Start up Current in Direct Torque Controlled Induction Motor Drives

Vojkan Kostic[1], Nebojsa Mitrovic[2], Milutin Petronijevic[3], Milan Bebic[4]

***Abstract* – In this paper DTC method is analysed with aspect of start up stator current. It is observe that start up stator current reach significant value. It can destroy switch powers of the inverter. A control method to limit start up stator current amplitude is presented. Simulations results are carried out for the comparison of a start up classical DTC scheme without current limitation and with hereby. Presented simulations results verify the effectiveness of the proposed stator current limitation strategy.**

***Keywords* – Induction Motor, Direct Torque Control, Start up Stator Current Limitation.**

I. INTRODUCTION

DTC schemes to become an alternative for the classic variable speed AC drives. A fast dynamic can be achieved by calculating the instantaneous torque and flux. Using switching table not only simplifies the control system, but also decreases computing time. With a three phase voltage source inverter, there are six non-zero voltage vectors and two zero voltage vectors which can be applied to the machine terminals. Integrating emf using measuring current and voltage vectors or DC link voltage can estimate the stator flux. The torque can be calculated using *qd* components of the estimated flux and measured currents [1-5].

Besides its advantages in application, the conventional DTC system has its drawback. First, its switching frequency varies according to the motor speed and the hysteresis bands of torque and flux. Second, large torque ripple is generated especially in a low speed region. Third, in DTC the stator current contains much more harmonics than that fed with sinusoidal voltage. Fourth, possible problems during start up.

One of problems during start up is short magnetizing transient with significant value of stator current. It can destroy switch powers of the inverter. Consequently, a current limit control is required [6,7].

After a description of DTC theory and transient current problems in start up, a control method to limit stator current amplitude is presented. Simulations results are carried out for the comparison of a start up classical DTC scheme without current limitation and with hereby. Presented simulations results verify the effectiveness of the proposed stator current limitation strategy.

II. PRINCIPLES OF DIRECT TORQUE CONTROL

The implementation of the DTC scheme requires flux linkages and torque computations and generation of switching states through a feedback control of the torque and flux directly without inner current loops.

The stator *q* and *d* axis flux linkages are:

$$\lambda_{qs} = \int (V_{qs} - R_s i_{qs})dt \tag{1}$$

$$\lambda_{ds} = \int (V_{ds} - R_s i_{ds})dt \tag{2}$$

where R_s is stator resistance and V_{qs}, V_{ds}, i_{qs}, i_{ds} are voltage and current *qd* components.

Consider the inverter shown in Fig. 1. The terminal voltage V_a, with respect to negative of the *dc* supply, is determined by a set of switches, S_a, consisting switching device T_1 and T_2 as shown in Table I. The switching of S_b and S_c sets for line *b* and *c* can be similarly derived. The total number of switching states possible with S_a, S_b, and S_c is eight and they are shown in Fig. 2. The stator *qd* voltages for each state are given by:

$$V_{qs} = V_{as} \tag{3}$$

$$V_{ds} = \frac{1}{\sqrt{3}}\left(V_{cs} - \mathrm{V_{bs}}\right) = \frac{1}{\sqrt{3}} V_{cb} \tag{4}$$

The limited states of the inverter create discrete movement of the stator voltage phasor $\mathrm{V_s}$, consisting of the resultant of V_{qs} and V_{ds}.

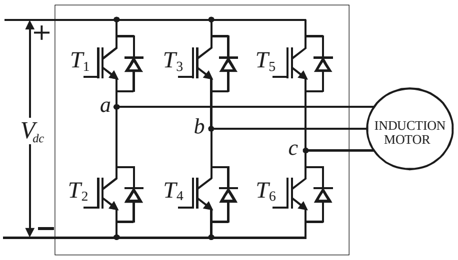

Fig. 1. Power circuit configuration of induction motor drive

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TABLE I
SWITCHING STATE OF INVERTER PHASE LEG *a*

T_1	T_2	S_a	V_a
On	Off	1	V_{dc}
Off	On	0	0

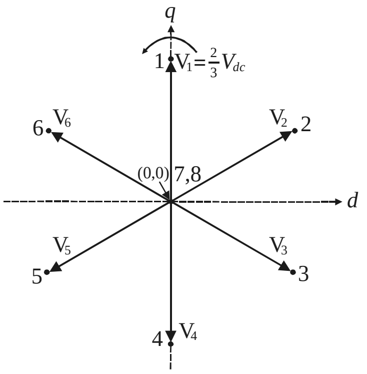

Fig. 2. Inverter output voltages

A uniform rotating stator flux is desirable, and it occupies one of the sectors at any time, Fig. 3 (for classical DTC). The stator flux phasor has a magnitude of λ_s with instantaneous position θ_{fs}.

