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Single Electronic Drive Controlling Two Synchronous Motors Via Modified Vector Control

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ABSTRACT

A novel control scheme of using a single electronic drive to synchronize two synchronous motors is investigated analytically. The developed control strategy extends the conventional *vector control* technology. Specifically, it utilizes the property that the motion of two motors can be independently controlled by the q-axis currents provided the desired q-axis currents can be achieved by adjusting physical armature currents. The latter part is indeed guaranteed by adding a position offset to one of the motors. This work has a potential of cost saving in practice where the cost of drive is a major concern.

Keywords: power electronics drives, control strategy, permanent magnet synchronous motors, simulation

1. Introduction

A novel control scheme of using one electronic drive to control two synchronous motors is reported. It is shown that, under certain conditions, the position of two synchronous motors can be synchronized by one drive. The control scheme extends the conventional vector control technology[1]-[3] in three aspects: 1) utilization of q-axis currents to generate the desired torque in each motor for position synchronization; 2) introduction of motor position offset to eliminate singularity in Park transform; 3) design of PID controller that achieves motor position trajectory tracking. The key point of the proposed control strategy is to control the q-axis currents in two motors independently via adjusting armature voltages v_a and v_b.

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This control scheme was developed for a sliding door control system, where two linear synchronous motors (LSM), driven by one inverter, were used to open and close two sliding doors. It was also extended to rotary synchronous motors (RSM). For each type of motors, two system configurations were considered, motors connected in series and in parallel. For the sake of briefness, only the results developed with RSMs connected in series are presented in this paper.

The paper is organized as the follows. In Section 2, a dynamic model of RSM is established. Control design and implementation of one drive controlling two RSMs are described in Section 3. Conclusions are given in Section 4.

2. Dynamic Model of RSMs

A rotary synchronous motor can be illustrated as in Figure 1, where the stator produces the traveling magnetic fields and the rotor provides the magnetic flux.

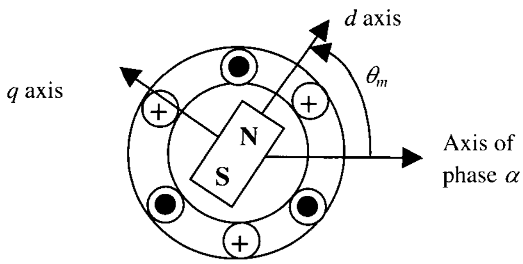

Fig. 1. A Rotary synchronous motor.

Suppose the synchronous motors considered have permanent magnet for field excitation, i.e., the excitation linkage flux is constant, and the motors have no damping. Then their dynamic models are established in the so-called $dq0$ coordinate as the following:

$$\begin{cases} v_d = Ri_d + L_d \dfrac{di_d}{dt} - L_q\omega \ i_q \\ v_q = Ri_q + L_q \dfrac{di_q}{dt} + L_d\omega \ i_d + \psi_f\omega \end{cases} \tag{1}$$

where, i_d, i_q, v_d, v_q are the instantaneous armature currents i_a, i_b, i_c and phase voltages v_a, v_b, v_c projected in the d-q coordinates, Ψ_d, Ψ_q, Ψ_f are the d-axis, q-axis and excitation linkage fluxes, ω is the angular velocity of the rotating magnetic field, R is the armature winding resistance, and L_d, L_q are the inductance in the d-q coordinates. Let N_p be the number of pole pairs, T_l be the load torque, B_m be the motor viscosity friction coefficient, and ω_m be the angular velocity of the motor shaft. Then the electromagnetic torque of a three-phase permanent magnet RSM is given by,

$$T_e = 3N_p[\psi_f i_q + (L_d - L_q)i_d i_q]$$

and the mechanical balance on the motor shaft is:

