White Paper

DTC
A motor control technique for all seasons

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Variable-speed drives (VSDs) have enabled unprecedented performance in electric motors and delivered dramatic energy savings by matching motor speed and torque to actual requirements of the driven load. Most VSDs in the market rely on a modulator stage that conditions voltage and frequency inputs to the motor, but causes inherent time delay in processing control signals. In contrast, the premium VSDs from ABB employ direct torque control (DTC) — an innovative technology originated by ABB — greatly increasing motor torque response. In addition, DTC provides further benefits and has grown into a larger technology brand which includes drive hardware, control software, and numerous system-level features.

Electric motors are often at the spearhead of modern production systems, whether in metal processing lines, robotic machining cells, or building and office automation systems. The motors we see today have certainly benefitted from advances in electric materials, manufacturing efficiencies, and analytical tools. However, their design principles have remained the same for over 100 years in the case of the workhorse asynchronous (or induction) alternating current (AC) motor. Rather, the remarkable performance of these motors in today's applications comes from modern electronic controls — variable-speed drives (VSDs) — and accurate motor models whose sophisticated control algorithms can be rapidly executed by high-performance digital signal processors. Moreover, the development of VSDs has enabled the use of new AC motor technologies such as permanent magnet synchronous motors and synchronous reluctance motors.

Initially, direct current (DC) motors drew the attention of drive developers. With an even longer history than their AC cousins, DC motors offered inherently simple speed and torque control. However, higher motor cost, more complex construction with a mechanical commutator, and brush maintenance issues were some tradeoffs associated with DC motors.

AC induction motors offered simpler, rugged construction, lower cost, and posed fewer maintenance concerns — characteristics that have led to their wide usage with a huge installed base worldwide. On the other hand, control of induction motors proved to be complex. Accurate speed control, and particularly torque control, remained elusive for early AC drives. Naturally the goal of the early designers was to emulate in AC drives the DC drive's simple control of motor torque by using armature current. Over time, AC drive designs have evolved offering improved dynamic performance. (One recent, noteworthy discussion of various available AC drive control methods appears in Ref. 1.)

Most high-performance VSDs in 1980s relied on pulse-width modulation (PWM). However, one consequence of using a modulator stage is the delay and a need to filter the measured currents when executing motor control commands — hence slowing down motor torque response.

In contrast, ABB took a different approach to high-performance AC motor control. AC drives from ABB intended for demanding applications use an innovative technology called direct torque control (DTC). The method directly controls motor torque instead of trying to control the currents analogously to DC drives. This means better accuracy in matching the load requirements of the driven system. Originated by one of the founding companies of ABB and patented in the mid-1980s, DTC further eliminates the need for an extra modulator stage and thus achieves control dynamics that are close to the theoretical maximum. ABB introduced its first AC industrial drive with direct torque control to the market in 1995 (Ref. 2).

In principle, DTC was already a leading technology back in 1995, but subsequent developments in processor computational power, communication interfaces, application programming, etc., have enabled higher performance, providing premium motor control for a broad range of applications.

