ABB DRIVES

Technical guide No. 1

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

Direct torque control

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.

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Introduction

General

Direct torque control – or DTC – is the most advanced AC drive technology developed by any manufacturer in the world. Inverter units are connected directly to a common DC-link.

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, and air conditioning 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 explanation of 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 5).

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 26.

Evolution of direct torque control

What is a variable speed drive?

To understand the answer to this question, we must 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, including its 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:

- DC motor drives 6
- AC drives, scalar V/f control 8
- AC drives, flux vector control using PWM 10
- AC drives, direct torque control 12

We examine each in turn, resulting in an overall picture that identifies the key differences between each.

DC motor drives

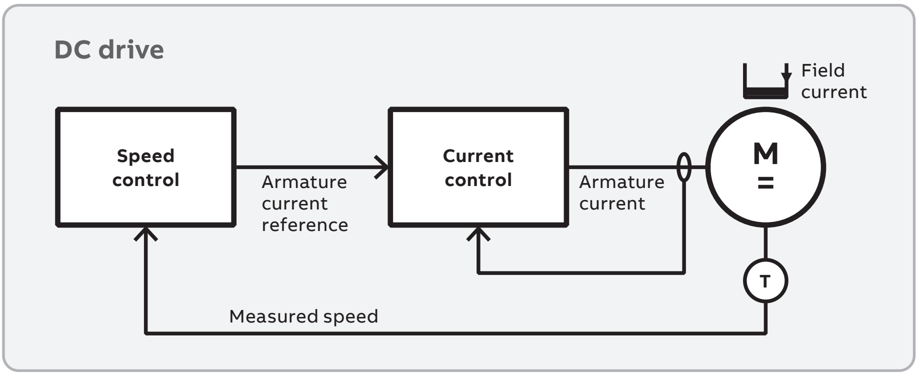

Figure 1. Control loops of a DC motor drive.

Features
- Field orientation via mechanical commutator
- Controlling variables are armature current and field current

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

Due to the field orientation, DC motor's torque is proportional to the armature current when the magnetising field current is kept constant.

Advantages
- Accurate and fast torque control
- High short-time torque capability
- High dynamic speed response
- Simple to control

Initially, DC drives were used for variable speed control because, even with simple electromechanical control systems, they could achieve reasonably good torque and speed response.

The advantage of DC drives is that both note the armature and field currents are easily measurable and controllable. In addition to torque, it is therefore easy to control the speed of the motor in the whole speed range, including zero speed. The torque controlling armature current is the inner control loop, and the speed is the outer control loop (see Figure 1).

With modern electronic control systems, the 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, as this is determined only by the rotor's electrical time constant (i.e., the total inductance and resistance in the armature circuit).

The speed control dynamics are boosted by the high short-time torque capability of DC motors, limited only by the commutator flashover and winding overtemperature. Typically, more than two times the rated torque can be temporarily obtained.

Drawbacks
- Reduced motor reliability
- Regular maintenance
- High purchase cost of big motors
- Needs speed sensor for accurate speed control

The main drawback of DC motors is the wear of the brushes and commutator, which reduces reliability and requires regular servicing. Although small DC motors for intermittent household use can be manufactured at low cost, DC motors for industrial applications can be costly to purchase.

For many applications, the accuracy of the methods used for DC motor speed estimation is insufficient, and a speed sensor is required. The sensor increases costs, and, as a wearable component, it reduces reliability.

AC drives – introduction

The evolution of AC variable speed drive technology has been partly driven by the desire to emulate the performance of the DC drive, including stepless speed variation and fast torque response, while utilizing the advantages offered by the standard three-phase AC motor:
- Small size
- Robust
- Simple in design
- Light and compact
- Low-maintenance
- Low cost

The main difference from DC motors is that the speed of an AC motor is defined by the frequency of the AC voltage fed to the stator windings. In DC motors, the AC current to the rotating armature windings is provided internally by the commutator and the brushes. Thus, the armature current frequency is always synchronized with the rotation of the rotor. While this electromechanical solution for DC motors is simple, AC motors offer more degrees of freedom for the control by allowing the use of electronics instead of mechanics to define the frequency.

Figure 2 shows a typical AC drive structure. The drive consists of a rectifier, DC link and inverter. The rectifier rectifies the fixed frequency AC voltage of the grid into DC. The inverter converts the DC voltage into variable frequency and variable voltage. Typically, the rectifier is a diode rectifier, and the inverter is based on IGBT transistors.

The AC voltage generation of the inverter is based on pulse width modulation (PWM). The DC voltage is chopped by the inverter transistors into pulses. The widths of the pulses are changed so that the way that the average phase-to-phase voltages fed to the motor vary sinusoidally with the required frequency and amplitude.

