Direct Suspension Force Control of Bearingless Permanent Magnet Synchronous Motor

Zhu Huangqiu[1,a], Tan Er [1,b]
[1]School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, China
[a]zhuhuangqiu@ujs.edu.cn, [b]taner2066@163.com

Abstract: The bearingless permanent magnet synchronous motor (BPMSM) is a strong-coupled nonlinear system. To solve the difficult problem of dynamic decoupling control among torque and suspension forces, the relationship between rotor radial suspension force and flux linkage are analyzed, the theory and method of direct torque control (DTC) are applied to the suspension control of the BPMSM in the paper. A double closed-loop control system, in which the inner closed-loop is radial suspension force loop and the outer closed-loop is rotor radial displacement loop, is constructed to control the radial suspension forces directly. The direct suspension force control (DSFC) algorithm based on space vector pulse width modulation (SVM) strategy is deduced, and the DSFC system for the BPMSM are designed and simulated using Matlab software. The simulation results show that the rotor can be suspended stability, torque and radial suspension forces can be controlled independently, the structure of control system is simple, and control system has strong robustness.

Keywords: Bearingless, Permanent Magnet Synchronous Motor, Direct Torque Control (DTC), Direct Suspension Force Control (DSFC), Space Vector Pulse Width Modulation (SVM)

Introduction

A bearingless permanent magnet synchronous motor is a kind of bearingless motor with excellent performance, which has realized bearingless technology on the basis of a permanent magnet synchronous motor. It succeeds some excellent performances of permanent magnet synchronous motor, such as great power density, high power factor and high efficiency, and has the magnetic bearings' excellent characteristics, such as no mechanical friction, needless lubrication, no pollution, long life-span and little maintenance. It has an important research value and application potential prospects in the special electric drive fields, such as high speed precision numerical control machine tool, turbine molecular pump, centrifugal machine, flywheel power storage, aerospace and spaceflight. The rotor radial suspension forces should be controlled currently in real-time when the BPMSM rotates, therefore, precise control of the radial suspension forces is stable operation precondition for the BPMSM [1-5].

At present, there are two kinds of control methods for traditional permanent magnet synchronous motors, namely vector control and direct torque control (DTC). Compared with the vector control, the DTC has many advantages, such as simple control structure, fast response speed, good static and dynamic performance, and strong robustness for motor's parameters. The DTC method has used widely in the permanent magnet synchronous motor [6]. The advantages of DTC based on space vector pulse width modulation (SVM) over conventional DTC include lower torque and flux linkage ripple, better dynamic and static performances, faster response speed and with a fixed switching frequency[7-8].

In generally, radial suspension forces of the BPMSM are controlled with the rotor magnetic orientated method. As the control arithmetic of radial suspension forces has current component of torque windings, there are couplings between torque and radial suspension forces. Besides couplings, radial suspension forces have nonlinear relation with radial suspension force's currents, thereby, accurate control of radial suspension forces is very difficult [4-5]. With the reference of the DTC, in the paper a double closed-loop control system, in which the inner closed-loop is radial suspension force loop and the outer closed-loop is rotor radial displacement loop, is constructed to control the radial suspension forces directly. The direct suspension force control (DSFC) algorithm based on space vector pulse width modulation (SVM) strategy is deduced, and the DSFC system for the BPMSM are designed and simulated using Matlab software. The simulation results have shown that the rotor can be suspended stability, torque and radial suspension forces can be controlled independently, the structure of control system is simple, and control system has strong robustness. The research results have provided foundations for speed sensorless operation of the BPMSM.

DSFC of the BPMSM

Shortcomings of Traditional Suspension Force Control Method. Traditional suspension force control method is vector control, which relies on motor's parameters too much, and it's difficult to achieve the theoretical results due to the complexity of vector coordinates transformation. An open-loop indirect control is adopted to control suspension forces, which affects the accuracy and dynamic response performance of suspension force control. Traditional suspension force vector control adopts current following inverter, which has high switch frequency, the utilization rate of inverter capacity is relatively lower.

