Summary

7. Direct Control Schemes For Induction Machines

7.1 Introduction

After examining the so called traditional structures of vector control, this note deals with schemes that are conversely defined as "non-conventional."

These schemes are inspired by a considerably different approach from what we have seen so far and have gained particularly in the traction applications. These solutions owe their origins to the studies carried out by Depenbrock: more specifically, the DSC (Direct Self Control) has been for years the most advanced solution in the field of heavy traction as a result of its ability to exploit even the limited capabilities of high power switches (thyristors or GTO) and the DTC (Direct Torque Control) is, more or less, the evolution towards solutions such as "sensorless" ie, where there is no expected device for measuring mechanical variables.

Please note right now that these techniques don't want to cover definitely the entire spectrum that fall under the definition of "Direct Action Vector Control" as a result of the large number of variants that can arise when we move from theory to implementation nor to be exhaustive in terms of control techniques.

Appropriately, in the following pages it is never referred to specific control strategies but we prefer to refer to industry standard PI controllers. This is due to a number of reasons that can basically be summarized by the following:

- the purpose of this discussion is to focus on the theoretical aspects related to the machine and its dynamics and does not seek to provide answers to the controller problems
- innovative techniques such as adaptive control, fuzzy or neuro-fuzzy, in fact have only changed the strategy for implementing the controller without going to act on the fundamental principles of the control related to the physical machine and then to the unified theory of electrical machines.

7.2 DSC technique

7.2.1 Foreword

In the field of induction motor drives for traction, the today’s trend is to develop control architectures that, compared to the traditional "field oriented", would achieve greater accuracy and faster system response.

The main limitation of field-oriented control is that it does not allow in a direct orientation of the stator magnetomotive force respect the flux, because the manipulated variable, i.e. the voltage, is not directly linked to the control variable (rotor flux). Consequently, the result is that this control method is not so great in terms of response speed.

In this perspective, vice-versa, the two control schemes, defined "direct", have good response. They will be addressed in this note.

7.2.2 Direct Self Control

As already introduced in the foreword, the direct self-control (DSC below) is based on controlling the orientation of the flux linked with the stator windings.

The fundamental point is the ability to directly manipulate the flux through the stator voltage, given the stator state equation, written on stationary reference frame (fixed with stator):

$$\overline{v_s} = R_s \cdot \overline{i_s} + p\overline{\psi_s}$$

If we neglect the voltage drop on the stator resistance (assumption valid for medium to large machines and for speed large enough to consider the derivative of the stator flux outweighs the term

$R_s \cdot \overline{i_s}$) the equation becomes:

$$\overline{v_s} \approx p\overline{\psi_s} \approx \frac{\Delta\overline{\psi_s}}{\Delta t}$$

This relationship indicates that the voltage can be interpreted as the speed with which the end of the stator flux vector is moving; this speed may be considered as instantaneous speed. It is also known that voltage and flux variation have the same direction.

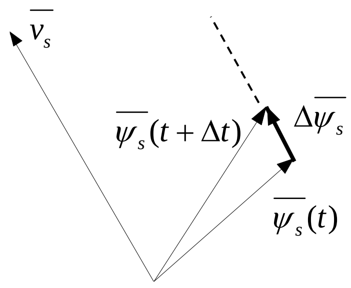

Figure 7-1: Voltage/flux relationship

If we consider the motor powered by a voltage source inverter, you have at your disposal, as it is known, eight speeds corresponding to the eight states that the voltage space phasor can take in the stationary reference frame: six states represented by non-zero vectors with a displacement of 60 electrical degrees each other and two states equal to the zero voltage.

The basic idea is to drive the stator flux according to the most suitable trajectory.

If you consider a three-phase symmetrical sinusoidal steady-state, the voltage phasor describes a circle in the reference frame; if one considers the linear mathematical model of the induction machine he can then say that the stator flux, at steady state, describes a circle trajectory: this trajectory is the optimal one.

The presence of an inverter that provides the supply voltage does not allow you to drive the flux along the optimal trajectory because there are only eight discrete states, two of which have a zero value. Given the stator flux, the variation can assume six different directions (as a function of applied voltage) or be null (zero voltages).

