# Continuous DTC of the Induction Motor

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***Abstract*—In the case of the classical direct torque control (DTC) of the induction motor, the minimum switching period of the inverter is equal with the sampling period of the control system. Due to this intrinsic characteristic, competitive real time control can be achieved only by using high performance control systems. If moderate performances system is used, the behavior of the drive is unsatisfactory, even inacceptable. The paper proposes continuous variants of the DTC, obtained by replacing the discrete controllers specific to the classical DTC with two or three continuous controllers, one of them being the speed controller. Thus, the sampling period of the control system is decoupled by the switching period of the inverter and a moderate performance real time control system can be used.**

***Index Terms*— continuous time systems, direct torque control, induction motor drives**

## I. INTRODUCTION

The regulation by direct torque control (DTC) of the induction motor is a quite "natural" method, being much lighter, as mathematical support, than the vector control, regardless the type of field considered for orientation. Despite its simplicity, the practical implementation of the method rise serious problems, mainly due to the fact that the sampling period for regulation purposes is right the minimum PWM period of the inverter which supplies the motor. Consequently, without using high performance command systems, the results can be far from the expectances. The paper deals with the simulation of such regulation system and highlights the importance on the performances of the sampling period. Experimental results obtained with a DS1102 system from dSPACE confirm the behavior described by the simulations. There are proposed two continuous variants of DTC. For both, the hysterezis controllers are replaced by PI ones, thus the switching period of the inverter being decoupled by the sampling period of the control system. The dependency of the performances by the sampling period is less tight.

The course of the paper is as follows: section II briefly describes the principle of the classical DTC and highlights by simulations the influence of the sampling period of the control system on the behavior of the drive. Section III presents the experimental results obtained with the dSPACE DS1102 board for the classical DTC of the induction motor which confirms on one hand the correctness of the simulations and on the other hand the unsatisfactory behavior of the drive controlled with large sampling periods. In section IV are proposed two continuous variants of the DTC and their simulation results. Section V presents some experimental results of the proposed schemes, obtained with the same control board. Once again, the simulations are confirmed. Finally in section VI some conclusions are drawn.

## II. CLASSICAL DTC: PRINCIPLE AND SIMULATIONS

The direct torque control (DTC) of the induction motor represents an alternative to the well known vector control. This control strategy was developed [1, 2] due to the necessity, for certain applications [3-5], of avoiding the precise position or speed transducer, required by the vector control schemes [6]. Basically, the DTC of the induction motor controls the torque by the mean of the speed of the estimated stator flux. In the same time, the amplitude of the stator flux must be maintained as close as constant. These two magnitudes (the speed and the amplitude of the stator flux) are controlled by the mean of the stator voltage applied to the motor by a voltage source inverter.

The actual stator flux can be estimated based on the applied stator voltages and on the measured stator currents:

$$\underline{\Psi}_s = \int \left( \underline{u}_s - R_s \cdot \underline{i}_s \right) dt, \qquad (1)$$

where $\underline{u}_s$ and $\underline{i}_s$ are the space vectors of the stator voltage and stator current respectively.

Practically, the stator flux vector is reconstructed by the mean of its αβ components, computed at them turn based on the αβ components of the stator voltage and currents [7]:

$$\begin{aligned} \Psi_{s\alpha} &= \int \left( u_{s\alpha} - R_s \cdot i_{s\alpha} \right) dt, \\ \Psi_{s\beta} &= \int \left( u_{s\beta} - R_s \cdot i_{s\beta} \right) dt. \end{aligned} \qquad (2)$$

It is to note that in practice only the stator currents are measured. The stator voltages are identified based on the inverter topology (switches states) and the measured DC voltage at the inverter input [8].

The developed electromagnetic torque can also be estimated, based on the αβ components of the stator flux resulted from (2) and the corresponding components of the stator currents, resulted from the measured ones:

$$T_e = \frac{3}{2} p \left( \Psi_{s\alpha} \cdot i_{s\beta} - \Psi_{s\beta} \cdot i_{s\alpha} \right), \qquad (3)$$

where $p$ is the number of pairs of poles of the machine.

