DTC: A motor control technique for all seasons

直接转矩控制：不断发展的电机控制技术

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White paper

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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.

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).

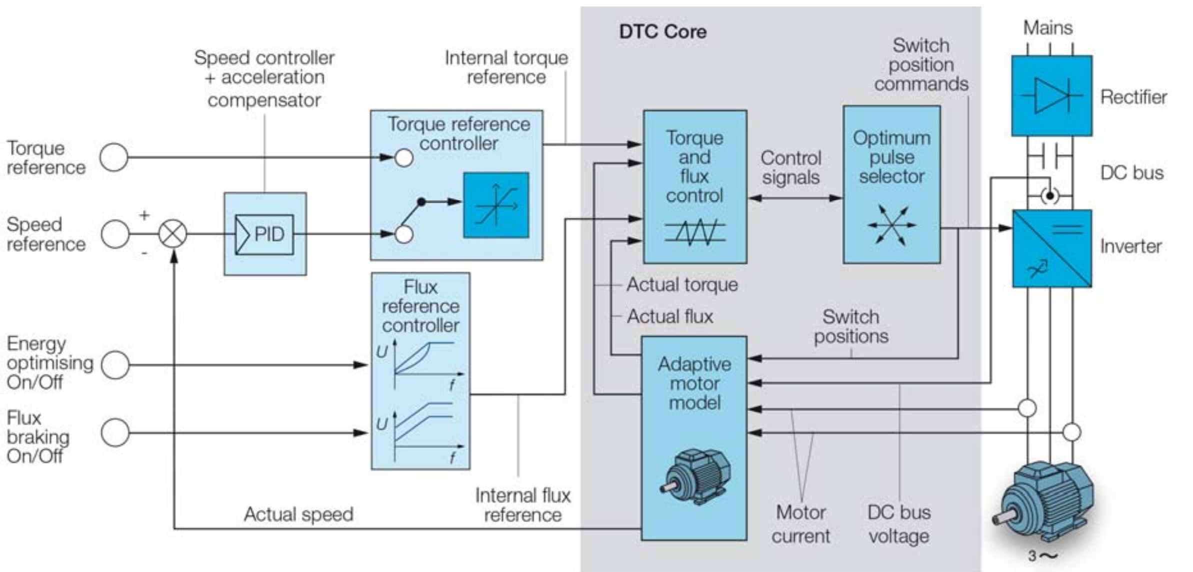


Figure 1: DTC's operation principle.

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.

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).

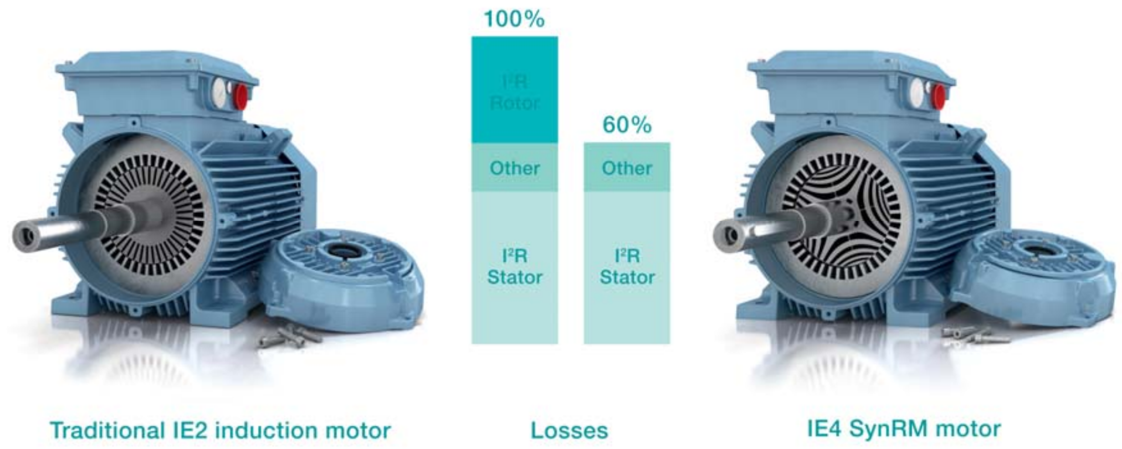


Figure 2: The new synchronous reluctance motor utilizes new rotor design and is optimized for VSD operation. The technology cuts down rotor losses, improves reliability and enables either smaller and lighter designs (high output SynRM motor-drive packages) or extremely high efficiency (IE4 SynRM motor-drive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

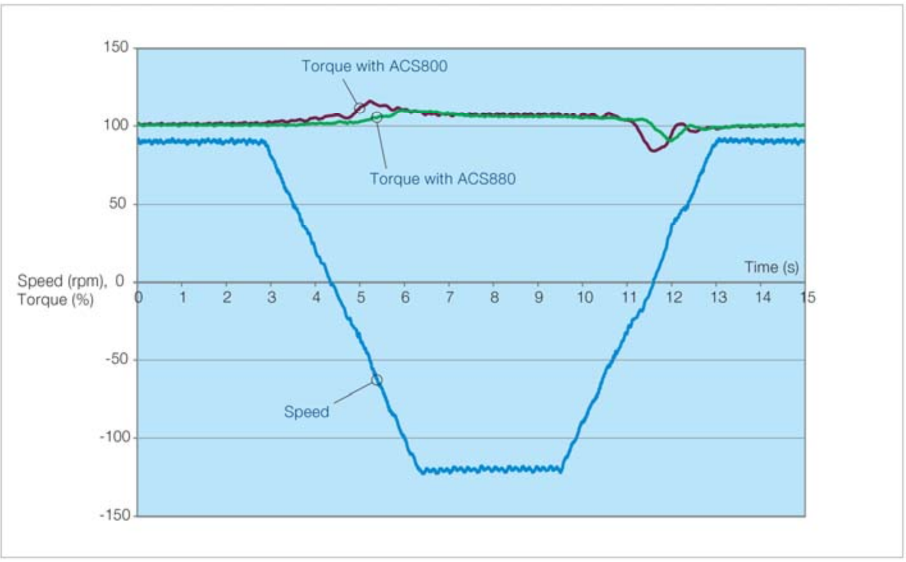
In addition to high dynamic motor control, DTC drives — combined with any of the efficient motor technologies mentioned above — offer great energy savings potential for the large number of variable-speed pump and fan applications. This can be visualized from so-called "affinity laws" associated with 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)

