CHAPTER 3.

FUZZY LOGIC DIRECT TORQUE CONTROL.

3.1 - Introduction.

In DTC induction motor drive there are torque and flux ripples because none of the VSI states is able to generate the exact voltage value required to make zero both the torque electromagnetic error and the stator flux error.

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. A null state is selected for the remaining switching period, 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. Therefore, this technique is based on a two-state modulation. These two states are the active one and a null one.

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 suggested Fuzzy Logic system is divided into two different Fuzzy Logic controllers. The first one will act each time that the selected active VSI state has changed, being different to the previous one. The second controller will act in the opposite situation, which is when the active VSI selected state is the same as the previous one. These Fuzzy Logic controllers and its functionality are explained deeper in section 3.2.

Both fuzzy logic controllers use the Centroid defuzzification method. The relation between different conditions in the same rule is done by means of "and" operator. On the other hand, the relationship between different rules is done by means of "or" operator.

3.2 - Fuzzy Logic Direct Torque Control.

3.2.1 - Fuzzy Logic controller 1.

3.2.1.1- Objectives.

From the section entitled "first approach" (2.3.2.1) was lead the idea of small and large torque increases or decreases (see figure 2.5). This idea will be taken into account by means of the stator flux position as input of the Fuzzy Logic system.

From the section entitled "second approach" (2.3.2.2) was born the idea of the working point. It does seem obvious that if the working point increases, then the duty cycle must tend to one and in the opposite case the duty cycle must tend to zero. This idea is considered by means of the working point membership input and its consequent distribution in the working plane.

Finally from the section entitled "third approach" (2.3.2.3) were born two main ideas. The first one is that the higher the working point is, the more torque is decreased by the null states (instead of keeping it constant). The second idea is that the torque decrease states decreases the torque too much. As a solution, once a small decrease in torque is required, it will be generated by means of modulating a torque increase state and a null one, being the result after the entire period a small reduction in torque. The torque maintaining state will be generated by means of a torque increase state, (which almost do not increase the torque under these conditions), instead of a null one. In this Fuzzy Logic controller these ideas from the third approach will be implemented by means of the working point and torque error inputs.

3.2.1.2- Inputs and output membership functions.

In such a Fuzzy Logic system, there are three inputs, stator flux position, electromagnetic torque error and the motor working point i.e. speed and torque. The output is the duty ratio.

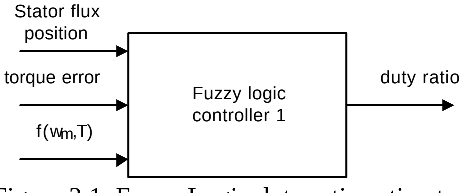

Figure 3.1. Fuzzy Logic duty ratio estimator

The fuzzy system comprises four groups of rules. Two of them are used when the stator flux is smaller than its reference value (Flux increase) and the other two in the opposite case (Flux decrease). The working point is firstly divided into two different cases. These two cases are speed w_{pc} higher than torque T_{pc} (both in percent) and the opposite case.
In any case just one fuzzy system is used per iteration, and it depends on the working point.

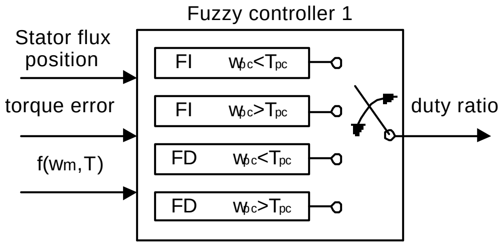

Figure 3.2. Fuzzy logic duty ratio estimator. It can be seen its four different groups of rules. Just one group of rules is used per iteration.

Stator flux position membership function is decomposed in three fuzzy sets as it is shown in figure 3.3.

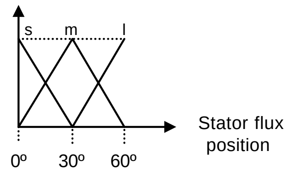

Figure 3.3. Stator flux position membership input.

The torque error membership function is decomposed in six fuzzy sets. The "tei" values are as follows: te1=5%Tn, te2=10%Tn, te3=20%Tn, where Tn is the nominal torque value. The absolute values will depend on the nominal values of each electrical machine.

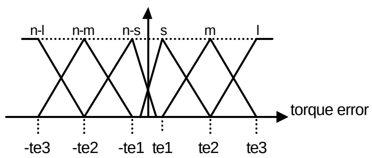

Figure 3.4. Torque error membership input.

The motor working point membership function is decomposed in just three fuzzy sets. However they are different depending on the working point position. The "wTi" values are as follows: wT1=120, wT2=200, wT3=275, wT4=100, wT5=160, wT6=270.
The different zones in the working plane T,w can be seen in figure 3.5.

It should be noted from figure 3.5 that the working plane behaviour can not be described by means of three lines in his entire plane. Therefore, the working plane is divided into two zones and the fuzzyfication of these two zones is as well different.

