4th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2013), Feb 13-14, 2013, Tehran, Iran

Modeling, Simulation and Control of an Anti Rotational PMSM for electric propulsion systems

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***Abstract*— It is necessary to verify operation of all subsystems of an electric vehicle, while experimental tests impose significant cost to the manufacturers such as test platform, equipment and various power supplies. At the same time, computer aided modeling makes it possible to reduce some of these costs. This paper concentrates on controlling speed and torque of an Anti Rotational Permanent Magnet Synchronous Motor (AR-PMSM) in an electric vehicle. This motor has inner and outer rotors and so it has two independent shafts. One of these rotors is the stator in the conventional PMSM motors. This structure has many applications like wind and hydro generators, electric vehicles and marine usages. This paper introduces an AR-PMSM, its principal and structure and gives the mathematical and simulation model. The simulation results for vector control (VC), SPWM and SVM control system show the validity of resulting model and also good dynamic performance of motor.**

Keywords*— *electric vehicle modeling; propulsion system; Anti Rotational PMSM; speed and torque control

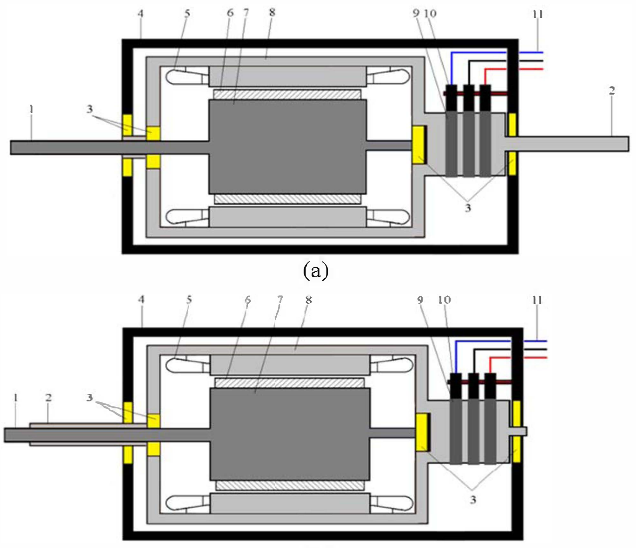
I. INTRODUCTION

Nowadays electrical propulsion system with many advantages like better performance, high efficiency and low noise has wide applications. The research on propulsion system that discussed in this paper is still at primary stages and in practical application process it has many problems therefore modeling and simulation of electric propulsion system with Anti Rotational PMSM can develop this kind of propulsion system [1].

Permanent Magnet Synchronous Motor (PMSM) has became very popular in recent years since it has advantages like lighter weight, smaller size, higher efficiency, better performance and low maintenance costs. Anti Rotational Permanent Magnet Synchronous Motor (AR-PMSM) is popular in electric vehicle [3], aviation turbines and marine propeller [4]. When this structure used as generator, it can make full use of energy and in low wind speed it has good performance since there is a strong mechanical relation between two rotors so more mechanical energy converts to electrical energy. A novel AR-PMSM with opposite-rotation dual rotors has been introduced. This motor can supply two equal and opposite direction torques, so it can drive two rotors and has two output shafts. Therefore, the torque density and efficiency of this motor has been improved greatly. The produced torques of two shafts have equal amplitude in opposite directions so this kind of motor has anti-rotational property. The AR-PMSM has the function of a differential gear in the conventional propulsion system [2]. For research on characteristics of AR-PMSM, its mathematical model has been derived and the simulation based on MATLAB for vector control (VC) [5], sinusoidal PWM (SPWM) [6] and space vector PWM (SVPWM) [7] have been proposed. Results show the validity of the model and good dynamic performance.

II. DESCRIPTION AND PRINCIPAL

There are some different in mechanical structure of AR-PMSM and conventional PMSM. In AR-PMSM the outer rotor (stator in conventional PMSM) can rotate in opposite-direction of inner rotor [2]. In fact stator can rotate freely so when electromagnetic field of armature forces the magnetic rotor, magnetic field also forces the armature (stator). Because of interaction law these forces are equal but in opposite direction so the produced torques of two rotors are balanced at any time and condition. Thus two rotors rotate inversely and in different speed since the moment of inertia and load torque are different. Because of rotation of stator the electricity is supplied through a slip ring to the outer rotor.



(a)

(b)

Figure 1. Two possible structure of AR-PMSM a) for electric vehicle applications b) for turbin and marine applications.

