

# Motor control

A reference guide



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High efficiency, reduced noise, extended lifetime, rapid time to market. And all at optimum cost. This is the challenge currently facing the many industries which use electric motors.

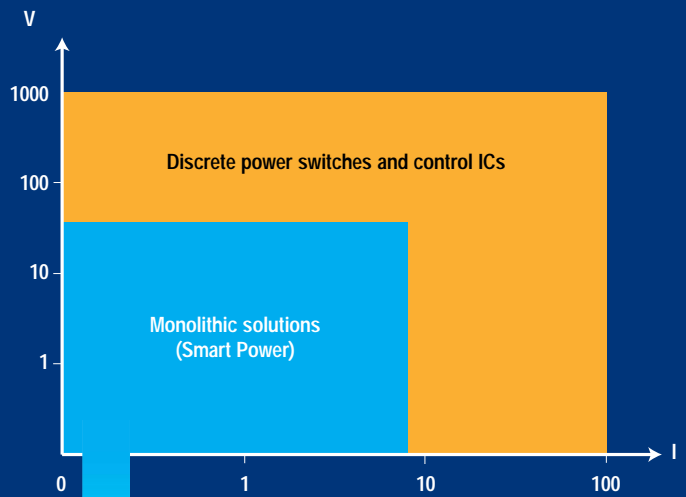
Today, the demand for electronic motor control is increasing rapidly, not only in the automotive and computer peripherals markets, but also in industrial applications and home appliances such as heating and ventilation systems, power tools, vacuum cleaners and white goods. All these mass-market applications need cost-effective solutions without compromising reliability.

**STMicroelectronics** was among the first to recognize this trend and today offers a full range of components for optimizing motor control systems. Whatever motor technology you use, this reference guide will help you to make the right choice of components.

### Single-chip versus multi-chip solution

ST is universally acknowledged as offering the most comprehensive semiconductor portfolio for applications which include:

- Microcontrollers
- Power discretes
- Smart power and dedicated ICs



A driver-on-chip solution is available along with multiple-IC solutions

## Product family highlights

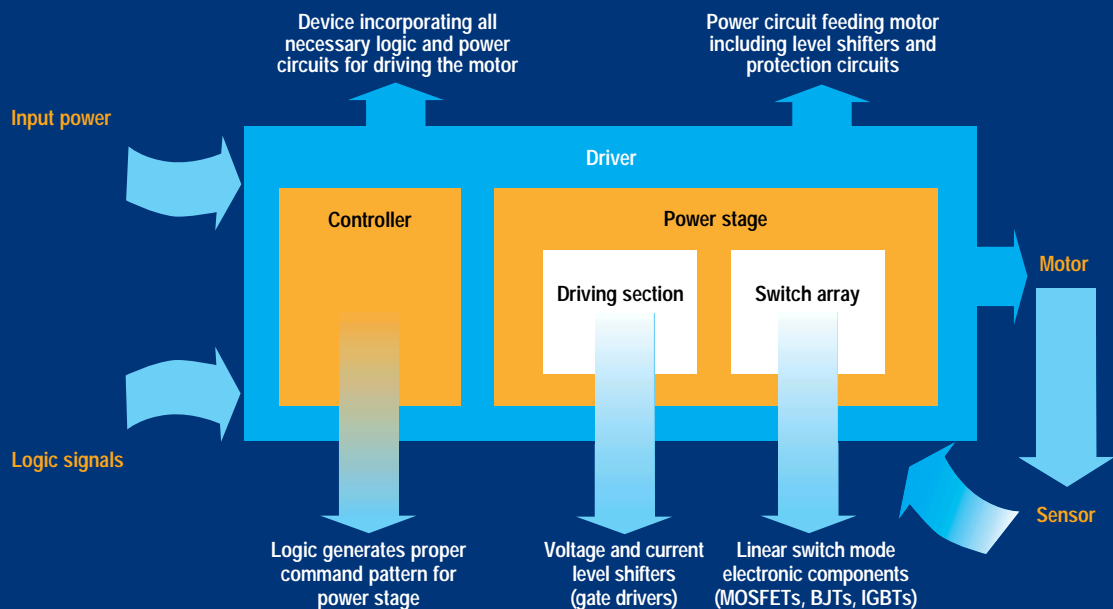
### Microcontrollers

ST supplies 8 and 16-bit microcontrollers which meet the performance requirements for controlling electric motors in various applications. The ST6 family for example, targets cost-sensitive universal and single-phase induction motor applications, where speed control can be enhanced using the ST7 MCU. The ST7 family, built around an industry standard architecture, also addresses three-phase brushless synchronous motor applications via a dedicated peripheral. The ST9's 8/16-bit register file architecture enables efficient

scalar control of three-phase induction motors, while the 16-bit ST10 allows vector control. ST52 8-bit products also include a dedicated fuzzy logic core. All families and products are supported by a comprehensive range of emulators, development kits, programmers and demonstration boards, plus an integrated development environment, C compilers, and graphical design aids. FLASH, OTP, EPROM and ROM versions are available.

# ST – committed to motor control

## Smart Power IC building blocks



## Power discretes

ST offers a broad selection of products for power discretes: MOSFET and IGBT transistors, thyristors, triacs and AC switches, fast rectifiers and protection devices ranging from 1 to 50A and 30 to 1,600V. Perfectly suited to medium power motor drive applications, ST is constantly enhancing the performance of its power discretes by upgrading process capabilities and product families. ST innovations include:

- enhancing the IGBT family with the new strip layout PowerMesh geometry, and the Turboswitch™ diodes family with the new 300V and 600V STTH series

- breaking MOSFET performance barriers using MDmesh™ high-voltage technology and StripFET low-voltage technology to lower  $R_{ds(on)}$  without sacrificing switching performance
- embedding control features into switch with VIPower™ technology for low-voltage motors
- adding over-voltage protection and a separating gate circuit with the ACS™ switch, designed around 500V and 800V ASD™ technology

## Smart power and dedicated ICs

With ST's proprietary BCD family of processes, which combine bipolar, CMOS and DMOS structures on the

same substrate, it is possible to achieve high levels of integration, including monolithic 600V gate drivers for mains-fed motor drive applications. For low-voltage applications such as automotive and PC peripherals, ST has developed a broad range of complete single-chip motor drivers incorporating control, drivers and power switches. Using a process as fine as 0.35mm, typical of ST's newest BCD6 process, even relatively complex digital circuits such as microcontrollers, DSP cores and non-volatile memories can be integrated into Power ICs, creating advanced Smart Power solutions. Single-chip versus multi-chip solutions are shown on page 4.

The universal motor is a brush motor with series excitation (see page 8). As its torque is independent of current direction, it can accept either AC or DC. Speed is controlled by varying motor voltage.

### Typical application parameters

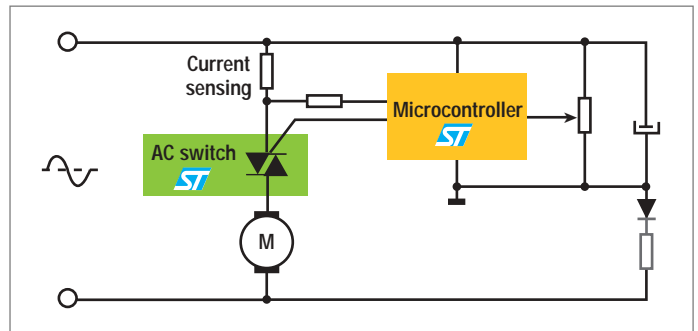
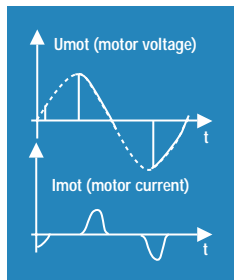
Voltage	Motor power	Speed range	Features
100 to 240Vac (or corresponding rectified voltage)	100 to 1,600W	0 to 20,000 RPM	High start-up and low speed torque capability

## AC universal motor drive

The motor is connected to the mains through an AC switch. The AC voltage varies across the motor in phase control mode by means of a microcontroller which sets the triac triggering time.

