**Int. j. adv. multidisc. res. stud.** 2023; 3(5):712-717

**Received:** 13-08-2022
**Accepted:** 23-09-2023

International Journal of Advanced Multidisciplinary Research and Studies

**ISSN: 2583-049X**

# Sliding Mode Control for Axial Flux Permanent Magnet Motor

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**Abstract**
The axial flux permanent magnet synchronous motor (AFPM motor) using magnet bearings instead of ball-bearings at both two shaft ends could allow rotational speed of shaft much greater than nominal speed. The paper proposes a controller for axial flux permanent magnet (AFPM) motor that adjusts both rotation rotor speed and axial rotor position by sliding mode controller. Controlled system performance is validated through a set of simulations.

**Keywords:** AFPM Motor, Speed Controller, Axial Posotion Controller, SMC

## 1. Introduction
Axial flux permanent magnet motor (AFPB) finds its important role in electric drive systems [1-4]. The motor studied in this paper is a synchronous motor with permanent magnets attached to the rotor and the two stators with windings on both sides of the rotor. The AFPB has two degrees of freedom: Rotation and displacement along the rotor axis [5-6]. Recent researches target mainly on the design problem of AFPM [7-10], a number of works looking at control aspect [11-17]. Most of the works done on control of AFPM use linear control technique that may result in limited operating range of the motor.

## 2. Mathematical Model of AFPM Motor
In terms of structure, the AFPM motor has its own particular specialists, in details, the stator module may include several types: A single module has one winding set and a dual module has two sets of winding sharing a common core and back-to-back establishment. Similarly, a single rotor module includes only one permanent magnet on one side, and in dual module one, both sides have permanent magnets leaning against each other. When a three-phase voltage is granted to stator coils, different currents are generated (including current $i_q$) flowing inside, they will interact with the magnetics of rotor to generate torque (*M*) and the currents in phase windings (component $i_d$) of stator generate thrust and drag (*F*) based on the principle of the electromagnet. Thanks to special structure and above-mentioned operating principle, the rotor of the motor will not generate axial displacement although both ends of the shaft have magnetic bearings. It allows the absence of additional axial movement block of the rotor, therefore, the motor structure is being compact. Due to the way of winding roll, the rotational magnetic field generates torques $M_1$ and $M_2$ on the same direction on the rotor shaft and generates thrust-drag forces *F1* and *F2* between the rotor and the stator on opposite direction. The total torque ($M=M_1+M_2$) is the summation of the torques but the total force is the difference of the axial attractive forces ($F=F_1-F_2$).
The mathematical model of AFPM motor was developed in *dq* coordinate system, as presented as the following.

Mathematical model of motor 1:

$$\begin{cases} u_{sd1} = R_s i_{sd1} + L_{sd1}\dfrac{di_{sd1}}{dt} - \omega_s L_{sq1} i_{sq1} \\ u_{sq1} = R_s i_{sq1} + L_{sq1}\dfrac{di_{sq1}}{dt} + \omega_s L_{sd1} i_{sd1} + \omega_s \psi_p \end{cases} \tag{1}$$

Mathematical model of motor 2:

$$\begin{cases} u_{sd2} = R_s i_{sd2} + L_{sd2}\dfrac{di_{sd2}}{dt} - \omega_s L_{sq2} i_{sq2} \\ u_{sq2} = R_s i_{sq2} + L_{sq2}\dfrac{di_{sq2}}{dt} + \omega_s L_{sd2} i_{sd2} + \omega_s \psi_p \end{cases} \quad (2)$$

Where:

$i_{sd1}, i_{sq1}, i_{sd2}, i_{sq2}$ are the currents on d,q axis of motor 1 and motor 2, respectively,

$u_{sd1}, u_{sq1}, u_{sd2}, u_{sq2}$ are the voltages on d,q axis of motor 1 and motor 2, respectively,

$L_{sd1}, L_{sq1}, L_{sd2}, L_{sq2}$ are the inductances after transformation in dq axis of motor 1 and motor 2, respectively,

$R_s$ is the resistor on stator,

$\psi_p$ is the magnet flux,

$\omega_s$ is the rotation speed of rotor.

