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OPEN LOOP POSITION AND CURRENT CONTROL OF A SYNCHRONOUS MOTOR/GENERATOR FOR A FLYWHEEL ACCUMULATOR

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Abstract: After analyzing the behavioral properties of a current-fed synchronous motor operating at variable speed in an open-loop mode, we demonstrate herein the performance of an open-loop control in the abc reference frame. Oscillation problems observed in the torque are solved by applying a control in an estimated reference frame dq. Due to inaccuracies in the model however, the use of a basic device that provides one impulse per revolution seems to represent an effective arrangement between a synchronous mode control and a classical sensor-free control. Within the control scheme of an energy storage system, two control loops are necessary (current and power). The subject of this work is confined to just the current control. The model used is then validated by experiment.

Keywords: Sensorless control, modeling, energy system management.

1. INTRODUCTION

In electromechanical energy storage involving high speeds (the case discussed herein concerns speeds in the range of 30000 rpm), the presence of mechanical sensors is not desirable. The two alternative control modes are: commutation without mechanical sensors and synchronous mode operation, *i.e.* with no knowledge of either the motor speed or the position. Variable-speed synchronous machines are almost always used nowadays in the commutation mode in order to prevent against any risk of stalling. However, in the very special case of an energy storage flywheel, where the load is fixed and known, both the torque and speed are varied by the control with no other source of disturbance, and a simple sensor-free control is then theoretically possible. In this paper, we will seek to apply this principle (see Fig. 1) to our application for operations at a maximum constant power between the base speed and the maximum speed. The brushless field winding is supplied with a controlled current I_f . This loop will not be studied herein. Voltage-fed synchronous motors operating at set frequencies are classical devices which have already been thoroughly described [1], yet nothing is available in the literature on current-driven synchronous motors in an open-loop position.

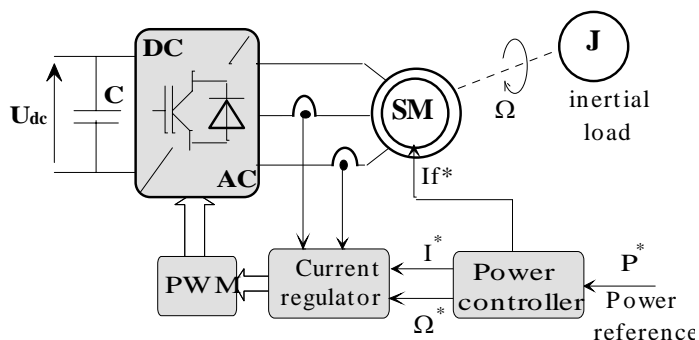


Figure 1: General control scheme

The following section has thus been included to describe the method employed to model the dynamic system, before examining a synchronous mode control. A test bench with a permanent-magnet synchronous motor connected to an inertial load, which represents a small storage system, will then be used to validate both the analytical model and the numerical simulations it enables generating (the simulation parameters are given in the Appendix).

2. MODELING, SIMULATION AND EXPERIMENTATION OF A MACHINE'S DYNAMIC PROPERTIES

Newton's second law of motion for rotational systems applied to a machine with non-salient poles, in linear operations and for a current drive, yields the following:

$$\frac{J}{p} \frac{d^2\theta}{dt^2} = 3p\Phi_f I \sin \xi - f \frac{d\theta}{dt} - C_0 - C_{asy} \quad (1)$$

with:

$$p\theta_m = \theta = \theta_s - \xi \quad (2)$$

The magnetic losses are contained in the C_{asy} term, which we first approximate as being proportional to the variation in ξ (see equation (3)). Such a simple model is acceptable in the vicinity of a rest point and for small variations. It is obviously an approximation; the results however do allow us to understand the behavior of a machine without a damping system (the case of a synchronous motor used for energy storage flywheels in which power losses must be minimized). Furthermore, knowing the time constant of the damper effects (magnetic, mechanical and aerodynamic) is very important when considering a synchronous mode control.

