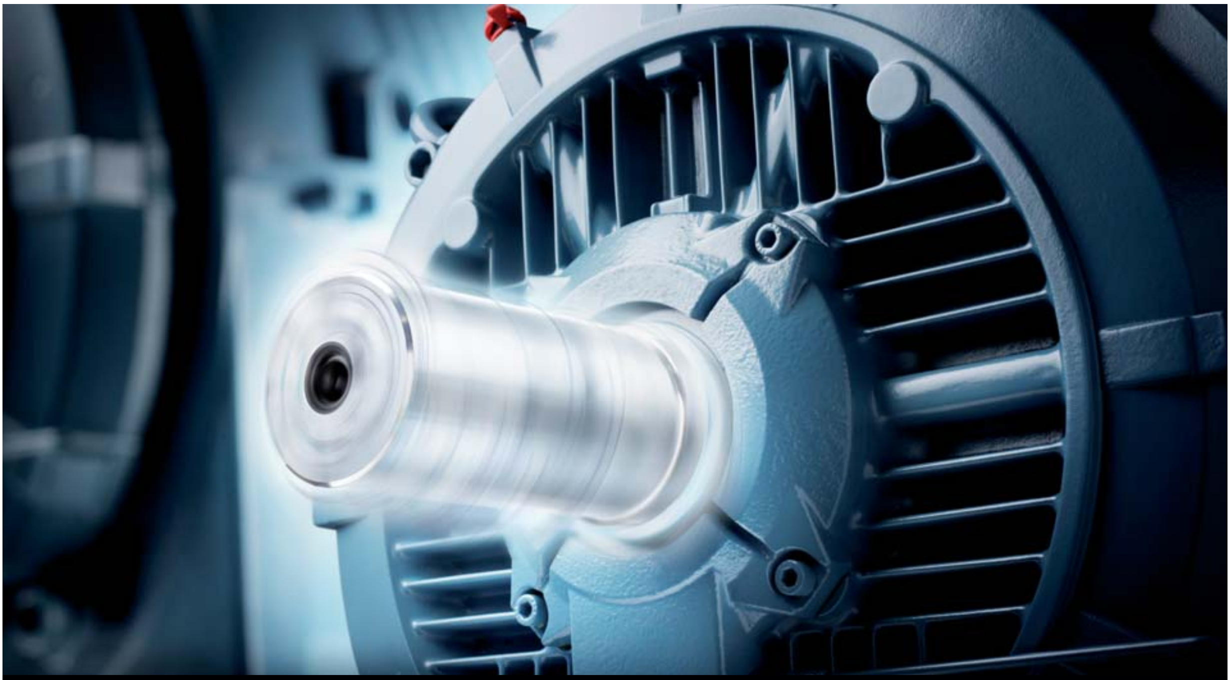

ABB drives

Technical guide No. 1
Direct torque control - the world's most advanced AC drive technology

Power and productivity
for a better world™

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Direct torque control - the world's most advanced AC drive technology

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Contents

Chapter 1 - Introduction

General

Direct torque control - or DTC - is the most advanced AC drive technology developed by any manufacturer in the world.

This technical guide's purpose

The purpose of this technical guide is to explain what DTC is; why and how it has evolved; the basic theory behind its success; and the features and benefits of this new technology.

While trying to be as practical as possible, this guide does require a basic understanding of AC motor control principles.

It is aimed at decision makers including designers, specifiers, purchasing managers, OEMs and end-users; in all markets such as the water, chemical, pulp and paper, power generation, material handling, air conditioning and other industries.

In fact, anyone using variable speed drives (VSD) and who would like to benefit from VSD technology will find this technical guide essential reading.

Using this guide

This guide has been designed to give a logical build up as to why and how DTC was developed.

Readers wanting to know the evolution of drives from early DC techniques through AC to DTC should start at chapter 2 (page 8).

For those readers wanting answers about DTC's performance, operation and application potential, please go straight to chapter 3 (page 17) Questions and answers.

For an understanding of DTC's basic control theory, turn to page 28.

Chapter 2 - Evolution of direct torque control

What is a variable speed drive?

To understand the answer to this question we have to understand that the basic function of a variable speed drive (VSD) is to control the flow of energy from the mains to the process.

Energy is supplied to the process through the motor shaft. Two physical quantities describe the state of the shaft: torque and speed. To control the flow of energy we must therefore, ultimately, control these quantities.

In practice, either one of them is controlled and we speak of “torque control” or “speed control”. When the VSD operates in torque control mode, the speed is determined by the load. Likewise, when operated in speed control, the torque is determined by the load.

Initially, DC motors were used as VSDs because they could easily achieve the required speed and torque without the need for sophisticated electronics.

However, the evolution of AC variable speed drive technology has been driven partly by the desire to emulate the excellent performance of the DC motor, such as fast torque response and speed accuracy, while using rugged, inexpensive and maintenance free AC motors.

Summary

In this section we look at the evolution of DTC, charting the four milestones of variable speed drives, namely:

We examine each in turn, leading to a total picture that identifies the key differences between each.

