Simulation, analysis and comparison of field-oriented control and direct torque control

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Abstract: *this article is about the analysis and the comparison of field-oriented control and direct torque control for induction machine drives, based on simulation results. In the first section the principles of the two control methods are introduced. The second section is about the examination of the two methods based on simulation results. The third section summarizes the results, marks the possible applications of the two methods and determines the further research needs to be done.*

Keywords: *field oriented control, direct torque control, induction motor, frequency converter, motor control, drive control, inverter*

1. Fundamentals of field-oriented control and direct torque control

1.1. The field-oriented controlled induction machine [1], [2]

In order to understand the basics of the field-oriented controlled induction machine drive, the so-called "d-q" coordinate-system must be defined. In this

coordinate-system the real axis (also called "d"-axis) is fixed to the rotor flux vector and the imaginary axis (also called "q"-axis) is perpendicular to the real axis. The illustration of this coordinate-system can be seen on figure 1.1.
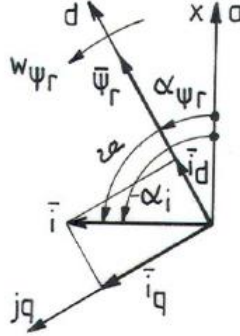

Figure 1.1: The d-q coordinate-system [1]

Where:

$\overline{\Psi_r}$: the rotor flux vector

$\overline{\imath}$: the stator current vector

$\overline{\imath_d}$: the real component of the stator current vector in the d-q coordinate-system

$\overline{\imath_q}$: the imaginary component of the stator current vector in the d-q coordinate-system

In the d-q coordinate-system, the real and the imaginary components of the stator current vector have special attributes. Equation 1.1 shows the relationship for the electromagnetic torque and equation 1.2 shows the relationship for the rotor flux.

$$m = \frac{3}{2}p\Psi_r i_q \qquad (1.1)$$

$$\Psi_r + T_{r0}\frac{d\Psi_r}{dt} = L_m i_d \qquad (1.2)$$

Where:

m: the electromagnetic torque

p: the number of pole-pairs

L_m: the mutual inductance

T_{r0}: the rotor time constant ($T_{r0} = \frac{L_m}{R_r}$)

As it can be seen from equation 1.2, the amplitude of the rotor flux vector is determined by the real component of the stator current vector only. If i_d is held constant then the electromagnetic torque will be determined by i_q only. This means that in the d-q coordinate-system the induction machine can be controlled like a compensated DC-machine. One quantity controls the flux (stator current for DC-machines, i_d for induction machines) and –if the flux-controlling quantity is held constant– one quantity controls the electromagnetic torque (rotor current for DC-machines and i_q for induction machines). By holding the flux-controlling quantity constant, good dynamic performance can be achieved. A simplified block-diagram for field-oriented control can be seen on figure 1.2.

However, this method has numerous drawbacks. The main disadvantage is –in contradiction to the case of permanent magnet synchronous machines– the position of the rotor flux vector cannot be measured directly (in the case of permanent magnet synchronous machines the poleflux vector is fixed to the rotor). This means that its position must be determined through computation, involving machine parameters. In practice, the machine parameters are not constant, i.e. the stator and the rotor resistances increase during operation due to the heating. Therefore, field-oriented control of induction machines is heavily parameter-sensitive.
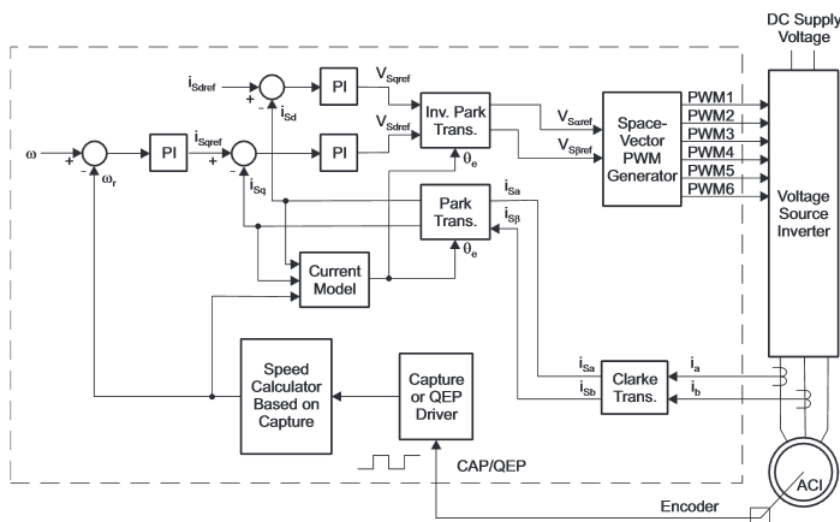