The locus of the top of the stator flux space vector (ideally, a circle) must be reconstituted as precise as possible, in order to avoid high currents and torque ripples [9]. However, this could be done by using the only six non-zero space vectors and the two "zero" space vectors available as output of the inverter [7, 8]. The six non-zero space vectors correspond each to a different topology of the inverter, when not all + connected or – connected switches are on.

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Depending on the actual position of the stator flux space vector and on the requested action, the next topology of the inverter is chosen in accordance with the commutation table [7]. The requested action is delivered by two hysteresis discrete controllers which give the necessary sense of evolution of the flux amplitude and of the developed torque.

The choice of one of the null vectors is performed having in mind the reduction of simultaneous commutations and consequently, the switching looses in the inverters legs [8].

As the necessary further inverter's topology and therefore the voltage vector is determined at each sampling period, it is obviously that the last must be as small as possible in order to achieve a convenient switching frequency.

In simulation it is possible to choose a fixed step size as small as we need, but for the real time control, the limitations of the control system must be considered.

By using the Simulink libraries previously developed by the author [10, 11], the model of the driving system was developed following the principle of the classical DTC (Fig. 1).

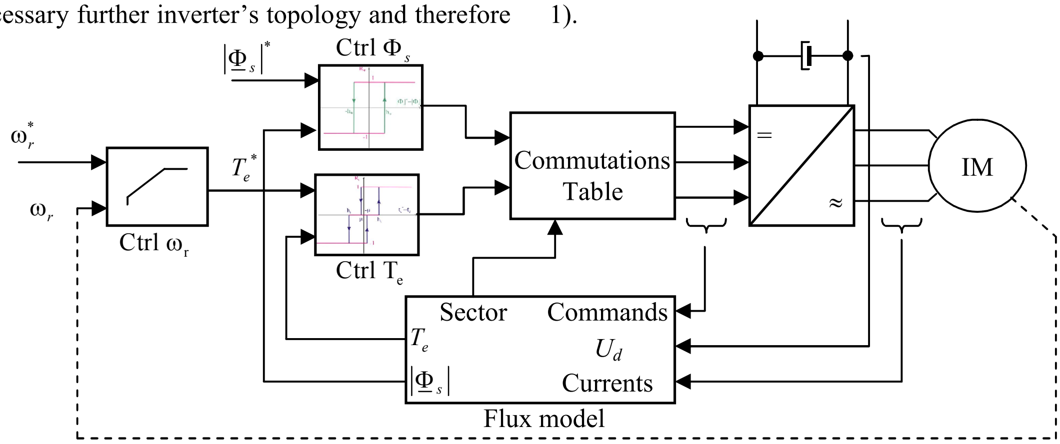
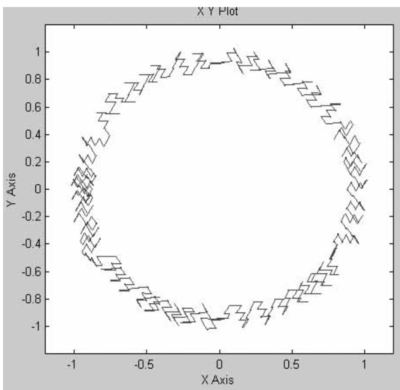


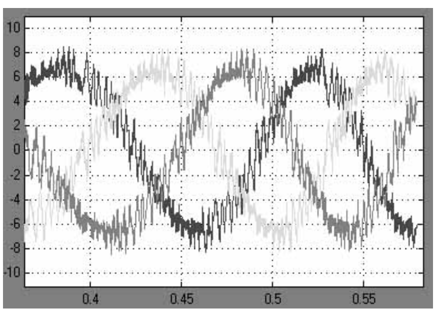

Fig. 1 The classical DTC of the induction motor.