DC motor drives

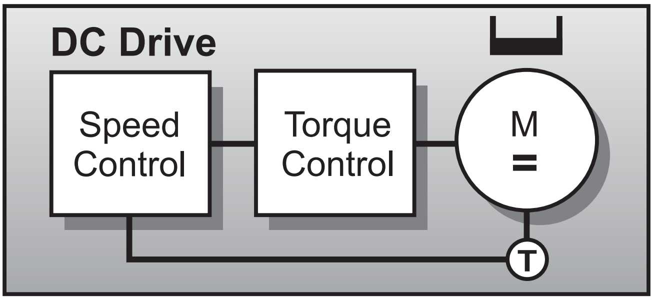


Figure 1: Control loop of a DC motor drive

Features

- Field orientation via mechanical commutator
- Controlling variables are armature current and field current, measured DIRECTLY from the motor
- Torque control is direct

In a DC motor, the magnetic field is created by the current through the field winding in the stator. This field is always at right angles to the field created by the armature winding. This condition, known as field orientation, is needed to generate maximum torque. The commutator-brush assembly ensures this condition is maintained regardless of the rotor position.

Once field orientation is achieved, the DC motor's torque is easily controlled by varying the armature current and by keeping the magnetising current constant.

The advantage of DC drives is that speed and torque - the two main concerns of the end-user - are controlled directly through armature current: that is the torque is the inner control loop and the speed is the outer control loop (see Figure 1).

Advantages

- Accurate and fast torque control
- High dynamic speed response
- Simple to control

Initially, DC drives were used for variable speed control because they could easily achieve a good torque and speed response with high accuracy.

A DC machine is able to produce a torque that is:

- **Direct** - the motor torque is proportional to the armture current: the torque can thus be controlled directly and accurately.
- **Rapid** - torque control is fast; the drive system can have a very high dynamic speed response. Torque can be changed instantaneously if the motor is fed from an ideal current source. A voltage fed drive still has a fast response, since this is determined only by the rotor's electrical time constant (ie, the total inductance and resistance in the armature circuit)
- **Simple** - field orientation is achieved using a simple mechanical device called a commutator/brush assembly. Hence, there is no need for complex electronic control circuitry, which would increase the cost of the motor controller.

Drawbacks

- Reduced motor reliability
- Regular maintenance
- Motor costly to purchase
- Needs encoder for feedback

The main drawback of this technique is the reduced reliability of the DC motor; the fact that brushes and commutators wear down and need regular servicing; that DC motors can be costly to purchase; and that they require encoders for speed and position feedback.

While a DC drive produces an easily controlled torque from zero to base speed and beyond, the motor's mechanics are more complex and require regular maintenance.

AC drives - introduction

- Small size
- Robust
- Simple in design
- Light and compact
- Low maintenance
- Low cost

The evolution of AC variable speed drive technology has been partly driven by the desire to emulate the performance of the DC drive, such as fast torque response and speed accuracy, while utilising the advantages offered by the standard AC motor.

AC drives - frequency control using PWM

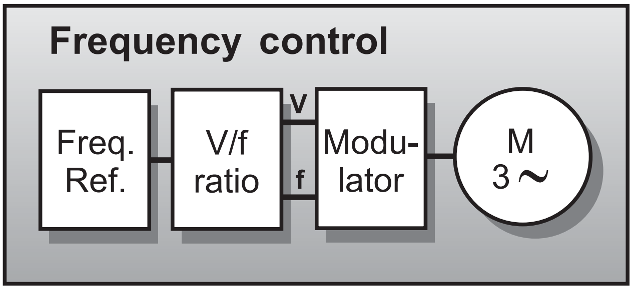


Figure 2: Control loop of an AC drive with frequency control using PWM

Features

- Controlling variables are voltage and frequency
- Simulation of variable AC sine wave using modulator
- Flux provided with constant V/f ratio
- Open-loop drive
- Load dictates torque level

Unlike a DC drive, the AC drive frequency control technique uses parameters generated outside of the motor as controlling variables, namely voltage and frequency.

Both voltage and frequency reference are fed into a modulator which simulates an AC sine wave and feeds this to the motor's stator windings. This technique is called pulse width modulation (PWM) and utilises the fact that there is a diode rectifier towards the mains and the intermediate DC voltage is kept constant. The inverter controls the motor in the form of a PWM pulse train dictating both the voltage and frequency.

Significantly, this method does not use a feedback device which takes speed or position measurements from the motor's shaft and feeds these back into the control loop.

Such an arrangement, without a feedback device, is called an "open-loop drive".

Advantages

- Low cost
- No feedback device required - simple

Because there is no feedback device, the controlling principle offers a low cost and simple solution to controlling economical AC induction motors.

This type of drive is suitable for applications which do not require high levels of accuracy or precision, such as pumps and fans.

Drawbacks

- Field orientation not used
- Motor status ignored
- Torque is not controlled
- Delaying modulator used

With this technique, sometimes known as scalar control, field orientation of the motor is not used. Instead, frequency and voltage are the main control variables and are applied to the stator windings. The status of the rotor is ignored, meaning that no speed or position signal is fed back.

Therefore, torque cannot be controlled with any degree of accuracy. Furthermore, the technique uses a modulator which basically slows down communication between the incoming voltage and frequency signals and the need for the motor to respond to this changing signal.