Figure 1.2: A simplified control-scheme for field-oriented control [3]

If the position of the rotor flux vector cannot be determined with mathematical accuracy then the decoupling between components i_d and i_q will cease, and this will inevitably lead to control-errors. The rate of the control-errors depend on the error of the rotor flux vector position-estimation. This problem can be overcome by the measurement of the machine parameters during operation (so-called "on-

line identification"), but this further complicates the control method and increases computation needs.

There are some other problems which make this control method even more sensitive to parameter-variation. The field-oriented controlled induction machine drive requires four controllers. The four controllers are: speed-controller, rotor flux controller, i_d-controller, i_q-controller. The latter three are of PI-type controllers and the optimal settings for them are heavily dependent on the machine parameters, further increasing the parameter-sensitivity of this method. Also, the relatively high amount of controllers makes it difficult to accomplish the optimal settings for the overall system, which makes the implementation of this method even more complicated.

To sum up, field-oriented control of induction machines is a complex method, requiring much computation and its parameter-sensitivity makes it difficult to implement it in practice. These problems have led to the development of other control methods. One of them is direct torque control, which is based on a completely different philosophy.

1.2. Direct torque control of induction machines [1], [2]

In order to understand the basic physics of the direct torque controlled induction machine drive, a closer look must be taken at the electromagnetic torque. The expression defining the electromagnetic torque is as follows:

$$\bar{m} = \frac{3}{2} p \overline{\Psi_r} \times \bar{\iota} \tag{2.1}$$

This can be further expressed as:

$$\bar{m} = \frac{3}{2} p \frac{\overline{\Psi_r} \times \overline{\Psi}}{L'} \tag{2.2}$$

Where:

$\overline{\Psi}$: the stator flux vector

L': the transient inductivity of the stator

Therefore, the absolute value of the electromagnetic torque:

$$m = \frac{3}{2} p \frac{\Psi_r \Psi \sin \delta}{L'} \approx \frac{3}{2} p \frac{\Psi_r \Psi \delta}{L'} \tag{2.3}$$

Where:

δ: the angle between the stator- and the rotor flux vector.

The stator flux vector can be expressed as

$$\overline{\Psi_r} = \overline{\Psi} + L' \bar{\iota} \tag{2.4}$$

Therefore, the angle between the stator- and the rotor flux vector is very small, so the electromagnetic torque is approximately:

$$m \approx \frac{3}{2} p \frac{\Psi_r \Psi \delta}{L'} \tag{2.5}$$

This means that the electromagnetic torque is the function of three parameters: the stator flux, the rotor flux and the small angle between them. In steady-state, the rotor flux vector revolves on a circular line with constant speed, preceded by the stator flux vector (figure 2.1).
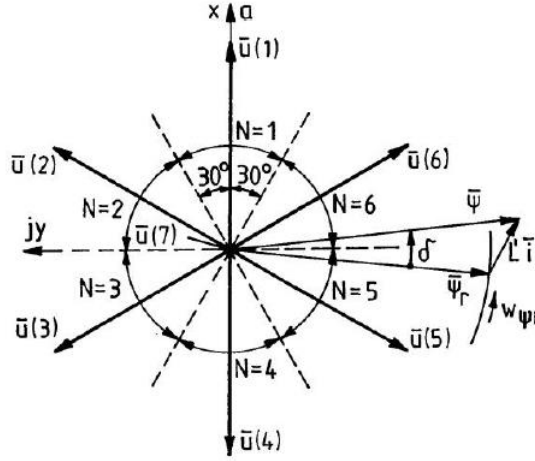

Figure 2.1: The stator flux vector and the rotor flux vector in steady-state [1]

Because of the $L'\bar{\imath}$ term in equation 2.4, the amplitude and the angle of the stator flux vector can be modified in a much faster way than those of the rotor flux vector. Therefore, it is worthwhile using the stator flux vector for electromagnetic torque control. The derivative of the stator flux vector can be expressed as:

$$\left(\frac{d\overline{\Psi}}{dt}\right)_k = \overline{u(k)} - R\bar{\imath} \approx \overline{u(k)} \qquad (2.6)$$

Where:

$\overline{u(k)}$: the stator voltage vector

R: the stator resistance

This means that the amplitude and the angle of the stator flux vector can be changed with the stator voltage vector. Figure 2.1 shows the voltage vectors belonging to the inverter switching states (shortly: switching voltage vectors). These are the voltage vectors that can be used for controlling the stator flux vector.

