Optik 125 (2014) 3693–3696

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Chaos control of permanent magnet synchronous motors via unidirectional correlation

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ARTICLE INFO

Article history:
Received 19 July 2013
Accepted 11 January 2014

Keywords:
Chaos control
Unidirectional correlation scheme
Permanent magnet synchronous motor

ABSTRACT

Permanent magnet synchronous motor (PMSM) displays chaotic oscillation with certain parameter values, which threatens the secure operation of the power system. An improved unidirectional correlation scheme is first proposed to control the undesirable chaotic behavior in PMSM. Simulation analysis shows that the presented control scheme is effective and one can control the PMSM to equilibrium point or non-equilibrium point by choosing appropriate correlation factor.

1. Introduction

The permanent magnet synchronous motor (PMSM) has direct applications in many fields especially for modern industries in low-medium power range, since it has outstanding characteristics such as simple structure, low manufacturing cost, high torque to inertia ratio and high torque to weight ratio.

However, the performance of the PMSM is sensitive to system parameter and external load disturbances in procession of work. Investigates show that the PMSM experiences chaotic behavior when system parameters fall into certain area [1–4]. Chaotic oscillations in PMSM can result in low-performance properties speed control of motor, low-frequency oscillations of current, intermittent ripples of torque, and even induce the motors collapse, therefore is highly undesirable. Thus, it is indispensable to suppress or control chaos in motor system. Up till now, several control strategies have been proposed for the chaotic control of PMSM [5–9].

The correlation control scheme is a feedback method which can be classified as a suppressing chaos algorithm [10]. As we know that chaotic systems have complex dynamics and intrinsic randomness, this randomness can weaken even eliminate the correlation of system state variables in some times. Therefore, to turn the system variables in order, one can strengthen the correlation among system variables via coupling partial system variables. The mutual correlation is executed only for chosen some state variables of dynamical system to cause the suppression of chaos. This scheme does not change the system parameters, so it may be useful even for these engineering systems in which we cannot directly access any of the system parameters.

In this paper, an improved unidirectional coupling correlation control scheme is first proposed to control the undesirable chaotic behavior in PMSM. Compared to the existing bidirectional correlation control scheme, the presented unidirectional correlation scheme is simpler and can be realized in engineering more convenient. Simulation analysis shows that when the correlation factor is small, a complicated evolutionary process is undergone to stable state, and one can control the PMSM to equilibrium point or non-equilibrium point by choosing appropriate correlation factor.

2. Model of PMSM

As considered in the study of bifurcations [2], in this paper, we consider the PMSM which is unforced. In this case, the motor is running freely with no loading conditions. The corresponding dimensionless mathematical model of PMSM can be given by [2–4]

$$\begin{cases} \dfrac{di_d}{dt} = -i_d + \omega i_q \\ \dfrac{di_q}{dt} = -i_q - \omega i_d + \gamma\omega \\ \dfrac{d\omega}{dt} = \sigma(i_q - \omega) \end{cases} \tag{1}$$

where i_d denotes the direct d-axis current; i_q denote the quadrature q-axis current; ω denotes the rotor angular frequency; γ and σ are the motor parameters.

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http://dx.doi.org/10.1016/j.ijleo.2014.01.131
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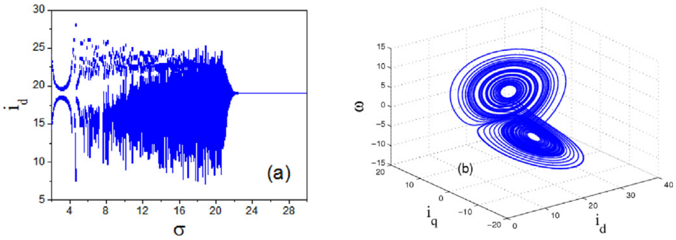

Fig. 1. Bifurcation diagram and chaotic attractor of system (1): (a) bifurcation diagram; (b) chaotic attractor.

We can obtain three equilibrium points of system (1) applying equilibrium condition, $-i_d+\omega i_q=0, \quad -i_q-\omega i_d+\gamma\omega=0, \quad \sigma=(i_q-\omega)=0$, as $P_0=(0,0,0), \quad P_{1,2}=(\gamma-1, \pm\sqrt{\gamma-1}, +\sqrt{\gamma-1})$.

Theoretical studies show that, with the operating parameters σ and γ falling into certain area, all the three equilibrium points become unstable, the motor exhibits chaos. The bifurcation diagram for $\sigma \in [2, 30]$ versus with $\gamma = 20$ and the typical chaotic phase diagram with $\gamma = 20$, $\sigma = 5.46$ are shown in Fig. 1. It is known from Fig. 1 that the motor system displays complex dynamical behavior.

3. Description of correlation control scheme

As we know that a key feature of chaotic systems is the intrinsic stochasticity, which can weaken even eliminate the correlation of system state variables in some times. Therefore, we can strengthen the correlation among system variables via coupling partial system variables, so as to turn the system variables in order and to suppress the undesirable chaos. This control scheme is independent of the system parameters, so it may be useful even for these engineering systems in which one cannot directly access any of the system parameters.

