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Research paper

Rotor Suspension and Stabilization of Bearingless SRM using Sliding Mode Controller

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Abstract

Motors working in extreme conditions such as ultra high and low temperatures, high contamination, high purity etc. require high maintenance of mechanical bearings and the regular lubrication. Hence there is a need of a motor without mechanical bearings and lubrication in addition to simple in control and less maintenance. There by, bearingless motors (BLMs) gain more attention. The bearingless switched reluctance motor's (BLSRM) is simple in construction and economical in addition to high speed capacity and high torque to inertia ratio. The magnetic nonlinearity arising due to double salient structure makes rotor eccentric displacement control and speed regulation complicate and needs robust control methodology such as sliding mode control (SMC) which has integrity, high certainty and rapid dynamic response when compared to typical controllers. Sliding mode can be realized with distinct classical reaching laws. This paper presents design and implementation of a SMC for a 12/14 BLSRM and the dynamic performance is endorsed by simulation using Matlab software.

Keywords: *BLSRM; Suspension Control; Speed Control; Sliding Mode Controller.*

1. Introduction

The problems arising due to mechanical bearings such as mechanical friction, temperature rise and contaminating lubricating oil can be avoided by using magnetic bearings (MB). The bearingless motor (BLM) is a motor integrated with MB's replacing the mechanical bearings and suspends the rotor in air without any contact [1-2] with the benefits of friction free , wear free, maintenance free and lubricant free operation.

Because of high power density, low maintenance and high efficiency, high performance applications, bearingless switched reluctance motor (BLSRM) is used widely, such as in robotics, aerospace, artificial hearts, and precision machine tools, etc [3-5]. The 12/14 hybrid pole type BLSRM contains two types of poles on stator, the first type is for rotor suspension, and the second is for torque generation. To control the rotor eccentric displacement of the BLSRM in x and y directions error the suspension pole winding currents are to be regulated based on the present position of the rotor.The torque, hence the speed can be controlled by adjusting the torque winding current value [6]. Now a day's novel control methods are very widely used and applied in industrial domain because of rapid development of power electronics and computer controls. The nature of the BLSRM is nonlinear, uncertain and highly affected by parameter variations, makes very difficult to derive the exact mathematical model. The absence of windings and permanent magnetic nature of rotor will give very high speed so it is hard to achieve the fine control utilizing the regular control procedure methodology [7-8].

Sliding Mode Control (SMC) has effectively been implemented to most of the non-linear feedback control systems which are severely affected by parameters changes and disturbance, and also with modeling uncertainties. The approach of the control technique is straightforward with two modes, initially, the system trajectory is driven towards a hyperplane, which represents desired dynamics called reaching mode and later the system trajectory is kept upon that hyperplane known as sliding mode. The technique has advantages such as fast response, negligible effect of unmodeled dynamics and independent of plant parameters and disturbance. The key problem of SMC is that the discontinuous feedback control switches at infinite high frequency from one part of hyperplane to another in the error space in finite time leading to undesired high frequency oscillations of the control called chattering. The most well known ways in the design of corrective control to eliminate the chattering are i) by replacing the discontinuous sign function with the saturation or the sigmoid function ii) insertion of a boundary layer gives better results, but causes finite steady-state error[9-11].

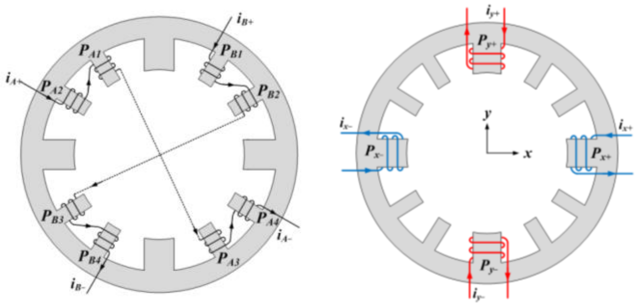
This paper presents the design and implementation of sliding mode controller (SMC) for rotor suspension control and speed tracking of a 12/14 BLSRM. The simulation studies are carried out with Matlab/Simulink software and results are analyzed to show the effectiveness of the controller at different operating conditions such as suspension from rest, accelerating to the desire speed and at variable speed conditions.

The organization of this paper is, at initially, in Section 2, the salient features of BLSRM construction, generation of rotor suspension force and torque, and their control introduced. In Section 3 the design methodology of SMC and in Section 4, the simulation and result analysis presented. The results affirm that smooth suspension of rotor and precise tracking of the desired speed is achieved with the designed controller.

