SLIDING MODE CONTROL OF ROTOR LEVITATION IN HYBRID POLE BEARINGLESS SWITCHED RELUCTANCE MOTOR

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ABSTRACT

The bearingless motors (BMs) play an important role in the industries with sensitive and high purity environments due to their advantages of non-contact and lubrication free rotation. The simplest and most adaptable type of BM is the bearingless switched reluctance motor (BSRM). Design of robust control system to achieve steady levitation of rotor with reduced vibration and high-speed tracking is a challenging task. This paper presents the design and implementation of sliding mode controller for control of a 12/14 BSRM with hybrid stator pole structure. Two independent control systems are designed using MATLAB/Simulink to control the levitation force and speed of BSRM and tests including speed regulation, vibration control are performed. As indicated by the simulation results, the proposed controller levitates the rotor steadily at standstill and during accelerating to the desired speed when compared to the conventional PID controller.

KEYWORDS: *BSRM, Levitation control, Sliding mode controller, Rotor vibration.*

I. INTRODUCTION

In the bearingless motor (BM) the function of mechanical bearings are performed by magnetic bearings (MB), which offers magnetic levitation force to levitate the rotor without any mechanical contact [1-2]. Therefore, the bearingless motor system is a natural solution for the applications suffering from mechanical friction issues. The BM consolidates the features of a MB and a motor into a single electromechanical structure with the benefits of lubricant free and maintenance free operation, less thermal loss, no frictional loss and reduced material wear. Subsequently, BMs are increasingly used in applications for example turbomolecular pumps, artificial hearts, precision machine tools, etc [3-6]. The simplest and most adaptable type of bearingless motor is the bearingless switched reluctance motor (BSRM). The BSRMs have great performance under exceptional conditions, because of their adaptation to extreme high and low temperature variations, robustness, and fault tolerance. They are especially appropriate for exceptional applications, such as blood pump, molecular pump, etc [7-8].In the past decade, a few BSRM structures proposed based on the quantity of windings on every stator pole, the number of phases for torque production, rotor segments, the magnet type etc [9-10]. The 12/14 hybrid pole type BSRM contains two types of poles on stator, the first type is for rotor levitation, and the second is for torque generation. The torque, hence the speed of the BSRM can be controlled by adjusting the torque winding current value [11]. To control the toque and levitation force in this structure, some control techniques such as PID and Fuzzy control are proposed. Since BSRM has weakness, for example, high nonlinear, uncertainty, variable parameter and structure, it is hard to obtain the exact mathematical model so it is hard to accomplish the fine control using the conventional linear control [12].

The control strategy based on the variable structure of the system, the sliding mode control forces the system state to track the selected surface in state space, which reflects the desired dynamics. The control law makes the system state switches to suitable side and slides along the surface towards the equilibrium point called sliding mode. Under controlled phase, once the system state enters the sliding

mode, the variations in system parameters have no impact and is unaffected by external disturbances. The SMC additionally has the undeniable chattering, which is the essential cause of the impact on the variable structure control technological improvement [13].
This paper presents the sliding mode controller for the rotor levitation and speed control of a 12/14 BSRM with hybrid stator pole structure. The controller designed using the Lyapunov stability condition which will eliminates the chattering causing the rotor vibration at standstill and during motoring. The simulation of the BSRM drive with two independent control systems carried out with Matlab/Simulink software and performs the tests such as speed regulation, vibration control. The simulation results indicate that, the proposed controller levitates the rotor steadily at standstill and during accelerating to the set speed at different operating conditions.
The organization of this paper is, at initially, in Section II, the salient features of BSRM construction, generation of rotor levitation force and torque, and their control introduced. In Section III the design methodology of SMC and in Section IV, the simulation and result analysis presented. The results affirm that smooth levitation of rotor and perfect tracking of the desired speed achieved with SMC regardless of external load variations.

