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A New Direct Torque Control Method for Switched Reluctance Motor Drives Compared with Vector Control

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Abstract: In this study, Direct Torque Control (DTC) and vector control of Switched Reluctance Motor (SRM) drives are proposed. In DTC scheme, current controllers followed by Pulse Width Modulation (PWM) or hysteresis comparators and coordinate transformations are not used. A position sensor is used at starting, to know the approximate rotor position. This study proposes a comparison between DTC and vector control of SRM. The simulation results prove the feasibility of the proposed direct torque control as compared with vector control.

Key words: Direct torque control, vector control, switched reluctance motor drives, position sensor

INTRODUCTION

Switched Reluctance Motor (SRM) drives have the attractive features of fault tolerance and the absence of magnets. It is one of the first invented machines, but the applications have been limited due to the lack of control electronics and fast switching power devices (Reinert and Schrder, 2002; Inderka *et al*., 2002). The main advantages of the switched reluctance motor drives are simple construction, low-inertia, high-speed performances, low costs and fault tolerance. Some of the important disadvantages are that the drives emit acoustical noise, need a converter, are nonlinear and information about the rotor position to make proper control scheme is necessary.

With the development of microcontrollers and power electronics devices, many different control loops have changed from analog to digital implementation which allows more advanced control features (Inderka *et al*., 2002; Ehsani and Fahimi, 2002; Jinupun and Luk, 1998). Several control techniques have fallen into two main categories (Blaabjerg *et al*., 1999; Xu *et al*., 1991; Hossain *et al*., 2003): those which used a linear motor model and those which used a nonlinear model which takes into account the motor saturation. In general, most techniques generate a voltage or current command profile in order to control the motor torque, speed, position and/or minimize the torque ripple (Islam and Husain, 2000; Blaabjerg *et al*., 1999).

Vector control reestablishes one the advantages of the dc drive through implementation of direct flux control (Ehsani and Fahimi, 2002; Xu *et al*., 1991). Torque control is indirect because of its position in the control algorithm prior to the vector control process, however, good torque response is achieved nonetheless. Inclusion of the pulse encoder insures high-performance speed and torque accuracy. The biggest disadvantage of vector control is the mandated inclusion of the pulse encoder. Another minor disadvantages is that torque is indirectly, rather than directly, controlled. Finally, the inclusion of the PWM modulator, which processes the voltage and frequency reference outputs of the vector control stage, creates a signal delay between the input references and the resulting stator voltage produced. These last two factors limit the ultimate ability of vector control to achieve very rapid flux and torque control.

Direct Torque Control (DTC) is an alternative solution to vector control problems achieves robust and fast torque response without the need of speed or position sensor, coordinates transformation, PWM pulse generation and current regulators (Jinupun and Luk, 1998; Cheok and Fukuda, 2002). In DTC schemes, the presence of hysteresis controllers for flux and torque determines variable switching frequency operation for the voltage source inverter. Furthermore, using DTC scheme a fast torque response over a wide speed range can be achieved only using different switching tables at low and high speed.

VECTOR CONTROL OF SRM

When the saturation is neglected, the motor torque is calculated by derivation of the equivalent self inductance of one phase which is a function of rotor position

$$T_e(\theta,i) = \frac{1}{2} i^2 \frac{\partial L(\theta)}{\partial \theta}\Big|_{i=\text{const}} \tag{1}$$

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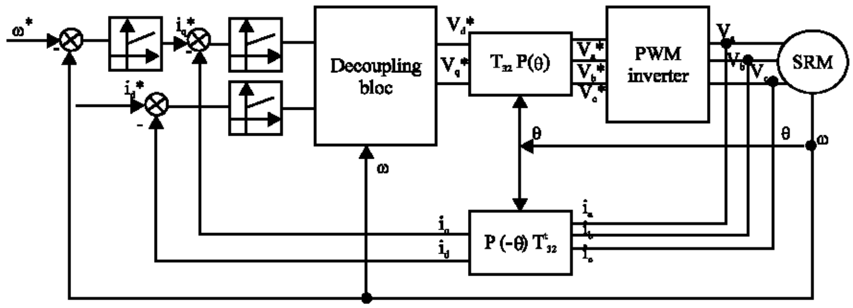

Fig. 1: The bloc diagram of an SRM drive with vector control

the positive torque is produced when the phase is switched on during the rising inductance. Consequently, if the phase is switched on during the period of falling inductance, negative torque will be produced. An SRM is normally operated by getting a feedback of the rotor position and firing the phases depending on this feedback. The phase is switched on when the rotor in the unaligned position and switched off before it reaches the aligned position. Control of the switched reluctance motor can be done in different ways. Current controllers followed by Pulse Width Modulation (PWM) or hysteresis comparators is normally used to control the torque efficiently. The basic structure of these controllers is indicated in Fig. 1.