The fastest control of electromagnetic torque can be achieved by changing the angle between the two flux vectors. The fastest way to change the angle between the two flux vectors is to use the switching voltage vectors approximately perpendicular to the rotor flux vector, because δ is small. For example, if a motor mode operation ($w_{\psi_r} > 0$ and $m > 0$) is considered like on figure 2.1, the fastest possible way to increase the electromagnetic torque is to switch to the $\overline{u(1)}$ voltage vector, while the fastest possible way to decrease the electromagnetic torque is to switch to the $\overline{u(4)}$ voltage vector. The $\overline{u(7)}$ voltage vector stops the stator flux vector, therefore decreases the electromagnetic torque. It is obvious that electromagnetic torque can be controlled in the simplest way, by using hysteresis controllers.

Stator flux amplitude can be controlled in a similar way: if the fastest increase in stator flux amplitude is needed then a switch to the $\overline{u(6)}$ or to the $\overline{u(5)}$ voltage vectors is the best solution, while the fastest decrease in the electromagnetic torque can be achieved by switching to the $\overline{u(3)}$ or to the $\overline{u(2)}$ voltage vectors. The $\overline{u(7)}$ voltage vector leaves the amplitude of the stator flux vector unmodified (but decreases the electromagnetic torque). Therefore, hysteresis controllers can be used for the control of the stator flux amplitude as well.

A simplified block diagram of the direct torque controlled induction motor drive can be seen on figure 2.2.
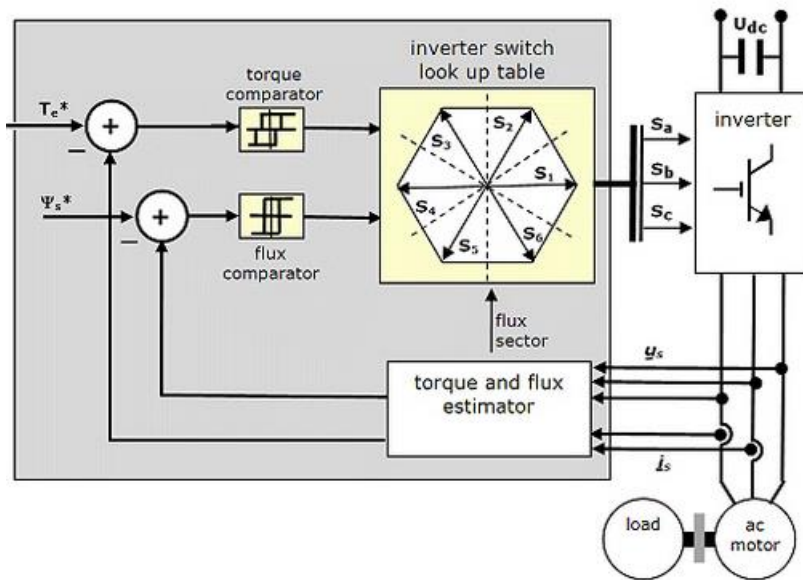

Figure 2.2: Simplified block diagram for direct torque control [4]

In the direct torque controlled induction motor drive hysteresis controllers are used to control electromagnetic torque and stator flux, which are easy to set and grant greater robustness compared to the case of the field-oriented controlled induction motor drive. Only one controller, the speed-controller is not hysteresis controller, but its setting is independent on the machine parameters. Because direct torque control uses hysteresis controllers to control stator-flux and electromagnetic torque, there is no need for voltage-modulators, contrary to the case of field-oriented control. Another great advantage is that direct torque control uses only the stator resistance from the machine parameters, which also contributes to the robustness of the method.