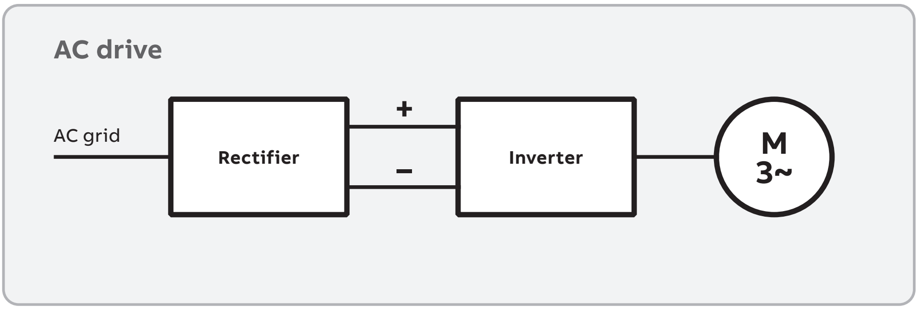

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Figure 2. Main parts of an AC drive.

AC drives – scalar V/f control

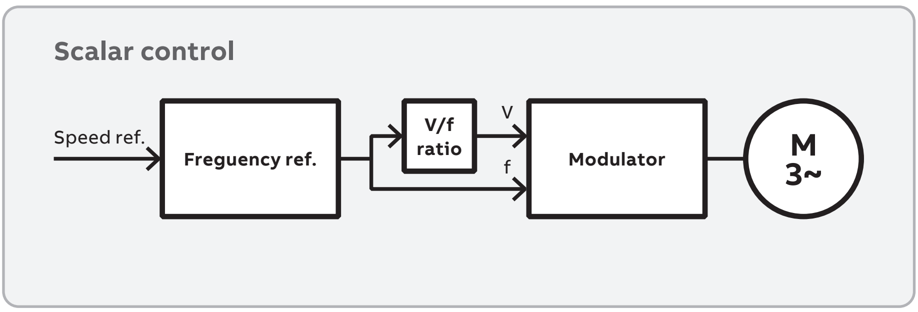

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Figure 3. AC drive with scalar V/f control.

Features
- Controlling variables are voltage (V) and frequency (f)
- Approximation of variable AC sine wave using modulator
- Constant magnetic flux is provided with constant V/f ratio
- Open-loop drive
- Load dictates torque level

In scalar control, the stator voltage and frequency references are both proportional to the speed reference. They are both fed into a modulator which defines the PWM pulse sequences of the motor voltage.

The essential feature of the scalar control is that it does not require the motor speed to be measured, as this is defined by the frequency. Such an arrangement, without a speed feedback device or estimation algorithm, is called an “open-loop drive.”

As the name of the motor implies, the speed of the synchronous motors can be precisely controlled. With asynchronous induction motors, the speed deviates from the synchronous speed by the load dependent slip. It is common to increase the accuracy by slip compensation function of the inverter control.

Advantages
- Low cost
- No feedback device required – simple

Because there is no feedback device, the operation principle offers a low cost and simple solution, especially for AC induction motor control.

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

Drawbacks
- Field orientation is not used
- Motor’s electromagnetic state is not measured or estimated
- Torque is not controlled
- Sluggish control

With this technique, it is assumed that the motor can always follow the frequency reference. Unfortunately, this is not always the case. A sudden increase in the load torque or speed reference will stall the motor, resulting in the slip and motor current becoming excessive, and causing either an overcurrent trip on the drive or the overheating of the stalled motor. Furthermore, starting the motor may be difficult if the load requires high breakaway torque.

To cope with these problems, the scalar control systems have functions that limit the acceleration and deceleration of the drive and automatically decrease the frequency if the motor current starts to become too high. Torque capability at starting can be enhanced by temporarily increasing the voltage fed to the motor. However, all these methods are quite rough and will work only if there is a reasonable margin in the dimensioning of the drive, and there are no requirements for rapid changes of speed.

Due to the lack of torque control, it is impossible to damp the torsional vibrations caused by cyclic loads. Moreover, motors with a rated power higher than 5…10 kW tend to have low inherent damping, which causes speed and torque fluctuations at low loads.

AC drives – flux vector control using PWM

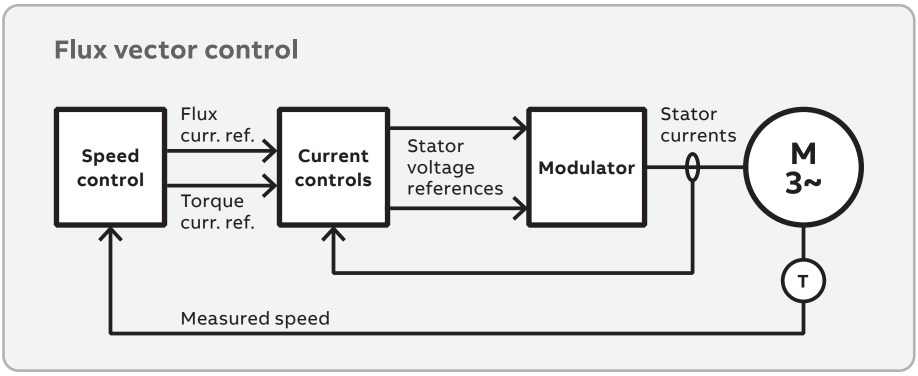

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Figure 4. Control of an AC drive with flux vector control using PWM.