The output of the speed controller generates the current references i_d^* and i_q^*, which are in the rotor flux reference frame. Regulating of currents i_d and i_q in closed loops leads indirectly to control of the motor developed torque according to the motor equation

$$T_e = p\left(L_d - L_q\right)i_d i_q \qquad (2)$$

where i_d and i_q are the stator d-q axes components of the stator current respectively. L_d and L_q are the stator inductances, p is the number of pole pairs.

When the effect of saturation is negligible i_d is maintained at a constant value, ψ_d is then imposed only by i_d current and torque it does not depend whereas only by i_q current. But when the level of saturation is not negligible any more, taking into account the crossed effect, even if the i_d current is maintained at a constant value, the values of inductances change with the load, therefore, with i_q. Thus, the model becomes nonlinear and not exploitable for control. However, we can obtain an enough simple model to be exploitable. It is enough to maintain saturation on a high constant level, in order to cancel the cross effect. This can be carried out by maintaining the i_d current with a high value i_{d0}, sufficiently for away from the elbow of saturation. In theory, i_d is selected so as to optimize the torque at the rated operation point, i.e. that i_d is fixed at a single value i_{d0} whatever the load. If there is no saturation (L_d and L_q constants), this value is $\sqrt{3/2}\,I_n$, where I_n is the effective value of the current in the three phase machine. In saturated mode, the maximum torque is obtained for a value i_{dopt} appreciably lower than $\sqrt{3/2}\,I_n$; moreover, it is necessary to respect the magnetic constraint of decoupling which assigns i_{d0} with a minimal value (in general rather near to $\sqrt{3/2}\,I_n$). i_d will thus, be fixed at a value i_{d0} equalizes with i_{dopt}. If the latter is higher than i_{dmin} and with i_{dmin} in the contrary case which is most current.

PRINCIPLE OF DIRECT TORQUE CONTROL

The basic idea of direct torque control is to choose the best voltage vector which makes the flux rotate and produce the desired torque.

Torque control: The two important torques in synchronous machines are the synchronous torque and the reluctance one. In the case of the SRM we have only the second one which is given by

$$T_{rel} = \left(\frac{p}{2}\right)\left[\frac{1}{L_q} - \frac{1}{L_d}\right]\psi_s^2 \sin(2\delta) \qquad (3)$$

We supposes that the rotor angular speed and the stator flux amplitude are constant and we applies an adequate voltage vector during a time interval smaller than the machine constant time. Torque variations can be expressed as

$$\Delta T_{rel} = \left(p\left[\frac{1}{L_q} - \frac{1}{L_d}\right]\psi_{s0}^2 \cos(2\delta_0)\right)\Delta\delta \qquad (4)$$

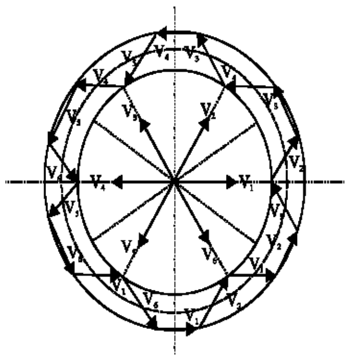

Fig. 2: The control scheme of the stator flux linkage using six voltage vectors

Table 1: Switching table for inverter

		Θ					
φ	τ	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5	Θ_6
φ =1	τ = 1	V_2	V_3	V_4	V_5	V_6	V_1
	τ = 0	V_6	V_1	V_2	V_3	V_4	V_5
φ = 0	τ = 1	V_3	V_4	V_5	V_6	V_1	V_2
	τ = 0	V_5	V_6	V_1	V_2	V_3	V_4

Equation (4) shows that to increase torque, δ should be increased. Torque is controlled via stator flux rotation speed.

Where ψ_{s0} is initial stator flux linkage; δ_0 is the initial load angle, Δδ represents variation of the load angle and p is pole pairs of the motor.

