CHAPTER 5.
EXPERIMENTAL RESULTS.

5.1 - Corroborating the real implementation.

5.1.1 - Classical DTC.

All graphics of the present chapter correspond to the experimental results obtained from the real plant just using the induction motor_1.5kW. In all cases, the reference values were as follows:

- Torque reference value = 4.9Nm. Torque hysteresis value = 1.3Nm.
- Flux reference value = 1.15Wb. Flux hysteresis value =0.05Wb.
- Sample time = Ts = Tz = 166μs.

All graphics try to show the correct behaviour of the classical DTC.

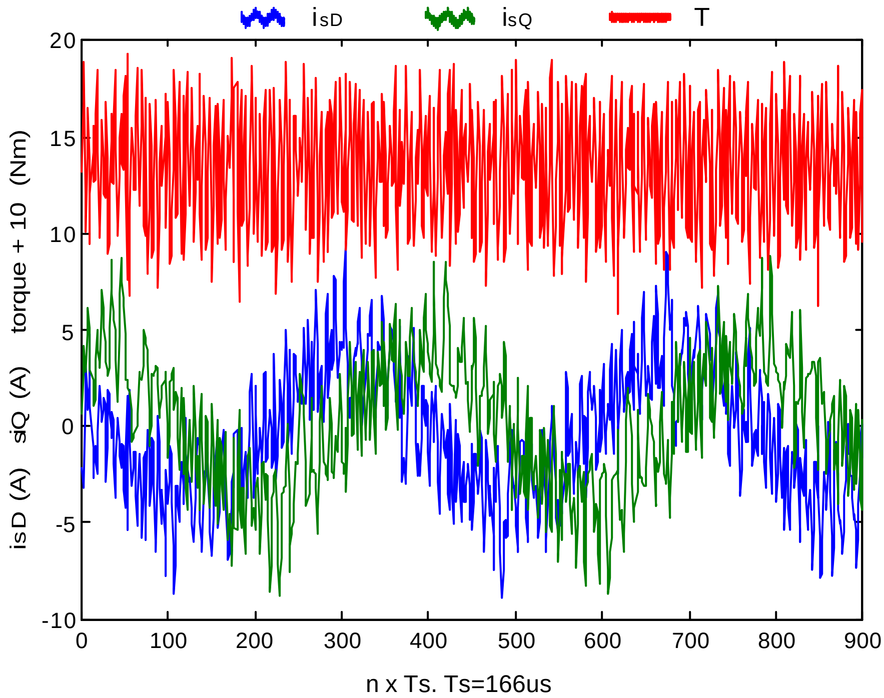

Figure 5.1. D and Q current components. Electromagnetic torque plus 10Nm.

Figure 5.2 should be compared with its simulated equivalent in figure 4.8. It can be said that the simulation matches perfectly with the experimentation.

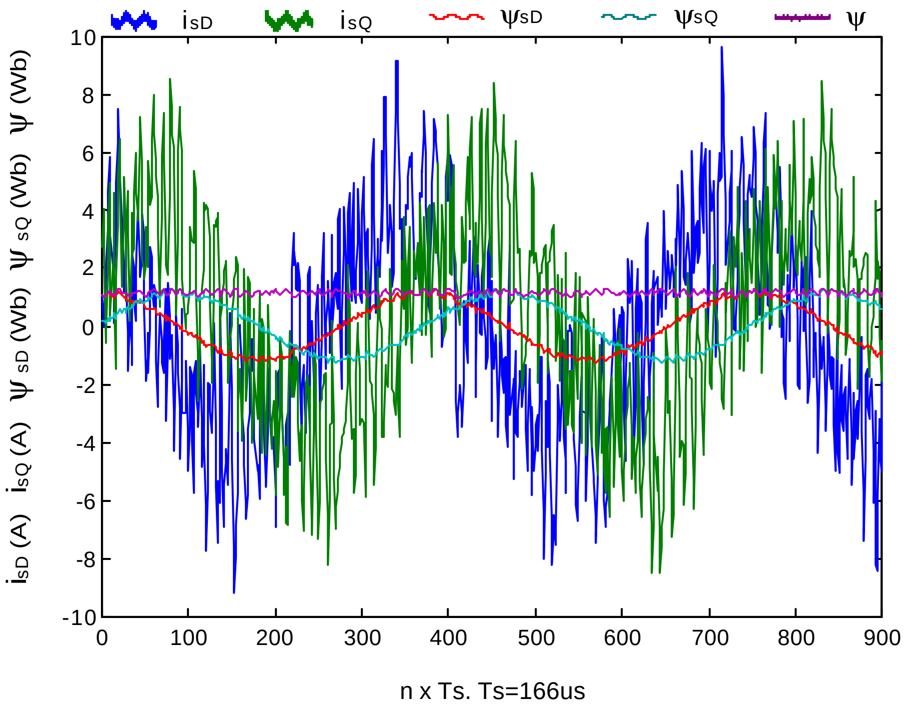

Figure 5.2. D and Q current components. D and Q flux components and its module.

Figure 5.3 should be compared with its simulated equivalent in figure 4.9. Again the simulated results are equal to the experimental ones.

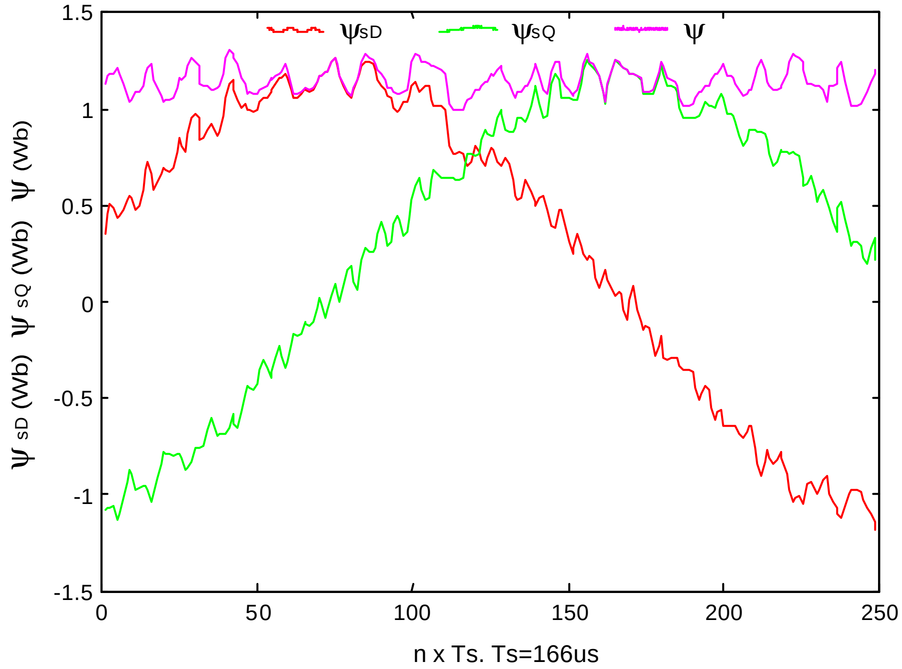

Figure 5.3. Figure 5.2 horizontal zoom of the samples 300 to 550.
D and Q stator flux components and its modulus value. Notice how once one component is zero, the other is equal to the modulus.