Features

- Field-oriented control – simulates DC drive
- Motor electrical characteristics are simulated – “motor model”
- Closed-loop drive
- Torque is controlled by the torque-producing component of the stator current

To emulate the magnetic operating conditions of a DC motor, i.e., 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 electronically rather than by the mechanical commutator/brush assembly of the DC motor.

First, information about the rotor's mechanical status is obtained by measuring the rotor speed or angular position relative to the stator by means of a pulse encoder. A drive that uses speed encoders is referred to as a “closed-loop drive.”

The motor’s electrical characteristics are also mathematically modeled in the control program code of the drive's microprocessor. The model needs rotor position and stator phase currents as inputs and rotor resistance and inductance as parameters.

The electronic controller of a flux vector drive calculates the rotor flux magnitude and direction using the motor model. When the direction of the rotor flux is known, it is possible to calculate which part of the stator current is producing torque, and which is producing magnetic flux. These correspond to the armature current and field current of a DC motor.

From the flux and torque references, the control calculates references for the two stator current components. Two current controllers control the flux and torque-producing current components according to their references by forming corresponding voltage references that are fed to the modulator. The modulator defines the PWM pulse sequences of the motor voltage.

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

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

Drawbacks
- Speed or position sensor is needed
- Costly
- Modulator is needed
- Motor model has computationally demanding coordinate transforms
- Torque control accuracy depends on the accuracy of motor model parameters
- System has many controllers that must be tuned for optimal performance.

To achieve a high level of torque and speed accuracy, a speed or position sensor is required. The sensor increases costs and as a wearable mechanical component, it reduces reliability. This also adds complexity to the traditional simple AC induction motor.

The motor model parameters are difficult to obtain accurately, as they are influenced by the rotor temperature and magnetic saturation of the iron, both of which tend to vary. Several methods have been developed to estimate the parameters when the motor is running, but there tend to be errors, especially when the operating point of the drive is changing.

It is possible to omit the sensor and instead estimate the rotor position. Such a drive is called a sensorless flux vector control drive. However, the performance of such control is more sensitive to errors in the motor model parameters. Especially at speeds close to zero there are problems to control the motor and continuous operation at zero, there are problems with controlling the motor, and continuous operation at zero output frequency with braking torque is impossible.

Regarding torque control dynamics, the delay caused by the modulator slows down the torque response. Furthermore, the current controllers are usually the proportional-integral type and have considerable overshoot if they are tuned for fast control.

Although the AC motor is itself mechanically simple, the drive control is complex and requires a high-performance microprocessor to perform calculations.

AC drives – direct torque control (DTC)

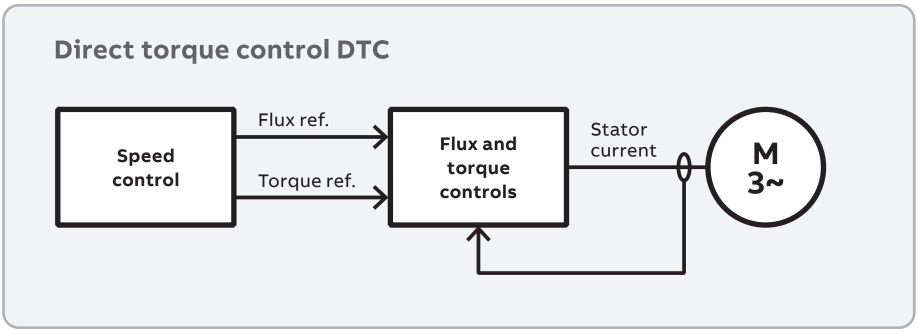

Figure 5. Control of an AC drive using DTC.

Controlling torque instead of currents
The revolutionary idea of DTC technology, developed by ABB, was that instead of trying to imitate the current controller-based system of DC drives, the torque of the motor was controlled directly. As the motor currents or magnetic flux are not important for the driven process application, it is possible to relax their control requirements and use the freed control resources to enhance torque control performance.

Another difference is that DTC has neither modulator nor computationally demanding coordinate transforms. When fast digital signal processing hardware is used, the result is a drive with a torque response that is close to the physical limits set by the motor.

Due to the advanced mathematical understanding of how a motor works, no tachometer or position encoder to feed back the speed or position of the motor shaft is needed in most applications.

Advantages
- Excellent torque response
- Good torque accuracy
- Accurate speed control even without speed sensor
- Full torque at zero speed also without speed sensor
- Low acoustic noise of the motor
- High efficiency of the drive

In DTC, the stator flux is estimated by integrating the stator voltage. This can be done very accurately in a wide speed range, as the only influencing motor parameter is stator resistance, which is easily measurable. The torque is calculated using the measured stator currents and the estimated stator flux. When high-quality current sensors are used, the accuracy of the calculated torque is very high.

