THE NEXT GENERATION MOTOR CONTROL METHOD, DTC DIRECT TORQUE CONTROL

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Abstract - Direct Torque Control (DTC) is the latest AC motor control method developed by ABB. ACS600 is the first application utilising DTC. DTC is a control method that embeds motor and inverter together and controls them together in most optimal way. In Direct Torque Control all switch changes are based directly on the electromagnetic state of the motor. Optimum switching is determined for every control cycle on a time level of 25 microseconds. The switch positions of the power module are determined by a calculated stator flux and motor torque.

I. INTRODUCTION

Direct torque control [4] is first applied to ACS600, ABB´s latest standard AC inverter. Direct Torque Control is the first control method that controls IGBT-inverter and motor as a complete system. An ordinary PWM drive simulates power network by adjusting motors static operation point and flux vector drive more or less emulates DC drive. In DTC both inverter and motor are controlled together. All delay making parts have been removed, as modulator. All switch changes of the inverter are based on the electromagnetic state of the motor. DTC allows very fast and flexible control of the induction motor. Torque rise time is extremely short - typically it is below 3 ms - and a variety of new motor control functions can be realised with DTC.

II. ACS600

ACS600 is a standard induction motor inverter. covering 2.2-315kW 380-500V. It has IGBT power circuitry, using latest Power Plates. ACS600 offers excellent over current capacity, which enables further better starting torque even over 200% and more stiff operation at load shocks. ACS600 has removable panel with various features as parameter upload-download. With help of modular software and hardware design ACS600 can support several communication protocols with option protocol modules.

III. CONCEPT OF DTC

The basic idea of Direct Torque Controlled inverter is represented in the figure 1. The core of the system is the Direct Torque Comparator and Flux Comparator block with the optimal switching logic. The accurate adaptive motor model is also a very essential part of the DTC. Motor model estimates the actual torque, stator flux and shaft speed by means of measurements of two motor phase currents and intermediate circuit dc voltage. Also different models can be used [4].

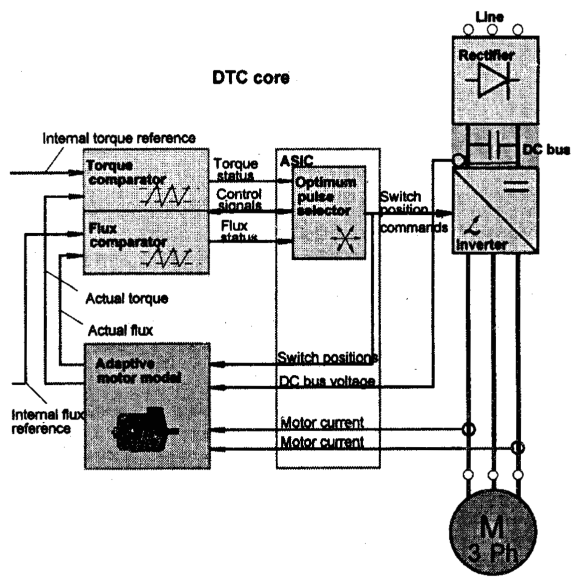

Fig. 1 : The core of the DTC is direct torque and flux control with optimal switching logic and motor model.

Torque and flux references are compared with the actual values and control signals are produced by using a two-level hysteresis control method. Optimum switching is determined for every control cycle on 25 microsecond time level. That is also the

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main difference between Direct Torque Control and the traditional AC drive control methods. In DTC, there is no separate voltage- and frequency-controlled PWM modulator. The optimal switching logic is realised by ASIC hardware. The switch references (S_1,S_2,S_3) for the power module are outputs of this logic. The feedback information of the power switches states are used in the calculation of the actual voltage vector.

A. Hysteresis control of stator flux and torque

The Direct Torque Control is based on the theory of field-oriented control of the induction machines [1],[5] and the theory of Direct Self Control [2]. A spatial vector presentation of motor quantities is used. Flux and current vectors and inverter voltage vectors can be represented e.g. in stator co-ordinates as in figure 2.