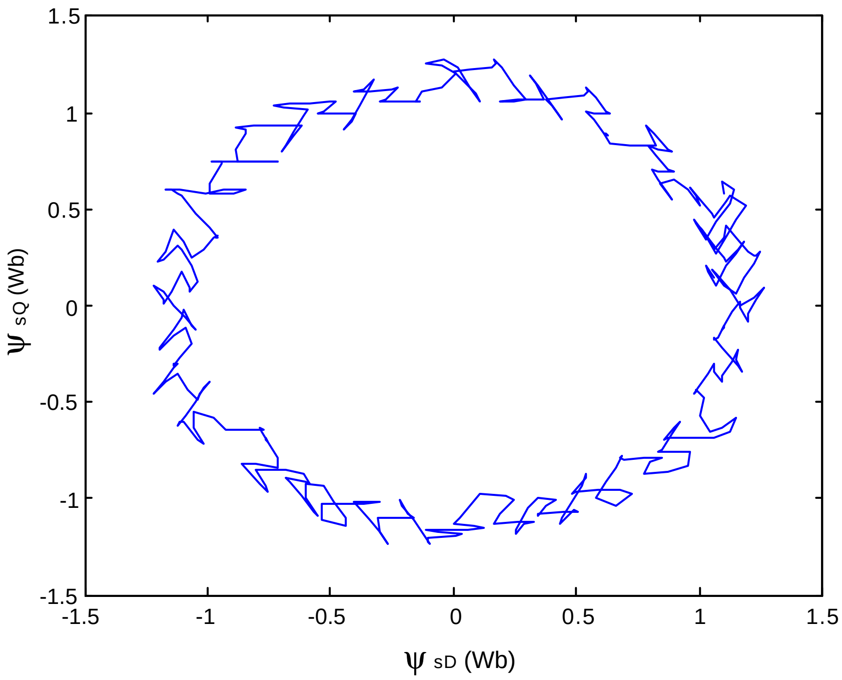

Figure 5.4. Stator flux. Notice how it follows a circular shape.

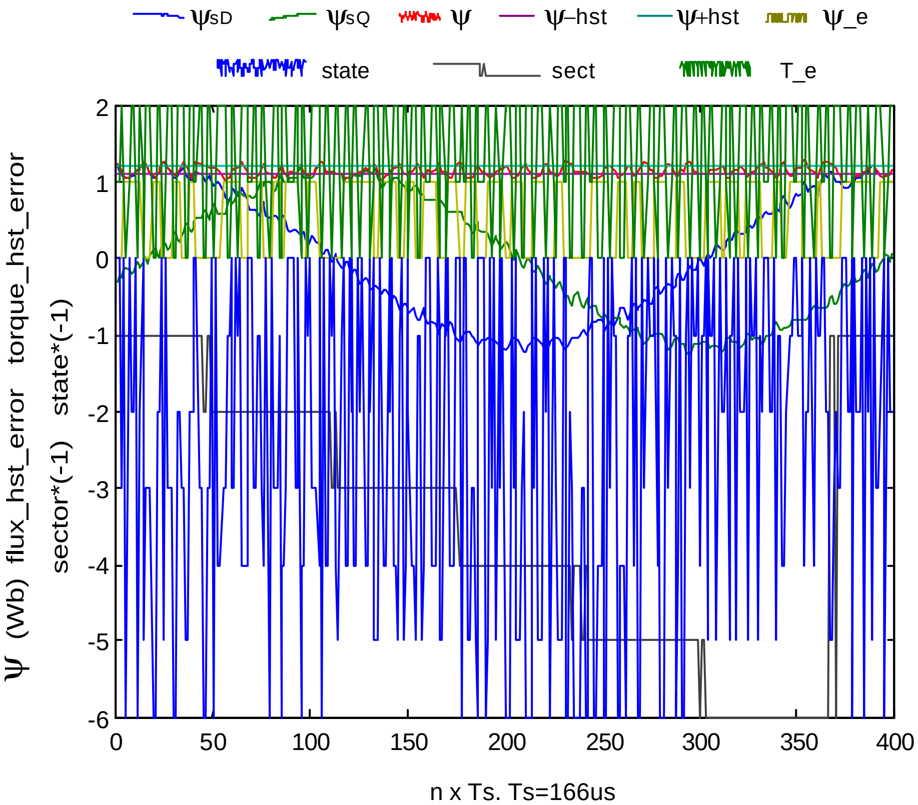

Figure 5.5 Flux and torque errors signals. Flux sector. Selected state and all the inputs in its look up table, which are flux and torque errors signals and flux sector. Moreover, it is shown D, Q, modulus and hysteresis limits, all magnitudes for the stator flux.

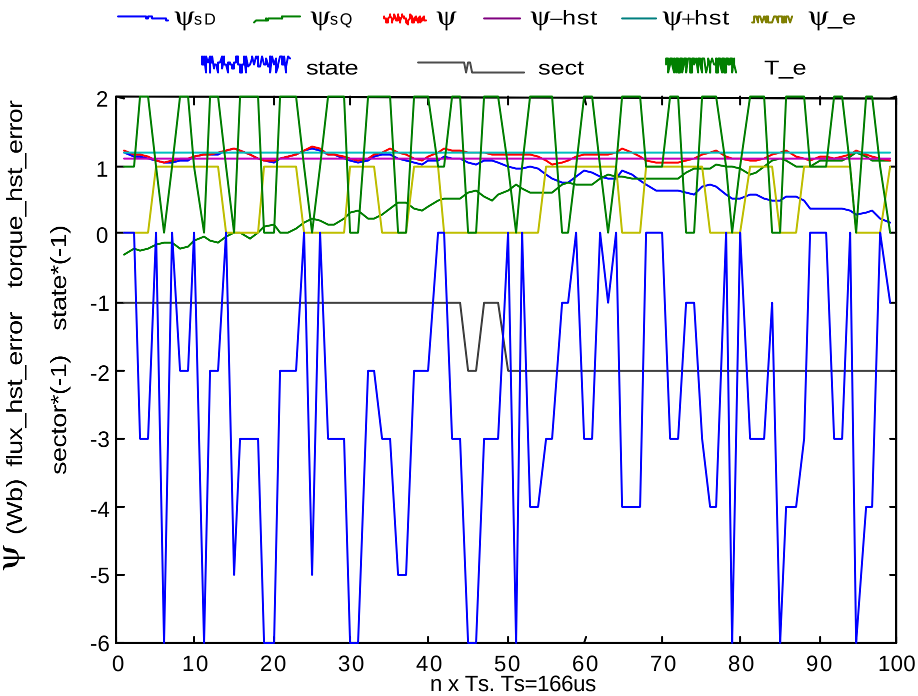

Figure 5.6. Figure 5.5 horizontal zoom of the samples 0 to100.