Basic Principle of DSFC. For the above shortcomings of suspension force vector control, a DSFC algorithm is proposed. Fig.1 shows the vector diagram for DSFC. λ is the angle between suspension force windings flux linkage vector $\boldsymbol{\psi}_{s2}$ and A-phase windings axis, μ is the angle between torque windings resultant air-gap flux linkage vector $\boldsymbol{\psi}_{m1}$ and A-phase windings axis, λ-μ is the angle between radial suspension force vector $\boldsymbol{F}$ and A-phase windings axis.

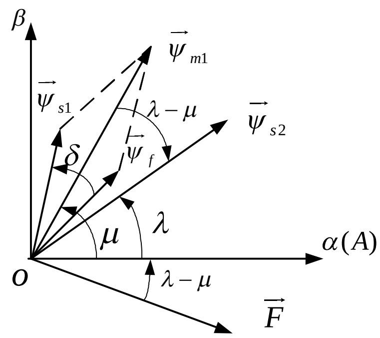


Fig. 1 Vector diagram of direct suspension force control

The mathematic models of suspension force formed by flux linkage can be written as

$$\begin{cases} F_\alpha = k_M \psi_{m1} \psi_{s2} \cos(\lambda-\mu) \\ F_\beta = k_M \psi_{m1} \psi_{s2} \sin(\lambda-\mu) \end{cases} \tag{1}$$

From equation (1), radial suspension force can be seen as a space vector, which amplitude is $k_M\psi_{m1}\psi_{s2}$ and phase is λ-μ. λ-μ is the angle between suspension force windings flux linkage and torque windings resultant air-gap flux linkage, ψ_{m1} is the amplitude of torque windings resultant air-gap flux linkage. To produce stable rotor radial suspension force, it is important to control two vectors in the same time, which include suspension force windings flux linkage and torque windings resultant air-gap flux linkage. Because the motor electrical time constant is much smaller than mechanical time constant, small signal model can be used to analyze the mathematic relationship among three variables, which include suspension force, suspension force windings flux linkage and torque windings resultant air-gap flux linkage. Assuming the location of the rotor is stationary within a very little time period Δt.

a. When in steady state, in which motor operates at rated speed or rated torque. Within time Δt, the amplitude and phase of torque windings resultant air-gap flux linkage are constant. So

suspension force can be controlled by regulating the amplitude ψ_{s2} and phase λ of suspension force windings flux linkage derived from equation (1).
b. When in transient state, in which motor operates at variable torque or motor speed change. Torque windings resultant air-gap flux linkage amplitude ψ_{m1} and angleμ are unstable within time Δt, torque windings flux linkage calculator can real time calculate torque windings resultant air-gap flux linkage amplitude ψ_{m1} and phase μ. When amplitude ψ_{m1} and phase μ are known, suspension force can be controlled by regulating the amplitude ψ_{s2} and phase λ of suspension force windings flux linkage.

The core idea of DSFC for BPMSM is that: to produce a stable radial suspension force, torque windings resultant air-gap flux linkage amplitude ψ_{m1} and phase μ are calculated firstly, the amplitude and phase of radial suspension force can be controlled by regulating the amplitude ψ_{s2} and phase λ of suspension force windings flux linkage.

DSFC Algorithm

DSFC Algorithm. According to the idea of DSFC for BPMSM, torque windings resultant air-gap flux linkage amplitude ψ_{m1} and phase μ can be calculated by torque windings flux linkage calculator, the amplitude and direction of suspension force can be controlled by regulating the amplitude ψ_{s2} and phase λ of suspension force windings flux linkage, therefore, firstly we must find out the mathematic relationship among two variables, which include suspension force vector and suspension force windings flux linkage vector. Fig.2 shows vector diagram of rotor radial suspension force and suspension force windings flux linkage.

