CHAPTER 2.
DIRECT TORQUE CONTROL.
PRINCIPLES and GENERALITIES.

2.1 - Induction motor controllers.

2.1.1 – Voltage/frequency.

There are many different ways to drive an induction motor. The main differences between them are the motor's performance and the viability and cost in its real implementation.

Despite the fact that "Voltage/frequency" (V/f) is the simplest controller, it is the most widespread, being in the majority of the industrial applications. It is known as a scalar control and acts imposing a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback. However, this controller doesn't achieve a good accuracy in both speed and torque responses mainly due to the fact that the stator flux and the torque are not directly controlled. Even though, as long as the parameters are identified, the accuracy in the speed can be 2% (except in a very low speed) and the dynamic response can be approximately around 50ms [LEO 1][LUD 2].

2.1.2 – Vector controls.

In these types of controllers, there are control loops for controlling both the torque and the flux [BOS 1]. The most widespread controllers are the ones that use vector transform such as either Park or Ku. Its accuracy can reach values such as 0.5% regarding the speed and 2% regarding the torque, even in stand still.

The main disadvantages are the huge computational capability required and the compulsory good identification of the motor parameters [ROM 1].

2.1.3 – Field Acceleration method.

This method is based on avoiding the electromagnetic transients in the stator currents, keeping its phase continuous. Therefore, the equations used can be simplified saving the vector transformation in the controllers.

It is achieved some computational reduction, overcoming the main problem in the vector controllers and then becoming an important alternative for the vector controllers [BED 5] [ROM 1] [YAM 1].

2.1.4 - Direct Torque Control.

In Direct Torque Control it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state.

Its main features are as follows [LUD 1] [VAS 2]:

- Direct torque control and direct stator flux control.
- Indirect control of stator currents and voltages.
- Approximately sinusoidal stator fluxes and stator currents.
- High dynamic performance even at locked rotor.

This method presents the following advantages:

- Absence of co-ordinate transform.
- Absence of voltage modulator block, as well as other controllers such as PID for flux and torque.
- Minimal torque response time, even better than the vector controllers.

Although, some disadvantages are present:

- Possible problems during starting.
- Requirement of torque and flux estimators, implying the consequent parameters identification.
- Inherent torque and flux ripples.

2.2 - Principles of Direct Torque Control.

2.2.1 - Introduction.

As it has been introduced in expression 1.81, the electromagnetic torque in the three-phase induction machines can be expressed as follows [BOL 1][VAS 2]:

$$t_e = \tfrac{3}{2} P \overline{\psi}_s \times \bar{i}_s \tag{2.1}$$

Where $\overline{\psi}_s$ is the stator flux, $\bar{i}_s$ is the stator current (both fixed to the stationary reference frame fixed to the stator) and P the number of pairs of poles. The previous equation can be modified and expressed as follows:

$$t_e = \tfrac{3}{2} P \left|\overline{\psi}_s\right| \cdot \left|\bar{i}_s\right| \cdot \sin(\alpha_s - \rho_s) \tag{2.2}$$

Where ρ_s is the stator flux angle and α_s is the stator current one, both referred to the horizontal axis of the stationary frame fixed to the stator.

If the stator flux modulus is kept constant and the angle ρ_s is changed quickly, then the electromagnetic torque is directly controlled.

The same conclusion can be obtained using another expression for the electromagnetic torque. From equation 1.83, next equation can be written:

$$t_e = \frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} \left|\overline{\psi}'_r\right| \times \left|\overline{\psi}_s\right| \cdot sin(\rho_s - \rho_r) \tag{2.3}$$

Because of the rotor time constant is larger than the stator one, the rotor flux changes slowly compared to the stator flux; in fact, the rotor flux can be assumed constant. (The fact that the rotor flux can be assumed constant is true as long as the response time of the control is much faster than the rotor time constant). As long as the stator flux modulus is kept constant, then the electromagnetic torque can be rapidly changed and controlled by means of changing the angle $\rho_s - \rho_r$ [TAK 2] [VAS 2].

2.2.2 - DTC Controller.

The way to impose the required stator flux is by means of choosing the most suitable Voltage Source Inverter state. If the ohmic drops are neglected for simplicity, then the stator voltage impresses directly the stator flux in accordance with the following equation:

$$\frac{d\overline{\psi}_s}{dt} = \overline{u}_s \tag{2.4}$$

Or:

$$\Delta\overline{\psi}_s = \overline{u}_s \Delta t \tag{2.5}$$

Decoupled control of the stator flux modulus and torque is achieved by acting on the radial and tangential components respectively of the stator flux-linkage space vector in its locus. These two components are directly proportional (Rs=0) to the components of the same voltage space vector in the same directions.

Figure 2.1 shows the possible dynamic locus of the stator flux, and its different variation depending on the VSI states chosen. The possible global locus is divided into six different sectors signalled by the discontinuous line.

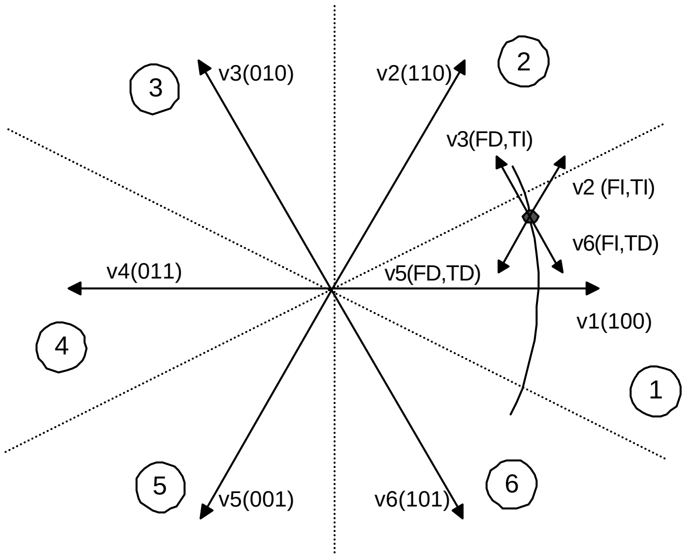

Figure 2.1. Stator flux vector locus and different possible switching voltage vectors. FD: flux decrease. FI: flux increase. TD: torque decrease. TI: torque increase.