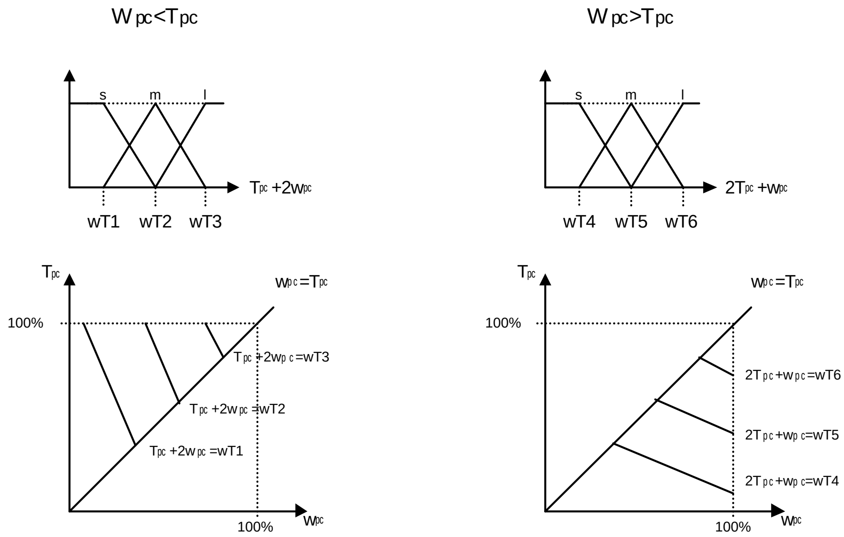

Figure 3.5. Working point membership inputs and the three different zones in the T,w plane. Left $w_{pc}<T_{pc}$. Right $w_{pc}>T_{pc}$.

Duty ratio membership function is decomposed in five fuzzy sets. Notice that its membership values are single tone to simplify the calculation. The "dci" values are as follows: dc1=0.15, dc2=0.50, dc3=0.75.

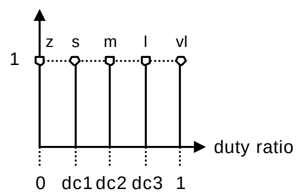

Figure 3.6. Duty ratio membership.

3.2.1.3- Rules:

The fuzzy system comprises four groups of rules, each of which contains 46 rules. Two of them are used when the stator flux is smaller than its reference value (Flux increase) and the other two in the opposite case (Flux decrease). In any case just one fuzzy system is used per iteration, and it depends on the working point.

All four groups of 46 rules are listed in section A.2.1.

3.2.2 - Fuzzy Logic controller 2.

3.2.2.1- Objectives.

The objective is to create an adaptive system. As long as the selected state is not changed, then taking into account the last evolution is possible to predict next duty ratio increment to reduce the torque error. Two examples are shown in figure 3.7.

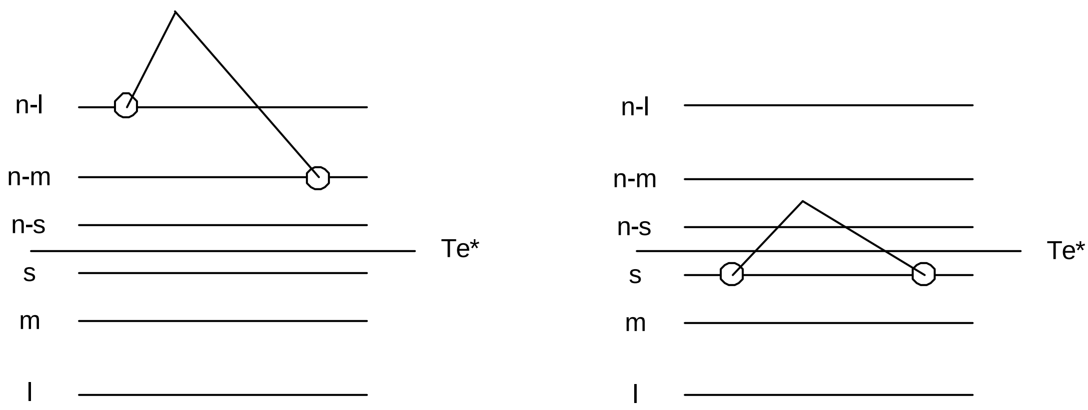

Figure 3.7. It can be seen the evolution of the torque during one Tz. Left: if the torque increment is negative medium, and the error in the previous iteration was negative large, the duty ratio increment has to be small. This case corresponds to the second rule (see section A.2.2). Right: if the torque increment is zero, and the error in the previous state was small, the increment in duty ratio has to be zero. This case corresponds to the seventeenth rule (see section A.2.2).

