B\omega + J\dfrac{d\omega}{dt} \end{cases} \quad (8)$$

In the formula (6), (7), (8) the main symbol physical meaning is as follows：

L_{sd} and L_{sq} are equivalent d axis and q axis self-induction respectively.

$L_{sd} = L_{ls} + L_{md}$, $L_{sq} = L_{ls} + L_{mq}$, L_{ls} is the stator leakage inductance, L_{md} is the windings mutual inductance of between the stator and rotor of d axis. L_{mq} is the windings mutual inductance of between the stator and rotor of q axis. ω is the electrical angular of rotation of d-q coordinate system and the rotor. n_p is pole pairs, T_L is the load torque, J is the moment of inertia, B is the damping coefficient, ψ_f is a permanent magnet flux.

3. Starting winding selection of PMSSG

Since starter-generator output is divided into two sets of three-phase windings, respectively is the high voltage winding and low voltage winding. Starting winding can choose double three phase current injection starting, can also according to the starting of three-phase motor current injection way[11]-[13], it can simplify the control circuit, at the same time, can use ordinary three-phase PMSM control method. If an ordinary three-phase motor starting mode, choose a starting input winding is needed.

Winding selection mainly consider several factors of starting current and starting torque, energy loss. Motor starting process, the first thing to consider is the starting torque values, namely the force created by the winding coil, because the motor starting depending on whether the torque values can meet the requirements.

In order to meet the need of qualitative analysis, quantitative motor performance parameters are given. A starter generator for example, low output voltage AC (12.5V ~ 28.5V), output power $7.5kW$; high voltage output AC (74V ~ 148V), output power $13.3kW$.Considering the condition of the same torque high-low voltage winding, Comparing high and low voltage winding as the starting winding performance of the resulting relationship.

The following analysis process is aimed at high voltage one phase winding and low voltage one phase winding, the comparison of high voltage winding starting with low voltage winding starting.

3.1. The relation between basic parameters.

High and low voltage winding back EMF:

$$\begin{cases} E_h = 4.44 fW_h\phi \\ E_l = 4.44 fW_l\phi \end{cases} \quad (9)$$

Where E_h and E_l are one phase EMF of generator of high voltage and low voltage winding. W_h and W_l are generator high voltage and low voltage coil of each phase winding, f 、ϕ are output voltage and frequency of motor flux.

Ignore the coil voltage drop and think in terms of generator, the coil number of turns ratio is proportional to the voltage.

$$\frac{W_h}{W_l} = \frac{U_h}{U_l} \quad (10)$$

In formula (10), U_h and U_l are the output voltage of considering the motor load. According to the numerical relationship given in front of the motor output voltage, it can be obtained:

$$\frac{U_h}{U_l} = \frac{5}{1} \quad \Rightarrow \quad \frac{W_h}{W_l} = \frac{5}{1} \quad (11)$$

According to the given conditions, high voltage and low voltage output power to meet:

$$\frac{P_h}{P_l} = \frac{13.3kW}{7.5kW} \approx 2 \quad (12)$$

Where P_h and P_l are high voltage and low voltage output power.

It can be obtained from formula (11) and (12), the cross-sectional area of the high voltage and low voltage coil should satisfy the following relationship:

$$\frac{S_h}{S_l} = \frac{2}{5} \quad (13)$$

3.2. The relationship between high and low voltage winding current at the same torque conditions.

Motor starting, whether high voltage windings or low voltage windings, torque should be the same $T_h = T_l$.

Besides, $T_h = W_h I_h$, $T_l = W_l I_l$

So, $$\frac{I_h}{I_l} = \frac{1}{5} \quad (14)$$

In the above formula, T_h、 T_l are starting torque of high voltage windings and low voltage windings. I_h、 I_l are current of high voltage windings and low voltage windings.

As can be seen under produce the same moment, the starting current of use the low voltage winding is larger than the starting current of use the high voltage winding.

3.3. The current heat effect

The starting process of winding its consumed energy is mainly embodied in the form of heat.

$$R_h = \rho \frac{l_h}{S_h}, \; R_l = \rho \frac{l_l}{S_l} \quad (15)$$

Where, R_h、 R_l are resistance of high and low voltage winding, l_h and l_l are length of the high and low voltage winding, ρ is the resistivity.