Fig1 shows two structure of AR-PMSM that (a) can use as electrical differential in electric vehicle or as generator for wind and hydroelectric turbines but (b) is useful for marine applications and wind turbines. In fig1 1-11 are inner shaft, outer shaft, shaft bearings, motor housing, armature winding, permanent magnet, inner rotor, outer rotor, slip rings, brushes and pin out of power supply, respectively.

III. MATHEMATICAL MODEL

Although AR-PMSM and conventional PMSM are different in their structures, if the armature part has taken as reference frame in d-q coordinate, they have similar electromagnetic relationship but their characteristics of mechanical relationship which is shown in (6) and (7) are different. With usual assumptions as PMSM, the d-q equations of AR-PMSM in armature part reference frame as stator in PMSM are (1)-(5).

$$\phi_d = L_d i_d + \phi_f \ , \quad \phi_q = L_q i_q \tag{1}$$

$$V_d = Ri_d + \frac{d\phi_d}{dt} - \omega_e \phi_q \tag{2}$$

$$V_q = Ri_q + \frac{d\phi_q}{dt} - \omega_e \phi_d \tag{3}$$

$$\omega_e = \omega_{e1} + \omega_{e2} \tag{4}$$

$$T_e = 3p(\phi_d i_q - \phi_q i_d)/2 \tag{5}$$

In above equations $\phi_d, \phi_q, V_d, V_q, i_d, i_q, L_d, L_q, R$ are d-q axes flux leakages, voltages, currents, effective inductances and resistance of outer rotor or armature respectively. ϕ_f is the flux leakage of permanent magnet of inner rotor, p is the number of pole pairs, T_e is the electromagnetic torque, ω_{e1} and ω_{e2} are the electrical angular velocity of inner and outer rotors respectively. Motion equations are shown in (6) and (7) where $J_1, J_2, T_{m1}, T_{m2}, B_{m1}, B_{m2}, \omega_1, \omega_2$ are moments of inertia, load torques, damping coefficients and mechanical angular speeds of inner and outer rotors respectively.

$$\frac{d\omega_1}{dt} = (T_e - B_{m1}\omega_1 - T_{m1})/J_1 \tag{6}$$

$$\frac{d\omega_2}{dt} = (T_e - B_{m2}\omega_2 - T_{m2})/J_2 \tag{7}$$

The parameters of AR-PMSM and dual propellers as mechanical loads for the motor that used in simulation are given in table 1.

TABLE I. THE CHARACTRISTIC PARAMETERS

AR-PMSM	Resistance, Ra (ohm)	2.87
	Inductance, La, Lq (H)	0.0085
	Number of pole pairs, p	4
	Inersia of inner rotor, J_1 (Kg.m^2)	0.00085
	Inersia of outer rotor, J_2 (Kg.m^2)	0.0009
	Damping coefficient, B_{m1}, B_{m2} (N.m.s)	0.0025
	Magnet flux linkage, Φ_f (Wb)	0.175
Dual propeller	Frontal propeller coefficient K_{p1} (N.m.s^2/rad^2)	0.0012
	Posterior propeller coefficient K_{p2} (N.m.s^2/rad^2)	0.0008

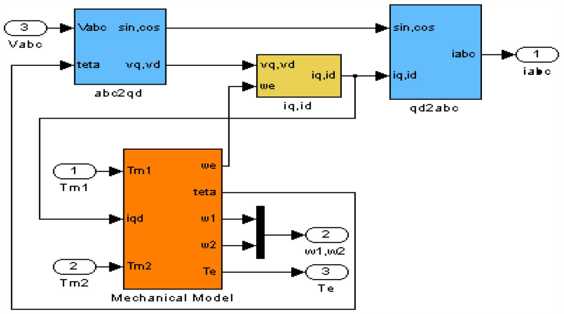


Figure 2. Simulink model of AR-PMSM

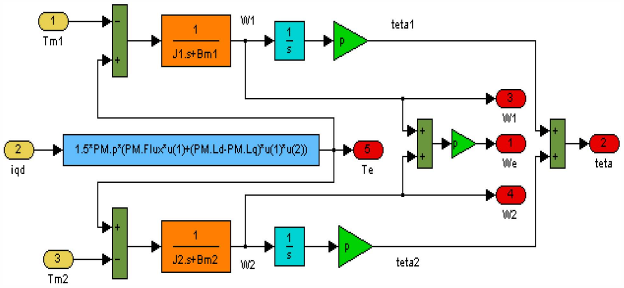


Figure 3. Mechanical Simulink sub-model of AR-PMSM

IV. SIMULATION MODEL

Simulation model of AR-PMSM using MATLAB based on (1)-(6) is shown in fig2. This model contains of two parts: mechanical and electrical. Electrical part is similar to conventional PMSM. But mechanical sub model that is shown in fig3 is different. If vector control, SVM or SPWM system is used for conventional PMSM, it can obtain good performance. For AR-PMSM, if the tree type of control systems are used the same we hope to it has good dynamic performance because they have similar dynamic parameter. So for verifying the validity of the model of AR-PMSM, the tree type of control system is used in simulation.