Here, the following three-dimensional nonlinear differential equation is considered to elaborate our control method

$$\begin{cases} \dfrac{dx_1}{dt} = f_1(x_1, x_2, x_3) \\ \dfrac{dx_2}{dt} = f_2(x_1, x_2, x_3) \\ \dfrac{dx_3}{dt} = f_3(x_1, x_2, x_3) \end{cases} \tag{2}$$

To control the undesirable chaos of nonlinear system (2), we couple the state variables x_1 and x_2 by the following rules

$$\begin{aligned} \hat{x}_1 &= (1-\delta^3)x_1 + \delta x_2 \\ \hat{x}_2 &= (1-\delta^3)x_2 + \delta x_1 \end{aligned} \tag{3}$$

where δ is the correlation factor with the values range from 0 to 1.

The controlled dynamical system is described as

$$\begin{cases} \dfrac{dx_1}{dt} = f_1(\hat{x}_1, \hat{x}_2, x_3) \\ \dfrac{dx_2}{dt} = f_2(\hat{x}_1, \hat{x}_2, x_3) \\ \dfrac{dx_3}{dt} = f_3(\hat{x}_1, \hat{x}_2, x_3) \end{cases} \tag{4}$$

We know from (3) and (4), when $\delta = 0$, $\hat{x}_1, \hat{x}_2$ degenerate to x_1, x_2, and system (4) evolves freely. So we can amend the correlation of system state variables by adjusting the correlation factor. In the actual operational process, we employ the unidirectional coupled mode, i.e. $\hat{x}_1 = (1-\delta^3)x_1 + \delta x_2$, or $\hat{x}_2 = (1-\delta^3)x_2 + \delta x_1$; what's more, we can simplify the control method, as is elaborated in Section 4.

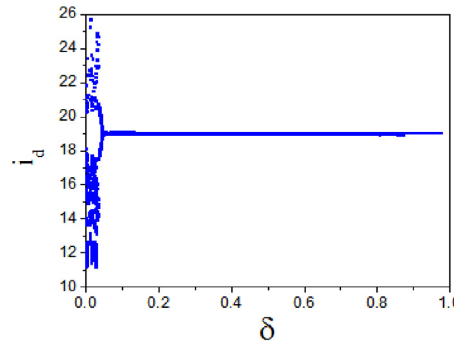

Fig. 2. Bifurcation diagram of system (5) vs δ.

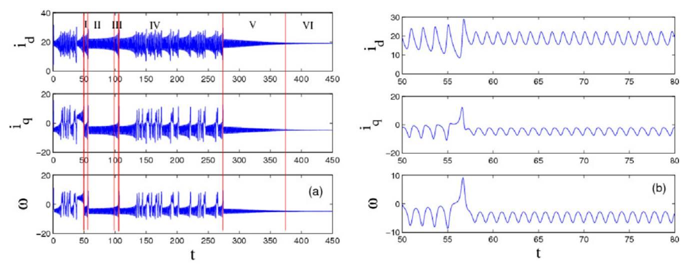

Fig. 3. Control results for the first case when $\delta = 0.04$.

4. Chaos control of PMSM

In order to control the chaos of PMSM, we put to use the coupling of currents i_d and i_q, as following: $\hat{i}_q = (1-\delta^3)i_q + \delta i_d$, $\hat{i}_d = (1-\delta^3)i_d + \delta i_q$. Here, three unidirectional correlation modes are considered.

First we consider the unidirectional correlation mode $\hat{i}_q = (1-\delta^3)i_q + \delta i_d$, the controlled motor system is given as

$$\begin{cases} \dfrac{di_d}{dt} = -i_d + \omega \hat{i}_q \\ \dfrac{di_q}{dt} = -i_q - \omega i_d + \gamma\omega \\ \dfrac{d\omega}{dt} = \sigma(i_q - \omega) \end{cases} \tag{5}$$

The bifurcation diagram for $\delta \in [0, 1]$ is shown in Fig. 2, which shows that as the value of correlation factor increases, the system is driven in a chaotic state following a reverse period doubling sequence. In the following numerical analysis, we put control scheme into effect when $t \geq 50$ s.

Fig. 3 shows the control results when $\delta = 0.04$. Seen from the time frames of Fig. 3(a), when the controller is put into effect, the PMSM is driven to chaotic state, period state, chaotic state, period state, chaotic state, attenuated oscillation, and finally tends to be stable (equilibrium point). Fig. 3(b) shows the state responses in time frame I, from which one can clearly observe the state evolution.

Fig. 4 shows the control results when $\delta = 0.3$. Seen from Fig. 4, when the controller is put into effect, the PMSM is driven to non-equilibrium point. Analogously for $\delta = 0.6$ and $\delta = 0.78$, shown in Fig. 5.