Abstract—Direct torque control (DTC) can be applied to all AC machine drives. The synchronous machine torque control, based on the DTC structure, permits to obtained high dynamic performances. This method is a concrete solution to robustness and dynamics problems find in other control structures. In this paper, we present a direct torque control strategy with minimization torque pulsations. We use a current sensor and an incremental position sensor. In order to control the torque, we use an hysteresis current controllers technique. This strategy consists on detecting the current at the voltage inverter input, and adjusted it to follow a reference with a high commutation frequency. The undesirable low harmonics are directly eliminated by the proposed position sensor. The obtained results are presented.

Index Terms—Direct torque control strategy, Permanent Magnet Synchronous machine, position sensor, minimization torque pulsations.

I. INTRODUCTION

Recently, much research effort has been accomplished on P.W.M-V.S.I supplied A.C. machines in order to obtained high dynamic performances [1]-[5]. In classical P.W.M. methods, the harmonics are eliminated from the inverter output voltage waveforms and this requires a microprocessor-based system for P.W.M control implementation.

In this paper, we present a direct control strategy with minimization torque pulsations. We use a single current sensor and an incremental position sensor [6]. In order to control the torque, we use the hysteresis current controllers technique. This strategy consists to detect the current at the voltage inverter output, and to impose it to follow a current reference with a high fixed commutation frequency. The undesirable harmonics elimination is realized directly through the obtained output signal of the position sensor which is in turn used as the control signal. The corresponding inverter control circuit is then very simple and there is no need for microprocessor nor for any specialized integrated circuits for P.W.M. control implementation [6], [7]. The obtained simulation results are compared to the practical ones, in the case of a permanent magnet synchronous machine (PMSM).

For comparison with classic control torque strategy, we choose to study the direct torque control (DTC) method which enables the minimum torque ripple control [5], [8]. This strategy is a solution for vector control problems and achieves robust and fast torque response without the need of speed or position sensor, coordinate transformation, PWM pulse generation and current regulators [5], [8], [9]. The basic principle of DTC is to select directly stator voltage vectors according to differences between the references of torque and stator flux linkage and their actual values, the parameters of the motor are not used in DTC systems, except the stator resistance. Simulation results are presented.

II. SYSTEM DESCRIPTION

Fig. 1. shows the overall system. It comprises a permanent magnet synchronous machine supplied from a voltage source inverter. The machine is controlled by using a position sensor fixed to the rotor shaft and allows for supply frequency setting to the value of the rotor frequency.

III. MODELLING OF THE OVERALL SYSTEM

The synchronous motor is modeled using voltage and flux equations in the (d,q) frame.

\[
\begin{align*}
V_d &= R_i i_d + \frac{d \phi_d}{dt} - \omega \phi_q \\
V_q &= R_i i_q + \frac{d \phi_q}{dt} + \omega \phi_d + \omega \phi_f
\end{align*}
\]

Where

\[
\begin{align*}
\phi_d &= L_d i_d + \phi_f \\
\phi_q &= L_q i_q
\end{align*}
\]
With \( R_s \) is the armature winding, \( L_d \) and \( L_q \) are \( d \) and \( q \) axial inductance, \( \Phi_f \) is the magnet flux, \( \omega \) is the angular velocity of rotor.

The mechanical equation is

\[
T_e - T_L = \left( \frac{J}{p} \right) \frac{d\omega}{dt} + \left( \frac{f}{p} \right) \omega
\]

(3)

With

\[
T_e = p(\Phi_d i_q - \Phi_q i_d) = p[\Phi_d i_q + (L_d - L_q)i_d i_d]
\]

(4)

Where \( f \) is the damping torque coefficient, \( J \) is the moment of the rotor inertia, \( T_L \) is the load torque and \( p \) is the number of pole pairs.

III. DIRECT TORQUE CONTROL STRATEGY WITH MINIMIZATION TORQUE PULSATIONS

A. Minimization Torque Pulsations

We use a position sensor (Fig. 2.), for elimination of undesirable harmonics and hence electromagnetic torque ripple minimization. The elimination is obtained directly through the obtained output signal of the position sensor [7]. The resulting inverter control circuit is very simple. The signal derived from the sensor is modulated so that harmonics influencing the machine performances are eliminated.

![Fig. 2. Position sensor for harmonics elimination.](image)

The practical results obtained without (Fig. 3.) and with harmonic elimination (Fig. 4.) are represented.

![Fig. 3 (a,b,c). Practical results without harmonic elimination.](image)

![Fig. 4 (a,b,c). Practical results with harmonic elimination.](image)

B. Torque Control Strategy With Minimization Torque Pulsations

In order to control the torque, we control the current machine by using the hysteresis current controllers technique. This strategy consists on detecting the current at the voltage inverter input, and to adjusted it to a reference with a high commutation frequency. The undesirable low harmonics are directly eliminated by the proposed position sensor. To measure the current machine, we use a method using a single current sensor which consist on isolating the anode of the low diodes from the low transistor emitters. This allows us to measure the machine current during the commutation (Fig. 5.) [6].
The current machine constitutes the only parameter of control. The practical results for the direct torque control strategy with harmonics elimination method are represented in Fig. 8(a,b,c,d).