In order to use the simulation model of AR-PMSM easily, it is masked in MATLAB as AR-PMSM. After that the simulation results can be got easily just by changing some parameters. The model of VC, SVM and SPWM systems are shown in fig4, fig5 and fig6 respectively.

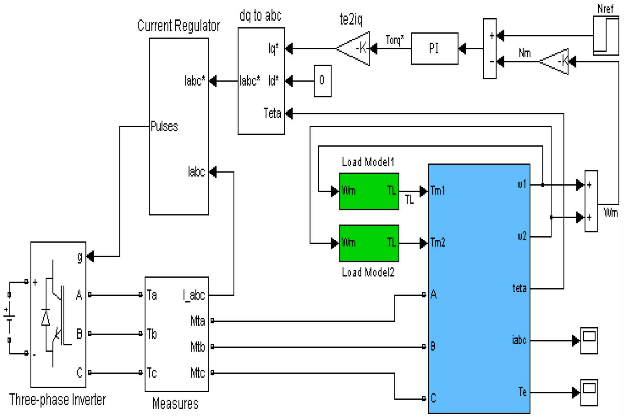


Figure 4. VC Simulink model of AR-PMSM

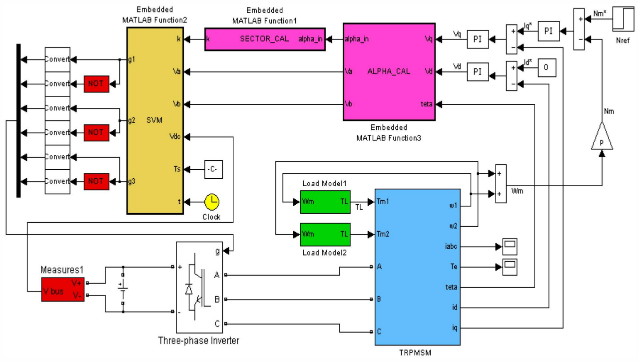


Figure 5. SVM control system of AR-PMSM

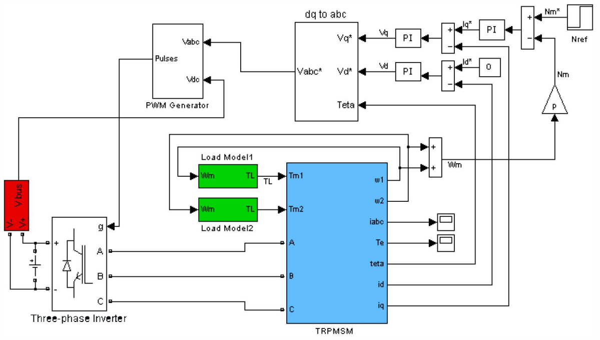


Figure 6. SPWM control system of AR-PMSM

V. SIMULATION RESULTS

Fig7 shows rotational speeds of inner and outer rotors by N_{m1} and N_{m2}, phase currents of armature, electromagnetic torque and load torque for each shaft respectively under VC system. The reference of two shafts respective rotational speed at 0.6sec has changed from 1000rpm to 1800rpm and an 8N.m load torque adds to each shaft at 0.4sec suddenly. With equal load torque for each shaft, inner rotor rotate quickly than outer rotor since the moment of inertia and damping coefficient of outer rotor are greater than inner rotor. Fig8 shows the performance of motor with dual propellers under VC system. It can be seen that the rotational speeds of two shafts are more different rather to pervious state since the load torque coefficient of outer propeller is bigger than inner propeller so outer propeller rotate slower to balance the load torque of outer shaft with the inner one.