2. Hybrid Pole Type 12/14 BLSRM

2.1 Structure

The principle of operation and constructional features of 12/14 BLSRM are same as the conventional SRM in many respects as shown in Fig.1.



(a) (b)

Fig. 1: Stator pole of 12/14 BSRM (a) Torque Poles (b) Suspension poles

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 suspension of the rotor and the remaining eight poles for torque generation. The four suspension 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 suspension 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 suspension winding, subsequently independent control of suspension and torque becomes possible.
The eccentric error due to dislodging of the rotor of BLSRM because of the non-presence of mechanical bearings. Fig.2 shows the suspension 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.

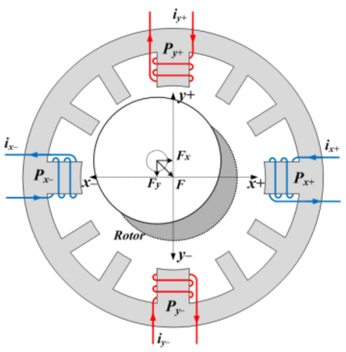


Fig. 2: Control of suspension force

To bring the rotor back to the stator center, the currents i_{x+} and i_{y-} of the selected suspension 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 suspension can be controlled from any point located in four quadrants of the x-y plane. The winding currents through the selected two suspension poles are controlled autonomously using H-bridge converter shown in Fig.3.

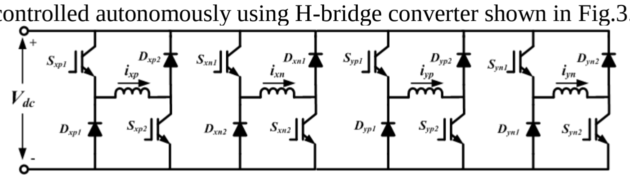


Fig. 3: H-bridge converter for suspension windings

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

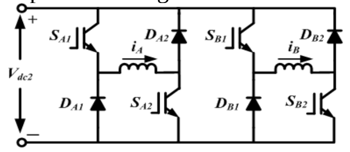


Fig. 4: H-bridge converter for torque windings

2.2 Mathematical Modelling

To analyze the dynamic behavior of the 12/14 hybrid bearingless motor and for the design of the controller a mathematical description is necessary.
The electromagnetic force on the rotor due to x- and y- directional suspension poles are given by

$$\begin{aligned} F_x(x,i_x) &\cong k_{rpx}\,x + k_{rix}\,i_x \\ F_y(y,i_y) &\cong k_{rpy}\,y + k_{riy}\,i_y \end{aligned} \tag{1}$$

The mechanical force on the rotor in terms of mass and rotor x and y directional displacements are given by

$$\begin{aligned} F_x &= m\frac{d^2x}{dt^2} \\ F_y &= m\frac{d^2y}{dt^2} + mg \end{aligned} \tag{2}$$

Using (1) to (2)

$$\begin{aligned} m\frac{d^2x}{dt^2} &= k_{rpx}\,x + k_{rix}\,i_x \\ m\frac{d^2y}{dt^2} &= k_{rpy}\,y + k_{riy}\,i_y - mg \end{aligned} \tag{3}$$

The concentrated torque phase windings makes the mutual inductance between two phases of BLSRM is negligibly small. The flux linkage depends on current i and the rotor position θ.
The voltage across phase winding is related to the flux linked in the winding

$$v_{A(B)} = R_{A(B)}\,i_{A(B)} + i_{A(B)}\frac{\partial L(\theta)}{\partial \theta}\omega + L(\theta)\frac{di_{A(B)}}{dt} \tag{4}$$

The total energy of the two phases (n = 2) is given by

$$W_{total} = \frac{1}{2}\sum_{j=1}^{n} L(\theta)\ i_j^2 = \frac{1}{2}\left[L(\theta)i_A^2 + L(\theta)i_B^2\right] \tag{5}$$

The motor total torque is the sum of individual torques due to two motor phases given by

$$T_e = \sum_{j=1}^{n} T_j = T_A + T_B = \frac{\partial W_{total}}{d\theta} = \frac{1}{2}\frac{\partial\left[L(\theta)i_A^2 + L(\theta)i_B^2\right]}{\partial \theta} \tag{6}$$

