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SPEED AND TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS

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Abstract: This paper present speed and torque control structures of a driving system with permanent magnet synchronous motor (PM-SM). After a brief synopsis of the most performant control methods of the PM-SM, a direct torque controlled (DTC) structure is described for the PM-SM, feded by a voltage source converter with optimal voltage switching control. Also a rotor field-oriented controlled (FOC) PM-SM driving system is presented. The simulated dynamic performances of both driving structures are analyzed and compared.

Key words: Direct torque control (DTC) and field oriented control (FOC) of PM-SM.

1. INTRODUCTION

The permanent magnet synchronous motor (PM-SM) finds a wide range of applications as variable speed drives. They recently are receiving increasing interest in low-power servo drives, like machine tools and industrial robots, but also in large-power industrial applications (up to 1 MW). The advantage of using a PM synchronous motor is given, comparatively to the DC motor, by the inexistance of brushes and comutators and because of their high efficiency (e.g. high power/weight and high torque/inertia ratio, smooth torque operation, high air-gap flux density). In AC variable speed drives the PM-SM has the advantage of good control performances (e.g. high torque controllability at low and zero speed, smooth torque operations, high-speed range). This paper will discuss and analyze the opportunities of different intelligent control structures for permanent magnet synchronous motor drives.

2 CONTROL STRATEGIES FOR A PM-SM DRIVING SYSTEM

For this type of synchronous machines, only one control quantity is available, namely the stator voltage (current), like results from the equations describing the PM-SM (see *appendix*). The user can impose and control for an application only one of the following performance criteria:

- *unity power factor* - by canceling the longitudinal armature reaction;
- *best energetic efficiency* - minimum active stator current for a load torque value;
- *magnetic optimal working point* - by imposing and controlling the stator flux.

For high-performant applications with PM-SM, two control methods are now widely accepted, namely the vector-controlled driving system and the direct torque controlled drives [1], [2], [4]. Both, vector controlled and direct torque controlled drives with PM-SM must be fed by variable frequency converters. Most used are the DC link (indirect) frequency converters with current source or voltage source inverters [3], [10]. Recently, applications with PM-SM fed by direct AC-AC matrix converters are also developed [11]. In direct torque control of PM-SM, mostly VSI based converter are used, because it normally uses an optimal voltage switching vector selection to control the drive [6].

2.1. Vector control of PM-SM

The main purpose of the vector control method is to decouple the control of the torque producing and flux producing components of the stator current. The current components are regulated by two independent controllers. So speed (position) or different fluxes can be directly controlled. The advantage consists in good dynamic behavior concerning the speed (position) of the driving system, but generally requires higher calculation abilities (powerful digital signal processors). According to the positions of the stator flux vector, stator voltage vector and the rotor of the PM-SM four field-orientation principle based control strategies are presented [1], [5]:

a) control method with *cancelled longitudinal armature reaction* by rotor orientation. The orientation is made after the PM flux. The motor will work at high energetic efficiency, having a minimum stator current phasor for an imposed load torque, unless the motor works in saturation. It is recommended to be used for low-power motors or for permanent magnet motors with salient poles and great transversal air-gap, feded by converters where the low power factor is compensated.
b) control method with *constant (imposed) stator flux;* orientation is made after the stator flux and its modulus is imposed to be constant. On the rotor-longitudinal axis it will be a demagnetizing component. This control method has to be used in applications with high power motors working at the optimal point on the magnetizing curve, feded by converters where the non-unitary power factor is compensated.
c) control method with *unity power factor*, by canceling the longitudinal reaction oriented after the stator-flux. The value of the stator flux can not be controlled and the motor works under the optimal magnetic value. If the longitudinal inductance is little, the motor works efficiently also at greater torque values. It is recommended to be used in applications where the power factor value can not be compensated.
d) by imposing the *stator voltage phasor perpendicular on the exciting flux*. The orientation is made after the rotor (exciting-flux/PM-flux). This method can be used in applications with demagnetized motors or at low-power motors with salient poles and great transversal inductance.