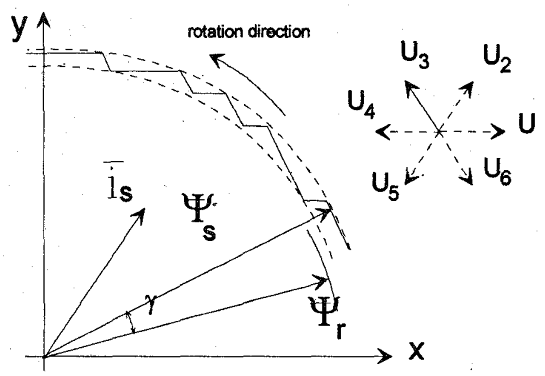

Fig. 2: The stator flux vector is controlled directly in order to achieve torque demand.

There are six voltage vectors and two different kinds of zero-voltage vectors available in the two-level voltage source inverter, as in figure 3.

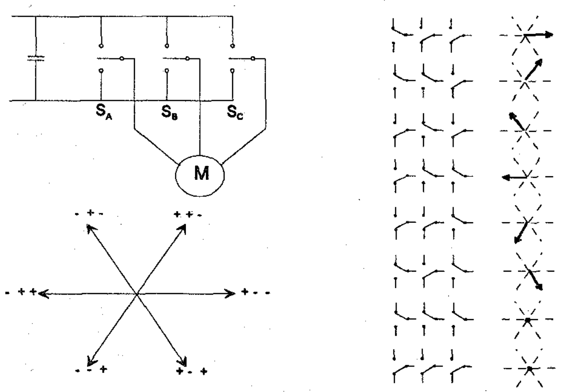

Fig 3. The stator voltage star of an inverter

Torque is a cross product of the stator and rotor flux vectors or stator current and flux as follows:

$$T_e = p_N \frac{1-\sigma}{\sigma L_m} \bar{\Psi}_r \times \bar{\Psi}_s \tag{1}$$

The length of the stator flux is normally kept constant and the motor torque is controlled by means of the angle γ between the stator and rotor flux or by means of stator flux and current. The rotor time constant of the standard induction machine is typically larger than 100 ms, thus the rotor flux is stable and it changes slowly compared with the stator flux. It is possible to achieve the required torque very effectively by rotating the stator flux vector directly in a certain direction as fast as possible.

The strategy of Direct Torque Control is straightforward: if more torque is needed, the purpose of the next power stage switching is to fulfil that demand. The instantaneous value of the stator flux vector is controlled in order to achieve the required motor torque. The stator flux vector is controlled by means of the inverter supply voltage. The optimal switching logic defines the best voltage vector according to the actual value of torque and torque reference.

For example, in the figure 2 the voltage vector U_4 decreases effectively the radial component of the stator flux vector and, at the same time, it moves the flux vector tangential in the direction of rotation. The tangential movement causes the angle γ and torque to increase. The radial change affects the length of the stator flux and thus magnetising of the motor is also changed. The aim is to force the stator flux vector in the direction where both reference values of the torque and stator flux are achieved. As the stator flux rotates, the effect of the voltage vector to the stator flux vector and to the torque changes. This is considered in the switching logic. The switch references are altered only if the values of the actual torque and the stator flux differ from their reference values more than the allowed hysteresis.

The behaviour of hysteresis-controlled torque is represented in figure 4 [3]. Annotation t0 means that more torque is not needed and thus the zero voltage vector is used. The actual value of torque T_e decreases (in motor state), until the torque falls below the value T_{ref}-ΔT_1. After that, an appropriate voltage vector is selected in order to increase the torque (t+). Note that the torque's derivation is dependent on motor's nature, and also rotor frequency and chosen voltage vector. in figure 4 [3] the derivation change during torque increasing is caused by vector chance by flux's amplitude hysteresis controller.

