Application Note DK9222-0410-0014

Motion Control

Keywords
Stepper motor
Fieldbus
Microstepping
Encoder
Phase current
Travel distance control
Speed interface
KL2531
KL2541

Stepper motor

Part A of this Application Example provides general information on stepper motors (design, areas of application, control, etc.), while part B describes the functionality of the KL2531 and KL2541 stepper motor terminals from Beckhoff and provides application examples for simple travel distance control at a PLC and for a speed interface via NC.

A General information on stepper motors

Stepper motors are special versions of the synchronous machine, in which the rotor is a permanent magnet, while the stator consists of a coil package. In contrast to synchronous motors, stepper motors have a large number of pole pairs. Motor operation requires a control unit, which energises the individual motor windings based on a certain pulse sequence. A stepper motor has a tendency to mechanical oscillation. Above its load limit it loses dynamic characteristics and may lose individual steps. Under high load the shaft may even stop. Safe positioning is therefore only guaranteed within the performance limits. If the motor is operated within its load limits, positioning without feedback of the rotor position can be achieved by linking individual steps. This operating mode (open loop control) and the durability of the stepper motor enable it to be used as a positioning drive in price-sensitive applications.

1. Basic function principles of a stepper motor

Like most electric motors, a stepper motor consists of a **stator** (fixed external winding) and a **rotor** (rotating shaft with magnets). The rotation of the motor shaft (rotor) is generated by rapid energising the electromagnetic field of the stator, causing the shaft to turn by the step angle a. In a minimum control configuration, the stepper motor is moved from pole to pole, or from step to step. A full turn of the motor shaft is therefore made up of individual steps. Energising of the motor windings results in a **magnetic field** in the motor from north to south (or south to north if the power supply has negative polarity and the winding is arranged accordingly). The movable stator with its permanent magnets aligns itself according to the direction of the external magnetic field of the stator.

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Basic stepper motor types

Stepper motors come in numerous varieties, which tend to be based on three basic types:

1– **V**ariable **r**eluctance (stepper) motor (VR)

2– **P**ermanent **m**agnet stepper motor, claw-poled PM motor, Tin-Can-Motor (PM)

3– **Hy**brid stepper motor (HY)

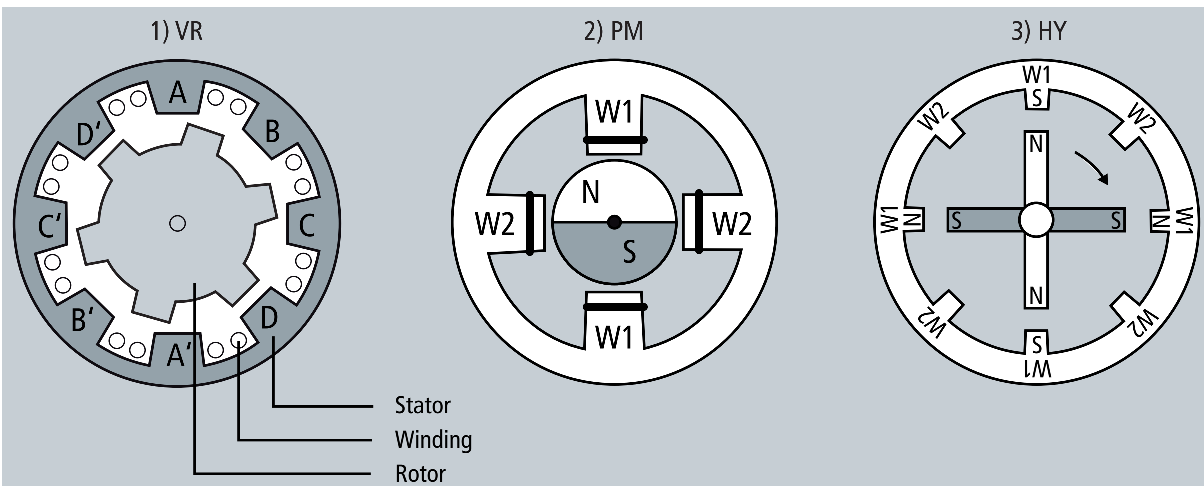

Fig. 1 **Basic stepper motor types: reluctance stepper motor, permanent magnet stepper motor, and hybrid stepper motor**

Variable Reluctance stepper motor (Fig. 1, left)

The rotor consists of a magnetically soft material with different tooth pitch compared with the pole pitch of the stator. When a phase element is excited the rotor assumes a position in which the magnetic resistance (reluctance) for the excited magnetic circuit is at a minimum. Movement of the rotor causes a torque that returns the rotor to its original position. The stator requires at least two phase windings in order to achieve a change in the direction of rotation. Due to the different tooth pitch of the pole and the rotor, the direction of the rotating field is opposite to the direction of rotation of the rotor. In de-energised state the motor has no holding torque.