2.2. Direct torque control of PM-SM

This control method for AC drives was developed in the middle of the 80s, introducing the concept of flux linkage control [6], [7]. First industrial application is realized in 1995 by ABB Industry Oy in Finland [8]. The direct torque control (DTC) of a synchronous motor involves the direct and independent control of the flux linkage and electromagnetic torque, by applying optimum current or voltage switching vectors to the converter, like presented in figure 1. In classical DTC drive [9], hysteresis comparators are used for the motor flux and electromagnetic torque values. In each sampling period the optimal voltage vector is applied to the motor, according to the torque and flux errors from the comparators and to the position of the flux vector. So, fast torque response and low harmonic losses (low switching frequency) are obtained.

Usually the stator flux linkage is used for the control but also the rotor or the magnetizing flux linkages can be used. In the case of stator flux linkage, it can be estimated by the voltage model. At low speeds, to overcome the fails of the voltage model, the rotor differential equations can be used. Other solutions are to use flux observers with on-line parameter estimators or predictive switching-voltage vector estimation. It is not necessary to determine the actual flux-linkage vector position, but only the sector where the flux linkage is located. In the case of current source inverter fed motor, the optimum current switching vector has to be selected.

We can conclude that in the case of DTC the flux and torque are directly controlled, while stator currents and voltages are indirectly controlled. The stator flux and currents are approximately sinusoidal, so reduced torque oscillations occur. The inverter switching frequency depends on the flux and torque hysteresis bands. Advantages of this direct torque control method of PM-SM consist on:

- the absence of coordinate transformation which permit a shorter computational time (useful in applications with not so performant digital signal processors);
- very good torque dynamics (even for high power driving systems) and reduced torque oscillations;
- high torque control linearity, even by low frequencies and zero speed.

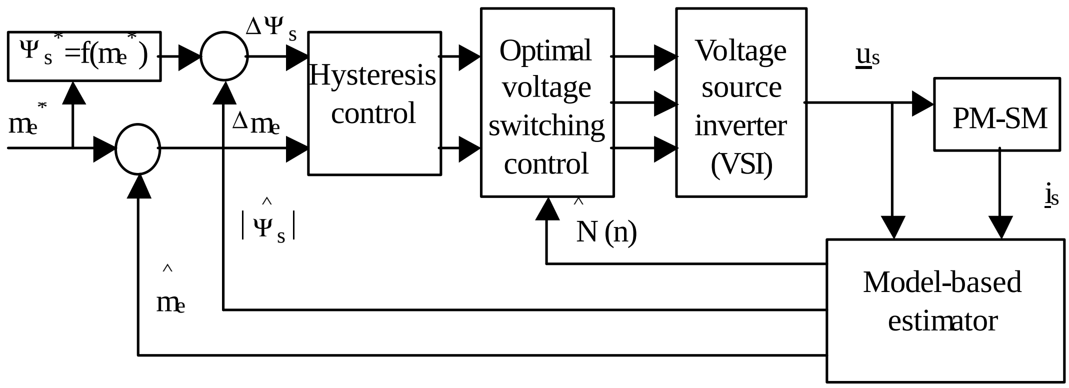

Fig.1. Direct torque control of PM-SM fed by VSI, using a model based estimator.

3. SIMULATED RESULTS

This paper will present simulated results for a direct torque control (DTC) structure of the PM-SM using a model-based estimator (like in figure 1) and for a speed control system of a rotor-field-oriented (vector-controlled) PM-SM. Both driving systems are fed by a IGBT two-level voltage source inverter. So 8 different switching configurations can be composed to describe the possible stator voltage vectors, namely the six active switching vectors ($\underline{u}_1$ to $\underline{u}_6$) and the two zero voltage vectors $\underline{u}_7$=[111] and $\underline{u}_8$=[000] presented in figure 2. The simulated results, realized in Matlab-Simulink 6 [13], and presented in this paper are for a PM-SM motor (type ES42 from Stoeber Antriebstechnik GmbH) with the following parameters:

- rated power	P_N	530 W;
- rated torque	M_N	1,6 Nm;
- PM flux	Ψ_{PM}	0,233 Wb;
- rated stator current	I_{sN}	1,7 A.

3.1. Torque control

The electromagnetic torque and the stator flux linkage are controlled directly by applying optimum switching vectors of the inverter. Each of the six active voltage switching vectors is in the middle of a 60 degrees sector (figure 2) covered each one by the angles N(1) to N(6) respectively. The goal is to select those voltage switching vectors which yields the fastest torque response. The electromagnetic torque comparator is a three-level comparator with double hysteresis while the stator flux-linkage is a two-level one. The two outputs of the hysteresis control unit and the position of the stator flux are inputs to the optimal voltage switching control block, presented in table I. The one or other of the two zero vectors ($\underline{u}_7$ and $\underline{u}_8$) are chosen in that way to have a minimum numbers of switches which has to be changed to reach the zero vectors.