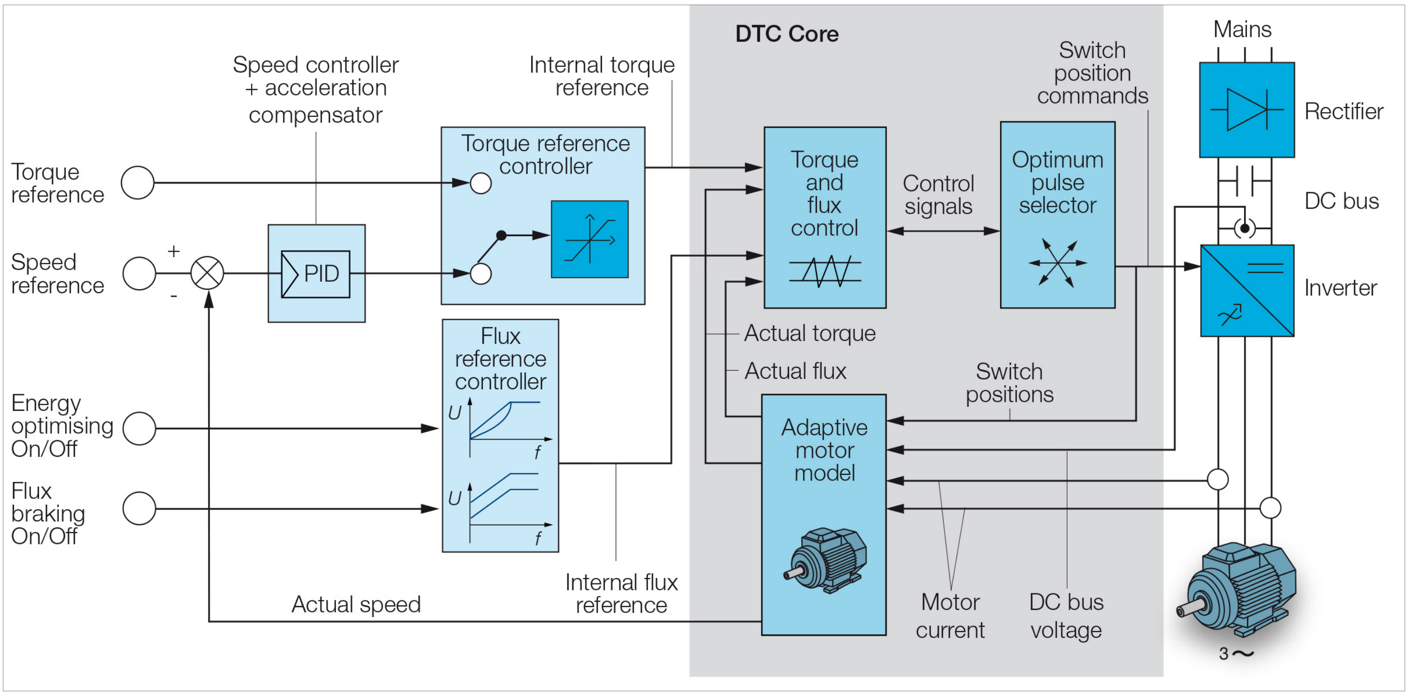


Figure 1: DTC's operation principle.

DTC's core is the torque control loop, where a sophisticated adaptive motor model applies advanced mathematical algorithms to predict motor status. Primary controlled variables—stator flux and motor torque—are accurately estimated by the motor model using inputs of motor phase currents and DC bus voltage measurements, plus the states of the power-switching transistors in the drive.
The motor model also calculates shaft speed. Temperature compensation helps to enhance calculation accuracy without an encoder.

Why use DTC?

Superior torque response is just one feature of DTC. The technology offers further customer benefits, including:

- No need for motor speed or position feedback in 95% of applications. Thus, installation of costly encoders or other feedback devices can be avoided.
- DTC control is available for different types of motors, including permanent magnet and synchronous reluctance motors.
- Accurate torque and speed control down to low speeds, as well as full startup torque down to zero speed.
- Excellent torque linearity.
- High static and dynamic speed accuracy.
- No preset switching frequency. Optimal transistor switching is determined for every control cycle, allowing the drive to more readily match driven load requirements.

In a larger view, benefits of DTC extend to software, user interfaces, maintenance, and system-level features.

As the name suggests, DTC seeks to control motor flux and torque directly, instead of trying to control these variables indirectly like DC drives and vector-controlled AC drives do. Separate torque and speed control loops make up the full DTC system but work together in an integrated way (see Fig. 1, DTC block diagram).

Additional motor parameters are automatically fed to the adaptive model during a motor identification run when the drive is commissioned. In many cases, appropriate model parameter identification can be done without rotating the motor shaft. For fine tuning of the motor model, which is only needed for few high-demand applications, the motor has to be run, but then only for a short time and without load.

Stator resistance (voltage drop) is the only and easily measurable parameter needed for estimating the motor's magnetic flux. Motor torque can then be calculated as the cross product of estimated stator flux and stator current vectors. While stator resistance is the main source of estimation error, its influence diminishes with increasing motor speed and voltage. Thus DTC has excellent torque accuracy in a wide speed range. Moreover, DTC includes advanced ways to minimize estimation error at low motor speeds.

