Model reference adaptive sliding mode drive for permanent magnet double rotor motor

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***Abstract*— In order to optimize the speed-control performance of the permanent-magnet double rotor motor (DRM), a control strategy based on sliding-mode control (SMC) method is developed in this paper. The SMC controller with reference model is implemented to control the speed and the vector control is used for the current loop. The model of the DRM is firstly presented and implemented using Matlab/Simulink. Then, the proposed control strategy is investigated and simulation results validate the performances of the SMC controllers.**

***Keywords*— DRM, SMC, MRAC, PI, Vector Control**

I. INTRODUCTION

The Hybrid electrical vehicles (HEV) take great interest of the researchers, thanks to their energy conservation, economic fuel consumption and reduction of pollutant emissions. The development of clean energy applications in the transport field can provide some solutions of the air pollution, the global warming and the over-exploitation of the petrol resources. The hybrid vehicles are divided into three architectures: series, parallel and power split vehicles [1]. Much AC electrical motors are used in HEV architectures as permanent magnet synchronous motor (PMSM), reluctance motors (RM) and switched reluctance motors (SWRM). The double rotor motor or dual mechanical port motor is used as energy transducer in power split HEV. There are classified into two types: The axial flux double rotor motor is used as a differential gear in the electrical vehicle [2] and the radial flux motor that is considered as an electrical variable transmission (EVT). There are several types of radial flux double rotor motors dependent on the inner and outer rotor structure and materials [8]. The model of the first type is discussed in [3], it is formed by a permanent magnet inner rotor, a cup-type rotor and a stator. The second type, the outer and inner rotors are formed by winding [4]. In our work, we are interested on double rotor permanent magnet motor (DRPMM). It is formed by an inner wound rotor, a permanent magnet outer rotor and a stator. Furthermore, this category is divided into two configurations: the non-uniformed magnetic field DRM and uniformed magnetic field DRM [5], [6]. For the first type, the outer rotor is formed by two layers permanent magnets localized in the inner and outer surface of the outer rotor with rational arrangements and they are separated by permeable material. Therefore, that the flux lines can pass through the metal. The magnetic coupling between inner and outer motors is weak and can be neglected in the motor model [7]. However, in the uniformed magnetic field DRM, the outer rotor is formed by buried permanent magnets. As the material of this rotor is impermeable, the magnetic field of the inner rotor is shared by the outer motor and the magnetic coupling is strong and important [8]. The strong flux coupling makes the control more difficult. Then the outer motor cannot operate at the high-speed region when the inner motor operates at the wide speed region. For these reasons, we choose the first type.

The vector control approach can give good results as seen in [9]. In the vector control strategy, the q-current command should be limited due to constraints imposed by the motor characteristics in order to protect the stator windings. However, performances will be deteriorated when the q-axis current command is saturated control low in places [13]. In order to have good results an anti -windup algorithm will be required [13].

The sliding mode control provides an optimization of the DRM speed control and can remove all effects of parameters uncertainties [11].

In this paper, we are interested to the control of DRM. A sliding mode controller (SMC) based on model reference adaptive control MRAC is proposed for the speeds control of the two rotors. SMC is a robust control strategy used frequently in the nonlinear system control. The anti-windup algorithm can be avoided in this case.

This paper is organized as follows: the second section introduces the mathematical model of the used DRM. The vector control strategy used in current control is described in section 3. Next, the MRAC with sliding mode control strategy (SMC) used in speeds control is presented in the fourth section. The model implementation and the simulation results are

Presented and discussed in section 5.

II. THE DRM MODELING

The DRM is considered as an electrical variable transmission (EVT). So that the internal combustion engine ICE operates at the optimal operation line, the inner motor compensates the speed difference between the ICE and car speed demand and the outer motor provides the torque difference [3].
The DRM is formed by two concentric permanent magnet motors: inner and outer motors.