II. HYBRID POLE TYPE BSRM

The principle of operation and constructional features of 12/14 BSRM are same as the conventional SRM in many respects as shown in figure.1. The rotor has symmetrically spaced 14 salient poles with no winding and the 12 poles of stator classified into two types based on their function. The Four poles used for levitation of the rotor and the remaining eight poles for torque generation. The four levitation poles P_{x+}, P_{x-}, P_{y+} and P_{y-} are located in four directions $x+$, $x-$, $y+$ and $y-$ in x-y plane and the corresponding winding currents controls the levitation force in the respective directions. The eight torque poles are arranged in two groups $P_{A1} - P_{A4}$ and $P_{B1} - P_{B4}$ to form two phases A and B, and the corresponding winding currents are i_A and i_B. This structure of non-uniform stator poles reduces the coupling effect on fluxes between the torque winding and levitation winding, subsequently independent control of levitation and torque becomes possible.

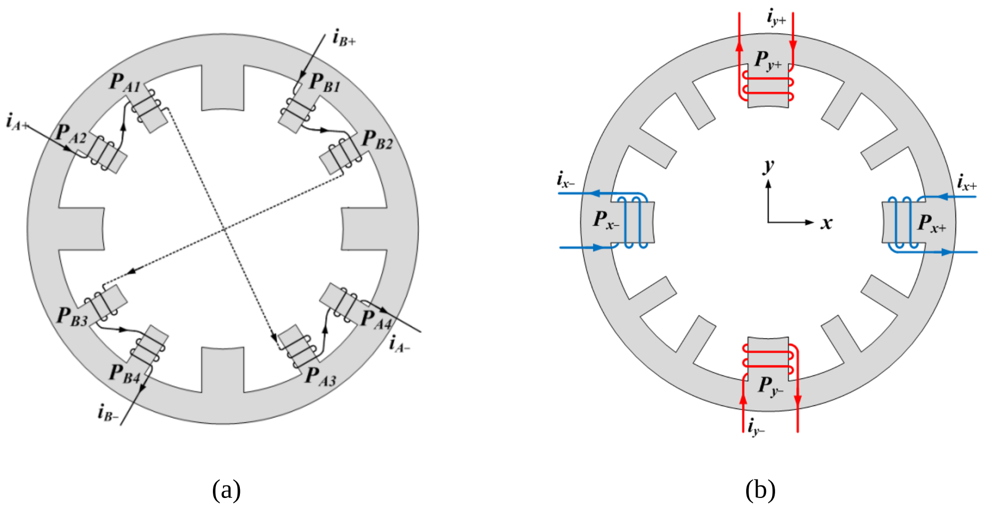

Figure 1. Stator pole arrangement of 12/14 BSRM (a) Torque Poles (b) Levitation poles

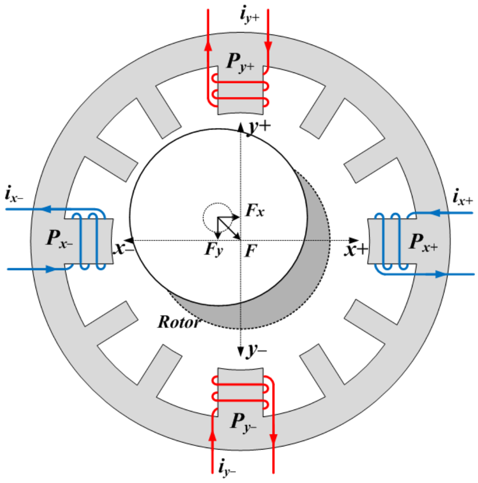

Figure 2. Control of levitation force

Figure.2 shows the levitation force generation, and control of rotor eccentric displacement when it is displaced towards the 2nd quadrant in the *x-y* plane from the stator center. To bring the rotor back to the stator center, the currents i_{x+} and i_{y-} of the selected levitation poles P_{x+} and P_{y-} respectively are to be controlled without disturbing the other two currents i_{x-} and i_{y+}. In the same manner, the rotor levitation can be controlled from any point located in four quadrants of the *x-y* plane. The winding currents through the selected two levitation poles are controlled autonomously using H-bridge converter shown in Figure.3.