From figure 3.7 can be seen the adaptive characteristic of the Fuzzy Logic controller. On the left of figure 3.7, it is obvious that next iteration should not decrease the duty ratio because the torque value would take a value under the reference torque value. Therefore, the action must be to increase a bit the duty cycle in order to place next torque value a bit above than the torque reference value. However, on the right of figure 3.7, it is obvious that the torque response has been excellent; therefore, it must continue with the same duty cycle value.

3.2.2.2- Inputs and output membership functions.

In such a Fuzzy Logic system, there are two inputs, torque increment and electromagnetic torque error in the previous iteration. The output is the increment in duty ratio.

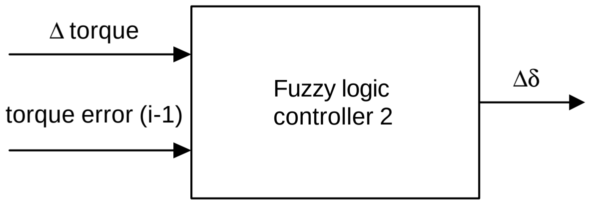

Figure 3.8. Fuzzy logic controller increment_duty ratio estimator.

The torque increment membership function is decomposed in seven fuzzy sets, and the torque error in the previous iteration membership function is decomposed in six as shown in figure 3.9.

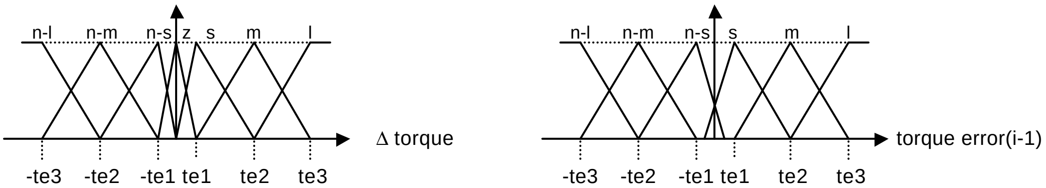

Figure 3.9. Torque increment and torque error in the previous iteration membership inputs.

The "tei" values in both cases are as follows: te1=1%Tn, te2=5%Tn, te3=10%Tn, where Tn is the torque nominal value. The absolute values will depend on the nominal values of each machine.

The increment duty ratio membership function is decomposed in nine fuzzy sets. Notice that its membership values are again single tone to simplify the calculation. The "Δδi" values are as follows: Δδ1=0.08, Δδ2=0.15, Δδ3=0.35 and Δδ4=0.5.

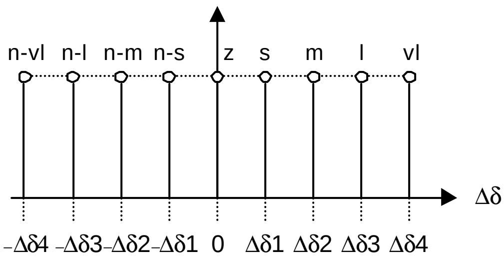

Figure 3.10. Increment duty ratio membership.

3.2.2.3- Rules:

The fuzzy system contains 37 rules. The rules number two and seventeen are explained in figure 3.7.

All 37 rules are listed in section A.2.2.

3.2.3 - Fuzzy Logic DTC schema.

Finally the schematic of the DTC based on fuzzy controllers is as shown in figure 3.11.

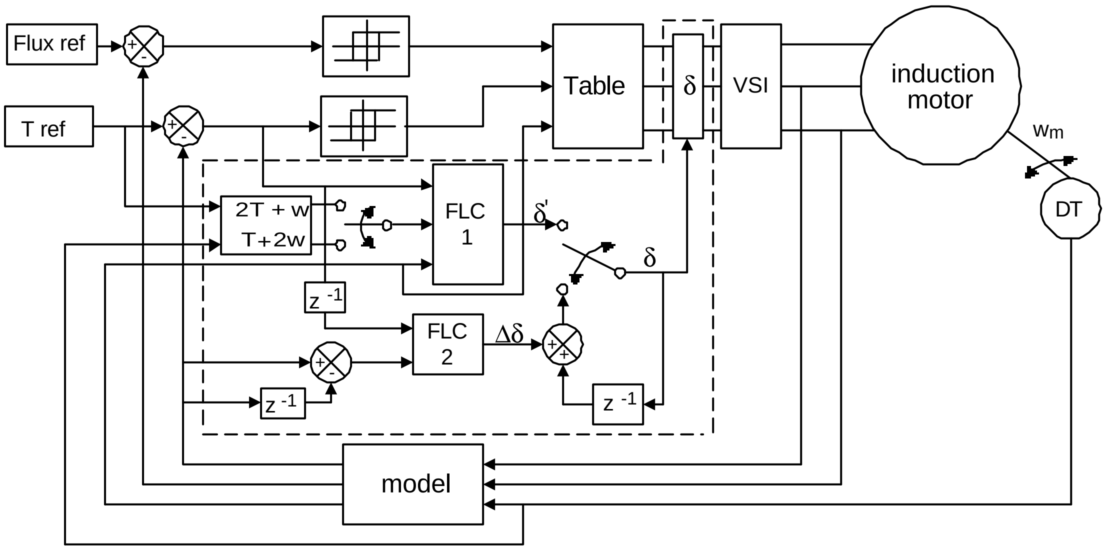

Figure 3.11. Schematic of the Fuzzy Logic DTC. In dashed line is separated the novel fuzzy controller part.

