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Passivity-Based Control of Permanent Magnet Synchronous Motor without Speed Sensors *

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Abstract: This paper introduces a sensorless nonlinear control scheme for controlling the torque of a permanent magnet synchronous motor (PMSM) driving a known load. The states of the motor are estimated via a nonlinear reduced order observer avoiding the use of mechanical sensors. The control strategy is designed by using the passivity theory, with torque tracking evaluated on estimated values. The system performance is evaluated by simulation.

Key words: PMSM; passivity-based control; reduced-order observer

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基于无源性的永磁电机无速度传感器控制

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摘要: 针对永磁电机(PMSM)提出了一种无速度传感器的非线性控制策略.该策略能在已知负载的基础上实现给定转矩的精确跟踪.电机的速度通过一非线性降阶观测器来实现估计.在此基础上,利用电机的无源特性来设计电机的控制策略.最后通过仿真验证了所提出策略的有效性.

关键词: 永磁电机; 无源性; 降阶观测器

1 Introduction

Recently over induction motor drives permanent magnet synchronous motors (PMSM) are performed because of its high efficiency and high torque in lower speed. So the high performance drive of the PMSM increasingly appeals to many engineers. Among many control methods, the control of using passivity as a building block is most encouraging. The passivity-based control (PBC) was firstly proposed by Ortega[1,2]. The PBC is developed fast thanks to its characters such as globally stable, simple and combination closely with the system physics. Nicklasson et al[3] have extended this nonlinear control method to a class of Blondel-park transformable electric machines. In this paper, a method based on the passivity of the PMSM is investigated. The resulting nonlinear control system inherits the benefit of the passivity-based control and also has its own favorable features.

In PMSM control system, the states are needed to perform the control law. For the system's cost and ruggedness, the observers are needed to estimate state. Several approaches to obtain PASM state observers have been proposed. In [4], nonlinear full observers are employed for speed estimation, but some steady-state error may still appear. In [5], the implementation of an extended Kalman filter is proposed. But there are singular points in existence, and the convergence of the estimated states is difficult to guarantee. Here a reduced order observer employing nonlinear techniques is designed. The proposed observer can guarantee the global convergence with the steady-state error is zero, and the convergence speed can be controlled.

The paper is organized as follows. In Section 2 the basic PMSM model from the total energy function is established, and the torque-tracking problem is presented. Section 3 contains the control laws. The nonlinear reduced order observer is used to estimate PMSM's speed and position in Section 4. System performance is evaluated in Section 5. Finally, we present some concluding

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remarks and future research.

2 PMSM model

The PMSM model will be established from the energy point as the induction motor in [1]. The machine consists of windings on stator. The permeability of the rotor core is assumed to be infinite and saturation. All the parameters are constant and can be measured. For simplicity the stationary two-axes ($\alpha\beta$ axes) are chosen as references.

Under the assumption above, the relationship between the stator flux linkage vector $\lambda = [\lambda_\alpha, \lambda_\beta]^{\mathrm{T}}$ and the current vector $\dot{q}_e = [\dot{q}_\alpha, \dot{q}_\beta]^{\mathrm{T}}$ can be established.

$$\lambda = D_e \dot{q}_e + \mu(q_m), \tag{1}$$

and

$$D_e = \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix}, \ \mu(q_m) = \lambda_m \begin{bmatrix} \cos(n_p q_m) \\ \sin(n_p q_m) \end{bmatrix},$$

where $q_m \in \mathbb{R}$ is the mechanical position of the motor, L is the inductance, λ_m is the amplitude of the flux linkage established by the permanent magnet and n_p is the number of the pole pairs.

Neglecting the capacitive effects in the windings of the stator and considering a rigid shaft, the potential energy of the motor is zero. The system Lagrangian is

$$L(\dot{q}_e, \dot{q}_m, q_m) = \frac{1}{2}\dot{q}_e^{\mathrm{T}} D_e \dot{q}_e + \mu(q_m)^{\mathrm{T}} \dot{q}_e + \frac{1}{2} D_m \dot{q}_m^2, \tag{2}$$

where $D_m > 0$ is the rotational inertia of the motor.