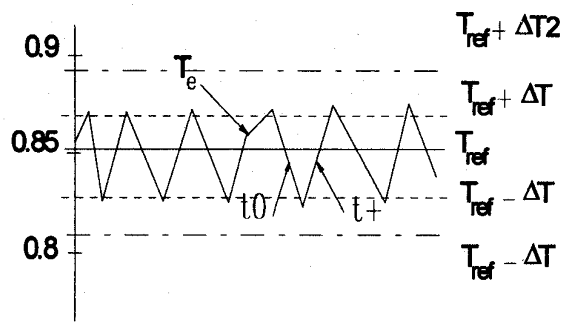

Fig. 4: Hysteresis control of torque. T_{ref} is torque reference and T_e actual torque and ΔT_1 and ΔT_2 are torque comparation levels.

If actual value of torque differs more than hysteresis limit ΔT_2 from the reference value, it is also allowed to use the voltage vector to decrease the torque.

B. *Motor Model*

Together with flux's and torque's hysteresis control, there is the motor model that produces the estimates of actual flux and torque for modulation, and also speed and frequency estimates for upper controls. Accuracy of the motor model is very essential in DTC, because there is no feedback from the shaft speed. Only two stator phase currents and dc voltage are measured. The motor model is based on the identification of the motor parameters and current feedback. The motor torque and shaft speed are also estimated in the motor model.

The main task of the motor model is to produce an accurate estimate of the stator flux on every control cycle (25 μs). The stator flux is calculated by means of the stator voltage vector and current as follows:

$$\Psi_s = \int (u_s - R_s i_s)dt \qquad (2)$$

The stator voltage vector is determined by measured dc voltage and actual switch selections. Stator resistance Rs is identified during the commissioning. Thermal compensation of the stator resistance is made by the temperature estimate of the thermal motor model. Threshold voltages and commutation dead times of the power stage are also considered in the stator flux estimation.

On the on-line state the estimate of stator flux is also corrected by current feedback. The idea of the current feedback is based on the equation (3), in which stator flux is represented by means of the stator and rotor current vectors.

$$\overline{\Psi}_s = L_s i_s + L_m i_r \qquad (3)$$

The estimate of the stator flux is corrected so that equation (3) is valid both in the continuous and dynamic state. The current feedback improves highly the stator flux estimate, especially at low speed. Extremely high starting torque can be produced and torque is very linear at the whole speed range, including zero mechanical speed.

The actual value of torque is calculated as a cross product of the stator flux and stator current. The motor model calculates also the estimates of the shaft speed and the electrical frequency. The electrical frequency is calculated by deriving the angle of the rotor flux vector as follows:

$$\omega_e = \frac{d\Theta_r}{dt} = \frac{\Theta_r(t_2) - \Theta_r(t_1)}{\Delta t} \qquad (4)$$

Time interval of the calculation is 1 ms (Δt), which allows to calculate frequencies up to 400 Hz. The angle of the rotor flux is calculated by following equations (5 and 6).

$$\overline{\Psi}_r = \frac{L_r}{L_m}(\overline{\Psi}_s - \sigma L_s i_s) = \Psi_{rx} + j\Psi_{ry} \qquad (5)$$

$$\Theta_r = \arctan\left(\frac{\Psi_{ry}}{\Psi_{rx}}\right) \qquad (6)$$

The mechanical speed of rotor is estimated by equation:

$$\omega_r = p_N\left(\omega_e - R_r \frac{T_e}{\phi_r^2}\right) \qquad (7)$$

The accuracy of the motor model is based on an identification run, which is made during the commissioning. Main parameters of the motor model are motor inductances and stator resistance.

The saturation effect of the inductances is also considered.

IV. CONTROLLING DTC

The core of DTC provides only effective torque control and estimates of the motor quantities. In order to make a real inverter several additional controllers are needed. The figure 5 represents a rough block diagram of the DTC controlled inverter. Most of additional functions are realised by means of the torque reference, but the flux reference and comparation level parameters are also utilised.