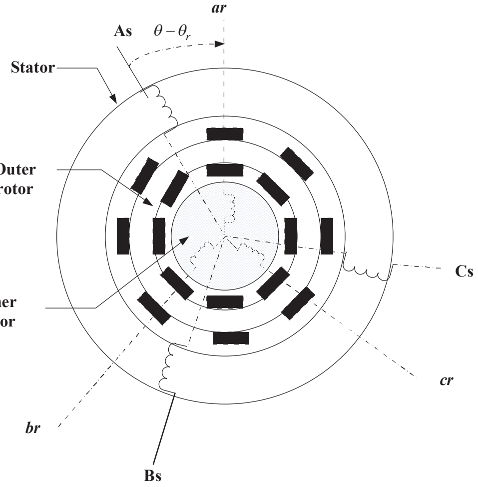

Fig .1 the DRM architecture

The global model is described by the following equations in the dq frame [4].

$$\frac{di_{ds}}{dt}=\frac{1}{L_{ds}}(u_{ds}-r_s i_{ds}+\omega L_{qs} i_{qs}) \qquad (1)$$

$$\frac{di_{qs}}{dt}=\frac{1}{L_{qs}}(u_{qs}-r_s i_{qs}-\omega L_{ds} i_{ds}-\omega\lambda_{m1}) \qquad (2)$$

$$T_{out}=\frac{3}{2}p\left[\lambda_{m1}i_{qs}+\lambda_{m2}i_{qr}+(L_{ds}-L_{qs})i_{ds}i_{qs}\right] \qquad (3)$$

$$\frac{d\omega_m}{dt}=\frac{1}{J_s}(T_{out}-T_l-B_s\omega_m) \qquad (4)$$

$$\frac{di_{dr}}{dt}=\frac{1}{L_{dr}}(u_{dr}-r_r i_{dr}+(\omega-\omega_r)L_{qr} i_{qr}) \qquad (5)$$

$$\frac{di_{qr}}{dt}=\frac{1}{L_{qr}}(u_{qr}-r_r i_{qr}-(\omega-\omega_r)L_{dr} i_{dr}-(\omega-\omega_r)\lambda_{m2}) \qquad (6)$$

$$T_{in}=-\frac{3}{2}p\lambda_{m2}i_{qr} \qquad (7)$$

$$\frac{d\omega_{rm}}{dt}=\frac{1}{J_r}(T_{in}-T_{ice}-B_r\omega_{rm}) \qquad (8)$$

We notice here that i_{ds} , i_{dr} , i_{qs} , i_{qr} are the direct and quadrature currents of the inner and outer motors. Similarly, u_{ds} , u_{dr} , u_{qs} , u_{qr} are the direct and quadrature voltages of the two motors. T_{in} And T_{out} are the electromagnetic torques in the inner and the outer air gaps respectively. ω_{rm} And ω_m are the mechanical speeds of the inner and outer rotors respectively. In this model, the motor parameters are denoted in the table 1 [4].

Table 1: The DRM parameters

Stator phase resistance	r_s	0.08 Ω
Inner rotor phase resistance	r_r	0.29 Ω
Stator q-axis inductance	L_{qs}	1.15 mH
Stator d-axis inductance	L_{ds}	1.85 mH
Inner rotor q-axis inductance	L_{qr}	1.5 mH
Inner rotor d-axis inductance	L_{dr}	1.5 mH
Number of pair of poles	p	3
Flux linkage of the outer motor	λ_{m1}	0.0728 Wb
Flux linkage of the inner motor	λ_{m2}	0.0889 Wb

III. VECTOR CONTROL STRATEGY

The regulators used in the currents control are proportional integral (PI) type. The PI parameters are inspired from transfer functions described in the four following equations.

$$\frac{i_{ds}}{u_{ds}+(r_s i_{dr}+\omega L_{qs} i_{qs})}=\frac{1}{(r_s+sL_{ds})} \qquad (9)$$

$$\frac{i_{qs}}{u_{qs}+(r_s i_{qr}-\omega L_{ds} i_{ds}-\lambda_{m1})}=\frac{1}{(r_s+sL_{qs})} \qquad (10)$$

$$\frac{i_{dr}}{u_{dr}+(r_r i_{ds}+(\omega-\omega_r)L_{qr} i_{qr})}=\frac{1}{(r_r+sL_{dr})} \qquad (11)$$

$$\frac{i_{qr}}{u_{qr}+(r_r i_{qs}-(\omega-\omega_r)L_{dr} i_{dr}-(\omega-\omega_r)\lambda_{m2})}=\frac{1}{(r_r+sL_{qr})}$$

(12)

The regulators provide the voltages command that ensure the reference tracking. Fig.1 presents the description schema of the currents control strategy used in this work. The voltage commands are limited by the DC link voltage limit.