AC drives - flux vector control using PWM

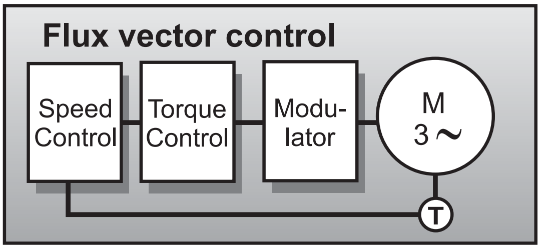


Figure 3: Control loop of an AC drive with flux vector control using PWM

Features

- Field-oriented control - simulates DC drive
- Motor electrical characteristics are simulated - “motor model”
- Closed-loop drive
- Torque controlled INDIRECTLY

To emulate the magnetic operating conditions of a DC motor, ie, to perform the field orientation process, the flux-vector drive needs to know the spatial angular position of the rotor flux inside the AC induction motor.

With flux vector PWM drives, field orientation is achieved by electronic means rather than the mechanical commutator/brush assembly of the DC motor.

Firstly, information about the rotor status is obtained by feeding back rotor speed and angular position relative to the stator field by means of a pulse encoder. A drive that uses speed encoders is referred to as a “closed-loop drive”.

Also the motor’s electrical characteristics are mathematically modelled with microprocessors used to process the data.

The electronic controller of a flux-vector drive creates electrical quantities such as voltage, current and frequency, which are the controlling variables, and feeds these through a modulator to the AC induction motor. Torque, therefore, is controlled INDIRECTLY.

Advantages

- Good torque response
- Accurate speed control
- Full torque at zero speed
- Performance approaching DC drive

Flux vector control achieves full torque at zero speed, giving it a performance very close to that of a DC drive.

Drawbacks

- Feedback is needed
- Costly
- Modulator needed

To achieve a high level of torque response and speed accuracy, a feedback device is required. This can be costly and also adds complexity to the traditional simple AC induction motor.

Also, a modulator is used, which slows down communication between the incoming voltage and frequency signals and the need for the motor to respond to this changing signal.

Although the motor is mechanically simple, the drive is electrically complex.

AC drives - direct torque control

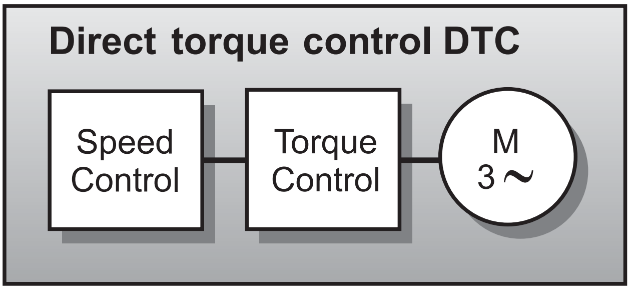


Figure 4: Control loop of an AC drive using DTC

Controlling variables

With the revolutionary DTC technology developed by ABB, field orientation is achieved without feedback using advanced motor theory to calculate the motor torque directly and without using modulation. The controlling variables are motor **magnetising flux** and **motor torque**.

With DTC there is no modulator and no requirement for a tachometer or position encoder to feed back the speed or position of the motor shaft.

DTC uses the fastest digital signal processing hardware available and a more advanced mathematical understanding of how a motor works.

The result is a drive with a torque response that is typically 10 times faster than any AC or DC drive. The dynamic speed accuracy of DTC drives will be 8 times better than any open loop AC drives and comparable to a DC drive that is using feedback.

DTC produces the first “universal” drive with the capability to perform like either an AC or DC drive.

The remaining sections in this guide highlight the features and advantages of DTC.

Comparison of variable speed drives

Let us now take a closer look at each of these control blocks and spot a few differences.

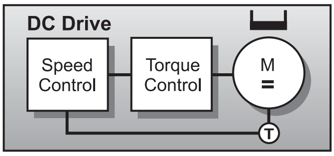


Figure 1: Control loop of a DC drive

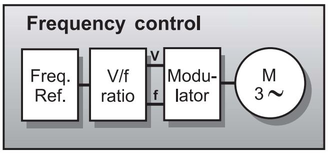


Figure 2: Control loop with frequency control

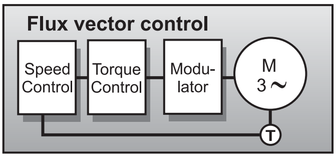


Figure 3: Control loop with flux vector control

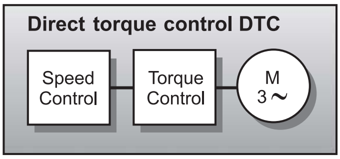
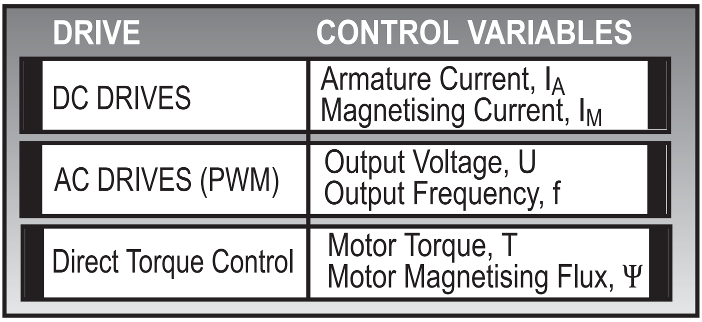


Figure 4 Control loop of an AC drive using DTC

The first observation is the similarity between the control block of the DC drive (Figure 1) and that of DTC (Figure 4).