As can be easily previewed, good results were obtained by choosing a small simulation step.

The Fig. 2 plots the results of the simulation with a fixed simulation step of 100μs which is equivalent to the sampling period for a future real time control. The locus of the top of the stator flux space vector (a) and the phase currents (b) were detailed for about one period during a step start, in order to highlight the successive commutations.




a)

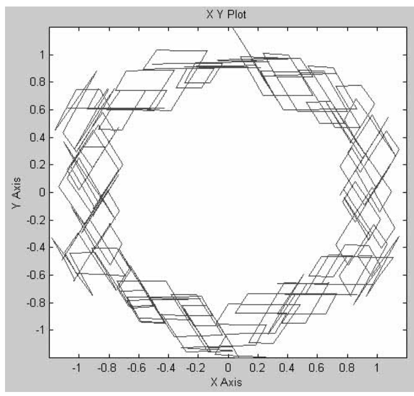


b)

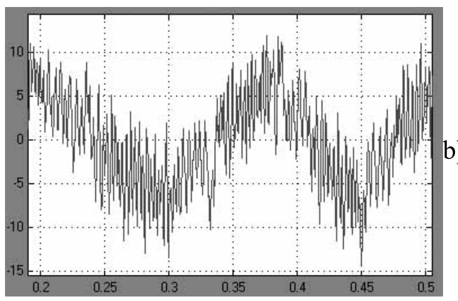
Fig. 2 Simulation results for fixed 100 μs simulation step: a – the locus of the top of the stator flux space vector; b – phase currents.

It is interesting to note the discrete displacement of the top of the stator flux space vector which follows, during each simulation step, the direction of the stator voltage space vector corresponding to the chosen topology.

However, this step is too small for the possibilities of the control board DS1102 that will be used to experimentally test the control. This why, the simulation step size was increased to 500 μs, as has been estimated that could be a feasible value for the real time control. The results of these simulations are plotted in Fig. 3, for a similar regime as in Fig. 2.




a)



b)

Fig. 3 Simulation results for fixed 500 μs simulation step: a – the locus of the top of the stator flux space vector; b – phase currents.

As the top of the stator flux space vector follows the direction of the stator voltage space vector during each fixed simulation step (sampling period), large errors in the flux amplitude (Fig. 3.a) occurs. It could be also noticed the quite disturbed shapes of the phase currents, due to the reduction of the switching frequency of the inverter to about 2 kHz. Consequently, the high ripples of the stator flux and phase currents will lead to important ripple of the electromagnetic torque.

## III. EXPERIMENTS ON CLASSICAL DTC

The real time control is implemented on a testing rig whose control is centered on a DSP based control all-in-one board from dSPACE GmbH, DS1102. Thanks to the advantages of the friendly interface between the DS1102 DSP board and the Matlab-Simulink® environment, it is possible the quick implementation of the control algorithms and the interfacing of the sensors [11, 12].

Using this friendly interface supplied by dSPACE, making only slight changes in the simulation diagrams, the experimentation of different control schemes requires less effort than any other experimentation platform. Basically, the structure of the Simulink control diagram rests as in simulations (Fig. 1), only the blocks specific to the interfacing with the power system must be added. These blocks substitute the models of the inverter and of the motor, as can be seen in Fig. 4.