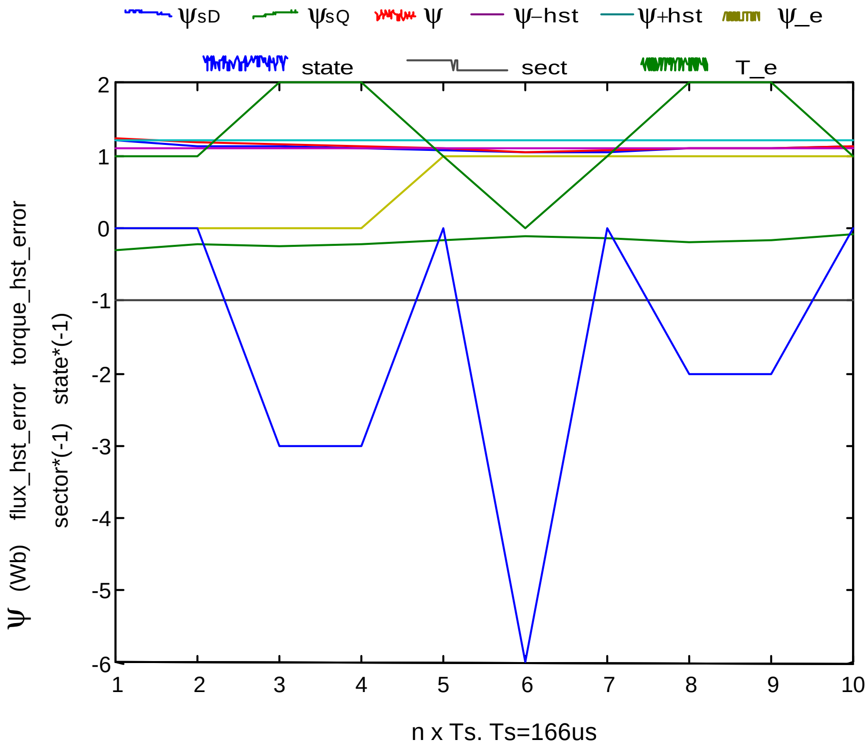

Figure 5.7. Figure 5.6 horizontal zoom of the samples 0 to10.
It can be deduced the correct behaviour of the look up table according to its inputs. For instance, in the third sample the look up table inputs are: torque increase, flux decrease and first sector. Therefore, the selected sate is the third.

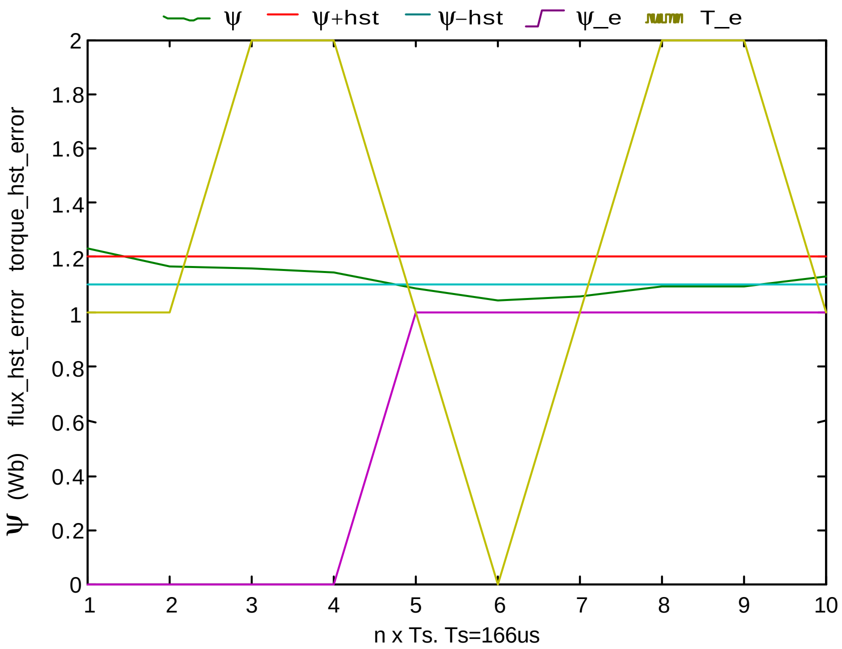

Figure 5.8. Figure 5.7 vertical zoom. It is shown the correct behaviour of flux hysteresis error value. For example, from samples 4 to 5, once the modulus decreases under the negative hysteresis value, its error value changes from 0 to 1.

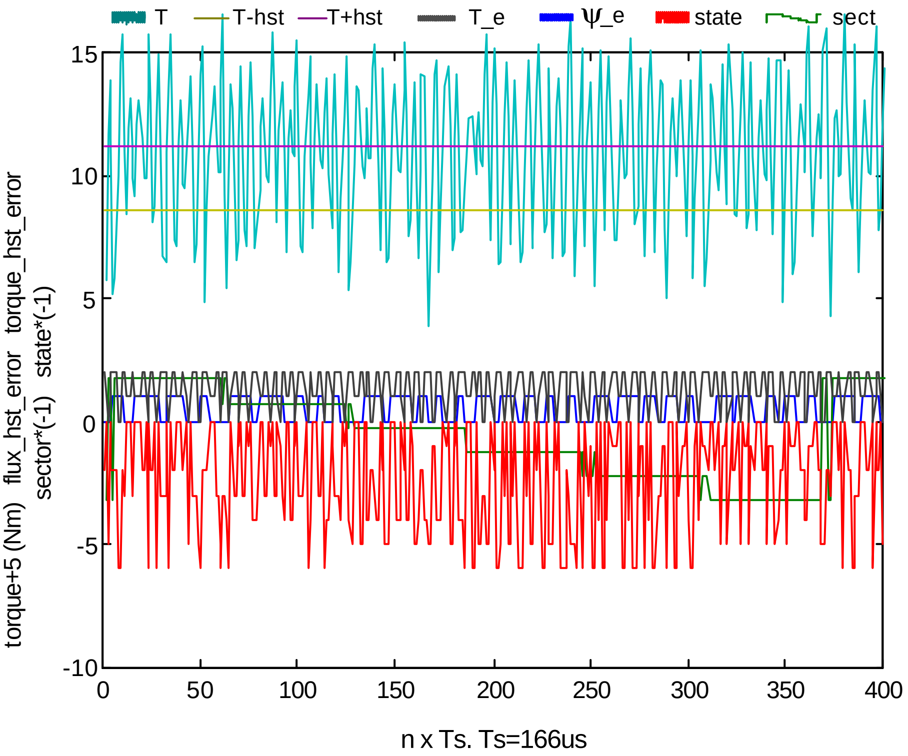

Figure 5.9. Selected state, all look up table inputs (being flux and torque errors signals and flux sector) and torque value plus 5 and its hysteresis limits plus 5.

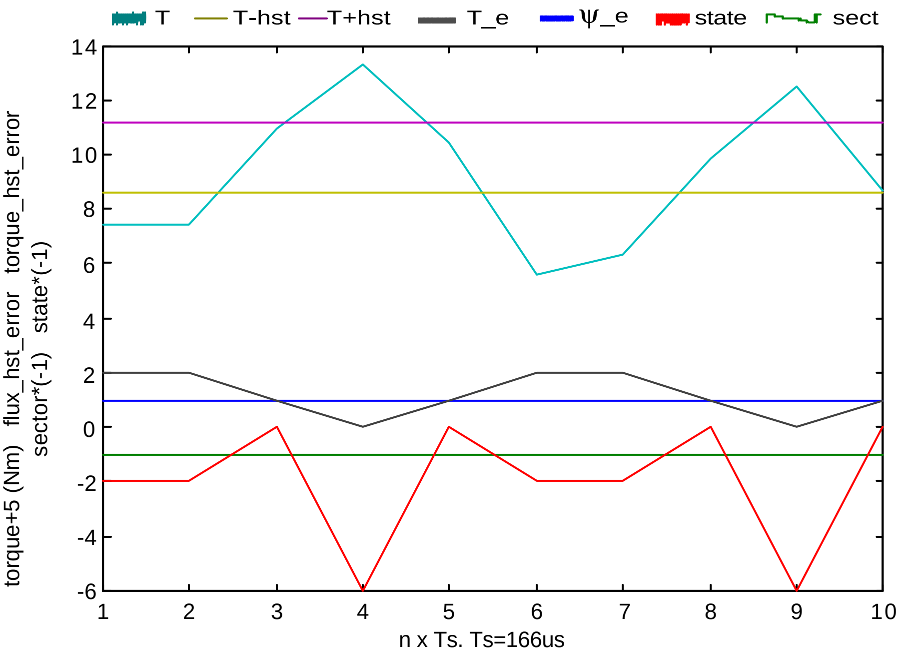

Figure 5.10. Figure 5.9 horizontal zoom of the samples 20 to 30.
It can be deduced the correct behaviour of the look up table according to its inputs and the torque hysteresis error signal. For example, from samples 2 to 4 the torque increases crossing both hysteresis limits, changing from 2 to 1 and finally to 0 the torque hysteresis error values. Of course, all selected states are the correct ones.