IV. SLIDING MODE CONTROL WITH MRAC

The model reference adaptive slide mode control used in this paper is developed in [11] for the control of PMSM speed and generates the q current command. But in these works the controller generates the torque command.
The mechanical equations of the rotors movement are described in equations 8 and 4.
The reference model of PMSM is described by the mechanical equation described as.

$$T_m=J_m\frac{d\omega_{rs}}{dt}+B_m\omega_{rs} \qquad (13)$$

The variable $x=\omega_{rs}-\omega_m$ denotes the difference between the reference model and the system outputs. The control strategy based on SMC is detailed for the outer motor. The same approach is the applicant to the inner rotor speed control.

The controller will generate the electromagnetic torque command that are necessary to ensure that the reference tracking. After subtracting (13) from (4), we deduct the equation below.

$$J_m \frac{dx}{dt} = -B_m x - (T_{out} - T_m) + (\Delta J \frac{d\omega_m}{dt} + \Delta B \omega_m + T_l)$$

Where $\Delta J = J_s - J_m$, $\Delta B = B_s - B_m$

From Equa.14, we deduct the following dynamic equation.

$$\dot{x} = a_m x - b_m \Delta u + e \tag{15}$$

Where $a_m = -\frac{B_m}{J_m}$, $b_m = \frac{1}{J_m}$, $\Delta u = T_{out} - T_m$

And $e = \frac{T_l}{J_m} + \frac{\Delta J}{J_m}\frac{d\omega_m}{dt} + \frac{\Delta B}{J_m}\omega_m$

where e is the generalized error equation and x is the speed error. The goal of the control algorithm is to converge x to zero. We apply the SMC to the generalized error equation, the switching surface with integral component described in equation (16) ensure the exponential stability for sliding mode speed control [11] .

$$s = x + c\int_0^t x(\tau)d\tau \tag{16}$$

In the slide mode, s=0 so that the dynamic equation described in equation (15) can be

$$\dot{x} = -cx \tag{17}$$

The Lyapunov function is denoted as $v = \frac{1}{2}s^2$, the condition $\dot{s} = s\dot{s} < 0$ ensure the Lyapunov stability theorem. As a result, we can deduct from Equa.15, Equa.16 and the Lyapunov condition the following dynamic equation.

$$s(a_m x - b_m \Delta u + e + cx) < 0 \tag{18}$$

By reference to [11], the switching controller that can remove the dynamic generalized error should be expressed as shown in equation (19).

$$\Delta u = \frac{a_m + c}{b_m} x + \beta f(s) \tag{19}$$

When we subtle equation (18) in equation (17), the stability condition will be expressed as follows.

$$s(-b_m \beta f(s) + e) < 0 \tag{20}$$

And the sign function f(s) is denoted as

$$\begin{cases} s > 0 \rightarrow f(s) = +1 \\ s < 0 \rightarrow f(s) = -1 \end{cases} \tag{21}$$

From equation (20), the condition $s\dot{s} < 0$ is satisfied, if the β value ensure these conditions.

$$\begin{cases} s > 0 \rightarrow \beta < \frac{e}{b_m} \\ s < 0 \rightarrow \beta > -\frac{e}{b_m} \end{cases} \Rightarrow \beta > \left|\frac{e}{b_m}\right| \tag{22}$$

The slide mode controller is determined if the β value is deduced. After the generation of the electromagnetic torque commands, the quadratic currents are expressed in equations (23) (24).

$$i_{qr}^* = \frac{-2T_{in}^*}{3p\lambda_{m2}} \tag{23}$$

$$i_{qs}^* = \frac{2(T_{eo}^* + T_{in}^*)}{3p\lambda_{m1}} \tag{24}$$

In this work, we are interested to control the DRM at the constant torque region, As a result the direct current references are forced to zero.