In Accordance with figure 2.1, the general table II.I can be written. It can be seen from table II.I, that the states V_k and V_{k+3}, are not considered in the torque because they can both increase (first 30 degrees) or decrease (second 30 degrees) the torque at the same sector depending on the stator flux position. The usage of these states for controlling the torque is considered one of the aims to develop in the present thesis, dividing the total locus into twelve sectors instead of just six [LUD 1].

VOLTAGE VECTOR	INCREASE	DECREASE
Stator Flux	V_k, V_{k+1}, V_{k-1}	$V_{k+2}, V_{k-2}, V_{k+3}$
Torque	V_{k+1}, V_{k+2}	V_{k-1}, V_{k-2}

Table II.I: General Selection Table for Direct Torque Control, being "k" the sector number.

Finally, the DTC classical look up table is as follows:

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
FI	TI	V_2	V_3	V_4	V_5	V_6	V_1
	T=	V_0	V_7	V_0	V_7	V_0	V_7
	TD	V_6	V_1	V_2	V_3	V_4	V_5
FD	TI	V_3	V_4	V_5	V_6	V_1	V_2
	T=	V_7	V_0	V_7	V_0	V_7	V_0
	TD	V_5	V_6	V_1	V_2	V_3	V_4

Table II.II. Look up table for Direct Torque Control.
FD/FI: flux decrease/increase. TD/=/I: torque decrease/equal/increase.
S_x: stator flux sector. Φ: stator flux modulus error after the hysteresis block.
τ: torque error after the hysteresis block.

The sectors of the stator flux space vector are denoted from S_1 to S_6. Stator flux modulus error after the hysteresis block (Φ) can take just two values. Torque error after the hysteresis block (τ) can take three different values. The zero voltage vectors V_0 and V_7 are selected when the torque error is within the given hysteresis limits, and must remain unchanged.

2.2.3 - DTC Schematic.

In figure 2.2 a possible schematic of Direct Torque Control is shown. As it can be seen, there are two different loops corresponding to the magnitudes of the stator flux and torque. The reference values for the flux stator modulus and the torque are compared with the actual values, and the resulting error values are fed into the two-level and three-level hysteresis blocks respectively. The outputs of the stator flux error and torque error hysteresis blocks, together with the position of the stator flux are used as inputs of the look up table (see table II.II). The position of the stator flux is divided into six different sectors. In accordance with the figure 2.2, the stator flux modulus and torque errors tend to be restricted within its respective hysteresis bands. It can be proved that the flux hysteresis band affects basically to the stator-current distortion in terms of low order harmonics and the torque hysteresis band affects the switching frequency [VAS 2].

The DTC requires the flux and torque estimations, which can be performed as it is proposed in figure 2.2 schematic, by means of two different phase currents and the state of the inverter.

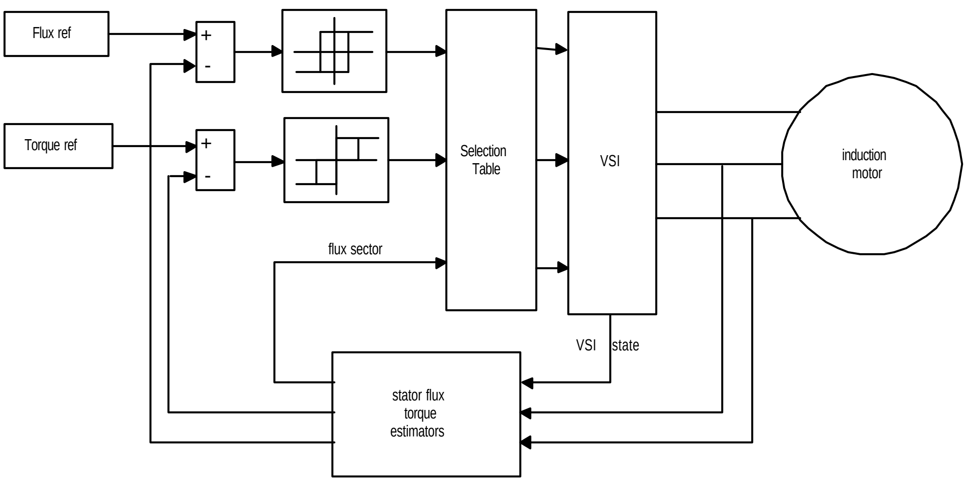

Figure 2.2. Direct Torque Control schematic.

However, flux and torque estimations can be performed using other magnitudes such as two stator currents and the mechanical speed, or two stator currents again and the shaft position [LUD 1] [TAK 2].

2.2.3.1 - Stator flux and torque estimator using w_m, i_{sA} and i_{sB} magnitudes.

This estimator does not require co-ordinate transform. It is used the motor model fixed to the stationary reference frame fixed to the stator.

Firstly, all three-phase currents must be converted into its D and Q components. By means of the Park transformation defined in equation 1.14, it can be said:

$$i_{sD} = c \cdot 1.5 \cdot i_{sA}$$
$$i_{sQ} = c \cdot \sqrt{3}/2 \cdot (2 \cdot i_{sB} + i_{sA}) \qquad (2.6)$$

If rotor current is isolated from equation 1.65 and substituted into 1.66 it can be said:

$$\bar{\psi}'_r \cdot \left(1 + p \cdot L_r/R_r - j \frac{L_r \cdot P \cdot wm}{R_r}\right) = L_m \bar{i}_s \qquad (2.7)$$

And if the expression 2.7 is rearranged:

$$\bar{\psi}'_r \cdot (R_r + p \cdot L_r) = L_m R_r \cdot \bar{i}_s + j \cdot \bar{\psi}'_r \cdot L_r \cdot P \cdot wm \qquad (2.8)$$

Expanding the previous equation into its D and Q components, is obtained:

$$\bar{\psi}'_{rD} \cdot (R_r + p \cdot L_r) = L_m R_r \cdot \bar{i}_{sD} - \bar{\psi}'_{rQ} \cdot L_r \cdot P \cdot wm \qquad (2.9)$$

$$\bar{\psi}'_{rQ} \cdot (R_r + p \cdot L_r) = L_m R_r \cdot \bar{i}_{sQ} + \bar{\psi}'_{rD} \cdot L_r \cdot P \cdot wm \qquad (2.10)$$