$$J_m\dot{\omega}_m = T_e - T_l - B_m\omega_m$$

Writing $\omega = d\theta/dt$ and $\omega_m = d\theta_m/dt$ with θ the electrical angle and θ_m the mechanical angle, we have the relation $\theta = N_p\theta_m$ and $\omega = N_p\omega_m$ when the motor is in synchronization. Putting everything together, we obtain a complete PM RSM dynamic model in d-q coordinate as:

$$\begin{cases} L_d \dfrac{di_d}{dt} = v_d - Ri_d + L_q N_p \omega_m \ i_q \\ L_q \dfrac{di_q}{dt} = v_q - Ri_q - L_d N_p \omega_m i_d - \psi_f N_p \omega_m \\ J_m\dot{\omega}_m = 3N_p[\psi_f i_q + (L_d - L_q)i_d i_q] \ -T_l - B_m\omega_m \end{cases} \tag{2}$$

For a given load T_l, the motion of a RSM is determined by currents i_d and i_q as shown in the third equation in (2). These currents are generated by magnetic flux and motor torque, respectively, and they are projections of the armature currents in the d-q coordinate via Park transformation.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix} \sin(\theta + 60^\circ) & \sin\theta \\ \cos(\theta + 60^\circ) & \cos\theta \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \tag{3}$$

where, θ is the electrical angle of the rotor. We have assumed a balanced system with $i_a + i_b + i_c = 0$. Control of a synchronous motor can be summarized in three steps: 1) Derive i_d and i_q currents under which the motor will have the derived motion for a given load; 2) Derive armature currents i_a, i_b and i_c that result in i_d and i_q currents required in step 1; 3) Design a PI controller that regulates voltages v_a, v_b and v_c to drive the actual currents i_a, i_b and i_c to the desired values, which in turn generates d-q currents i_d and i_q to drive the motor to achieve the desired motion. This control strategy is known as *vector control* in synchronous motor literature. In the rest of the paper, we will extend this control strategy to control of two synchronous motors using one drive, and we assume a balanced system with $i_a + i_b + i_c = 0$ is considered.

3. One Drive Controlling Two RSMs

In this section, we present the main results: synchronize two RSMs using one drive. We first show the feasibility and then design and implement the synchronization control algorithms.

3.1 Control Feasibility Analysis

When two RSMs are controlled by one drive, their motions are described by:

$$J_{mj}\dot{\omega}_{mj} = 3N_p[\psi_{fj}i_{qj} + (L_{dj} - L_{qj})i_{dj}i_{qj}] - T_{lj} - B_{mj}\omega_{mj}, \quad j = 1,\ 2 \tag{4}$$

It is very important to note that torque producing currents i_{q1} and i_{q2} do not need to be equal even when two motors share the same armature currents (i_a, i_b, i_c) in a serial connection[1]. The same is true for flux generating currents i_{d1} and i_{d2}. It is this property that makes it possible to control two motors with one drive. For a balanced three-phase system, the Park transformation in Eq. (3) determines a one-to-one mapping between (i_d, i_q) and (i_a, i_b). When two motors connected in series are driven by a single power source, they share the same currents i_a and i_b, which have projections i_{d1}, i_{q1}, i_{d2} and i_{q2}, respectively. Among these projected currents, however, only two are independent and let's assume they are i_{q1} and i_{q2}. Then Eq. (3) can be revised to describe the relation between (i_{q1}, i_{q2}) and (i_a, i_b) as,

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = T(\theta_1, \theta_2) \begin{bmatrix} i_{q1} \\ i_{q2} \end{bmatrix} \quad with$$
$$T(\theta_1, \theta_2) = \frac{1}{\sin(\theta_2 - \theta_1)} \begin{bmatrix} \cos\theta_2 & -\cos\theta_1 \\ -\cos(\theta_2 + 60^\circ) & \cos(\theta_1 + 60^\circ) \end{bmatrix} \tag{5}$$

Hence, i_{q1} and i_{q2} can be used as the independent control variables in motor motion control so long as Eq. (5) is valid, i.e., $\theta_1 \neq \theta_2$. Eq. (5) will be referred to as the revised Park transformation. To guarantee a valid revised Park transformation, we add an angle offset to one of the motors as shown in Figure 2. If the horizontal axis is used as the reference for synchronization, two motors are synchronized when $\theta_1 = \theta_2 - \theta_0$.