Control of the amplitude of stator flux linkage: The stator flux linkage can be expressed in the stationary reference frame as

$$\psi_s(t) = \int_0^t (V_s - R_s i_s)dt + \psi_s(0) \tag{5}$$

since stator resistance R_s is relatively small, the voltage drop $R_s i_s$ might be neglected (5) is then rewritten as

$$\psi_s(t) = \psi_s(0) + V_s T_s \tag{6}$$

Where $\psi_s(0)$ is the initial stator flux linkage at the instant of switching and T_s is sampling time.

Equation 6 implies that the end of the stator flux vector will move in the direction of the applied voltage vector. To select the voltage vectors for controlling the amplitude of the stator flux linkage, the voltage plane is divided into six regions, in each region, two adjacent voltage vectors, which give the minimum switching frequency, are selected to increase or decrease the amplitude of ψ_s, respectively (Fig. 2). The switching table for controlling both the amplitude and rotating direction for both directions of operations of an SRM is represented in Table 1. The output of the torque hysteresis comparator is denoted as τ, the output of the flux hysteresis comparator as φ and the flux linkage sector is denoted as Θ.

PROPOSED DTC STRUCTURE

The block diagram of the proposed DTC for SRM is shown in Fig. 3. The αβ-axes currents, can be obtained from the measured three phase currents by applying the Concordia transformation

$$I_\alpha = \sqrt{\frac{3}{2}} I_a \tag{7}$$

$$I_\beta = \sqrt{\frac{1}{2}} (I_b - I_c) \tag{8}$$

The αβ-axes voltages are calculated from dc-link voltage, since the voltage vectors determined by the switching table are known.

$$V_\alpha = \sqrt{\frac{2}{3}} U_0 (S_a - 0.5(S_b + S_c)) \tag{9}$$

$$V_\beta = \sqrt{\frac{1}{2}} U_0 (S_b - S_c) \tag{10}$$

The stator flux linkage can be calculated from

$$\psi_\alpha(t) = \int_0^t (V_\alpha - R_s i_\alpha)dt + \psi_\alpha(0) \tag{11}$$

$$\psi_\beta(t) = \int_0^t (V_\beta - R_s i_\beta)dt + \psi_\beta(0) \tag{12}$$

The electromagnetic torque can be estimated from

$$T_e = p(\psi_\alpha I_\beta - \psi_\beta I_\alpha) \tag{13}$$

As the indirect inductance is very low, the machine magnetizing on the indirect axis requires an important current. To avoid it using of a position sensor to know the approximate rotor position is necessary. For this purpose a position sensor is proposed as shown in Fig. 4. Subsequently, this later is not needed.

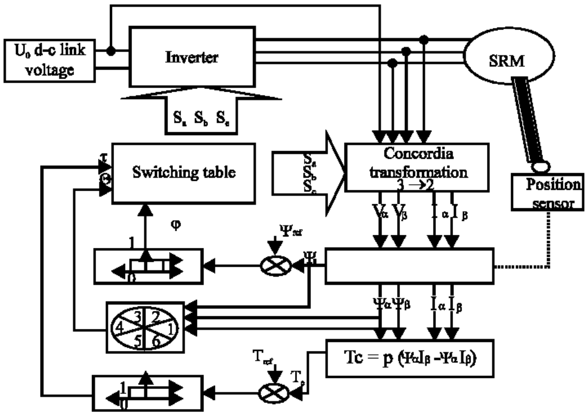

Fig. 3: The bloc diagram of an SRM drive with DTC

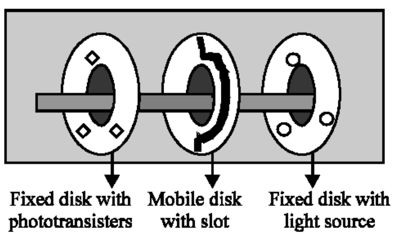

Fig. 4: Position sensor description

The proposed position sensor is an optic type (Rekioua *et al.*, 2001) this one is attached to the rotor shaft and is made of two fixed disks. The first disk is fixed to the stator and supports 3 light sources at 120° electrical degrees distance from each other. The second disk supports the phototransistor elements placed in front of the first one. A third mobile disk which is placed between two former, fixed to the machine shaft.

