Direct torque control in AC drive technology

Variable speed drives (VSDs) control the flow of energy from the mains to the process. Energy is supplied to the process through the motor shaft. Two variables describe the state of the shaft: torque and speed. We must control these quantities to control the flow of energy. In practice, either one of them is controlled and we speak of “torque control” or “speed control”. Speed and torque are determined by load in both torque and speed control mode.

DC motors were initially used as VSDs as they could achieve the required speed and torque with ease and without the need for sophisticated electronics. However, the evolution of AC VSD technology was aimed partly at combining advantages of the DC motor such as its fast torque response and speed accuracy with the ruggedness and economy of the maintenance-free AC motor.

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

Once field orientation is achieved, the DC motor’s torque is controlled easily.
by varying the armature current and by keeping the magnetising current constant. The advantage of DC drives is that speed and torque, the two main concerns to the end-user, are controlled directly through armature current: torque is the inner control loop and speed is the outer control loop (see Fig. 1).

Advantages
DC motor drives provide accurate and fast torque control, high dynamic speed response and are simple to control. They were initially used for variable speed control because they could easily and accurately achieve good torque and speed response. DC motors can produce a torque that is:

- Direct: the motor torque is proportional to the armature current: the torque can therefore be controlled directly and accurately.
- Rapid: torque control is fast: the drive system can have a very high dynamic speed response. Torque can be changed instantaneously if the motor is fed from an ideal current source. A voltage-fed drive still has a fast response as this is determined by the rotor’s electrical time constant only (i.e. the total inductance and resistance in the armature circuit).
- Simple: field orientation is achieved with a commutator-brush assembly. There is, therefore, no need for complex electronic control circuitry which would increase the cost of the motor controller.

Disadvantages
The disadvantages of the DC motor are reduced motor reliability, the need for regular maintenance, its high purchase price and the fact that it needs an encoder for feedback. While a DC drive produces an easily-controlled torque from zero to base speed and beyond, the motor’s mechanics are more complex and require regular maintenance.

AC motor drives
These machines are small and robust, of simple design, compact, require low maintenance and are not expensive to buy. AC variable speed drive technology was developed to combine advantages of the DC drive (such as fast torque response and speed accuracy) with those of the standard AC motor.

AC drives: flux vector control using PWM

Evolution of direct torque control
The flux-vector drive must know the spatial angular position of the rotor flux inside the AC induction motor to emulate the magnetic operating conditions of a DC motor, i.e. to perform the field orientation process. With flux vector PWM drives, field orientation is achieved by electronic means rather than with the mechanical commutator-brush assembly of the DC motor.

Information on the rotor status is obtained by feeding back rotor speed and angular position relative to the stator field by means of a pulse encoder. A drive which uses speed encoders is known as a "closed-loop drive".
The motors’ electrical characteristics are also modelled mathematically by means of microprocessors. The electronic controller of a flux-vector drive creates electrical quantities such as voltage, current and frequency which are the controlling variables. It feeds these to the AC induction motor through a modulator. Torque, therefore, is controlled indirectly. Advantages include good torque response, accurate speed control and full torque at zero speed.

Feedback and modulators are, however, needed and they are costly to buy. A feedback device is required to achieve high torque response and speed accuracy. This can also be costly and adds complexity to the traditional, simple AC induction motor. The modulator slows down communication between incoming voltage and frequency signals, resulting in the motor responding to this changing signal. The motor is mechanically simple but the drive is electrically complex.

**AC drives: direct torque control**

**Controlling variables**

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

With DTC, there is no modulator and no requirement for a tachometer or position encoder to feed back the speed or position of the motor shaft. DTC uses the fastest digital signal processing hardware available and a more advanced mathematical “understanding” of how motors work.

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

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

**VSDs: a comparison**

When noting the differences between the control blocks (see Figs. 1 – 4), the first observation is the similarity between the control block of the DC drive (Fig. 1) and that of DTC (Fig. 4). Both use motor parameters to control torque directly, but DTC has added benefits. These are the fact that no feedback device or external excitation is required, as well as all the benefits of AC motors.

As can be seen from Table 1, both DC and DTC drives use actual motor parameters to control torque and speed. With DTC, no tachometer or encoder is needed to feed back speed or position signals.

**DTC: basic control theory**

Fig. 5 shows the complete block diagram for direct torque control. The block diagram shows that DTC has two fundamental sections: the torque control loop and the speed control loop.

**Torque control loop**

- **Step 1:** two motor phase currents and the DC bus voltage are simply measured in normal operation, together with the inverter’s switch positions (see Fig. 6).
- **Step 2:** the measured information from the motor is fed to the adaptive motor model. The sophistication of this motor model allows precise data about the motor to be calculated. The motor model is fed information...
about the motor collected during a motor identification run before it operates the DTC drive. This is called auto tuning and data such as stator resistance, mutual inductance and saturation coefficients are determined along with the motor’s inertia. The identification of motor model parameters can be done without a rotating motor shaft. This also makes it easy to apply DTC technology in retrofits. The extremely fine tuning of the motor model is achieved when the identification run also includes running the motor shaft for some seconds. There is no need to feed back any shaft speed or position with tachometers or encoders if the static speed accuracy requirement is over 5%, as it is for most industrial applications. This is a significant advance over other AC drive technology. The motor model is, in fact, key to DTC’s unrivalled low speed performance. It outputs control signals which represent actual motor torque and stator flux. The motor model also calculates shaft speed.

**Step 3:** The information needed to control power switches is produced in the torque and flux comparators. Both actual torque and actual flux are fed to the comparators where they are compared to a torque and flux reference value every 25 ms. Torque and flux status signals are calculated by means of a level hysteresis control method. These signals are then fed to the optimum pulse selector.

**Step 4:** Both the latest 40 MHz digital signal processor (DSP) and ASIC hardware to determine the switching logic of the inverter are within the optimum pulse selector. All control signals are transmitted via optical links for high-speed data transmission. This configuration brings immense processing speed and the inverter’s semiconductor switching devices are supplied with optimum pulses for reaching or maintaining accurate motor torque every 25 ms. The correct switch combination is determined at every control cycle and there is no predetermined switching pattern. Unlike traditional PWM drives where up to 30% of switch changes are unnecessary, each switching is needed and used with DTC. This high-speed switching is fundamental to the success of DTC. The main motor control parameters are updated 40,000 times per second, allowing for extremely rapid response on the shaft. This also allows the motor model (see step 2) to update the information. The high performance figures including a static speed control accuracy of some 0.5% (without encoder) and the torque response of less than 2 ms are thanks to this processing speed.

**Speed control**

**Step 5:** within the torque reference controller, the speed control output is limited by the torque limits and DC bus voltage (see Fig 7). It also includes speed control for when external torque signal is used. The internal torque reference from this block is fed to the torque comparator.

**Step 6:** The speed controller block consists of a PID controller and an acceleration compensator. The external speed reference signal is compared to the actual speed produced in the motor model. The error signal is then fed to the PID controller and the acceleration compensator and the output is the sum of both their outputs.

**Step 7:** An absolute stator flux value can be given from the flux reference controller to the flux comparator block. The ability to control and modify this absolute value provides an easy way to realise many inverter functions such as flux optimisation and flux braking.

Contact Mark Sheldon, ABB South Africa, Tel 010 202-5868, mark.sheldon@za.abb.com