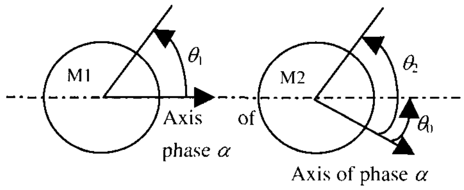

Fig. 2. Adding an angle offset to one of the motors.

[1] Currents in the d-q coordinate of a synchronous motor are the projections of the armature currents, and such projections depend on the rotor position. Therefore, two motors having the same armature current could have different d-q currents if they have different rotor positions.

3.2 Control Design

We design the control laws for i_{q1} and i_{q2} to fulfill the control objective for motor synchronization. For the sake of simplicity, we assume $L_{dj} = L_{qj}$,[2] j=1,2, and rewrite Eq. (4) as,

$$J_{mj}\ddot{\theta}_{mj} = K_{mj}i_{qj} - T_{lj} - B_{mj}\dot{\theta}_{mj} \tag{6}$$

with $K_{mj} = 3N_p\Psi_{fj}$. Then the control objectives can be stated as: drive θ_{m1} and θ_{m2} - θ_0 to track a predefined common reference trajectory, θ_r. This will result in $\theta_{m1} = \theta_{m2} - \theta_0$ as the tracking errors

$$e_1(t) = \theta_{m1}(t) - \theta_r(t), \quad e_2(t) = \theta_{m2}(t) - \theta_0 - \theta_r(t)$$

become zero. Writing Eq. (6) in terms of the tracking errors, we get

$$J_{mj}\ddot{e}_j = K_{mj}i_{qj} - T_{lj} - B_{mj}\dot{e}_j - B_{mj}\dot{\theta}_r - J_{mj}\ddot{\theta}_r, \quad j = 1,2.$$

Suppose the load torque is constant with possible step changes and the position reference θ_r has a velocity profile consisting of constants and ramp functions. Then a PID control law for I_{qj}

$$I_{qj}(s) = -(K_{pj} + K_{dj}s + K_{ij}/s)E_j(s), \quad j = 1,2, \tag{7}$$

will drive the tracking errors to zero regardless what the load is. In other words, the PID controller in Eq. (7) will drive the motor to track the given position reference. Moreover, a desired tracking performance can be achieved by properly choosing the control gains.

3.3 Control Implementation

While the control commands for q currents are derived, the motors' real q-axis currents may not be directly adjusted for two reasons. First, i_{q1} and i_{q2} are not physical variables in terms of being directly adjustable but rather

[2] This assumption is not critical in the sense of deriving the control laws. When i_{q1} and i_{q2} are chosen as the independent variables, currents i_{d1} and i_{d2} can be expressed in terms of i_{q1} and i_{q2}, and the electromagnetic torque of each motor will be a function of i_{q1} and i_{q2}. However, the resulting Eq. (6) will be nonlinear and coupled, and in that sense, they are more complicated to deal with.