A typical dynamic error in speed sensorless operation is less than 4% when the motor speed is higher than 5% of the nominal speed. With a speed sensor, a high accuracy can be achieved in the whole speed range, including continuous operation at zero speed.

Figure 6 shows the shaft torque measurement of a speed sensorless DTC drive, where motor speed is slowly reversed from +90 rpm to −120 rpm and back with constant torque reference. Note that 90 rpm corresponds to about 6% of the nominal speed and level change of the torque after speed reversal is partly due to friction.

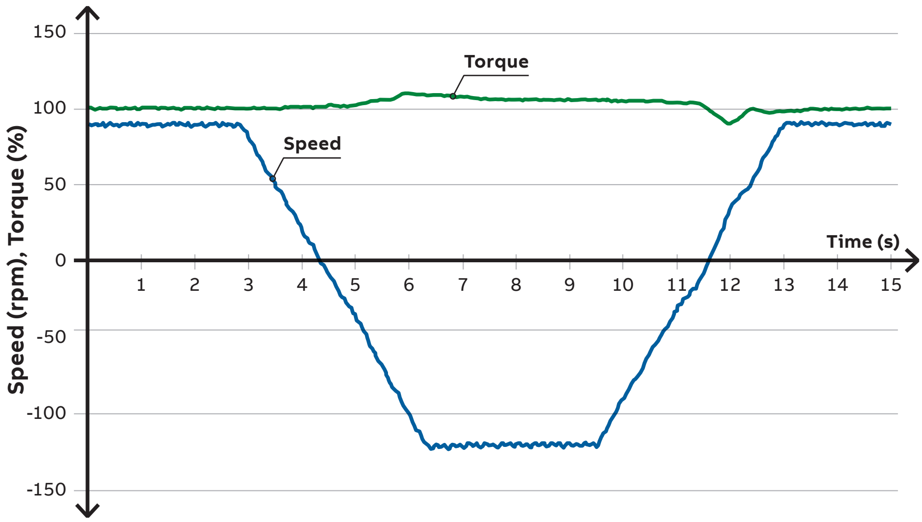

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Figure 6. Slow speed reversals of speed sensorless DTC drive (ACS880) showing excellent dynamic torque accuracy, even when the drive is operating for several seconds close to zero speed.

DTC uses hysteresis control for torque and magnetic flux. Both are controlled to stay within their tolerance bands by selecting a new optimal combination of inverter transistors to conduct every time the borders of the tolerance bands are hit. As torque is more important for the controlled process than flux, tighter tolerance band can be selected for torque than for the flux.

The efficiency of the drive is high because the transistor switching losses are minimized by the DTC hysteresis control, which switches the transistors only when necessary to keep the flux and torque close to their reference values.

In dynamic situations, the torque reference changes rapidly. DTC responds immediately to a corresponding change in the position of the tolerance band to bring the torque within the band in the fastest possible way. As the DTC control principle avoids complex calculations and does not need any separate modulator, the value of the torque and flux can be checked every few microseconds.
As a result, DTC has excellent torque control dynamics – typically, ten times faster than those of conventional AC or DC drives.

Regarding speed controller-related performance, it is important to note that it is always influenced by the mechanical properties of the driven load, such as the load inertia and stiffness of the coupling. The main advantage of fast torque control is that it allows the use of stiffer mechanics with higher torsional resonance frequencies and thus correspondingly increased speed control dynamics. Typically, the dynamic speed accuracy (time integral of speed deviation under a 100% load impact) of a sensorless DTC drive can be about eight times better than with a typical conventional open-loop AC drive and comparable to a conventional DC drive using speed feedback. Moreover, the fast control makes it possible in many cases to increase the damping of the torsional resonances by control means, thus decreasing the stress caused by fluctuating loads.

The acoustic noise of the motor can be annoying when driven by a frequency converter. As DTC operates the transistors of the inverter in a random sequence, the acoustic emissions are spread in the audio frequency range, thus avoiding high single-frequency peaks in the spectrum. The low sizzling sound from a DTC controlled motor is thus less disturbing to people.

Drawbacks

- High-quality current sensors are required
- Speed or position sensor is needed if continuous braking torque is required close to zero speed

The correct operation of DTC requires that the deviation of torque outside its tolerance band is immediately detected. This requires that there is no delay in the motor current measurements, and the measured signal is free of noise and spurious transients. As the average pulse frequency of the DTC is about 3 kHz and may temporarily be a few dozen kilohertz, it is clear that the required bandwidth of the current sensors must be from DC to more than 100 kHz. The design of such a current sensor system at a reasonable cost was quite a challenge, but ABB's engineers managed to solve it.

Induction motors have an inherent problem when fed by zero frequency, i.e., DC. In such a situation, it is impossible to detect the rotor speed from the stator voltage and current. For many applications, this is not a problem, as the load torque is typically zero at standstill, and the speed will therefore also be zero when the motor is fed with zero frequency. However, hoists and cranes, for example, require high torque even at zero frequency to prevent the hanging load from falling. In such applications, all induction motor drives, regardless of the control method used, must be equipped with a speed sensor. Alternatively, a mechanical brake can be used that is activated when the speed approaches zero.