The equivalent phase power becomes

$$P_{eq}(t) = V_{dc} i_t(t) \tag{7}$$

$$T_e \omega = P_{eq}(t) = V_{dc} i_t(t) \tag{8}$$

The electromagnetic torque over the switching period is then

$$T_e = \left(\frac{V_{dc}}{\omega}\right) i_t(t) = K_t i_t(t) \tag{9}$$

Where, K_t is a torque constant and $i_t(t)$ is the equivalent dc-link current causing torque generation.
Mechanical subsystem can be expressed as

$$J\frac{d^2\theta}{dt^2} = T_e - T_L - B\frac{d\theta}{dt} \tag{10}$$

Where, J and B are the moment of inertia and coefficient of friction, respectively, and T_L is the torque load.
In case of bearingless motors, coefficient of friction $B = 0$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(T_e - T_L\right) = \frac{1}{J}\left(K_t i_t(t) - T_L\right) \tag{11}$$

3. Sliding Mode Control

The sliding mode control (SMC) strategy 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.
Consider an n^{th}-order uncertain nonlinear system expressed as:

$$\begin{aligned} \dot{x}_i &= x_{i+1} \\ \dot{x}_n &= \alpha(\mathrm{x}) + \Delta\alpha(\mathrm{x}) + \beta(\mathrm{x})\ u(t) \end{aligned} \tag{12}$$

Where $\mathrm{x} = [x\ \ \dot{x}\ \ \ldots\ \ x^{(n-1)}]^{\mathrm{T}}$ is the vector of phase variable states, u(t) and y are control signal and output of the system, α(x) and β(x) are nonlinear functions, Δα(x) is the uncertainty of unmodeled dynamics and $\|\Delta\alpha(\mathrm{x})\| \le \varepsilon$ Where ε is positive constant ,and let the desired trajectory as

$$\mathrm{x}_r^T = [x_r\ \ \dot{x}_r\ \ \ldots\ \ x_r^{(n-1)}] \tag{13}$$

The tracking error is expressed as

$$\begin{aligned} \mathrm{e} &= \mathrm{x} - \mathrm{x}_r = [e\ \ \dot{e}\ \ \ldots\ \ e^{(n-1)}] = [e_1\ \ e_2\ \ \ldots\ \ e_n] \\ \dot{e}_n &= x^{(n)} - x_r^{(n)} = \alpha(\mathrm{x}) + \Delta\alpha(\mathrm{x}) + \beta(\mathrm{x})\ u(t) - x_r^{(n)} \end{aligned} \tag{14}$$

The sliding function reflecting the desired system dynamics, is considered as

$$\sigma = \sum_{i=1}^{n-1} c_i\, e_i + e_n \qquad c_i > 0, i = 1,2,\ldots, n-1 \tag{15}$$

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

$$V = \frac{1}{2\beta(\mathrm{x})}\sigma^2 > 0 \tag{16}$$

According to the Lyapunov stability analysis, the control law u forces the error to zero, if derivative of V becomes negative,

$$\dot{V} = \sigma\,\dot{\sigma} = \sigma\left(\sum_{i=1}^{n-1} c_i\, e_{i+1} + \alpha(\mathrm{x}) + \Delta\alpha(\mathrm{x}) + \beta(\mathrm{x})\ u(t) - x_r^{(n)}\right) \tag{17}$$

The control law u, contains two parts, the equivalent control u_{eq} and switching control u_{sw} is expressed as $u = u_{eq} + u_{sw}$

$$u_{eq} = \frac{1}{\beta(\mathrm{x})}\left(-\sum_{i=1}^{n-1} c_i\ e_{i+1} - \alpha(\mathrm{x}) - \Delta\alpha(\mathrm{x}) + x_r^{(n)}\right) \tag{18}$$

The terms Δα(x) are unknown and the modified equivalent control input is

$$u_{eq} = \frac{1}{\beta(\mathrm{x})}\left(-\sum_{i=1}^{n-1} c_i\ e_{i+1} - \alpha(\mathrm{x}) + x_r^{(n)}\right) \tag{19}$$

The switching control term is considered as

$$u_{sw} = \frac{\lambda}{\alpha(\mathrm{x})}\,\mathrm{sgn}\,(\sigma) \tag{20}$$

Where λ is positive constant
The final output of SMC becomes

$$u_{eq} = \frac{1}{\beta(\mathrm{x})}\left(-\sum_{i=1}^{n-1} c_i\ e_{i+1} - \alpha(\mathrm{x}) + x_r^{(n)} + \lambda\,\mathrm{sgn}\,(\sigma)\right) \tag{21}$$