Permanent magnet stepper motor/claw-pole stepper motor (Fig. 1, centre)

A permanent magnet stepper motor consists of a stator with individually controllable windings and a rotor with a permanent magnet. The rotor may be configured as a cylindrical ferrite rod with multi-pole magnetisation along its circumference. The permanent-magnetic rotor always aligns itself with the right polarity relative to the stator winding. Permanent magnet stepper motors have a holding torque to which a non-energised motor can be subjected without causing a continuous rotation.

Hybrid stepper motor (Fig. 1, right)

Combination of VR (small step angles) and PM (high torque, holding torque). The rotor consists of a permanent magnet arranged in axial direction and positioned between two magnetically soft toothed discs. The toothed discs are offset by half a tooth pitch. Due to the arrangement of the permanent magnets in the rotor one of the toothed discs forms the north pole, the other the south pole of the rotor. The rotor teeth align themselves with the stator teeth, depending on which stator phase is current-carrying.

1.1 Special features

Resonance

Irregular operation in certain speed ranges, usually in combination without coupled load, indicates that the stepper motor runs at its resonance frequency. The motor may even stop. A distinction can be made between resonances in the lower frequency range up to approx. 250 Hz and resonances in the medium to upper frequency range: Medium to high-frequency resonances are mainly caused by electrical parameters such as inductance of the motor winding and capacitances in the supply lines. Due to the high frequency they have no significant effect on the torque and can be controlled relatively easily through appropriate timing. The resonances in the lower frequency range are mainly caused by mechanical parameters of the motor. In addition to irregular movement they also lead to significant loss of torque, which not only interferes with the application but may even obstruct it through loss of step.

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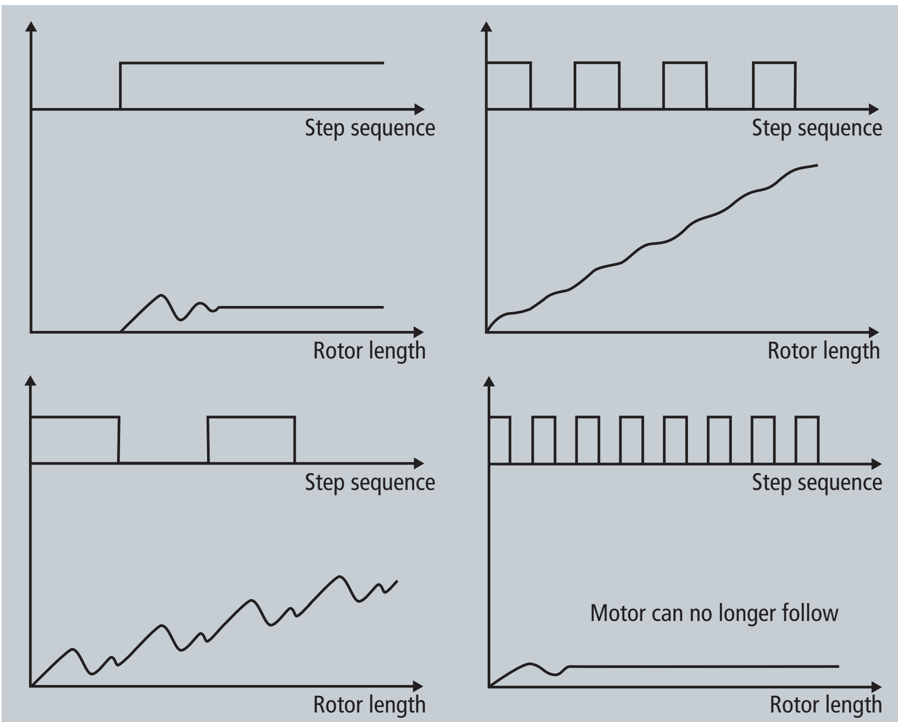