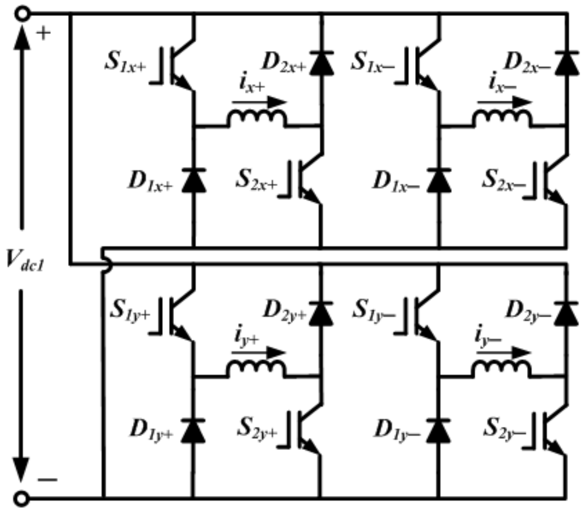

Figure 3. H-bridge converter for levitation windings

The torque hence the speed of the rotor can be regulated using H-bridge converter shown in Figure.4. by controlling the currents i_A and i_B flowing in two phase windings.

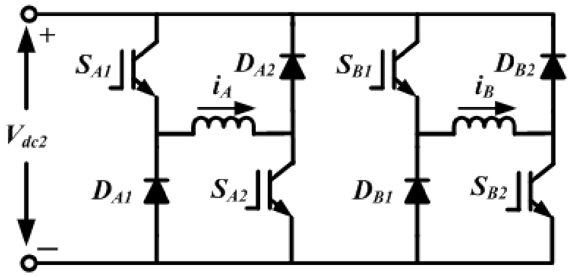

Figure 4. H-bridge converter for torque windings

III. SLIDING MODE CONTROL

The sliding mode control (SMC) strategy that is based on the variable structure of the system, has accomplished much significance over the most recent two decades, because of its robustness, effortlessness, high exactness, and quick dynamic response. The SMC forces the system state track of selected surface in state space, which reflects the desired dynamics.

Design of SMC includes two phases: (i) Selection of switching surface: A stable surface in the error phase plane on which the movement of state trajectory ought to be confined, and

(ii) Synthesis of control law: A control function, which attracts the trajectory always towards the selected sliding surface.

The movement of the trajectory in phase plane is classified into two modes a) Reaching mode: The trajectory starting from a non-zero initial state and reaches the sliding surface, and b) Sliding mode: The trajectory after reaching mode, stays on the sliding surface for all times and consequently behaves as per the dynamics specified by the sliding surface.

Consider an nth-order uncertain nonlinear system expressed as:

$$\begin{aligned} \dot{x}_i &= x_{i+1} \\ \dot{x}_n &= \alpha(\mathrm{x}) + \Delta\alpha(\mathrm{x}) + \beta(\mathrm{x})\, u(t) + \eta(t) \\ y &= x_1 = x \end{aligned} \quad (1)$$

Where $\mathrm{x} = [x \quad \dot{x} \quad \dots \quad x^{(n-1)}]^{\mathrm{T}}$ is the vector of phase variable states, $u(t)$ and y are control signal and output of the system, $\alpha(\mathrm{x})$ and $\beta(\mathrm{x})$ are nonlinear functions, $\Delta\alpha(\mathrm{x})$ is the uncertainty of unmodeled dynamics and $\eta(t)$ is the disturbance.

$$\|\Delta\alpha(\mathrm{x})\| \le \varepsilon \quad \text{and} \quad \|\eta(t)\| \le \gamma \quad (2)$$

Where ε , γ are positive constants.

Let the desired trajectory as

$$\mathrm{x}_r^T = [x_r \quad \dot{x}_r \quad \dots \quad x_r^{(n-1)}] \quad (3)$$

The tracking error between the actual and the desired state trajectories is expressed as

$$\mathrm{e} = \mathrm{x} - \mathrm{x}_r = [e \quad \dot{e} \quad \dots \quad e^{(n-1)}] = [e_1 \quad e_2 \quad \dots \quad e_n] \quad (4)$$

$$\dot{e}_n = x^{(n)} - x_r^{(n)} = \alpha(\mathrm{x}) + \Delta\alpha(\mathrm{x}) + \beta(\mathrm{x})\, u(t) + \eta(t) - x_r^{(n)} \quad (5)$$

The surface in state space, which reflects the desired dynamics, is selected as

$$\sigma = \sum_{i=1}^{n-1} c_i\, e_i + e_n \qquad c_i > 0, i = 1,2,\dots,n-1 \quad (6)$$