The greatest advantage of all is that there is no need for the accurate determination of the stator flux vector; it is enough to know its position with 60 electrical degrees accuracy. This makes direct torque control a very robust method compared to field-oriented control. Because of the $L'\bar{\imath}$ term in equation 2.4, electromagnetic torque can be controlled in a much faster way than in the case of field-oriented control. These advantages can make direct torque control more capable of controlling induction motor drives requiring high dynamic performance.

2. Simulation results

The following figure shows the process of acceleration and deceleration for field-oriented control. The measured variable is rotor speed. The speed-reference signal is represented by the yellow curve and the rotor-speed is represented by the purple curve.
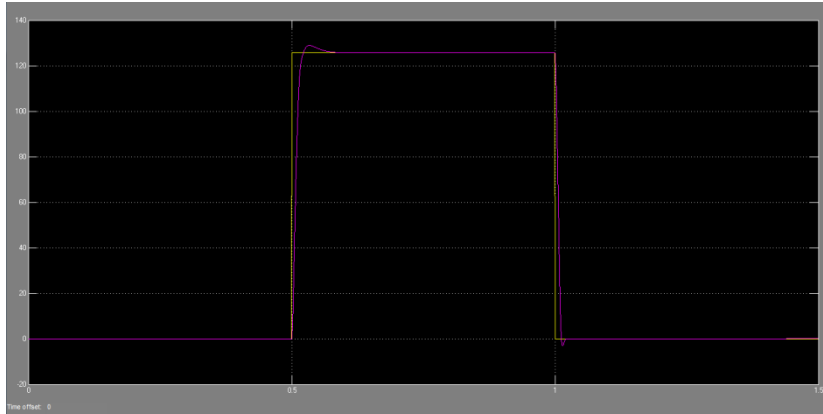

Figure 2.1: The process of acceleration and deceleration for field-oriented control

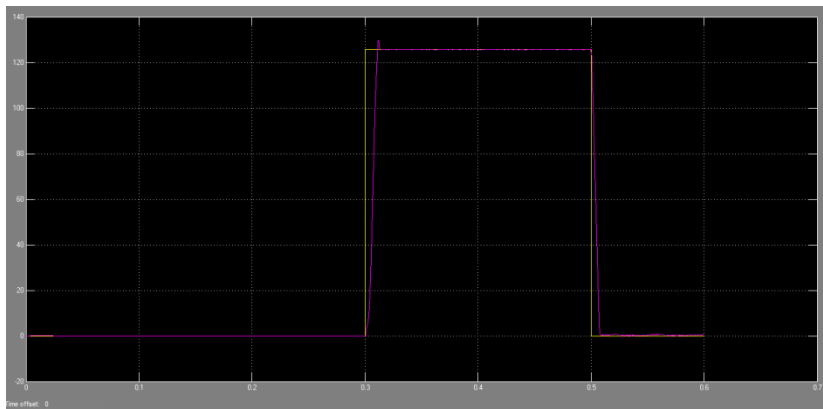The next figure shows the same process for the direct torque controlled induction machine drive. The notation is the same as before.

Figure 2.2: The process of acceleration and deceleration for direct torque control

Figure 2.3 and figure 2.4 shows the starting process enlarged for the two control methods. The time required for reaching the 90% of the speed-reference signal from standstill is approximately 14 ms in the case of field-oriented control and

approximately 10 ms in the case of direct torque control. The situation is similar during deceleration.
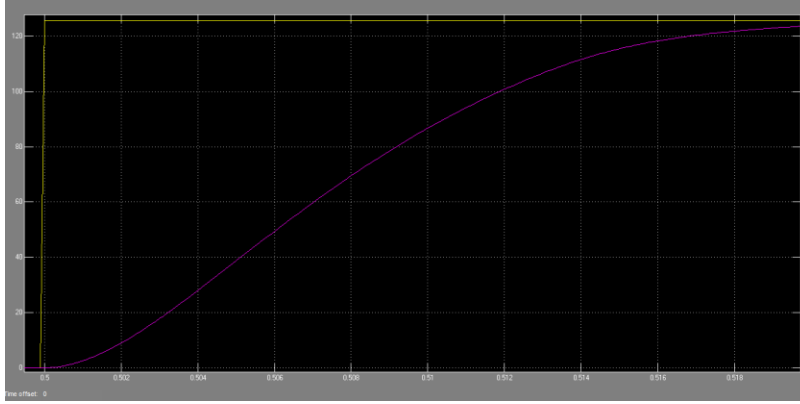