RESULTS

To verify the analysis in Fig. 1 and 3 an Switched Reluctance Motor (SRM) is used in simulation, whose the parameter used in this study are shown in Table 2. The value of the sampling interval and the dc link voltage adopted in the simulation are 500 microseconds and 165 V.

Figure 5 shows the dynamic performances of the vector controlled SRM in the cases of starting up from standstill to a speed of 330 rd/s, when a load torque of 4 Nm is applied to the motor at 0.19s. Figure 5c shows that the motor electric torque increases to satisfy the load torque requirements. We notice that the torque

Table 2: Parameters of the srm used in this study

SRM	Value [unit]
Number of stator/rotor pole	12/8
Rs	2[O]
Ld	0.049[H]
Lq	0.01[H]
f	0.0001[N.m.s/rad]
J	0.0006[Kg.m2]

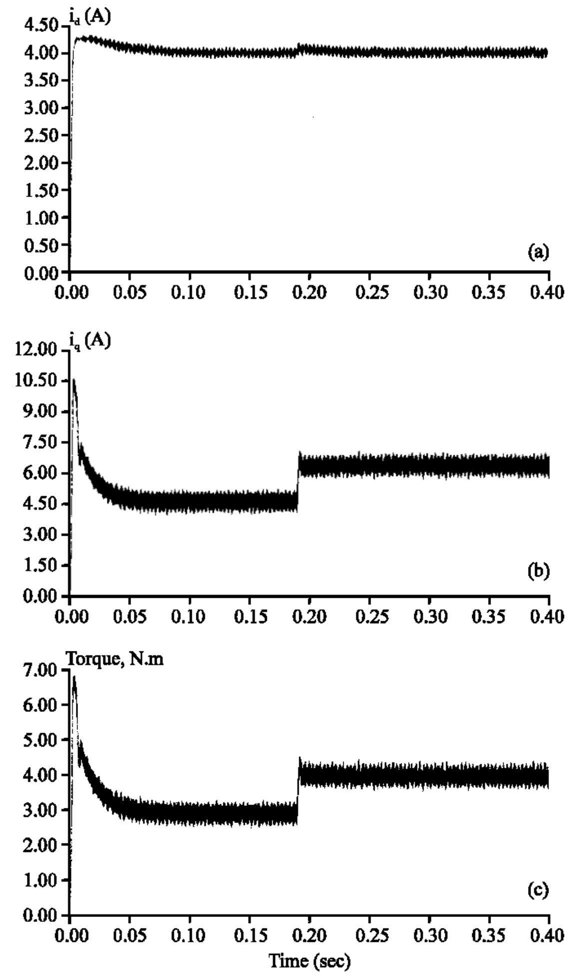

Fig. 5: Dynamic response of SRM drive with vector control. (a) d axis stator current . (b) q axis stator current. (c) Torque

is proportional to the quadrature current component (Fig. 5c and b) when the direct current is forced to be 4A Fig. 7a.

To examine the basic Direct Torque Control (DTC) algorithm, the value of the sampling interval adopted in the simulation is 10 microseconds. Figure 6 shows the dynamic response of the system when the reference value of the torque and the stator flux are 3 Nm and 0.283 wb, respectively. Figure 6c shows that the stator flux linkage