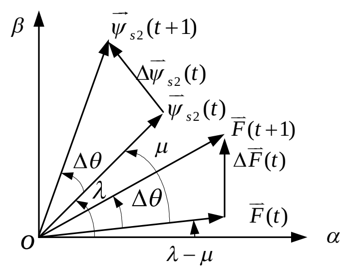


Fig. 2 Vector diagram of suspension force and flux linkage

From Fig.2, it can be seen vector diagram of suspension force and suspension force windings flux linkage during the period from t to t+1. At t moment, suspension force is $\boldsymbol{F}(t)$. Small signal model is used, assuming rotor position is stationary during the period from t to t+1, and the torque windings resultant air-gap flux linkage amplitude ψ_{m1} and phase μ are real-time calculated by voltage-circuit model. Suspension force can be written as

$$\begin{cases} F_\alpha(t) = k_M \psi_{m1}(t)\psi_{s2}(t)\cos(\lambda-\mu) \\ F_\beta(t) = k_M \psi_{m1}(t)\psi_{s2}(t)\sin(\lambda-\mu) \end{cases} \tag{2}$$

Suspension force command value is $\boldsymbol{F}(t+1)$ at t+1 moment.

$$\begin{cases} F_\alpha(t+1) = k_M \psi_{m1}(t)\psi_{s2}(t+1)\cos(\lambda+\Delta\theta-\mu) \\ F_\beta(t+1) = k_M \psi_{m1}(t)\psi_{s2}(t+1)\sin(\lambda+\Delta\theta-\mu) \end{cases} \tag{3}$$

According to geometry knowledge, it can be seen triangle $\Delta\boldsymbol{F}(t+1)o\boldsymbol{F}(t)$ and triangle $\Delta\boldsymbol{\psi}_{s2}(t+1)o\boldsymbol{\psi}_{s2}(t)$ are two similarities triangle from Fig.3, after geometry calculating, triangle $\Delta\boldsymbol{F}(t+1)o\boldsymbol{F}(t)$ sides length are $k_M\psi_{m1}(t)$ times than triangle $\Delta\boldsymbol{\psi}_{s2}(t+1)o\boldsymbol{\psi}_{s2}(t)$ similitude sides length. The angle between vector $\boldsymbol{\psi}_{s2}(t)$ and vector $\boldsymbol{F}'(t)$ can be written as

$$\lambda - (\lambda - \mu) = \mu \tag{4}$$

Triangle $\Delta\boldsymbol{\psi}_{s2}(t+1)o\boldsymbol{\psi}_{s2}(t)$ is equivalent to triangle $\Delta\boldsymbol{F}(t+1)o\boldsymbol{F}(t)$, which takes o as the endpoint with the counterclockwise rotation angle μ, and its sides length are reduced to $1/k_M\psi_{m1}(t)$ times. So vector $\Delta\boldsymbol{\psi}_{s2}(t)$ is equivalent to vector $\Delta\boldsymbol{F}(t)$, which takes o as the endpoint with the counterclockwise rotation angle μ, and its amplitude is reduced to $1/k_M\psi_{m1}(t)$ times. Rotating coordinates transformation can be used to calculate the mathematic relationship between $\Delta\boldsymbol{F}(t)$ and $\Delta\boldsymbol{\psi}_{s2}(t)$. Fig.3 is connected vector diagram of suspension force and flux linkage.