Consider the following Lyapunov function, to confirm the stability of the controller using Lyapunov stability analysis

$$V = \frac{1}{2\beta(\mathrm{x})}\sigma^2 > 0 \quad (7)$$

According to the Lyapunov stability analysis, the designed control law u drives the tracking error to zero, if $\dot{V}$ becomes negative,

$$\dot{V} = \sigma\ \dot{\sigma} = \sigma \left(\sum_{i=1}^{n-1} c_i\, e_{i+1} + \alpha(\mathrm{x}) + \Delta\alpha(\mathrm{x}) + \beta(\mathrm{x})\ u(t) + \eta(t) - x_r^{(n)} \right) \quad (8)$$

The general expression for the control law u, comprises of the equivalent control u_{eq} corresponding to the sliding mode when σ=0 and switching control u_{sw} corresponding to the reaching mode when $\sigma \neq 0$ is expressed as

$$u = u_{eq} + u_{sw} \tag{9}$$

$$u_{eq} = \frac{1}{\beta(\mathrm{x})}\left(-\sum_{i=1}^{n-1} c_i\, e_{i+1} - \alpha(\mathrm{x}) - \Delta\alpha(\mathrm{x}) - \eta(t) + x_r^{(n)} \right) \tag{10}$$

The terms $\Delta\alpha(\mathrm{x})$ and $\eta(t)$ are unknown and the modified equivalent control input is

$$u_{eq} = \frac{1}{\beta(\mathrm{x})}\left(-\sum_{i=1}^{n-1} c_i\, e_{i+1} - \alpha(\mathrm{x}) + x_r^{(n)} \right) \tag{11}$$

The switching control term is considered as

$$u_{sw} = -\frac{\lambda}{\alpha(\mathrm{x})}\operatorname{sgn}(\sigma) \tag{12}$$

Where λ is positive constant, and the function $sgn(*)$ is shown in Figure.5.

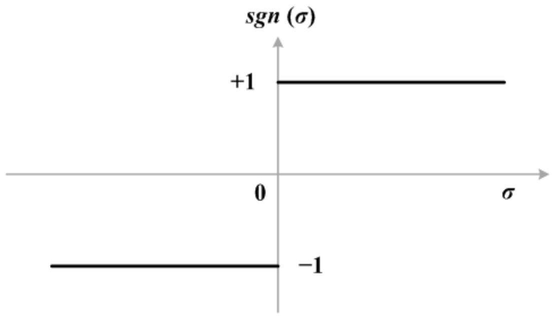

Figure 5. Signum function

IV. SIMULATION AND RESULTS

Figure. 6 shows the Simulink model of BSRM, comprising four subsystems, two for rotor leviation and toque control, one for the BSRM model and fourth one contains speed sensor algorithm.

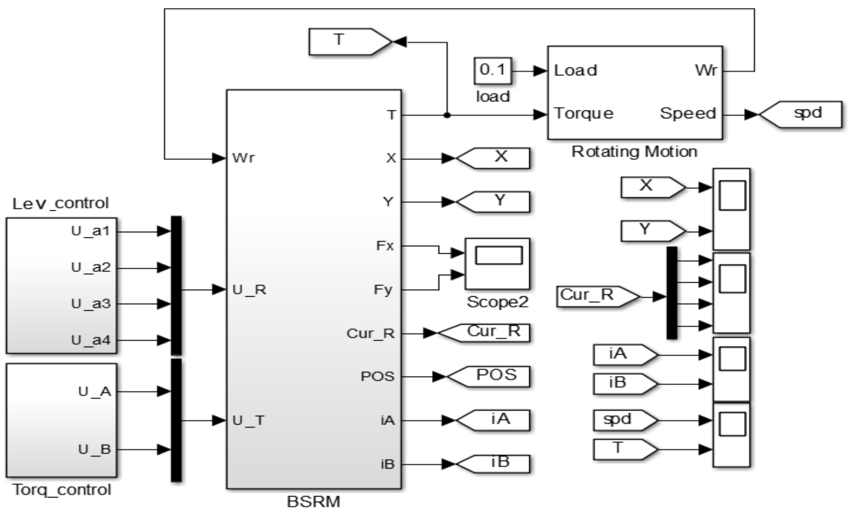

Figure 6. Simulink model of BSRM system with SMC

The levitation control subsystem is shown in Figure.7. The rotor displacement is controlled by appling the error between the reference and actual displacements in *x* and *y* directions as input to the respective *x* and *y* directional sliding mode controllers. The controller outputs are the force commands ($F_x^*$and F_y^*) which are transformed into levitation winding currents.