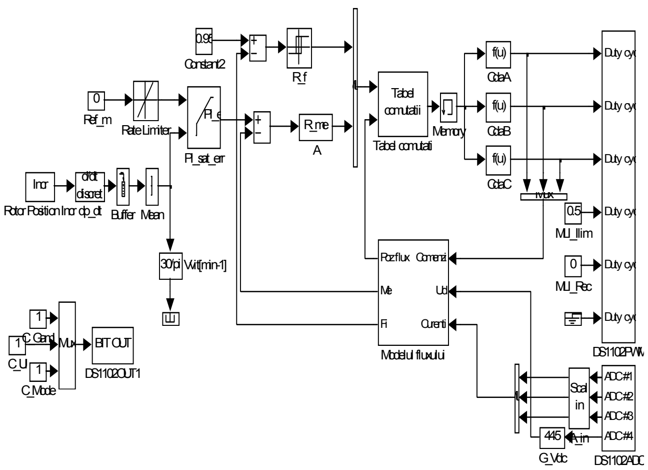



Fig. 4 The Simulink diagram for the real time control of the driving system with induction motor and classical DTC.

Several blocks are also added which control mainly the system functionality (power on/off, currents and speed measurement). The system does not allow to be set sampling period smaller that the execution time of the compiled control diagram. The use of the PWM output block increases significantly the execution time, so the sampling period was set to 550 μs. The experimental results were, as could be easily anticipated, not very satisfactory, an example being depicted in Fig. 5, where a period of the phase current is plotted.

## IV. CONTINUOUS DTC

In this section two variants of the proposed continuous DTC for the induction motor will be presented.

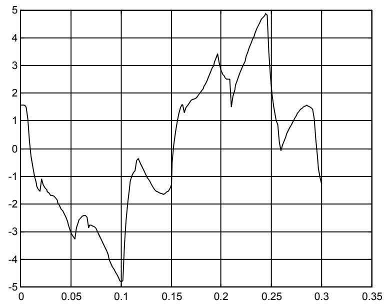



Fig. 5 Phase current with 550 μs sampling time for classical DTC.

### IV.1 Complete continuous DTC

As was stated above [7] and demonstrated by simulations, in the case of classical DTC, the switching frequency of the inverter's devices is given by the sampling frequency of the whole control system. The minimum pulse width is exactly the sampling period. When, due to the limitations of the real time control system, large sampling periods are used, the results are not satisfactory.

The continuous DTC that we propose breaks the dependency between the sampling period of the control system and the minimum pulse width of the inverter.

For achieving this, the discrete controllers specific to the classical DTC (bi-positional for flux and three-positional for torque), will be replaced with continuous ones of PI type.

As the amplitude of the flux is determined essentially by the voltage amplitude (1), one PI controller will compare the reference value of the stator flux amplitude with the actual one, obtained, as in the classical control, from the same flux model. The output of this controller will have the significance of voltage amplitude.

A second PI controller will compare the preset value of the torque with the actual one. As in the classical DTC, the torque is controlled by the way of the speed of the stator flux which, at its turn, is controlled by the stator voltage. The output of this controller will have the significance of the slip between the stator flux and the rotor. The output of this controller will be added to the actual mechanical speed of the rotor (previously multiplied by the number of pairs of poles of the motor). The result will be the necessary stator flux speed. This speed will be integrated in order to obtain the position of the anticipated stator voltage. Following, this position will be used, together with the output of the first PI controller to obtain the $\alpha\beta$ components of the necessary stator voltage.

It is true, the way how the further position of the stator voltage is obtained, needs the measurement of the actual mechanical speed which is one of the drawbacks avoided by the classical DTC, where the reference value of the torque can be directly applied as reference value to the torque controller, as in case of electric traction applications. But, if is considered a speed loop, the measured rotor speed is used also as reaction for the speed controller which will give the reference value of the torque. This is the case we have considered.

The diagram of the complete continuous DTC is depicted in Fig. 6.