And taking into account that this expression will be evaluated in a computer it should be expressed in z operator instead of p one. Therefore doing the z transform of equations 2.9 and 2.10 the following equation are obtained:

$$\bar{\psi}'_{rD} \cdot \left(z - e^{-\left(R_r/L_r\right)Tz}\right) = \frac{1 - e^{-\left(R_r/L_r\right)Tz}}{R_r}\left(L_m R_r \cdot \bar{i}_{sD} - \cdot \bar{\psi}'_{rQ} \cdot L_r \cdot P \cdot wm\right) \qquad (2.11)$$

$$\bar{\psi}'_{rQ} \cdot \left(z - e^{-\left(R_r/L_r\right)Tz}\right) = \frac{1 - e^{-\left(R_r/L_r\right)Tz}}{R_r}\left(L_m R_r \cdot \bar{i}_{sQ} + \cdot \bar{\psi}'_{rD} \cdot L_r \cdot P \cdot wm\right) \qquad (2.12)$$

And in time variable:

$$\psi'_{rD}(k) = \psi'_{rD}(k-1) \cdot e^{-\left(R_r/L_r\right)Tz} + \frac{1 - e^{-\left(R_r/L_r\right)Tz}}{R_r}\left(L_m R_r i_{sD}(k-1) - L_r \cdot P \cdot \psi'_{rQ}(k-1) \cdot wm(k-1)\right) \qquad (2.13)$$

$$\psi'_{rQ}(k) = \psi'_{rQ}(k-1) \cdot e^{-\left(R_r/L_r\right)Tz} + \frac{1 - e^{-\left(R_r/L_r\right)Tz}}{R_r}\left(L_m R_r i_{sQ}(k-1) + L_r \cdot P \cdot \psi'_{rD}(k-1) \cdot wm(k-1)\right) \qquad (2.14)$$

Finally, stator flux can be obtained as follows:

$$\psi_{sD}(k) = i_{sD}(k) \cdot \tfrac{L_x}{L_m} + \psi'_{rD}(k) \cdot \tfrac{L_m}{L_r} \tag{2.15}$$

$$\psi_{sQ}(k) = i_{sQ}(k) \cdot \tfrac{L_x}{L_m} + \psi'_{rQ}(k) \cdot \tfrac{L_m}{L_r} \tag{2.16}$$

Torque is obtained using equation 1.82.

2.2.3.2 - Stator flux and torque estimator using V_{dc}, i_{sA} and i_{sB} magnitudes.

In case that sensor-less direct torque control is desired, neither rotor speed nor rotor position are available. In order to obtain an estimation of the stator flux space vector, two possible methods may be applied:

- An estimation that does not require speed or position signals may be used.
- The motor speed may be estimated and fed into a flux estimator.

Stator flux and torque estimation based on the stator voltage equation does not require speed or position information when stationary co-ordinates are applied. Thus, from the VSI state and having the instantaneous value of the V_{dc}, it can be deduced the voltages in each phase. Once the voltage and the current values are calculated and measured respectively, they are transformed in D and Q components by means of Park transformations.

Finally from equation 1.64 it can be said:

$$\overline{\psi}_s = \int \left(\overline{u}_s - R_s \cdot \overline{i}_s \right) dt \tag{2.17}$$

And expressing this equation in z operator by means of the z transform:

$$\overline{\psi}_s = \frac{z^{-1}}{1 - z^{-1}} \cdot Ts \cdot \left(\overline{u}_s - R_s \cdot \overline{i}_s \right) \tag{2.18}$$

Expressing the previous equation in time and in its D and Q components:

$$\psi_{sD}(k) - \psi_{sD}(k-1) = Ts \cdot u_{sD}(k-1) - Ts \cdot R_s \cdot i_{sD}(k-1)$$

$$\psi_{sQ}(k) - \psi_{sQ}(k-1) = Ts \cdot u_{sQ}(k-1) - Ts \cdot R_s \cdot i_{sQ}(k-1) \tag{2.19}$$

It may be deduced that the stator voltage space vector components are derived from the inverter internal switch settings. This fact avoids the measurement of the stator voltage pulses. In practice, the D.C. link voltage is measured, thus the D and Q components of the stator voltage space phasor can be derived. It should be noted that a co-ordinate transform is not required. However, the accuracy of the estimation is limited due to the open loop integration that can lead to large flux estimation errors [LUD 1].

2.2.4 - Parameter detuning effects.

Stator flux and torque estimators DTC based systems, shown in sections 2.2.3.1 and 2.2.3.2, depart from their ideal behaviour when the motor model parameters used are not different from the true motor model parameters. It can be proved that estimators that uses either position or speed have similar characteristics, which are good enough, as long as the estimated parameters have an error lower than 10%. However, the estimator that uses V_{dc} performs very poorly when just small errors of its parameters are present [LUD 1].

In further chapters will be used the estimator introduced in section 2.2.3.1.

2.3 - Improvements in Direct Torque Control.

2.3.1 - Introduction.

In the classical DTC, there are several drawbacks. Some of them can be summarised as follows:

- Sluggish response (slow response) in both start up and changes in either flux or torque.
- Large and small errors in flux and torque are not distinguished. In other words, the same vectors are used during start up and step changes and during steady state.

In order to overcome the mentioned drawbacks, there are different solutions, which can be classified as follows:

- Non artificial intelligence methods, mainly "sophisticated tables".
- Predictive algorithms, used to determine the switching voltage vectors. A mathematical model of the induction motor is needed. Electromagnetic torque and stator flux, are estimated for sampling period for all possible inverter sates. Then, the predictive algorithm selects the inverter switching states to give minimum deviation between the predicted value of the electromagnetic torque and the reference torque.
- Fuzzy logic based systems.

Next sections deal with all these methods, achieving a good knowledge of all them in order to realise the best DTC improvement.

2.3.2 – Different tables.

2.3.2.1- First approach.

2.3.2.1.1 - Six sector table but different zones.

First idea that comes up, when it is tried to improve the DTC by means of changing the tables, is to use six sectors, as in classical DTC, but changing the zones. Hence, instead of having as a first sector the zone from -30º up to 30º, it will be from 0º up to 60º. It can be observed that in this case, the states not used in the first zone will be V_3 and V_6 instead of V_1 and V_4. This novel sector division is shown in figure 2.3.