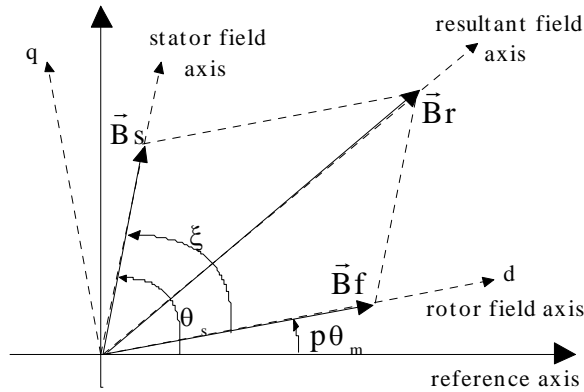


Figure 2: Vector diagram

$$C_{asy} = K_D \cdot \frac{d\xi}{dt} \quad (3)$$

From equations (1) and (2), we obtain:

$$\frac{J}{p} \left(\frac{d^2\theta_s}{dt^2} - \frac{d^2\xi}{dt^2} \right) = 3p\Phi_f \cdot I \cdot \sin \xi - C_0 - f \left(\frac{d^2\theta_s}{dt^2} - \frac{d^2\xi}{dt^2} \right) + K_D \cdot \xi \quad (4)$$

From the above relation it is possible to calculate the transfert function between ξ and ω_s by linearizing the equation around the operating point. The Laplace transfer function then becomes:

$$\frac{\Delta\xi(s)}{\Delta\omega_s(s)} = \frac{s + \frac{f}{J}}{s^2 + \left(\frac{f}{J} + \frac{p \cdot K_D}{J}\right)s + \frac{p \cdot K_S}{J}} \quad (5)$$

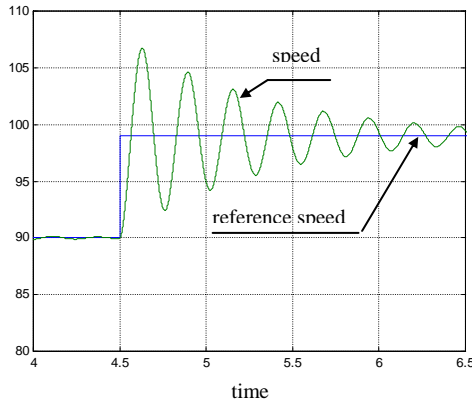
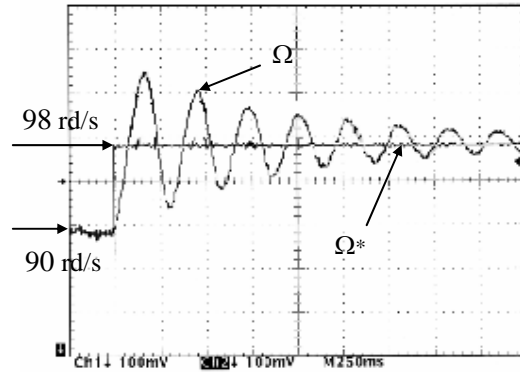


fig.3 Simulation results.



X: 250 ms/div – Y: 5 rd.s⁻¹/div
Figure 4: Experimental results

For small variations in the vicinity of a rest point and for low friction, we have found that the response to a speed step of amplitude ω_{s0} is expressed as follows:

$$\Omega(t) \approx \Omega_0 + \frac{\omega_{s0}}{p} \cdot u(t) - \frac{\omega_{s0}}{p} \cdot \frac{e^{-Z\omega_n t}}{\sqrt{1-Z^2}} \cdot \sin\left(\omega_n \sqrt{1-Z^2} \cdot t + \pi - \arccos Z\right) \cdot u(t) \quad (6)$$

in which:

$$\omega_n = \sqrt{\frac{p \cdot K_S}{J}} \quad \text{undamped natural frequency} \quad (7)$$

$$Z = \frac{1}{2} \cdot \frac{f + p \cdot K_D}{\sqrt{J \cdot p \cdot K_S}} \quad \text{damping ratio} \quad (8)$$

$$K_S = 3p\Phi_f I \sin\xi_0 \quad (9)$$

- K_S is referred to as the synchronizing torque coefficient (expressed in W.s.rad) at the operating point,
- K_D is the asynchronous torque coefficient (expressed in W.s².rad⁻¹).