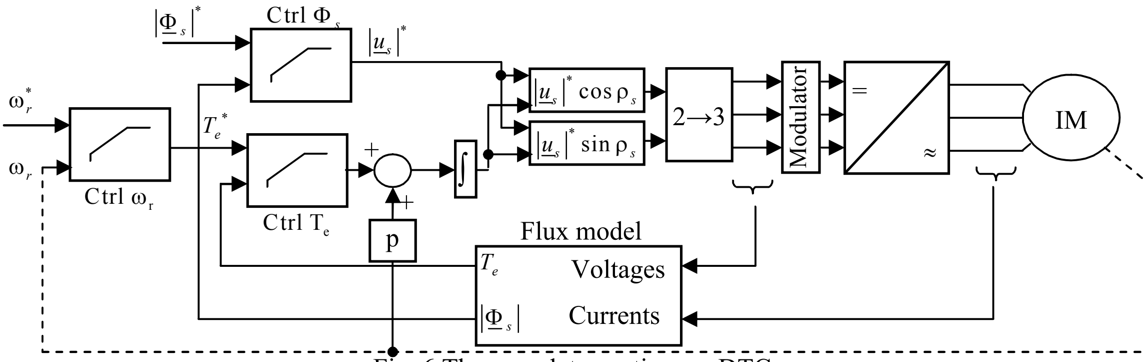


Fig. 6 The complete continuous DTC.

It is to note that this time there is no model of the inverter considered, as in the case of classical DTC (Fig. 1). The T2_3 block makes the transformation of the αβ components of the stator voltage in instantaneous phase voltages which are directly applied to the motor. This can be possible if we assume the inverter as being an ideal amplifier. The hypothesis is correct if the switching frequency of the inverter is high enough. In our case, the inverter used in experiments uses MOS transistors which are switched at 30 kHz.

The simulation of the system was performed by using a 500 μs fixed step. The main results are plotted in Fig. 7.

In Fig. 7.a are plotted the phase currents. As the inverter was considered as ideal amplifier, the phase currents are quasi sinusoidal. Consequently, the electromagnetic torque has no ripple (Fig. 7.b). The dynamic response of the system is quite satisfactory, the reference speed of 70 rad/sec being achieved in about 0.55 sec after the step application (Fig.7.c).

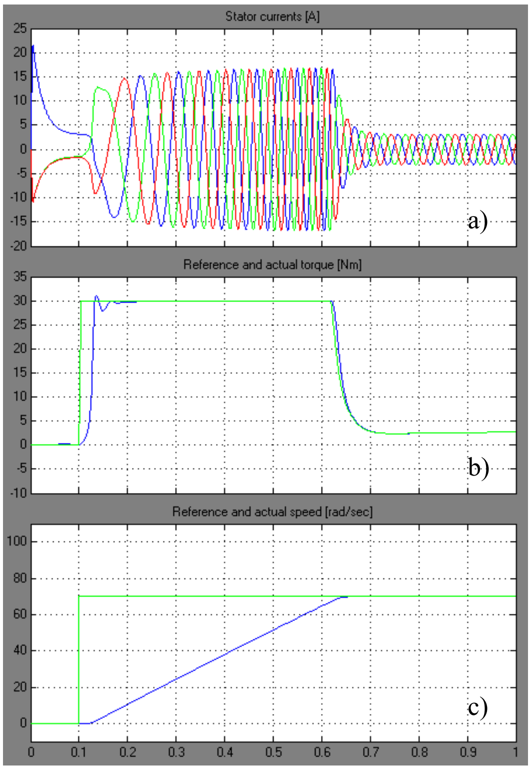


Fig. 7 Results of the simulation of the complete continuous DTC with 500 μs fixed simulation step.

The good behavior of the control system is confirmed also by the plot of the locus of the top of the stator flux space vector during the whole dynamic regime, Fig. 8. This one is almost a perfect circle and it must be compared with the distorted shape depicted in Fig. 3.a, being obtained with the same 500 μs fixed simulation step.

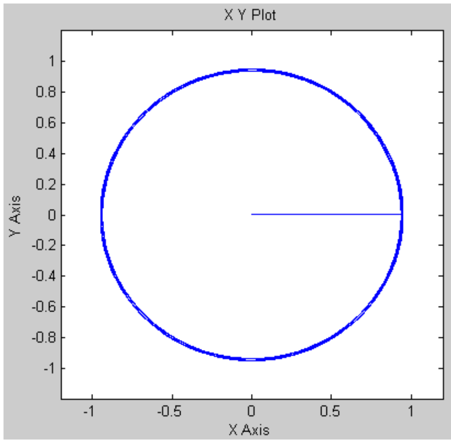


Fig. 8 The locus of stator flux space vector top for complete continuous DTC.