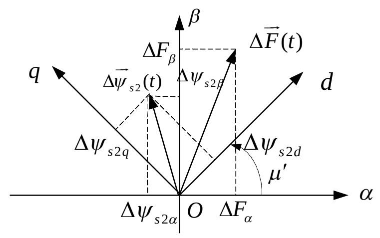


Fig. 3 Connected vector diagram of suspension force and flux linkage

Fig.3 shows the vector diagram of suspension force increment $\Delta\boldsymbol{F}(t)$ and suspension force windings flux linkage increment $\Delta\boldsymbol{\psi}_{s2}(t)$. It can be seen the rotating coordinates dq components of $\Delta\boldsymbol{\psi}_{s2}(t)$ are equivalent to the stationary coordinates $\alpha\beta$ components of $\Delta\boldsymbol{F}(t)$, which rotate with counterclockwise angle μ, and their amplitude are reduced to $1/k_M\psi_{m1}(t)$ times. Supposing $k_F=k_M\psi_{m1}(t)$,

$$\begin{pmatrix} \Delta F_\alpha \\ \Delta F_\beta \end{pmatrix} = k_F \begin{pmatrix} \Delta\psi_{s2d} \\ \Delta\psi_{s2q} \end{pmatrix} \tag{5}$$

ΔF_α and ΔF_β are determined from $\alpha\beta$ components of suspension force windings flux linkage $\Delta\psi_{s2\alpha}$ and $\Delta\psi_{s2\beta}$ as,

$$\begin{pmatrix} \Delta F_\alpha \\ \Delta F_\beta \end{pmatrix} = k_F \begin{pmatrix} \cos\mu & \sin\mu \\ -\sin\mu & \cos\mu \end{pmatrix} \begin{pmatrix} \Delta\psi_{s2\alpha} \\ \Delta\psi_{s2\beta} \end{pmatrix} \tag{6}$$

Torque Windings Resultant Air-Gap Flux Linkage Calculate. Torque windings resultant air-gap flux linkage amplitude ψ_{m1} and phase μ can be calculated by equation (7)~(10) , $u_{1\alpha}$, $u_{1\beta}$ is α, β components of torque windings three phase voltage, $i_{1\alpha}$, $i_{1\beta}$ is α, β components of torque windings three phase circuit.

$$\begin{cases} \psi_{s1\alpha} = \int (u_{1\alpha} - R_s i_{1\alpha}) dt \\ \psi_{s1\beta} = \int (u_{1\beta} - R_s i_{1\beta}) dt \end{cases} \tag{7}$$

where $\psi_{s1\alpha}$, $\psi_{s1\beta}$ is α, β components of torque windings flux linkage.

$$\begin{cases} \psi_{m1\alpha} = \psi_{s1\alpha} - L_{1l} i_{1\alpha} \\ \psi_{m1\beta} = \psi_{s1\beta} - L_{1l} i_{1\beta} \end{cases} \tag{8}$$

where $\psi_{m1\alpha}$, $\psi_{m1\beta}$ is α, β components of torque windings resultant air-gap flux linkage, L_{1l} is torque windings leak inductance.

$$\psi_{m1} = \sqrt{\psi_{m1\alpha}^{\ \ 2} + \psi_{m1\beta}^{\ \ 2}} \tag{9}$$

$$\mu = \arctan(\psi_{m1\beta} / \psi_{m1\alpha}) \tag{10}$$

Design and Simulation of DSFC System Based on SVM

A double closed-loop control system, in which the inner closed-loop is radial suspension force loop and the outer closed-loop is rotor radial displacement loop, is constructed to control the radial suspension forces directly in the paper. Fig.4 shows the block diagram of DSFC system. It can be seen that torque windings flux linkage calculator can real time calculate torque windings resultant air-gap flux linkage amplitude ψ_{m1} and phase μ. Rotor radial displacement sensors detect the rotor radial displacements x and y, which are regulated by PID controllers to produce the reference suspension force F_α^*, F_β^*. Suspension force windings flux linkage estimator calculates the amplitude ψ_{s2} and phaseλ, which can work out suspension force F_α, F_β by combining with the amplitude ψ_{m1} and phaseμ. Then the increment of suspension force windings flux linkage $\Delta\psi_{s2\alpha}$ and $\Delta\psi_{s2\beta}$ are generated by equation (6), according to the error between suspension force F_α, F_β and its command values F_α^*, F_β^*. Finally the appropriate voltage space vectors are selected for suspension force windings, and voltage source inverter switching signals are generated by SVM.