The parameters of the motor are as follows:
Number of poles on stator and rotor are 12 and 14 respectively, rotor pole arc is 12.85 deg, Levitation pole arc is 25.7 deg, Torque pole arc is 12.85 deg, air gap length is 0.3 mm, Diameter of shaft is 18 mm, rotor yoke length is 9.7 mm, No of turns in torque pole and levitation poles windings are 80 and 100 respectively.
The designed sliding mode controllers for rotor eccentric displacement control in x-, y-directions and speed control are

$$\begin{aligned} u_x &= 0.0208\left((6.43\times10^5)e + \lambda_x\dot{e} + K_x\,\mathrm{sgn}(\sigma_x)\right) \\ u_y &= 0.0208((6.43\times10^5)e + \lambda_y\dot{e} + 9.8 + K_y\,\mathrm{sgn}(\sigma_y)) \\ u_\omega &= 0.001412\left((\lambda_\omega e_\omega + 4115\ T_L) + K_\omega\ \mathrm{sgn}(\sigma_\omega)\right) \end{aligned} \tag{22}$$

4. Simulation and Results

Fig. 8 shows the Simulink model of BLSRM, comprising four subsystems, two for rotor suspension and toque control, one for the BLSRM model and fourth one contains speed sensor algorithm. Fig. 9 shows the Simulink models of x-, y-directional and speed control SMC.

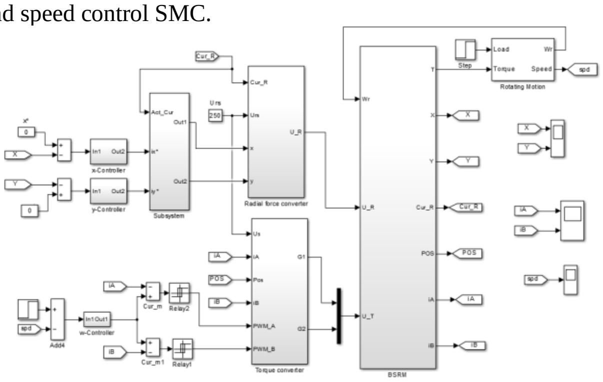
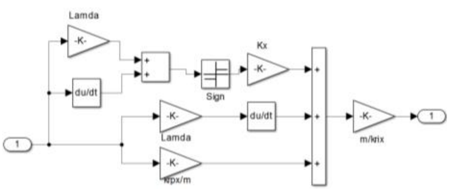
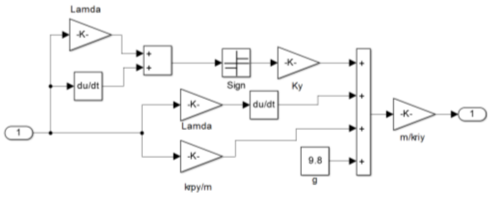


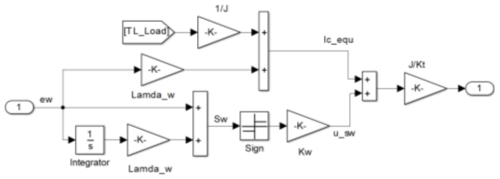
Fig.8: Simulink model of BLSRM system



(a)



(b)



(c)

Fig.9: Simulink models (a) x- directional SMC (b) y- directional SMC (c) speed SMC

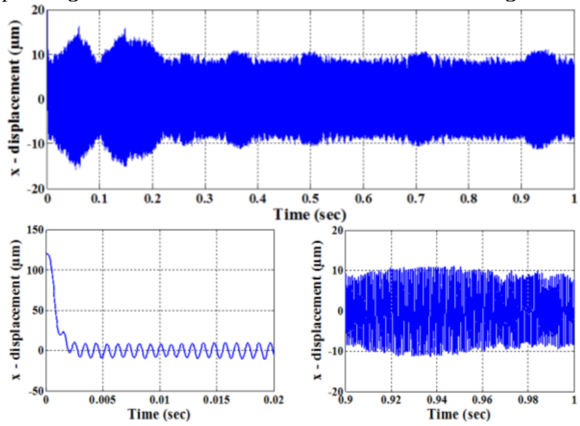
The tuned parameters of the designed controllers are shown in Table-1.