The length of the wire is proportional to the number of turns of the coil.

$$\frac{l_h}{l_l} = \frac{W_h}{W_l} = 5 \quad (16)$$

The resistance of the winding ratio:

$$\frac{R_h}{R_l} = \frac{l_h}{S_h} \times \frac{S_l}{l_l} = 12.5 \quad (17)$$

The heat generated by the winding relationship:

$$\frac{P_{cah}}{P_{cal}} = \frac{I_h^2 \cdot R_h}{I_l^2 \cdot R_l} = 0.5 \quad (18)$$

3.4. The conclusion of comparison

It can be seen from the previous comparative analysis, on the premise of produce the same torque, high voltage winding heating power P_{cah} is only part of the low voltage winding calorific power P_{cal} 0.5 times, but the needs of low voltage winding current I_h is needed for the high voltage winding current I_l five times. If the current is too large, the selection of control circuit and inverter current device is difficult, even threaten the reliability of the controller, so the high voltage winding starting than low voltage winding is starting well.

Using the previous analysis methods, the high-low voltage winding series starting mode is compared with the high voltage winding starting mode, the current of high-low voltage winding in series will be reduced, and power consumption will be reduced. Therefore, the best way to start high-low voltage winding in series, but for high-low voltage winding in series in the physical realization is relatively complex.

4. High-low voltage winding in series starting physical implementation

4.1. high-low voltage winding in series starting principle

In the process of starting, through the three switch S1, S2, S3 action to achieve access winding. The three-phase winding short circuit when the switch is closed, the three-phase winding access circuit when switch off.

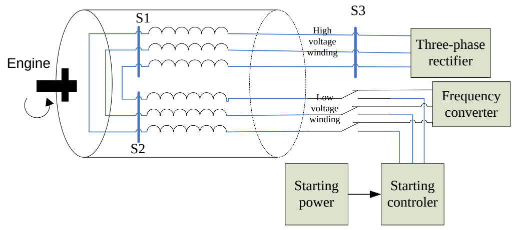

Figure 2. Schematic diagram of high-low voltage winding in series

4.2. Switching logic

Starting before and after starting three switch S1, S2, S3 in different state of switch, three the working state of the switch as shown in table 1. "1" means switch is closed, "0" means switch is open.

Table 1. Switch state

condition	S1	S2	S3
Before starting	0	0	1
After starting	1	1	0

5. Starting solution validation

5.1. simulation model

According to equation (1)-(8), simulation model [14]-[15] based on Matlab/simulink dual three-phase PMSSG as shown in figure 3. The input variables of the simulation model for magnetic double three-phase voltage, load torque and permanent magnet flux linkage, the output is a dual three-phase stator current and electromagnetic torque and speed.

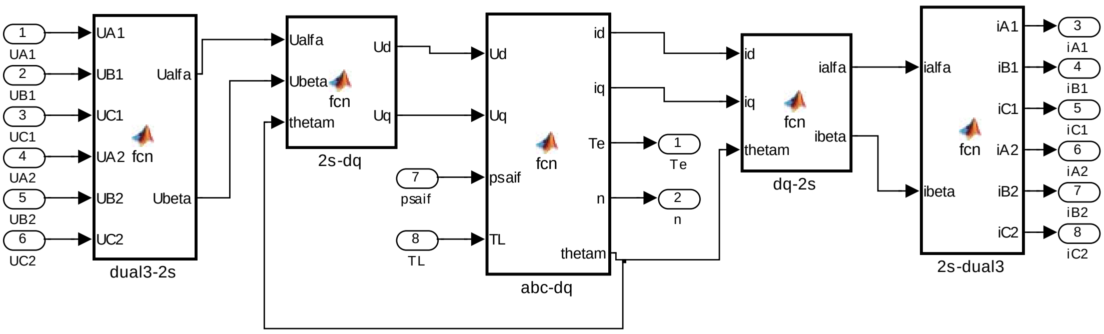

Figure 3. Simulation mode of dual three-phase PMSSG

According to Figure 1 the start control theory, such as the establishment of control is shown in the figure 4 of high and low voltage winding of double three-phase PMSM control. Here we only consider the high-voltage winding starting and the low-voltage winding starting in two cases. A vector control method $i_{d=0}$ using ordinary three-phase motor.

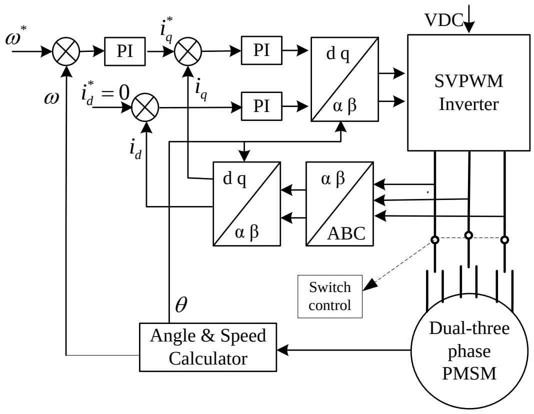

Figure 4. High and low voltage winding switching control of dual three-phase PMSM

5.2 The simulation results

Through the previous analysis, respectively, were double three-phase permanent magnet synchronous motor simulation, a low voltage winding starting simulation and a high voltage winding starting simulation.