Output signals from the motor model — which represent actual stator flux and motor torque — go to a flux comparator and torque comparator, respectively (Fig.1). These separate control units compare their inputs to a flux and torque reference value. Already in mid 1990s the first DTC controlled drives performed these functions every 25 microseconds (μs) using a high-power digital signal processor (DSP). In the latest control generation the interval is reduced down to 12.5 μs, thus further enhancing control performance. Each comparator seeks to hold its respective flux or torque vector magnitude within a narrow hysteresis band around a reference value. DTC's fast torque response without overshoot comes, in part, from ability to minimize these vector fluctuations. Exceptional motor response is also due to the DSP control algorithms updating the adaptive motor model at the same high cycle rate.

Flux and torque errors — differences between estimated and reference values — and the angular position (or sector) of the stator flux vector are used to calculate flux and torque status in the hysteresis controllers. Then, these status values become inputs to the optimum pulse selector, where the optimum voltage vector is selected from the look-up table (Fig. 1). In this way, the most appropriate signal pulses for each control cycle can be sent to power switches in the inverter to obtain or maintain precise motor torque.

A form of programmable logic — so-called field-programmable gate array (FPGA) — assists the DSP with determining inverter switching logic and other tasks. The FPGA allows for control modifications or drive design updates versus an application-specific integrated circuit (ASIC) which, if used, requires locking-in the design. The speed-control loop, which comprises the rest of DTC's functional blocks, is described in Appendix 1.

Performance indicators
DTC provides customers superior performance features over competing drive methods. Being a "sensorless" (speed estimation instead of measurement) control method from its foundations, costly motor speed or position feedback devices are not needed in most cases. Depending on motor size, static speed accuracy as low as ±0.1% is typically obtained. For higher demand applications, a DTC drive equipped with a standard encoder (1,024 pulses/rev) typically achieves ±0.01% speed accuracy.

Dynamic speed accuracy (time integral of speed deviation under a 100% load impact) is 0.3–0.4 %sec with typical equipment driven by the motor. Using an encoder, speed accuracy typically improves to 0.1 %sec and matches servo drive accuracy.

Torque response time to a 100% torque reference step is typically 1–5 milliseconds (ms), which approaches the motor's physical limit. Torque repeatability under the same reference command is typically as low as 1% of nominal torque across the drive's speed range. As for control at very low motor speeds, DTC provides 100% torque down to zero speed—without (or with) speed feedback, as well as a position control feature when using an encoder. The foregoing performance values refer specifically to induction motor control.

Beyond induction motors
DTC was originally developed for AC induction motors because of their popularity in myriad industrial and commercial applications. No doubt the "workhorse role" of induction motor technology will prevail over the foreseeable future. However, in the quest for higher power density and evolving international efficiency regulations other motor topologies are drawing renewed interest.

For example, standard IEC 60034 part 30 (Ref. 3) defines international efficiency (IE) classes, the highest of which — IE4 (super-premium efficiency) — is becoming difficult to meet for induction motors. An even higher, IE5 class has been proposed, although without further specification, in the latest approved 2nd edition of IEC 60034-30.

The good news is that DTC is equally applicable to other motor types, such as permanent magnet (PM) synchronous and synchronous reluctance (SynRM) motors. The main difference occurs during motor starting. Unlike induction motors, PM synchronous motors and SynRM motors require the control system to estimate rotor position at startup from the location of poles in the rotor, if no position sensor is used.

In these motors, absence of rotor windings and the slip-speed effect inherent to induction motors substantially reduce losses. Thus resulting efficiency gains are achieved. Moreover, synchronous operation means that excellent speed accuracy is achieved even without a speed or position sensor. Thus, a sensor can be omitted in most cases except in applications such as winches and hoists that require non-zero torque at standstill for long periods.

Permanent magnets are commonly mounted on the rotor's outer surface. However, a PM synchronous motor variant, the internal PM (IPM) rotor design, embeds the magnets within the rotor structure. An extra reluctance torque component generated in IPM synchronous motors makes them attractive for high-demand applications.

In addition, embedded magnets create very pronounced rotor-pole saliency, which allows accurate speed estimation and enhances DTC's basic sensorless operating mode. Due to high torque to motor size ratio, a simpler system drive train may be possible when using PM synchronous motors. For example, a direct-driven low speed PM motor can eliminate the gearbox in packaging machines.

Numerous applications for PM synchronous motors include machine tools, marine propulsion, wind turbines (generators), and cooling tower fans for electric power plants.