Figures 5.11 and 5.12 are shown in order to justify the validity of the torque values. If it is considered the particular moment that the Q flux component is equal to zero, then the torque expression is simplified as it is shown in equation 5.1.

$$T = P \cdot c \cdot (\psi_{sD} \cdot i_{sQ} - \psi_{sQ} \cdot i_{sD}) \cong 1.6 \cdot \psi_{sD} \cdot i_{sQ} \quad (5.1)$$

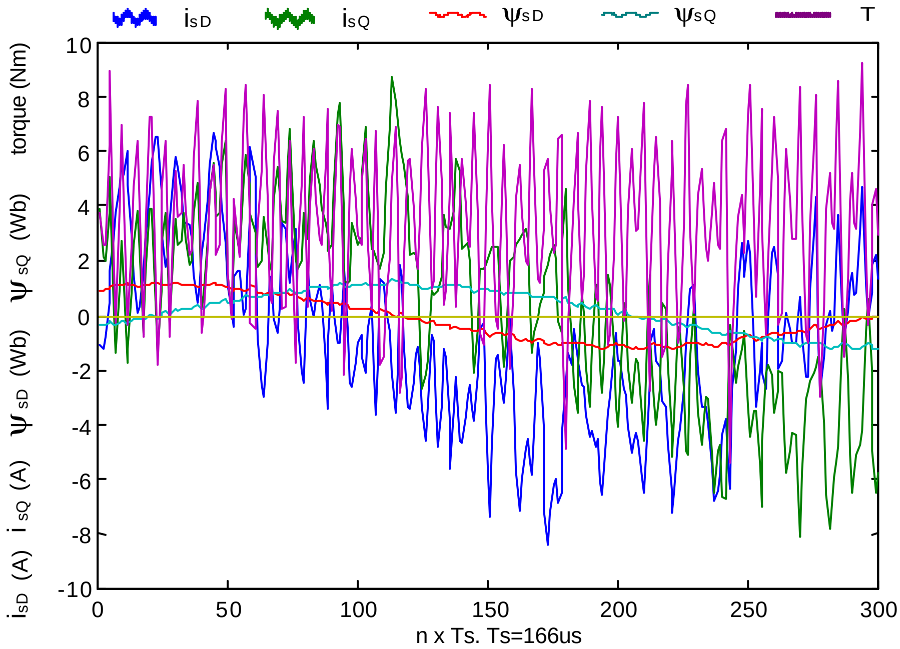

Figure 5.11. D, Q flux and current components and torque value.

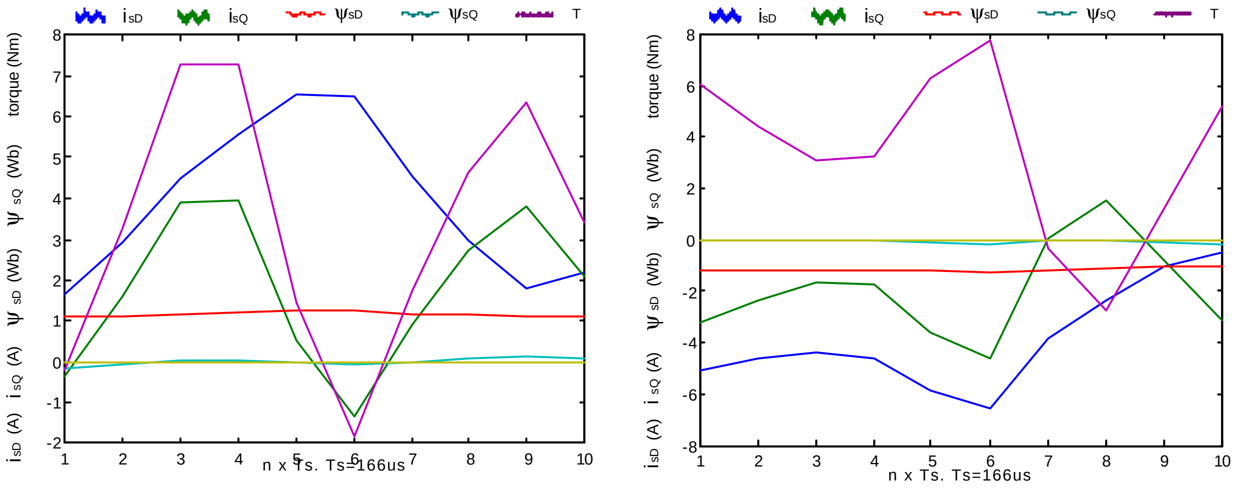

Figure 5.12. Left: figure 5.11 horizontal zoom of the samples 20 to 30.
Right: figure 5.11 horizontal zoom of the samples 205 to 215.
In both cases Q flux component tends to zero. Therefore, the torque value is equal to 1.6 times the product of D flux component and Q current component. Considering that the flux modulus is 1.15, the torque value is 1.84 the Q current component.

5.1.2 - Fuzzy Logic DTC.

All graphics of the present chapter correspond to the experimental results obtained from the real plant. In all cases, the reference values were as follows:

Torque reference value = 1.9Nm. Torque hysteresis value = 1.3Nm

Flux hysteresis value = 0.05Wb

Sample time = Ts = Tz = 166µs.

The flux reference value is the optimum one obtained from equation 2.23.

All graphics show the correct behaviour of the FLDTC.

