Modeling for A Dual Three-Phase Induction Motor Based On A Winding Transformation

Wang Bu-lai Gong Zhe-song Gu wei Zhu Jian-xin Guo Yi
Shanghai Maritime University
Shanghai, China
blwang@cle.shmtu.edu.cn

***Abstract*—A novel mathematic model for a dual three-phase induction motor was proposed. A set of equivalent three-phase windings was built based on same magnetomotive force and power. A dual three-phase induction motor was substituted equivalently by a three-phase induction motor after a winding transformation. Then with the mathematical model of the three-phase induction motor in the stationary reference frame, the model of a dual three-phase induction motor was determined. A 4 pole dual three-phase induction motor was simulated and tested. Compared the simulation results with corresponding test results , the maximum error was lower than 2%. So this winding transformation and modeling method are validated and correct.**

***Keywords*—winding transformation, a dual three-phase induction motor, equivalent, simulation, test**

I. Introduction

A dual three-phase motor system has apparently advantages over conventional three-phase motor system[1-4]: low voltage standard power switches could be used in high voltage and power place； Higher effective harmonic order increases while its amplitude and torque pulsating decrease; Efficiency is higher and noise is lower； The total system reliability is improved.

[5-6] investigated modeling and simulation of multi-phase synchronous motors separately. [7-8] gave mathematical model of a dual three-phase induction motor. They all got motor model in the original six-dimensional space firstly, then transformation to the new two-dimensional orthogonal stationary reference frame by the technique of vector space decomposition. This paper firstly got an equivalent three-phase induction motor by a winding conversion. After that with the well-known modeling of a three-phase induction motor in two-dimensional stationary reference frame, the model of a dual three-phase induction motor is determined. By comparing the results of simulation and corresponding test, this kind of modeling of a dual three-phase induction motor is verified to be correct.

II. Modeling of a Dual Three-Phase Induction Motor

The following assumptions and approximations are adopted in the process of developing this model.

1) The motor air gap is uniform.

2) Magnetic saturation of the motor iron is neglected.

3) Magnetic field in air gap is sinusoidally distributed.

4) Steady state current is a sinusoidal variable.

A. Equivalent Transformation From A Dual Three-Phase Winding to A Three-Phase Wingding

According to the principle of coordinate transformation, the transformation winding is equivalent with the former only if magnetomotive force and power keep same. Fig. 1 shows the scheme of a dual three-phase winding. A set of three-phase winding $A_1B_1C_1$ leads $A_2B_2C_2$ 30° electrical degree corresponding phase spacially. When dual three-phase currents flow along the dual three-phase windings(phase current of $A_1B_1C_1$ leads phase current of $A_2B_2C_2$ 30° time electrical degree corresponding), the two sets of three-phase winding produce same fundamental magnetomotive force in air gap. So the total MMF in air gap equals their algebraic sum.

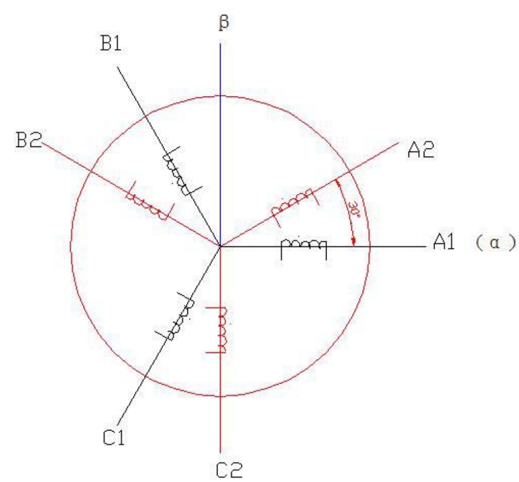


Fig. 1 scheme of a dual three-phase winding

Now suppose that there is a new set of three-phase winding, which is in the same spacial position with $A_1B_1C_1$. If fundamental MMF produced by new winding is same as the total fundamental MMF produced by the dual three-phase winding, then the new three-phase winding may substitute the dual three-phase winding. In this case, following equation is established.