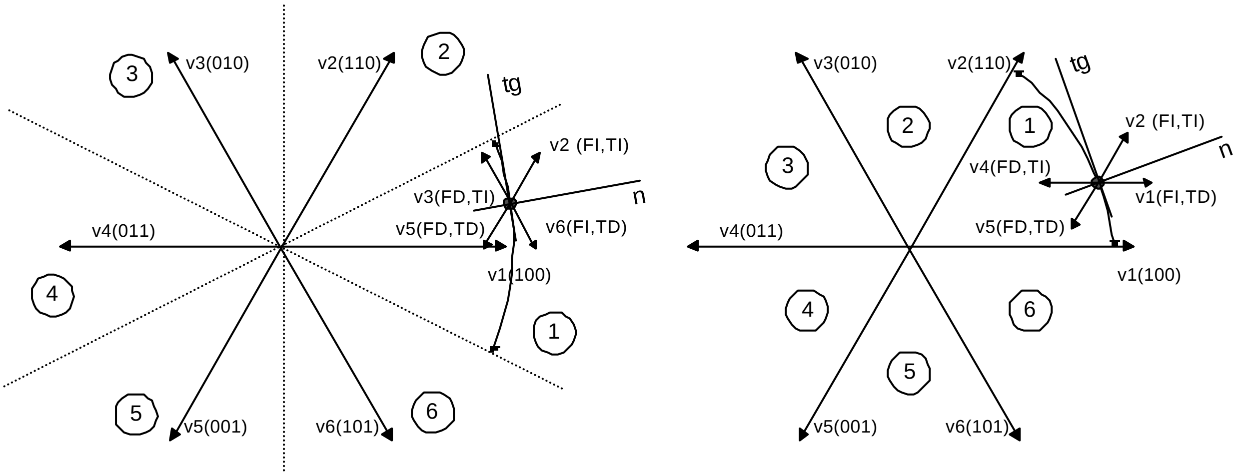

Figure 2.3. Left: Classical DTC and its six sectors.
Right: Modified DTC and its new six sectors.

In Accordance with the figure 2.3, the general table II.III can be written.

	CLASSICAL DTC -30º → 30º	**MODIFIED DTC** 0º → 60º
V_1	30º → -30º Torque ambiguity	0º → -60º TD, FI
V_2	90º → 30º TI, FI	60º → 0º TI, FI
V_3	150º → 90º TI, FD	120º → 60º Flux ambiguity
V_4	-150º → 150º Torque ambiguity	180º → 120º TI, FD
V_5	-90º → -150º TD, FD	-120º → -180º TD, FD
V_6	-30º → -90º TD, FI	-60º → -120º Flux ambiguity

Table II.III: Behaviour of each state just in the first zone for the classical DTC (left) and the modified DTC (right). It is shown the angle of the voltage vector in the sector with reference to the normal and tangential axis. TI/TD: Torque Increase/Decrease. FI/FD: Flux Increase/Decrease

It can be seen that the states V_1 and V_4, are not used in the classical DTC (c_DTC) because they can increase or decrease the torque at the same sector depending on if the position is in its first 30 degrees or in its second ones. In the modified DTC (m_DTC), V_3 and V_6 are the states not used. However, now the reason is the ambiguity in flux instead of torque, as it was in the c_DTC. This is considered to be an advantage in favour of the m_DTC as long as the main point is to control the torque. Therefore, it is better to loose the usage of two states for flux ambiguity that for torque one.

Table II.IV shows the m_DTC look up table for all its six sectors.

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
FI	TI	V_2	V_3	V_4	V_5	V_6	V_1
	T=	V_0	V_7	V_0	V_7	V_0	V_7
	TD	V_1	V_2	V_3	V_4	V_5	V_6
FD	TI	V_4	V_5	V_6	V_1	V_2	V_3
	T=	V_7	V_0	V_7	V_0	V_7	V_0
	TD	V_5	V_6	V_1	V_2	V_3	V_4

Table II.IV. Look up table for Modified DTC. FD/FI: flux decrease/increase.
TD/=/I: torque decrease/equal/increase.
S_x: stator flux sector. Φ: stator flux modulus error after the hysteresis block.
τ: torque error after the hysteresis block.

2.3.2.1.2 - Twelve sector table.

In classical DTC there are two states per sector that present a torque ambiguity. Therefore, they are never used. In a similar way, in the modified DTC there are two states per sector that introduce flux ambiguity, so they are never used either.

It seems a good idea that if the stator flux locus is divided into twelve sectors instead of just six, all six active states will be used per sector. Consequently, it is arisen the idea of the twelve sector modified DTC (12_DTC). This novel stator flux locus is introduced in figure 2.4. Notice how all six voltage vectors can be used in all twelve sectors. However, it has to be introduced the idea of small torque increase instead of torque increase, mainly due to the fact that the tangential voltage vector component is very small and consequently its torque variation will be small as well.

