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TORQUE CONTROL OF AN ELECTRICAL DRIVE SYSTEM WITH PERMANENT MAGNET SYNCHRONOUS MACHINE

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Abstract. *This paper presents a direct torque controlled (DTC) structure for the stator-flux oriented driving system with permanent magnet synchronous motor (PM-SM) fed by a voltage source converter with optimal voltage switching control. The dynamic performances of the driving system can be analyzed in the simulated results presented at the end of this paper.*

Keywords: *Direct torque control; Permanent magnet synchronous machine.*

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 inexistence of brushes and commutations 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).

Direct torque control of a PM-SM driving system

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 [1-4]. The DTC 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], [10], hysteresis comparators are used for the motor flux and electromagnetic torque values. In each sampling period the optimal voltage vector (or current vector) is applied to the motor, according to the torque and flux errors from the comparators and according to the position of the flux vector. So, fast torque response and low harmonic losses (low switching frequency) are obtained.

This paper will present simulated results for a direct torque control (DTC) structure of the PM-SM fed by a voltage source inverter (VSI), using a model-based estimator, like in figure 1. The electromagnetic torque and the stator flux linkage are controlled directly by applying optimum switching vectors to the inverter, a IGBT two-level voltage source inverter.

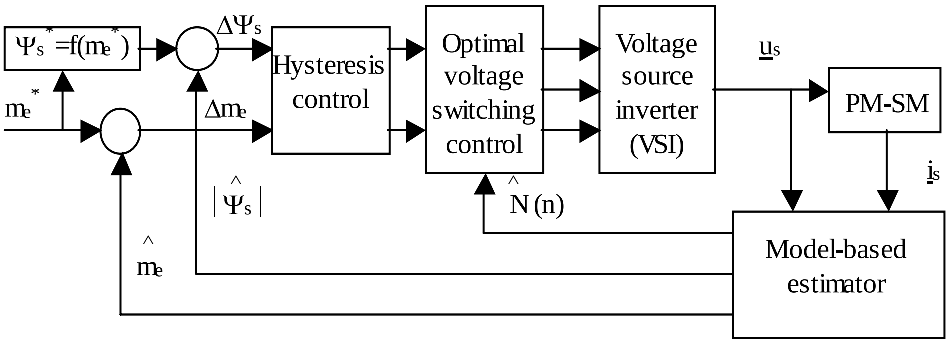

Fig.1. Direct torque control of a driving system with permanent-magnet synchronous servomotor fed by a voltage source inverter, using a model based estimator.

The output terminals of the stator phases are connected either to the positive or the negative rail of the DC link ($+U_d/2$ or $-U_d/2$) by the semiconductors, which can be replaced with three bipolar switches. So, 8 = 2^3 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], like presented in figure 2. The goal is to select those voltage-switching vectors that yield the fastest torque response.

The electromagnetic torque error and the stator flux-linkage error are inputs to the hysteresis comparators of the hysteresis control block, presented in figure 3. 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 (actually not the exact angle, only the 60 degree sector in which the stator flux is) are inputs to the optimal voltage switching control block.

The two zero voltage vectors are imposed by the intermediate (zero) value of the three-level torque comparator. The one or other of the two zero vectors ($\underline{u}_7$[111] and $\underline{u}_8$[000]) are chosen in that way to have a minimum numbers of switches which has to be changed to reach the zero vectors. The stator-flux linkage and the electromagnetic torque are estimated by the model-based estimator presented in figure 1. It is based on the small position perturbation algorithm and current model estimator [14], equations (1)-(6), and gives also the sector number, described by N(n), in which the stator-flux vector is. It is a robust estimation method, based on the fact that only the average of the stator-flux phasor has to be estimated with accuracy, while his position has to be determined only as one of the six sectors.

The first estimation procedure consists of computing the stator flux-linkage space vector from the imposed stator voltages and measured stator currents in stator reference frame (with $\hat{\Psi}$, $\hat{i}$ and $\hat{\theta}$ estimated values and Δ as small perturbation):

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

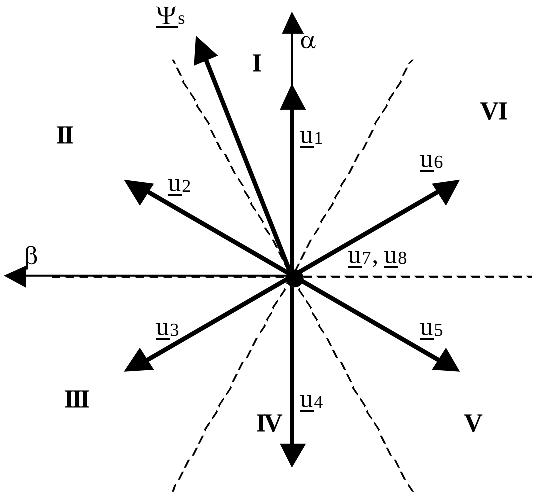

Fig.2. The voltage space vectors and the 6

possible sectors.