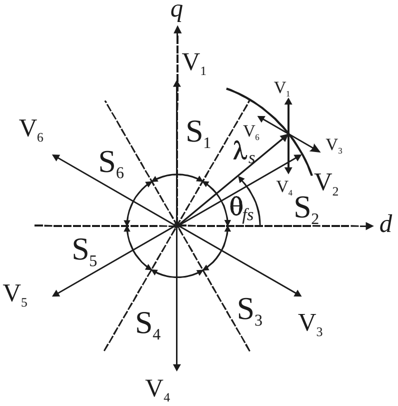

Fig. 3. Division of sectors for stator flux identification

If the stator flux phasor is in sector 2, Fig. 3, the left influencing voltage phasor has to be either V_6 or V_1. As seen from phasor diagram, in case switching voltage phasor V_1, the flux phasor increases in magnitude. In case of phasor V_6, it decreases. This implies that the closer voltage phasor set increase the flux and the farther voltage phasor set decreases the flux and both of them change (rise) the flux phasor in position. Similarly for all other sectors, the switching logic can be developed. A flux error (λ_s^*-λ_s) thus determines which voltage phasor has to be called, and this flux vector is converted to a digital signal S_λ with hysteresis controller with hysteresis band of $\delta\lambda_s$. The switching logic to realize S_λ is given in Table II.

TABLE II
SWITCHING LOGIC FOR FLUX ERROR

State	S_λ
λ_s* - λ_s > $\delta\lambda_s$ / 2	1
λ_s* - λ_s < - $\delta\lambda_s$ / 2	0

Torque control is exercised by comparison of the command torque to the torque measured from the stator flux linkages and stator currents as:

$$T_e = \frac{3}{2}\frac{P}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) \tag{5}$$

where *P* is pole number.

Torque error is processed through hysteresis controller to produce digital outputs, S_T as shown in Table III. Interpretation of S_T is as follows: when it is 1 amount to increasing the voltage phasor, 0 means to keep it at zero, -1 requires retarding the voltage phasor.

TABLE III
SWITCHING LOGIC FOR TORQUE ERROR

State	S_T
T_e* - T_e > δT_e / 2	1
-δT_e / 2 ≤ T_e* - T_e ≤ δT_e / 2	0
T_e* - T_e < -δT_e / 2	-1

Combining the flux error output S_λ, the torque error output S_T, and the sextant of the flux phasor S_θ, a switching table can be realized to obtain the switching states of the inverter. The sectors of the stator flux space vector are denoted from S_1 to S_6. Stator flux modulus error after the hysteresis block can take just two values. Torque error after the hysteresis block can take three different values. The zero voltage vectors V_7 and V_8 are selected when the torque error is within the given hysteresis limits, and must remain unchanged. Finally, the classical DTC look up table is shown in Table IV.

TABLE IV
SWITCHING STATES FOR CLASSICAL DTC

S_λ	S_T	S_1	S_2	S_3	S_4	S_5	S_6
1	1	V_6	V_1	V_2	V_3	V_4	V_5
1	0	V_8	V_7	V_8	V_7	V_8	V_7
1	-1	V_2	V_3	V_4	V_5	V_6	V_1
0	1	V_5	V_6	V_1	V_2	V_3	V_4
0	0	V_7	V_8	V_7	V_8	V_7	V_8
0	-1	V_3	V_4	V_5	V_6	V_1	V_2

III. START UP CURRENT LIMITATION METHOD

Stator current amplitude is determined by equation:

$$i_s = \sqrt{i_{ds}^{\,2} + i_{qs}^{\,2}} \tag{6}$$

where:

$$i_{qs} = \frac{L_r}{L_s L_r - M^2}\left(\lambda_{qs} - \frac{M}{L_r}\lambda_{qr}\right) \tag{7}$$

$$i_{ds} = \frac{L_r}{L_s L_r - M^2}\left(\lambda_{ds} - \frac{M}{L_r}\lambda_{dr}\right) \tag{8}$$

and L_s, L_r, M stator self-inductance, rotor self-inductance, mutual inductance, respectively.

Before start up of no magnetized induction machine, stator and rotor fluxes' *qd* components are equal to zero. When start up, flux and torque have be increase and, in accordance with

DTC principles, inverter generate appropriate voltages. It provokes a fast variation of stator flux and much slower variation of rotor flux. It follow, in accordance with (6) to (8) can be expect a fast variation of stator current amplitude.

In other words, during start up of no magnetized induction machine, due to a fast stator flux and torque transient, occur short transient with stator current significant value. It can destroy switch powers of the inverter. Consequently, a current limit control is required.