The experimental results yield values for both Z and ω_n . These parameters then allow us to determine the value of K_D at the operating point.

$$Z = \mathbf{0.045}; \quad \omega_n = \mathbf{20 \text{ rd/s}}; \quad K_D = \mathbf{14 \cdot 10^{-3} \text{ W.s}^2 \cdot \text{rad}^{-1}}$$

Simulation and experimentation (Figs. 3 and 4), under the same conditions, show that the model used is valid in spite of the approximation for K_D . The machine's natural damper effects are very weak and due essentially to magnetic losses (K_D is more significant than f).

According to equation (6), the settling time constant is:

$$\tau_D = \frac{2J}{f + pK_D}$$

(10)

In the case of an energy storage system, τ_D becomes very large (high inertia and low friction). Consequently, oscillations must be eliminated by using an appropriate control.

3. CONTROL IN THE abc REFERENCE FRAME

The angle ξ is governed by a second-order differential equation with very low damping. Any variation of this angle thereby creates oscillations which are hardly absorbed at all and which can destroy the motor's synchronism if ξ exceeds $|\pi/2|$. One solution is to hold the angle ξ constant while setting the stator current at the amplitude needed to reach the desired accelerating torque. In the stationary reference frame (stator), the equations of a current-driven synchronous motor are:

$$J \frac{d\Omega}{dt} = T_{em} - f\Omega - C_0$$

(11)

$$T_{em} = 3p\Phi_f I \sin\xi_0$$

(12)

From these two equations and for a given torque reference T_{em}^* , it is therefore possible to deduce the two following references, I^* and Ω^* (equations (13) and (14)), required to eliminate transient conditions:

$$I^*(p) = \frac{T_{em}^*(p)}{3p\Phi_f} \tag{13}$$

$$\Omega^*(p) = \frac{T_{em}^*(p)}{Jp + f} \tag{14}$$

ξ_0 is known provided the operation is stabilized at the time an acceleration command is applied. Let us assume that ξ_0 is known and equal to $\pi/3$ (within a synchronous mode control, flexibility in the choice of ξ_0 is necessary in order to prevent against the risk of stalling). Fig. 5 displays the behavior of the synchronous motor for a series of step torque references. The simulation appears to yield satisfactory results; however, since the current loop's response time is not zero, it is possible for oscillations to be created (see Fig. 5). Furthermore, according to the transmittance (5) for a speed ramp input, the angle ξ does not remain at its initial value ξ_0 and drifts as follows:

$$\Delta\xi(t) \xrightarrow{t \rightarrow \infty} \frac{\omega_{s0}}{\omega_n^2} \frac{f}{J} \cdot t \tag{15}$$

ξ
(rd)

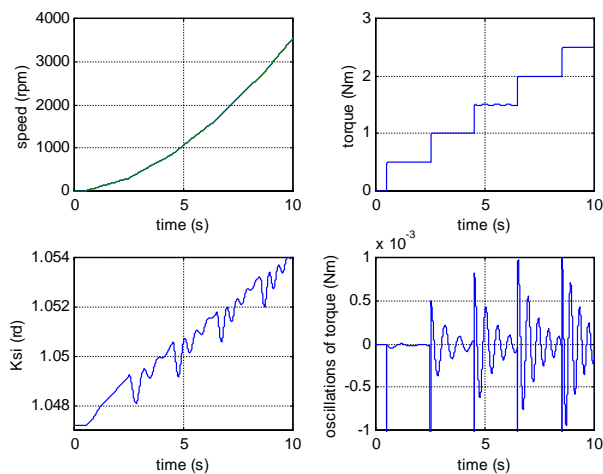


Figure 5: Simulation of a control in the abc reference frame

This phenomenon is very slow (because f is small), but the synchronism could drop for a long-term energy storage machine.

Before concluding this section, it should be noted that the control must be able to minimize I^2R and magnetic losses. This can be achieved with a particular value of ξ [8]. For example, if only the I^2R losses were considered, $\pi/2$ would be the optimal value, which is simply not possible. This type of control (in the abc reference frame) is thus inadequate. To eliminate these oscillations and variations of ξ , we would therefore prefer to work in the dq reference frame.

4. CONTROL IN AN "ESTIMATED dq" REFERENCE FRAME

This is a known sensor-free control set-up (with no mechanical sensor, see Fig. 7), in which the reference frame is changed to a position estimated by means of calculation. Let's initially consider a torque control and observe its behavior (see Figs. 8 and 9). In this particular case, the reference torque T_{em}^* directly provides the current references i_d^* and i_q^* which, by virtue of being slaved, establish an oscillation-free torque.

