Decoupling Control for Bearingless Synchronous Reluctance Motors Based on Differential Geometry

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Background

Bearingless synchronous reluctance motor (BSRM) has been received increasing attention due to its advantages of simple structure, low cost, low loss, low temperature rise, and high reliability because of the absence of windings and permanent magnets on the rotor. However , BSRM is a typical nonlinear multivariable system with strong coupling between the electromagnetic torque and the radial suspension force. Therefore, the dynamic decoupling control of this nonlinear system is of particular importance.

Objectives

- ❖ The necessary and sufficient conditions for exact feedback linearization of the system are proved based on differential geometry theory.
- ❖ The system of BSRM can realize dynamic decoupling control among the torque and the radial suspension forces in *x*- and *y*- directions.

Conclusion

- ❖ A novel decoupling control strategy based on differential geometry theory has been proposed for the BSRMs.
- ❖ By using exact feedback linearization and coordinate transformation, the nonlinear system of BSRM can realize linearization and dynamic decoupling control among the torque and the radial suspension forces in *x*- and *y*- directions.
- ❖ When the external disturbance appears, the control system has strong ability of resisting disturbance.
- ❖ Both simulation and experimental results confirm the validity of the proposed decoupling control strategy for BSRMs.
- ❖ This control strategy can readily be extended to other types of BMs that can realize decoupling control .

Methods

Proof of sufficient and necessary conditions of exact linearization

Based on differential geometry theory, the Lie derivative and relative degree of output functions can be calculated.
The relative degree of this system satisfies the condition $r_1 + r_2 + r_3 = 5 = n$ (n is the dimension of the state variables).

The decoupling matrix $A(\mathbf{x})$ can be deduced as follows:

$$A(\mathbf{x}) = \begin{bmatrix} -\frac{1}{m}k_{m1}i_d & -\frac{1}{m}k_{m2}i_q & 0 \\ -\frac{1}{m}k_{m2}i_q & \frac{1}{m}k_{m1}i_d & 0 \\ 0 & 0 & \frac{3P_M^2 i_d}{2J}(L_d - L_q) \end{bmatrix}$$

The matrix $A(\mathbf{x})$ is nonsingular. Based on the necessary and sufficient condition of exact linearization of nonlinear system, the original system can realize exact linearization.

Coordinate transformation and exact linearization

The coordinate transformation constructed by differential geometry is expressed as follows:

$$\begin{aligned} z_1 &= \varphi_1(\mathbf{x}) = h_1(\mathbf{x}) = x_1 \\ z_2 &= \varphi_2(\mathbf{x}) = L_f h_1(\mathbf{x}) = x_3 \\ z_3 &= \varphi_3(\mathbf{x}) = h_2(\mathbf{x}) = x_2 \\ z_4 &= \varphi_4(\mathbf{x}) = L_f h_2(\mathbf{x}) = x_4 \\ z_5 &= \varphi_5(\mathbf{x}) = h_3(\mathbf{x}) = x_5 \end{aligned}$$

The original affine nonlinear system can be transformed into Brunovsky standard form through coordinate transformation as follows:

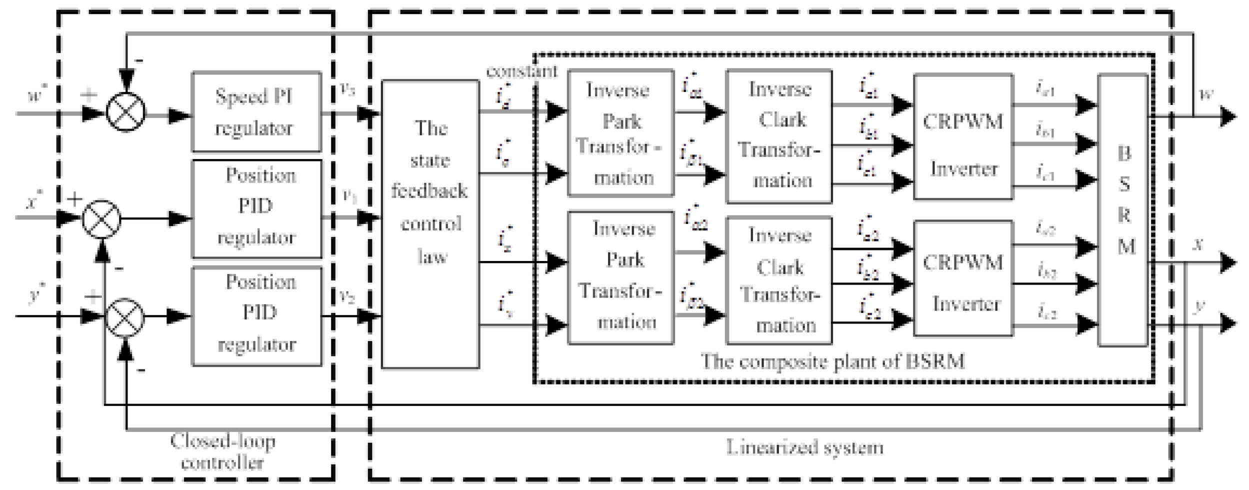
$$\dot{z}_1 = z_2, \dot{z}_2 = v_1, \dot{z}_3 = z_4, \dot{z}_4 = v_2, \dot{z}_5 = v_3$$

Through inverse mapping $\boldsymbol{x}=\boldsymbol{\varphi}^{-1}(\boldsymbol{z})$, the state feedback control law of the original nonlinear system of the BSRM can be obtained.