One partly economic drawback of PM synchronous motors is their reliance on so-called rare-earth (RE) magnet materials for best performance. Most used of the RE materials is the compound neodymium-iron-boron. Recent pricing and global supply issues of RE materials have created serious concern for equipment manufacturers that reaches well beyond electric motors (Ref. 4). Here is where synchronous reluctance motors provide an alternative.

ABB has included a line of SynRM motor and drive packages in its product offerings, in part, to anticipate possible rare-earth magnet supply problems (Ref. 5). Synchronous reluctance motors have a stator structure similar to induction motors. However, the rotor consists of axially stacked steel laminations shaped to provide a cross section with four poles — alternate high permeable (iron) axes and low-permeable (air) axes. Importantly, no magnets are needed in the rotor.

Typical SynRM motor applications include driving pumps and fans, where there is a quadratic torque (and thus cubic power) relationship with speed (see below).

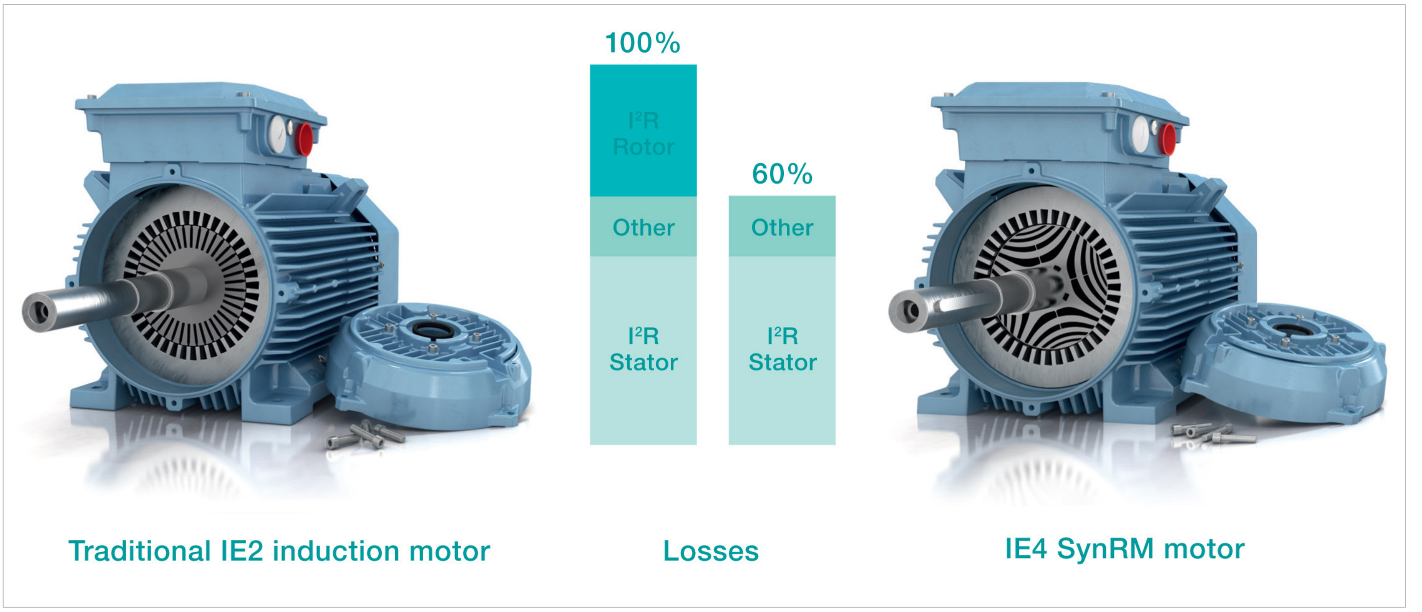


Figure 2: The new synchronous reluctance motor utilizes new rotor design and is optimized for VSD operation. The technology cuts down rotor losses, improves reliability and enables either smaller and lighter designs (high output SynRM motor-drive packages) or extremely high efficiency (IE4 SynRM motor-drive packages).

Versions of DTC modified for PM synchronous and SynRM motors have been implemented by ABB. Important to customers is that ABB's latest DTC drives allow easy upgrading of an existing induction motor application to run a PM synchronous or SynRM machine and benefit from enhanced performance.

In addition to high dynamic motor control, DTC drives — combined with any of the efficient motor technologies mentioned above — offer great energy savings potential for the large number of variable-speed pump and fan applications.