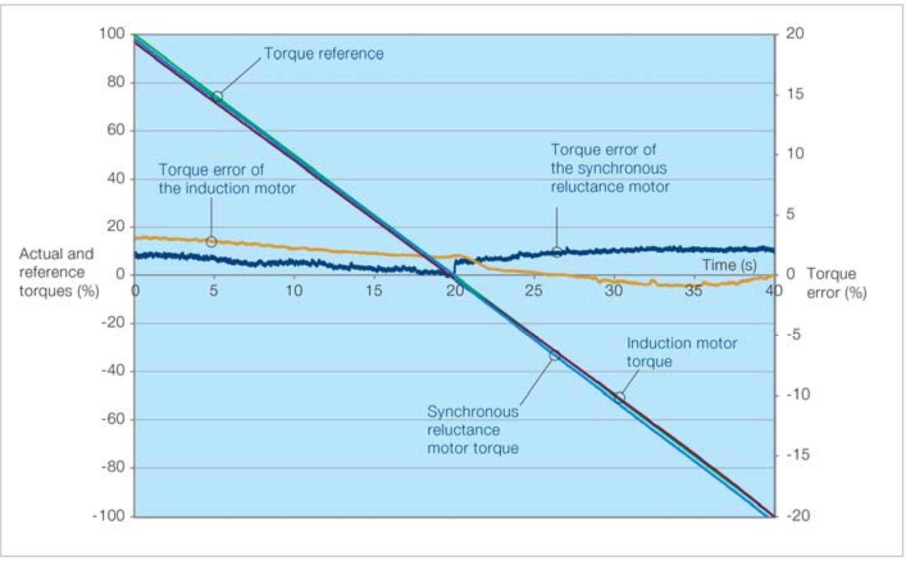
Graph 1 compares the torque control accuracy of ABB's ACS800 and new ACS880 industrial drives in sensorless (open-loop) operating mode. In the tests, the drives run a 15 kW, four-pole induction motor with its rated torque reference and with the load machine controlled to make slow speed reversals near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

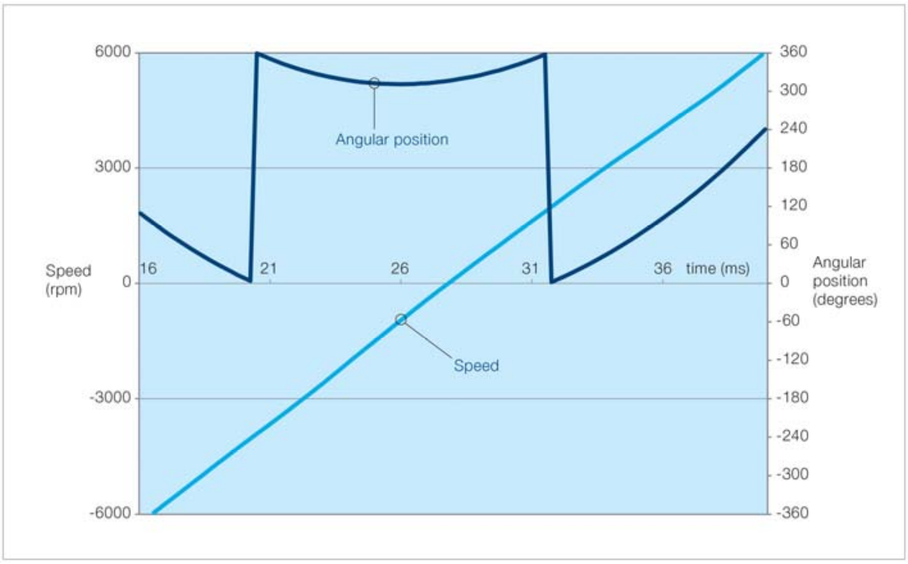


Graph 2. For both motor types the torque deviation from reference is held to only a few percent of rated torque by DTC, both in motoring and braking mode. Maximum torque error is slightly less for the tested synchronous reluctance motor than for the induction motor.

White paper

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 cm^2 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

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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.