$$2 \cdot \frac{3}{2} \cdot \frac{4}{\pi} \cdot \frac{\sqrt{2}}{2} \frac{N_6 I_{A1}}{n_p} = \frac{3}{2} \cdot \frac{4}{\pi} \cdot \frac{\sqrt{2}}{2} \frac{N_3 I_A}{n_p}$$

Where N_6 and I_{A1} are equivalent number of turns per phase and A_1 phase current of dual three-phase winding separately; N_3 and I_A are equivalent number of turns per phase and A_1 phase current of equivalent three-phase winding separately. Considering the power should keep same after winding transformation, the number of turns becomes 2 times than before, so

$$i_A = i_{A1} \tag{1}$$

And phase voltage is 2 times than before too. The voltage relation is obtained

$$u_A = 2u_{A1} \tag{2}$$

Suppose that phase resistance, leakage inductance and maximum mutual inductance of dual three-phase stator winding are R_{s1}, L_{lS1} and L_{ms1} respectively, while those of equivalent three-phase stator winding are R_s, L_{lS} and L_{ms}. Then their relation is as follows

$$\begin{cases} R_S = 2R_{S1} \\ L_{ls} = 2L_{ls1} \\ L_{ms} = 2L_{ms1} \end{cases} \tag{3}$$

Similar with stator side, the relation of squirrel rotor winding before and after a winding transformation also is obtained

$$\begin{cases} i_a = i_{a1} \\ R_r = 2R_{r1} \\ L_{lr} = 2L_{lr1} \\ L_{rs} = 2L_{ms1} \end{cases} \tag{4}$$

Equations (1)-(4) are the mathematical presentation of an equivalent three-phase induction motor from a dual three-phase induction motor. In these equations all parameters of rotor side have been transformed to stator side. And for saving the length of this paper, only one phase current and voltage is given. The others are easy to obtain by symmetric relation.

B. *Model of the Equivalent Three-Phase Induction Motor In Two-Directional Stationary Reference Frame[9]*

Voltage-current mathematic model is

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \\ u_{r\alpha} \\ u_{r\beta} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & \omega L_m & R_r + L_r p & \omega L_r \\ -\omega L_m & L_m p & -\omega L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{r\alpha} \\ i_{r\beta} \end{bmatrix} \tag{5}$$

Eletromagnetic torque is given by

$$T_e = n_p L_m (i_{s\beta} i_{r\alpha} - i_{s\alpha} i_{r\beta}) \tag{6}$$

And motion equation is given by

$$T_e = T_L + \frac{J}{n_p}\frac{d\omega}{dt} \tag{7}$$

In equation (5)-(7), L_s, L_r and L_m are self inductance and mutual inductance of same axial stator and rotor two-phase stationary winding. They are given by

$$\begin{cases} L_s = L_m + L_{ls} = \frac{3}{2}L_{ms} + L_{ls} = 3L_{ms1} + 2L_{ls1} \\ L_r = L_m + L_{lr} = \frac{3}{2}L_{ms} + L_{lr} = 3L_{ms1} + 2L_{lr1} \\ L_m = \frac{3}{2}L_{ms} = 3L_{ms1} \end{cases} \tag{8}$$

C. *Simulation Model of A Dual Three-Phase Induction Motor*

With (1)-(8), combining transformation and inverse transformation relation[9] from three-phase induction motors to two-phase induction motors in stationary reference frame, simulation model of a dual three-phase induction motor is determined as fig. 2

III. COMPARISON BETWEEN SIMULATION AND TEST

To verify the effectiveness of modeling, a prototype was designed. The motor specifications are given in table 1.

Table 1 specifications of a prototype

Power rating	1100W	R_{S1}	3.8 ohms
pole pairs	2	R_{r1}	3.0 ohms
power voltage	190V	L_{lS1}	0.0107 H
phase number	dual 3	L_{lr1}	0.0177 H
J	0.01kg.m^2	L_{ms1}	0.161 H

By (3-4) and (8), resistance and inductance in two-directional stationary reference frame are gained in table 2.