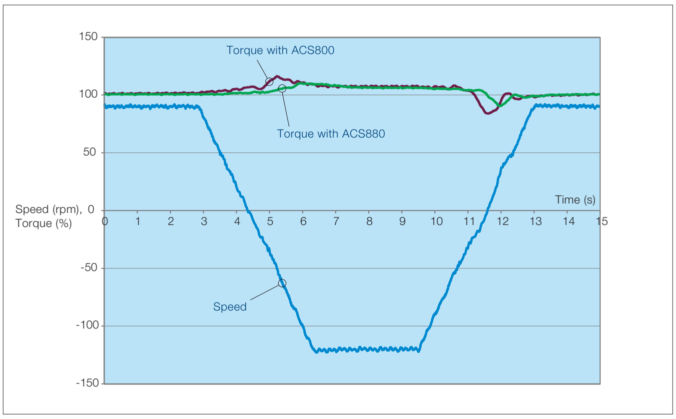
This can be visualized from so-called "affinity laws" associated with pumps and fans that relate variables such as flow volume, pump speed, pressure, power, etc. For example, pump speed versus power has a cubic relationship, meaning that when a process sequence allows the pump to run at ½ of full speed, only 1/8 of full power is required. Of course, reduced motor and drive efficiencies at partial loads would lower the "system" efficiency but overall less energy will be used.

Recent performance measurements

In mid-2012, ABB conducted a series of measurements to ensure that the continuing improvements in DTC technology are keeping ABB AC drives at the top of performance. Significant results of the test measurements are summarized here.

Torque stability near zero speed (ACS800 vs. ACS880 drives)

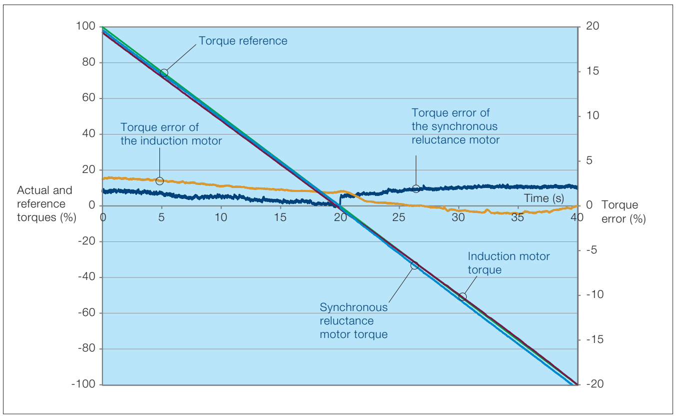
Graph 1 compares the torque control accuracy of ABB's ACS800 and new ACS880 industrial drives in sensorless (open-loop) operating mode. In the tests, the drives run a 15 kW, four-pole induction motor with its rated torque reference and with the load machine controlled to make slow speed reversals near zero speed. (Note that 90 rpm is about 6% of the nominal speed of the motor).



Graph 1. Both drives have remarkable sensorless control ability to operate long periods in the near zero speed range. However, the new ACS880 has less deviation from the torque reference and thus can provide better motor control performance than ACS800.

Torque accuracy during ramping (induction motor vs. SynRM motor)

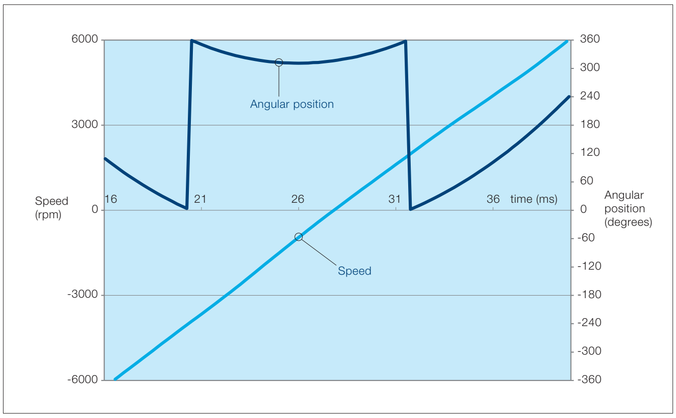
Graph 2 shows the ACS880 drive's sensorless torque control accuracy compared for two types of 15 kW motors tested (at 50% of rated speed) — a four-pole induction motor and a synchronous reluctance motor.