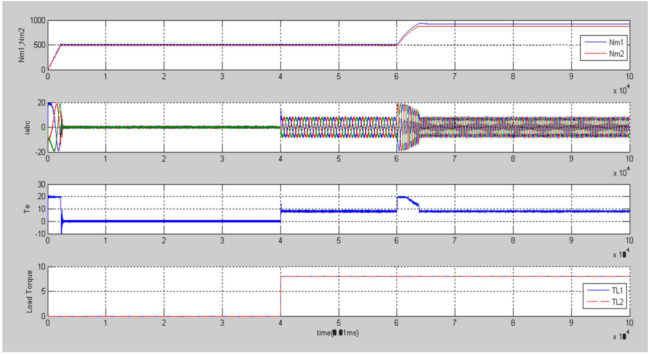


Figure 7. AR-PMSM under VC system with 8N.m step load torque

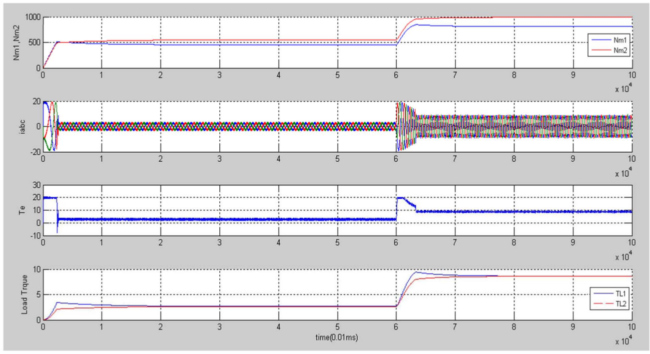


Figure 8. AR-PMSM under VC system with dual propellers load

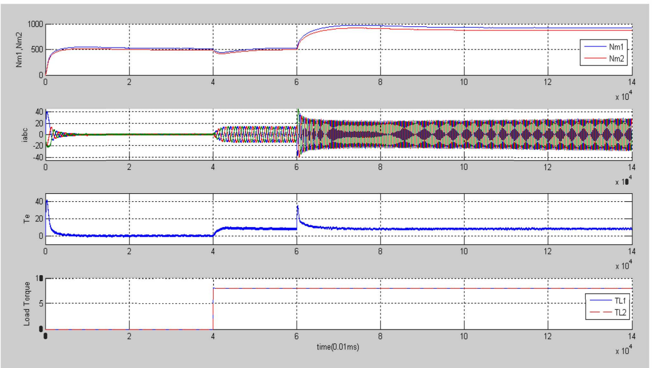


Figure 9. AR-PMSM under SVM control system with 8N.m step load torque

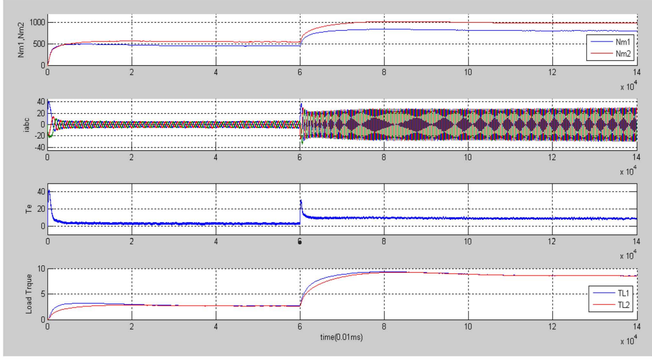


Figure 10. AR-PMSM under SVM control with dual propellers load

With simplification we can assume next equation for load torque of a propeller. In (8) Tp is load torque, Kp is torque coefficient and ω is mechanical angular speed of propeller. Torque coefficients for a dual propeller that is used as the load of the AR-PMSM are given in table1. Because of different diameter and screw parameter, torque coefficients of two propellers of a dual one are unequal.

$$T_p = K_p \omega^2 \tag{8}$$

The simulation results for AR-PMSM with SVM control system are shown in fig9 for an 8N.m step load torque and in fig10 for a dual propellers load. In comparison with VC it can be seen that SVM has slower dynamic response. Simulation results with pervious state conditions for SPWM control system are shown in fig11 and fig12. It can be seen that dynamic response with SPWM control system is similar to SVM.