Fig. 2 Rotor position as a function of step sequence

In principle, the stepper motor represents an oscillatory system (comparable to a mass/spring system), consisting of the moving rotor with a moment of inertia and a magnetic field that creates a restoring force that acts on the rotor. Moving and releasing the rotor creates a damped oscillation. Each current pulse leads to a transient phenomenon of the rotor position (Fig. 2, top left). With increasing frequency the transient phenomenon is superimposed by the subsequent pulse, resulting in smoothing of the speed curve (Fig. 2, top right and bottom left). If the control frequency matches the resonance frequency the oscillation is amplified, so that in the worst case the rotor can no longer follow the steps and starts oscillating between two positions (Fig. 2, bottom right).

Heat generation

Stepper motors also draw their rated current when at a standstill, although in this case they cannot convert it into movement. This inevitably results in heating of the motor, and the motor temperature may be 100 °C warmer than ambient, depending on the configuration. Many manufacturers recommended temperature monitoring.

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1.2 Advantages of stepper motors compared with other motors

In contrast to other motors stepper motors have a high holding torque even at low speed, and even on standstill. Another advantage is the simple control of stepper motors: Alternate energising of the individual coils causes the motor to move step by step. The fixed number of steps per revolution always enables the current position to be determined if the steps are counted and the motor is operated within its performance limits. No encoder is required for simple positioning tasks within the performance limits. Stepper motors are therefore ideally suited as cost-effective solutions for simple positioning tasks.

1.3 Areas of application for the different stepper motor types

1– PM:

Technologically relatively simple solution for low-powered drives with low or medium requirements in terms of dynamics | Suitable for automotive and building automation (HVAC) applications

2– VR:

Less significant | can be produce economically | only achieves low efficiency | no holding torque | stronger tendency to mechanical vibrations than polarised stepper motors

3–HY:

Best motor from an energy perspective with best performance parameters | above 100 cNm torque no improvement of the mass/performance ratio | small performance classes dominate in peripheral data processing devices (printers/scanners, etc.) | higher performance classes typical for high-quality positioning tasks (robotics)

Typical versions are stepper motors with the following parameters:

	Reluctance stepper motor	Claw-pole stepper motor	Hybrid stepper motor
Step angle in °	1.8…30	6…45	0.36…15
Holding torque M_H in cNm	1.0…50	0.5…60	3…1000

Fig. 3

2. Basic control principles

Since it is not sufficient to apply a constant supply voltage to the stepper motor in order to generate a rotation of the shaft, the individual coils have to be energised alternately. To this end control electronics are required for setting the speed and direction. In addition, the control electronics must support the three different step patterns that are used for influencing the indexing position of the shaft.

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2.1 Full step and half step

Full step

Two adjacent windings are energised at any one time, so the rotor aligns itself centrally between the pole axes. In this way a high torque can be achieved.

Half step

Between two full step positions only one winding is energised, so that the step angle is halved at the expense of a smaller, non uniform torque.