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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使电机速度和转矩与所驱动负载的实际需求相匹配，调速变频器（VSD）通过这种方式让电机获得无可比拟的性能，并达到显著节能的效果。市场上的大多数变频器依赖于调节电机电压和频率的调制器，但这会造成处理控制信号的延迟。与此相反，ABB 高端变频器采用直接转矩控制（DTC）技术，这项源自 ABB 的创新技术可大大缩短电机转矩响应时间。此外，DTC 还能带来更多优势，并已发展成为一个技术品牌，涵盖传动硬件、控制软件和许多系统级功能。

电机常常处于现代化生产的最前沿——无论是金属制品加工线、机器人生产线，还是在楼宇和办公自动化系统中。我们如今所看到的电机，无疑受益于电气材料、生产效率和分析工具的发展。但是，就异步（或感应）交流电机而言，其设计原则 100 多年来一直保持不变。这些电机在当今应用中的出色表现源自于现代电子控制装置——调速变频器（VSD），以及精确的电机模型——其复杂的控制算法可由高性能数字信号处理器迅速执行。此外，调速变频器的发展，使得对永磁同步电机和同步磁阻电机等全新交流电机技术的利用成为了可能。

最初，变频器研发人员关注的是直流电机。直流电机拥有比交流电机更长的历史，采用简单的速度和转矩控制方式。不过，更高的电机成本、机械换向器的复杂结构及电刷维护问题，也同时是直流电机存在的问题。

交流感应电机具有更简单、坚固的结构，成本更低，并且维护问题也更少，这些特点令其获得广泛应用，在全球各地拥有庞大的客户群。但是，对感应电机的控制是颇为复杂的。早期的交流传统难以进行精确的速度控制，特别是转矩控制。自然而然，早期设计人员的目标就是，通过利用电枢电流，在交流传动中模拟直流传动对电机转矩的简单控制。随着时间的推移，交流传动的设计不断发展，实现了动态性能的改善。（最近值得注意的对各种可用交流传动控制方法的讨论，见参考 1。）

20 世纪 80 年代，大多数高性能 VSD 采用的是脉冲宽度调制（PWM）方式。不过，利用调制器会导致延迟，以及在执行电机控制命令时需要过滤测得的电流，因而降低了电机转矩响应速度。

与此相反，ABB 采取不同的方式来实现高性能交流电机控制。专为高要求应用而设计的 ABB 交流传动，采用了一项创新技术，该技术被称之为直接转矩控制（DTC）。这种方法采用直接控制电机转矩的方式，而不是尝试像直流传动那样控制电流，这意味着能更准确地匹配驱动系统的负载要求。DTC 源于 ABB 公司，并在 20 世纪 80 年代获得专利，利用 DTC，就不必采用额外调制器，从而实现了接近理论最大值的控制动态性能。ABB 于 1995 年将采用直接转矩控制技术的首个交流工业传动推向市场（见参考 2）。

DTC 早在 1995 年就已是一项领先技术，但是，随着处理器计算能力、通信接口、应用编程等领域的发展，现在其具备更高性能，可针对广泛应用进行更优的电机控制。

为什么使用 DTC？

出色的转矩响应只是 DTC 的一个特点。该技术可为客户带来更多优势，包括：

- 在 95% 的应用中无需电机速度反馈或位置反馈。因此，可避免安装费用高昂的编码器或其他反馈装置。
- DTC 控制可用于不同型号的电机，包括永磁电机和同步磁阻电机。
- 低速状态下精确的转矩和速度控制，零速下可保持完全启动转矩。
- 出色的转矩线性性能。
- 高的静态和动态速度精度。
- 没有预设的开关频率。最佳晶体管开关针对每个控制周期来确定，从而让传动更易于匹配驱动负载的要求。

此外，DTC 还涵盖软件、用户界面、维护和系统级功能。

顾名思义，DTC 力图直接控制电机磁通和转矩，而不是像直流传动和矢量控制的交流传动那样试图间接控制这些变量。独立的转矩控制回路和速度控制回路构成完整的 DTC 系统，但它们以集成方式一起工作（见图 1，DTC 逻辑框图）。

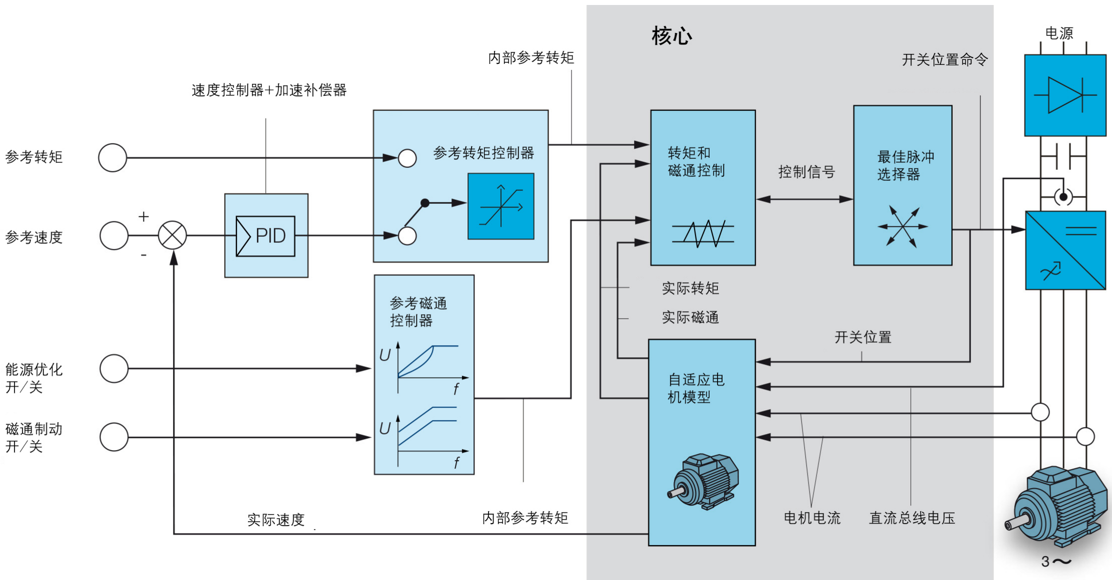


图 1：DTC 的工作原理

DTC 的核心是转矩控制回路，其中复杂的自适应电机模型应用高级算法来预测电机状态。主要控制变量（定子磁通和电机转矩）是利用电机相电流和直流总线电压测量值以及功率开关晶体管的状态，依照电机模型进行准确估计的。电机模型也计算轴速度。温度补偿有助于在不带编码器的情况下提高计算精度。