Permanent magnet and synchronous reluctance motors

In addition to induction motors, DTC is used to control permanent magnet (PM) and synchronous reluctance (SynRM) motors. These motors have no windings in their rotor and thus have no rotor losses either. Due to lower losses, more power from the same frame size can be produced, or a smaller motor can be used than with induction motors. SynRM motors have the additional advantage that the magnetic properties of the rotor rely only on the special shape of the rotor iron. Expensive rare earth materials commonly used in permanent magnets are therefore not required.

As both PM and SynRM motors are synchronous motors, their speed is exactly defined by the inverter frequency. Excellent speed accuracy is achieved, even in sensorless operation.

The torque accuracy of these motors is slightly better than with induction motors. See Figure 7.

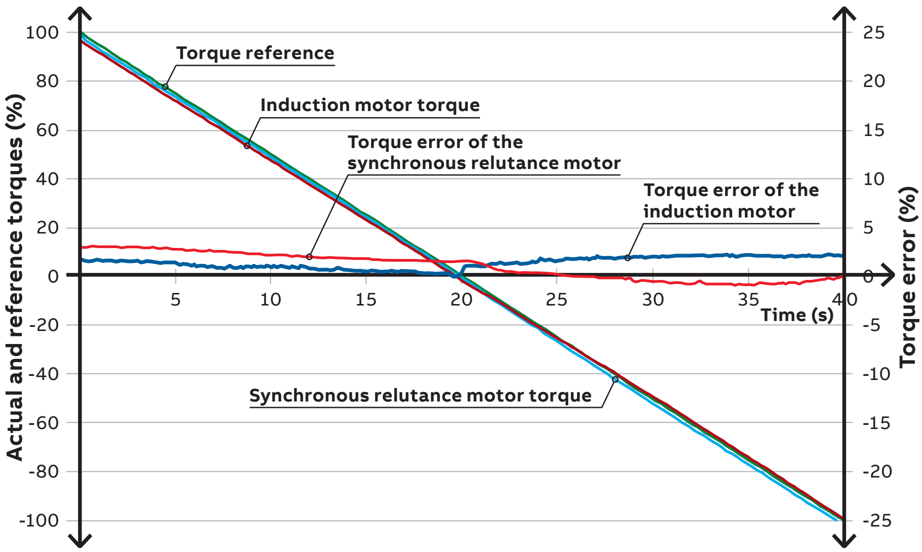

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Figure 7. Torque deviation from reference for DTC-controlled sensorless induction and SynRM motors measured at half the nominal speed.

The starting of the PM and SynRM motors differs from induction motors, as the position of the rotor must be estimated if no position sensor is used. The pronounced saliency makes this easy with SynRM. However, with PM motors, the situation depends on the position of the magnets. The magnets can be on the surface of the rotor or embedded inside it. The preferred type is the embedded one due to its more distinct rotor-pole saliency and the extra reluctance torque that the saliency provides.

DTC and frequency converter's supply unit
A diode bridge rectifier cannot feed braking energy back to the grid. Furthermore, the phase current of the diode bridge is not sinusoidal, which means the phase current contains quite a lot harmonics that distort the grid voltage. The situation can be improved improved by replacing the diode bridge with a similar transistor inverter that drives the motor. With such an IGBT-based active supply unit, it is possible to feed energy back to the grid and control the phase currents so they are almost sinusoidal.

DTC control, as when applied to an active supply unit, is basically similar to motor control as the grid can be thought of as a big machine. The main difference is that instead of speed control, DC voltage is controlled. With DC voltage control, the DC voltage variation due to grid voltage changes is largely eliminated.

Older ACS600 and ACS800 active supply units had a continuous phase current frequency spectrum similar to the phase current of DTC-controlled motors. However, due to recent changes in the power quality measurement standards that now require grouping or sub-grouping to be used in the harmonic current measurements, the measured harmonics were increased between 2 to 3 times that of the values previously mentioned. This sometimes made compliance with the limits difficult in the frequency range around 1 kHz, where the limits are very low. Thus, in the new ACS880 active supply units, DTC has been modified to use a constant pulse frequency that will also guarantee compliance in the future.

Questions and answers

General

What is direct control?

Direct torque control – or DTC as it is called – is the premium AC drive technology developed by ABB that is used instead of traditional PWM drives of the open- and closed-loop type, especially in demanding applications.

Why is it called direct torque control?

Direct torque control describes how the control of torque and magnetic flux are directly controlled based on the electromagnetic state of the motor. DTC is the best technology to control the “real” motor control variables of torque and flux instead of the motor currents or voltage and frequency.

What is the advantage of this?