IV.2 Simplified continuous DTC

The control diagram can be simplified, by avoiding one PI controller, the torque one respectively. Indeed, by a proper tuning of the speed controller, its output can have now directly the significance of the slip not of the reference torque to be applied to the following torque controller.

In this case, the resulted control diagram will have only two continuous controllers of PI type, including the one for speed. One controller regulates the voltage amplitude and the other controls the speed and consequently the slip. The resulted control diagram is depicted in Fig. 9.

Elimination of the torque controller makes unnecessary the torque reaction computed by the flux model (3). This leads to an additional simplification and reduction of the calculus effort of the real time control system.

The results of the simulation are plotted in Fig. 10 and they must be compared with the ones obtained with the complete simplified DTC (Fig. 7). It is to notice the high similarity between the two sets of waveforms. This confirms the good behavior of the simplified control system. This control was used to be implemented on the testing rig.

For completing the comparison with the complete continuous DTC, Fig. 11 plots the locus, during the whole dynamic regime, of the stator flux space vector top. As was expected, the shape continues to be an almost perfect circle which gives the guarantee that the torque ripple is negligible.

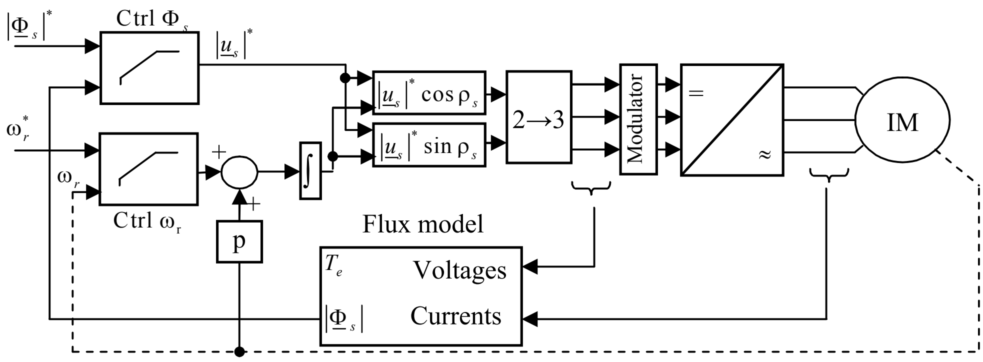



Fig. 9 Simplified continuous DTC.

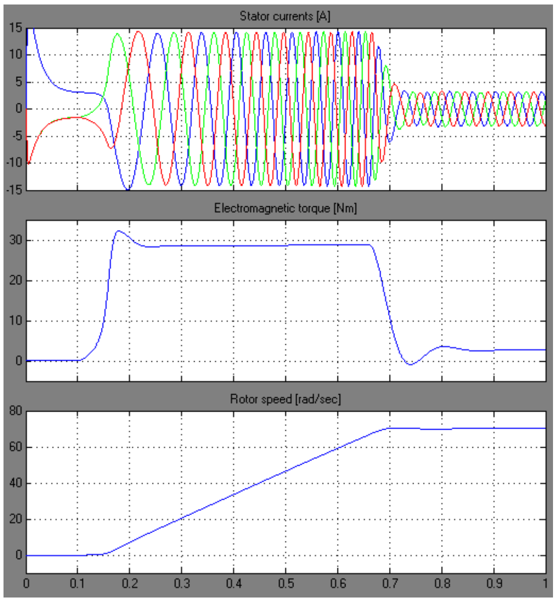



Fig. 10 Results of the simulation of the simplified continuous DTC with 500 μs fixed simulation step.