对变频器进行调试时，在电机识别过程中，其他电机参数会自动输入自适应模型。许多情况下，可在不旋转电机轴的情况下进行相应的模型参数识别。如果要进行电机模型微调（只有少数高需求应用才有这种需要），电机必须处于运行状态，但只是较短时间，并且无需负载。

定子电阻（电压降）是用于估算电机磁通所需的唯一且容易测量的参数。然后，电机转矩可通过这种方式计算：估算的定子磁通和定子电流矢量的向量积。尽管定子电阻是产生估算误差的主要原因，但其影响会随着不断增加的电机速度和电压而变小。因此，DTC 在较宽速度范围内具有出色的转矩精度。此外，DTC 通过先进方法最大限度减小电机低速时的估算误差。

来自电机模型的输出信号（代表实际定子磁通和电机转矩），分别传输至磁通比较器和转矩比较器（见图 1），这些独立的控制单元将输入值与参考值加以比较。20 世纪 90 年代中期，第一批 DTC 传动就已经利用高功率数字信号处理器（DSP）每隔 25 微秒时间来执行这些功能。在最新一代控制装置中，时间间隔被缩短至 12.5 微秒，从而进一步提高了控制性能。每个比较器力图使其各自磁通或转矩矢量幅度保持在围绕参考值的回差区间内。DTC 无过冲的快速转矩响应，部分源于能够使这些矢量波动减至最低限度。 电机异常响应也源于以相同高循环率更新自适应电机模型的 DSP 控制算法。

磁通和转矩误差，即估算值与参考值之差，以及定子磁通矢量的角位置（或扇区），用于计算磁滞控制器中的磁通和转矩状态。然后，这些状态值成为最佳脉冲选择器的输入来选择最佳电压矢量（见图 1）。这样，每个控制周期最适当的信号脉冲可被发送至逆变器中的电源开关，以获得或保持精确的电机转矩。一种可编程逻辑，即所谓的现场可编程门阵列（FPGA），协助 DSP 确定逆变器开关逻辑及其他任务。FPGA 支持对控制改造或传动设计更新，而使用专用集成电路（ASIC）需要锁定设计。包含 DTC 其他功能块的速度控制回路在附录 1 中有所描述。

性能指标

DTC 的优异性能超过其他传动控制方法的性能。作为“无需传感器”（速度估算代替测量）控制方法，大多数情况下并不需要费用高昂的电机速度反馈或位置反馈装置。根据不同的电机尺寸，通常可获得低至 ±0.1% 的静态速度精度。对于有更高要求的应用，配备标准编码器（1,024 个脉冲 / 转）的 DTC 传动，通常能达到 ±0.01% 的速度精度。

在电机驱动典型设备的情况下，动态速度精度（100% 转矩阶跃下的速度偏差时间积分）为 0.3-0.4 % 秒。利用编码器，速度精度通常可提高到 0.1 % 秒，达到伺服传动精度。

转矩响应时间（达到 100% 参考转矩）通常为 1-5 毫秒，接近电机的物理极限。相同参考命令之下的转矩可重复性，在整个传动速度范围通常低至额定转矩的 1%。至于在电机速度非常低时的控制，DTC 可以零速提供 100% 转矩——没有（或有）速度反馈，以及使用编码器时具备位置控制功能。上述性能值特指感应电机控制。

感应电机以外的应用

DTC 起初针对交流感应电机而研发，这是因为交流感应电机在众多工商业应用中的日益普及。毫无疑问，感应电机技术的“主力角色”会在不久的将来得以体现。但是，为了提高功率密度和制定国际效率规范，其他电机拓扑也引起了业界新的兴趣。

譬如，标准 IEC 60034 part 30（参考 3） 定义了国际效率（IE）等级，其最高等级 IE4（超高效率）正在变得感应电机难以满足其要求。在最新通过的第二版 IEC 60034-30 中已经推出更高的 IE5 等级，但尚未有进一步的规范。

可喜的是，DTC 同样适用于其他电机类型，比如永磁（PM）同步和同步磁阻（SynRM）电机，主要区别是在电机启动期间。与感应电机不同的是，如果未使用位置传感器，永磁同步电机和同步磁阻电机要求控制系统估计启动时的转子位置。

在这些电机中，没有感应电机的转子绕组和滑速影响，可大大减少损耗，因而效率得以提高。此外，同步运行意味着，即便没有速度或位置传感器也能实现极好的速度精度。因此，大多数情况下传感器可省略，但是，要求非零转矩的长时间处于静止状态的绞车和起重机等应用除外。

永久磁铁通常安装在转子的外表面。不过，永磁同步电机的变体，即内部永磁（IPM）转子设计，将磁铁嵌入转子结构内。永磁同步电机所产生的一个额外磁阻转矩分量，使其对于高需求应用具有很大吸引力。此外，嵌入的磁铁会产生非常明显的转子极凸起，可实现精确的速度估算，并增强 DTC 的无传感器运行模式。