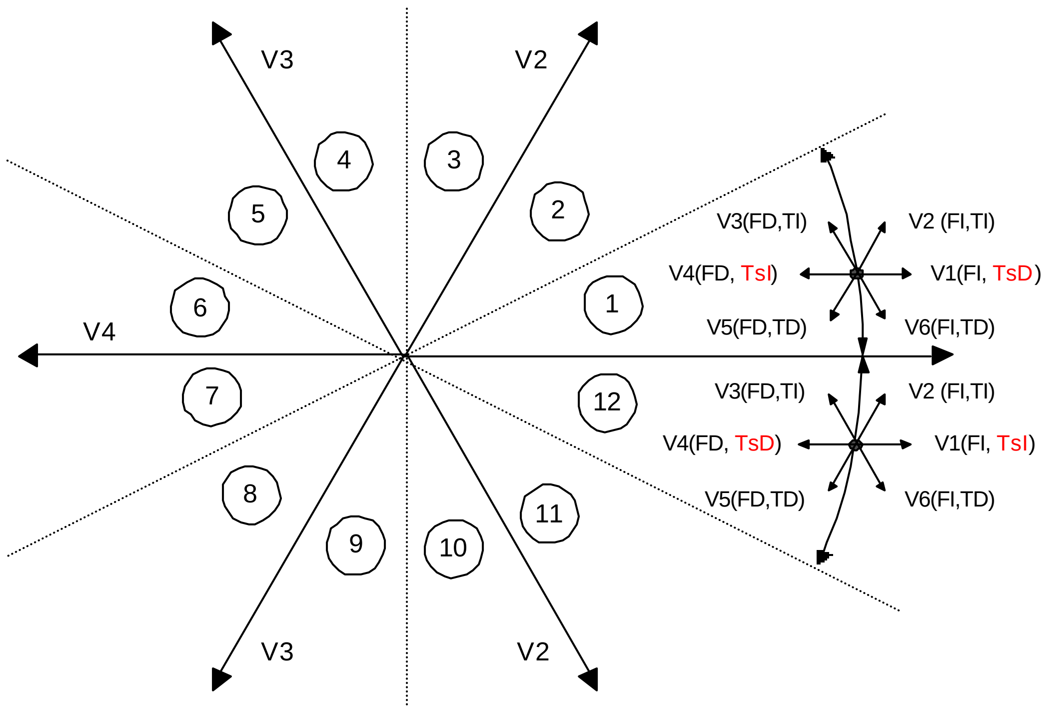

Figure 2.4. Twelve sector modified DTC (12_DTC) and its sectors.
FD/FI: flux decrease/increase. TD/TI: torque decrease/increase. TsD/TsI: torque small decrease/increase. Notice how all six voltage vectors can be used in all twelve sectors, disappearing all ambiguities.

Table II.V can be written when a twelve-sector locus is used.

S_{12}	INCREASE	DECREASE
Stator Flux	V_1, V_2, V_6	V_3, V_4, V_5
Torque	V_1, V_2, V_3	V_4, V_5, V_6
S_1	INCREASE	DECREASE
Stator Flux	V_1, V_2, V_6	V_3, V_4, V_5
Torque	V_2, V_3, V_4	V_5, V_6, V_1

Table II.V: Table for sectors 12 and 1 in the 12_DTC. Notice how all six voltage vectors can be used in all sectors disappearing all ambiguities.

As it has been mentioned in the previous paragraph, it is necessary to define small and large variations. It is obvious that V_1 will produce a large increase in flux and a small increase in torque in sector S_{12}. On the contrary, V_2 will increase the torque in large proportion and the flux in a small one.

It is reasonable to deduce that the torque error should be divided in the number of intervals that later on will be measured. Therefore, the hysteresis block should have four hysteresis levels at is suggested in table II.VI.

If the flux and torque effects are divided into eight groups, it can be drawn figure 2.5.

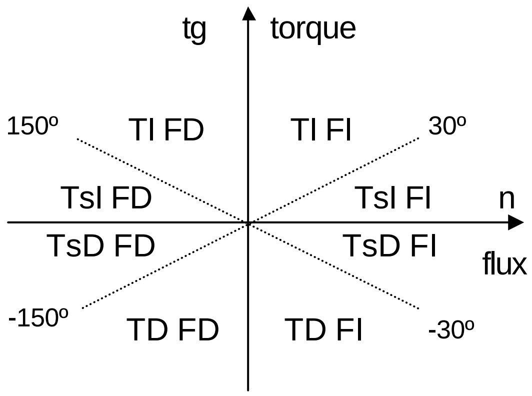

Figure 2.5. Eight levels of flux and torque variation for the flux stator locus in the 12_DTC. FD/FI: flux decrease/increase. TD/TI: torque decrease/increase. TsD/TsI: torque small decrease/increase. Notice how all six active voltage vectors can be used in all twelve sectors, disappearing all ambiguities.

Finally, the look up table is presented in table II.VI.

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
FI	TI	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
	TsI	$*V_2$	V_2	$*V_3$	V_3	$*V_4$	V_4	$*V_5$	V_5	$*V_6$	V_6	$*V_1$	V_1
	TsD	V_1	$*V_1$	V_2	$*V_2$	V_3	$*V_3$	V_4	$*V_4$	V_5	$*V_5$	V_6	$*V_6$
	TD	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
FD	TI	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3
	TsI	V_4	$*V_4$	V_5	$*V_5$	V_6	$*V_6$	V_1	$*V_1$	V_2	$*V_2$	V_3	$*V_3$
	TsD	V_7	V_5	V_0	V_6	V_7	V_1	V_0	V_2	V_7	V_3	V_0	V_4
	TD	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5

Table II.VI: Switching table for the 12_DTC.
FD/FI: flux decrease/increase. TD/=/I: torque decrease/equal/increase.
S_x: stator flux sector. Φ: stator flux modulus error after the hysteresis block.
τ: torque error after the hysteresis block.
(* there is no suitable state. It has been chosen the second most suitable).

2.3.2.1.3 - Simulations, results and conclusions.

In order to compare the responses, it is needed an index error. The one that is used is IE2, which is the integral of the square error. It should be noted the fact that the index is computed by means of the square error instead of just the error; therefore, the more error is produced the more emphasis it is given in the index.

The torque reference value is described in figure 2.6.

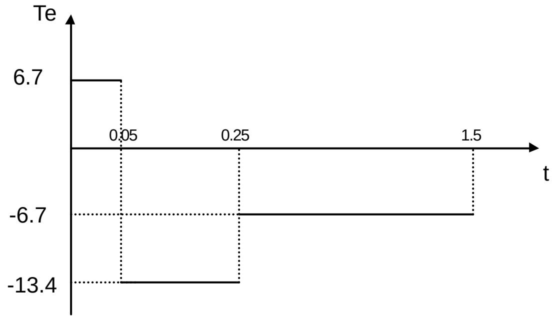

Figure 2.6. Input torque reference value.

Stator flux set point was set to its nominal value. All simulations have been done just for the Motor_1kW (see chapter 4).

The torque load was proportional to the motor speed, and it was equal to the nominal motor torque at nominal speed.

The simulated results for first approach modified DTC are shown in table II.VII. Results are not as good as expected.

IE2	Flux	Torque
c_DTC	0.003161	1.019
m_DTC	--	--
12_DTC	0.002869	1.3509

Table II.VII: IE2 values after the simulations. The reference torque value is shown in figure 2.6, and the stator reference flux value was the nominal one.
(-- meaning that it didn't work).

Conclusions:

- At the beginning and end of each sector, the flux locus is worse in both c_DTC and m_DTC. It was believed that 12_DTC would solve this problem but it didn't.
- It is observed that c_DTC performs better in steady state flux and worse in transient flux. However, it performs worse in steady state torque and better in transient torque.
- It is observed that m_DTC performs worse in steady state flux and better in transient flux. However, it performs better in steady state torque and worse in transient torque.