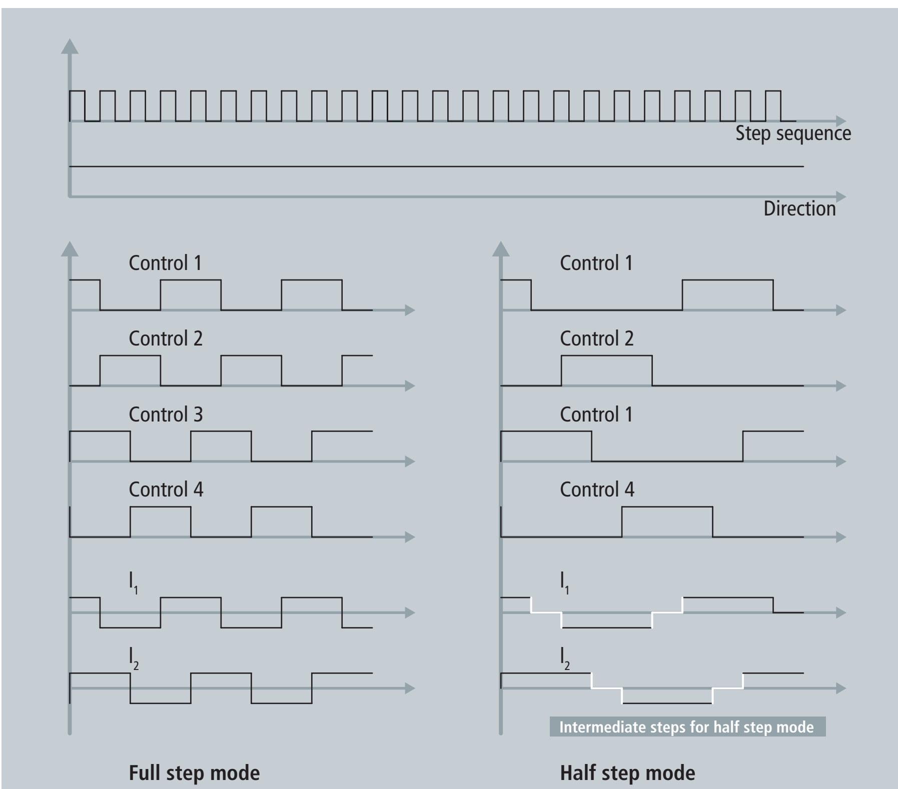

Fig. 4 Differences in the control modes for stepper motors (left: full step, right: half step)

2.2 Microstep

Both in full step mode and in half step mode complete windings are energised based on a certain pulse pattern. The motor rotates suddenly by a fixed angle. In microstepping mode the control electronics generate a PWM with very fine resolution, so that the windings are supplied with a constant current flow in SinCos shape. In this mode the motor torque is directly related to the current intensity.

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B Stepper motor terminals KL2531 and KL2541 from Beckhoff

The KL2531 and KL2541 stepper motor terminals integrate a compact Motion Control solution for stepper motors up to 200 W within a very small space, which can be used for direct control of unipolar and bipolar stepper motors. No additional output stage is required, since the terminals include output stages for two motor coils. Through full integration into the fieldbus, the terminals can be adapted to the application and the motor via the fieldbus configuration tool with a few parameters.

3. Basic principles of the terminal structure and function

Both terminals provide two controlled SinCos currents. 25 kHz current control enables smooth current output without resonance. Highly dynamic, low-inductance motors run just as well as stepper motors with small rotor mass. The current resolution is 64 steps per period (64-fold microstepping). They differ in terms of performance class.

KL2531

– lower performance range
– small size: 12 mm wide, PWM for two motor coils and two digital inputs (24 V DC)
– up to 24 V DC supply voltage
– peak current 1.5 A per phase
– direct connection of different stepper motors
– straightforward adaptation to the motor and the application

KL2541

– higher performance class (small servo drives)
– width: 24 mm
– torque up to 5 Nm (depending on the motor)
– up to 50 V DC supply voltage
– peak current 5 A per phase
– integrated incremental encoder interface (24 V DC)
– high mechanical output (up to 200 W range)
– direct connection of different stepper motors
– straightforward adaptation to the motor and the application

Note that for typical applications the rated output of the motor power supply can be dimensioned such that the load current is 50% of the current of a stepper motor phase. This means that a KL2541 that operates a stepper motor with a maximum coil current of 5 A in a typical application can generally be operated with a 48 V/2.5 A power supply unit.

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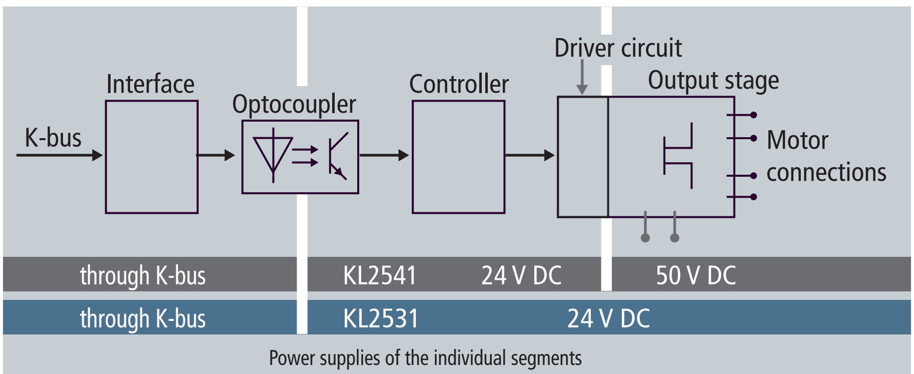
3.1 Block diagram



3.2 Stepper motor configuration

For VR stepper motors no change in the polarity of the current is required for a change in direction of the torque. Stepper motors with permanent magnets require current linkage with two polarities, which means they can be controlled unipolar or bipolar. In bipolar mode higher efficiency can be achieved, although in unipolar mode the connection is simpler.