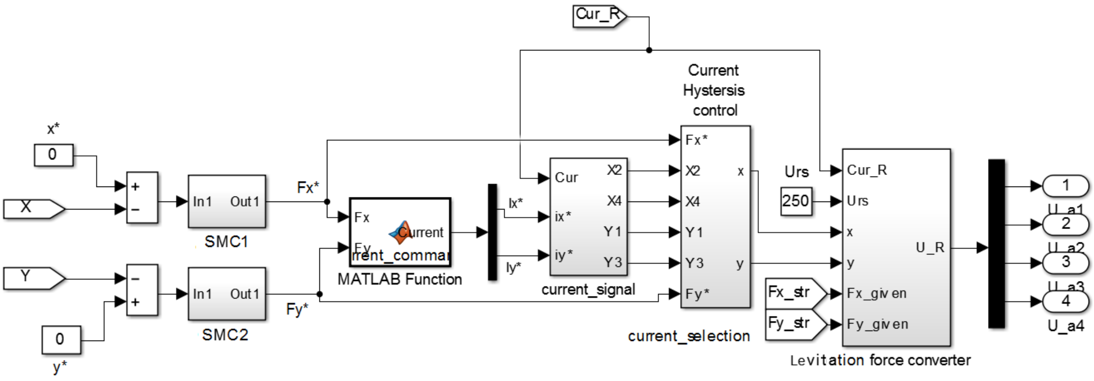

Figure 7. Simulink model of the levitation control subsystem

The torque control subsystem is shown in Figure.8. The speed controller converts the error signal between the reference and actual motor speed into a current command for the two phase windings, then these are compared with actual values to produce PWM pulses for the H-bridge converter.

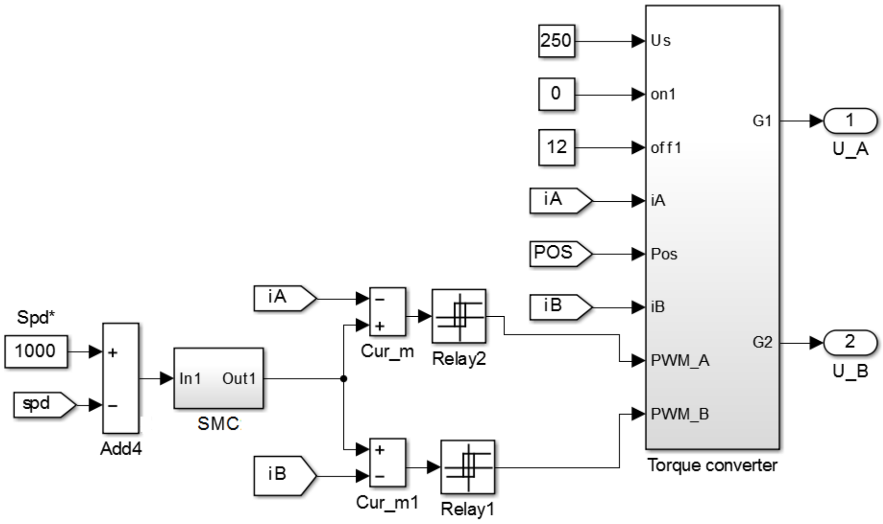

Figure 8. The Simulink model of the torque control subsystem

In the levitation control sub system, the instantaneous rotor eccentric displacements in *x*, *y* directions are compared with the reference values $x^*= y^*=0$. The tuned parameters of desined controllers are shown in Table-1.

Table 1. Parameters of SMC

Controller	c_1	λ
x –directional SMC	0.8	1
y –directional SMC	0.8	1
SMC in speed subsystem	1	1.2

4.1 Rotor levitation from stand still.

The displacemets in both *x* and *y* directions when the rotor is levitating from standstill under no load is shown in Figure.9. From the Figure, it can be observed that with SMC the rotor rises from initial displacement of 120 µm in positive *x* direction and negative *y* directions to the stator center position within 0.018 sec and 0.015 sec respectively and with the conventional PID controller the rotor experiences vibrations. During the initial levitation the two controllers generates high forces to bring back the rotor to the centre and results gradual reduction in the rotor vibration when compared to the PID controller. The corresponding command forces are shown in Figure.10.