Table I Switching table for the stator voltage vectors.

Controller output		Sector number N(n)					
DΨ	Dm	I	II	III	IV	V	VI
1	1	$\underline{u}_2$	$\underline{u}_3$	$\underline{u}_4$	$\underline{u}_5$	$\underline{u}_6$	$\underline{u}_1$
	0	$\underline{u}_7$	$\underline{u}_8$	$\underline{u}_7$	$\underline{u}_8$	$\underline{u}_7$	$\underline{u}_8$
	-1	$\underline{u}_6$	$\underline{u}_1$	$\underline{u}_2$	$\underline{u}_3$	$\underline{u}_4$	$\underline{u}_5$
-1	1	$\underline{u}_3$	$\underline{u}_4$	$\underline{u}_5$	$\underline{u}_6$	$\underline{u}_1$	$\underline{u}_2$
	0	$\underline{u}_8$	$\underline{u}_7$	$\underline{u}_8$	$\underline{u}_7$	$\underline{u}_8$	$\underline{u}_7$
	-1	$\underline{u}_5$	$\underline{u}_6$	$\underline{u}_1$	$\underline{u}_2$	$\underline{u}_3$	$\underline{u}_4$

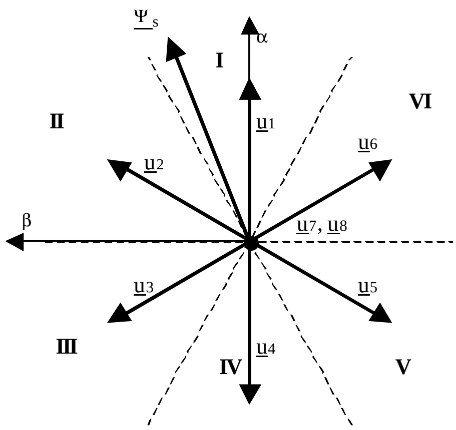

Fig.2. The voltage space vectors.

The stator-flux linkage and the electromagnetic torque estimations are realized by the model-based estimator presented in figure 1. It is based on the small position perturbation algorithm and current model estimator [12]. The estimation procedure consists of computing the stator flux-linkage space vector from the imposed stator voltages and measured stator currents in stator reference frame:

$$\hat{\underline{\Psi}}_s = \int (\underline{u}_s - R_s \underline{i}_s)dt \qquad (1)$$

The electromagnetic torque response simulation in figure 3 shows the fast dynamic

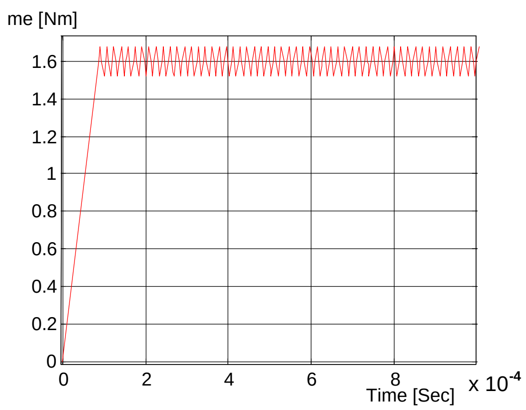

Fig. 3. Electromagnetic torque response.

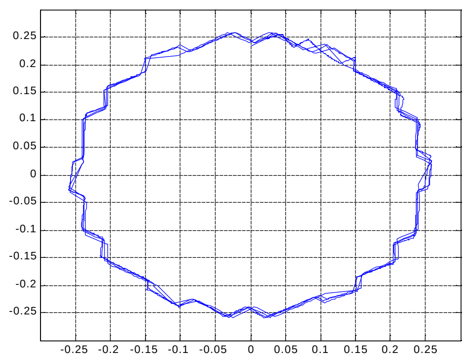

Fig. 4. Stator flux-linkage space phasor.

performance of the DTC method. The flux-linkage control can be analyzed in the space phasor diagram of figure 4.