由于高转矩电机尺寸比，在使用永磁同步电机时就可以使用更简单的系统传动。譬如，低速直驱永磁电机可使包装机不必使用齿轮箱。

永磁同步电机的众多应用包括：机床、船舶推进装置、风轮机（发电机）和发电厂的冷却塔风机。

永磁同步电机在经济方面的一个缺点是，依赖所谓的稀土磁铁材料来实现最佳性能。所用大多数稀土材料都是钕 - 铁 - 硼的化合物。稀土材料最近的价格和全球供应问题引起了设备生产商的深切关注（见参考 4）。而同步磁阻电机提供了另一种选择。

ABB 提供一系列同步磁阻电机和变频器的打包方案，以应对可能的稀土磁铁供应问题（见参考 5）。同步磁阻电机具有类似于感应电机的定子结构。但是，转子由轴向叠片组成，横截面呈四极——高磁导性铁轴和低磁导性空气轴交错布局。重要的是，转子中无需磁铁。

典型的同步磁阻电机应用包括：泵和风机，其速度与扭矩为平方关系（与功率为立方关系）（见下图2）。

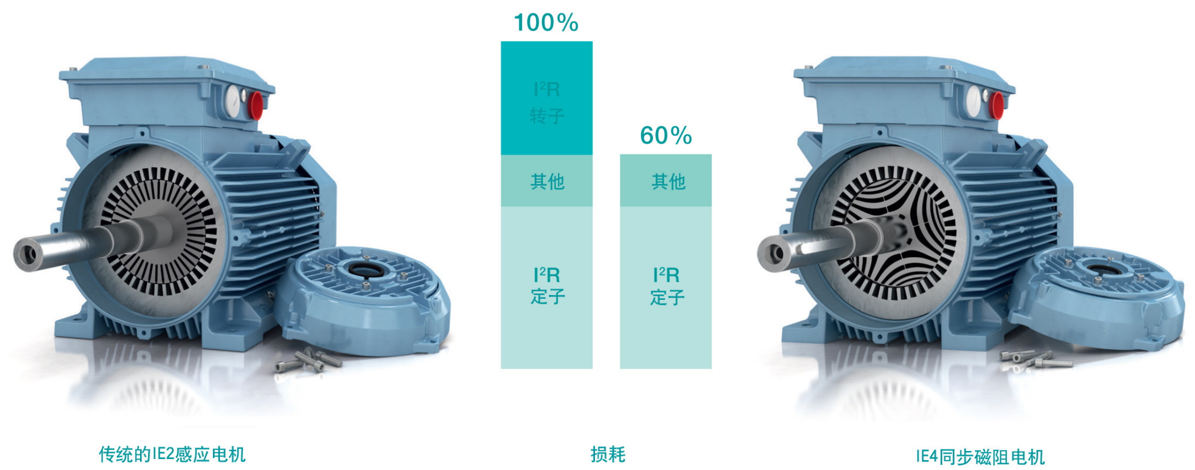


图 2：新型同步磁阻电机利用全新转子设计，并针对变频器运行进行了优化

新型同步磁阻电机利用全新转子设计，并针对变频器运行进行了优化。这项技术可降低转子损耗，提高可靠性，并能实现更小巧的轻型设计（高输出同步磁阻电机和变频器打包方案）或极高的效率（IE4 同步磁阻电机和变频器打包方案）。

ABB 已针对永磁同步电机和同步磁阻电机对 DTC 进行了改良。对客户而言重要的是，ABB 最新的 DTC 变频器支持对现有感应电机应用的轻松升级，即除了可以控制感应电机外，还可以控制永磁同步电机或同步磁阻电机，从而使客户受益于更强大的性能。

除了更出色的动态电机控制外，DTC 变频器与上文提及的任何高效电机技术相结合，将为大量变速泵和风机应用带来巨大的节能潜力。这可以从与泵和风机相关的所谓“相似定律”中看出，涉及流量、泵速、压力、功率等变量。譬如，泵的速度与功率呈立方关系，意思是当泵机以全速的二分之一运行时，只需要全功率的八分之一。当然，部分负荷时电机和传动效率降低，会降低“系统”效率，但总体上能耗减少。