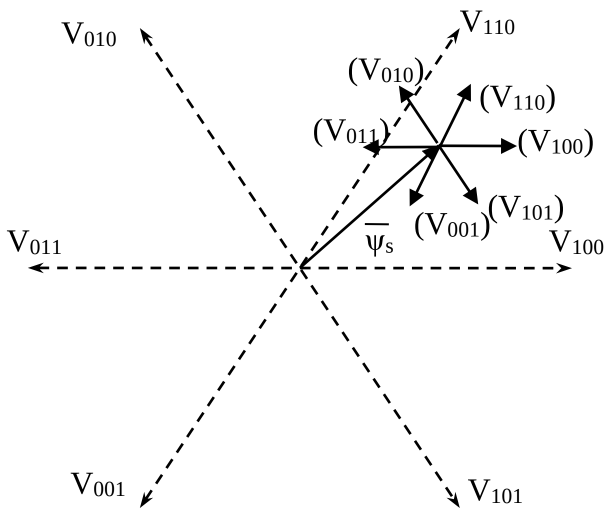

Figure 7-2: Stator flux variation as a function of the applied voltage

It is possible to drive the flux, however, according to a hexagonal trajectory, appropriately selecting the six nonzero voltage vectors according to the logic which is described below.

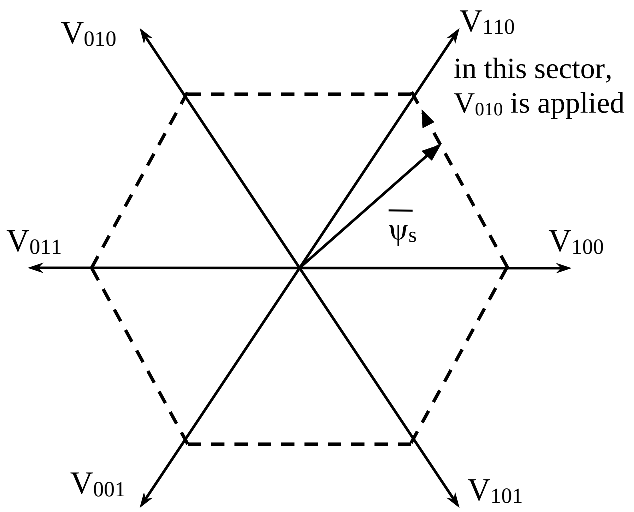

Figure 7-3: Stator flux trajectory

Before entering into the study of the method, it is however worth remembering the characteristics of the operating regions of a typical variable speed drive, as illustrated in Figure 7-4.

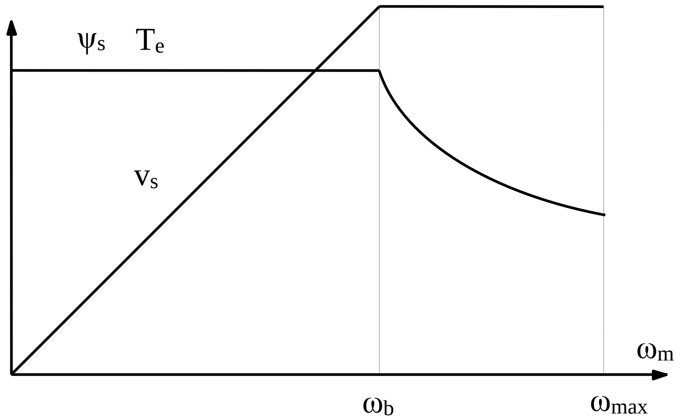

Figure 7-4 Torque and flux control region as a function of the mechanical speed

These characteristics identify two areas of operation: the first area is that of low-speed ($\omega_m<\omega_b$) and is characterized by having a voltage approximately proportional to the speed and a nearly constant value of the stator flux and the torque; the second area is that of high-speed ($\omega_m>\omega_b$) and has a constant voltage and a flux and a torque with speed decreasing as the hyperbolic trend. For the induction machine, there is a further limitation imposed by the maximum torque (not shown in the figure).

7.2.3 The DSC controller at low speeds

In the range $0<\omega_m<\omega_b$ the stator flux moves along a hexagon that has the same side.

The inverter switching instants are determined by evaluating the projection ψ_s^* of the stator flux vector along the direction corresponding to that of the applied voltage vector, rotated 30° leading (bisector of the next sector). When this projection equals the reference value ψ_b, the voltage reference is changed and becomes the following the last applied (rotated 60° in advance) (in Figure 7-5 the new configuration is V_{011}).