Both are using motor parameters to directly control torque.

But DTC has added benefits including no feedback device is used; all the benefits of an AC motor (see page 10); and no external excitation is needed.



DRIVE	CONTROL VARIABLES
DC DRIVES	Armature Current, I_A Magnetising Current, I_M
AC DRIVES (PWM)	Output Voltage, U Output Frequency, f
Direct Torque Control	Motor Torque, T Motor Magnetising Flux, Ψ

Table 1: Comparison of control variables

As can be seen from table 1, both DC drives and DTC drives use actual motor parameters to control torque and speed. Thus, the dynamic performance is fast and easy. Also with DTC, for most applications, no tachometer or encoder is needed to feed back a speed or position signal.

Comparing DTC (Figure 4) with the two other AC drive control blocks (Figures 2 & 3) shows up several differences, the main one being that no modulator is required with DTC.

With PWM AC drives, the controlling variables are frequency and voltage which need to go through several stages before being applied to the motor. Thus, with PWM drives control is handled inside the electronic controller and not inside the motor.

Chapter 3 - Questions and answers

General

What is direct control?

Direct torque control - or DTC as it is called - is the very latest AC drive technology developed by ABB and is set to replace traditional PWM drives of the open- and closed-loop type in the near future.

Why is it called direct torque control?

Direct torque control describes the way in which the control of torque and speed are directly based on the electromagnetic state of the motor, similar to a DC motor, but contrary to the way in which traditional PWM drives use input frequency and voltage. DTC is the first technology to control the “real” motor control variables of torque and flux.

What is the advantage of this?

Because torque and flux are motor parameters that are being directly controlled, there is no need for a modulator, as used in PWM drives, to control the frequency and voltage. This, in effect, cuts out the middle man and dramatically speeds up the response of the drive to changes in required torque. DTC also provides precise torque control without the need for a feedback device.

Why is there a need for another AC drive technology?

DTC is not just another AC drive technology. Industry is demanding more and existing drive technology cannot meet these demands.

For example, industry wants:

- Better product quality which can be partly achieved with improved speed accuracy and faster torque control.
- Less down time which means a drive that will not trip unnecessarily; a drive that is not complicated by expensive feedback devices; and a drive which is not greatly affected by interferences like harmonics and RFI.
- Fewer products. One drive capable of meeting all appliction needs whether AC, DC or servo. That is a truly “universal” drive.
- A comfortable working environment with a drive that produces much lower audible noise.

These are just some of the demands from industry. DTC can deliver solutions to all these demands as well as bringing new benefits to many standard applications.

Who invented DTC?

ABB has been carrying out research into DTC since 1988 following the publication of the theory in 1971 and 1985 by German doctor Blaschke and his colleague Depenbrock. DTC leans on the theory of field oriented control of induction machines and the theory of direct self control. ABB has spent over 100 man years developing the technology.

Performance

What are the main benefits of DTC technology over traditional AC drive technology?

There are many benefits of DTC technology. But most significantly, drives using DTC technology have the following exceptional dynamic performance features, many of which are obtained without the need for an encoder or tachometer to monitor shaft position or speed:

- **Torque response:** - How quickly the drive output can reach the specified value when a nominal 100 percent torque reference step is applied.
  For DTC, a typical torque response is **1 to 2 ms** below 40 Hz compared to between 10-20 ms for both flux vector and DC drives fitted with an encoder. With open loop PWM drives (see page 11) the response time is typically well over 100 ms. In fact, with its torque response, DTC has achieved the natural limit. With the voltage and current available, response time cannot be any shorter. Even in the newer “sensorless” drives the torque response is **hundreds of milliseconds.**

- Accurate **torque control at low frequencies**, as well as full load torque at zero speed without the need for a feedback device such as an encoder or tachometer. With DTC, speed can be controlled to frequencies below 0.5 Hz and still provide **100 percent torque** right the way through to zero speed.

- **Torque repeatability:** - How well the drive repeats its output torque with the same torque reference command. DTC, without an encoder, can provide 1 to 2 percent torque repeatability of the nominal torque across the speed range. This is half that of other open-loop AC drives and equal to that of closed-loop AC and DC drives.

- **Motor static speed accuracy:** - Error between speed reference and actual value at constant load. For DTC, speed accuracy is 10 percent of the motor slip, which with an 11 kW motor, equals 0.3 percent static speed accuracy. With a 110 kW motor, speed accuracy is 0.1 percent without encoder (open-loop). This satisfies the accuracy requirement or 95 percent of industrial drives applications. However, for the same accuracy from DC drives an encoder is needed.

  In contrast, with frequency controlled PWM drives, the static speed accuracy is typically between 1 to 3 percent. So the potential for customer process improvements is significantly higher with standard drives using DTC technology.

  A DTC drive using an encoder with 1024 pulses/revolution can achieve a speed accuracy of 0.01 percent.