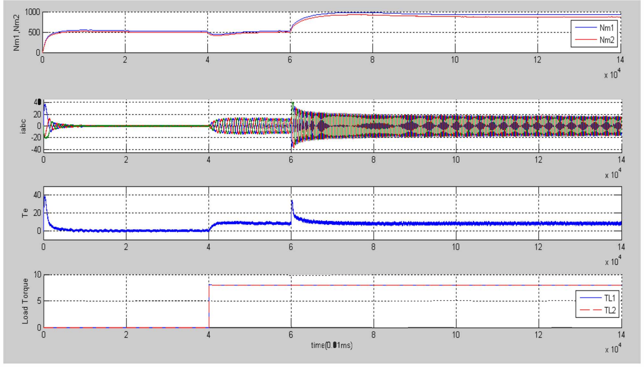


Figure 11. AR-PMSM under SPWM control with 8N.m step load torque

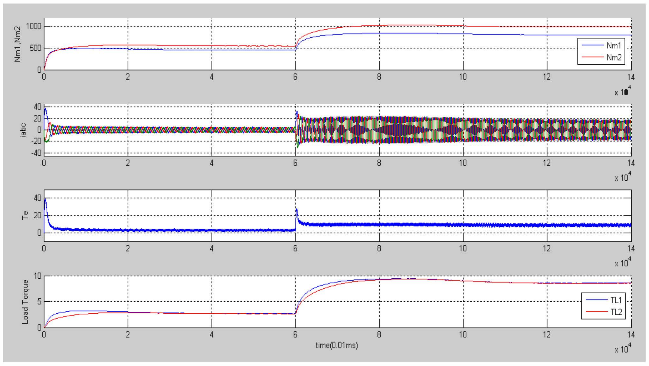


Figure 12. AR-PMSM under SVM control with dual propellers load

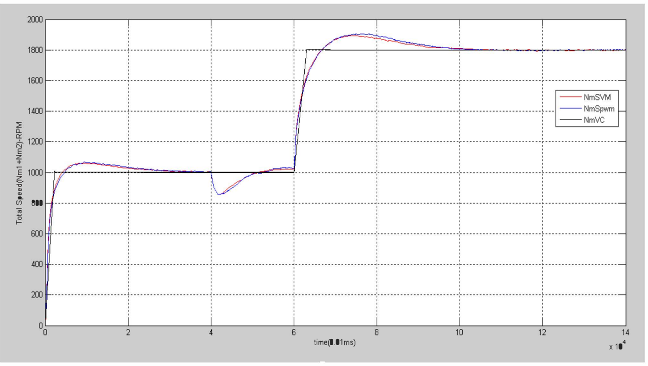


Figure 13. Shafts respective rotational Speed of AR-PMSM under VC, SVM and SPWM control systems with an 8N.m step load torque at 0.4 sec

For comparison of the three control systems fig13 and fig14 show two shafts respective rotational speed with step load torque and dual propellers respectively. It can be seen that VC system has a fast dynamic response so if a load suddenly adds to the shafts of AR-PMSM; VC can control the output rotational speeds quickly. SPWM and SVM control system have slower dynamic response but they can control the motor easily. Thus all three control method has good dynamic performance. With respect to the application we can select one of above three control system to control the AR-PMSM.

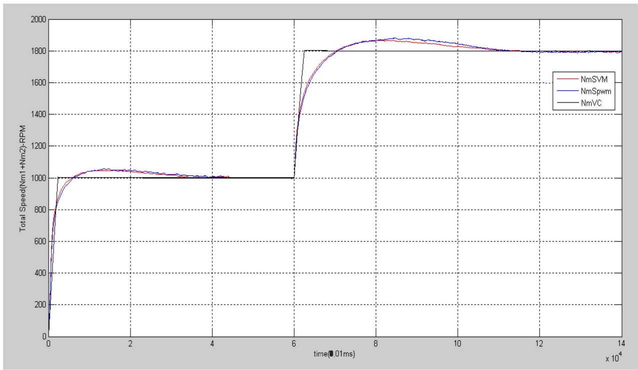


Figure 14. Shafts respective rotational Speed of AR-PMSM under VC, SVM and SPWM control systems with dual propellers load

VI. CONCLUSIONS

The introduced AR-PMSM has main advantages like lower weight and volume, higher efficiency and better performance in comparison with conventional PMSM. The principal, structure, mathematical and simulation model, VC, SVM, SPWM control systems are given. The simulation results are given based on MATLAB.

The results show that the proposed model of AR-PMSM is correct and it has good performance under various control system. This motor can supply two equal torques but in opposite direction of each other. Simulation results with dual propellers load show that AR-PMSM has an anti-rotational property that can balance the torques of two shafts and so it can use widely in marine applications and electric vehicle as electric differential for propulsion systems. AR-PMSM has some problems like slip rings and weak thermal dispatching that limit their high power applications so next studies can be focused on elimination of these problems.

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