It should be clear that despite the fact that there are two Fuzzy Logic controllers, just one fuzzy controller is used per iteration. Therefore, the computation capability of the real system won't be necessarily that much.

It should be noted as well, that the schematic in figure 3.11 is pretty similar to the classical DTC one in figure 2.2, including the motor model, which will calculate the torque, stator flux modulus values and its position. However, the torque error is just given in two levels instead of three. It means that from the classical DTC table II.II just four rows are used, being discharged the null states. However, null states are introduced by means of the duty cycle.

Obviously, there is a novel part that corresponds to the novel Fuzzy Logic controller already described. Finally this new controller will give a duty ratio value, which can be obtained by means of two different ways. The first way is through the FLC1 (Fuzzy Logic controller 1). This way will be the least used. The second way corresponds to the adaptive controller thought to track the reference values. This other way gives an increment of the duty ratio, which will be added to the previous duty ratio value.

The full system will work first as the classical DTC obtaining the active state through the classical table. Then the fuzzy controller will give the duty ratio.

3.2.4 - Stator Flux Reference Optimum Controller.

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 both 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 reactive power consumption taken from the mains supply.

The optimum expression, which gives the just large enough stator flux for the desired torque is given in equation 2.23 from section 2.3.5.

In figure 3.12 can be seen the final Fuzzy Logic DTC schema with the stator flux reference optimum controller. Notice how the optimum stator flux value is calculated from the torque set point value.

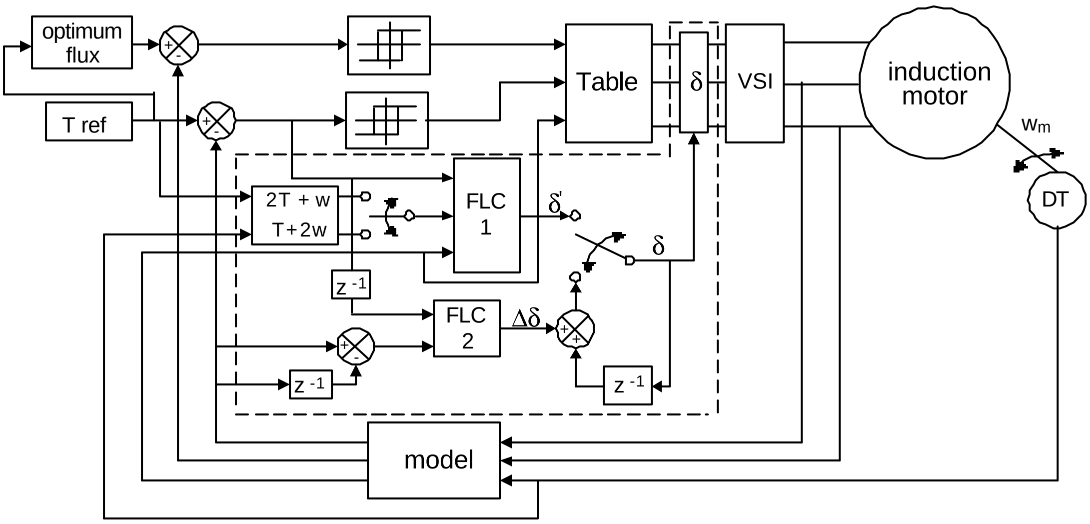

Figure 3.12. Flux reference optimised controller in a Fuzzy Logic DTC.

3.3 - Simulated results.

It is shown the simulation results per different working points, comparing the classical DTC and the Fuzzy Logic DTC (FLDTC). More simulations than the ones shown have been done, and the obtained results have been summarised in table III.I and table III.II.

In all simulations presented, it can be observed a much better behaviour of the FLDTC performance, achieving one of the main objectives of the present work, which was to reduce the torque ripple and consequently improve the motor performance.

A good adaptation of the FLC to any motor is proved since the simulation results are done for two different motors, achieving in both cases a good response. These motors are the "motor_1kW" and "motor_1.5kW". (All motors' details can be found in chapter 4).

An index error has been used to quantify the error in both the stator flux and torque responses. This index is the integral of the square error (IE2), which 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.

All simulations have been realised with an ideal induction motor drive with no delays and the sampling time (Tz) has been fixed to 100μs.