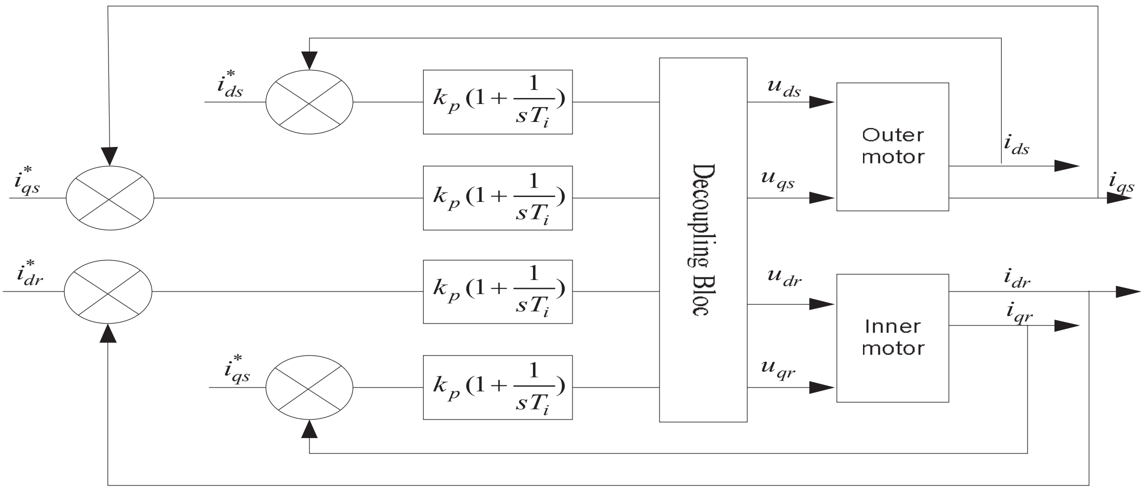

Fig. 2 Current control bloc

V. MODEL IMPLEMENTATION AND SIMULATION RESULTS

The fig. 2 presents the control strategy used to control the output speed of the outer motor. The same strategy is used in the inner motor speed. The implemented model is simulated using Matlab-Simulink. Fig.4 presents current responses in the inner and outer motors. The direct current responses are cancelled, so that current controllers achieve a good precision and stability. For the quadrature currents, their responses denote a good tracking performance that help to have a good speed tracking also. The fig.5 denotes the speed and torque responses of the outer and inner rotor. We notice here that the output speeds follow the references when the outer and inner motor operates as a motor or a generator. The proposed control strategy presents robust performances as good stability, rapidity and precision. The system response is fast. The parameters of the reference model have effected in the speed response rapidity. In the first case, we choose the parameters of two references models as $\begin{cases} J_m = J_s \\ B_m = B_s \end{cases}$.The speed response with these parameters are presented in fig.6 (a) and fig.6 (b). In the second case, we use $\begin{cases} J_m = \dfrac{J_s}{2} \\ B_m = \dfrac{B_s}{2} \end{cases}$.

The two-speed responses to the step references are shown in fig.6 (c) and (d). We notice here that the speed responses in the second case are faster and they reach the reference with a smaller response time. We conclude that the sliding mode controller based on reference model improve the dynamic performances of the system.