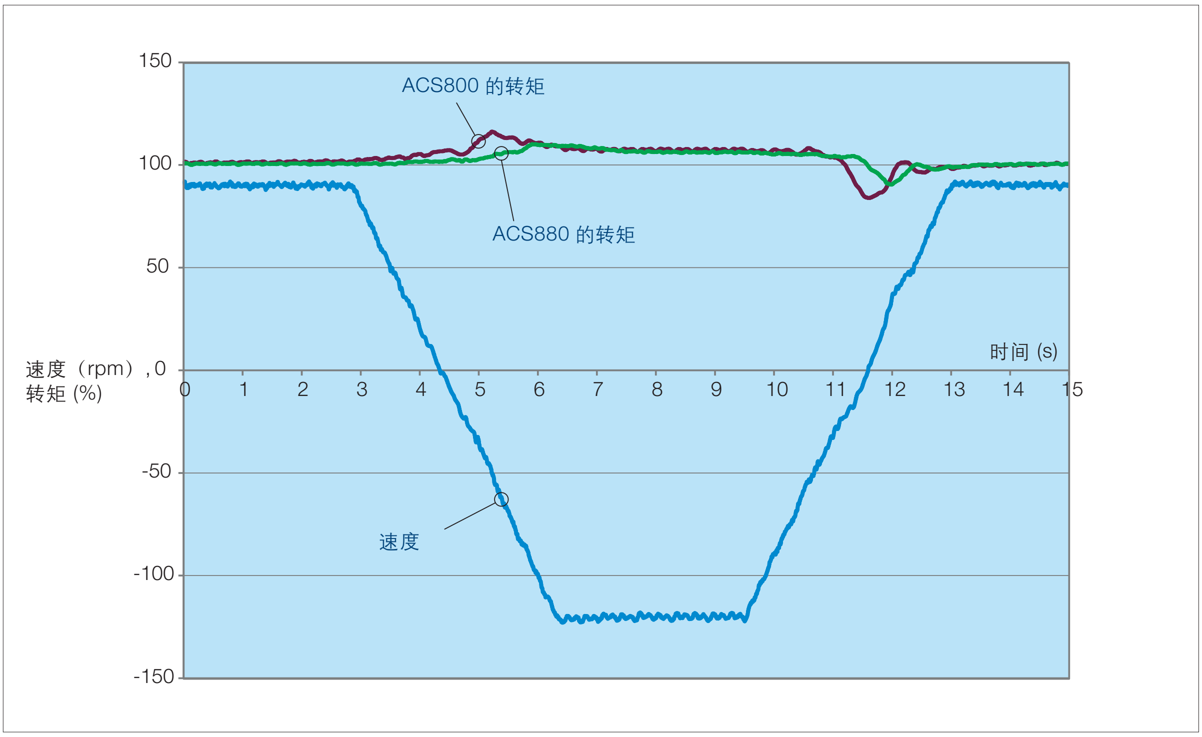
最新的性能测量

在 2012 年年中，ABB 进行了一系列测量，以确保对 DTC 技术的持续改进使得 ABB 交流传动保持最高性能。下面对试验测量的结果进行了总结。

接近零速时的转矩稳定性（ACS800 与 ACS880 传动相比较）

表 1 比较了 ABB ACS800 和新型 ACS880 工业传动在无传感器（开环）运行模式下的转矩控制精度。在测试中，传动以额定转矩参考值运行一台 15 kW 四极感应电机，并且使低速反向接近零速。（注意，90rpm 约为电机额定速度的 6%）。

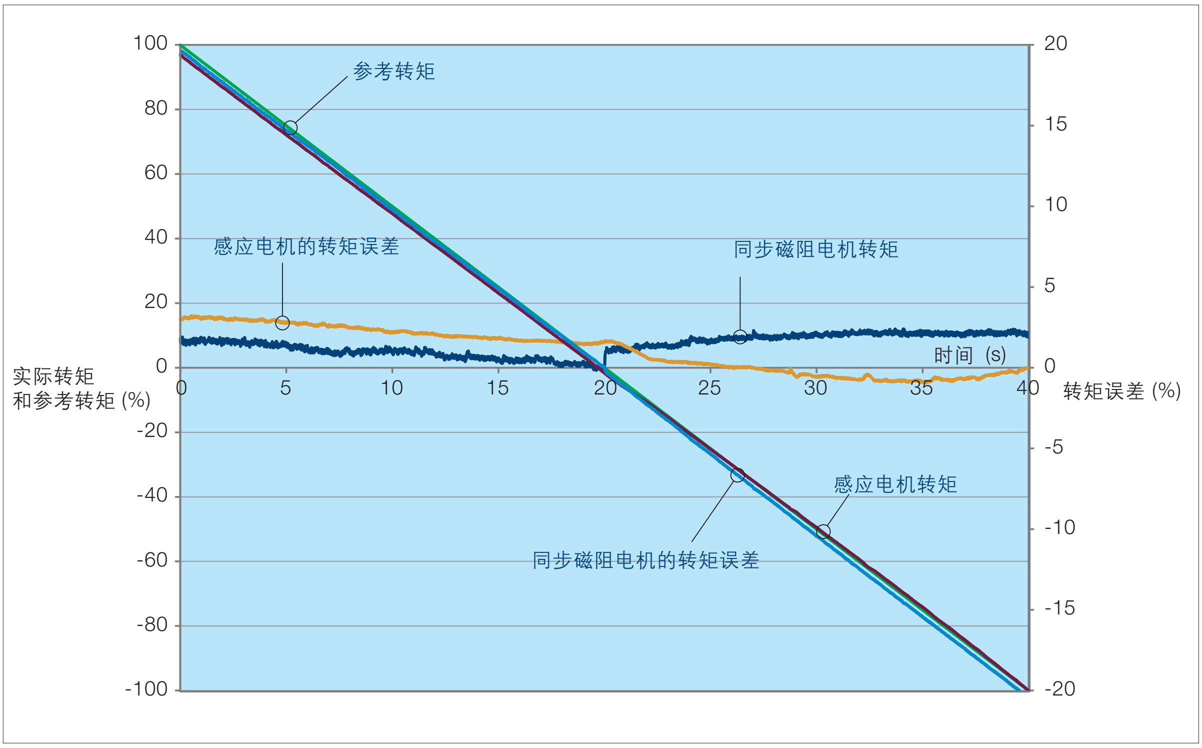
由表 1 可见，ACS800 和 ACS880 均具备非凡的无传感器控制能力，可以在近零速度范围内长时间运行。



