Elimination of Undesirable Transients in Direct Torque Control of Induction Motor

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Abstract— Direct torque control methods of induction motors are characterized by their simplicity with regard to the vector control. The main advantages of the direct torque control methods are the high robustness and the ability of quick torque changes that ensure very good dynamic properties of the induction motor drives. In case of the direct torque control, undesirable transients can easily occur in the process of the induction motor excitation and torque reversal. To eliminate or to reduce the undesirable transients, different ways are utilized. In the paper, there are some methods for the elimination of these undesirable transients described and experimentally verified on a laboratory stand with the induction motor drive.

1. INTRODUCTION

In the past, several methods were developed for a direct torque control (DTC) of induction motors. Depenbrock's method (D-DTC) and Takahashi's method (T-DTC) are included among the oldest known. In an effort to improve or simplify these methods of the direct torque control, there was also developed other methods, for example a modified Takahashi's method (M-DTC), a twelve-sector method (TS-DTC), a method with direct calculation of the voltage vector (DVC-DTC). In some applications, it is advantageous to achieve a constant switching frequency of a voltage source inverter (VSI) that basic principles of the direct torque control do not allow. For these applications, a pulse-width modular has to be integrated into the control structure of the direct torque control (PWM-DTC) [1–3].

The DTC methods can be easily implemented into a microcomputer control system. The main quantities such as the motor torque and the stator magnetic flux are calculated from the measured values using the mathematical model of the induction motor [4].

2. PRINCIPLE OF THE DIRECT TORQUE CONTROL

All methods of the direct torque control use a similar basic principle: a rotating magnetic field in the stator is created on the basis of a calculating algorithm with the help of active voltage vectors, where the rotation speed of the magnetic field, and subsequently the amount of motor torque, can be controlled by the switching of the zero vectors or the switching of the active vectors working in the opposite direction of the magnetic field [5].

The stator flux Ψ_S and motor torque T are calculated on the basis of the measured voltage of the DC link, switching combination and phase currents by the following equations:

$$\begin{aligned} &\Psi_{S\alpha} = \int (u_{S\alpha} - R_S\, i_{S\alpha})dt, \quad \Psi_{S\beta} = \int (u_{S\beta} - R_S i_{S\beta})\, dt, \\ &\left|\mathbf{\Psi}_S^S\right| = \sqrt{\Psi_{S\alpha}^2 + \Psi_{S\beta}^2}, \quad T = \frac{3}{2} p_p \left(\psi_{S\alpha} i_{S\beta} - \psi_{S\beta} i_{S\alpha}\right), \end{aligned} \tag{1}$$

where $\Psi_{S\alpha}$, $\Psi_{S\beta}$ — components of the stator flux vector $\mathbf{\Psi}_S^S$; $i_{S\alpha}$, $i_{S\beta}$ — current components of the stator current vector $\mathbf{i}_S^S$; $u_{S\alpha}$, $u_{S\beta}$ — voltage components of the stator voltage vector $\mathbf{u}_S^S$; R_S — stator resistance; T — motor torque; p_p — number of pole-pairs.

3. UNDESIRABLE TRANSIENTS IN DIRECT TORQUE CONTROL OF INDUCTION MOTOR

3.1. Transients during the Excitation of the Induction Motor

An induction motor start by simply running the DTC algorithm is problematic. In general all described DTC methods allow the start of the induction motor. This start process is not optimal in any way.

The DTC algorithms require a special subroutine for the motor excitation. By running DTC methods without the special subroutine for the induction motor excitation, it is possible to describe two different transients during the motor excitation:

1) In the case of D-DTC and M-DTC, there is a linear increase of the stator flux in the direction of the switched active voltage vector. The time constant of the stator flux increase is greater than the time constant of the stator current increase. Therefore, when the stator flux modulus reaches its reference value, the stator current has already achieved relatively large value. This transient is prohibited and may lead to a reaction of the voltage inverter protection, or even it can damage the inverter.

2) The methods T-DTC, TS-DTC, DVC-DTC and PWM-DTC have a spiral-shaped increase of the stator flux. This is also accompanied by an unacceptable increase of the stator currents, but the maximum value is smaller than in the previous case.

The best way that ensures the reliable excitation of the induction motor and limits the stator currents is an application of the pulse-width modulation. The motor start is practically performed so that the subroutine is executed before the start of the DTC algorithm and it switches between the selected active voltage vector and one of the zero vectors. The average value of the stator current during the induction motor excitation can be set by the switching ratio of the active and zero voltage vectors [6].

3.2. Transients during the Torque Reversal of the Induction Motor

A direction change of the motor rotation is achieved by the sign change of the desired torque. The induction motor speed begins to decrease with the steepness according to the desired torque and then the induction motor is running in the opposite direction. Some mentioned DTC methods are able to perform this reversal without any undesirable transient, for example TS-DTC and PWM-DTC. This means that there are not the over currents even a torque overshoot. Their switching table (or algorithm for the calculation of the voltage vector in the case of PWM-DTC) does not depend on the direction of the induction motor rotation, i.e., these methods are able to maintain the motor torque at the desired value even when the rotation direction disagrees with the sign of the desired torque.