The DSFC system simulation models of BPMSM are established in Simulink platform. In this system, variable step size selects ode15s, and simulation time selects 0s to 0.15s. Simulation parameters are as follows: torque windings rated voltage is 240V and rated current is 4.87A, speed n=6000r/min, the quality of rotor m=1kg, rotational inertia J=5.6×10^{-4}kg·m^2, pole pairs of torque windings is 2, pole pairs of suspension force windings is 1. Stator torque windings: resistance is 1.65Ω, direct axis and cross axis inductance are 8mH; permanent magnet flux linkage is 0.125Wb, airgap 0.375mm, airgap of auxiliary machinery bearings 0.25mm.

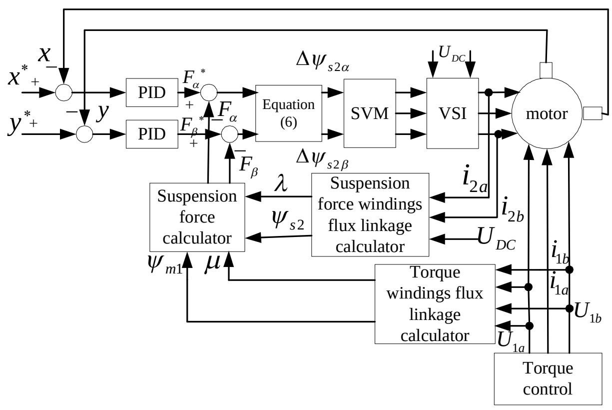
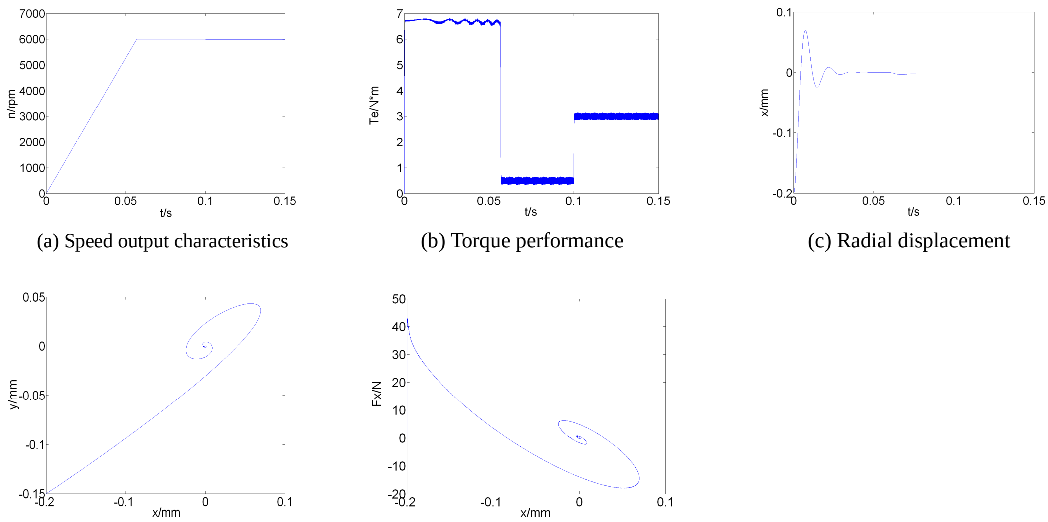


Fig. 4 Block diagram of direct suspension force control system

The speed has been set to 6000r/min, motor load torque is 0.5N·m at starting, then added to 3N·m at 0.1s, the initial displacement in the x direction is -0.2mm and y direction is -0.15mm. The Fig.5 shows the simulation results.