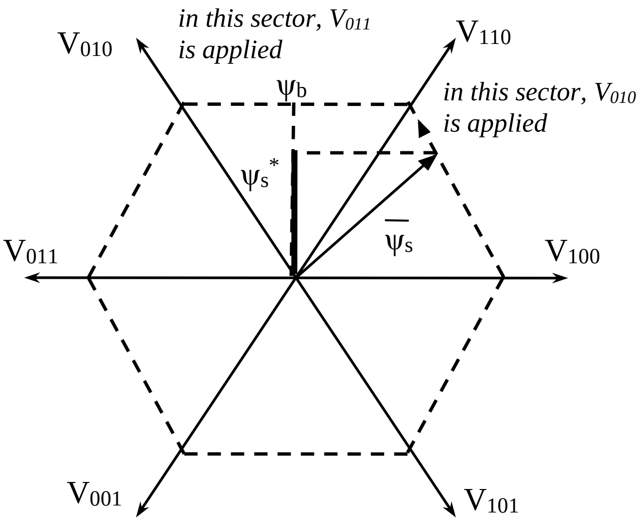

Figure 7-5: Switching instant definition

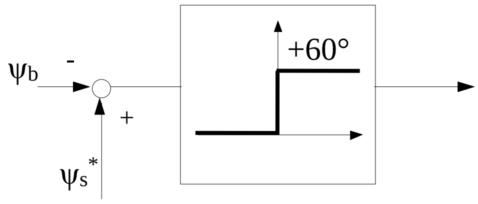

Figure 7-6 Flux comparator

If we consider the flux and voltage first harmonic and a steady state, the average speed ω_1 of the stator flux (neglecting the resistive drop) is:

$$\omega_1 = \frac{\left|\overline{v_{s1}}\right|}{\left|\overline{\psi_{s1}}\right|}$$

Since the module of the first harmonic of the flux is held constant, you may control the speed by changing the module of the voltage fundamental. This can be achieved using inverter configurations which correspond to a zero voltage. In fact, any imposition of the zero voltage vector stops the flux phasor (if neglecting the voltage drop on the resistance is a valid approximation); so it is possible that the flux follows always the hexagon trajectory, for different average speeds. The voltage modulation is obtained indirectly, through the torque control.

In fact the torque T_e, calculated by the state observer (see chapter 7.4), is compared with two thresholds characterized by an appropriate amplitude, symmetric around the reference torque $T_{e\,ref}$.

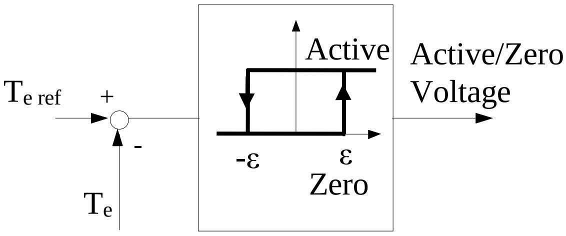

Figure 7-7 Torque comparator

When the upper threshold ($T_{e\,ref}+\varepsilon$) is reached, the torque controller requires a zero voltage; in this way, the stator flux stops immediately (if neglecting the voltage drop on the resistance is a valid approximation), while the rotor flux (which has a much slower dynamic than the stator flux) continues its trajectory with a nearly constant speed (equal to the speed *ω_1* of the first harmonic of the stator flux), approaching the stator flux. Since the torque depends on the product between the modules of the stator and rotor fluxes and the sine of the angle between them, during this period the torque decreases.

The energy balance, presented in the field-oriented vector control, is:

$$T_e = n_p \cdot \mathrm{Im}(\overline{\psi}_r \underline{i}_r)$$

but it is also true that:

$$T_e = n_p \,\mathrm{Im}(\overline{i}_s \underline{\psi_s}))$$

And, with a four parameters model

$$T_e = \frac{n_p}{L_{ks}} \mathrm{Im}(\overline{\psi_s} \underline{\psi_r})) = \frac{n_p}{L_{ks}} \left|\overline{\psi_s}\right| \left|\overline{\psi_r}\right| \sin(\delta)$$

where δ represents the angle between the stator and rotor fluxes.

You can change the expression using the relationship between fluxes and currents.

Regardless of the model used, it is therefore:

$$T_e = k \left|\overline{\psi_s}\right| \left|\overline{\psi_r}\right| \sin(\delta)$$

Typical expression of an electromagnetic joint.

Similarly, when the lower threshold ($T_{e\ ref}$-ε) is reached, the controller restores the original voltage value (active configuration): in this way the stator flux begins to move at a speed equal to ω_b, moving away from the rotor flux; during this period the torque increases.

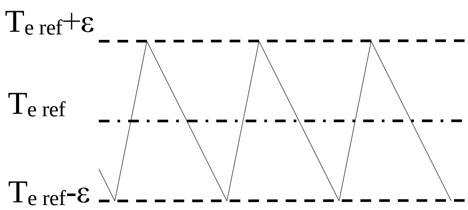

Figure 7-8 Amplitude modulation of the torque

A theoretical justification of the fact that the rotor flux has a dynamic much lower than that of the stator flux can be evident looking at the dynamic equations of the induction machine, given by the FOC theory:

$$v_{sd} = R_{ks} \cdot i_{sd} + L_{ks} p i_{sd} - \frac{R_r}{M} \cdot \psi_r - \dot{\theta}_s \cdot L_{ks} \cdot i_{sq}$$