Because torque and flux are motor parameters are directly controlled, there is no need for a modulator, as used in PWM drives, to control the frequency and voltage. In effect, this cuts out the middleman and dramatically speeds up the response of the drive to changes in the required torque. DTC also provides precise torque control without the need for a speed sensor.

DTC seems to be better in every respect. Why is ABB still selling drives with other AC drive technologies?

DTC requires high-performance current sensors and instrumentation. Unfortunately, this influences the price tag, especially in the low power range. Many applications perform well with even the simple V/f type control. However, industry is developing more demanding applications, and other drive technologies 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 downtime, which means a drive that will not trip unnecessarily; a drive that is not complicated by expensive speed sensors; and a drive which is not greatly affected by interference like harmonics and RFI.
- Fewer products. One drive capable of meeting all application needs, whether AC, DC or servo. This is truly a “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.

My application does not need high dynamics. Why should I buy a DTC drive?

Many fan and pump drives indeed do not need rapid changes of speed. Thus, in many cases, simple V/f control or flux vector control performs well enough. However, there are applications such as compressors with step-up gear and high diameter fans, where the driven load has high inertia. Such applications are often problematic due to the low damping of the torsional resonances, which may cause the breaking of shafts and couplings. With the high dynamic performance of a DTC drive, it is often possible to tune it to artificially damp the mechanical system to such extent that continuous operation in the full speed range can be tolerated, even in sensorless operation.

Furthermore, low acoustic noise from the motor, better compliance with grid voltage dips, and interruptions and the reliable starting of the drive for a rotating motor are valuable features of DTC in less demanding applications.

Who invented DTC?

ABB conducted research into DTC in the early 1980s, resulting in a patent application in 1984 by Manfred Depenbrock, who called it direct self-control. About the same time, Isao Takahashi and Toshihiko Noguchi published a paper about a slightly different method in a Japanese journal, which they called direct torque control. This later became the established name for both methods. Note that this is renumbered as Table 1, as the previous table has been deleted. The first applications of DTC in ABB were traction drives for locomotives at the end of the 1980s. The first industrial drive series, ACS600, was introduced to the market in 1995.

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 and 20 ms for both flux vector and DC drives fitted with an encoder. With open-loop PWM drives (see page 10), the response time is typically well over 100 ms.

Indeed, with its torque response, DTC has achieved the natural limit. With the available voltage and current, the 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 more than 100 percent motoring 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:*** The error between the speed reference and actual value at constant load. For DTC, the speed accuracy is 10 percent of the motor slip, which with an 11 kW motor, equates to 0.3 percent static speed accuracy. With a 110 kW motor, speed accuracy is 0.1 percent without an encoder (open-loop). This satisfies the accuracy requirement or 95 percent of industrial drives applications. However, an encoder is needed for the same accuracy from DC drives.

  In contrast, with frequency-controlled PWM drives, the static speed accuracy is typically between 1 and 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 1,024 pulses/revolution can achieve a speed accuracy of 0.01 percent. The same static accuracy is possible with synchronous reluctance and permanent magnet synchronous motors without an encoder.

- ***Dynamic speed accuracy:*** The time integral of speed deviation when a nominal (100 percent) torque speed is applied. DTC open-loop dynamic speed accuracy is typically between 0.3 to 0.4 %sec. The performance depends on the gain adjustment of the speed controller, which in turn depends on the properties of the driven mechanical system. The fast torque control dynamics of DTC makes it possible to achieve better speed dynamics by allowing the use of stiffer couplings.

  With other open-loop AC drives, the dynamic accuracy is typically eight times less, and in practical terms around 3 %sec. If we furnish the DTC controller with an encoder, the dynamic speed 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 more consistent product quality.

FEATURE	RESULT	BENEFIT
Good motor speed accuracy without tachometer.	Allows speed to be controlled with accuracy 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 truly 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 5 ms.	Similar performance to DC but without tachometer. Reduced mechanical failures for machinery. Less downtime. Lower investment.
Control down to zero speed and position with encoder.	No mechanical brake needed in many applications. 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.
Full torque at zero speed with or without tachometer/encoder.	Servo drive performance.	Cost-effective, high-performance torque drive; provides position control and better static accuracy. High accuracy control with standard AC motor.

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Table 1. Dynamic performance features and benefits offered by DTC technology.

- ***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. With a winder, tension control can also be achieved from zero through to maximum speed.

- ***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 quickly.

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 to achieve the fastest torque response ever from an AC drive. This saves initial costs.

A DTC drive also features a patented method for rapid starting in all motor electromagnetic and mechanical states. The motor can be started immediately without delay.

What benefits does DTC bring to power quality?

DTC also provides solutions for problems with power quality, such as a poor power factor and voltage distortion when a conventional diode bridge is replaced with an IGBT-based active supply unit.