Graph 2. For both motor types the torque deviation from reference is held to only a few percent of rated torque by DTC, both in motoring and braking mode. Maximum torque error is slightly less for the tested synchronous reluctance motor than for the induction motor.

Servo-class dynamic performance

Graph 3 indicates measured speed and angular position of a tested 1.5 Nm, 6,000 rpm permanent magnet synchronous motor (with 0.57 kg cm2 rotor inertia) during fast speed reversal from - 6,000 rpm to + 6,000 rpm in less than 25 milliseconds (ms). This is very close to the theoretical limit you can achieve with the torque limit set to twice the rated torque. Theoretical limit refers to the motor's mechanical time constant of 24 ms, which is the time needed to accelerate the motor from zero to nominal speed using nominal torque.



Graph 3. Although not a servo drive, ACS880 drive with DTC can change motor speed very fast and accurately both with closed loop and sensorless motor control modes. One performance measure is torque accuracy during extremely fast acceleration, as determined by comparing measured acceleration time to the motor's mechanical time constant. Acceleration times of 24.4 ms (100% torque) and 12.1 ms (200% torque) were measured in open loop mode, compared to 24 ms and 12 ms, respectively, which correspond to acceleration times for absolute torque accuracy.

Wider applications

Another aspect of the DTC story is its expansion beyond applications for which the technology was created. Demanding, high-dynamic applications were targeted early on, because they could justify costly initial software developments and available microprocessors. That scenario has changed greatly. Control system software has been amortized over the growing sales volume of AC drives and economically justified to implement in drives for more standard applications. High-performance DSPs also have become common and affordable.

Ability to respond rapidly to changes in process variables such as pressure, tension, or position using exceptional speed and torque control dynamics has made DTC attractive to wider industrial and process applications.

DTC can provide protective functions to connected machinery or the motor itself (see more in Appendix 2). Tight torque control can optimize tuning of the speed controller to damp out torsional vibrations.

DTC has also been applied to reduce harmonic distortion from the drive, hence improving power line quality. Low-frequency harmonics can be mitigated in the line currents by replacing the diode rectifier of an AC drive with a DTC-controlled IGBT supply unit (ISU). The LCL filter of the ISU removes high-frequency harmonics and provides additional filtering for the grid. In many cases even voltage distortion in the grid may be reduced by using a drive with an ISU. Moreover, with an ISU it is possible to feed the braking energy back to the grid. Thus in applications that require frequent deceleration energy cost savings can be achieved.

DTC today, tomorrow

Resting on firm theoretical foundations, direct torque control has shown a continuum of hardware and software improvements over its more than 25-year lifespan. A DSP-based technology from the start, DTC has overcome limitations of the early processors for speedy calculation of control algorithms. DSP limitations also restricted the drive's maximum switching frequency in the past, hence its output frequency. DTC relies on rapid switching of the drive's transistors for optimal performance and timely updating of motor model parameters. Powerful processors are now readily available.

Today, DTC drives have higher output frequency, allowing motors to run faster. This is an important feature for certain applications, such as test benches and machine tools. ABB drives running induction motors in an industrial application typically provide 2-4 kHz switching frequencies that maximize the efficiency, while ABB machinery drives powering PM synchronous motors typically supply 5-8 kHz switching to run the motors with best possible dynamics.

Software has been another key element behind the success of DTC. Improvements and updates include redesigned and optimized code for the whole control system (from customer interface to motor shaft) to further enhance drive response time and performance.

Motor models also receive regular updating. Control algorithms are periodically analyzed and the resulting improvements are thoroughly verified through laboratory testing with different motors. This can include investigating some new features or control ideas with an existing or modified motor; or looking at some special customer application requirement.

After an improvement has been confirmed, it may be incorporated into the next software release as part of normal design flow. Each software release is likely to introduce some new features or better control performance. If the solution to a customer problem has enough general appeal, it could likewise become part of a later software version.

A more robust motor identification algorithm has also been incorporated into DTC. Enabled by the drive's more powerful microprocessor, this software improves motor identification at standstill. As mentioned earlier, the identification algorithm automatically finds a driven motor's correct properties for optimal control tuning during drive commissioning — even if name plate values are not known or prove inaccurate.

ABB has focused its respected drive engineering heritage and invested substantial resources on the development of direct torque control.
Today, DTC remains a living technology, having built a continuum of advances atop a solid foundation. As a result, DTC has grown into a brand offering larger than "torque control"—incorporating intelligent user interfaces, drive maintenance and diagnostic features, and higher level software functions, among other features.