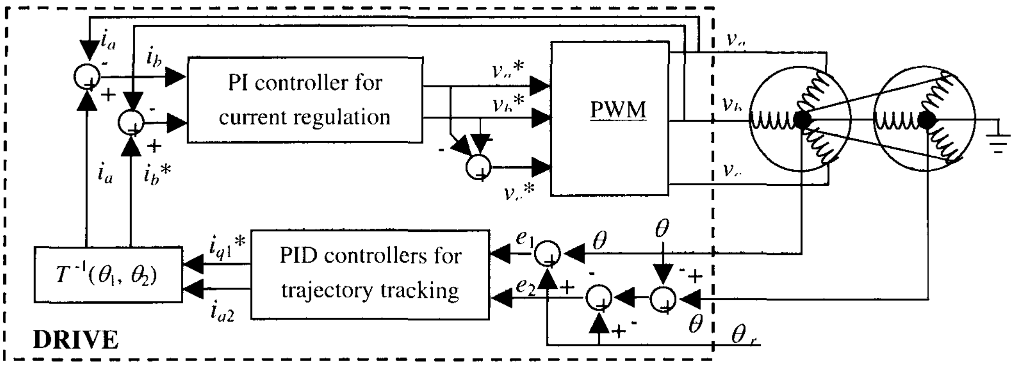

Fig. 3. The complete control system for motors connected in series.

derived quantities from the winding currents. They are controlled by currents i_a and i_b through the map in Eq. (5). Second, Currents i_a and i_b can not be directly manipulated unless a current source power supply is used and the motors are connected in series. To make the control scheme generally useful, we consider a voltage source power and design PI controllers to regulate the currents to the desired values. A complete control system for RSMs connected in series is shown in Figure 3, where $T(\theta_1, \theta_2)$ is a revised Park transformation defined in Eq. (5), and current regulations are achieved by the PI controls defined as,

$$v_j^*(t) = K_{pj}[i_j^*(t) - i_j(t)] + K_{ij}\int_0^t [i_j^*(\tau) - i_j(\tau)]d\tau, \quad j = a,b$$

The resulting commands v_a*, v_b* and v_c* will be the inputs to a voltage source inverter.

The proposed control algorithm for synchronizing two rotary motors with one drive has been demonstrated in a simulation. As shown in Figure 4, a reference trajectory was given as a velocity profile. The motors were requested to be synchronized, i.e., $\theta_1 = \theta_2 - \theta_0$, and to track the reference θ_r obtained from the desired velocity profile. During the simulation, motor one load torque increased 50% and motor two load torque doubled at a later time. Figure 4 shows the tracking results of motor velocities and the load torque changes; Figure 5 demonstrates the tracking results of motor angular positions; Figure 6 displays the q-d currents on both motors. As indicated in Figure 5, the resulting tracking errors are small and synchronization error, $\theta_1-(\theta_2 - \theta_0)$, is even smaller. Hence, we conclude motor synchronization has been achieved with the developed algorithm[3].

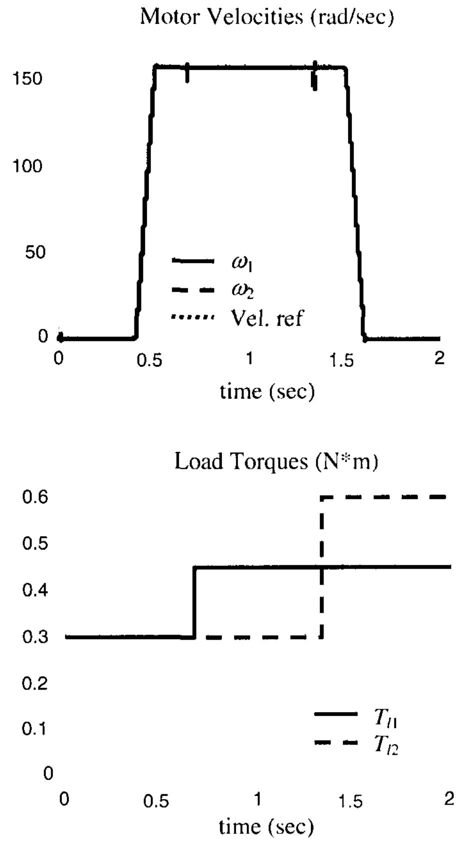

Fig. 4. Simulation results of motor velocities and load torques.