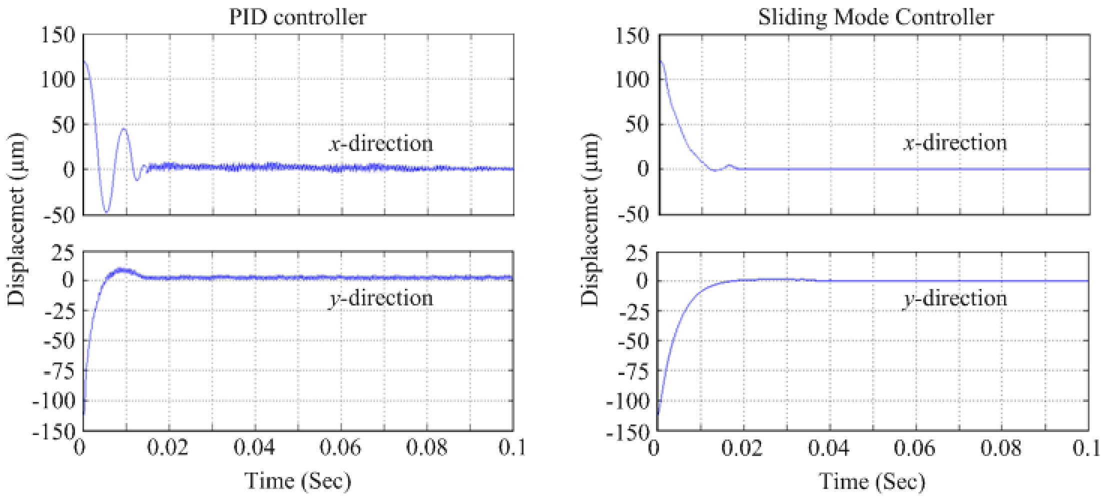

Figure 9. Rotor displacements with PID and Sliding Mode Controllers

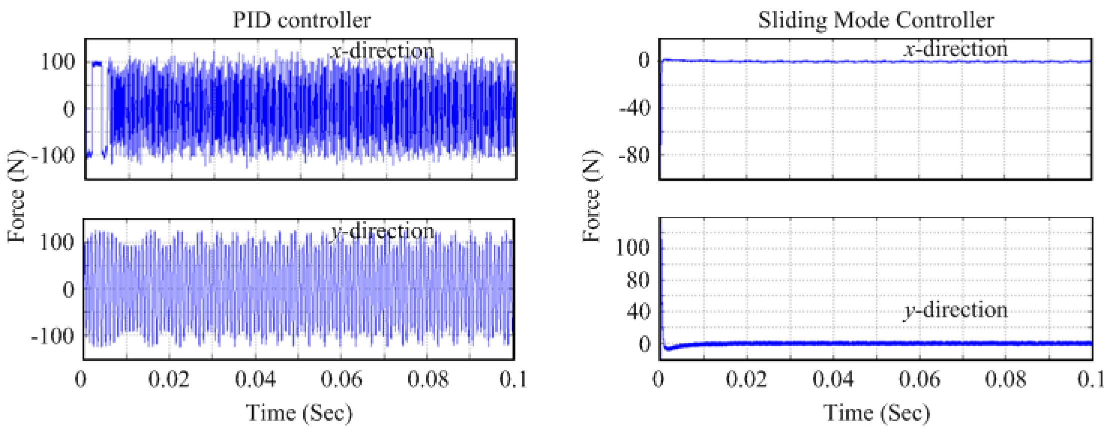

Figure 10. Generated resultant forces by PID and Sliding Mode Controllers

4.2 When the reference speed is 3000 rpm.

The results of speed tracking and torque generated when the rotor completely levitates and stays at the stator center are shown in Figure.11. From the Figure, it can be observed that the rotor rises from standstill to the reference speed set at 3000 rpm without any overshoots, with the SMC the speed settles in 0.042 sec when compared to 0.058 sec with PID controller. From the generated torques, it can be observed that with the SMC, the magnitude of torque is reduced and the presence of ripples is limited to 0.04 sec.