Control system design of BSRM

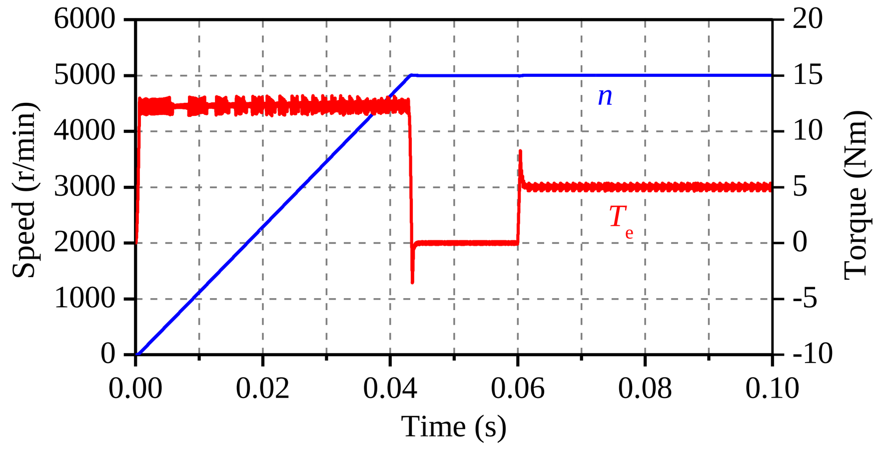
Through the series connection between the state feedback control law and the composite plant of BSRM, the linearized system of the original system is obtained and the original nonlinear system is decoupled into three independent linear subsystems. Then, the linear control theory can be used for the closed-loop control of the system.

The BSRM is a complicated MIMO system. In case of parameters change or external disturbance, the decoupling control based on differential geometry cannot achieve the ideal effect and thus additional PID controllers should be designed for the linearized system. The PID controllers and the decoupling control law form the composite controller of the BSRM.



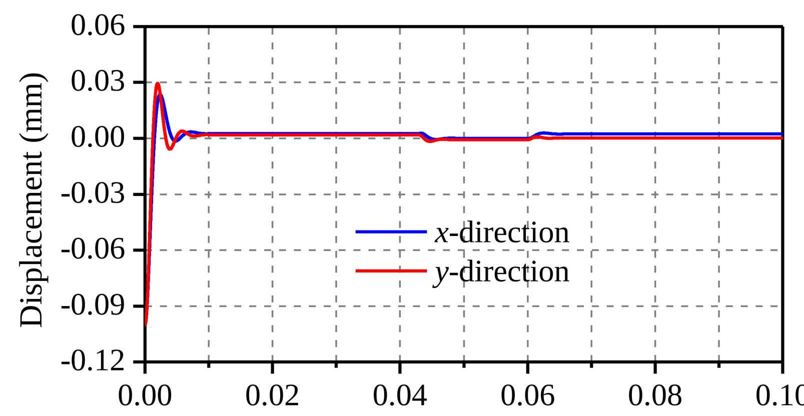
Results

Simulation research



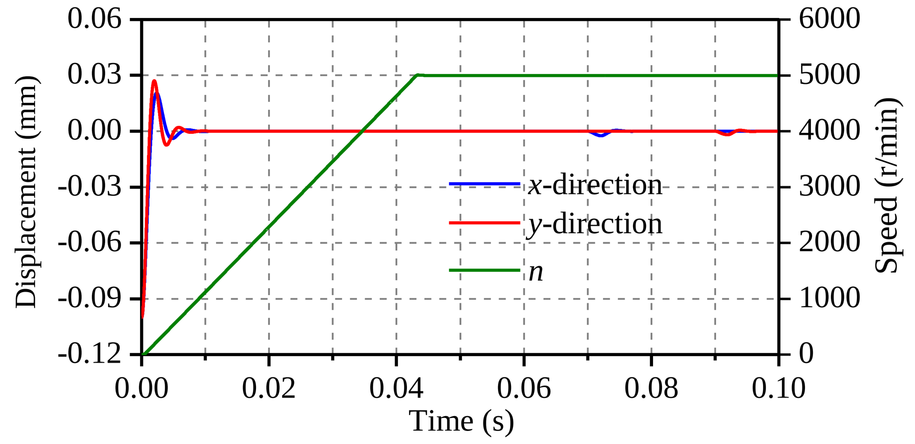
Speed and torque response curves.