[3] It should be noted that the d axis currents are not zero under the proposed control scheme. This is in fact the price one has to pay to save the extra drive. Furthermore, the efficiency of the overall control system could be reduced, as the d axis currents get large. This issue can be addressed by making a trade-off between the control performance and control efficiency using an optimization scheme. This is, however, out of the scope of this paper.

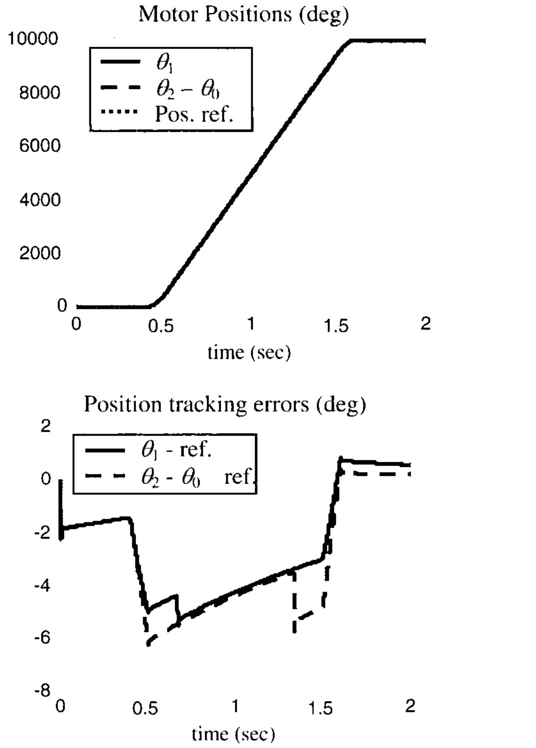

Fig. 5. Simulation results of motor angular positions and tracking errors.

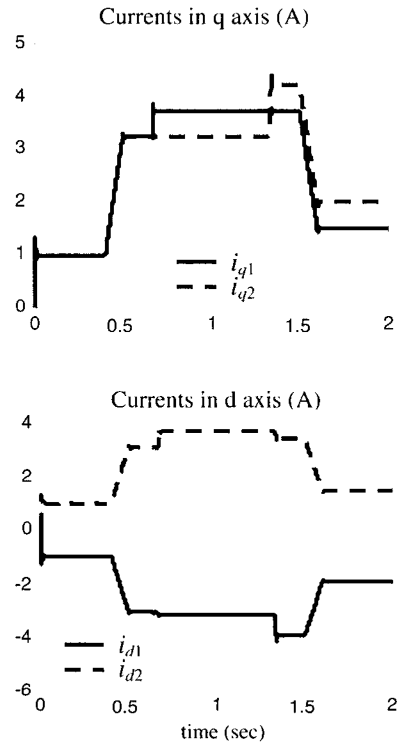

Fig. 6. Simulation results of motors' q-d currents.

4. Conclusion

In this paper, we have demonstrated that position synchronization of two RSM motors can be maintained by using one drive despite of possible disturbances on the motor loads. The key development of a control strategy for one drive controlling two synchronous motors is two-fold, one in the control design and one in control implementation. For any synchronous motor, once its dynamics are expressed in the d-q coordinate, it is clear that the motor motion can be controlled by the current in q-axis. When two motors are connected, in parallel or in series, it is important to realize that the q currents of two motors may not be the same. In fact, it has been shown that these two currents could be independently manipulated, and therefore, they can be used as the control variables to fulfill the control objectives. Once the control algorithms are developed for the q currents, the issue becomes how to implement them. As the q-axis currents are not physical variables to be adjusted, part of the implementation is to convert the commands to q currents to the commands to physical currents, and this requires revision of the original Park transformation as two motors are involved. The other part of implementation is current regulation that converts the current commands to voltage commands such that a voltage source power supplier can be used. This work has a potential of cost saving in practice where the cost of drive is a major concern.

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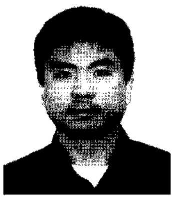

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