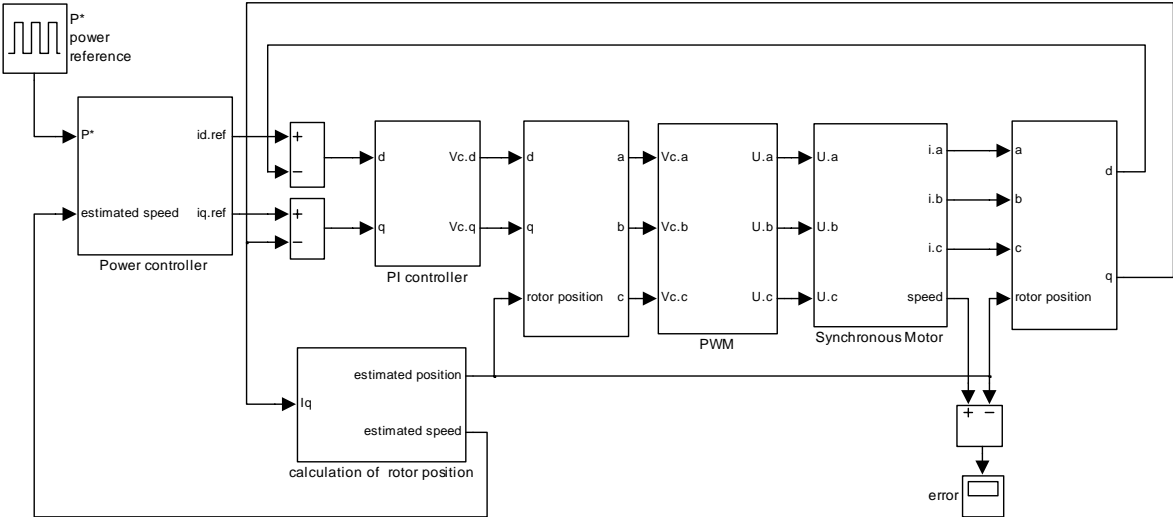


Figure 7: Control scheme in an estimated dq reference frame

By seeking to optimize only the I^2R losses, the i_d must be equal to 0 (constant air gap); therefore, for a given T_{em}^* in the dq reference frame, the following applies:

$$T_{em} = p(\Phi_d \cdot i_q) \tag{16}$$

$$\frac{d^2\theta}{dt^2} = \frac{p^2\Phi_d I_q}{J} - \frac{f}{J} \frac{d\theta}{dt} - \frac{pC_0}{J} \tag{17}$$

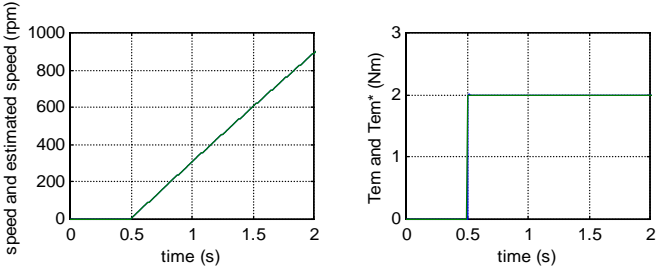


Figure 8: Simulation with an ideal model

From equation (17), the calculation of θ can be deduced. Only mechanical parameters are needed herein. Fig. 6 shows the block diagram used in the calculation of θ . Such an operation proves to be simple and suitable for a digital implementation.