但是，全新 ACS880 与转矩参考值的偏离更小，因而可以提供较 ACS800 更佳的电机控制性能。

升速期间的转矩精度（感应电机与同步磁阻电机相比较）

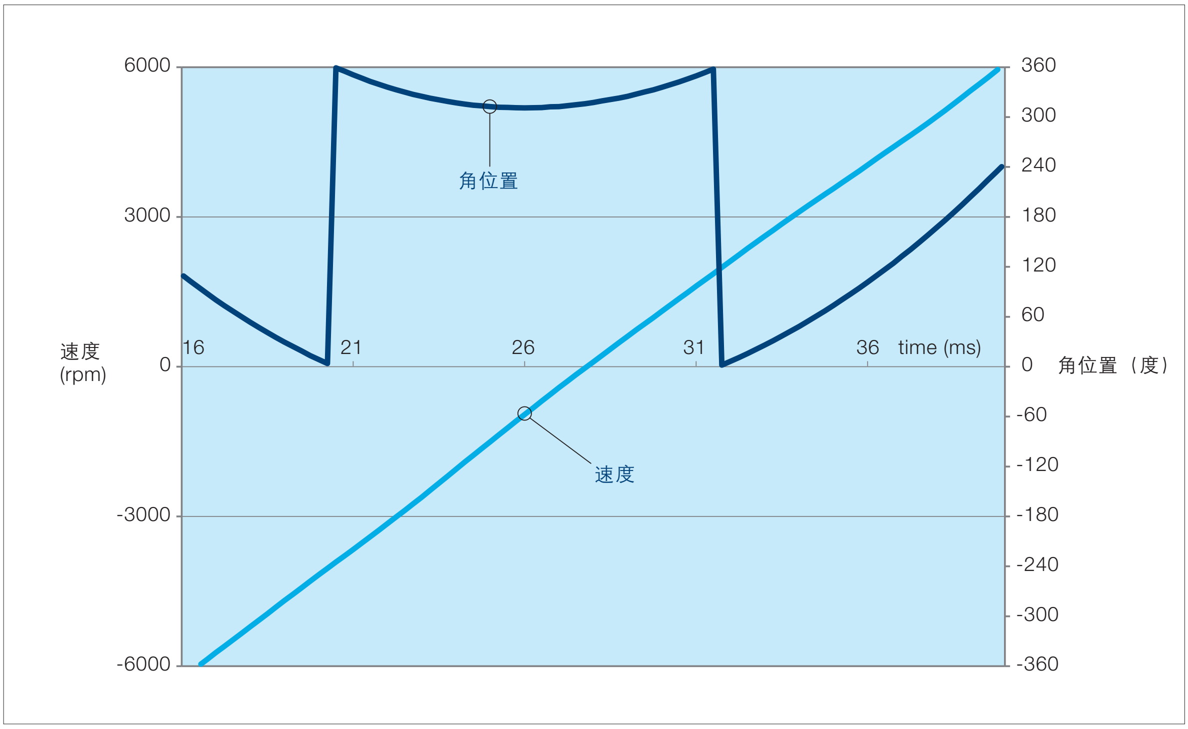
表 2 显示 ACS880 传动的无传感器转矩控制精度，对比测试的是两种 15 kW 电机（测试速度为额定速度的 50 %）：一台四极感应电机和一台同步磁阻电机。



由表 2 可见，对于这两种电机，在电机运行和制动模式下，通过 DTC，转矩与参考值的偏离只有额定转矩的百分之几。与感应电机相比，同步磁阻电机的最大转矩误差略小。

伺服级动态性能

表 3 指出测试的 1.5 Nm, 6,000 rpm 永磁同步电机（转子惯量 0.57 kg cm2）在从 - 6,000 rpm 到 + 6,000 rpm 快速换向期间在不到 25 毫秒时间内所测得的速度和角位置。这与将转矩限值设为额定转矩两倍情况下可实现的理论限值非常接近。理论限值指的是电机的机械时间常数 24 毫秒，这是利用额定转矩将电机从零加速至额定速度所需的时间。



由表 3 可见，尽管不是伺服传动，但是，配备 DTC 的 ACS880 传动可非常快速准确地改变电机速度，在闭合回路和无传感器电机控制模式下均如此。一个性能指标是在极快加速期间的转矩精度，这是通过对比测得的加速时间与电机的机械时间常数来确定的。开路模式下测得的加速时间 24.4 毫秒（100% 转矩）和 12.1 毫秒（200% 转矩），而绝对转矩精度的加速时间分别为 24 毫秒和 12 毫秒。

更广泛的应用

DTC 发展历史的另一个方面是，扩展到了该技术专用领域以外。早期针对的是高要求、高动态应用，因为它们初始软件开发和微处理器成本高昂。这种情况目前已经发生了很大变化。控制系统软件成本已在交流传动销量日益增长的过程中得以摊销，并且可以经济地在更多标准应用中实施。高性能 DSP 也已经变得比较常见，并在价格上比较实惠。

能够进行出色的速度和转矩控制，对压力、张力或位置等过程变量的变化能快速响应，这使得 DTC 对广泛的工业和过程应用也具有极大吸引力。

DTC 可为所连接机械或电机本身提供保护功能（见附录 2）。直接转矩控制可优化对速度控制器的调整，以减小扭转振动。

此外，DTC 还用于减小传动的谐波失真，从而提高电力线路的质量。通过利用 DTC 控制的 IGBT 供电单元（ISU）取代交流传动的二极管整流器，可使得线电流中的低频谐波得以缓和。ISU 的 LCL 过滤器去除高频谐波，并为电网提供额外的滤波。在许多情况下，通过利用配备 ISU 的传动，可减少电网的电压畸变情况。此外，借助 ISU，可以将制动能回馈到电网。因此，在需要频繁减速的应用中，可节省能源成本。