- If the stator flux locus is observed the evolution is as shown in figure 2.7.

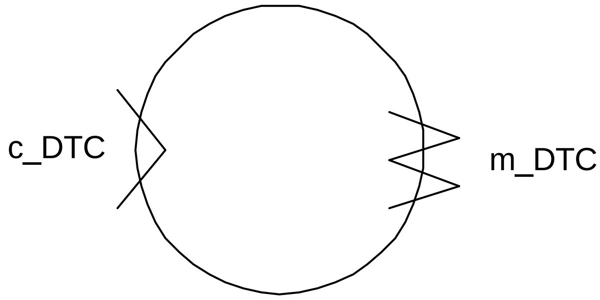

Figure 2.7. Evolution of the flux stator locus in the classical DTC and modified DTC. It can be seen how the flux ripple is higher in the m_DTC than in the c_DTC.

- According to the definition given in figure 2.5, it can be said that all the states in m_DTC produce large variation in flux, meanwhile the ones in c_DTC produce large variation in torque. Table II.VIII can be written. This fact explains both, the locus in figure 2.7 in the previous conclusion and why the m_DTC is unable to reach nominal conditions. It can be concluded that depending on the voltage vector angle referred to the normal reference axis, the variation in flux and torque will be either small or large.

S_1	**c_DTC** **-30º ® 30º**	**m_DTC** **0º ® 60º**
V_1	30º → -30º Not used	0º → -60º Flux large
V_2	90º → 30º Torque large	60º → 0º Flux large
V_3	150º → 90º Torque large	120º → 60º Not used
V_4	-150º → 150º Not used	180º → 120º Flux large
V_5	-90º → -150º Torque large	-120º → -180º Flux large
V_6	-30º → -90º Torque large	-60º → -120º Not used

Table II.VIII. Behaviour of each state just in the sector 1 for the classical DTC (left) and the modified DTC (right). It is shown the angle of the voltage vector in the sector with reference to the normal axis. Large flux and large torque variations.

- States, which are supposed to increase the torque in a small way (because they are either between 0º and 30º or 150º and 180º), don't increase the torque at all. Instead they do decrease the torque.
- If index error flux (IE2) improves, the torque one becomes worse and the other way round. It seems almost impossible to improve both at the same time.

2.3.2.2 - Second approach.

After the bad previous results regarding c_DTC, m_DTC and 12_DTC; it is done a further investigation in order to find out why the expectations were not achieved.

m_DTC				c_DTC				Stator
TI / FI		TI / FD		TI / FI		TI / FD		Flux angle
	0º		120º		60º		120º	60º
	15º		135º	V3	75º	V4	135º	45º
V2	30º	V4	150º		90º / 30º		150º / 90º	30º
	45º		165º		45º		105º	15º
	60º / 0º		180º / 120º	V2	60º	V3	120º	0º
	15º		135º		75º		135º	-15º
V1	30º	V3	150º		90º / 30º		150º / 90º	-30º
	45º		165º	V1	45º	V2	105º	-45º
	60º		180º		60º		120º	-60º

small torque

medium torque

large torque

Table II. IX. It is shown different possibilities for choosing the appropriate states attending the criteria of the level of torque variation required. Just for the stator flux angle from -60º up to 60º. It is shown the angles of each voltage vector referred to the tangential and normal reference axis.

From table II.IX seems evident that for nominal torque the best table is the c_DTC because large torque variation must be available. However, for small torque m_DTC is more appropriate because small torque variations are needed. On the other hand, 12_DTC has got plenty of sense when medium torque is required. This fact gives the idea that could be worthy use different tables depending on the working point, which means depending on both the speed and torque. Hence, four general working points are distinguished:

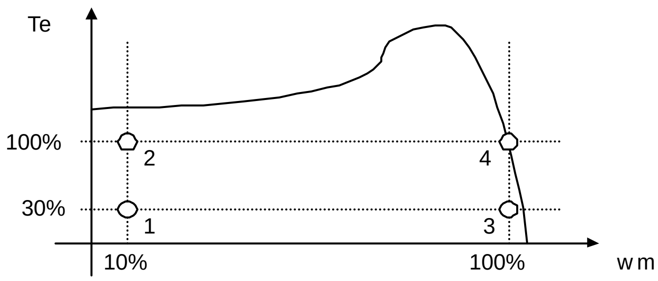

Figure 2.8. It is shown the typical torque-speed induction motor characteristic. It is defined four working points.

Simulations have done during 1.5s. Torque and flux reference values have been set to its nominal values for the motor 1_kW (see chapter4).

IE2	c_DTC		m_DTC	
Work point	Flux	Torque	Flux	Torque
1	0.0177	0.3383	0.0023447	0.25697
2	0.00304	0.6084	0.0018883	0.56425
3	0.01592	0.5748	---	---
4	0.03161	1.019	---	---

Table II.X. IE2 simulated values. (--- meaning that it didn't work).

Conclusions:

- It is born the idea of the working point, due to the fact that each working point has different most suitable look up table.
- It is proved why in nominal conditions the best was c_DTC.

2.3.2.3 - Third approach.

It has been observed that some states don't behave, as they should, regarding torque. It should be remembered that if its tangential component in the flux locus is positive the state is supposed to increase the torque and the other way round. However, a more accurate study of the torque expression gives the idea that the torque just depends on the "sin(ρs-ρr)", as it is introduced in expression 2.3.

Once the speed is high, then the angle of the stator flux increases fast. Under these circumstances, states that are supposed to increase the torque do it in a very small quantity. Null states, which are supposed to keep the torque in the same level, decrease it in a notable way. Finally, the voltage states which are supposed to decrease the torque do it but in a very strong way, producing a big ripple in the torque response. Once one of the decreasing states is applied, it is needed several increasing states to recuperate the set point value again.

This fact leads to the idea of modifying the c_DTC table once the working point is near to nominal conditions; that is to say, always than both magnitudes are higher than 50% of the nominal conditions. In this new table, the decreasing states are not used and the null states are used instead. The states that are used for maintaining the torque value, are the increasing ones. Hence, another modified DTC (m2_DTC) is created and its table is shown in table II.XI.