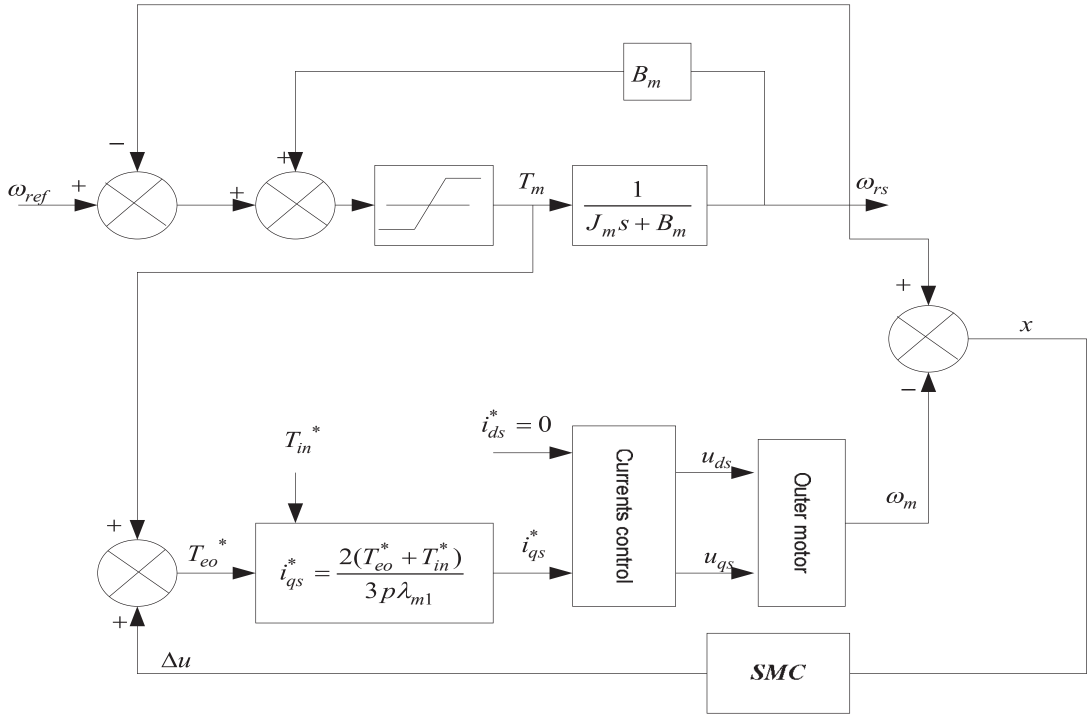

Fig. 3 The control strategy implementation

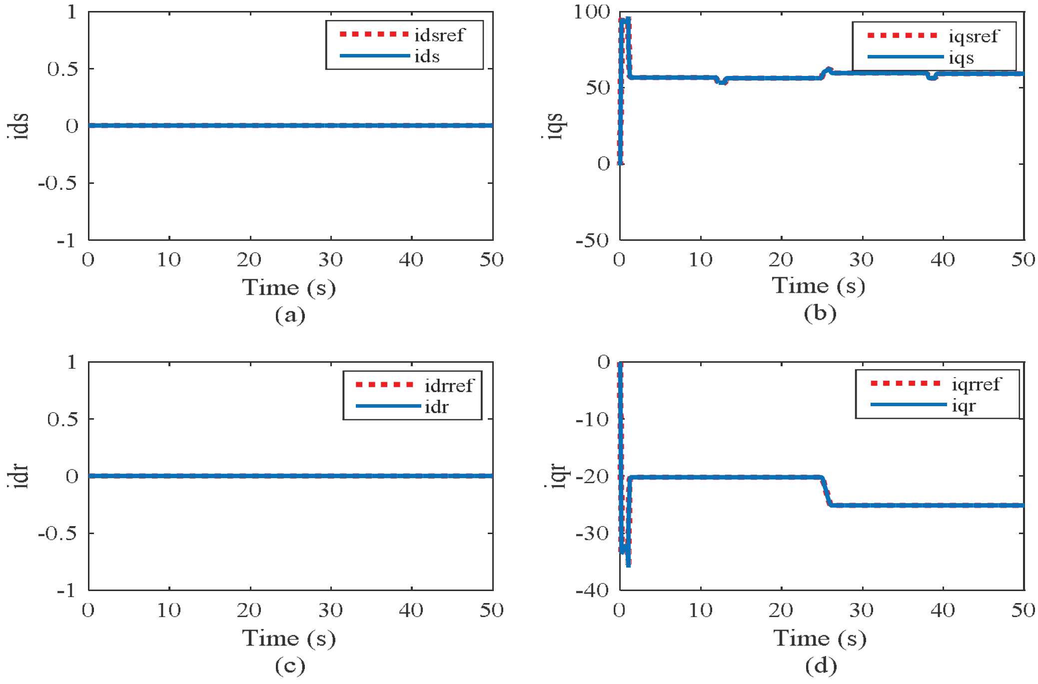

Fig.4 Current responses of the DRM:
(a) outer direct current (b) outer quadrature current, (c) inner direct current (d) inner quadrature current