Fig.5 (a) shows the speed output characteristics, the speed command is 6000r/min, speed overshoot is under 0.2%, and the fluctuating error of speed in steady state is less than 10r/min, it can be seen the control system has good speed performance. Fig.5 (b) shows the performance of the torque. The pulsating movement of torque is less than 10%. A good dynamic performance for a BPMSM is shown in Fig.5 (a)-(b). Fig.5 (c) shows the radial displacement in *x* axis when the radial disturbance force is 10N. The stable suspension is realized with radial displacement error less than 10 μm. It can be seen that the system has satisfactory suspension performance. Fig.5 (d) shows the track for the mass center of the suspended rotor. The rotor approaches to the center in a helix track, and suspends stably in the center. Fig.5 (e) shows *x* axis radial suspension force, with the greater offset and the greater radial suspension force, finally rotor stabilizes in the center balance position.

From Fig.5(c), it can be concluded that the radial displacement is not interfered by the load torque. Fig. 5(b) shows that the torque is not disturbed by radial interference force. It can be seen that the control system has good decoupling performance, torque and rotor radial suspension force can be controlled independently.



(a) Speed output characteristics (b) Torque performance (c) Radial displacement

(d) Rotor suspend (e) *x* axis radial suspension force

Fig. 5 Simulation results of the control system

Conclusions

Based on the relation of flux linkage and suspension force of the BPMSM, the direct suspension force control (DSFC) method is proposed. The ideas of DTC are applied to a BPMSM system to control suspension force directly. A double closed-loop control system, in which the inner closed-loop is radial suspension force loop and the outer closed-loop is rotor radial displacement loop, is constructed to control the radial suspension forces directly. The control algorithms of radial suspension forces are deduced, and the simulation models of control system are established in Matlab/Simulink. The simulation results have shown that the method is valid, and the control system has a good static and dynamic performance. The rotor can be suspended stability, torque and radial suspension forces can be controlled independently.

Acknowledgements

This work is sponsored by the National High Technology Research and Development of China (2007AA04Z213), the National Natural Science Foundation of China (60974053), and the Research Fund for the Doctoral Program of Higher Education of China (20093227110002).

References

[1] A. Chiba, T. Fukao, and M.A. Rahman: Radial force and speed detection for improved magnetic suspension in bearingless motors, IEEE Transactions on Industry Application, Vol. 42(2006), p. 415-422.

[2] M. Ooshima, A. Chiba, and M. A. Rahman:An improved control method of buried-type IPM bearingless motors considering magnetic saturation and magnetic pull variation, IEEE Transactions on Energy Conversion， Vol.19(2004), p. 569-575．

[3] H.Q. Zhu, and T. Zhang: Finite element analysis for bearingless permanent magnet-type synchronous motors, Proceedings of the CSEE, Vol. 26(2006), p. 136-140 (in Chinese).

[4] H.Q. Zhu, and H.L. Zhai: Design and simulation of control system for bearingless permanent magnet synchronous motors, Proceedings of the CSEE, Vol. 25(2005), p. 120-124 (in Chinese).

[5] H.Q. Zhu, and L. Wu:The research on rotor magnetic flux oriented control system for bearingless permanent magnet synchronous motor, China Engineering Science, Vol.8(2006), p. 35-40 (in Chinese).

[6] Y. Wang, Z.Q. Deng, and X.L. Wang: Direct torque control of bearingless induction motor". Proceedings of the CSEE, Vol.28(2008), p. 80-84(in Chinese).

[7] J. Liu, X.G. Chu, and H.Y. Bai: Study of permanent magnet synchronous motor direct torque control based on the strategy of reference stator flux linkage and voltage space vector modulation, Transactions of China Electrotechnical Society, Vol.20(2005), p. 11-15(in Chinese).

[8] D. Sum, and Y.K. He: Space vector modulated based constant switching frequency direct torque control for permanent magnet synchronous motor,Proceedings of the CSEE, Vol.25, p. 112-116 (in Chinese).