$$v_{sq} = R_{ks} \cdot i_{sq} + L_{ks} p i_{sq} + \dot{\theta}_m \cdot \psi_r + \dot{\theta}_s \cdot L_{ks} \cdot i_{sd}$$

$$p\psi_r = R_r \cdot i_{sd} - \frac{R_r}{M} \cdot \psi_r$$

$$0 = R_r \cdot i_{sq} - \dot{\theta}_r \cdot \psi_r$$

The rotor flux depends on the direct-axis current. Starting from the first equation, the current i_{sd} is related to the voltage v_{sd}, apart the disturbances and the coupling terms, but through a rather low time constant (L_{ks}/R_{ks} where L_{ks} represents the leakage flux).

The third equation shows that the time constant of the dynamic between the rotor flux and the current i_{sd} is very high ((M/R_r). So, the voltage has an effect on the rotor flux with a very high time constant (as if it were through a low-pass filter). The stator flux, however, is directly connected to the voltage (the voltage is the stator flux speed).

The rotor flux is then associated with a good approximation to the only first harmonic of the stator flux (fundamental), if the slip is much less than 1 (if the control system works well, slip is limited to some per cent, whatever is the mechanical speed); i.e. it is slightly variable compared to stator flux.

From all this, it follows that a voltage step quickly moves the stator flux, causing an increase in the angle between the stator and the rotor flux and consequently an increase in the torque (which is proportional to the modules of these fluxes and to the sine of the angle between them); once the upper threshold of the torque is reached, forcing a zero voltage the stator flux is stopped; the slow evolution of the rotor flux causes a decrease in the angle just considered and then a decrease of torque.

It is important to note that the stop of the stator flux vector also leads to a reduction of the average speed of the flux itself as it increases the time required to complete a period; the stator flux takes longer time to reach its reference.

The mechanical speed, if the torque controller works properly, assumes values very close to those of the average speed of the stator flux (which is also the speed of the rotor flux) as the slip is very low, due to the torque control (in the mechanical characteristic torque/speed at constant voltage and frequency you are working on the low-down straight portion, in which the torque is practically proportional to the slip frequency). As always, in an induction machine, the torque control corresponds to a slip control.

Increasing the mechanical speed, also the average speed of the stator flux must increase. It arrives at a point such that the average speed of the stator flux is such that there no way to stop the flux itself. It has come to the base speed, where the inverter is working in square wave mode (no longer use configurations with zero voltage). This is the maximum speed that can be achieved if you want to keep the stator flux constant (hexagonal trajectory). The torque controller has no more room for working.

7.2.4 The DSC controller at high speeds

In the range $\omega_m > \omega_b$, the first harmonic modulus of the voltage is kept constant (the inverter works in a six step operation mode), while the stator flux decreases in inverse proportion to the speed.

The torque is controlled by varying the speed of the stator flux. To increase torque, it is enough to accelerate the stator flux, moving away from the rotor flux and vice versa.

The speed variations are determined dynamically by changing the module of the stator flux vector, that is, putting that vector on hexagons of different sizes (smaller is the hexagon less time uses the stator flux to accomplish it entirely; the tangential speed of the flux does not change as it is closely linked to the module of the applied voltage, but the period for making the total turn is less).

If, for example, you want to increase the speed, it is sufficient to decrease the side of the hexagon imposing a lower reference flux ψ_b; this results in an increase of the pulsation of the first harmonic of the stator flux, which thus moves away from the rotor flux, causing an increase in torque.

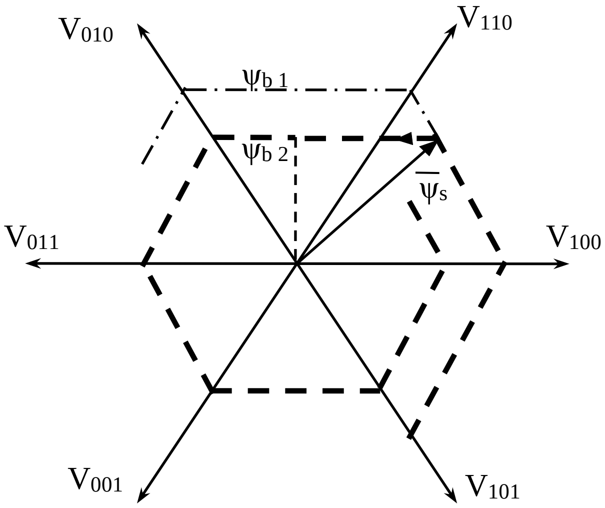

Figure 7-9 Flux reference change in order to increase the torque

Control is achieved by requiring that the electromagnetic torque is equal to a fixed reference torque (given by the operating region) and modifying the flux reference as a function of the torque error, by means of a corrective term ψ_{corr}.