- **Dynamic speed accuracy:** - Time integral of speed deviation when a nominal (100 percent) torque speed is applied. DTC open-loop dynamic speed accuracy is between 0.3 to 0.4%sec. This depends on the gain adjustment of the controller, which can be tuned to the process requirements.

  With other open-loop AC drives, the dynamic accuracy is eight times less and in practical terms around 3%sec.If we furnish the DTC controller with an encoder, the dynamicspeed accuracy will be 0.1%sec, which matches servo drive performance.

What are the practical benefits of these performance figures?

- **Fast torque response:** - This significantly reduces the speed drop time during a load transient, bringing much improved process control and a more consistent product quality.

- **Torque control at low frequencies: -** This is particularly-beneficial to cranes or elevators, where the load needs to be started and stopped regularly without any jerking. Also with a winder, tension control can be achieved from zero through to maximum speed. Compared to PWM flux vector drives, DTC brings the cost saving benefit that no tachometer is needed.

- **Torque linearity:** - This is important in precision applications like winders, used in the paper industry, where an accurate and consistent level of winding is critical.

- **Dynamic speed accuracy:** - After a sudden load change, the motor can recover to a stable state remarkably fast.

FEATURE	RESULT	BENEFIT
Good motor speed accuracy without tachometer.	Allows speed to be controlled better than 0.5% accuracy. No tachometer needed in 95% of all applications.	Investment cost savings. Increased reliability. Better process control. Higher product quality. Leads to a true universal drive.
Excellent torque control without tachometer.	Drive for demanding applications. Allows required torque at all times. Torque repeatability 1%. Torque response time less than 5ms.	Similar performance to DC but without tachometer. Reduced mechanical failures for machinery. Less downtime. Lower investment.
Full torque at zero speed with or without tachometer/encoder.	No mechanical brake needed. Smooth transition between drive and brake. Allows drive to be used in traditional DC drive applications.	Investment cost saving. Better load control. Can use AC drive and motor instead of DC. Standard AC motor means less maintenance and lower cost.
Control down to zero speed and position with encoder.	Servo drive performance.	Cost effective, high performance torque drive; provides position control and better static accuracy. High accuracy control with standard AC motor.

Table 2: Dynamic performance features and benefits offered by DTC technology

Apart from excellent dynamic performance figures, are there any other benefits of DTC drive technology?

Yes, there are many benefits. For example, DTC drives do not need a tachometer or encoder to monitor motor shaft speed or position in order to achieve the fastest torque response ever from an AC drive. This saves initial cost.

FEATURE	RESULT	BENEFIT
Rapid control DC link voltage.	Power loss ride through.	Drive will not trip. Less down time. Avoids process interruptions. Less waste in continuous process.
Automatic start (Direct restart).	Starting with motor residual inductance present. No restarting delay required.	Can start into a motor that is running without waiting for flux to decay. Can transfer motor from line to drive. No restart. No interruptions on process.
Automatic start (Flying start).	Synchronises to rotating motor.	No process interruptions. Smooth control of machinery. Resume control in all situations.
Flux braking.	Controlled braking between two speed points.	Investment cost savings. Better process control. No delay required as in DC braking. Can be used for decelerating to other than zero speed. Reduced need for brake chopper and resistor.
Flux optimization.	Motor losses minimised. Less motor noise.	Controlled motor.
Self identification/ Auto-tuning.	Tuning the motor to drive for top performance.	Easy and accurate set-up. No parameter tuning required. Less commissioning time. Guaranteed starting torque. Easy retrofit for any AC system.
No predetermined switching pattern of power devices.	Low noise. No fixed carrier, therefore acoustic noise reasonable due to “white” noise spectrum.	Cost savings in acoustic barriers in noise sensitive applications. No harmful mechanical resonances. Lower stresses in gearboxes, fans, pumps.
No limits on maximum acceleration and deceleration rate.	Can accelerate and decelerate in quickest time possible without mechanical constraints.	Better process control.

Table 3: User features and benefits offered by DTC technology

Also a DTC drive features rapid starting in all motor electromagnetic and mechanical states. The motor can be started immediately without delay.

It appears that DTC drives are most advantageous for high performance or demanding drive applications. What benefits does DTC bring to standard drives?

Standard applications account for 70 percent of all variable speed drives installed throughout industry. Two of the most common applications are in fans and pumps in industries like heating, ventilating and air conditioning (HVAC), water and food and drinks.

In these applications, DTC provides solutions to problems like harmonics and noise.

For example, DTC technology can provide control to the drive input line generating unit, where a conventional diode bridge is replaced with a controlled bridge.

This means that harmonics can be significantly reduced with a DTC controlled input bridge. The low level current distortion with a DTC controlled bridge will be less than a conventional 6-pulse or 12-pulse configuration and power factor can be as high as 0.99.

For standard applications, DTC drives easily withstand huge and sudden load torques caused by rapid changes in the process, without any overvoltage or overcurrent trip.

Also, if there is a loss of input power for a short time, the drive must remain energised. The DC link voltage must not drop below the lowest control level of 80 percent. To ensure this, DTC has a 25 microseconds control cycle.

What is the impact of DTC on pump control?