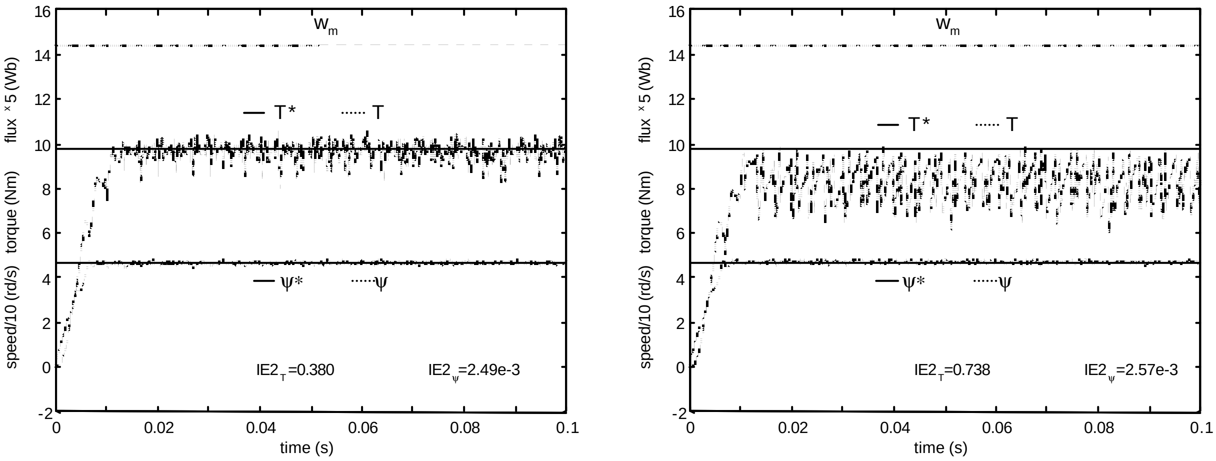

Figure 3.13 A. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right). $T=100\%T_n$. $w_m=100\%w_{mn}$. Notice the IE2 flux and torque error indexes values.

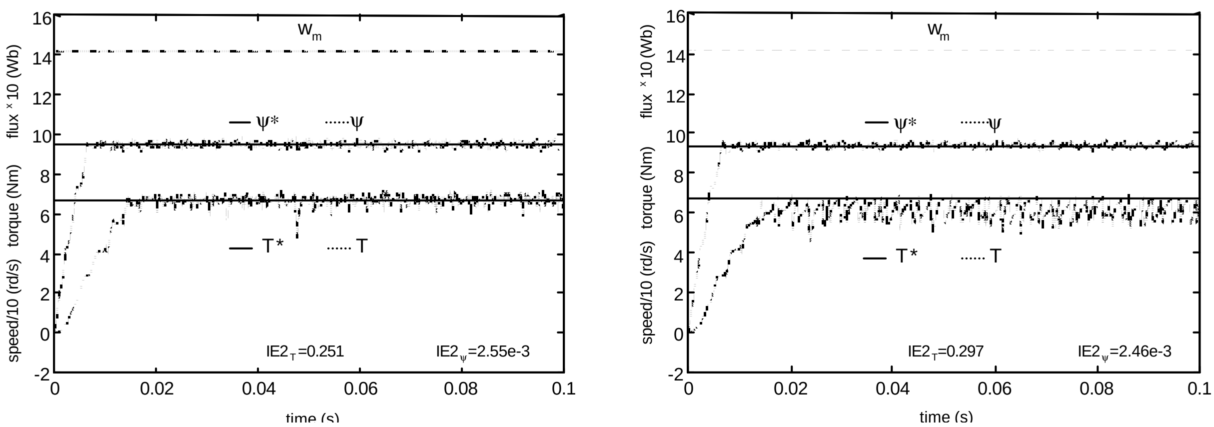

Figure 3.13 B. Stator flux, torque and speed motor_1kW responses in Fuzzy Logic DTC (left) and classical DTC (right). $T=100\%T_n$. $w_m=100\%w_{mn}$. Notice the IE2 flux and torque error indexes values.