FEATURE	RESULT	BENEFIT
Rapid control of 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 flux present. No restarting delay required.	Can start in a motor that is running without waiting for flux to decay. Can transfer motor from line to drive. No restart. No interruptions to process.
Automatic start (Flying start).	Synchronizes with rotating motor.	No process interruptions. Smooth control of machinery. Resume control in all situations.
Flux braking.	Faster deceleration without additional devices.	Investment cost savings, as brake chopper and resistor are not needed. No delay required as in braking using DC current injection or plugging. Better process control, as with flux braking, the motor can be decelerated accurately to desired speed.
Flux optimization.	Motor losses minimized. Less motor noise.	Better efficiency and more comfortable workplace.
Self identification/ Auto-tuning.	Tuning the motor to drive for top performance.	Easy and accurate setup. 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.
High acceleration and deceleration rates are possible.	Can achieve servo class performance.	Better process control.

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Table 2. User features and benefits offered by DTC technology.

This means that harmonics can be significantly reduced with a DTC-controlled supply unit built in regenerative and low-harmonic drives. The low-frequency current distortion with a DTC-controlled active supply unit is a small fraction of the distortion of a conventional 6-pulse or 12-pulse configuration and power factor can be as high as 0.99. Furthermore, an active supply unit can be controlled to provide reactive power and thus improve the power factor of the whole plant.

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 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 to 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 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, the controller and motor) is greatly improved in fan and pump applications.

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

This directly impacts 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. Millions of installations have been delivered and are in use since the introduction of the first DTC drive in 1995. ABB is the leading manufacturer of AC drives, partly because of DTC technology.

How suitable is DTC for winder applications?

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

The Solution:
Open-loop DTC drives have replaced traditional DC drives and later 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 a significant investment cost saving.

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. Moreover, in flux vector control, the voltage reference is defined by

current controllers, which need filtering the measured phase currents to remove the ripple caused by modulation.

The modulator software processing time and delay caused by filtering currents 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 directly determine the optimum control of the inverter transistors. Therefore, with DTC, there is no need for a separate voltage and frequency-controlled PWM modulator and current controllers. Another big advantage of a DTC drive is that no speed sensor 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 27).
- The controlling variables are taken directly from the motor (see page 27).
- The fast processing speeds of the DSP and optimum pulse selector hardware (see page 27).
- No modulator is needed (see page 12).

When combined to form a DTC drive, the above features produce the latest DTC drives, capable of calculating the ideal switching voltages 80,000 times every second. It is fast enough to control individual switching pulses. Quite simply, it is the fastest ever achieved.

Once every 12.5 microseconds, the inverter's semiconductors are supplied with an optimal 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 full motoring torque down to zero speed without encoder feedback. At low frequencies, the nominal torque step can be increased in less than 1 ms. 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 at which DTC operates. As mentioned above, the torque response is the quickest available.

To achieve a fast torque loop, ABB has utilized the latest high-speed signal processing technology and spent hundreds of person years developing and refining the highly advanced motor model, which precisely simulates the actual motor behaviour within the controller. Several patents dealing with the features of the model have been granted to ABB.

For a clearer understanding of DTC control theory, see page 26.

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 tripping unnecessarily. As DTC controls the torque and flux directly, the 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 far as the physics of the motor allow. As explained above, thanks to the sophistication of the motor model and the ability to carry out 80,000 calculations every second, a DTC drive knows precisely what the motor shaft is doing in most applications. This is reflected in the exceptionally high torque response and speed accuracy figures quoted on pages 13 and 15.

DTC can cover 95 percent of all industrial applications. The exceptions, mainly applications where continuous braking torque at zero frequency, extremely precise speed control or torsional resonance damping is needed, are 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.
So 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 27). The dead time is measured and is taken into account by the motor model when calculating the actual flux. If we compare this to a PWM drive, the problem with PWM is in a range of 20 to 30 Hz, which causes a torque ripple.

What kind of stability does 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 to 100 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. The motor slip of 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 is best to use the scalar control macro of the drive's control, which is similar to basic V/f drive control.

Can DTC work with any type of motor?

Yes, any type of three-phase motor. That is, asynchronous squirrel cage motors, permanent magnet synchronous motors and synchronous reluctance motors. For wind turbines a special control version has also been made that can control doubly fed machines.

Basic control theory

How DTC works

Figure 8 below shows the complete block diagram for direct torque control (DTC).