DTC has an impact on all types of pumps. Because DTC leads to a universal drive, all pumps, regardless of whether they are centrifugal or constant torque type (screw pumps) can now be controlled with one drive configuration, as can aerators and conveyors. DTC technology allows a drive to adjust itself to varying application needs.

For example, in screw pumps a drive using DTC technology will be able to adjust itself for sufficient starting torque for a guaranteed start.

Improved power loss ride through will improve pumping availability during short power breaks.

The inherent torque control facility for DTC technology allows the torque to be limited in order to avoid mechanical stress on pumps and pipelines.

What is the impact of DTC technology on energy savings?

A feature of DTC which contributes to energy efficiency is a development called motor flux optimization.

With this feature, the efficiency of the total drive (that is controller and motor) is greatly improved in fan and pump applications.

For example, with 25 percent load there is up to 10 percent total energy efficiency improvement. At 50 percent load there can be 2 percent total efficiency improvement.

This directly impacts on operating costs. This feature also significantly reduces the motor noise compared to that generated by the switching frequency of a traditional PWM drive.

Has DTC technology been used in many installations?

Yes, there are hundreds of thousands of installations in use. For example, one of the world's largest web machine manufacturers tested DTC technology for a winder in a film finishing process.

The Requirement:
Exact torque control in the winder so as to produce high quality film rolls.

The Solution:
Open-loop DTC drives have replaced traditional DC drives and latter flux vector controlled AC drives on the centre drives in the rewind station.

The Benefits:
Winder station construction simplified and reliability increased. The cost of one tachometer and associated wiring equals that of one 30 kW AC motor. This provides significant investment cost savings.

Operation

What is the difference between DTC and traditional PWM methods?

- **Frequency control PWM and flux vector PWM**

Traditional PWM drives use **output voltage** and **output frequency** as the primary control variables but these need to be pulse width modulated before being applied to the motor.

This modulator stage adds to the signal processing time and therefore limits the level of torque and speed response possible from the PWM drive.

Typically, a PWM modulator takes 10 times longer than DTC to respond to actual change.

- **DTC control**

DTC allows the motor's **torque** and **stator flux** to be used as primary control variables, both of which are obtained directly from the motor itself. Therefore, with DTC, there is no need for a separate voltage and frequency controlled PWM modulator. Another big advantage of a DTC drive is that no feedback device is needed for 95 percent of all drive applications.

Why does DTC not need a tachometer or position encoder to tell it precisely where the motor shaft is at all times?

There are four main reasons for this:

- The accuracy of the motor model (see page 29).
- Controlling variables are taken directly from the motor (see page 29).
- The fast processing speeds of the DSP and optimum pulse selector hardware (see page 30).
- No modulator is needed (see page 14).

When combined to form a DTC drive, the above features produce a drive capable of calculating the ideal switching voltages 40,000 times every second. It is fast enough to control individual switching pulses. Quite simply, it is the fastest ever achieved.

Once every 25 microseconds, the inverter's semiconductors are supplied with an optimum switching pattern to produce the required torque. This update rate is substantially less than any time constants in the motor. Thus, the motor is now the limiting component, not the inverter.

What is the difference between DTC and other sensorless drives on the market?

There are vast differences between DTC and many of the sensorless drives. But the main difference is that DTC provides accurate control even at low speeds and down to zero speed without encoder feedback. At low frequencies the nominal torque step can be increased in less than 1ms. This is the best available.

How does a DTC drive achieve the performance of a servo drive?

Quite simply because the motor is now the limit of performance and not the drive itself. A typical dynamic speed accuracy for a servo drive is 0.1%s. A DTC drive can reach this dynamic accuracy with the optional speed feedback from a tachometer.

How does DTC achieve these major improvements over traditional technology?

The most striking difference is the sheer speed by which DTC operates. As mentioned above, the torque response is the quickest available.

To achieve a fast torque loop, ABB has utilised the latest high speed signal processing technology and spent 100 man years developing the highly advanced motor model which precisely simulates the actual motor parameters within the controller.

For a clearer understanding of DTC control theory, see page 28.

Does a DTC drive use fuzzy logic within its control loop?

No. Fuzzy logic is used in some drives to maintain the acceleration current within current limits and therefore prevent the drive from tripping unnecessarily. As DTC is controlling the torque directly, current can be kept within these limits in all operating conditions.

A drive using DTC technology is said to be tripless. How has this been achieved?

Many manufacturers have spent years trying to avoid trips during acceleration and deceleration and have found it extraordinarily difficult. DTC achieves tripless operation by controlling the actual motor torque.

The speed and accuracy of a drive which relies on computed rather than measured control parameters can never be realistic. Unless you are looking at the shaft, you are not getting the full picture. Is this true with DTC?

DTC knows the full picture. As explained above, thanks to the sophistication of the motor model and the ability to carry out 40,000 calculations every second, a DTC drive knows precisely what the motor shaft is doing. There is never any doubt as to the motor's state. This is reflected in the exceptionally high torque response and speed accuracy figures quoted on pages 18 and 19.

Unlike traditional AC drives, where up to 30 percent of all switchings are wasted, a drive using DTC technology knows precisely where the shaft is and so does not waste any of its switchings.