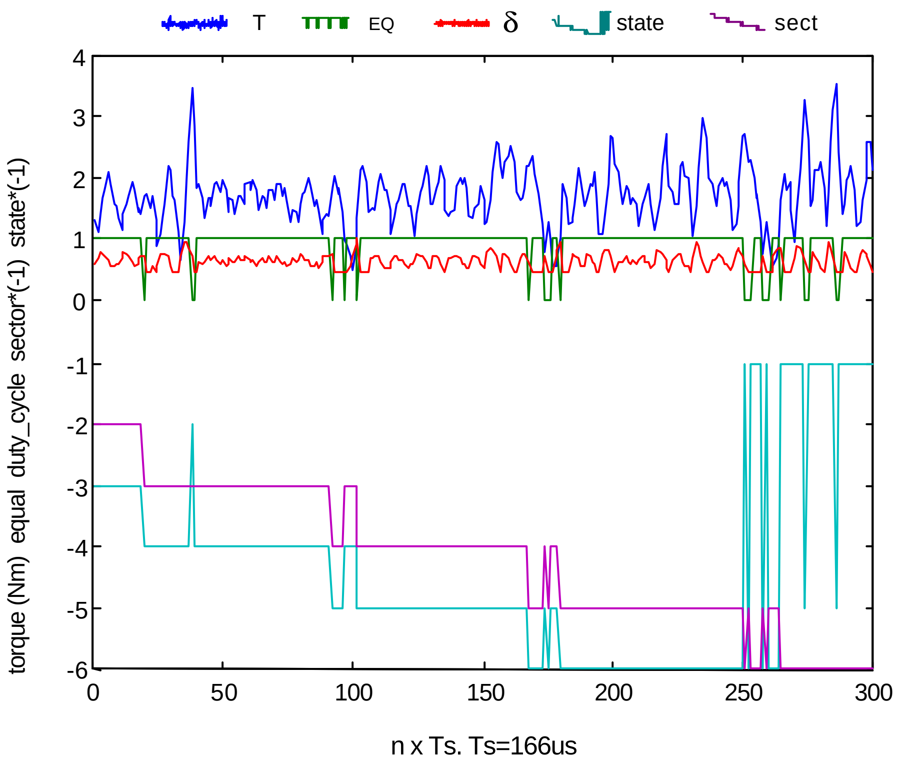

Figure 5.13. This graphic shows the excellent behaviour FLDTC. Notice how during almost all sectors the active selected state is almost always the same, keeping the torque ripple into a good value.

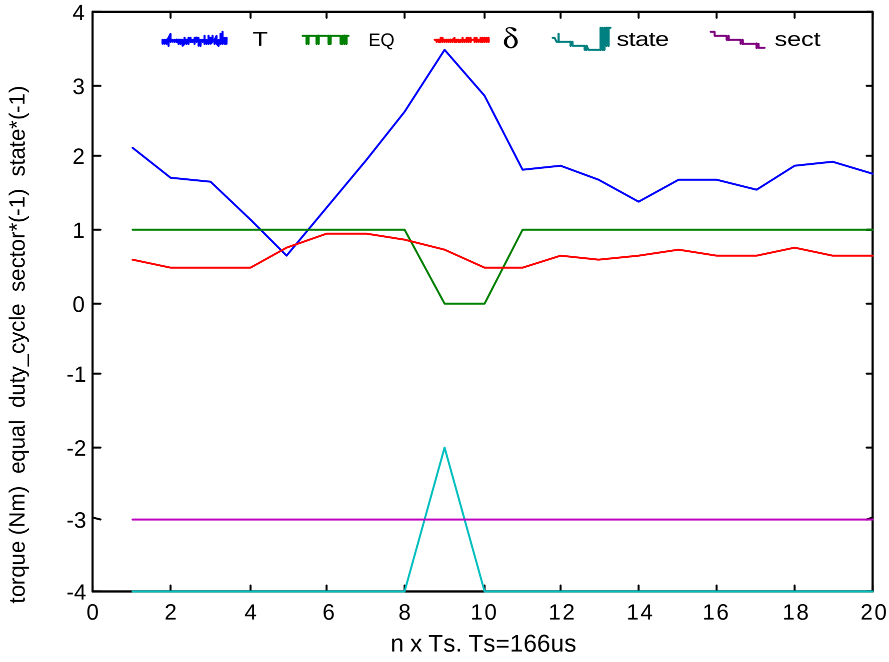

Figure 5.14. Figure 5.13 horizontal zoom of the samples 35 to 55.
The sector is always the third and the selected state is the fourth except in the sample nine being the second. Once the selected state changes, the equal value changes from one to zero switching the FLC from the adaptive to the non-adaptive one.

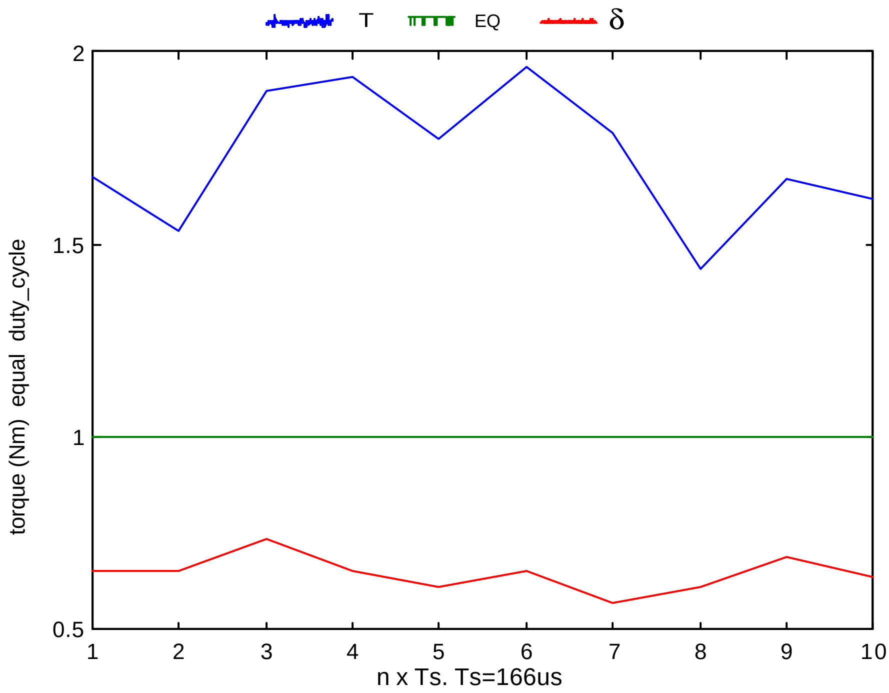

Figure 5.15. Figure 5.13 horizontal and vertical zoom of the samples 51 to 60.
It is shown the excellent behaviour of the adaptive FLC, modulating the duty cycle value in order to keep the torque among its reference value.

5.2 - FLDTC and DTC comparison.

Results obtained from the reported investigation, when comparing the classical DTC drive system with the novel FLDTC drive system, are illustrated from figure 5.16 to 5.25. Each torque reference value has been applied to two different load conditions, being the resistance values connected to the DC generator equal to 4 ohms and 8 ohms.

When the torque response characteristic for the two drive systems is compared, it can be seen that the ripple in the torque characteristics is very much less for the novel FLDTC system than for the classical DTC system for any torque reference value.

The torque ripple compared to the simulated results from chapter 3 is much bigger. This is due to the following different reasons:

- Simulations were done with a sample time equal to 100μs, meanwhile the real system works at 166μs.
- The real system has got an inherent delay of 80μs, meanwhile the simulations were done without taking into account any delay.
- Despite the fact that the controller should work properly for any sample time value, the implemented controller was the optimum for 100μs as a sampling time and no delay, being possible finding a more optimised FLC for the real plant conditions.
- Due to the delays in executing the fuzzy controllers, the duty cycle can not take all the possible values, being higher than 50%, as it is explain deeper in 4.3.3.

However, some simulations were done in section 4.4 taking into account all the previously mentioned real limitations. These simulated results matches completely with the experimental ones.

Figure 5.16 should be compared with its simulated equivalent in figure 4.5. It can be said that the simulation matches perfectly with the experimentation due to the fact that the simulated results did take into account all the real limitations.