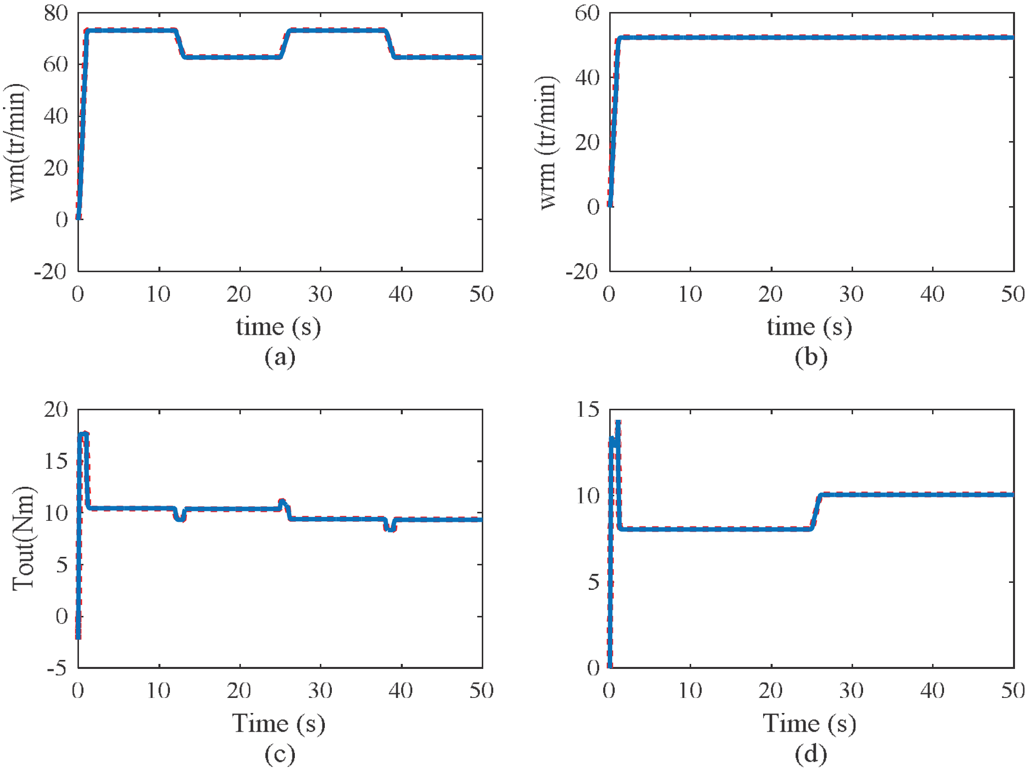

Fig.5 Speed and torque outputs of the DRM:
(a) outer rotor mechanical speed (b) inner rotor mechanical speed, (c) outer electromagnetic torque (d) inner electromagnetic torque

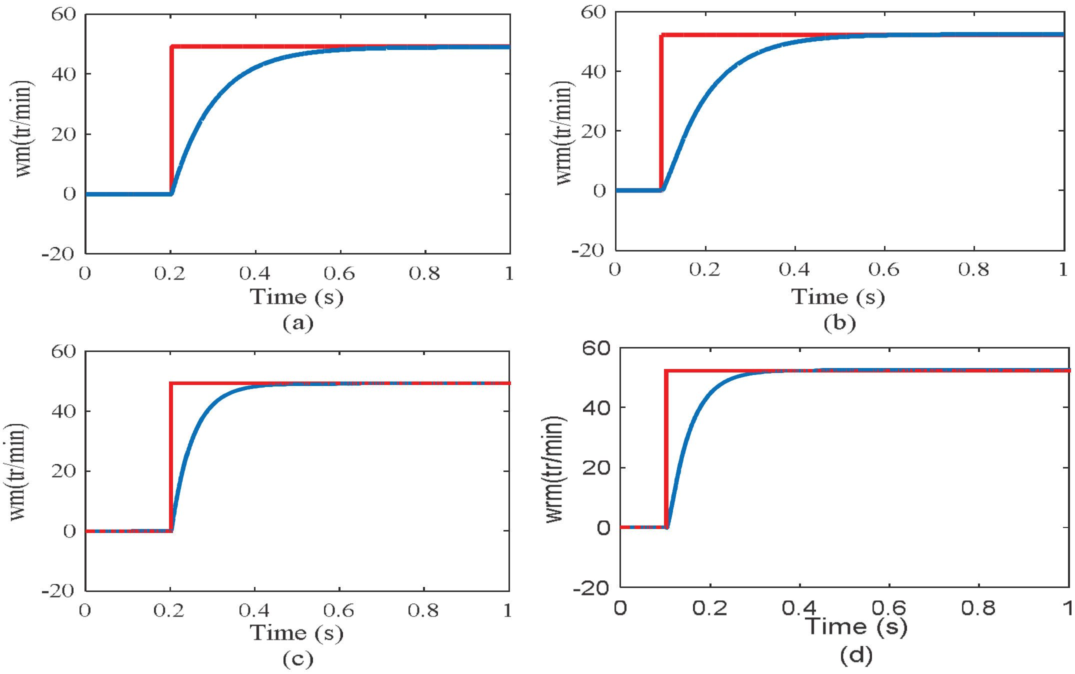

Fig.6 Step speeds responses
(a) outer rotor speed in the first case (b) inner rotor speed in the first case, (c) outer rotor speed in the second case (d) inner rotor speed in the second case