A strategy of solving current limitation problem is to add magnetizing machine with a zero torque control in applying a delay on the torque reference application. During the magnetizing phase, a same non zero voltage is applied until the stator flux amplitude reaches its reference, λ_s*. This magnetizing method doesn't respect DTC principles since stator flux control is chosen as against torque progression witch reduce torque control performance.

An example is given in Fig 4, with applied a non-zero voltage vector V_1 (magnetizing phase 1). There is no tangential variation of the stator flux vector, the stator pulsation and torque are null. However, stator flux amplitude progress very quickly in the machine and provokes a fast variation of stator current amplitude. To control current variation a zero voltage vector is applied when the amplitude of the stator current reaches its limit value, $i_{s\,\mathrm{lim}}$ (magnetizing phase 2). The current control is carried out by a simple hysteresis controller whose a bandwidth is $\Delta i_{s\,\mathrm{lim}}$. When stator flux reaches its reference value, magnetization is over and begins DTC control.

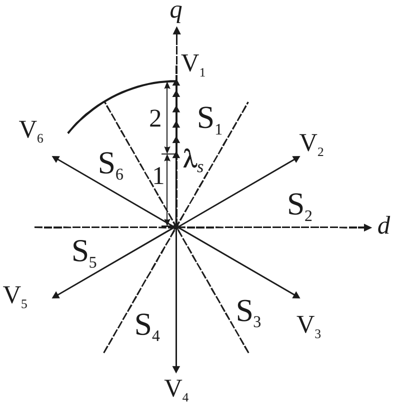

Fig. 4. Start up strategy with stator flux control

IV. SIMULATION RESULTS

Simulations have been carried out for the comparison of a start up classical DTC scheme without magnetizing phase and with hereby. The simulations were conducted using Matlab/Simulink simulation package. Simulation model is discretized with 2 μs. The system is run under nominal load torque and with nominal rotor speed. Control system sampling frequency and switching frequency is 10 kHz. The motor's parameter is listed in Table V. Stator current limit is set to 15 A and stator current controller bandwidth is set to 5 % of current limit.

Fig. 5 and 6 shows stator flux, effective value of stator current, electromagnetic torque and rotor speed in start up of induction machine without magnetizing phase. It can be noted that torque response is fast, but stator current start up value reach significant value (about 600% of rated value). It can destroy switch powers of the inverter if is larger of inverter switch maximal current. Fig. 9a and 9b shows stator flux locus in this case.

TABLE V
INDUCTION MOTOR PARAMETERS

Rated power	2.2 kW
Rated line to line voltage	380 V
Pole pairs	1
Rated torque	8.61 Nm
Rated stator flux	0.936 Vs
Rated stator current	5.26 A
R_s	2.615 Ω
R_r	2.3957 Ω
L_s	0.282 H
L_r	0.282 H
M	0.2717 H
Load inertia	0.0184 kgm^2

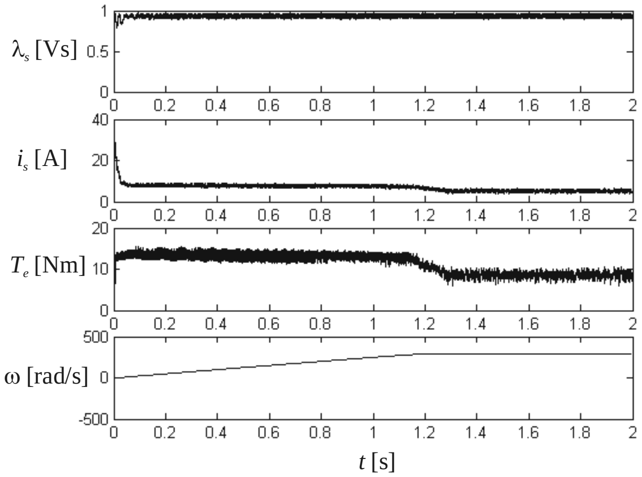

Fig. 5. Start up of induction machine without magnetizing phase

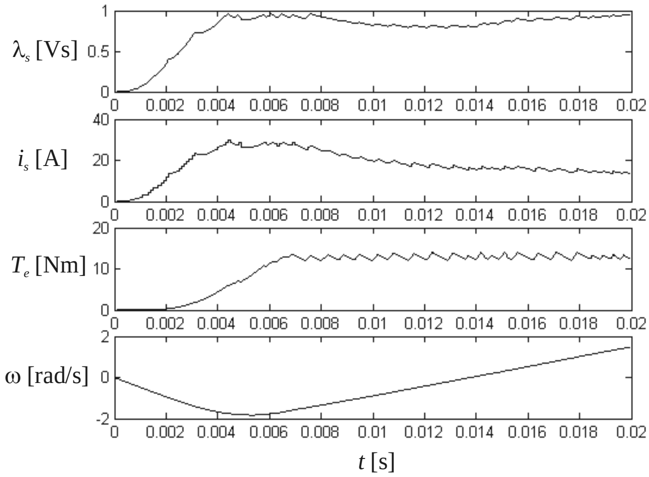

Fig. 6. Start up of induction machine without magnetizing phase (first 0.02 seconds)