The equation that show properties of rotation rotor speed:

$$\frac{3}{2} z_p \left[ \psi_p i_{sq1} + i_{sd1} i_{sq1} (L_{sd1} - L_{sq1}) + \psi_p i_{sq2} + i_{sd2} i_{sq2} (L_{sd2} - L_{sq2}) \right] = m_m + \frac{J}{z_p}\frac{d\omega}{dt} \quad (3)$$

Where:

$m_m$ is the external torque ( the load)

$J$ is the inertia of rotor

$z_p$ is number of dual pole

The equation that show properties of axial rotor position:

$$m\ddot{z} + F_L = k_1 (i_{2d} - i_{1d}) + k_1 (i_{2d} - i_{1d}) z - k_2 z \quad (4)$$

Where:

$z$ is the axial displacement,

$m$ is the mass of rotor,

$F_L$ is the external force influencing on rotor,

$$k_1 = 2\frac{\mu_0^2 N^2}{g_0^2}\psi_p; \; k_2 = 2\frac{\mu_0}{S_p g_0}\psi_p^2.$$

**3. Control Design for AFPM Motor**

There are some system’s parameters that will be changed like load torque, the force influencing rotor...So, conventional PID controller is not good enough to apply in controlling speed and axial position. We propose the sliding mode controller to replace PID. With plenty of outstanding advantages like robust with external disturbances, adjusting with the changes of system’s parameters, the responses of outer-loop will be improve significantly as well as system performace.

**Rotation Rotor Speed Controller**

Rewrite the dynamic equation (3) as following:

$$BI_{sq} = m_m + \frac{J}{z_p}\dot{\omega} \quad (5)$$

Where:

$$I_{sq} = \left[ i_{sq1} \quad i_{sq2} \right]^T \qquad B = \frac{3}{2} z_p \left[ \psi_p + i_{sd1}(L_{sd1} - L_{sq1}) \quad \psi_p + i_{sd2}(L_{sd1} - L_{sq1}) \right]$$

Choose the sliding surface as:

$$S_\omega = \omega - \omega_r \quad (6)$$

The purpose of control signal is driving the system's state ( in this case is the rotation speed) to the sliding surface, then the controller will drive the sliding surface to zero. So that, there are two components of control signal:
$I_{sqeq}$ is the signal that keep state on the sliding surface, this signal can be computed by condition: $\dot{S}_\omega = 0$
From (5) and (6), we obtain:

$$\frac{z_p}{J}\left(BI_{sqeq} - m_m\right) - \dot{\omega}_r = 0$$
$$<=> I_{sqeq} = B^T\left(BB^T\right)^{-1}\left(m_m + \frac{J}{z_p}\dot{\omega}_r\right) \quad (7)$$

$I_{sqsw}$ is the signal that drive the sliding surface to zero, this signal can be computed by condition: $S_\omega \dot{S}_\omega < 0$
From (5), (6) and above condition, we can choose the control signal as following:

$$I_{sqsw} = B^T\left(BB^T\right)^{-1}\frac{J}{z_p}\left(-c_\omega sign\left(S_\omega\right)\right) \quad (8)$$

Where $c_\omega$ is a positive gain

The final control signal is the combination of above signals:

$$I_{sq} = I_{sqeq} + I_{sqsw}$$
$$= B^T\left(BB^T\right)^{-1}\left(m_m + \frac{J}{z_p}\left(\dot{\omega}_r - c_\omega sign\left(S_\omega\right)\right)\right) \quad (9)$$

**Axial Rotor Position Controller**
Rewrite the dynamic equation (4) as:

$$K\Delta I_d - k_2 z - F_L = m\ddot{z} \quad (10)$$

Where: $K = k_1 + k_1 z$; $\Delta I_d = i_{2d} - i_{1d}$
Choose the sliding surface for axial displacement as:

$$S_z = \lambda z + \dot{z} \quad (11)$$

Where $\lambda$ is a controller's variable, we will choose $\lambda$ so that the equation (11) guarantees the Hurwitz Stable Standard. The control signal will drive all components of sliding surface (11) to zero, it means that not only the axial displacement will be drive to zero, but also it's differential will not change. Similarly above section, the control signal in this case also has 2 components, and they can be caculated by these following conditions:

$$\begin{cases} \dot{S}_z = 0 \\ S_z \dot{S}_z < 0 \end{cases} \quad (12)$$

From condition (12), we can compute the signal that keep state ( axial displacement) on the sliding surface as:

$$\Delta I_{deq} = \frac{m}{K}\left(-\lambda\dot{z}\right) + k_2 z \quad (13)$$

And we choose the signal that drive sliding surface to zero as:

$$\Delta I_{dsw} = \frac{m}{K}\left(-c_z sign\left(S\right)\right) \quad (14)$$

The final control signal is the combination of the signals (13)and (14):

$$\Delta I_d = \Delta I_{deq} + \Delta I_{dsw} = \frac{m}{K}\left(-\lambda \dot{z} - c_z sign(S)\right) + k_2 z \quad (15)$$

## 4. Simulation Results

**The system is simulated under conditions:** Desired rotate speed 3000 r/m; load 2 N.m added at 2s; external force influencing in rotor added at 3s.

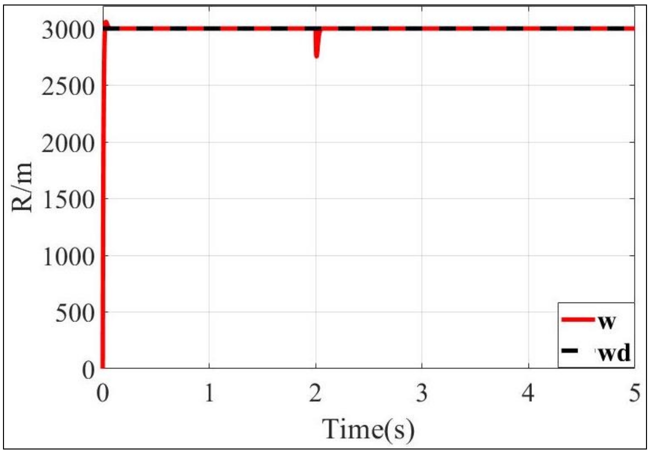


**Fig 1:** Rotation speed response

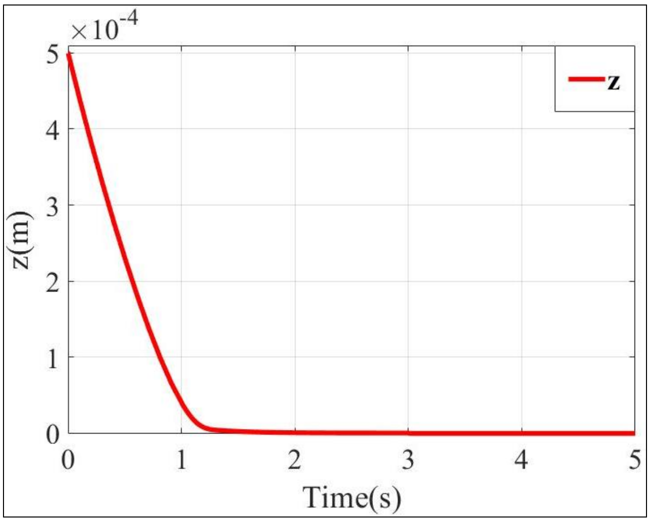


**Fig 2:** Axial displacement response

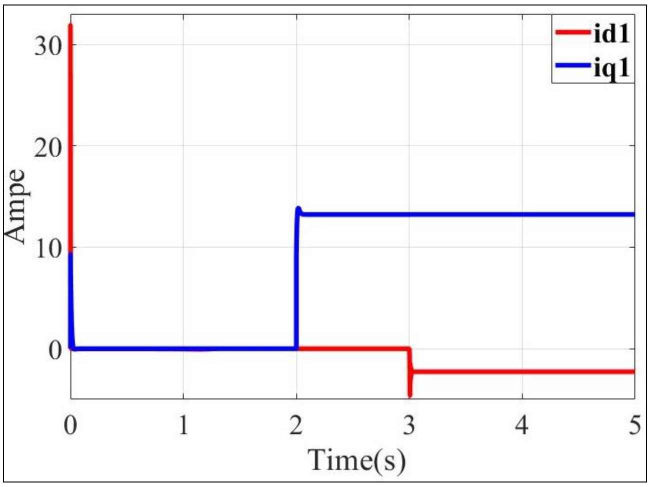


**Fig 3:** Current response of Stator 1

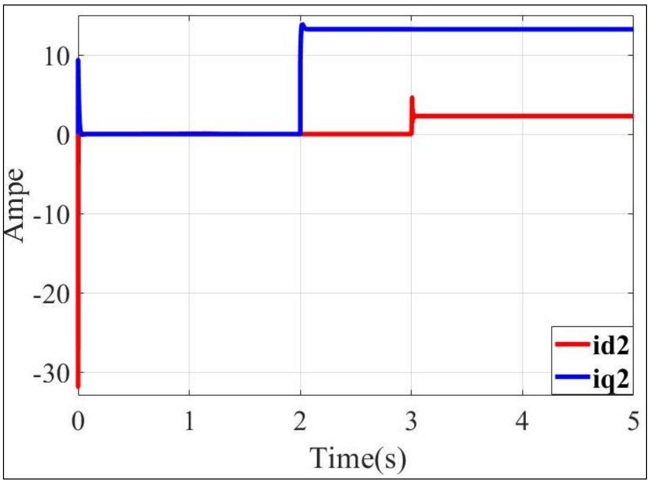