Table-1. Parameters of SMC-SN Controllers

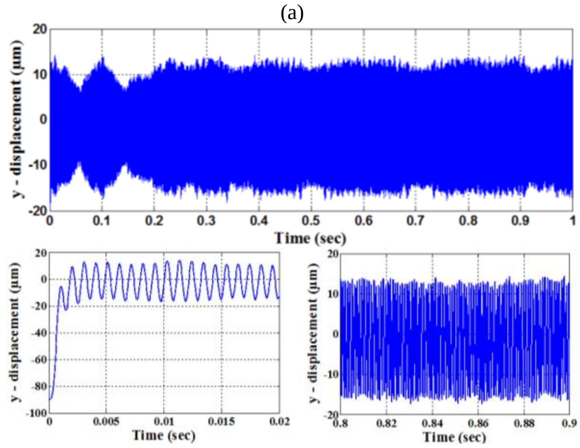
Parameter	x-directional SMC	y-directional SMC	Speed SMC
Sliding function	$c_x = 2000$	$c_y = 2000$	$c_\omega = 2000$
Switching control	$\lambda_x = 10$	$\lambda_y = 5$	$\lambda_\omega = 5$

4.1 Rotor Suspension from Standstill

The displacements in both x and y directions when the rotor is suspending from standstill under no load is shown in Fig.10.



(a)



(b)

Fig.10: Rotor eccentric displacements under standstill condition
(a) x-direction (b) y-direction

From the Fig, the rotor rises from initial displacement of 120 µm in +x direction and 90 µm in −y direction to the stator center position within 0.003 sec. Finally the rotor settles at the centre of the stator with net eccentric error in the range of +14 µm to −16 µm and results gradual reduction in the rotor vibration.

4.2 Acceleration to the Desired Speed

The results of speed tracking and rotor displacements when the rotor completely levitates and stays at the stator center are shown in Fig.11 and Fig 12. From the Fig 11, it can be observed that the rotor rises from standstill to the reference speed set at 2000 rpm without any overshoots, and settles in 0.3 sec. The speed ripple is negligibly small at ±15 rpm.

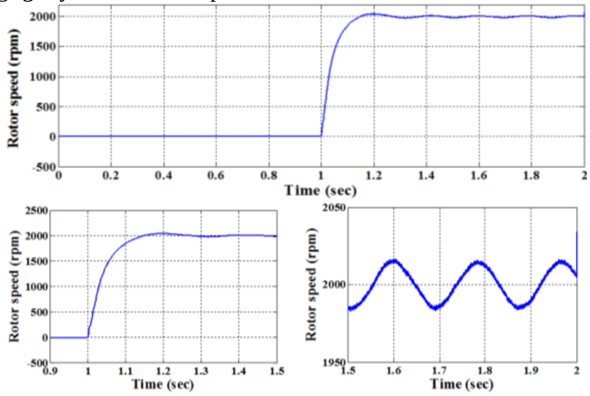
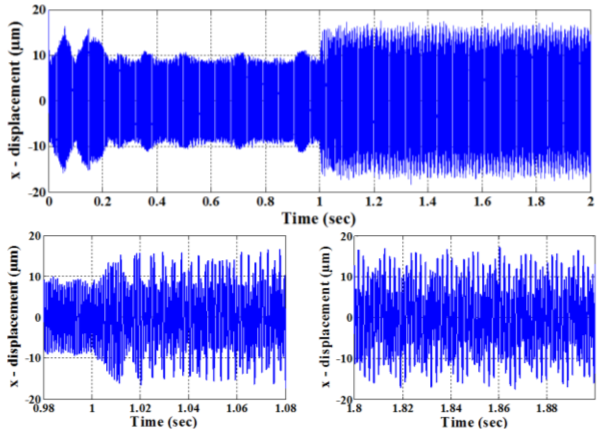
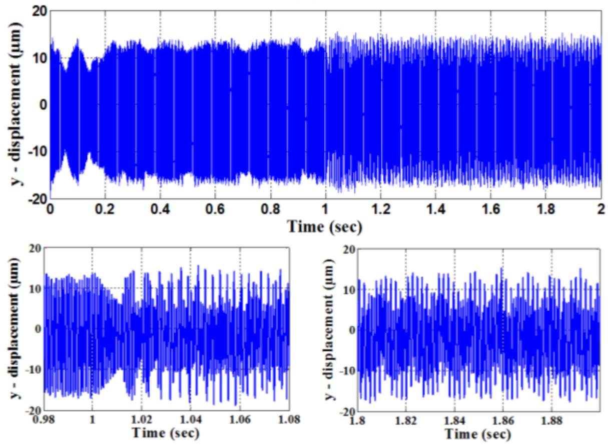


Fig.11: Rotor speed under accelerating condition

Fig 12(a) and 12(b) shows the eccentric displacements of rotor in x and y directions during acceleration to the desired speed, it can be observed that the rotor eccentric error is limited to ±18 µm in the x-direction and ±16 µm in the y-direction. During acceleration the rotor attains stable suspension and gradual reduction in the rotor vibration.