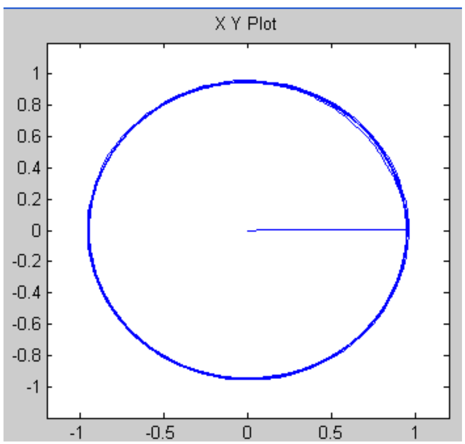



Fig. 11 The locus of stator flux space vector top for simplified continuous DTC with 500 μs fixed simulation step.

## V. EXPERIMENTS ON CONTINUOUS DTC

Using the same testing rig described in Section III, the simplified continuous DTC was implemented.

The execution time of the whole control diagram is about 450 μs, but for avoiding the processor overloading and consequently the system catch, the sampling period (fixed step execution time) was set to 550 μs.

Fig. 12 plots a detail of the phase current. It is obvious that, comparing with the shape of the current obtained for classical DTC (Fig. 5), the behavior of the simplified continuous DTC is much less disturbing.

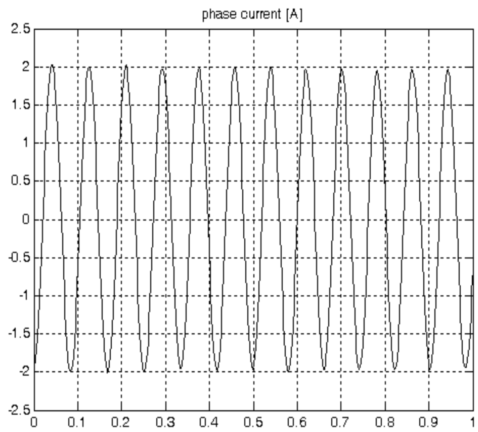



Fig. 12 Phase current with 550 μs sampling time for simplified continuous DTC.

The locus of the stator flux space vector top is plotted in Fig. 13. Again, as in simulations (Fig. 8 and 11), it describes an almost perfect circle due to the decoupling between the sampling period of the control system and the switching period of the inverter.

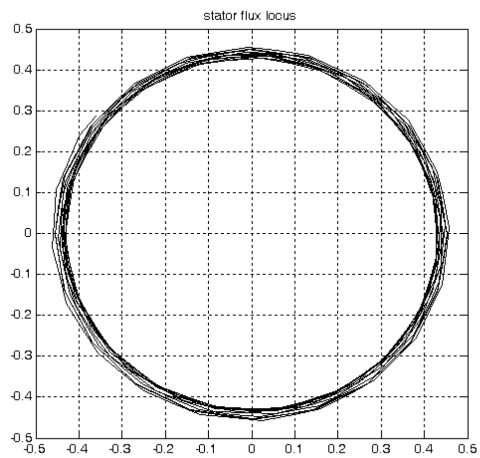



Fig. 13 The locus of stator flux space vector top for simplified continuous DTC with 550 μs sampling period.

During the tests was noticed a certain lack of stability during the no load operation, but, as the figures describe, a good behavior if the drive is loaded.

## VI. CONCLUSION

The paper analyses the behavior of the classical DTC of the induction motor when large values of the sampling period are used in real time control due to the hardware limitations. The conclusion drawn is that the implementation of the classical DTC implies the necessity of a high quality real time control system. Otherwise, the results are quite unsatisfactory.

Following, there are presented two variants of continuous direct torque control (DTC) technique for the induction motor. The proposed strategies break the link between the switching frequency of the inverter and the sampling period of the control system, being able to obtain good results, even with large sampling periods.

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