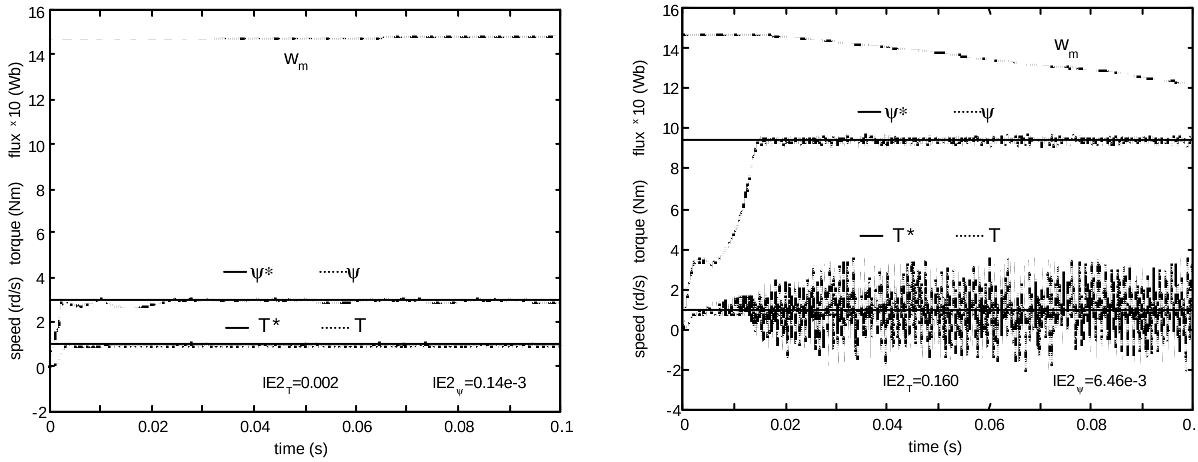

Figure 3.14 A. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right). $T=10\%T_n$. $w_m=10\%w_{mn}$. Notice the IE2 flux and torque error indexes values.

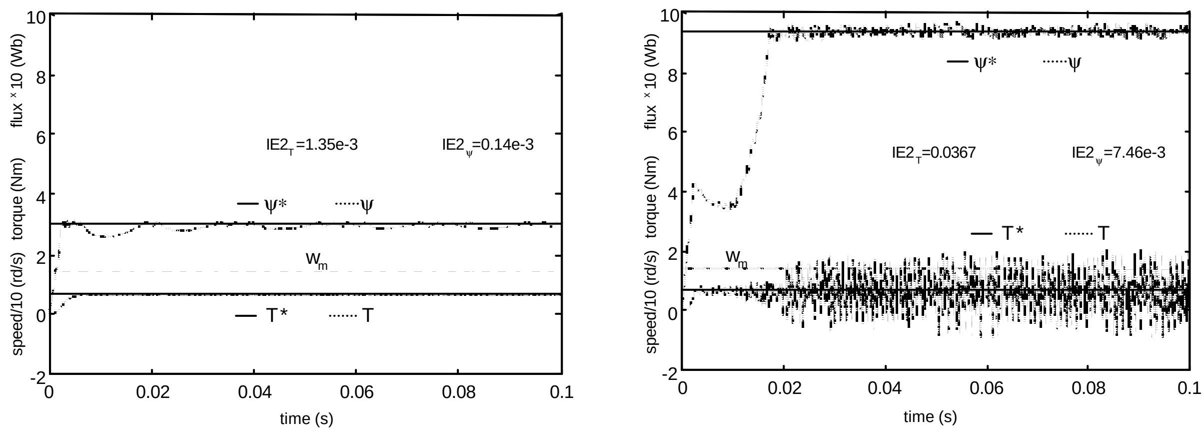

Figure 3.14 B. Stator flux, torque and speed motor_1kW responses in Fuzzy Logic DTC (left) and classical DTC (right). $T=10\%T_n$. $w_m=10\%w_{mn}$. Notice the IE2 flux and torque error indexes values.

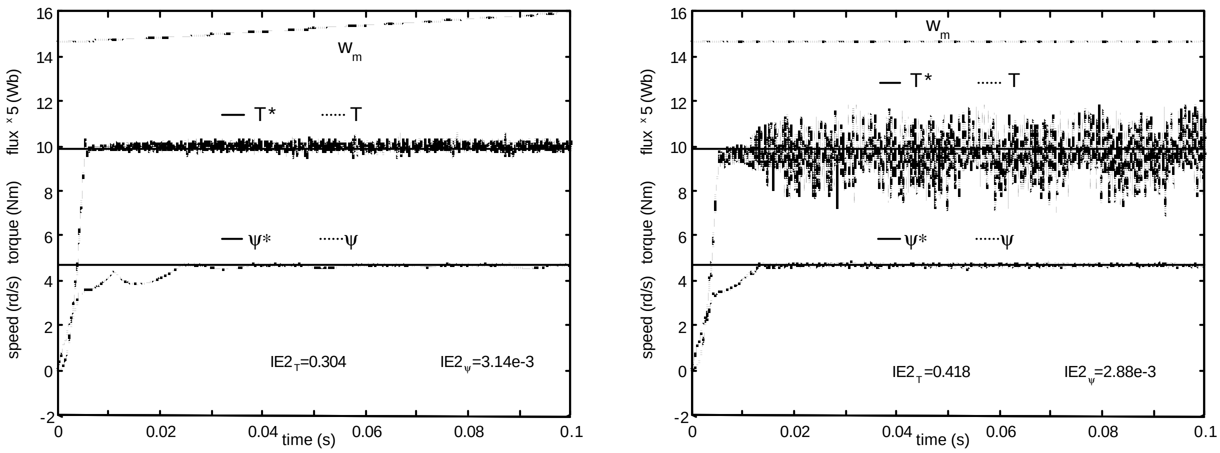

Figure 3.15 A. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right). T=100%T_n. w_m=10%w_{mn}. Notice the IE2 flux and torque error indexes values.