Figure 2.3: The starting process enlarged for field-oriented control
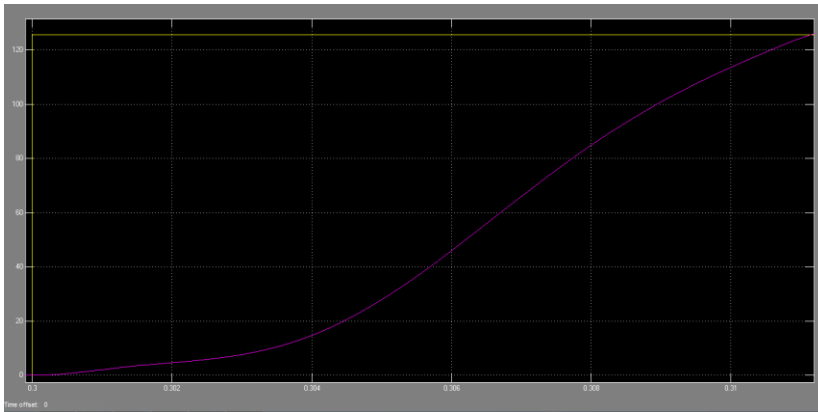

Figure 2.4: The starting process enlarged for direct torque control

At first glance, direct torque control seems to be more capable of controlling drives systems requiring high dynamic performance. But, if a closer look is taken at the pictures at steady-state the main disadvantage of direct torque control can be discovered. Figure 2.5 shows that for field-oriented control the rotor-speed in steady-state is perfectly flat, precisely following the speed-reference-signal, whereas in the case of direct torque control on figure 2.6 a relatively high amount of speed-ripple can be noticed. The speed-reference is $125.66 \frac{rad}{s}$, so the maximum of the speed-error in the case of direct torque control is $\frac{125.85-125.66}{125.66} =$

0.15%. Although direct torque control provides higher dynamic performance than field-oriented control, but only field-oriented control is well-suited for an application requiring the precise traction of the speed-reference signal.
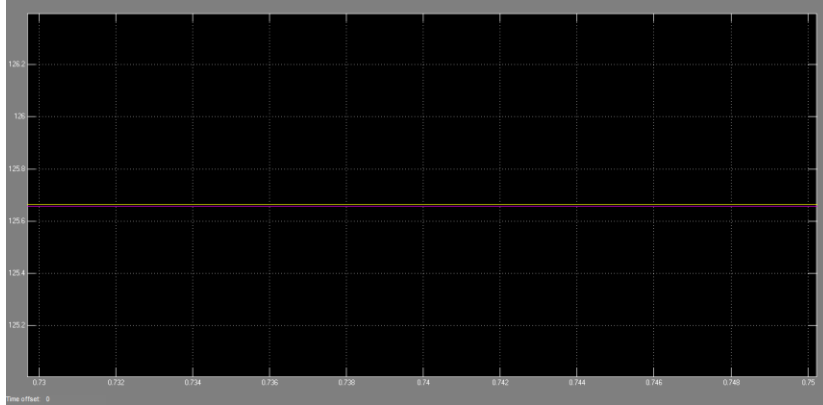

Figure 2.5: The speed-reference signal and the rotor-speed in steady-state for field-oriented control
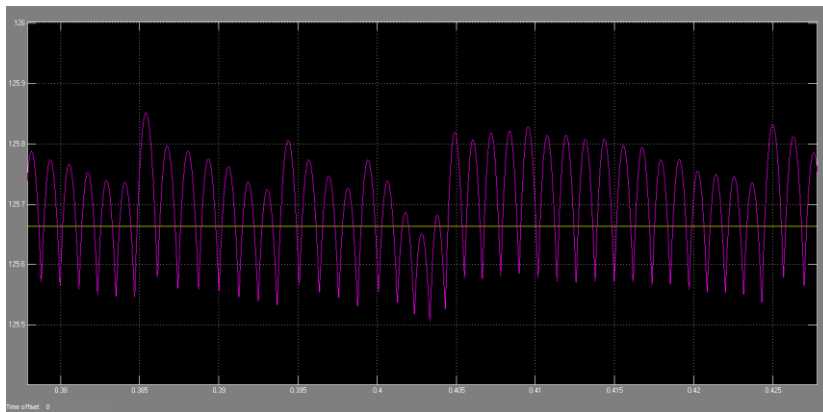