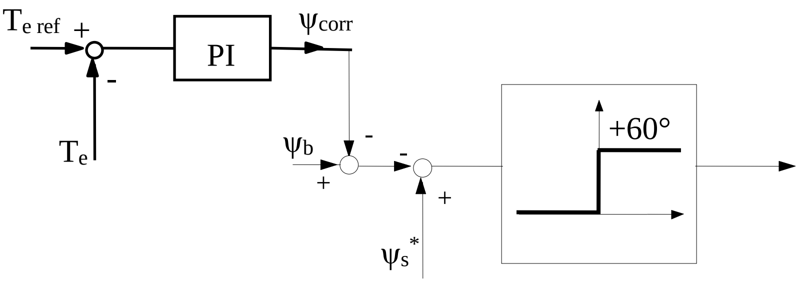

Figure 7-10 Torque controller for high speed application

it is evident that, with a lower value of the stator flux, you can not get the rated torque, but it is necessary to decrease the limit value (look at the operating regions, that represent steady state values).

The control schemes work if you know the position and the module of the stator flux (used to calculate ψ_s^*) and the torque. These values are generally estimated using techniques similar to those described in section 7.4.

The DSC can also work for negative speeds (clockwise). Just that the flux controller provides the most appropriate change of the voltage to be applied (counterclockwise: + 60°, clockwise: -60°).

7.3 DTC

The direct torque control (DTC) can be considered like the evolution of DSC as it maintains, in some aspects, the same basic principles.

The main innovations compared to the former controller are essentially about how to control the trajectory of stator flux and the ways in which the on and off commands are given to the switches of the inverter.

7.3.1 Flux control loop

It has already been widely discussed, in the previous section, about the relationship between the stator flux and the voltage supplied by the inverter; in particular it has highlighted the fact that the stator flux is directly manipulated by the stator voltage and has a very fast response to rapid changes in the voltage itself. We have seen so that the flux vector can follow a hexagonal trajectory in relation to the six non-zero states that the voltage vector can take.

In fact, the hexagonal trajectory is not the most optimal to follow: it can be approached with greater approximation to the optimal trajectory (the circumference) by confining the end of the stator flux vector in a circular ring; the module of this vector is maintained, as well as for the torque, inside a band. The control logic is to compare the flux, given by the state observer (paragraph 7.4 State estimator), with two symmetric thresholds with respect to a given reference flux; the appropriate voltage vector is selected, according to whether the upper or lower threshold is exceeded and according to the position of the flux vector respect the reference frame.

It is therefore necessary to have a good observer, able to give a good estimation of the stator flux vector from the measured variables: the stator voltages and currents (paragraph 7.4).

A hysteresis controller compares the module of the flux vector with the flux reference providing discrete output of 0 or 1 depending on whether the flux exceeds the thresholds above or below respectively.

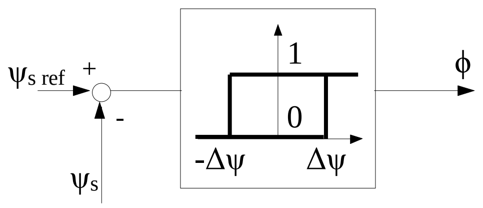

Figure 7-11 Flux comparator

The reference frame is divided into six equidistant sectors each containing a voltage vector and numbered as in Figure 7-12.