Figure.12 shows the both phase currents (A and B) when the rotor rises from standstill to the reference value and with SMC the both phase windings draws 0.6A when compared to 0.77A with PID.

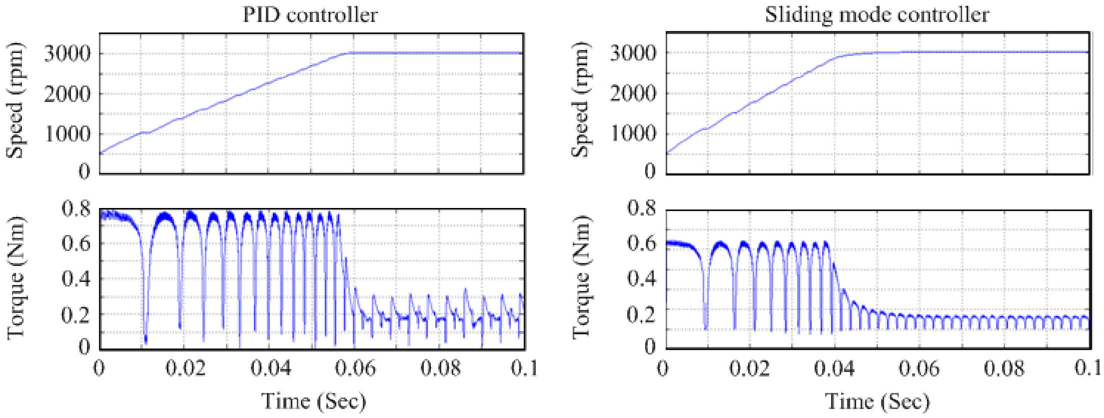

Figure 11. Speed and Torque generated with PID and Sliding Mode Controllers

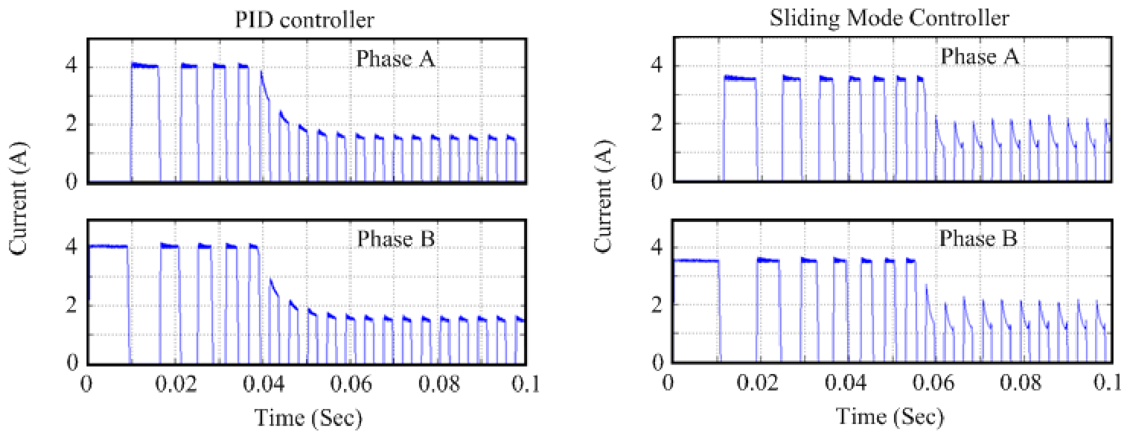

Figure 12. Currents in two phases with PID and Sliding Mode Controllers

V. CONCLUSION

The bearingless switched reluctance motor is a highly nonlinear system with modeling uncertainties and parameter variations, so it is hard to accomplish the effective control using the conventional linear control methods. This paper presents sliding mode control strategy for designing two independent control systems for the levitation of the rotor and speed control. The simulation results ensure that with the SMC, the rotor can be steadily levitated from standstill and accelerates to the desired speed with fewer vibrations, compared to the PID controller. The settling time during the periods of the levitation and acceleration of the rotor is less with SMC and the magnitudes of the torque generated and phase currents are also reduced.

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