Table 2 parameters in two-phase coordinates

R_S	7.6 ohms	R_{r1}	6.0 ohms
L_S	0.5044 H	L_r	0.5184 H
L_m	0.483 H		

A. *Simulation Results*

Fig. 3 shows simulation results. Supplied voltage source is ideal sinusoidal variable. Fig. 3(a)-(c) are the simulation results of given 1.96N.m load torque starting while given 3.78N.m load torque after 0.4 seconds. And fig. 3(d)-(f) are the simulation results of given 5.66N.m load torque starting while given 7.52N.m load torque after 0.4 seconds. Steady state A_1 phase current I_{A1} and motor rotating speed n are shown in table 3

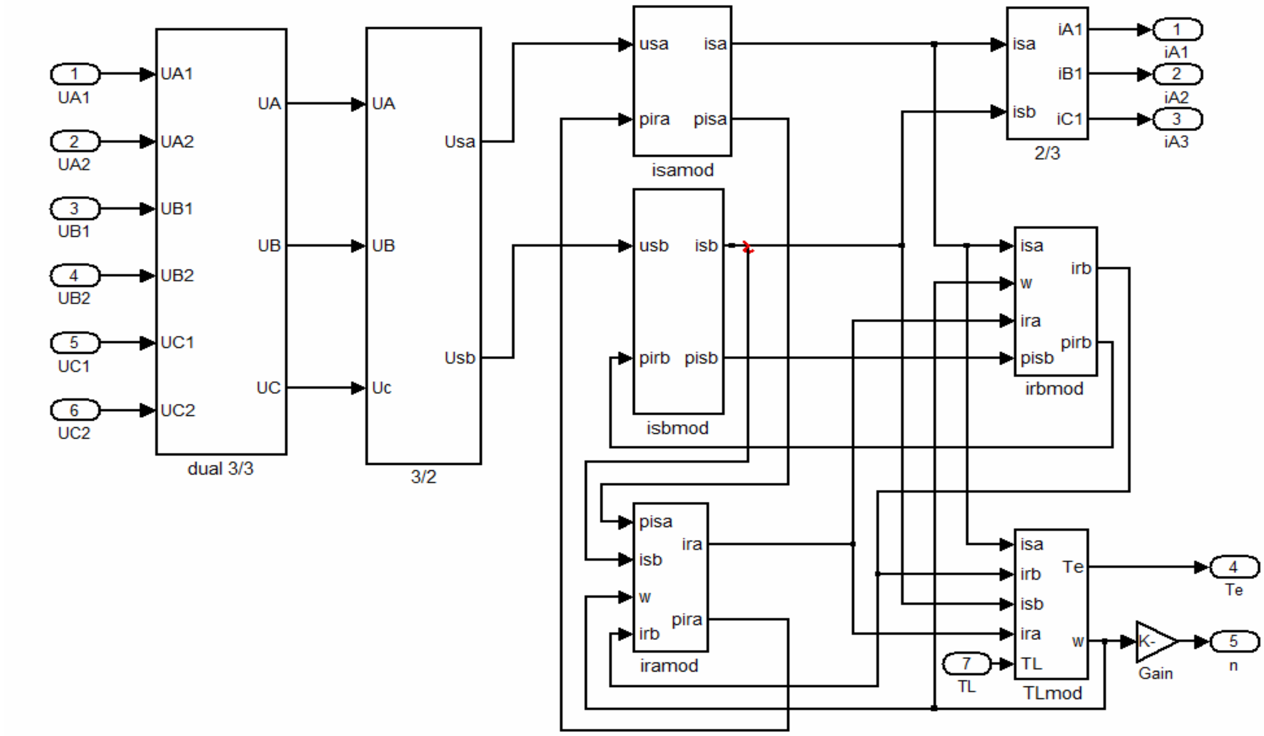


Fig. 2 simulation diagram of a dual three-phase induction motor

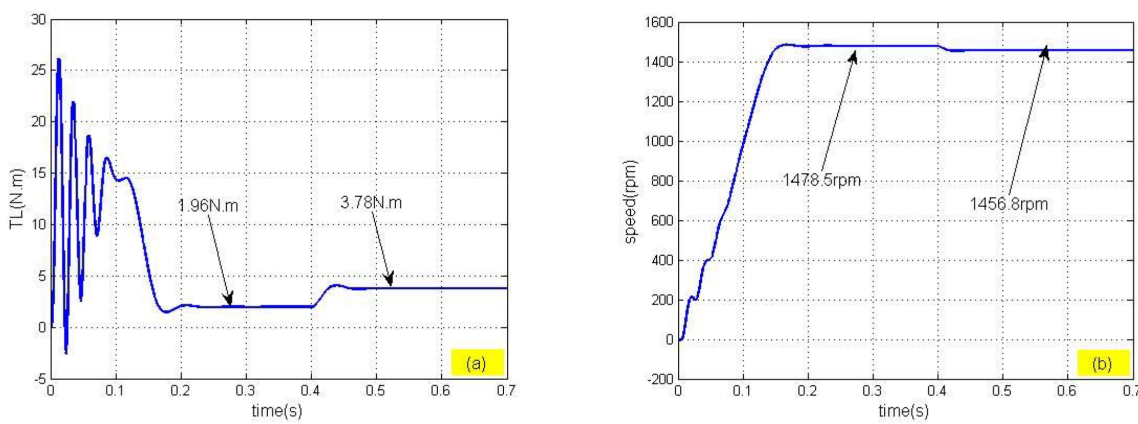
Table 3 simulation data

T_L(N.m)	T_2(N.m)	n（rpm）	I_{A1}
1.96	1.82	1478.5	1.463
3.78	3.62	1456.8	1.697
5.66	5.48	1432.3	2.065
7.52	7.32	1405.0	2.531

In table 3, T_2 is output torque, which equals electromagnet torque minus mechanic and additional torque. Mechanic loss values 18W according to experience, and additional loss values about 1% of input power.

B. Test Resultst

Fig.4 is connection diagram of the dual three-phase induction motor. This test system can set different output in one time test. Fig.5 is test cutting diagram, and main test results are shown in table 4. In the table, the second column is input power P_1 of the motor and the fifth column is efficiency η of the motor. Fig. 6 is a test photo of the motor.