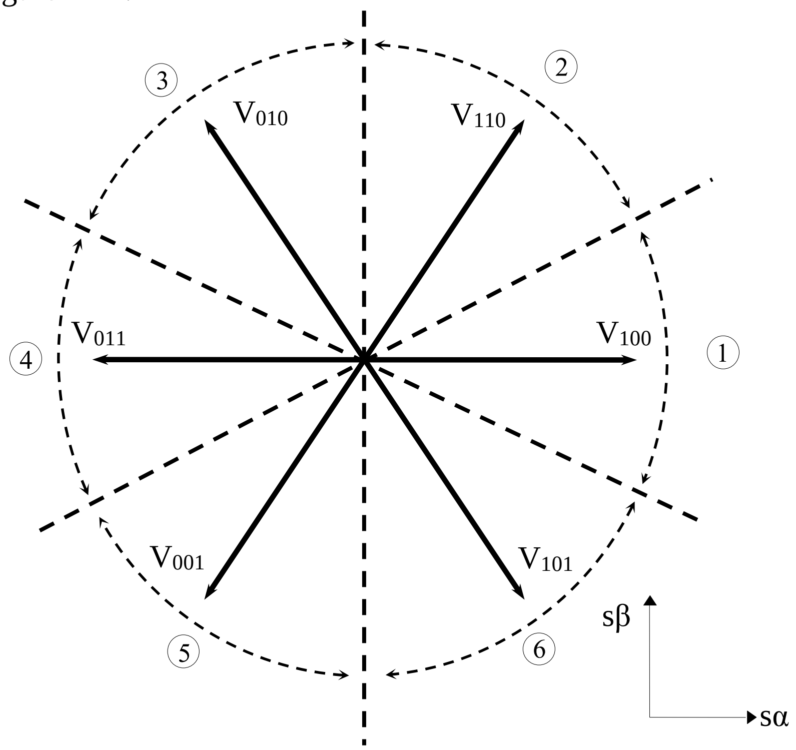

Figure 7-12: Stator flux sectors

The angle between the flux vector and the "α" axis of the reference frame is used to determine which of the six areas has the vector inside.

The selection logic of the voltages, as a function of the stator flux vector, provides that in every sector the voltage vectors, belonging to the two sectors following the actual one, are selected: the nearest one is used to increase the amplitude of the stator flux, while the second one is used to decrease the amplitude. This guarantees the converter to make the lowest number of switching. As a result of this choice, always only two switches come into play at a time, thus limiting the switching losses and the excessive heat, to the benefit of the heat sink size, and increasing the lifespan of the switches.

Assume that the stator flux is within the first flux sector: the voltages that must be selected are therefore vectors V_{110} (in order to increase the amplitude and to rotate) and V_{010} (flux amplitude decreasing and to rotate).

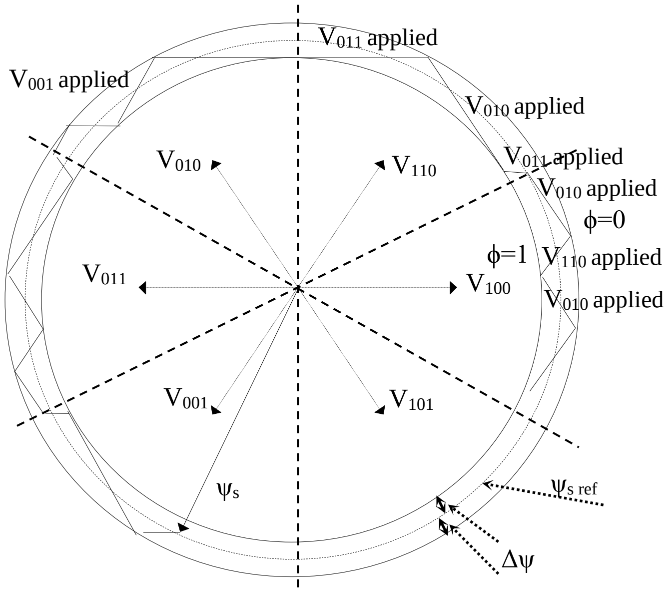

Figure 7-13 Theoretical trajectory of stator flux

The confinement of the stator flux vector inside the circular ring provides a much better harmonic content than that provided by the DSC controller (hexagon).

With the improvement of the flux waveform, the waveform of the stator currents improves; with it the Joule and eddy current losses decrease; on the other hand the switching losses increase, due to the necessarily higher switching frequencies.

Above the base speed, the machine enters in the weakening region by reducing the value of the flux reference (this results in a decrease in size of the circular path) as a function of the operating region of the machine.

7.3.2 Torque control loop

The torque control is obtained in the same way seen for the DSC, arresting or advancing the stator flux vector in order to confine the torque in a given band. The comparator level is similar to that seen for the flux, and it is also able to provide torque if you want to reverse the speed of the machine. It provides an output value of 0 when the torque exceeds the upper threshold, the value 1 when the torque reaches the bottom and the rotation of the flux vector is counterclockwise, the value -1 when the torque reaches the bottom and the rotation of the flux vector is clockwise.

Assume that the flux is rotating counterclockwise.

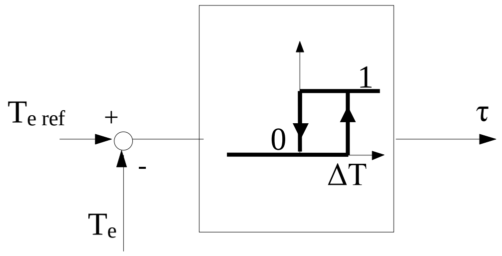

Figure 7-14 : Torque comparator (counterclockwise rotation)

The controller output is 0 when the torque exceeds the upper threshold (T_{ref}), 1 when the torque reaches the lower threshold (T_{ref}-ΔT).

In the case in which the flux rotates in a clockwise direction, the controller output is 0 when the torque reaches the lower threshold (T_{ref}), the value -1 when the torque reaches the upper threshold (T_{ref}+ΔT).