Figure 2.6: The speed-reference signal and the rotor-speed in steady-state for direct torque control

Figure 2.7 and figure 2.8 shows the electromagnetic torque for the same process in the case of field-oriented control and in the case of direct torque control, respectively. During starting and braking a short-time transient can be noticed. This is normal because both of them are transient procedures. The duration of the starting transient is approximately 20 ms for field-oriented control and approximately 14 ms for direct torque control. The situation is similar during braking. This means that direct torque control is capable of a much faster torque-control than field-oriented control. This is the reason for the higher dynamic performance. However, field-oriented control produces zero torque-ripple even in

the transient state, while a relatively high amount of torque-ripple can be noticed in the case of direct torque control, even in steady-state. This is what makes accurate speed-control impossible for a direct torque controlled induction motor drive.
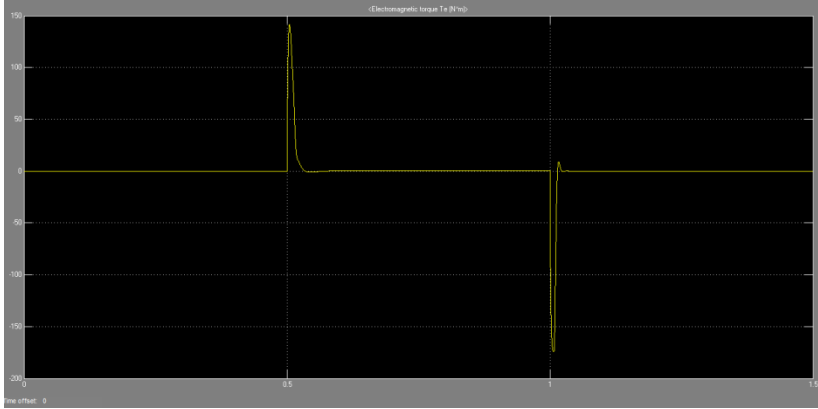

Figure 2.7: Electromagnetic torque during acceleration and deceleration for field-oriented control
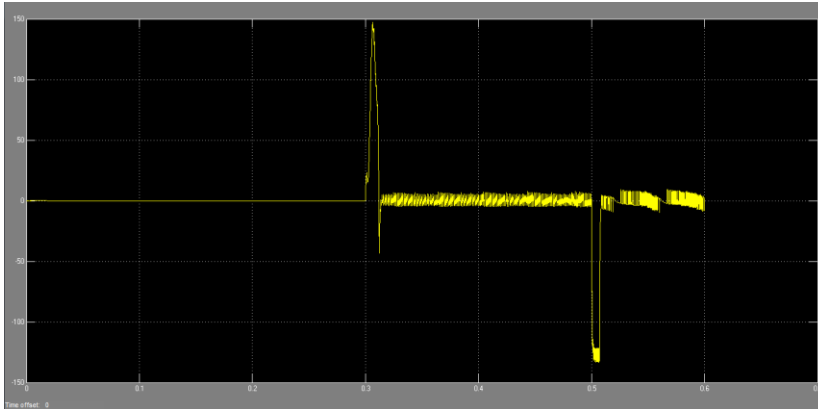

Figure 2.8: Electromagnetic torque during acceleration and deceleration for direct torque control