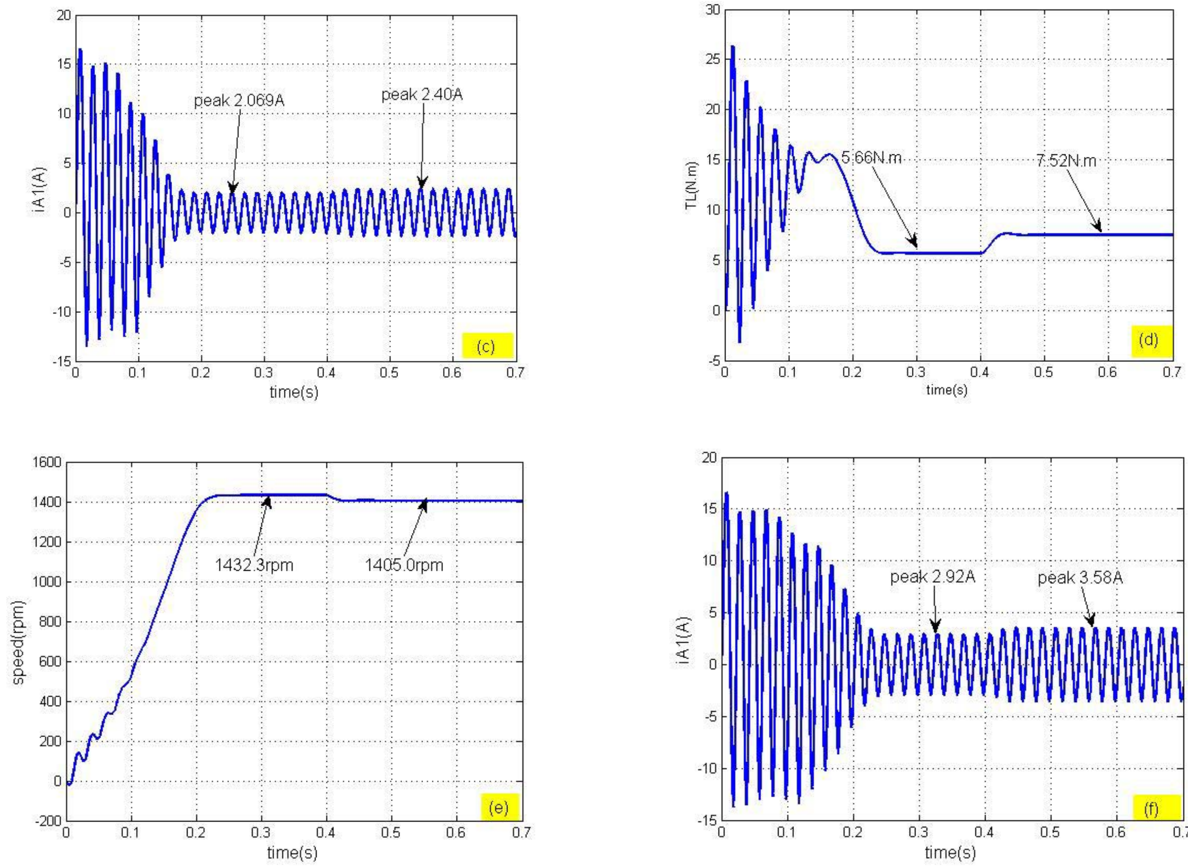


Fig. 3 simulation results of a dual three-phase induction motor

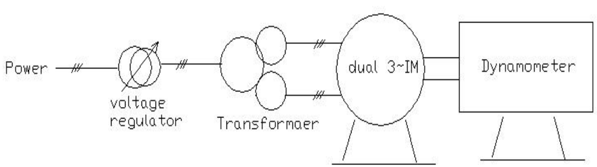


Fig. 4 connection diagram of test

Table 4 test data

T_2(N.m)	P_1(W)	n（rpm）	I_{A1}	η(%)
1.82	384	1482.4	1.447	73.5
3.62	677	1465.3	1.694	82.0
5.48	1005	1446.0	2.077	82.6
7.32	1343	1424.1	2.552	81.3

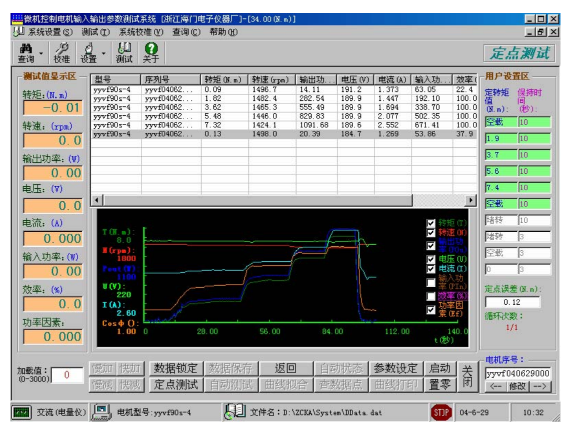


Fig. 5 test cutting diagram

C. Comparison and Analysis of The Results Between Simulation and Test

Compaed table 3 and 4 , error between simulation and test is given in table 5. In the table, the second column is test motor speed n, the third column is the error e1 between simulation and test ((simulation speed-n)/n*100%), the fourth column is test A_1 phase RMS current I_{A1} and the fifth column is the error e2 between simulation and test((simulation A_1 current-I_{A1})/I_{A1}*100%).

Table 5 simulation error

T_2(N.m)	n（rpm）	e1 (%)	I_{A1}	e2 (%)
1.82	1482.4	-0.263	1.447	1.106
3.62	1465.3	-0.580	1.694	-0.177
5.48	1446.0	-0.947	2.077	-0.385
7.32	1424.1	-1.341	2.552	-0.823

Fig. 6 test photo

It shows that results of simulation match results well from table 5. The maximum error between them is lower than 2%. Such an error could be neglected in engineering.

IV. Conclusion

An equivalent three-phase induction motor was got by winding transformation. Then mathematical modeling for a dual three-phase induction motor was decided. By comparing the results of simulation and test corresponding, this paper shows the novel modeling is validated and correct.

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