**Fig 4:** Current response of Stator 2

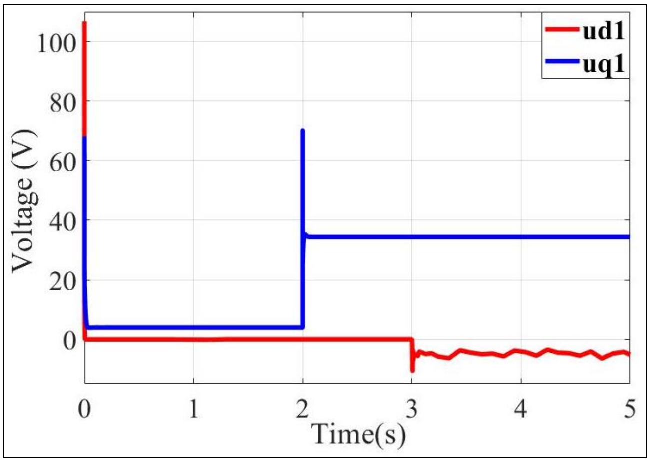


**Fig 5:** Control signal of Stator 1

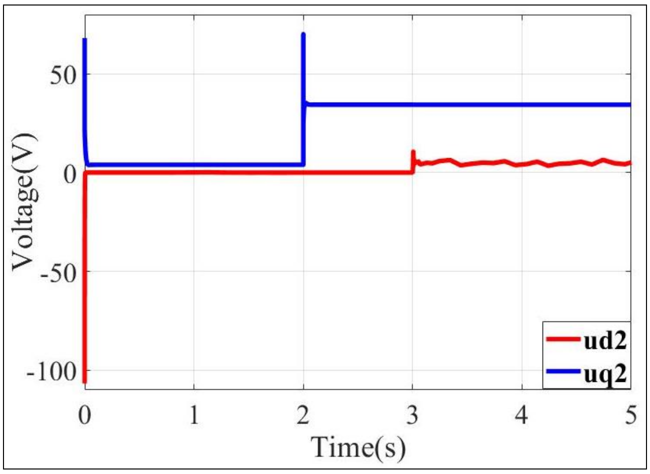


**Fig 6:** Control signal of Stator 2

When load and an external force are applied to the system the control still drive the axial position to the equilibrium and the rotational speed to the desired value.

## 4. Conclusion

The paper deal with control problem of an axial flux permanent magnet motor, and focuses on the SMC controller designing for the position and speed of an axial flux permanent magnet motor . The motor creates the magnetic field to lift the motor along the shaft and generate rotating torque. The motor electro-mechanical relations are analyzed to formulate an accurate mathematical model, then a control structure is proposed. The system simulation results show that the drive system ensures stability and tracking performance.

**5. Acknowledgement**
The authors thank the Thai Nguyen University of Technology for supporting this work.

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