3.2. Speed control

The most simple vector control principle recommended to be applied to synchronous machines with constant exciting field is achieved by the permanent canceling of the longitudinal armature reaction. That means the direct component of the stator-current space phasor is zero. Consequently, the control methods developed for the dc machines can be here applied. The stator current vector split into components leads to the characteristic loops of a field-oriented control system, namely: speed control loop, implemented with a robust controller; minor loop, necessary for the field-orientation based on the rotor position; stator current control loop of the PWM generator [1].

The speed controller was designed and simulated using more optimizations criteria. So we obtained a PI controller and robust controllers (H_2 and H_{00}). The H_{00} controller was implemented because of the best dynamically behavior and very good perturbations rejection (load, inertia moment). Figure 5 presents the speed response for three different controllers, figure 6 the electromagnetic and load torques for the same motor.

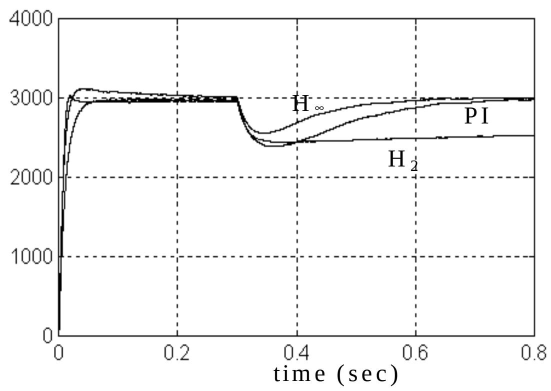

Fig. 5. Speed response for speed and torque steps.

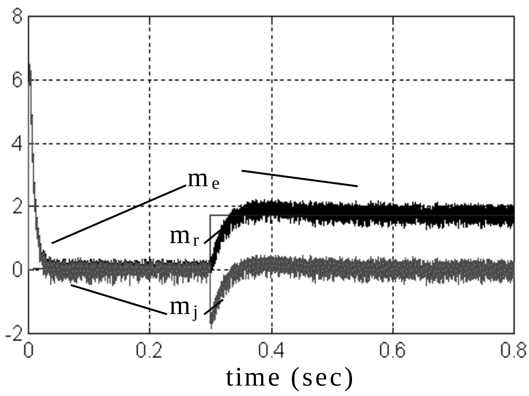

Fig. 6. Torque response for speed and torque steps.

4. CONCLUSIONS

Using the direct torque control (DTC) of the PM-SM the fastest possible torque response is achieved. Since the determination of the stator-flux linkage is mainly based on the voltage integration it is possible to keep the drive stable even when the parameters of the drive are not accurate. Stator flux and torque are directly controlled while stator currents and voltages are indirectly controlled. The inverter switching frequency depends on the flux and torque hysteresis bands. The absence of coordinate transformations gives shorter computational time for the control algorithm and allows short sampling times. The simulated results presented in this paper demonstrate the good dynamic performances of the proposed direct torque control driving system with permanent magnet synchronous machine.

Using the field-orientd control (FOC) of the PM-SM, high precision of speed tracking control is achieved by using robust speed control methods. The best control performances have been obtained using H_{00} robust controllers. A disadvantage is the necessity of a fine computation of the weighting functions. The simulated results presented in this paper demonstrate the performances of the control strategies, with applications in drive systems with nonlinearities and high accuracy.

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Appendix. General equations (including dynamic operations) of the PM-SM (in the $d\theta$-$q\theta$ rotor oriented synchronously rotating frame):

$$u_{sd\theta} = R_s i_{sd\theta} + L_{sd}\frac{\mathrm{d}i_{sd\theta}}{\mathrm{d}t} - \omega_r L_{sq} i_{sq\theta} \quad (2)$$

$$u_{sq\theta} = R_s i_{sq\theta} + L_{sq}\frac{\mathrm{d}i_{sq\theta}}{\mathrm{d}t} + \omega_r (L_{sd} i_{sd\theta} + \Psi_M) \quad (3)$$

$$\omega_r = \frac{\mathrm{d}\theta}{\mathrm{d}t} \quad (4)$$

$$m_e = \frac{3}{2} z_p \left[\Psi_M i_{sq\theta} + (L_{sd} - L_{sq}) i_{sd\theta} i_{sq\theta}\right] \quad (5)$$

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