For methods with the switching table (D-DTC, T-DTC, M-DTC, or algorithm for the calculation of the voltage vector in the case of DVC-DTC), which depend on the direction of the motor rotation, it is necessary to use a special reversal subroutine. If the sign change of the desired torque and the replacement of the switching table are at the same time, then an uncontrolled torque overshoot occurs during the torque reversation. This overshoot increases with the speed value at the reversation time. Therefore it is necessary to insert to these DTC methods the subroutine that ensures the correct time course of the motor torque during the torque reversation.

It is preferred to use the active vectors to increase the torque and the zero vectors to decrease the torque by reason of the torque ripple reduction, voltage deformation reduction and increased efficiency. In general switching on the zero vector does not always mean a reduction of the torque, and therefore it is important to understand and describe the status of the drive when the zero vector does not lead to the torque decrease [6].

The principle of the torque reduction to the desired value is shown in Figure 1 that can be divided into three parts:

In part (I) there is identical the sign of the torque with the sign of the direction of the stator flux vector rotation. In this part the torque increase is caused by switching the active vector acting in the direction of the required torque and torque reduction is achieved by switching the zero vector.

In part (II) the sign of the required torque is changed to negative, but the sense of rotation of the stator flux vector is still positive. To reduce the torque, the active vector is switched on, which

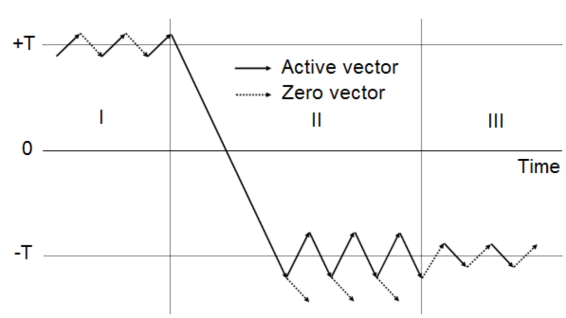


Figure 1: Principle of torque control during torque reversal.

acts in the direction of the new required torque. After reaching the requested torque value it must be switched on such a vector, that causes the torque decrease (in absolute value). According to the switching logic in part (I), it should be the zero vector. Switching on of the zero vector leads to even more increase of the torque, because sense of the torque change caused by the zero vector in part (II) is identical to part (I). It is possible to explain the cause of this torque overshoot for untreated reversal of the drive controlled by direct torque control, the DTC selection algorithm of the voltage vector is dependent on the direction of the motor rotation. For these types of methods it occurs during untreated reversal that switching on of the zero vector should cause a drop in the torque. In fact in this case the zero vector causes an even greater increase of the torque, and it remains switched on until such time, when the stator magnetic field sufficiently drops. During the time, when the zero vector is switched on, the motor behaves as an electrodynamic brake. The adverse influence of switching the zero vector during reversal can be seen on the example of untreated reversal (see Figure 3).

In part (III) is the sign of torque already identical with the sign of rotation direction of the magnetic flux vector, and therefore is already possible to use the same method in the torque control like in part (I).

3.2.1. Options of Overshoot Limitations for the Torque during Reversation

As already stated, the basic principle of some methods of direct torque control is not able to correctly handle the reversal process. Therefore it is necessary to insert into these methods the subroutine, which ensures the correct reversal of the drive. There are several possibilities how to solve this subroutine:

1) The first option is to replace the switching table at the right moment. Determination of this moment is complicated. If the table is replaced too soon it leads to the torque overshoot. In the opposite case if the table is changed too late it occurs a transient torque drop below the desired value, which is not optimal too.

2) The next option is to avoid the zero vector switching during reversal. For decrease of the torque it does not use the vectors $\underline{\mathbf{u}}_0$ or $\underline{\mathbf{u}}_7$ but it is used the active vectors acting against the direction of the motor rotation. The disadvantage of this method is the voltage deformation and big enough torque ripple. It is therefore appropriate to reduce the torque in this way for the necessary time only, i.e., during the time, when the sign of the speed is not identical with the sign of the desired torque. The disadvantage of this method is the requirement to know the direction of the motor rotation or the end point of the magnetic flux vector.

Theoretically the easiest way how to determine the direction of the motor rotation is by means of a speed sensor. For practical using of DTC a speed sensor is not good choice, because it causes an increase in cost and complexity of the drive. Next disadvantages are the need for maintenance and the possibility of sensor failure. The use of a speed sensor is only preferred in the cases, when the sensor is already mounted on the induction motor because of the accurate speed control of the drive.