(a)



(b)

Fig.12: Rotor eccentric displacements under accelerating condition
(a) x-direction (b) y-direction

4.3 Variation in Speed

Fig. 13 shows the simulationl results of speed when the reference speed is varied from 2000 rpm to 4000 rpm at 2 sec under constant load of 1 N-m. From the Fig it can be observed that the rotor takes 0.3 sec and 0.5 sec to settle at 2000 rpm and 4000 rpm respectively. The speed ripple is limited to ±13 rpm at both speeds which is negligibly small.

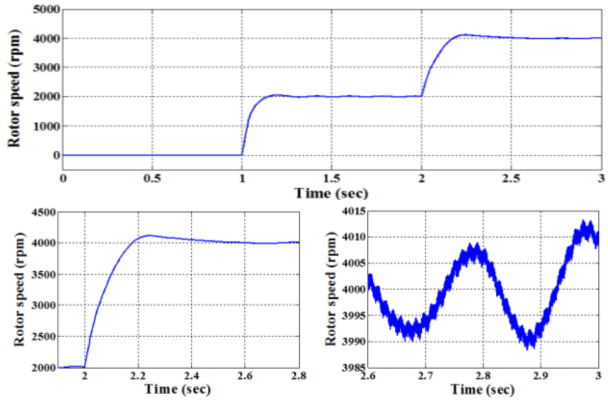
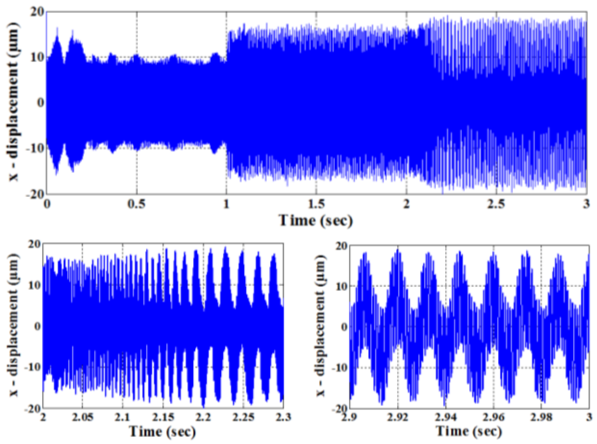
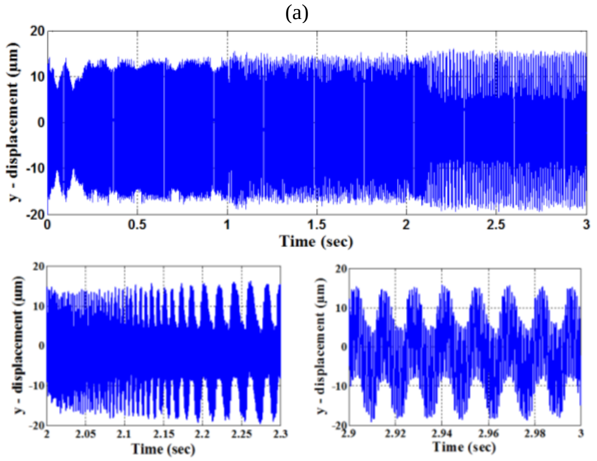


Fig.13: Rotor speed under variable speed condition

Fig 14(a) and 14(b) shows the eccentric displacements of rotor in x and y directions during change in speed condition, it can be observed that the rotor eccentric error is limited to ±19 µm in the x-direction and ±17 µm in the y-direction. During change in speed the rotor attains stable suspension and gradual reduction in the rotor vibration.



(a)



(b)

Fig.14: Rotor eccentric displacements under variable speed condition (a) x-direction (b) y-direction

5. Conclusion

The bearingless switched reluctance motor(BLSRM) is a highly nonlinear system with modeling uncertainties and parameter variations, so it is hard to derive exact mathematical model and which makes it difficult to accomplish the effective control using the conventional control methods. The robust control method SMC makes possible the control of rotor suspensionn and speed independently even in the presence of profound nonlinearities and uncertainties. This paper presents design and implementation of sliding mode controller. The designed independent controllers for rotor suspension control (x and y) and speed control. The simulation results ensure that with the SMC combination, the rotor can be steadily levitated from standstill and accelerates to the desired speed with fewer vibrations. The settling time during the periods of the suspension and aacceleration phases is in satisfactory limits.

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