Looking ahead, ABB intends to follow the same path with its enduring DTC technology. Customers of ABB drives can be confident that the benefits of direct torque control technology in which they invest today will continue for the long term.

For help with any technical terms in this release, please go to: **www.abb.com/glossary**

References

1) Kazmierkowski, M.P., et al, “High-Performance Motor Drives,” IEEE Industrial Electronics Magazine, Sept. 2011, Vol. 5, No. 3 (p. 6-26).

2) “Direct Torque Control Comes to AC Drives,” Control Engineering, March 1995, Vol. 42, No. 3 (p. 9).

3) Standard IEC 60034-30, Ed.2: Rotating electrical machines - Part 30: Efficiency classes (IE-code), International Electrotechnical Commission. www.iec.ch

4) “Rare-earth magnet supply and cost issues,” Control Engineering, Aug. 2011. http://www.controleng.com/index.php?id=483&cHash=081010&tx_ttnews[tt_news]=55091

5) “Super premium efficiency synchronous motor and drive package: Taking energy efficiency to a new level,” ABB Low-voltage AC motors and drives brochure (2011).

Appendix 1
The rest of DTC's function blocks story

The main article summarized the workings of DTC's torque control loop. Here is a brief description of the associated speed-control loop. These two loops are integrated and function as a holistic unit. Separate descriptions are intended only to simplify understanding of the block diagram. So here's the rest of the "walk around the block."

Three main elements comprise the speed-control loop: the speed controller block itself and separate torque reference and flux reference controllers. The speed controller includes a PID (proportional-integral-derivative) controller and an acceleration compensator. Input to the speed controller is the error found when comparing an external speed reference signal and the actual speed signal from the adaptive motor model — part of the torque and flux control loop (see main article). This error signal, calculated from the speed reference change and the derivative term, goes to both the PID unit and acceleration compensator. Their combined outputs become the speed controller's output.

That output is sent to the torque reference controller where the speed control's output is regulated by preset torque limits and DC bus voltage. An external (or user's) torque reference signal can also be used instead of the speed control as an input for this block. Torque reference controller output is the so-called "internal torque reference" that goes to the torque comparator block in the torque and flux control loop.

Similarly, the flux reference controller provides an "internal flux reference" to the flux comparator block (part of torque and flux control loop). This signal is an absolute stator flux value, which DTC can appropriately regulate and modify to obtain useful inverter functions. Examples include energy optimization — which minimizes motor losses and cuts motor noise — and flux braking, which by temporarily increasing the motor losses allows faster motor braking when no special braking resistor is used.

Appendix 2
Customer benefits of DTC

AC drives with direct torque control (DTC) offer various features that benefit specific user applications. Customers in industries such as papermaking, web materials production, and extruder machines for film materials can expect DTC's rapid torque response and accurate torque control to translate into more uniform product quality and higher process output. Torque linearity becomes a further advantage for constant tension winding of the rolls needed in these applications.

Cost reduction for conveyors and transfer lines, as well as packaging machines, is possible because in many applications, there is no need for encoders or other motor speed/position feedback devices. Besides initial cost, encoders require maintenance and accuracy checks over time.

Moreover, for packaging machine manufacturers it may be possible to eliminate a mechanical brake in a section of the machine due to torque control down to zero speed provided by DTC — and an ability to hold 100% torque at zero speed. Note, however, that a speed or position sensor is required if a braking (generating) torque is required close to zero speed for more than few seconds. A braking resistor or an IGBT supply unit is also needed in the drive if high deceleration is required.

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Ability to closely monitor the state of the motor can benefit still other customer applications. Minimizing overloads and shock loads becomes possible through timely detection of connected system parameter changes and DTC's fast control response. The concept can be extended to driven-system failure detection. For example, sudden torque loss might indicate a conveyor belt breakage —or higher than normal torque needed to produce some output may indicate binding or abnormal wear in the machine — which requires appropriate user response to prevent further damage.

As mentioned in the main article, drives can be used as a part of process diagnostics. This becomes beneficial to customers with process control applications since changes in driven-system variables such as pressure, tension, or position can be related to motor torque and speed characteristics. Altered motor characteristics can be an early warning of unwanted process changes.

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