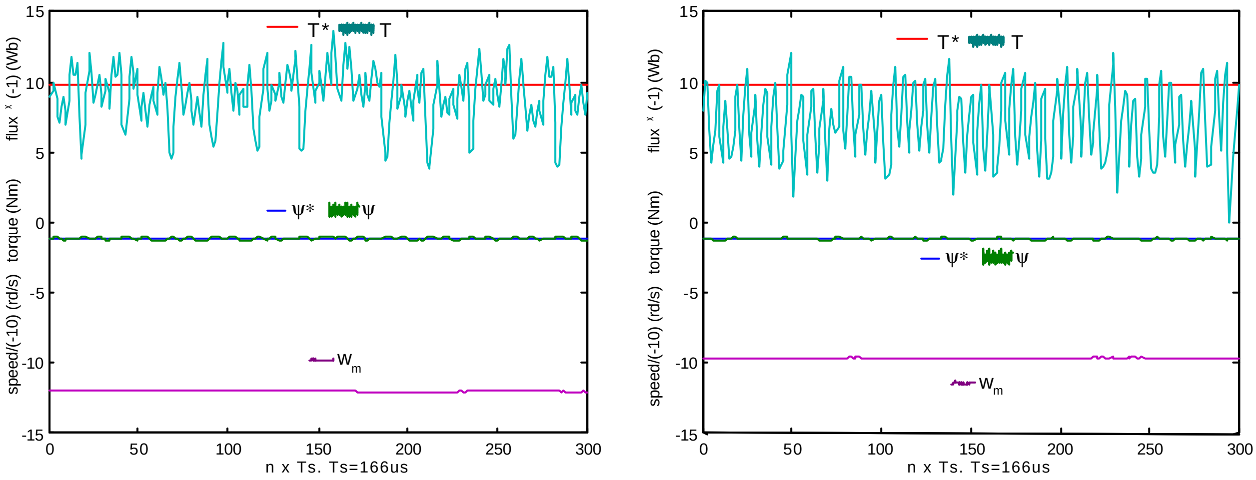

Figure 5.16. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 4Ω. Torque reference value is 9.8Nm, i.e. T=100%T_n.

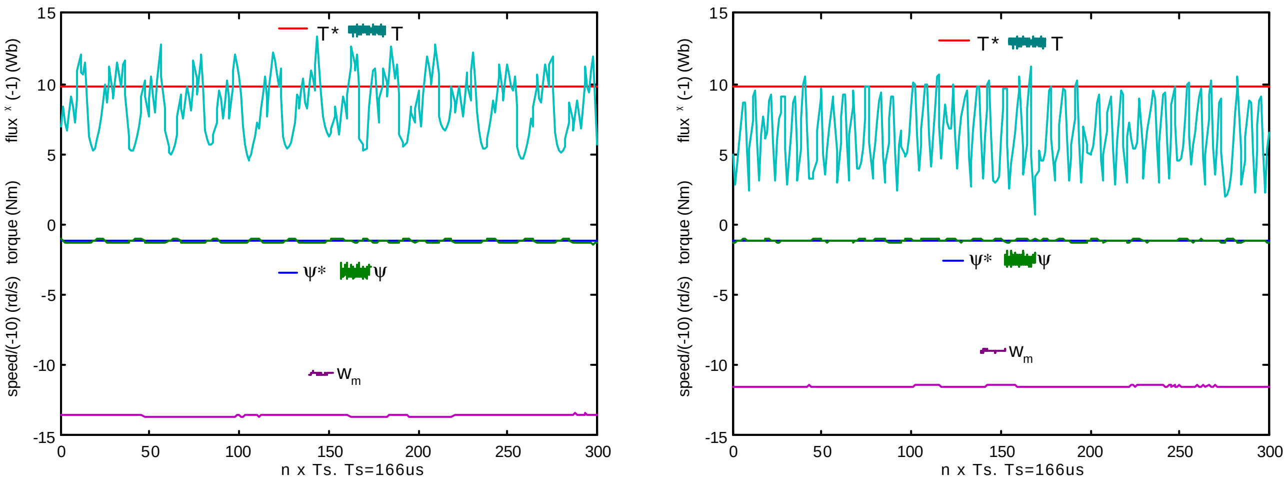

Figure 5.17. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 8Ω. Torque reference value is 9.8Nm, i.e. T=100%T_n.

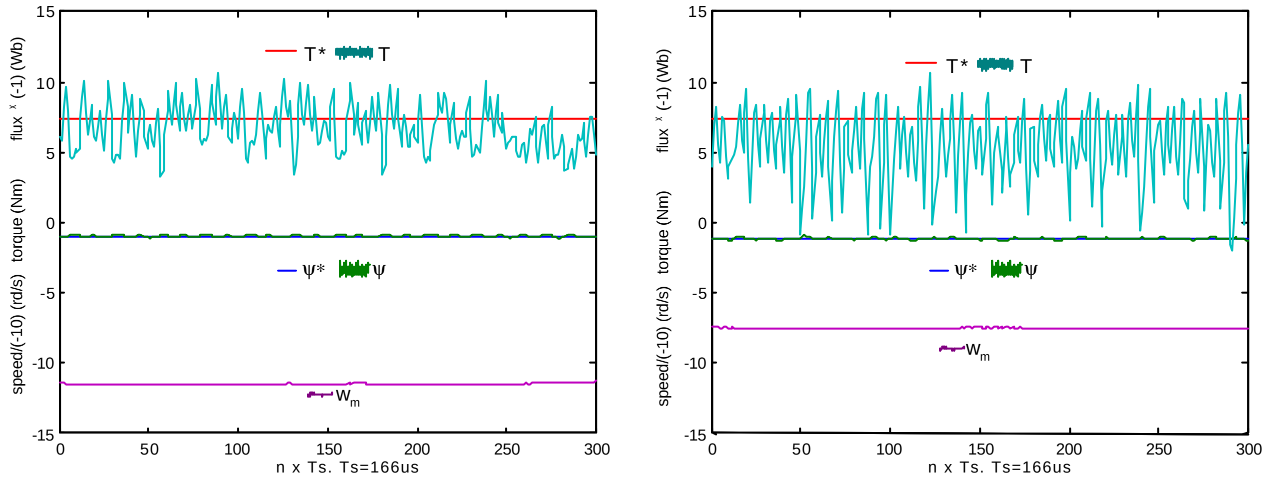

Figure 5.18. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 4Ω. Torque reference value is 7.35Nm, i.e. T=75%T_n.

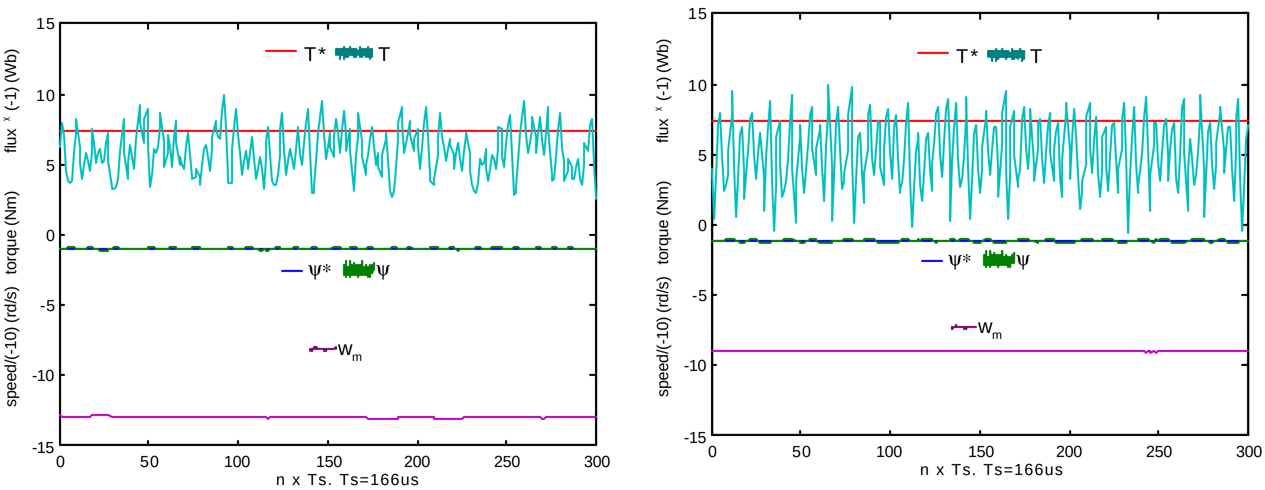

Figure 5.19. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 8Ω. Torque reference value is 9.8Nm, i.e. T=75%T_n.