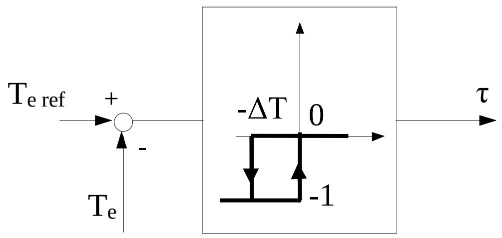

Figure 7-15 : Torque comparator (clockwise rotation)

Overall, the torque controller is:

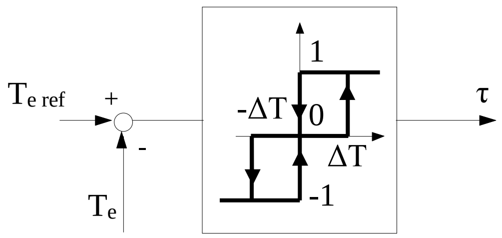

Figure 7-16 Torque comparator

Again the switching configuration is designed in such a way as to minimize the number of commutations: stopping the flux, equivalent to the imposition of zero voltage (τ=0 output from the comparator), is realized by the simultaneous turning-on of all above or below switches of the inverter, i.e. V_{000} or V_{111} (it depends on the number of commutations).

As speed increases, the periods in which the stator flux is stopped is reduced. When you reach the minimum value, it means that it has come to the maximum voltage and then to the base speed. Above base speed you must deflux the machine decreasing the value of the reference flux (the result is a decrease in the size of the circular trajectory) as a function of the field of operation of the machine. The control logic, however, remains the same as the control at low speed.

This type of control, therefore, allows a spontaneous realization in numerical form: the use of threshold logic in fact reduces the output to discretized values, easily manageable by digital algorithms.

But the peculiarity of the controller DTC is, with no doubt, the *switching-table*. The switching-table is a table of configurations that the voltage vector should take as a function of the stator flux module, of its position in the reference frame and of the torque value.

It receives the discrete values ϕ and τ of the outputs from the torque and flux comparators, together with the value θ(N) which represents the sector where the stator flux is located, and returns the value of the voltage vector that must be selected, in the form of on and off commands of the appropriate switches.

In practice, it is a three-dimensional array 2x3x6 achievable, under the hardware profile, by using a programmable memory.

The DTC logic therefore allows a very easy switching and management without the use of sophisticated algorithms, with the advantage of speed and simplicity of realization.

The use of comparators also allows you to control the switching frequency of the switches, according to the extent of the bands.

Table 7-1 shows the "switching-table"; ϕ and τ represent the output values of the comparator of flux and torque; $\theta(N)$ the sector where the stator flux is located.

		$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
$\phi=0$	$\tau=1$	V_{010}	V_{011}	V_{001}	V_{101}	V_{100}	V_{110}
	$\tau=0$	V_{000}	V_{111}	V_{000}	V_{111}	V_{000}	V_{111}
	$\tau=-1$	V_{001}	V_{101}	V_{100}	V_{110}	V_{010}	V_{011}
$\phi=1$	$\tau=1$	V_{110}	V_{010}	V_{011}	V_{001}	V_{101}	V_{100}
	$\tau=0$	V_{111}	V_{000}	V_{111}	V_{000}	V_{111}	V_{000}
	$\tau=-1$	V_{101}	V_{100}	V_{110}	V_{010}	V_{011}	V_{001}