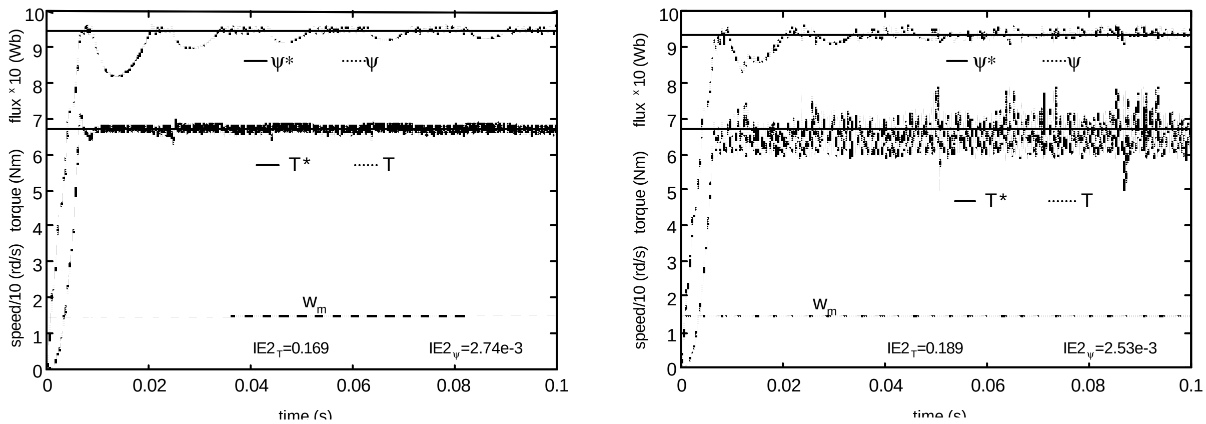

Figure 3.15 B. Stator flux, torque and speed motor_1kW responses in Fuzzy Logic DTC (left) and classical DTC (right). T=100%T_n. w_m=10%w_{mn}. Notice the IE2 flux and torque error indexes values.

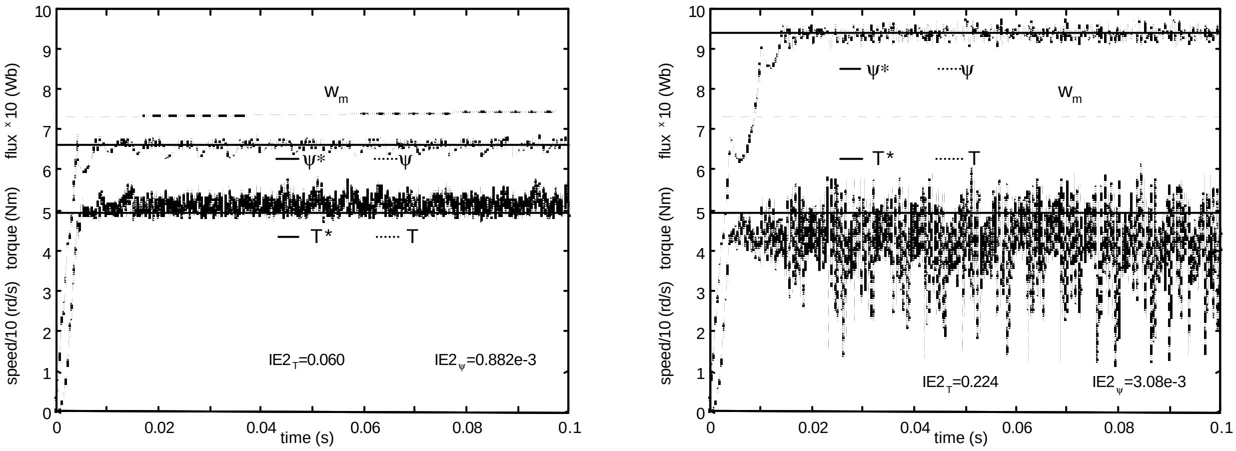

Figure 3.16 A. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right). $T=50\%T_n$. $w_m=50\%w_{mn}$. Notice the IE2 flux and torque error indexes values.