Fig. 7 and 8 shows stator flux, effective value of stator current, electromagnetic torque and rotor speed in start up of induction machine with magnetizing phase. It can be noted that torque response is delayed and slower than in foregoing case, but stator current start up value is limited. Fig. 9c and 9d shows stator flux locus in this case. It can be noted that similarity of stator flux of Fig. 9d and Fig. 4 that was expected.

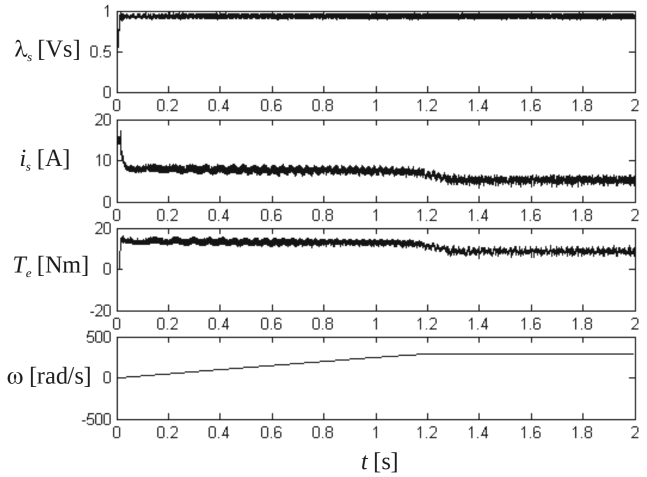

Fig. 7. Start up of induction machine with magnetizing phase

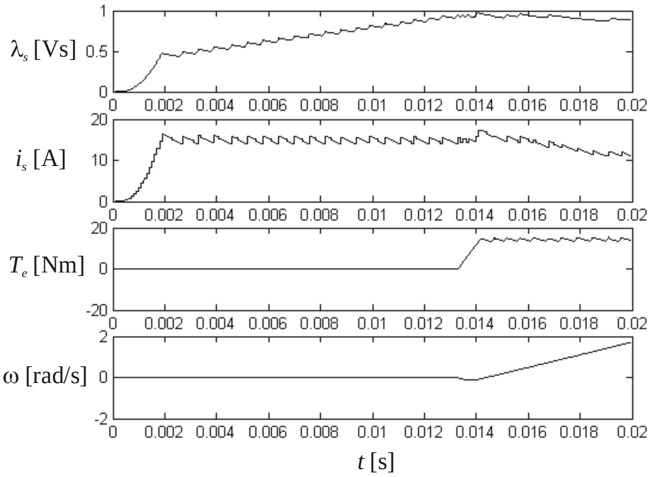

Fig. 8. Start up of induction machine with magnetizing phase (first 0.02 seconds)

V. CONCLUSION

In this paper, a current limitation strategy is presented to limit stator current amplitude in start up of an induction machine controlled by DTC method. This current limitation strategy is simple and easy to practical implementation in DTC algorithm. Simulation results show that the proposed strategy limits start up current. In that manner switch powers of the inverter are secure.

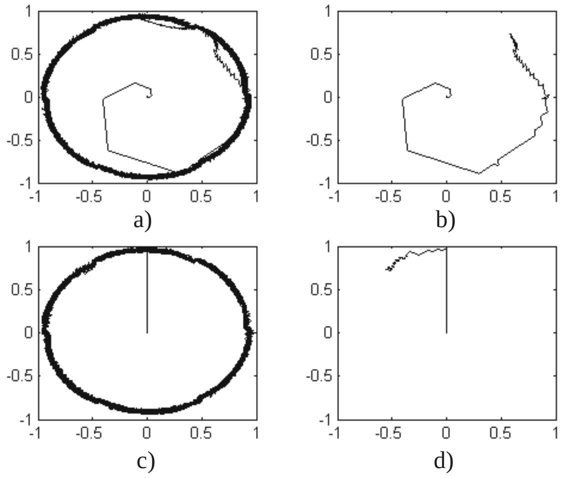

Fig. 9. Flux locus in start up of induction machine

a) without magnetizing phase
b) without magnetizing phase (first 0.02 seconds)
c) with magnetizing phase
d) with magnetizing phase (first 0.02 seconds)

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