Figure 5.20 should be compared with its simulated equivalent in figure 4.6. Again, the simulated results match perfectly with the experimental ones.

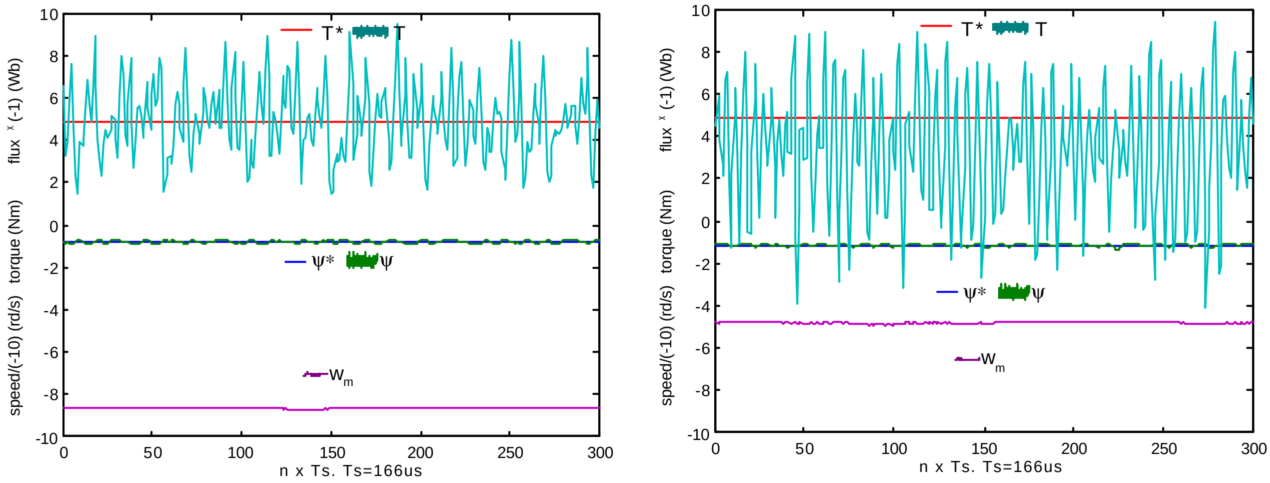

Figure 5.20. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 4Ω. Torque reference value is 4.9Nm, i.e. $T=50\%T_n$.

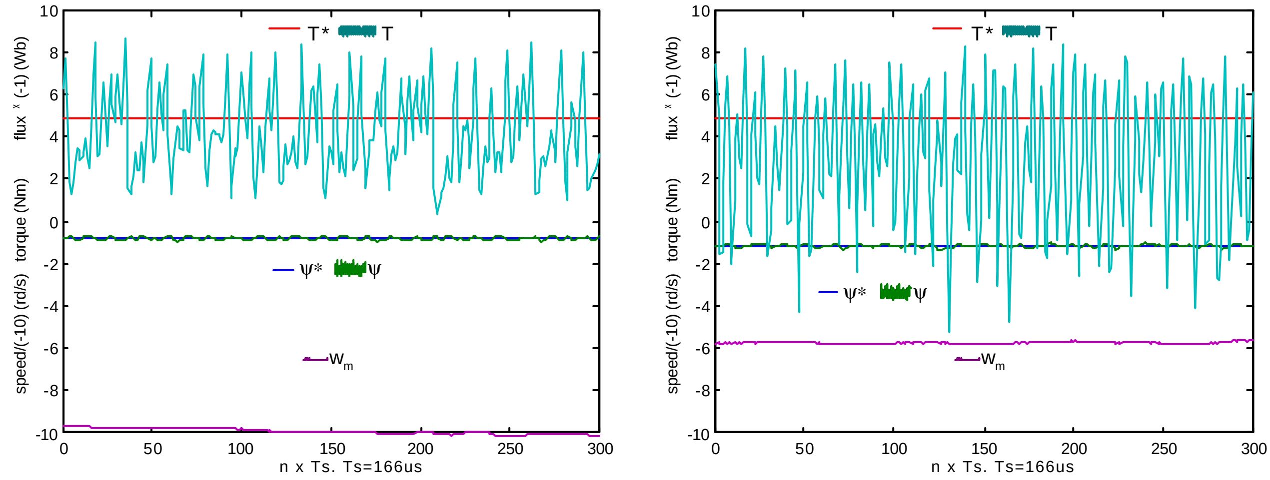

Figure 5.21. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 8Ω. Torque reference value is 4.9Nm, i.e. $T=50\%T_n$.

Figure 5.22 should be compared with its simulated equivalent in figure 4.7. It can be said that the simulation matches perfectly with the experimentation due to the fact that the simulated results took into account all the non-ideal limitations.

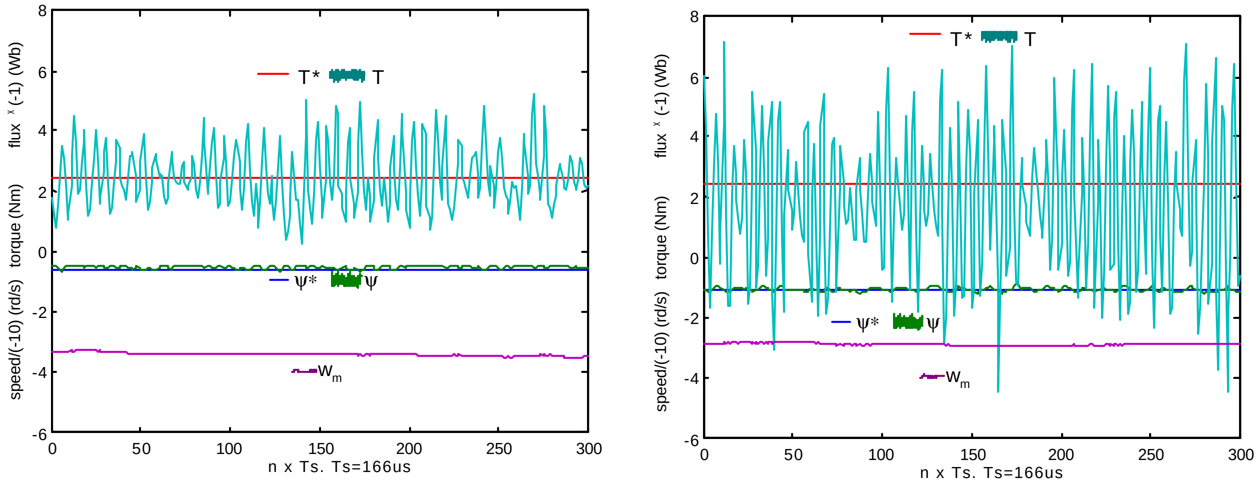

Figure 5.22. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 4Ω. Torque reference value is 2.45Nm, i.e. T=25%T_n.