Fig. 5. Machine current measurement principle.

Fig. 6. Electromagnetic torque (a) and current machine (b). Simulation results obtained are represented in Fig. 7 (a,b,c,d).

Fig. 7 (a,b,c,d). Simulation results in the case of direct torque control strategy with harmonics elimination method.

Fig. 8 (a,b,c,d) Practical results in the case of direct torque control strategy with harmonics elimination method.
IV. CLASSICAL DIRECT TORQUE CONTROL STRATEGY

A. System Description

The block diagram of the proposed DTC is shown in Fig. 9. The position sensor is not needed, except for the initial rotor position. Stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configurations. Basically, DTC schemes require the estimation of stator flux and torque.

B. Stator Flux Estimation

The stator flux can be evaluated by integrating from the stator voltage equation (5)

$$\frac{d\phi_s}{dt} = V_s - R_s i_s$$

(5)

Thus

$$\phi_s(t) = \int (V_s - R_s i_s) dt + \phi_s(0)$$

(6)

Assuming that the voltage drop is small ($V_s \gg R_s i_s$), we obtain

$$\phi_s(t) = V_s . T + \phi_s(0)$$

(7)

With $\phi_s(0)$ is the stator flux initial value at the switching time, $T$ is the period in which the voltage vector is applied to stator windings.

The stator voltage vector ($V_s$) is selected using Table I. [5], [8], where signs of torque ($C_T$) and flux error ($C_\phi$) are determined with a zero hysteresis band [6]. The definition of flux sector and the inverter voltage vectors are shown in Fig. 10, where the stator flux vector is rotating with a speed of $\omega$.

C. Torque Control

The two important torques in synchronous machines are the synchronous torque and the reluctance one. We suppose that the rotor angular speed and the stator flux amplitude are constant, and we apply an adequate voltage vector during a time interval $T$ smaller than the machine constant time, then equations (8) and (9) show respectively that synchronous and reluctance torque variations are controlled from the rotation speed of the vector stator flux.

$$\Delta C_{\phi s} = \left[ \frac{p}{L_s} \phi_{s,0} \phi_{s,0} \cos \delta_0 \right] \Delta \delta$$

(8)

$$\Delta C_{rel} = \left[ p \left( \frac{1}{L_s} - \frac{1}{L_d} \right) \phi_{s,0} \cos 2\delta_0 \right] \Delta \delta$$

(9)

Where $\phi_{s,0}$, $\phi_{r,0}$ are initial stator and rotor flux, $\delta_0$ the initial angle initial between the stator flux vector and the rotor axis, $\Delta \delta$ the angle $\delta$ variation.
D. Proposed DTC structure

The stator flux linkage is calculated from voltage and current models of synchronous motor

\[ \phi_a(t) = \int_0^t (V_a - R_i_a)dt + \phi_a(0) \]  
\[ \phi_b(t) = \int_0^t (V_b - R_i_b)dt + \phi_b(0) \]  

where

\[ I_a = \frac{3}{2} I_s \]
\[ I_b = \frac{1}{2} (I_s - I_i) \]

\[ V_a = \frac{2}{3} U_e (S_{s} - \frac{1}{2} (S_b + S_i)) \]
\[ V_b = \frac{1}{2} U_e (S_b - S_i) \]

The electromagnetic couple can be written as:

\[ T_e = p (\phi_a I_s - \phi_b I_i) \]  

The initial position is obtained from a position sensor fixed to the rotor shaft. An optic position sensor is proposed in Fig. 11.

![Fig. 11. Position sensor description](image)

The position sensor modeling is based on the decomposition of the disk, fixed to the rotor shaft, into six sectors (a sector is about 60°), (Fig. 12.).

![Fig. 12. Position sensor modeling](image)

We have

\[ \text{compt} = \text{integer part} \left( \frac{\theta_i}{60} \right) + 1 \]  

There will be change of sector if the following condition is verified

\[ (\theta_1 \cdot \theta_2) < 0 \]  

And then:

\[ \text{compt} = \text{compt} + 1 \]  

Simulation results obtained are represented in Fig. 13 (a,b,c,d).

![Fig 13. Simulation results with classical DTC Strategy](image)

APPENDIX

List of motor specification and parameters
110 V, 3Φ, 0.75 kW, 2 poles, 3000 rpm.

Motor Parameters
\[ R_s = 6.05 \Omega \]
\[ L_d = 0.668 \text{ H} \]
\[ L_q = 0.359 \text{ H} \]
\[ J = 0.1 \text{ kg-m}^2 \]
\[ F = 0.01 \text{ N-m/rad/s} \]
\[ \Phi_f = 1.5 \text{ Wb} \]

CONCLUSION

The direct control torque with minimization torque pulsations method was developed in this paper. The loop current using a single current sensor allow to obtained a direct control torque with good dynamics performances and the undesirable low harmonics are directly eliminated by proposed position sensor control output signal. In conclusion, this method is very simple and these results prove the perform of this system.
REFERENCES


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