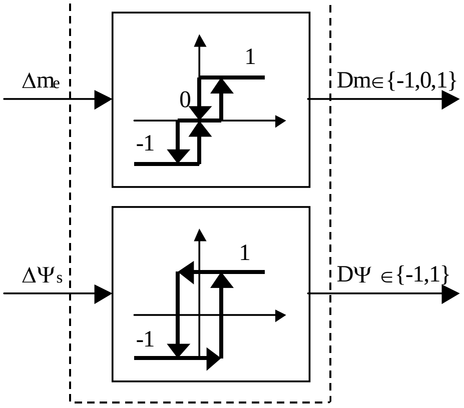

Fig. 3. Electromagnetic torque and stator-flux phasor hysteresis control block.

The estimated currents depends, according to the machine model, on the estimated flux-linkage:

$$\hat{\underline{i}}_s = \frac{1}{L_s}\left(\hat{\underline{\Psi}}_s - \underline{\Psi}_M e^{j\hat{\theta}}\right), \tag{2}$$

obtained by integrating the voltage equation (1). At low speeds, the rotor differential equations are used to avoid the integrating errors. Consider the errors, which appear between the measured stator currents of the PM-SM and the estimated one:

$$\Delta\underline{i} = \underline{i} - \hat{\underline{i}} \tag{3}$$

or in the rotating reference frame ($d\theta$- $q\theta$)

$$\Delta\underline{i}_\theta = \left(\underline{i} - \hat{\underline{i}}\right)e^{-j\theta}. \tag{4}$$

Assuming that it is a small difference (position perturbation) between the real rotor position and the estimated one, this perturbation can be described as a function of the stator current error:

$$\Delta\hat{\theta} = -L\frac{1}{\Psi_M}\Delta i_{q\theta}. \tag{5}$$

Next step is to transform the position perturbation (which can be considered for small time values as a derivative of a position) into the estimated position:

$$\hat{\theta} = \int \Delta\hat{\theta}\,\mathrm{d}t \tag{6}$$

To avoid the integrating inaccuracies given by equation (6), a PI controller and a low-pass filter can be used instead of relations (5)-(6). We have used in our simulation both computing methods combined by a weighting function. The sector number N(n) of the estimated stator-flux linkage vector can be deduced considering equation (1) depict on the two reference axes. To estimate the rotor position with this procedure, only the stator current has to be measured. The voltage can be calculated using the DC voltage and the PWM instantaneous configuration. This estimation method requires only one machine parameter, namely the stator resistance. It can be considered as a proof of the robustness of the estimating procedure.

Simulated results

The results presented in this paper are for a direct torque control drive system (figure 1) with permanent magnet synchronous machine (type ES42 from Stoeber Antriebstechnik GmbH) and using a model based estimator for electromagnetic torque, stator flux-linkage and rotor position. The main PM-SM parameters are: 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. The simulations are computed with help of Matlab-Simulink software tools [15]. The Simulink structure of the direct torque control drive system with PM-SM is presented in figure 4, describing the main blocks of the control diagram.

At speeds over the rated value we have to pass in the flux-weakening region. Normally the imposed stator-flux value is computed depending on the speed reference. Because speed is indirectly controlled in the DTC method, we chose to compute the imposed stator flux in the weakening region as a function of the torque reference $\Psi_s^* = f\,(m_e^*)$, like presented in figure 1.

The electromagnetic torque response simulation in figure 5 shows the fast dynamic performance of the DTC method. The stator phase voltage is indirectly controlled (like the stator current) and is presented in figure 6. Figure 7 presents the estimated values of the stator current components in fixed reference frame, computed in the model-based estimator, described by equations (1)-(2) and the evolution of the stator current phasor is presented in figure 8. The flux-linkage control can be analyzed in the space phasor diagram of figure 10. The amplitude variations of both torque and flux are controlled through the hysteresis bands, like in figures 5 and 9.