The torque-ripples can be noticed in the stator phase-currents as well. Figure 2.9 shows that for field-oriented control the stator currents are perfectly sinusoidal, whilst in the case of direct torque control on figure 2.10 the stator currents are only roughly sinusoidal. This is due to the fact that field-oriented control controls the stator currents directly with PI-control algorithm, whereas direct torque control uses a hysteresis method to control the stator flux and the electromagnetic torque directly and thus the stator currents are controlled indirectly in a hysteresis way.
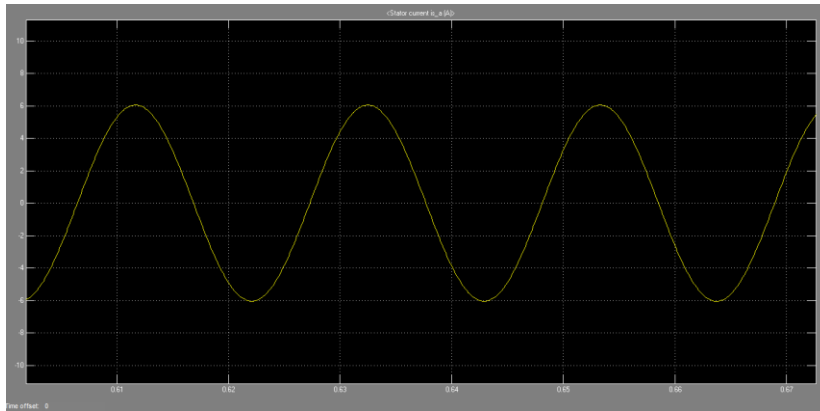
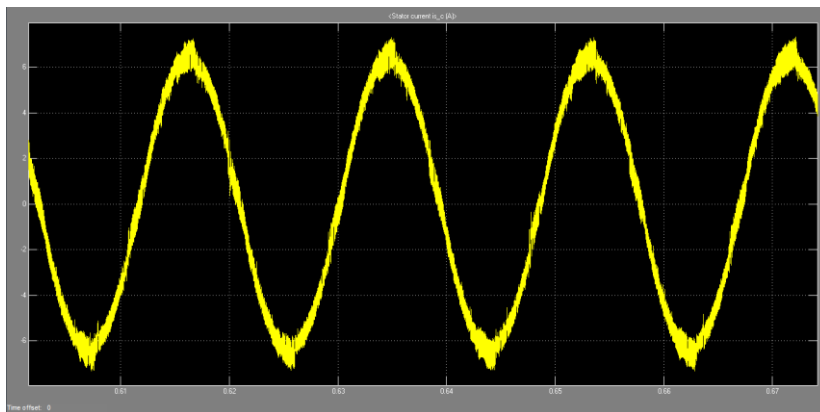Figure 2.9: A stator phase-current for field-oriented control

Figure 2.10: A stator phase-current for direct torque control

Fast torque-response is a very important feature of a drive requiring high dynamics. Figure 2.11 and figure 2.12 shows the step-responses for both methods. The load torque is applied to the motor in steady-state. The settling-time for field-oriented control is approximately 20 ms, while in the case of direct torque control it is lower than 5 ms (approximately 3.5 ms). It can be clearly seen that direct torque control is much faster when it comes to torque control. However, the torque-ripples which are inherent to the method are intolerable in most applications.
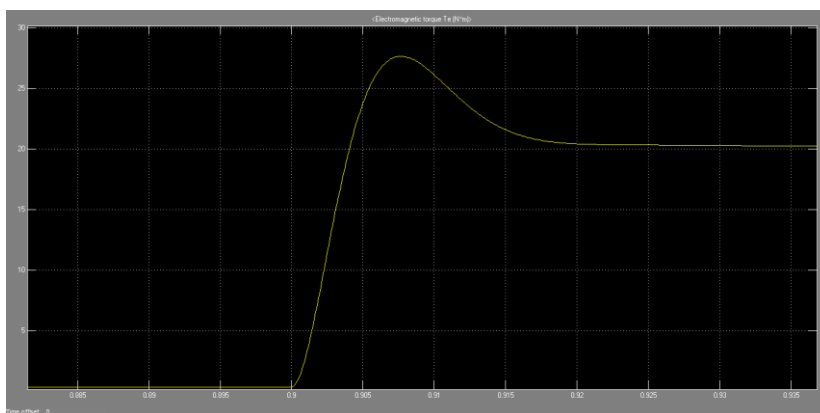
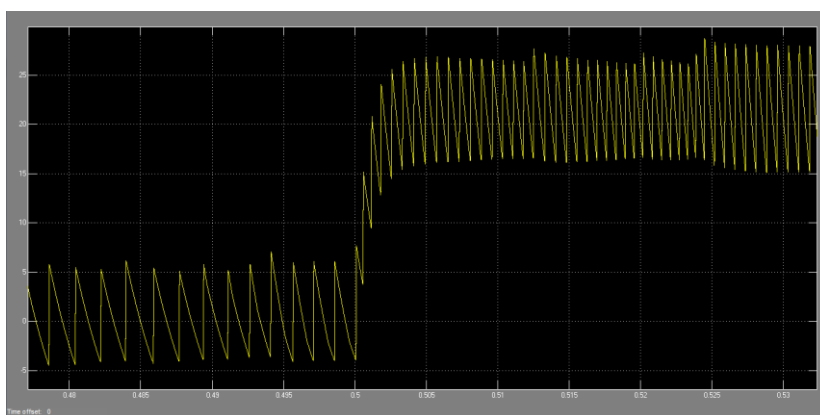Figure 2.11: The load-torque step-response for field-oriented control