VI. CONCLUSION

The proposed control strategy based on sliding mode control with reference model proposed is robust, which provides good precision and stability. In our work, we control the speeds of the two rotors in DRM using the slide mode controller. These results were applied to the PMSM, in this paper the studied method is applied to the DRM without the consideration of the mutual inductances between the inner rotor and the stator. The simulation results validate the good performances of the control strategy adopted such as rapidity, stability and precision.

As a prospect, the simulation results will be validated by experimental application and can also be used in the high-speed region. Also the proposed control strategy will be applied in the control of DRM with mutual inductance.

Reference

[1] V. K. W. X. a. H. H. Z. Amit Vilas Sant, «Four-Axis Vector-Controlled Dual-Rotor PMSM,» *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,* vol. 62, n° %15, 2015.

[2] H. C. a. L. Xu, «Modeling and Control for Cage Rotor Dual Mechanical Port Electric Machine—Part II: Independent Control of Two Rotors,» *IEEE TRANSACTIONS ON ENERGY CONVERSION,,* vol. 30, n° %13, 2015.

[3] S. Q. W. X. Z. F. a. F. T. ZHUANG Xingming, «Coupling Characteristics and Control of Dual Mechanical Port Machine with Spoke Type Permanent Magnet Arrangement,» *CHINESE JOURNAL OF MECHANICAL ENGINEERING,* vol. 27, n° %16, 2014.

[4] H. Cai, «MODELING AND CONTROL OF DUAL MECHANICAL PORT ELECTRIC MACHINE,» Thesis, 2015.

[5] L. Xu, «Concept and application of a new electric,» *IEEE INDUSTRY APPLICATIONS MAGAZINE,* 2009.

[6] L. S. K. Z. a. L. S. Xiaoguang Zhang, «Nonlinear Speed Control for PMSM System Using Sliding-Mode Control and Disturbance Compensation Techniques,» *IEEE TRANSACTIONS ON POWER ELECTRONICS,* vol. 28, n° %13, 2013.

[7] W. S. a. S. A. E. Jerome Meisel, «Evaluation of the through-the-road architecture for plug-in hybrid electric vehicle powertrains,» chez *Electric Vehicle Conference (IEVC), 2013 IEEE International*, Santa Clara, CA, 2013.

[8] A. A. J. B. a. C. O. Jordi Espina, «Speed Anti-Windup PI strategies review for Field Oriented Control of Permanent Magnet Synchronous Machines,» chez *POWER ELECTRONICS CONTROLLERS FOR POWER SYSTEMS*, 2009.

[9] Q. Z. G. a. H. W. Lianbing Li, «Analysis of Feasibility of Double-Rotor Motor Applied to Hybrid Electric Vehicle,» chez *Vehicle Power and Propulsion Conference, 2008. VPPC '08. IEEE*, Harbin, 2008.

[10] X. Y. a. Q. L. Rujing Xiao, «Simulation and Analysis on Novel Dual-Rotor Permanent-Magnet Synchronous Motor,» chez *2010 International Conference on Electrical and Control Engineering*.

[11] B. Zhang, B. Acad. Sinica et Y. Li, «A PMSM sliding mode control system based on model reference adaptive control,» chez *Power Electronics and Motion Control Conference, 2000. Proceedings. IPEMC 2000. The Third International*, Beijing, 2000.

[12] P. Zheng, R. Liu, W. Fan et J. Han, « Research on the Control of a Radial-Radial Flux Compound-Structure Permanent-Magnet Synchronous Machine Used for HEVs,» chez *2008 14th Symposium on Electromagnetic Launch Technology,*, Victoria, BC, 2008.

[13] H.-B. Shin, «New Antiwindup PI Controller for Variable-Speed Motor Drives,» *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,* vol. 45, n° %13, 1998.