DTC can cover 95 percent of all industrial applications. The exceptions, mainly applications where extremely precise speed control is needed, will be catered for by adding a feedback device to provide closed loop control. This device, however, can be simpler than the sensors needed for conventional closed loop drives.

Even with the fastest semiconductors some dead time is introduced. Therefore, how accurate is the auto-tuning of a DTC drive?

Auto-tuning is used in the initial identification run of a DTC drive (see page 29). The dead time is measured and is taken into account by the motor model when calculating the actual flux. If we compare to a PWM drive, the problem with PWM is in the range 20 to 30 Hz which causes torque ripple.

What kind of stability will a DTC drive have at light loads and low speeds?

The stability down to zero speed is good and both torque and speed accuracy can be maintained at very low speeds and light loads. We have defined the accuracies as follows:

Torque accuracy: Within a speed range of 2 to 100 percent and a load range of 10 to100 percent, the torque accuracy is 2 percent.

Speed accuracy: Within a speed range of 2 to 100 percent and a load range of 10 to 100 percent, the speed accuracy is 10 percent of the motor slip. Motor slip of a 37 kW motor is about 2 percent which means a speed accuracy of 0.2 percent.

What are the limitations of DTC?

If several motors are connected in parallel in a DTC-controlled inverter, the arrangement operates as one large motor. It has no information about the status of any single motor. If the number of motors varies or the motor power remains below 1/8 of the rated power, it would be best to select the scalar control macro.

Can DTC work with any type of induction motor?

Yes, any type of asynchronous, squirrel cage motor.

Chapter 4 - Basic control theory

How DTC works

Figure 5, below, shows the complete block diagram for direct torque control (DTC).

Walk around the block

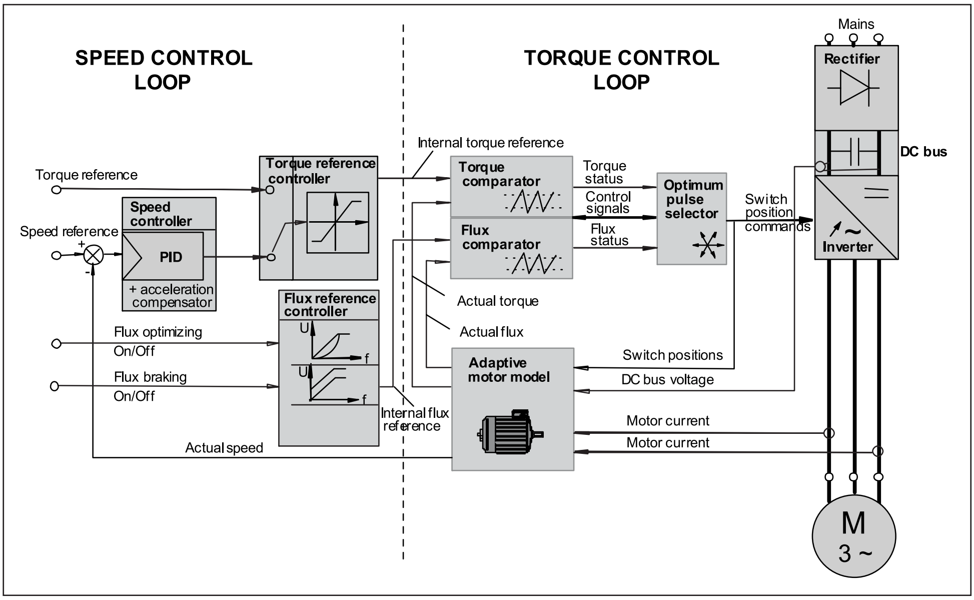
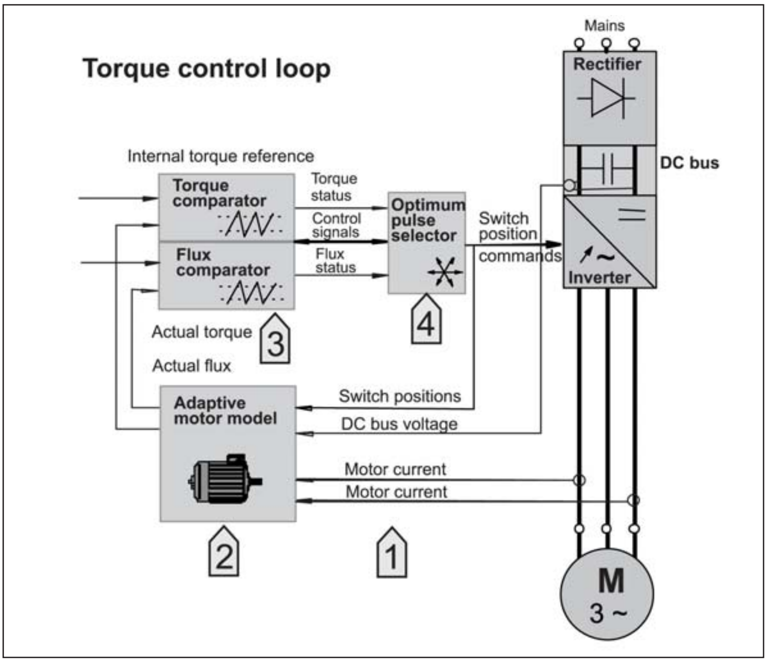


Figure 5: DTC comprises two key blocks: Speed control and torque control

The block diagram shows that DTC has two fundamental sections: the torque control loop and the speed control loop. Now we will walk around the blocks exploring each stage and showing how they integrate together.