The simulations we made indicate some inaccuracies obtained at low speed (low frequency) and during passing through zero (when a torque reverse is imposed). The problems occur because of the values computed by the model-based estimator. Even by using the rotor differential equations to avoid the integrating errors of equation (1) in estimating the stator flux, or by using a low-pass filter for equation (6) to estimate the position θ, the inaccuracies could not be eliminated. In applications where high dynamic performances are needed in the area of low speeds the solution we consider is to use more complex stator-flux and position estimators.

Conclusions

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. Using the direct torque control 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. An advantage is the very good torque dynamics (even for high power driving systems) and reduced torque oscillations. The absence of coordinate transformations (which are typically for vector control structures) and the reduce number of controllers gives shorter computational time for the control algorithm and allows short sampling times.

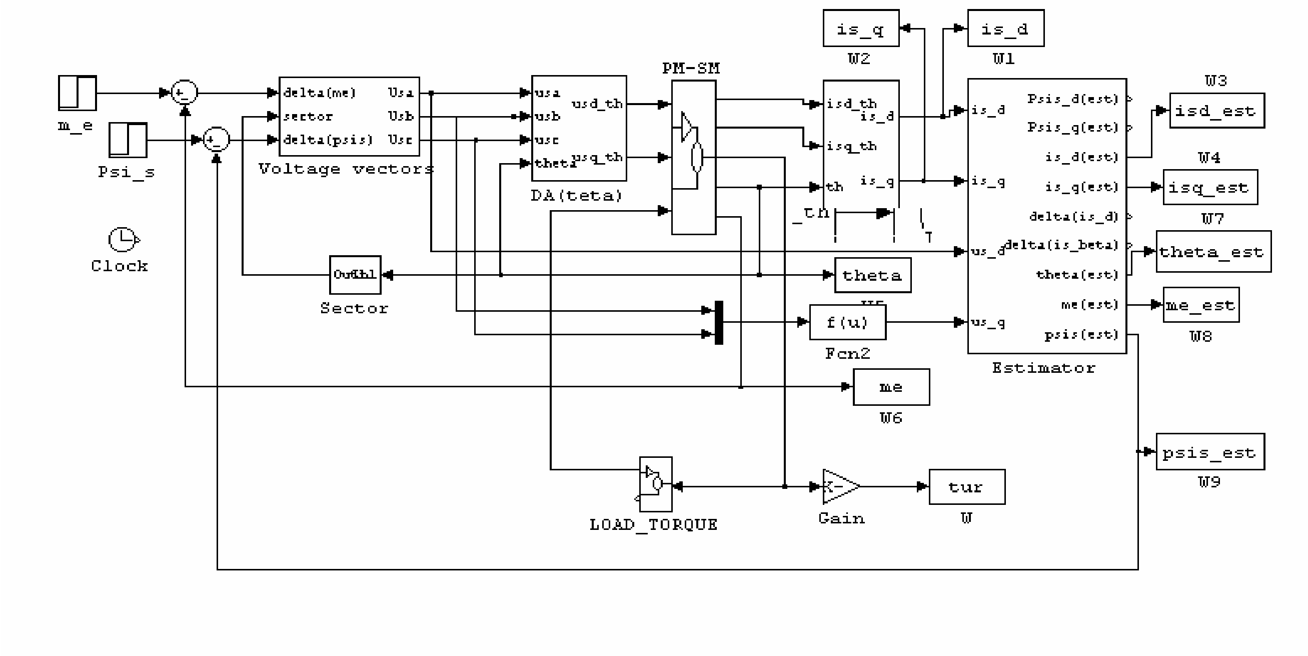

Fig. 4. The Simulink structure of the direct torque control drive system with PM-SM.

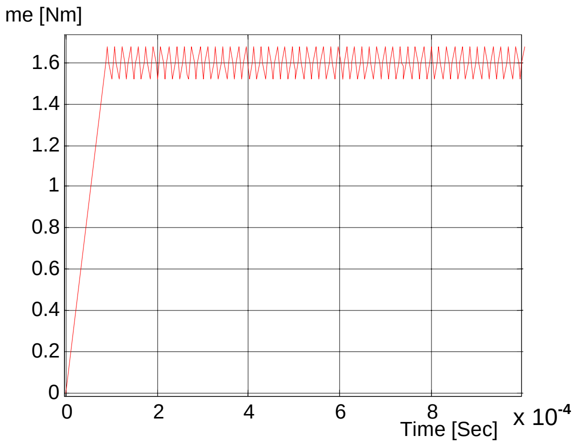

Fig. 5. Electromagnetic torque response for rated torque step.