Table 7-1 The switching table

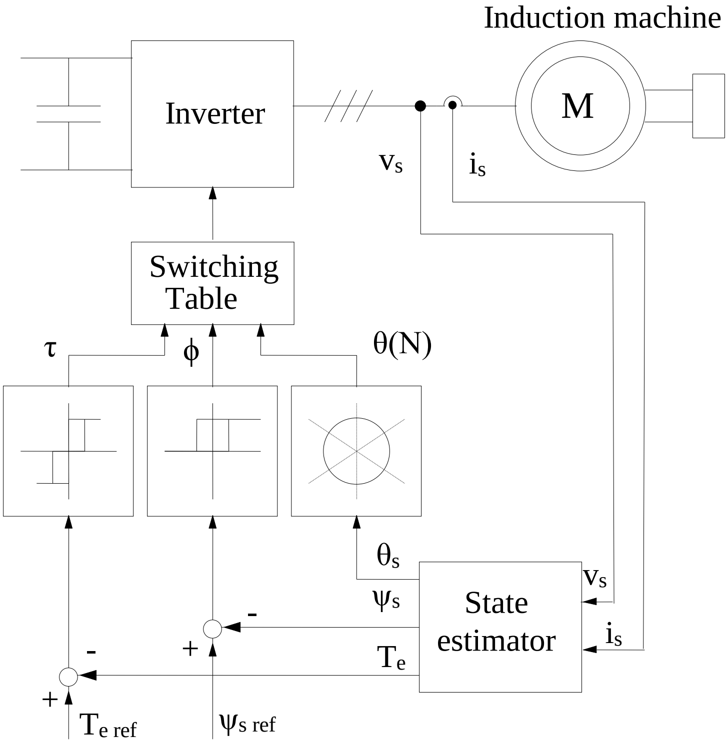

Figure 7-17 DTC drive

7.4 State estimator

Both for the DSC control that for the DTC, the module and the position of the stator flux and the torque value must be known. These quantities usually are not measured but estimated.

The state estimator is based on the classical V-I scheme, limited to the stator flux expression.

The equations are referred to a stationary reference frame. The inputs are the stator voltages and currents. There is no need of the mechanical speed. The stator flux is obtained from the integration of the voltage after the stator resistance. The torque is calculated by one of the many expressions.

Starting from the stator equation in a stationary frame:

$$\overline{v}_s = R_s \cdot \overline{i}_s + p\overline{\psi}_s$$

the equations become:

$$\psi_{s\alpha} = \int (v_{s\alpha} - R_s i_{s\alpha}) dt$$

$$\psi_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta}) dt$$

$$\theta_s = \arctan\left(\frac{\psi_{s\beta}}{\psi_{s\alpha}}\right)$$

$$T_e = n_p \operatorname{Im}(\overline{i}_s \underline{\psi}_s)$$

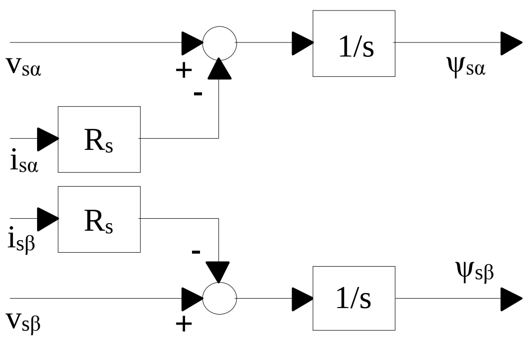

Figure 7-18 Flux estimator

It has the same problem of the VI estimator, seen in the field-oriented control of the induction machine.

7.5 General considerations about DSC and DTC controller

The direct control methods for induction machines based on adjusting the flux and the torque through two thresholds and hysteresis are four key benefits:

- simplicity
- excellent dynamic performance
- robustness
- possibility to directly set the desired torque and flux ripple.
- low sensitivity to parameter variation

The DSC method has been applied in traction applications, so for medium to high power machines, requiring relatively small switching frequencies.

The main problem is that it generates a stator flux hexagonal trajectory and then the currents are affected by low harmonics (5 and 7 times the fundamental frequency): these currents are, as it is well known, particularly harmful at low frequencies.

At low speed the DSC method is leaved for the benefit of other types of regulation (usually classical PWM) to ensure a satisfactory harmonic content of the currents.

Of course this kind of problem is not felt by the DTC controller because the stator flux is maintained within a circular ring; then it presents a good harmonic content, which is reflected identically to the currents, much more profitable than the DSC one.

Another problem, common to both types of regulatory, concerns once again the low speed operation. It is due to the influence of the term $R_s\, i_s$, which, in this range, is not negligible compared to the value of the supply voltage; there is a deterioration of the trajectory of stator flux whenever the zero voltage vector is imposed (i.e. every time the torque reaches the high threshold). When the inverter provides zero voltage, the flux follows the direction of the stator current vector with the law:

$$\overline{\psi_s} = \int -R_s \cdot \overline{i_s} \cdot dt$$

so coming out from the theoretical trajectory.

The effects have two negative consequences:

- the value of the flux becomes smaller than that imposed as a reference
- the distortion of the currents increases with consequent deterioration of the harmonic content.

Finally, another problem common to both types of controllers is the starting: DTC and DSC methods fail when they operate at near-zero speed with a torque reference equal to zero (the state observer doesn't work well). In fact, in these conditions they are unable to control the flux in a direct way.

You must then start the machine in other ways, such as with traditional methods of PWM or methods of indirect control of the flux, up to about 0.25 Hz.

But the main drawback of these methods consists in the high sampling frequencies of the currents (much greater than that which occurs in a vector control, in which the sampling frequency corresponds to the frequency of the PWM), in the estimation of the torque and the flux at the same high rate, in order to be able to recognize, with good precision, the reaching of the extremes of the bandwidth of the comparator of flux and torque. These frequencies are not compatible with a hardware-based microcontroller, but they need, generally, dedicated hardware.