Applying Euler-Lagrange equations, the state equations of the $\alpha\beta$ model is

$$\begin{cases} D_e \ddot{q}_e + W_1(q_m)\dot{q}_m + R_e \dot{q}_e = u, \\ D_m \ddot{q}_m - y(\dot{q}_e, q_m) + R_m \dot{q}_m = -T_L, \end{cases} \tag{3}$$

where

$$W_1 := \frac{\mathrm{d}\mu(q_m)}{\mathrm{d}q_m}, \ R_e = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix},$$

the control signals $u = [u_\alpha, u_\beta]^{\mathrm{T}}$ are stator voltage. $R_s > 0$ is the stator resistance. $R_m > 0$ is the motor damping coefficient, and T_L is the load torque. The output is the generated torque:

$$y := W_1(q_m)^{\mathrm{T}} \dot{q}_e. \tag{4}$$

After we establish the PMSM model, the control problem can be formulated as follows:

Consider the PMSM model (3) with measurable outputs (stator currents $\dot{q}_e$ and rotor speed $\dot{q}_m$), control u, known smooth load disturbance T_L, and regulated signals y. We assume that the torque reference y_d is a bounded differentiable function with known derivative. The objective is to design a smooth control law that will guarantee global asymptotic torque tracking and flux regulation, i.e. $\lim\limits_{t\to\infty}(y - y_d) = 0$ with all internal signals uniformly bounded.

3 Controller design

To design the passivity-based controller, there are three steps to follow:

Firstly the PMSM system dynamics must be represented as the negative feedback interconnection of the following passive (electrical and mechanical) subsystems

$$\Sigma_e : \begin{bmatrix} u \\ -\dot{q}_m \end{bmatrix} \mapsto \begin{bmatrix} \dot{q}_e \\ y \end{bmatrix}, \ \Sigma_m : (y - T_L) \mapsto \dot{q}_m.$$

From (3), (4), a conclusion is obtained easily. According to [1], the control law only acts on the electrical part Σ_e, and treats the effect of mechanical subsystem Σ_m as a passive perturbation. To ensure the latter does not "destroy" the stability of the whole system, the map from control input to measurable output, i.e. Σ_e must be strictly passive.

If there is a nonlinear output feedback of the form

$$u = v + W_1 \dot{q}_m - K\dot{q}_e, \tag{5}$$

then the dynamic of Σ_e can be described as follows

$$D_e \ddot{q}_e + R_{es} \dot{q}_e = v,$$

where $R_{es} = R_e + \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}$.

Taking the time derivative of the total energy of Σ_e, that is, $H_e := \frac{1}{2}\dot{q}_e^{\mathrm{T}} D_e \dot{q}_e$, along the trajectories of Σ_e we get

$$\dot{H}_e = \dot{q}_e^{\mathrm{T}} v - \dot{q}_e^{\mathrm{T}} R_{es} \dot{q}_e.$$

If choosing $K = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} > 0$, then integration of $\dot{H}_e$ proves the strict passivity of Σ_e.

Since the model is defined in $\alpha\beta$ axes, the "workless force" is not found like the induction motor. It makes the controller's design more simple and direct only by adding the 3/2 linear transformation. On the other hand, as can be seen from (5), the term $W_1 \dot{q}_m$ from the permanent magnets must be cancelled. The reason for the cancellation is that there is a drawback of the scheme. However, the term is a vector with periodic functions in a measurable quantity (position q_m).

The second step is to define a set of attainable currents $\dot{q}_{ed}$, i.e. for a given desired torque the following equation holds

$$y_d = W_1(q_m)\dot{q}_{ed}^{\mathrm{T}}. \tag{6}$$

Proposition 1 While the desired currents and their derivatives are defined as

$$\begin{aligned} \dot{q}_{ed} &= \mathrm{e}^{-Jq_m}\dot{z}_{ed}, \\ \ddot{q}_{ed} &= J\mathrm{e}^{-Jq_m}\dot{q}_m\dot{z}_{ed} + \mathrm{e}^{-Jq_m}\ddot{z}_{ed}, \end{aligned} \tag{7}$$

where $\dot{z}_{ed}$ is chosen to satisfy

$$y_d = W_1^{\mathrm{T}}(0)\dot{z}_{ed} \tag{8}$$

with $\dot{z}_{ed}, \ddot{z}_{ed} \in L_\infty^2$, then equation (6) will be satisfied.