The speed increases from 0 to 5000 r/min in 0.044 s. The overshoot is approximately 0.05%. Under no load condition, the starting torque is approximately 12.5 Nm, and the torque decreases to zero after the stabilization of speed. A loading torque (5 Nm) is applied on the motor at t = 0.06 s, which can increase the electromagnetic torque to the set value rapidly after a small fluctuation.



Displacement curves in x- and y-directions.

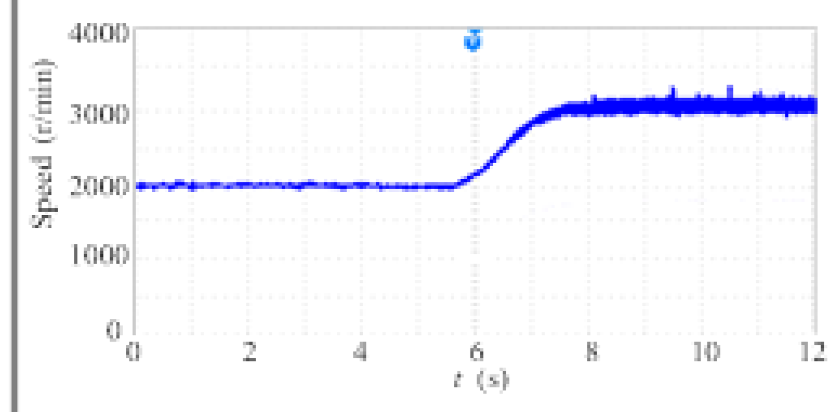
The radial displacements in *x*- and *y*-directions take 0.01 s to reach the set value from the initial position. When the load torque changes to 5 Nm at t = 0.06 s, the radial displacements return to the set values rapidly after a small fluctuation, which indicates the realization of decoupling control between radial suspension force and electromagnetic torque.

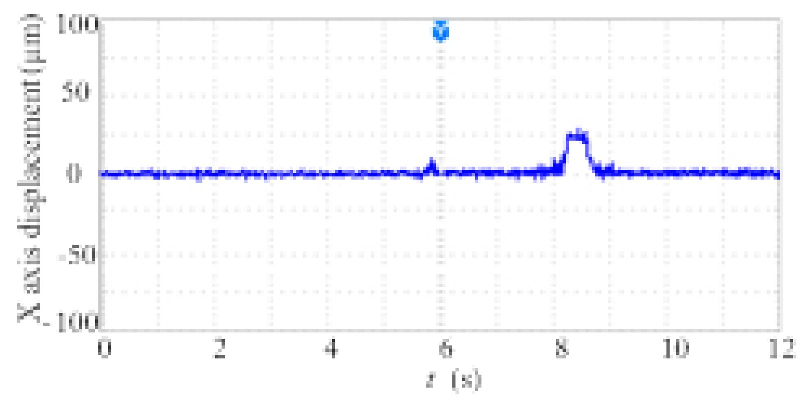


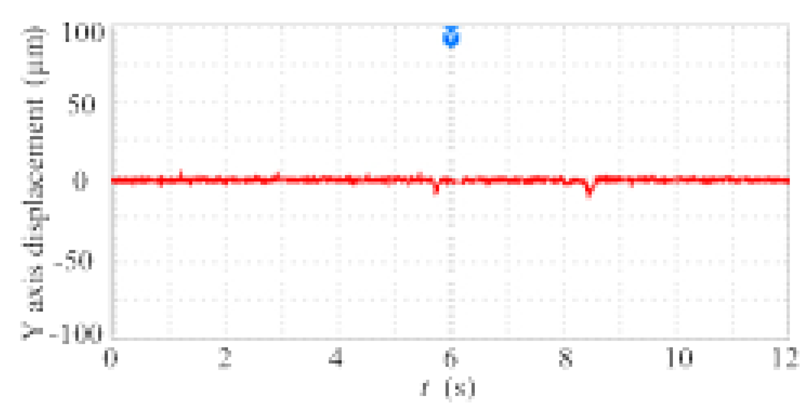
Speed and displacement with external disturbance.

Under no load condition, the disturbing forces 20 N in *x*- and *y*-directions are applied to the motor for 0.002s at t = 0.07s and t = 0.09 s, respectively. The radial displacements of the two-degree of freedom do not affect each other, and the speed is almost the same when the radial displacements are changed.

Experiment result







The speed increases from 2000r/min to 3000r/min at t = 5.6 s, the motor realizes rapid response, and the overshoots of the radial displacement are approximately 10 μm to 13 μm in *x*- and *y*-directions, respectively. Moreover, when the external disturbance force in *x*-direction is added on the rotor at t = 8 s, the vibration amplitude of the *y*-axis radial displacement is extremely small, and the rotor achieves stable suspension at 3000 r/min. The experimental results further prove the effectiveness of the decoupling control strategy.