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
FI	TI	V_2	V_3	V_4	V_5	V_6	V_1
	T=	V_2	V_3	V_4	V_5	V_6	V_1
	TD	V_0	V_7	V_0	V_7	V_0	V_7
FD	TI	V_3	V_4	V_5	V_6	V_1	V_2
	T=	V_3	V_4	V_5	V_6	V_1	V_2
	TD	V_7	V_0	V_7	V_0	V_7	V_0

Table II.XI. Look up table for m2_DTC.
FD/FI: flux decrease/increase. TD/=/I: torque decrease/equal/increase.
S_x: stator flux sector. Φ: stator flux modulus error after the hysteresis block.
τ: torque error after the hysteresis block.

Simulation results for working point 4, which were performed in the same conditions as in 2.3.2.2, have been as follows:

IE2	Flux	Torque
c_DTC	0.003161	1.019
m2_DTC	0.003171	0.6731

Table II.XII. IE2 simulated values for the classical DTC and the second modified DTC.

From this third approach can be concluded that when the working point is near to the nominal conditions, it is a good idea do not use the torque decreasing states and use the null ones instead. Under the same circumstances, for torque maintaining states is better use the increase states instead of the null ones.

2.3.2.4 - Conclusions.

Several conclusions from, all this different look up tables study, have been obtained:

- There is not a remarkable improvement in the motor performance changing the look up tables. However, some little improvements can be achieved.

- The working point determines the most suitable voltage state. In other words, the most suitable state not only depends on flux and torque error values and on the sector, but also on the working point (torque and speed values).
- The voltage vector angle referred to the normal reference axis implies a small or large variation in stator flux and torque.
- If the working point is high, the torque decreasing states are forbidden because they introduce a high ripple. Instead of them, it is much better to use the null states.

2.3.3 – Predictive methods.

The point of this method is to choose the switching vectors that are in accordance with the range of flux and torque errors, overcoming therefore, one of the main drawbacks of the classical DTC. For this purpose a suitable mathematical model of the induction machine is used and the electromagnetic torque is estimated for each sampling period for all possible inverter modes. The predictive algorithm then selects the inverter switching states to give minimum deviation between the predicted electromagnetic torque and the reference torque.

It is obtained a reference voltage value; therefore Space Vector Modulation has to be applied [ARI 1]. If the machine is not in steady state, the probability of obtaining a reference voltage decreases. In this case, the classical DTC will be applied.

The main problems for this solution are the procedure for calculating the voltage reference and the following decomposition by means of SVM. The calculation of the voltage reference value and the SVM need a high computation capability, loosing one of the best advantages of DTC, which is its simplicity in calculus. Moreover, in any transient this predictive method won't work properly being compulsory the usage the classical DTC instead.

A brief summary of the mathematical expression for implementing this method is introduced in equations (2.20) and (2.21) [CAS 1] [HAB1] [VAS 2].

Equations (2.20) and (2.21) show the fact that this method increases the calculus of the drive in a considerable way. Moreover, a good machine model is needed in order to know all the parameters that appears in equation (2.20). Therefore, the mentioned method is not considered a good solution for improving the DTC.

In order to obtain the voltage reference value, equations (2.20) must be solved.

$$a \cdot \overline{u}_{ref\_D}^{2} + b \cdot \overline{u}_{ref\_D} + c = 0$$
$$a = T_z^2 + \left({\psi_{sQ} \cdot T_z} \big/ {\psi_{sD}} \right)^2$$
$$b = 2 \cdot \alpha \cdot \psi_{sQ} \cdot \left({T_z^2} \big/ {\psi_{sD}} \right)^2 + 2 \cdot T_z \cdot \psi_{sD} + 2 \cdot {\psi_{sQ}^2 \cdot T_z} \big/ {\psi_{sD}}$$
$$c = 2 \cdot \alpha \cdot T_z \cdot \left({\psi_{sQ}} \big/ {\psi_{sD}} \right)^2 + \psi_{sD}^2 + \psi_{sQ}^2 - \psi_{s\_ref}^2$$
$$\alpha = \frac{2 \cdot \Delta t_e \cdot L_s}{3 \cdot P \cdot T_z} + \psi_{sD} \cdot e_{sQ} - \psi_{sQ} \cdot e_{sD} \tag{2.20}$$

Once the reference voltage value is obtained, it must be added the stator resistance drops.

$$\overline{v}_{ref} = \overline{u}_{ref} + R_s \cdot \overline{i}_s \tag{2.21}$$

This thesis, after being studied this predictive method, will be focused on the Fuzzy Logic controllers, because it is thought that they can improve in a better way the classical DTC without increasing the complexity in calculus that much.

2.3.4 - Fuzzy logic based systems.

In the classical DTC induction motor drive there are torque and flux ripples because none of the inverter switching vectors is able to produce the desired changes in both torque and stator flux. However, using various techniques can be reduced the ripples in the electromagnetic torque and stator flux. Some of these techniques involve the usage of high switching frequencies or the change in inverter topology, but it is also possible to use schemes which do not involve any of the mentioned techniques, such as the duty ratio control [BIR 1] [VAS 3].

In DTC induction motor drive, the increase of switching frequency is desirable since it reduces the harmonic content of the stator currents, and also leads to reduce torque harmonics. However, if high switching frequency is used, it will result in an increment of switching losses (leading to an efficiency reduction). It also will increase the stress of the semiconductor devices of the inverter. Furthermore, in case of high switching frequency, a fast processor is required since the control processing time becomes small. This increases the cost.

When changed the inverter topology is used, it is possible to use an increased number of switches, but this will also increase the costs [MAR 2].

However, it is also possible to use schemes, such as duty ratio control, which do not involve using inverters with a higher number of switches.

In the classical DTC induction motor drive a voltage vector is applied for the entire period, and this causes the stator current and electromagnetic torque exceeds its reference value early during the cycle, causing a high torque ripple. Switching cycles then follows this, in which the zero switching vectors are applied in order to reduce the electromagnetic torque to reference value.

The suggested technique is based on applying to the inverter the selected active states just enough time to achieve the torque and flux references values. The rest of the switching period a null state is selected which won't almost change both the torque and the flux. Therefore, a duty ratio (δ) has to be determined each switching time. By means of varying the duty ratio between its extreme values (0 up to 1) it is possible to apply any voltage to the motor.