The motor parameters are given. The pole number is 4, $\varphi_f = 0.17Wb$, moment of inertia is $J = 0.004kg.m^2$; High-voltage winding is $R_1 = 0.092$, Armature inductance is $L_{s1} = 1mH$; High-voltage winding is $R_1 = 0.092$, Armature inductance is $L_{s1} = 1mH$.

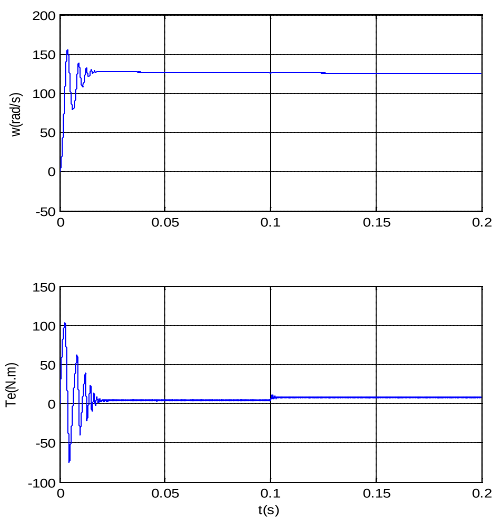

Figure 5. Simulation waveform of dual-three phase PMSM

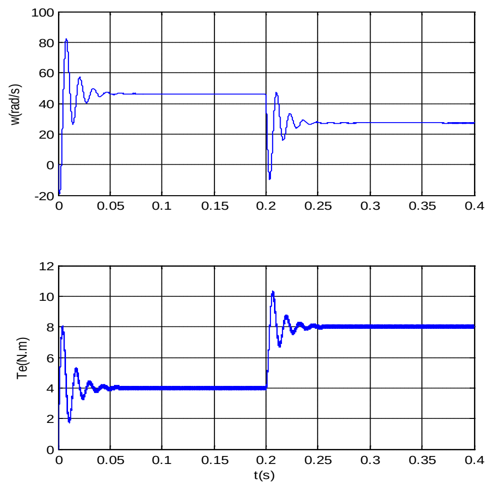

Figure 6. Waveform of low-voltage winding starting

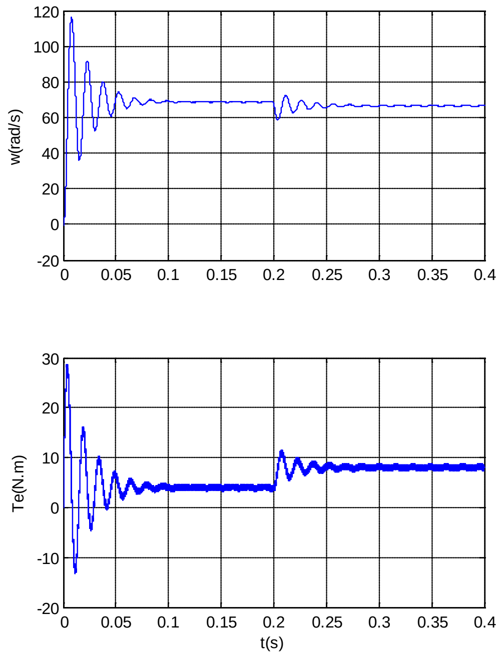

Figure 7. Waveform of high-voltage winding starting

The simulation of starting torque given consistent, $i_{d=0}$ control conditions, q axis equivalent current is proportional to the electromagnetic torque of the machine. It can be seen from the figure 5, the double three-phase starting control method of starting process faster, increase the torque during 0.1 s, the simulation speed basic remain unchanged. It can be seen from the figure 6, low voltage winding starting control, when the electromagnetic torque increase, speed changes slightly. Contrast figure 6 and figure 7, high voltage winding of starting motor operation performance is more stable. Ordinary three-phase starting way is a bit slow than double three phase starting way, but to be able to meet the requirements of starting motor starting.

6. Conclusion

In this paper, a comprehensive analysis of dual three-phase permanent magnet synchronous generator start method, a theoretical basis is given starting scheme, and through simulation experiments verify the feasibility. In this paper, the starting program, to achieve the dual three phase PMSSG start reliably and dynamic performance is good. The user can according to the actual application environment, the actual conditions of use, choose the appropriate starting scheme.

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