Walk around the block

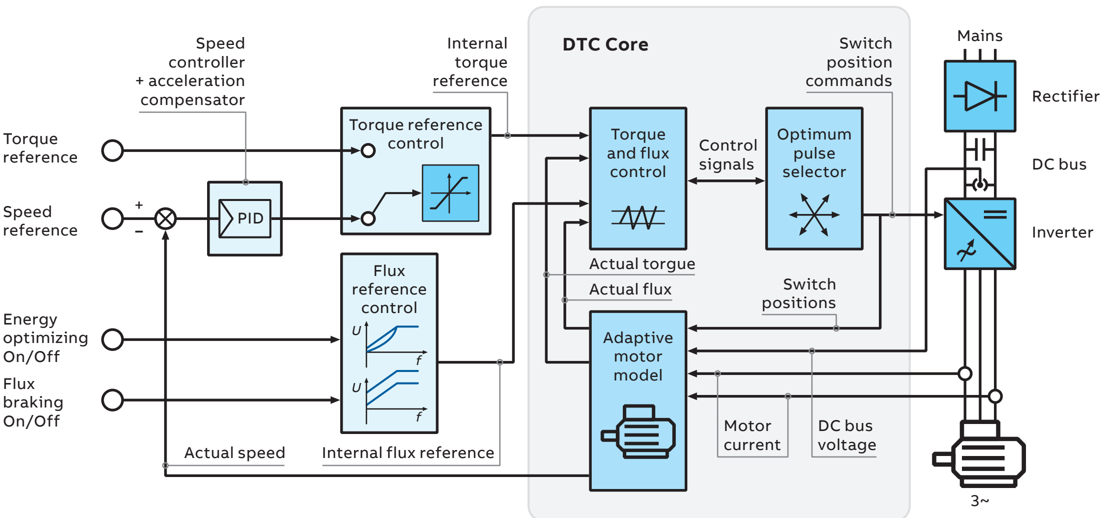

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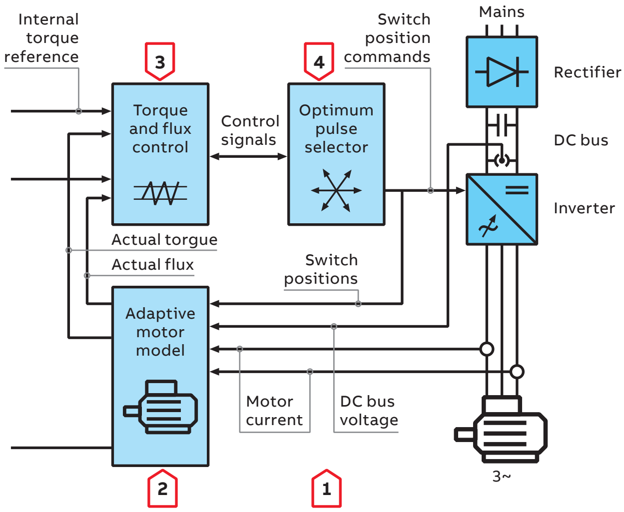
Figure 8. DTC comprises two key blocks: Speed control and torque control.

The block diagram shows that DTC has two fundamental sections: the torque control loop and the speed control loop. We will now 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 measured, together with the inverter's semiconductor switch positions defined by the state of the IGBT transistors.

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 the precise state of the motor to be calculated. Before operating the DTC drive for the first time, 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. This also makes it easy to apply DTC technology in retrofits. Coarse identification of motor model parameters can be done without rotating the motor shaft. The extremely fine tuning of the motor model is achieved when the identification run also includes the running of the motor shaft for some seconds.

There is no need to feed back any shaft speed or position with tachometers or encoders if a 0.5 percent static speed accuracy requirement is enough, 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. The shaft speed is also calculated within the motor model.

Step 3. Torque comparator and flux comparator
The information to control the IGBT transistors of the inverter is produced in the torque and flux comparator.

Both actual torque and actual flux are fed to the comparators, where they are compared every 12.5 milliseconds 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 digital signal processor (DSP), with FPGA hardware to determine the switching logic of the inverter. Furthermore, all control signals are transmitted via optical links for high-speed data transmission.

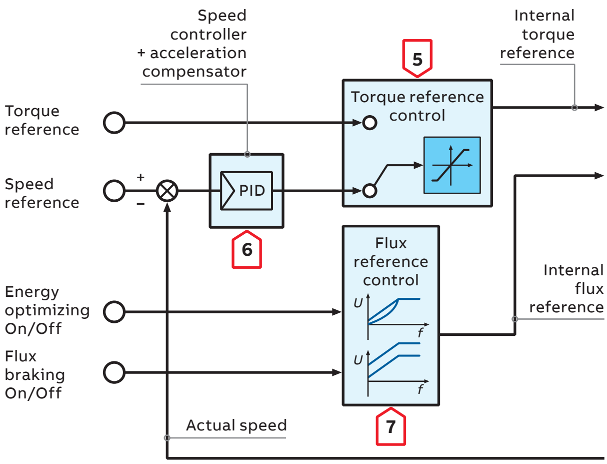
This configuration brings immense processing speed such that every 12.5 microseconds the inverter's semiconductor switching devices are supplied with optimal control to reach or maintain an accurate motor torque.

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, each and every switching is needed with DTC.

This high-speed switching is fundamental to the success of DTC. The main motor control parameters are updated 80,000 times a second. This allows an extremely rapid response on the shaft and is necessary for the motor model (see step 2) to update this information.

It is this processing speed that brings the high-performance figures, including a static speed control accuracy, without an encoder, of ±0.5 percent and a 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 of both a PID controller and an acceleration compensator. The external speed reference signal is compared to the actual speed estimated 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 the outputs from both.

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 realize many inverter functions such as flux optimization and flux braking (see page 21).

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