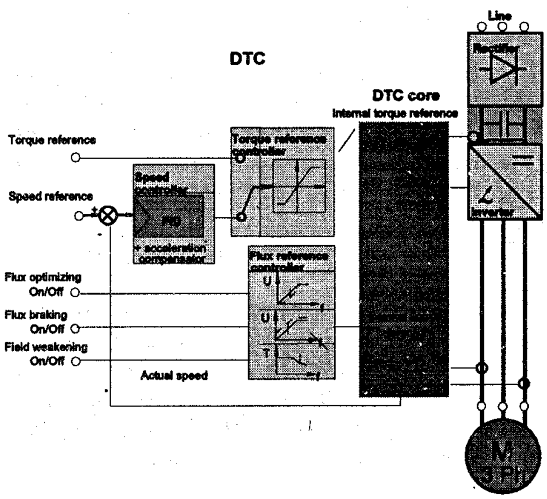

Fig. 5: Block diagram of the DTC controlled inverter.

A. Torque reference chain

The input of torque chain is either the torque reference of the speed controller or an external torque reference. Torque reference is modified in order to keep the dc intermediate circuit voltage and electrical frequency limited. Torque reference is also limited in order to prevent the motor torque from exceeding the pull-out torque. The inverter is protected from overload by limiting the torque. Inverter is allowed to be overloaded for limited level and time.

B. Speed control

ACS600 is speed controlled which differs from traditional frequency converters. Slip compensation is instant and its accuracy is typically 10% of the nominal slip. That means 0.1 to 0.5 speed accuracy. The basic algorithm of the speed controller is PID. An acceleration compensator i.e. feed forward coupling from speed reference's derivate is also included in the speed controller. The compensator is very useful in order to minimise the control deviation in the acceleration and deceleration of inertia. PID controller can be tuned to be more as a load compensator. The PID controller and acceleration compensator is tuned by an automatic tuning method, which is based on the identification of the mechanical time constant of the drive. Time constant can be identified during the commissioning or normal operation.

C. Flux reference

An absolute value of the stator flux can be given as a reference value to the DTC block. The ability to control and modify flexibly the absolute value of stator flux reference provides an easy way to realise many inverter functions. For example, flux reference control is utilised in the flux optimisation, field weakening control, etc.

V. COMMISSIONING ACS600

ACS600 needs to know motor name plate data in order to be able to create accurate mode of the motor. These name plate values are motors nominal: current, voltage, speed, power, frequency.

Then there is possibility to run so called id-run. During id run control adapts more accurate to the motor. Even if the id run is not possible to carry out during first start the control can create accurate model and also measure stator resistance and leakage inductance and same saturation coefficients.

ACS600 can also be adjusted to so called scalar mode, when amount of motors is not constant or motor is extremely small compared to inverter. The later case means that motor current is not measurable and direct torque calculation is neither possible

VI. SPECIAL FUNCTIONS OF DTC

A. Starting properties

The motor can be started in all electromagnetic states almost as fast as possible by DTC. In flying start completely new method has been developed, which does not need any kind of frequency scanning. Starting is just like turning the power ON.

B. Flux braking

The flux braking provides an effective method to enforce the braking ability. Braking ability is equal to dc-current braking, but during the flux braking inverter is normally controlled.

C. Flux optimisation

The DTC motor model can calculate the most optimal magnetising level compared to load automatically. Flux optimisation improves the total efficiency of motor drive. That is especially true at lower motor loads, where losses can be reduced more than 60%. 50% magnetising current leads to 75% reduction in resistive losses, when there is no load at all.

D. Supply voltage loss

When loss of supply voltage occurs, DTC keeps the voltage level in DC intermediate circuit within appropriate limits. When the network recovers, the motor can be loaded immediately. The length of the supply voltage loss the drive survives depends on the load and inertia of the system. That time varies from one second to many minutes.