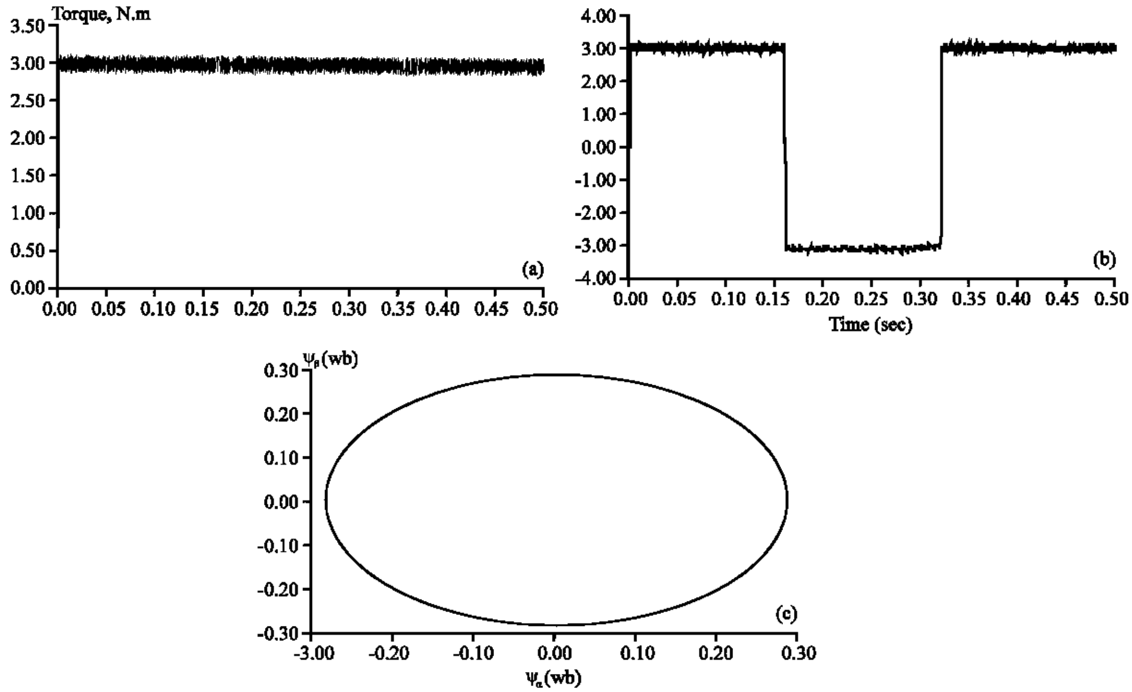

Fig. 6: Dynamic response of SRM drive with DTC. (a) and (b) Torque. (c) Stator flux linkage

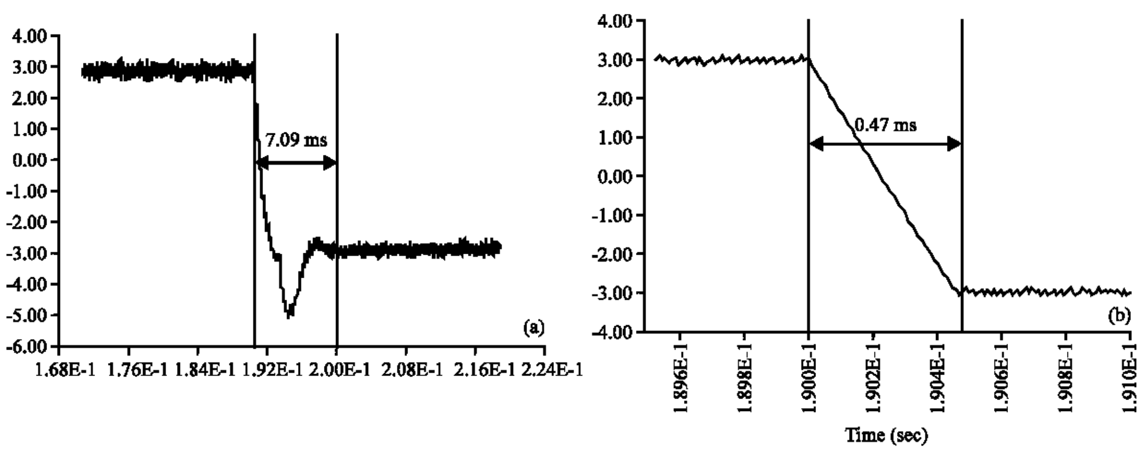

Fig. 7: Torque responses with vector control and DTC : (a) Torque response under vector control. (b) Torque response under DTC

is controlled at its required value quite well. The trajectory of $ø_{â}$ and $ø_{â}$ is a circle as expected. According to Fig. 6(a) and (b) The actual torque is controlled within the bandwidth and follows the reference rapidly.

Figure 6b shows the dynamic torque response when the reference torque abruptly changes from 3Nm to -3Nm.

Figure 7 shows the torque response with direct torque controlled SRM (Fig. 7b) and vector controlled SRM (Fig. 7a), it should be not however that the torque response with direct torque control is much faster than the one with PWM vector control.

CONCLUSION

The biggest disadvantages of vector control is the mandated inclusion of the pulse encoder. Torque is indirectly controlled and the inclusion of the PWM modulator which processes the voltage and frequency reference outputs of the vector control stage, creates a signal delay between the input reference and the resulting stator voltage produced, which limit the ultimate ability of vector control to achieve very rapid flux and torque control. Compared with vector control, direct torque control has many advantages such as less machine parameter dependence (stator resistance), simpler implementation and quick torque response.

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