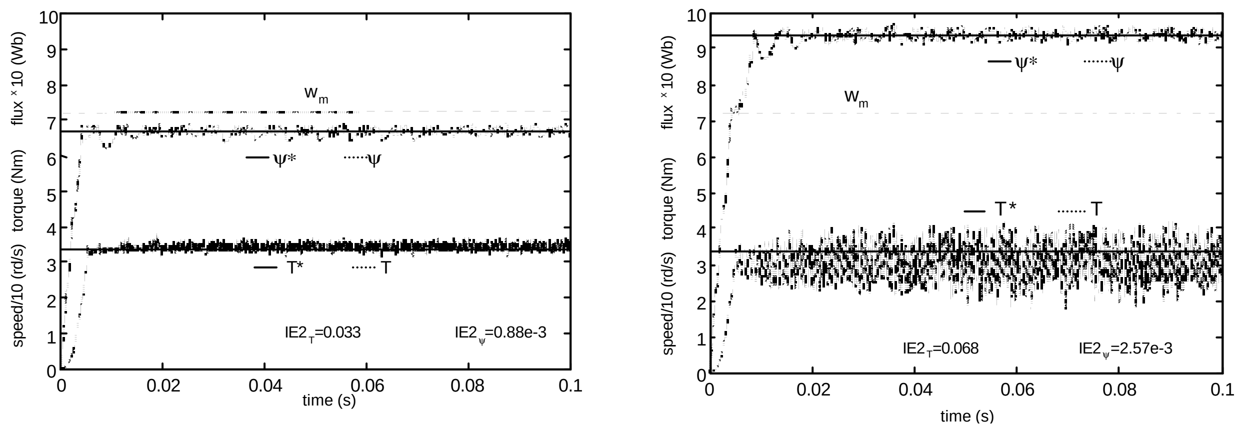

Figure 3.16 B. Stator flux, torque and speed motor_1kW responses in Fuzzy Logic DTC (left) and classical DTC (right). $T=50\%T_n$. $w_m=50\%w_{mn}$. Notice the IE2 flux and torque error indexes values.

3.4 - Interim conclusions.

After all the research done in section 2.3, this thesis is focused on introducing a modulation in the DTC. A Fuzzy Logic controller controls this modulation, between the selected active state and a null one. Therefore, it has been suggested and deeply described the Fuzzy Logic controller, which together with the DTC will create the Fuzzy Logic DTC. The Fuzzy Logic controller designed is adaptive, improving even more the whole FLDTC.

Simulation results show the validity of the FLDTC method not only achieving a considerable reduction in torque ripple, but also reducing the reactive power consumption taken from the mains supply.

Simulated results corroborate all the presented work. Moreover, the simulations correspond to two different motors being proved the validity of the FLDTC for any motor. It has been used just one switching period (100μs) in all simulations, and no delays have been considered.

In table III.I is shown the error value index (IE2) obtained in the simulations per different working points for the motor_1.5kW.

In table III.II is shown the error value index (IE2) obtained in the simulations per different working points for the motor_1kW.

In both motors the results are pretty similar. Therefore, the first conclusion is that the Fuzzy Logic controller works properly in any motor, thus the FLDTC is a good control method for any motor.

From the tables III.I and III.II, it can be concluded:

- IE2 in torque is always smaller in FLDTC than in classical DTC. Therefore, the validity of FLDTC is corroborated.
- IE2 in flux is nearly always smaller in FLDTC than in classical DTC. The smaller the torque set point is the smaller flux FLDTC IE2 value is. However, there are just a few exceptions when the torque set point is near to the nominal one. Under these circumstances, both flux error indexes are pretty similar. The reason is that the stator flux ripple is reduced by means of the stator flux reference optimum controller introduced in section 2.3.5, that always works but when the torque set point is near to the nominal value.

IE2	FLDTC		c_DTC	
Tpc Wpc	**Flux**	**Torque**	**Flux**	**Torque**
100% 10%	3.14e-3	0.30441	2.88e-3	0.4184
50% 50%	0.882e-3	0.06047	3.08e-3	0.2248
10% 10%	0.1494e-3	0.002641	6.46e-3	0.16093
100% 100%	2.49e-3	0.3806	2.57e-3	0.7385
100% 50%	2.61e-3	0.322	2.61e-3	0.499
50% 100%	0.86e-3	0.06832	2.60e-3	0.2557
75% 75%	1.635e-3	0.171	2.61e-3	0.383

Table III.I: Error index values (IE2) obtained form the motor_1.5kW simulations per different working points. A comparison between the classical DTC and the Fuzzy Logic DTC is done, not only for the torque error values but also for the stator flux ones.

IE2	FLDTC		c_DTC	
Tpc Wpc	**Flux**	**Torque**	**Flux**	**Torque**
100% 10%	2.74e-3	0.169	2.53e-3	0.189
50% 50%	0.88e-3	0.033	2.57e-3	0.068
10% 10%	0.14e-3	0.00135	7.46e-3	0.0367
100% 100%	2.55e-3	0.251	2.46e-3	0.297

Table III.II: Error index values (IE2) obtained form the motor_1kW simulations per different working points. A comparison between the classical DTC and the Fuzzy Logic DTC is done, not only for the torque error values but also for the stator flux ones.