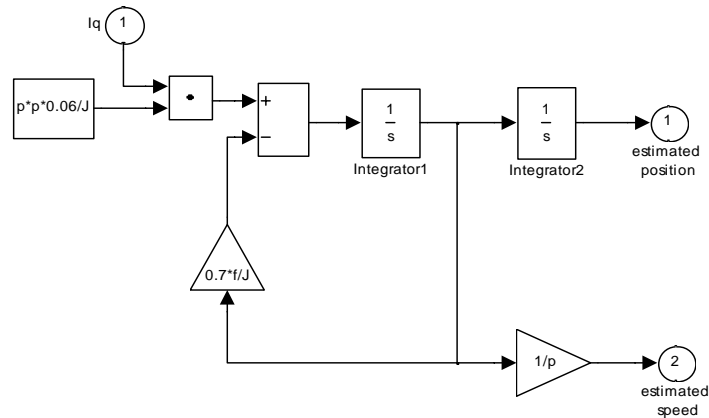


Figure 6: Simulation diagram used for computation of the rotor position

By evaluating the position on the basis of the measured current i_q , the dynamics of the current loop can be taken into consideration. The simulation performed according to Fig. 8, with precise knowledge of the parameters J and f (and thus zero error in the position evaluation), results in perfect self-control, although it turns out to be unfeasible because of imprecise identification, time uncertainty and other factors.

An analytical calculation using equation (17) reveals that an error introduced in evaluating these parameters generates a drift in the position evaluation; the rate of this drift is inversely related to the ratio J/f .

A simulation has been conducted (see Fig. 9) with an inaccurate value of f : $0.9*f$ (-10%) was chosen, with f being the actual value. Consequently, the actual dq frame slid with respect to the estimated dq frame and made the synchronous machine stall. This kind of control is obviously inadequate for our application, yet a computation has demonstrated that it can be adapted to flywheel systems with short-term energy storage (see fig.10).

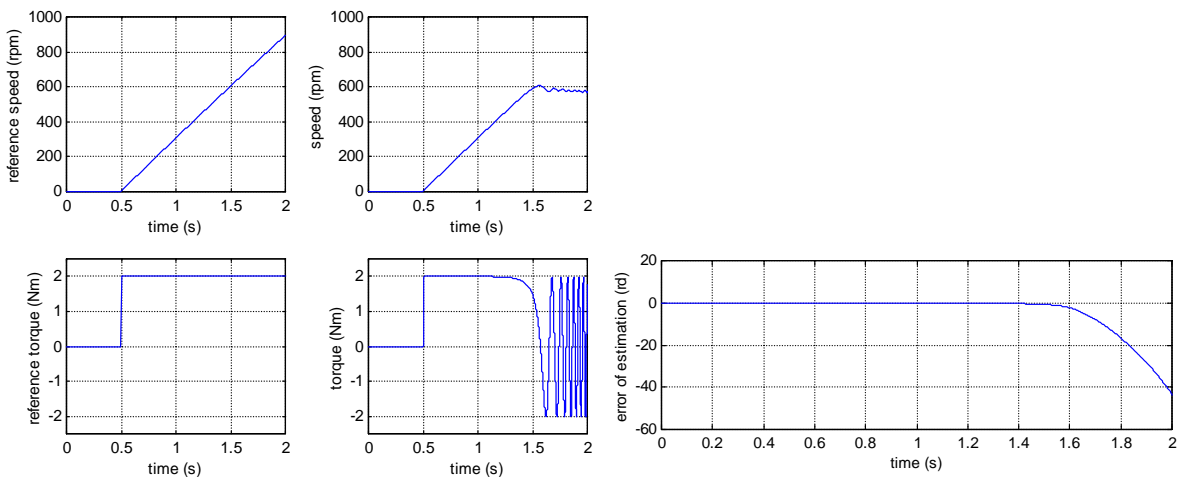


Figure 9: Simulation with an error of -10% on f value

The energy storage system studied in our laboratory required the following values:

- $P = 3000$ W (maximum power),
- $J = 5.5$ kg.m²,
- $f \approx 1 e^{-6}$ (typical value with a background pressure of $10e^{-4}$ mbar and with magnetic bearings [9]),
- $\Omega_b = 1000$ rd/s,

- $C_M = 3Nm$.

In practice, knowing the value of the ratio f/J with an accuracy margin of 30% only seems to be realistic. Even with a good identification of the ratio f/J , the vacuum system's behavior is actually capable of changing over time. For this reason, a margin of 30% must be incorporated. Figure 10 shows the error introduced in the calculation of θ with three different values of the ratio f/J and for a constant torque reference (C_M). For the purposes of our application, with a 30% error margin, the motor stalls after a few minutes. In spite of a correct value for the torque, minimizing losses therefore proves impossible because of inaccurate parameters.