VII. PERFORMANCE OF DTC AC DRIVE

Torque response and linearity, DTC offers extremely fast torque response (typically below 2 ms). This can be seen in the figure 6, in which the estimate of the air-gap torque is represented. Figure 7 represents phase current during the fast reversing with 20% load torque. The linearity of the torque control is also very good for a non-tacho inverter drive. Figure 8 represents shaft torque during the slow reversing with 80% load torque. Figure 9 represents slow torque ramp at zero speed. Actual shaft torque is measured and linearity error is below 10%. Typical error without pulse encoder is 4% and 3% with pulse encoder. Responce time less than 5ms in both cases.

Speed accuracy, the accuracy of shaft speed estimate is very good in the whole speed range. This enables the use of DTC inverter in many applications where previously a tacho-based vector control was needed. For most demanding applications it is possible to add to ACS600 a pulse-encoder option module. Figure 10 represents the speed estimate during the slow torque ramp at zero speed.

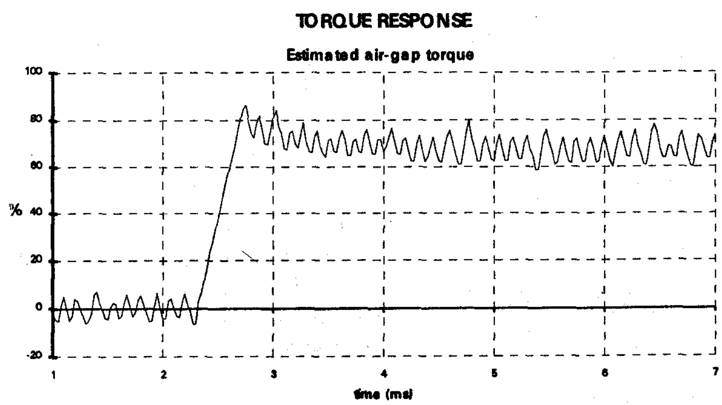

Fig. 6:
70% torque reference step at 25 Hz.
Estimated air-gap torque.
No pulse encoder

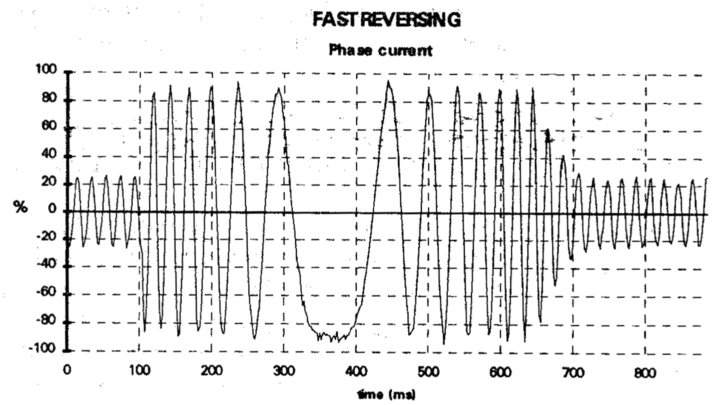

Fig. 7:
Fast reversing with constant load (-20%).
Phase current is measured.
No pulse encoder

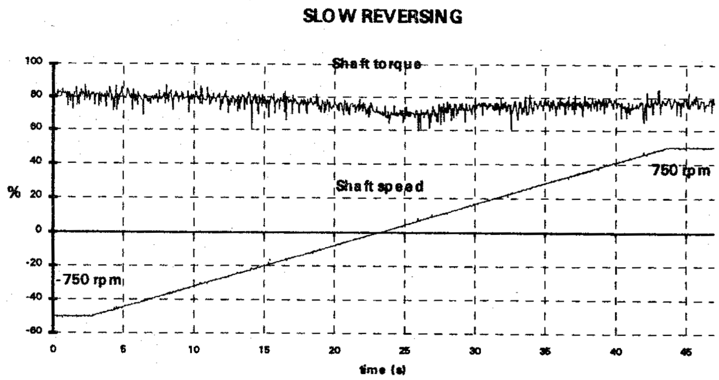

Fig. 8:
Slow reversing with constant torque reference (80%).
Shaft torque and speed are measured.
No pulse encoder on torque controlled ACS600. Speed controlled equipped with pulse-encoder option