Let's start with DTC's torque control loop.

Torque control loop



Step 1 Voltage and current measurements

In normal operation, two motor phase currents and the DC bus voltage are simply measured, together with the inverter's switch positions.

Step 2 Adaptive motor model

The measured information from the motor is fed to the Adaptive Motor Model.

The sophistication of this motor model allows precise data about the motor to be calculated. Before operating the DTC drive, the motor model is fed information about the motor, which is collected during a motor identification run. This is called **auto-tuning** and data such as stator resistance, mutual inductance and saturation coefficients are determined along with the motor's inertia. The identification of motor model parameters can be done without rotating motor shaft. This makes it easy to apply DTC technology also in retrofits. The extremely fine tuning of motor model is achieved when the identification run also includes running the motor shaft for some seconds.

There is no need to feed back any shaft speed or position with tachometers or encoders if the static speed accuracy requirement is over 0.5 percent, as it is for most industrial applications.

This is a significant advance over all other AC drive technology. The motor model is, in fact, key to DTC's unrivalled low speed performance.

The motor model outputs control signals which directly represent actual motor torque and actual stator flux. Also shaft speed is calculated within the motor model.

Step 3 Torque comparator and flux comparator

The information to control power switches is produced in the torque and flux comparator.

Both actual torque and actual flux are fed to the comparators where they are compared, every 25 microseconds, to a torque and flux reference value. Torque and flux status signals are calculated using a two level hysteresis control method.

These signals are then fed to the optimum pulse selector.

Step 4 Optimum pulse selector

Within the optimum pulse selector is the latest 40 MHz digital signal processor (DSP) together with ASIC hardware to determine the switching logic of the inverter. Furthermore, all control signals are transmitted via optical links for high speed data transmission.

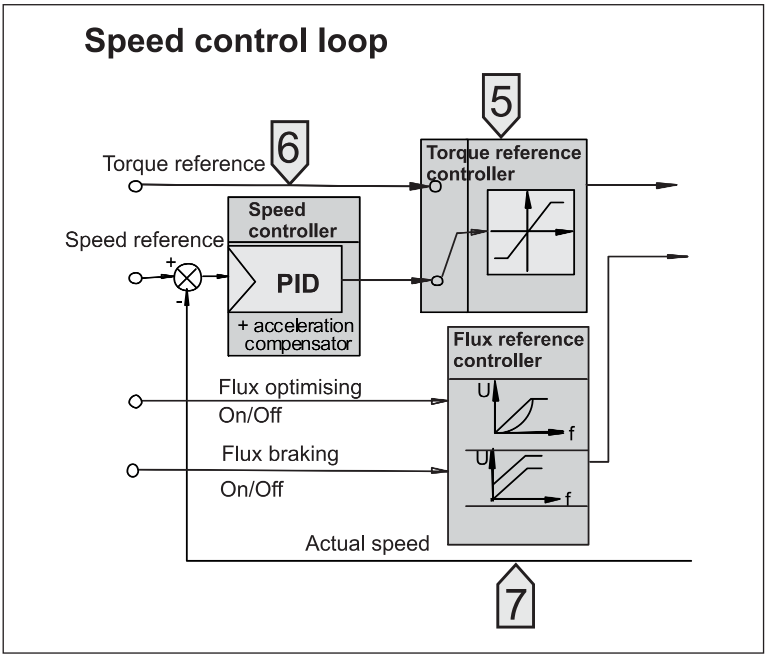
This configuration brings immense processing speed such that every 25 microseconds the inverter's semiconductor switching devices are supplied with an optimum pulse for reaching, or maintaining, an accurate motor torque.

The correct switch combination is determined every control cycle. There is no predetermined switching pattern. DTC has been referred to as “just-in-time” switching, because, unlike traditional PWM drives where up to 30 percent of all switch changes are unnecessary, with DTC each and every switching is needed and used.

This high speed of switching is fundamental to the success of DTC. The main motor control parameters are updated 40,000 times a second. This allows extremely rapid response on the shaft and is necessary so that the motor model (see step 2) can update this information.

It is this processing speed that brings the high performance figures including a static speed control accuracy, without encoder, of ±0.5 percent and the torque response of less than 2 ms.

Speed control



Step 5 Torque reference controller

Within the torque reference controller, the speed control output is limited by the torque limits and DC bus voltage.

It also includes speed control for cases when an external torque signal is used. The internal torque reference from this block is fed to the torque comparator.

Step 6 Speed controller

The speed controller block consists both of a PID controller and an acceleration compensator. The external speed reference signal is compared to the actual speed produced in the motor model. The error signal is then fed to both the PID controller and the acceleration compensator. The output is the sum of outputs from both of them.

Step 7 Flux reference controller

An absolute value of stator flux can be given from the flux reference controller to the flux comparator block. The ability to control and modify this absolute value provides an easy way to realise many inverter functions such as flux optimization and flux braking (see page 21).

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