Figure 2.12: The load-torque step-response for direct torque control

3. Summary

As it can be seen from the simulation results, direct torque control is capable of a much faster torque control than field-oriented control, therefore it provides a much higher dynamic performance than field-oriented control. However, in the case of the direct torque controlled induction machine drive, a relatively high amount of torque-ripple can be observed even in steady-state, whereas in the case of the field-oriented controlled induction machine drive no torque-ripple can be observed at all in both steady-state and transient state. The reason for this is that direct torque control uses hysteresis controllers to control stator flux and electromagnetic torque, while filed-oriented control uses PI-type controllers (except for the speed-controller) to control rotor flux and electromagnetic torque.

Although the main disadvantage of direct torque control is the relatively high amount of torque-ripple produced by the method, there are still some other drawbacks. Another problem is the constantly changing switching frequency which can create mechanical resonance as well. Also, when the switching frequency is very low, audible noise is created, but when the switching frequency is very high, the power electronics starts to heat dramatically, decreasing the overall efficiency of the system.

Although direct torque control is much less parameter-sensitive than field-oriented control, it is still parameter-sensitive. For example, during starting or low-speed operation, the flux- and torque-estimations will become inaccurate due to the increasing stator resistance caused by the heating. Therefore, the drive will not be able to produce even the nominal-torque in the low-speed regions. This is a great problem, because many applications require high starting torque, i.e. hoisting applications like cranes and elevators, servo-drives etc. In order to solve this problem, on-line identification of the stator-resistance is needed in the case of direct-torque control as well.

The high amount of torque-ripple even in steady-state dramatically limits the possible applications of the current form of direct torque control. Applications like servo-drives, hoisting-drives and vehicle-drives are out of the question because in these applications the absence of torque-ripples is a basic demand. Therefore, in these applications the implementation of field-oriented control is recommended. In the case of general-purpose applications like pumps, fans etc. the application of direct torque control is still disadvantageous because of the high amount of torque-ripples produced by the method even in steady-state. Fast torque-response is needless in these applications because the load varies slowly and a simple V/f-

control (with the optional usage of slip-compensation) perfectly satisfies the demands needed for these applications.

To sum up, direct torque control has a lot of potential in itself. If it was possible to overcome the high amount of torque-ripple problem, it could be far more suitable for applications requiring high dynamic performance (i.e. servo-drives) than field-oriented control. Its robustness is still a great advantage in applications not requiring high dynamic performance. Fast torque-responses are advantageous in hoisting-applications because it guarantees the safe lifting and sinking of the load. Therefore, further research is needed in the field of direct torque control.

The main focus of the further research must be the elimination of the torque-ripples. This can be done with the revision of the current algorithm used for selecting the optimal voltage vector. The reason for this is that the current algorithm does not consider the degree of errors in stator flux amplitude and electromagnetic torque. Also, this is the best way to eliminate the constant change in switching frequency. Another task is to achieve the best accuracy in the estimation of the stator resistance. This can be done using the thermal model of the machine.

It must be noted that the spreading of the direct torque controlled induction machine drive does not fully depend on the advancement of this method. It has a technological side, too. For example, if it was possible to produce switching devices that can be used on extremely high switching frequencies without significant heating and their production was cost-effective, then the amount of torque-ripple could be minimised by using low bandwidths in the hysteresis controllers, thus the main problem of direct torque control would be eliminated (in practice, there is a small amount of torque-ripple in the case of field-oriented control as well, because of the parameter-sensitivity).

The last aspect that must be taken into consideration is that the optimal controller settings for both control methods are not the same in the case of speed-reference step and in the case of load-torque step. Therefore, more robust controllers should be used both in the speed-loop (i.e. PF- and PDF-controllers [5], [6]) and in the underling control loops (this is also a reason why direct torque control is worthy of further research).

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