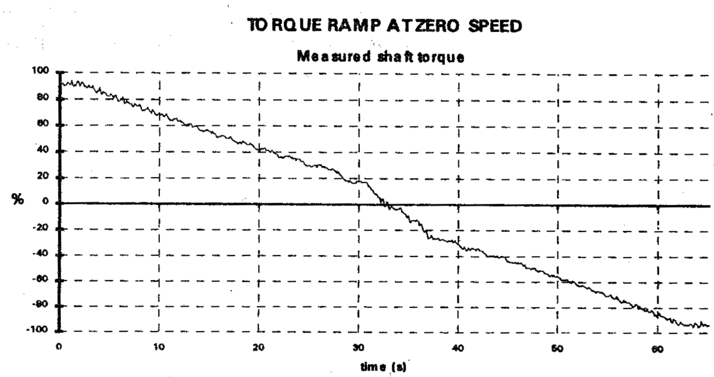

Fig. 9:
Torque ramp from T_{nom} to $-T_{nom}$ at zero speed.
No pulse encoder
Shaft torque is measured.

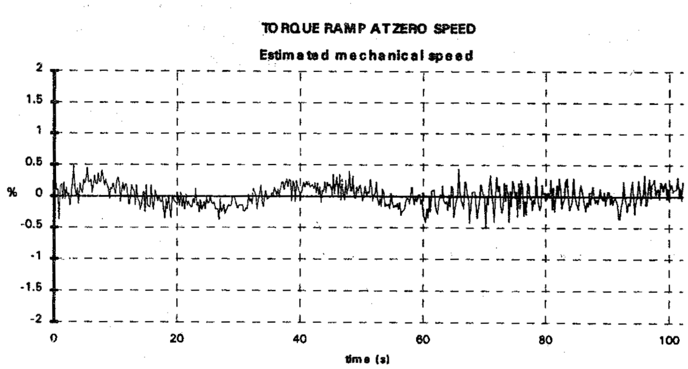

Fig. 10:
Torque ramp from T_{nom} to $-T_{nom}$ at zero speed. No Tacho.
Estimated shaft speed.
No pulse encoder

VI. CONCLUSION

DTC is a totally new kind of induction machine control method. Very effectively combined motor and power stage control offers superior control performances. Accurate and fast torque control is provided without tacho feedback even at low speeds. Performances of DTC are good enough for even most demanding applications. Flexibility of the DTC control enables many new kinds of inverter function to be realised: e.g. flux braking, fast starting function and flux optimisation.

Test Drive

Two standard ABB's induction motors are connected together with a torque measurement shaft. Test inverters have a common dc intermediate circuit. Load motor is equipped with a tachometer.

Data of the test and load motors:

Type	HXA	160LA
Power	15	kW
Nom. Current	30	A
Nom. Voltage	380	V
Pole pairs	2	
Nom. Freq.	50	Hz
Nom Speed	1460	rpm

Data of the test Inverters:

Type	ACS601-0025-3	
Power	25	kVA
Nom. Voltage	400	V

Symbols

T_e	estimated air-gap torque
T_{ref}	torque reference
T_{nom}	nominal torque
ψ_s	stator flux vector
ψ_r	rotor flux vector
γ	angle between stator and rotor flux
i_s	stator current vector
u_s	stator voltage vector
Ui	inverter voltage vectors (i=0...6)
p_N	pole pairs of motor
R_s	stator resistance
R_r	rotor resistance
L_s	stator inductance
L_m	magnetizing inductance
σ	leakage factor
ΔT_1	torque hysteresis 1
ΔT_2	torque hysteresis 2
Θ_r	rotor position angle in stator co-ordinates
ψ_{rx}	re-component of rotor flux
ψ_{ry}	im-component of rotor flux
ω_e	angular speed of rotor flux vector
ω_r	angular speed of rotor
S_j	state of power switch (j=0,2,3)

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