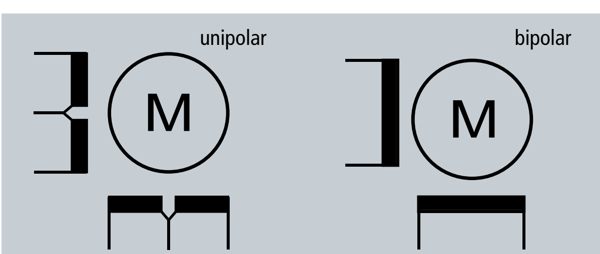


Fig. 6 Stepper motors operating modes: unipolar and bipolar

Unipolar:

Each stator coil features a centre tap with a fixed connection to the supply voltage. The current flows through the phase windings in only one direction, since each phase is wound in parallel with two wires. The current direction of the stator coil depends on which coil end is connected to earth. This configuration results in savings in the control electronics (see Fig. 4, left).

Bipolar:

In bipolar mode each phase windings of the motor is supplied via a full bridge and can therefore carry current in both directions. Therefore the polarity of the whole coil is reversed in all instances, and not just one half. If the stepper motor phases are wound with two parallel wires, the two branches of a coil have to be connected in parallel (see Fig. 4, right)

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Note:
For further information regarding connection of the motors to the terminals see Documentation -> Installation and Wiring -> Connection Examples. Download link at the end of the document

3.3 Complementary products

The KL9750 buffer capacitor terminal with can be used with particularly ripple current-resistant 500 µF capacitors to complement the stepper motor terminal. It stabilises the power supply, absorbs back EMF and offers overvoltage protection for highly dynamic drives. If the back EMF exceeds the capacity of the capacitors, an external ballast resistor prevents overvoltage.

4. Application examples

The terminals contain only one data interface, which uses the register DataOUT either for position or speed specification, depending on the operating mode. The following application examples illustrate the functionality of the travel distance control (position specification) and speed interface (speed specification) modes.

4.1 Travel distance control (with simple PLC)

For positioning taken over from a PLC, travel distance control is the optimum solution. In this mode, a 16 bit position value and various parameters such as speed and acceleration are specified for the terminal. Once enabled, the terminal automatically travels to the target position.

Travel distance control mode can be used to realise simple positioning tasks from a conventional PLC (without NC). Travel/positioning commands can be written via the controller directly into the registers of the memory within the terminal. The stepper motor terminal enables simple referencing (homing). In referencing mode the digital inputs are used for limit switch feedback.

The following travel commands are available in travel distance control mode:

- manual
- simple travel command
- multiple travel command
- auto-start function
- auto-stop function
- fast-stop function
- referencing/homing (via the digital inputs)
- self-adjustment

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4.2 Speed interface (operation in conjunction with NC)

Direct speed mode is the optimum solution for applications where positioning is handled by the NC. The stepper motor terminal is operated in a closed control loop, while the NC operates as a speed set value generator. The terminal follows these set values and returns the current position value as feedback to the NC. The used ramps and controller parameters (P, I) are configured in the NC.

In direct speed mode all functions and travel commands from the standard Motion Control TwinCAT CNC library are available. The most common commands are listed below (the list is not exhaustive):

- Move absolute
- Move relative
- Read Position
- Referencing/homing to limit switch or 0-track (C-signal) of the encoder
- MC Reset

– Stepper motor terminal, 24 V DC, 1.5 A **www.beckhoff.com/KL2531**
– Stepper motor terminal, 50 V DC, 5 A, with incremental encoder **www.beckhoff.com/KL2541**
– The modular fieldbus system for automation **www.beckhoff.com/Busterminal**
– Stepper motor terminal documentation
http://download.beckhoff.com/download/Document/BusTermi/BusTermi/KL2531_KL2541en.chm