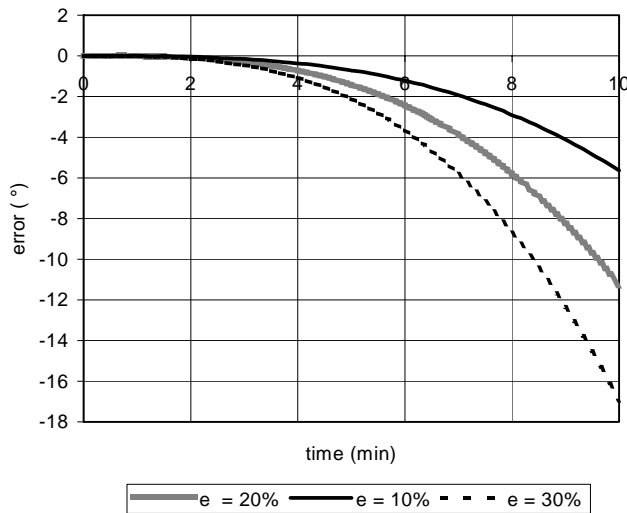


Figure 10: Estimated electrical error position

5. SINGLE-IMPULSE POSITIONING CONTROL

Many investigations have been reported in the literature on the sensor-free control of synchronous motors [2]-[6]. Most of these investigations have used algorithms which provide high-quality torque control for the required applications. While these solutions are all very efficient, they also turn out to be rather complicated. In the particular case of the flywheel accumulator, which is characterized by high speed and high inertia, a high dynamic performance is not necessary. Speed variations are in fact limited due to long-term energy storage. A single impulse per rotation sensor has therefore been chosen. This solution is suitable and easy to implement, especially for the new design under study herein. A solution using a single-pulse position sensor has been proposed in [7]. The position can then be extrapolated with good accuracy for high speed and small acceleration. According to [7], with one impulse, the angle error is given by:

$$\Delta\theta = p \left[2\pi - \frac{1}{2\gamma} \left(\sqrt{\Omega_0^2 - 4\pi\gamma} + \Omega_0 \right) \left(\sqrt{\Omega_0^2 + 4\pi\gamma} - \Omega_0 \right) \right] \quad (18)$$

Fig.11 shows the angle error in the case of our energy storage system. In the range speed between Ω_b and Ω_M , the error can be considered as negligible. A such control is then completely suitable for this application and will be finally implemented.

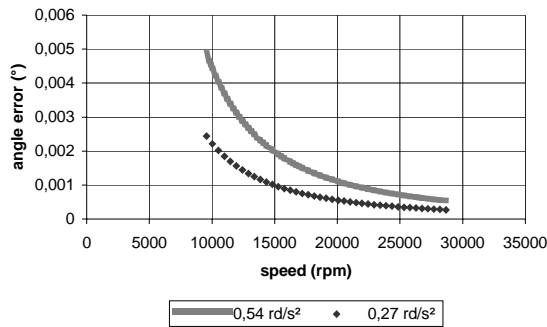


fig.11 angle error with two different accelerations

6. CONCLUSION

The control of a synchronous machine in an open-position loop shows that a drift is unavoidable in the angular difference between the stator and rotor fields. The effects of the machine's dampers (viscous friction and eddy-current losses) are highly inadequate to use this control in an abc reference frame. Moreover, operations at ξ values of less than $\pi/2$ prevent against energy optimization. Control in the dq reference frame therefore seems to be the most efficient solution as long as the values of the f and J parameters are sufficiently well known and the load cycles remain less than a few minutes. Beyond this cycle period, even though a large mechanical time constant helps slow the drift in the estimated position with respect to the actual position, the use of a simple device which provides one pulse per revolution is necessary and satisfactory.

APPENDIX

Test bench data:

| | | | |
|----------------------|------------|-------------------|----------------------|
| Moment of inertia | J | 0.031 | kg·m ² |
| Power | P | 1.5 | kW |
| Friction | f | 10e ⁻³ | m/rad.s ¹ |
| Base speed | Ω_b | 105 | rad.s ⁻¹ |
| Maximum speed | Ω_M | 315 | rad.s ⁻¹ |
| PM flux | Φ_f | 60 | mWbs |
| Number of pole pairs | p | 5 | |

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