Proof According to equation (3)

$$W_1(q_m) = \lambda_m\begin{bmatrix} -\sin(q_m) \\ \cos(q_m) \end{bmatrix}$$

and by simple calculation, (6) is obtained from (7) and (8).

The last step is to find a control law that ensures $\lim\limits_{t\to\infty}\dot{q}_e = \dot{q}_{ed}$ that implies $\lim\limits_{t\to\infty} y = y_d$ with internal stability.

Proposition 2 If $\dot{q}_{ed}$ and $\ddot{q}_{ed} \in L_\infty^2$ satisfy (7) and in (5) v satisfy

$$v = D_e\ddot{q}_{ed} + R_{es}\dot{q}_{ed}, \tag{9}$$

the system can keep globally asymptotic torque tracking with internal stability.

Proof First we can get the error signal equation by (3), (5) and (9):

$$D_e\ddot{\tilde{q}} + R_{es}\dot{\tilde{q}} = 0, \tag{10}$$

where $\dot{\tilde{q}} = \dot{q}_e - \dot{q}_{ed}$. The equation is locally Lipschitz in state, so there exists $t > 0$ such that in the time interval $[0, t)$ the solution exists and is unique.

Taking the time derivative of the designed energy function $H_{ed} = \frac{1}{2}\dot{\tilde{q}}_e^{\mathrm{T}}D_e\dot{\tilde{q}}_e$ along the trajectory (10), we have $\dot{H}_{ed} = -\dot{\tilde{q}}_e^{\mathrm{T}}R_{es}\dot{\tilde{q}}_e$. It follows from (5) that R_{es} is positive, so $\lim\limits_{t\to\infty}\dot{\tilde{q}}_e = 0$ and $\dot{q}_e$ is bounded. From Proposition 1, it follows that $\lim\limits_{t\to\infty} y = y_d$ with y is bounded. So the control law is obtained from (5), (7) and (9).

Here we initially introduced the passivity-based control to the PMSM. The method is easily implemented because it need not perform the nonlinear geometric transformation, compared with the other nonlinear control. And it also inherits the benefits of the invariance of the passivity. Then unlike the induction motor the "workless force" is inexistent because a transformation does not influence the system's passivity. The control law is obtained from the physics of the system, so the controller can guarantee the system's global stability to the overall system. Although the electrical subsystem is already strict passivity, we still reshape the system's natural energy by injecting the damping too. It enhances the robustness of the system and makes it easy to achieve the control objective.

4 Reduced order nonlinear observer

However, the states $\dot{q}_m, q_m, \dot{q}_e$ are needed to implement the control law, so a reduced order observer is used to estimate the rotor position q_m and speed $\dot{q}_m$. The observer's equations are as follows

$$\begin{bmatrix} \dfrac{\mathrm{d}\hat{q}_m}{\mathrm{d}t} \\ \dfrac{\mathrm{d}\hat{\dot{q}}_m}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} \dot{\hat{q}} \\ \hat{a} \end{bmatrix} + G(\dot{\hat{q}}, \hat{q}_m)\begin{bmatrix} \ddot{q}_\alpha - \ddot{\hat{q}}_\alpha \\ \ddot{q}_\beta - \ddot{\hat{q}}_\beta \end{bmatrix} \tag{11}$$

with

$$\hat{a} = D_m^{-1}(W_1(\hat{q}_m)^{\mathrm{T}}\dot{q}_e + R_m\dot{\hat{q}}_m - T_L)$$

and $\ddot{q}_e$ satisfies equation (3). While the rotor position and speed are replaced by the estimated value, $\ddot{\hat{q}}_e$ is gotten by (3). The matrix of gains $G(\dot{\hat{q}}_m, \hat{q}_m)$ is designed as follows:

Proposition 3 For a given positive definite matrix P whose maximum eigenvalue is p, if $G(\dot{\hat{q}}_m, \hat{q}_m)$ is found to satisfy the equation $-Q = G^{\mathrm{T}}P + PG$, and Q is symmetric, the positive definite matrix and its minimum eigenvalue q satisfies

$$-q + 2pm < 0, \tag{12}$$

where m is a constant related with (13), then the convergence of the observer to zero error is exponential; moreover its speed is defined by the choice of $G(\dot{\hat{q}}_m, \hat{q}_m)$.