The optimum duty ratio per sampling period is a non-linear function of the electromagnetic torque error, the stator flux position and the working point, which is determined by the motor speed and the electromagnetic torque. It is obvious that it is extremely difficult to model such an expression since it is a different non-linear function per working point. Thus, it is believed that by using a Fuzzy Logic based DTC system it is possible to perform a fuzzy-logic-based duty-ratio controller, where the optimum duty ratio is determined every switching period [BIR 1][VAS 3].

The mentioned Fuzzy Logic method is considered a good solution for improving the DTC. This thesis after being studied this method will be focused on the Fuzzy Logic controllers, because it is thought that they can improve in a better way the classical DTC without increasing the complexity in calculus that much.

2.3.5 - Regulating the flux.

As it has been explained in the previous sections, the ripples in the electromagnetic torque and stator flux are extremely reduced by using controllers based on Fuzzy Logic systems or predictive methods. However, in order to obtain even a better reduction, stator flux reference value has to be adapted to an optimum value, which should be just large enough to produce the desired torque. The reason is that with this optimum value the increase in the active state is just large enough and the slight reduction in the null states is lower. Moreover, it is achieved a reduction in the power reactive consumption taken from the mains supply.

The optimum expression, which gives the just large enough stator flux for the desired torque is obtained from expressions 1.97, 1.98 and 1.99. Re-arranging the mentioned expressions, the final expression, which relates the stator flux and the torque, is given in 2.22

$$y_s = \sqrt{\frac{\left[\frac{R_r}{s}\left(L_{s1} + \frac{3}{2} L_{sm}\right)\right]^2 + \left[w_s\left(L_{r1}\left(L_{s1} + \frac{3}{2} L_{sm}\right) + \frac{3}{2} L_{sm} L_{s1}\right)\right]^2}{3\frac{P}{2}\frac{R_r}{s}\frac{1}{w_s}\left(w_s \frac{3}{2} L_{sm}\right)^2} T} \tag{2.22}$$

Equation 2.22 can be presented as in equation 2.23.

$$\psi_s = \mathrm{cte} \cdot \sqrt{\mathrm{T}}$$

$$\mathrm{cte} = \sqrt{\frac{\left[\frac{R_r}{s}\left(L_{s1} + \frac{3}{2} L_{sm}\right)\right]^2 + \left[w_{sn}\left(L_{r1}\left(L_{s1} + \frac{3}{2} L_{sm}\right) + \frac{3}{2} L_{sm} L_{s1}\right)\right]^2}{3\frac{P}{2}\frac{R_r}{s}\frac{1}{w_{sn}}\left(w_{sn} \frac{3}{2} L_{sm}\right)^2}} \tag{2.23}$$

Finally the schematic of the DTC based on fuzzy controllers and optimising its reference stator flux value is as follows:

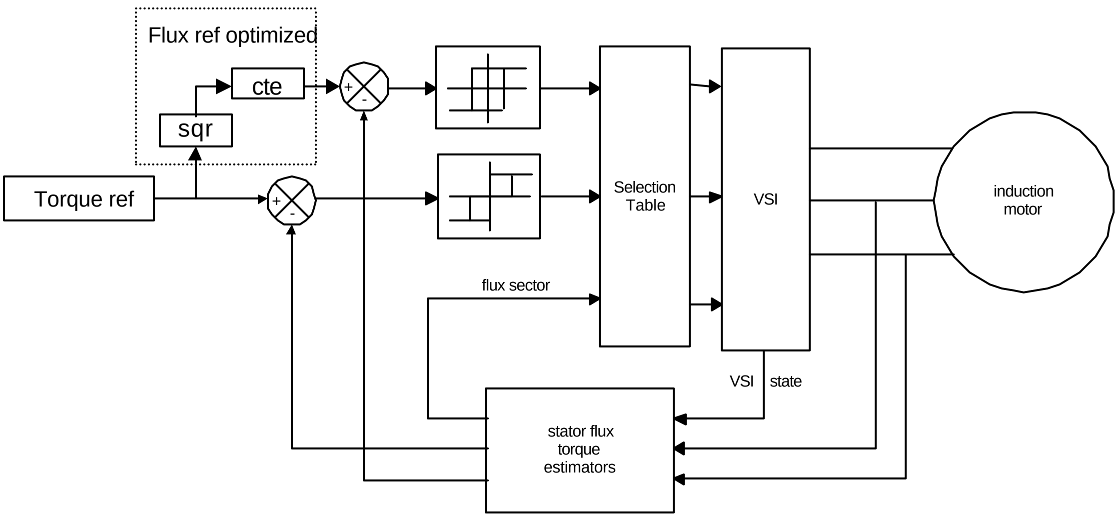

Figure 2.9. Flux reference optimised controller in a classical DTC.

It should be noted that this optimised stator flux value it is not only valid in DTC but also in any drive.

2.4 - Interim conclusions.

It has been explained the basic concepts of the Classical Direct Torque Control. Two different estimators for the stator flux and torque have been fully developed. However, just the estimator from section 2.2.3.1 has been used in further chapters and has been implemented for the further experimental results.

Despite the fact that the aim of this thesis is not the parameters detuning effects, it has been studied its main effects and has been shortly summarised in section 2.2.4.

Four different methods for improving the classical DTC, which is the aim of the thesis, have been studied and deeply discussed:

- The first method is the search of a better look up table. After the research done in this field, it can be concluded that by means of changing the table can not be remarkably improved the DTC performance. However, some little improvements can be achieved. Many conclusions have been obtained in this study, being the fundamental ideas for the development of the most suitable Fuzzy Logic controller, as it is explained in next section 3.2.1.1.
- The second method is the predictive one. It has been concluded that it is too complicated regarding its real implementation because of its calculus, eliminating one of the DTC advantages, which is its simplicity.
- The application of the Fuzzy Logic for implementing a simple modulation between the selected active state and a null one, is the third method. It can be concluded that this method is very promising and this thesis will be focused on that in the following chapters.
- Finally, the fourth method is the regulation of the stator flux reference value. This method can be applied in any motor drive. Not only it reduces the torque ripple improving the motor performance, but also reduces the power reactive consumption taken from the mains supply. Therefore, this method will be considered in further sections as well.