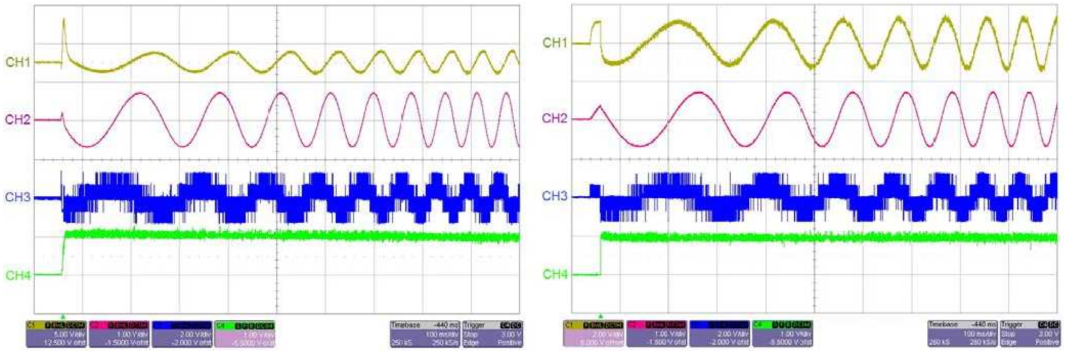
The most suitable and relatively easy realized by software is evaluation of the direction of the motor rotation on the basis of internal variables. For the evaluation it can be used the fact that during speed reversal the magnetic flux vector rotates in the direction of mechanical speed until such time, when the speed is close to zero. A possible approach how to determine the rotation direction of the magnetic flux vector is to evaluate the position of its endpoint. For example, when the magnetic flux vector skips from the first to the second quadrant, the sense of rotation is positive, in the opposite when the magnetic flux skips from the first to the fourth quadrant; the sense of rotation is negative [6].

4. EXPERIMENTAL RESULTS

For the verification of the control algorithms, a laboratory machine set with the induction motor drive and load DC machine was realized. This machine set consists of the induction motor 2.7 kW, load DC machine, frequency converter with the DC link and digital signal processor (DSP) control system. The DSP TMS320F2812 was used in the control system [6].

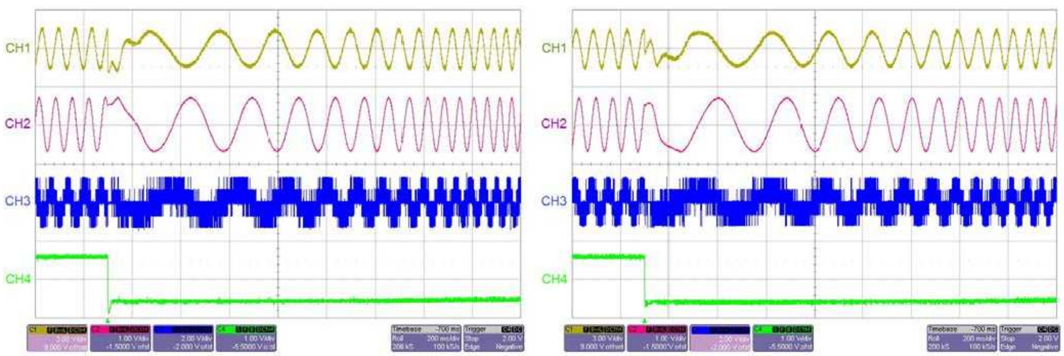
Figure 2 and Figure 3 show the time courses of the important quantities that were measured on the laboratory machine set. The meaning of quantities which are shown in individual Figures 2 and 3 is as follows:

T_{ref} — reference torque; T — real calculated torque; i_{Sa} — phase stator current; u_{Sa} — phase stator voltage; Ψ_{Sref} — reference stator magnetic flux; $\Psi_{S\alpha}$-α — component of stator flux vector.



(a) (b)

Figure 2: IM start (a) without and (b) with start subroutine; DVC-DTC method; $T_{ref} = 5\,\mathrm{Nm}$; $\Psi_{Sref} = 0.7\,\mathrm{Wb}$; (**ch1**: $i_{S\alpha} = f(t)$, 15 A/scale; **ch2**: $\Psi_{S\alpha} = f(t)$, 1 Wb/scale; **ch3**: $u_{S\alpha} = f(t)$, 200 V/scale; **ch4**: $T = f(t)$, 5 Nm/scale).



(a) (b)

Figure 3: IM torque reversal (a) without and (b) with torque subroutine; DVC-DTC method; $T_{ref} = +6/-6\,\mathrm{Nm}$; $\Psi_{Sref} = 0.7\,\mathrm{Wb}$; (**ch1**: $i_{S\alpha} = f(t)$, 9 A/scale; **ch2**: $\Psi_{S\alpha} = f(t)$, 1 Wb/scale; **ch3**: $u_{S\alpha} = f(t)$, 200 V/scale; **ch4**: $T = f(t)$, 10 Nm/scale).

5. CONCLUSIONS

The direct torque control methods of the induction motors are accompanied by the undesirable transients in the process of the induction motor excitation and torque reversal that can cause an emergency state of the induction motor drives. In the paper, there are described and explained possibilities for solving these undesirable transients. The experimental verification of the designed ways confirmed the expected results.

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