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \rho(z, \dot{q}_e) =$$

$$\begin{bmatrix} \dfrac{\lambda_m(k_\alpha z_1^2 - k_\beta z_1 z_2)}{L(z_1^2 + z_2^2)} - \dfrac{T_L L}{D_m\lambda_m}\dfrac{z_1}{\sqrt{z_1^2 + z_2^2}} - \sqrt{z_1^2 + z_2^2}\,\dfrac{z_2 L}{\lambda_m} \\ \dfrac{\lambda_m(k_\alpha z_1 z_2 - k_\beta z_2^2)}{L(z_1^2 + z_2^2)} - \dfrac{T_L L}{D_m\lambda_m}\dfrac{z_2}{\sqrt{z_1^2 + z_2^2}} + \sqrt{z_1^2 + z_2^2}\,\dfrac{z_1 L}{\lambda_m} \end{bmatrix} \tag{13}$$

with $k_\alpha = -\lambda_m \dot{q}_\alpha / D_m$, and $k_\beta = -\lambda_m \dot{q}_\beta / D_m$.

Proof First express the system in the new coordinate z, and the equation becomes

$$\ddot{q}_e = z + C,$$
$$\ddot{\hat{q}}_e = \hat{z} + C$$

with $z = T(\dot{q}_e, q_e)$, $\hat{z} = T(\dot{\hat{q}}_e, \hat{q}_e)$ so if the error $e = z - \hat{z}$ converges to zero, the proposition is proved.

The proposed observer in z coordinates is given by

$$\frac{\mathrm{d}\hat{z}}{\mathrm{d}t} = \rho(\hat{z}, \dot{q}_e) + G(\ddot{q}_e - \ddot{\hat{q}}_e),$$

then $\frac{\mathrm{d}e}{\mathrm{d}t} = Ge + \Delta\rho = Ge + (\rho - \hat{\rho})$. Considering Lyapunov function $V_e = e^{\mathrm{T}} Pe$,

$$\frac{\mathrm{d}V}{\mathrm{d}t} = e^{\mathrm{T}}(G^{\mathrm{T}}P + PG)e + (\Delta\rho)^{\mathrm{T}}Pe + e^{\mathrm{T}}P\Delta\rho. \tag{14}$$

Because $\rho(z, \dot{q}_e)$ satisfies the Lipschitz condition in the first variable, there exists constant m which makes $\| \Delta\rho \| \leqslant m \| e \|$ uniform in $\dot{q}_e$. According the condition in Proposition 3, equation (14) becomes

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -e^{\mathrm{T}}Qe + 2e^{\mathrm{T}}P\Delta\rho \leqslant -q \| e \|^2 + 2pm \| e \|^2$$

and while (12) is satisfied, the equilibrium point ($e = 0$) is asymptotically stable. Moreover, since $V(t) \leqslant V(t_0) e^{(\frac{-q+pm}{p})(t-t_0)}$, the convergence is exponential.

Once G is designed, since $\hat{z} = T(\dot{\hat{q}}_e, \hat{q}_e)$, the observer's equation (13) needs to be transformed to the origin coordinates, i. e. the observer nonlinear gain $G(\dot{\hat{q}}_e, \hat{q}_e)$ is given by the inverse of the Jacobian matrix of the transformation evaluated on the estimated state and a constant matrix G.

Here a nonlinear observer is designed. A mathematical transformation follows the simplification of the problem of designing the nonlinear correction term. Following the procedure presented in the paper, the stable state-error is zero and the convergence speed of the observer may be set by choosing the parameter of the observer.

5 Torque control and performance evaluation

The proposed passivity-based controller with the observer is shown in Fig. 1. The performance was verified by means of simulations. Parameter values of the PMSM, the observer and the controller are given in the appendix. We present here the simulations of a sinusoidal torque reference.