DTC 的现在和未来

直接转矩控制技术立足于坚实的理论基础，在超过 25 年的使用寿命期间持续进行软硬件改进。DTC 从一开始就基于 DSP 技术，克服了早期处理器需要控制算法进行快速计算的限制。DSP 限制在过去还限制了传动的最大开关频率，从而限制输出频率。DTC 依赖快速切换传动晶体管，以实现最佳性能，并对电机模型参数进行及时更新。目前能获得功能强大的处理器。

如今，DTC 传动具有更高的输出频率，让电机能以更快速度运行。这对于试验台和机床等应用而言是一个重要功能。在工业应用中驱动感应电机的ABB传动，通常提供2-4 kHz开关频率，以最大限度提高效率，而驱动永磁同步电机的 ABB 传动，通常提供 5-8 kHz 开关频率，以便以最佳动态性能驱动电机。

软件已是确保 DTC 成功应用的另一关键要素。其改进与更新包括，重新设计和优化整个控制系统的代码 （从客户界面到电机轴），进一步缩短传动响应时间，并提高性能。

电机模型还定期更新。定期分析控制算法，并通过对不同电机的实验室测试针对相应改进进行彻底验证。这包括核查现有或改良版电机的一些新特性或控制理念，或着眼于一些特殊的客户应用需求。

在确认改进后，可作为正常设计流程的一部分被纳入下一软件版本。每个软件版本很可能引入一些新功能或更佳的控制性能。如果针对客户问题的解决方法具有普遍吸引力，那么同样可能成为以后软件版本的一部分。

DTC 还采用了一个更强大的电机识别算法。在传动所配备的更强大微处理器的支持下，该软件可改进静止状态时的电机识别能力。如前所述，识别算法自动发现所驱动电机的正确属性，用于完成传动调试期间的最优控制调整——即便铭牌值未知或证明是不准确的。

ABB 沿袭其备受推崇的传动工程传统，并投入大量人力物力发展直接转矩控制技术。如今，DTC 技术仍充满活力，在坚实的基础之上得以不断发展。因此，DTC 已发展为不仅涵盖“转矩控制”内容，它还包括智能用户界面、传动维护和诊断特点，以及更高级别的软件功能等。

展望未来，ABB 打算一如既往地大力发展历久弥新的 DTC 技术。ABB 传动客户可以确信，他们现在所投资的直接转矩控制技术，其种种优势必将持续下去。

查找本文中的技术术语，敬请访问：www.abb.com/glossary

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参考文献

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).

附录 1：DTC 速度控制回路

正文描述了 DTC 转矩控制回路。下面是速度控制回路的简单描述。这两个回路集成在一起，作为一个整体运行。单独描述只用于简化对框图的理解。因此，下面对速度控制加以描述。

速度控制涉及三个部分：速度控制器、参考转矩控制器与参考磁通控制器。速度控制器包含 PID 控制器和加速补偿器。速度控制器的输入是，在对比外部速度参考信号和来自自适应电机模型的实际速度信号时发现的误差——这是转矩和磁通控制回路（见正文）的一部分。这个利用速度变化计算出来的误差信号传输到 PID 单元和加速补偿器。其组合输出成为速度控制器的输出。

该输出被发送至参考转矩控制器，其中速度控制输出由预设转矩限值和直流总线电压进行调整。外部（或用户的）参考转矩信号也可代替速度控制用作该功能块的输入，参考转矩控制器输出是所谓的“内部参考转矩”， 传输到转矩和磁通控制回路中的转矩比较器。

类似地，参考磁通控制器可提供传输至磁通比较器（转矩和磁通控制回路的一部分）的“内部参考磁通”。该信号是绝对定子磁通值，DTC 可相应地对其进行调节和修改，以获得有用的逆变器功能。示例包括，能源优化（可最大限度地降低电机损失并减少电机噪声）和磁通制动：在未使用特殊制动电阻时，通过暂时增加电机损耗，更快速地完成电机制动。

附录 2：DTC 带给客户的优势

配备直接转矩控制（DTC）的交流传动，可使特定用户应用受益匪浅。造纸、织物材料生产和生产薄膜的挤出机等行业的客户，可希望 DTC 的快速转矩响应和精确转矩控制转化为更统一的产品质量和更高的过程输出。对于这些应用而言，除了所需的恒定辊张力之外，转矩线性性能又是一大优势。

因为在许多应用中，无需编码器或其他电机速度 / 位置反馈装置 ，传送带以及包装机成本得以降低。因为除了初始成本之外，编码器还需要进行维护和精度检查。
此外，对于包装机制造商而言，通过低至零速的 DTC 转矩控制（在零速时保留 100% 转矩），有可能不使用机械制动。但要注意，如果要求制动（回馈）转矩有数秒以上时间接近零速，那么需要配备速度或位置传感器 。如果要求快速减速，那么，传动中还需要制动电阻或 IGBT 供电单元。

密切监控电机状态的能力，也能让使用其他应用的客户受益。通过及时检测所连接系统的参数变化和 DTC 快速控制响应，可以最大限度减小过载和冲击负载。这个概念可扩展到所驱动系统的故障检测。譬如，突然的转矩损失可能表明输送机皮带断裂；高于产生某些输出所需的正常转矩，可能表明机器的堵转或异常磨损——这些需要用户做出相应反应，以防进一步损坏。

诚如正文中所提及的，变频器可用作过程诊断的一部分。由于压力、张力或位置等传动系统中变量的变化与电机的转矩和速度特性息息相关，电机特性的报警功能可以预先提示意外的过程变化，因此客户可以从过程控制应用中受益。