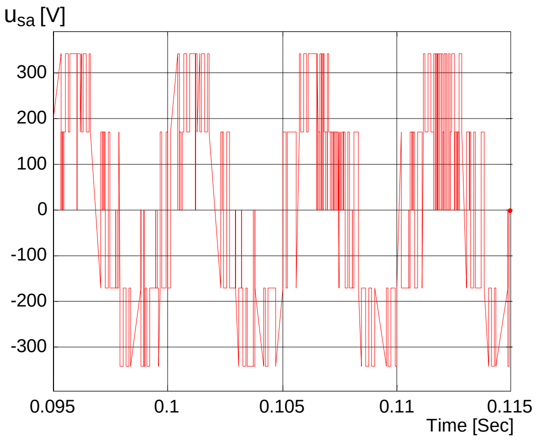

Fig. 6. Stator phase voltage in the DTC control structure.

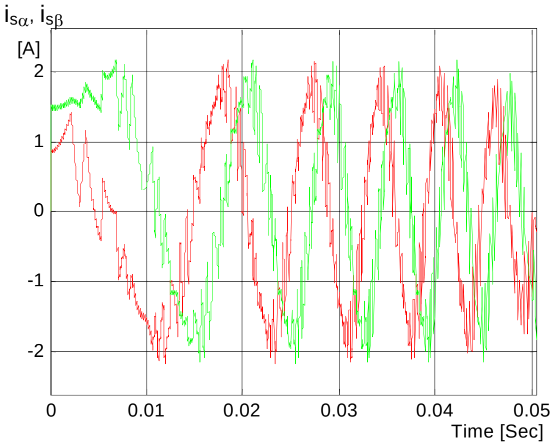

Fig. 7. Stator current components in the fixed reference frame.

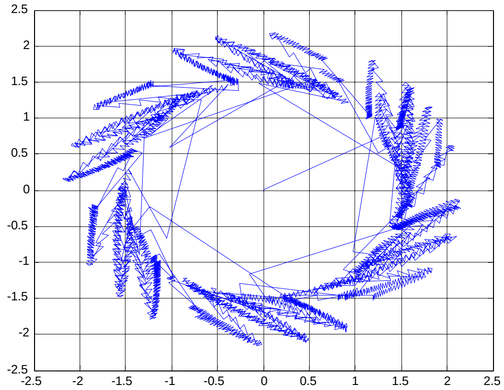

Fig. 8. Stator current space phasor in DTC control of PM-SM.

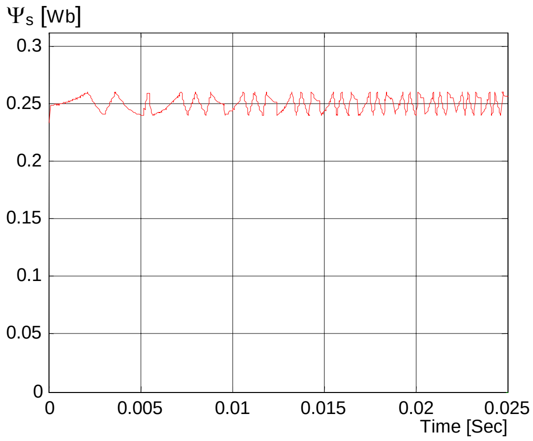

Fig. 9. Amplitude variations of stator flux controlled through the hysteresis bands.

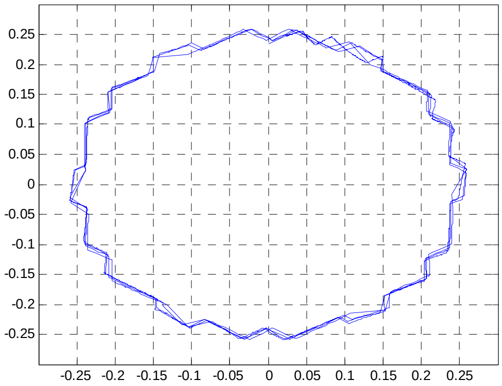

Fig. 10. Stator flux-linkage space phasor in DTC control of PM-SM.

The main disadvantages of the proposed DTC structure are the computing errors at starting and driving with low speed or at torque reversals during zero passing. To avoid this, complex estimators have to be used. Other disadvantages are the variable commutation frequency and the necessary compromise between low torque ripples versus lower losses. We proposed a simple and robust direct torque control driving system with permanent magnet synchronous machine.

The simulated results presented in this paper demonstrate the good dynamic performances, excepting the range of low speeds. The next steps of our research is to improve the performances at low speeds, without using complex estimators and to implement this DTC driving system on a computer system based on digital signal processor (DSP).

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