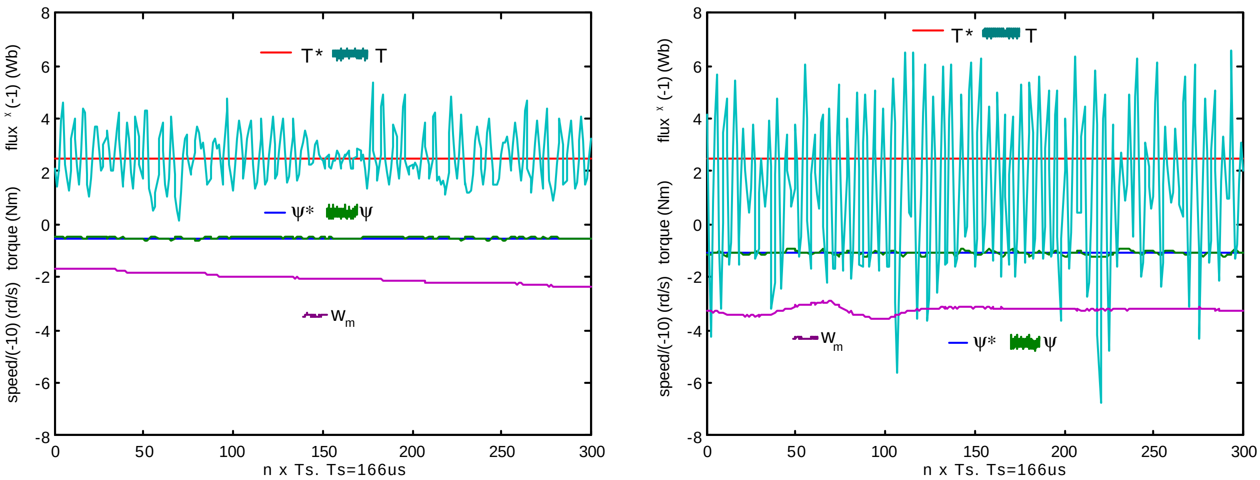

Figure 5.23. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 8Ω. Torque reference value is 2.45Nm, i.e. T=25%T_n.

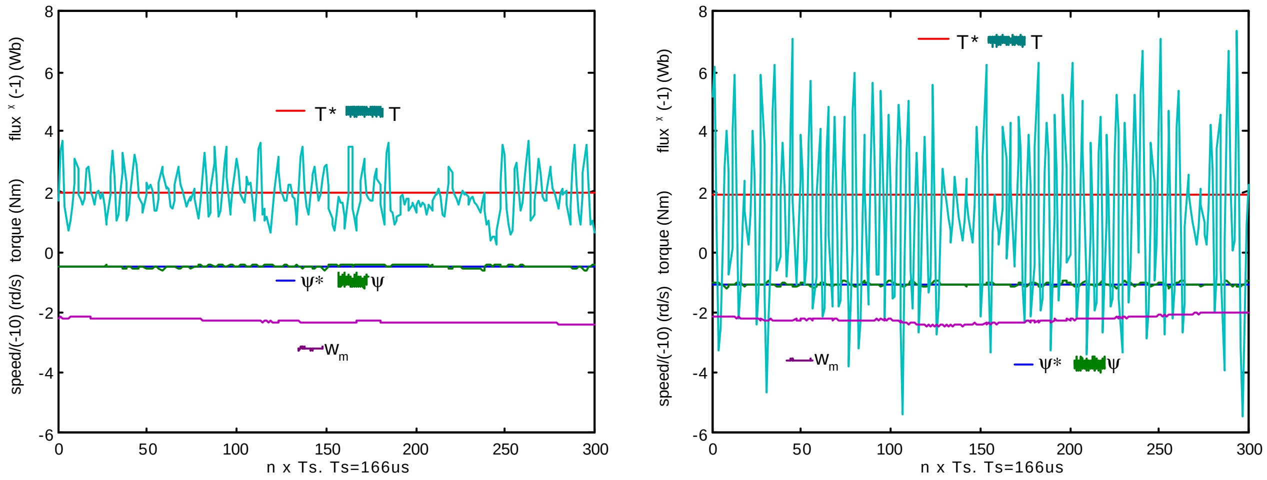

Figure 5.24. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 4Ω. Torque reference value is 1.9Nm, i.e. T=19%T_n.

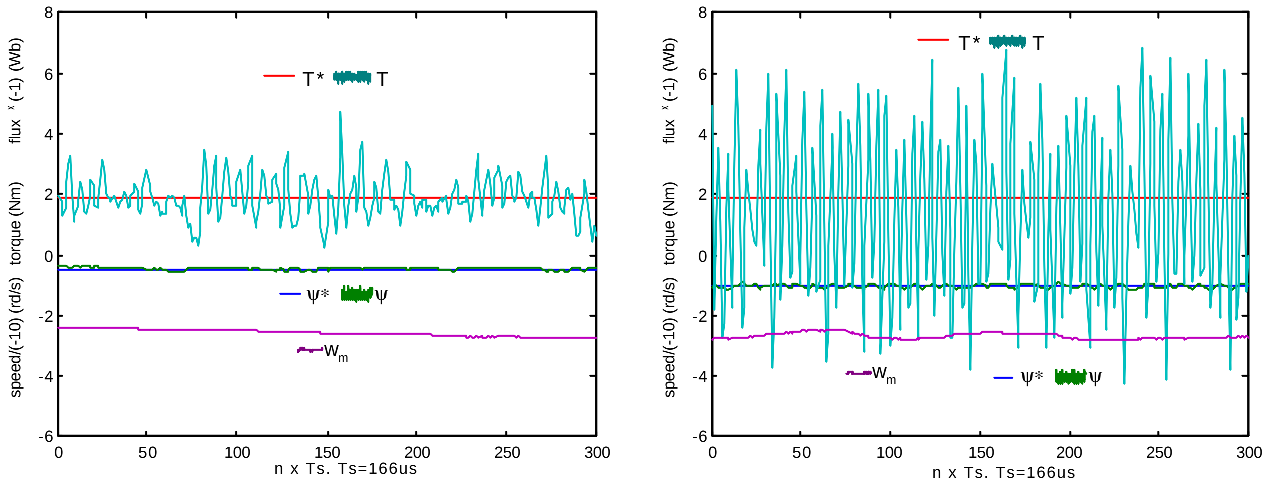

Figure 5.25. Stator flux, torque and speed motor_1.5kW responses in Fuzzy Logic DTC (left) and classical DTC (right).
Load resistance is 8Ω. Torque reference value is 1.9Nm, i.e. T=19%T_n.

5.3 - Interim conclusions.

In this chapter, the implementation of two high performance control strategies for three cage rotor induction motors has been described. Being the first classical DTC and the second the FLDTC, both with stator flux and torque estimation.

Experimental results are shown to analyse in detail the correct behaviour of both implementations. All magnitudes evolution are analysed and justified.

Also, the main research point of the present thesis, which is the torque ripple reduction, has been experimentally proved by means of the torque, flux and speed real experimental results.

Moreover, the adaptation of the ideal FLC not only to any motor but also to the limitations of the real systems is corroborated.