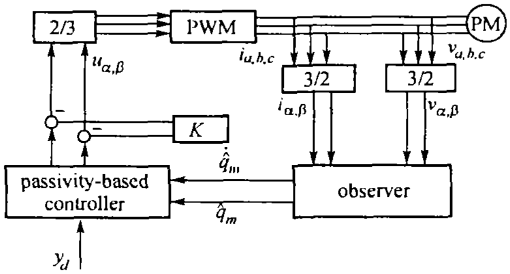

Fig. 1 Control scheme:block diagram

Fig. 2 shows the response of the generated and the desired torque. As seen from the figure, the performance of the proposed controller with observer is quite remarkable. In Fig. 3 the rotor speed are compared with their observed values when the load torque is 1.9Nm. The initial estimated speed was set at 10 rad/min, while the estimated position was set at 0 rad. Notice that although the observation error of rotor speed and position converges to zero, it is still influenced by the uncertainties of many parameters.

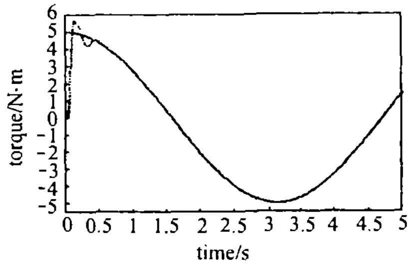

Fig. 2 Generated (dashed) and desired (solid) torque

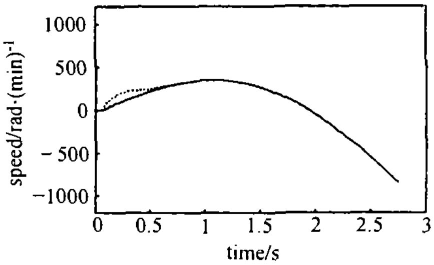

Fig. 3 Actual (solid) and observed (dashed) speed

As mentioned above, the damping matrix $K\dot{q}_e$ is injected to the electrical subsystem. In Fig. 4, we show the performance of the system by applying a load torque, which varies between ±20%. From the figure, it follows that the performance of the system is influenced little by the variable load. So the injecting of the damp really enhances the system robust performance.

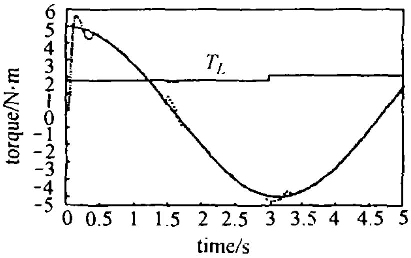

Fig. 4 Generated (dashed) and desired (solid) torque while load varied

6 Conclusion

A sensorless passivity-based control strategy was introduced for controlling the torque of a PMSM motor. The proposed controller inherits many benefits of the PBC such as simplicity, strong robustness and easy implementation. The reduced-order nonlinear observer was used to estimate the variables to be fed back to the controllers. The proposed control scheme was tested by the simulations, and performed satisfactorily in the whole torque tracking range. And the paper only considers the torque control and known load. The next objective is forwarding to the speed/position control with unknown load torque. Another objective is to compare the passivity-based control with the other nonlinear control method in PMSM-like induction motor. And the experiments are also needed to prove the effectiveness of the control method. However for the permanent magnet of the motor, a nonlinear term needs to be left out. How to avoid the cancellation in the PMSM is also a main problem in the future PBC research.

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Appendix

The data and parameters of the device considered in the paper are: $T_m = 7\mathrm{N\cdot m}$, $n_e = 1500\mathrm{rpm}$, $n_p = 1$, $L = 20.5\mathrm{mH}$, $R = 1.55\Omega$.

PMSM:

$$\lambda_m = 0.22\mathrm{N\cdot m/A},\ D_m = 2.2\times10^{-3}\mathrm{Kg\cdot m^2}.$$

Observer: $$G = \begin{bmatrix} 5\times10^4 & 0 \\ 0 & 5\times10^4 \end{bmatrix}.$$

Controller: $$K = \begin{bmatrix} 20 & 0 \\ 0 & 20 \end{bmatrix}.$$

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