### Main applications

- Vacuum cleaners
- Power tools
- Washing machines
- Food processors



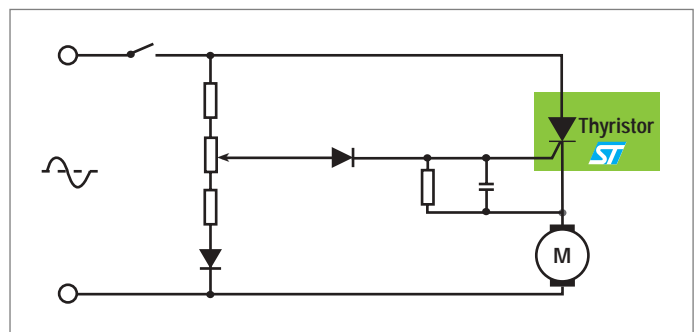
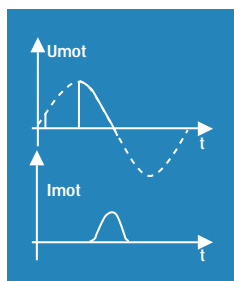
AC universal motor drive

## DC universal motor drive

A thyristor supplies the motor during the positive mains half cycle. Both the thyristor and its control are connected in such a way that the motor back-EMF compensates load variations to adjust the speed. This low-cost circuit is popular for low-power and intermittent-use equipment.

### Main applications

- Food processors
- Power tools



DC universal motor drive

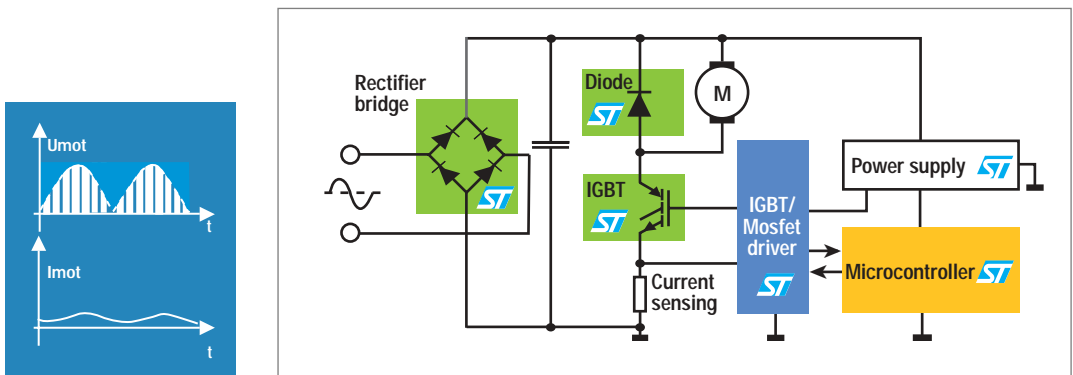
# Universal motor

## High-frequency PWM universal motor drive

A rectified voltage across the motor varies in PWM mode at an inaudible switching frequency. A DC supply provides smooth current operation, reducing (acoustic) motor noise and improving motor efficiency.

### Main applications

- Washing machines
- Treadmills
- Food processors
- Industrial motion control



High-frequency PWM universal motor drive

## Product highlights

Microcontrollers	A low-cost 8-bit microcontroller with proven EMC behaviour and low power consumption is ideal for this application. ST7, ST6 and ST52 family MCUs have an on-chip clamping diode for zero crossing detection through a resistor, a high current sinking capability for direct triac drive and PWM generation. In addition, they offer multiple, external interrupts and analog inputs, fully configurable I/Os and a range of timers for accurate control and speed measurement.
Power transistors	The IGBT is the best 600V rated device for the PWM brush DC motor drive. PowerMESH™ IGBTs combine low $V_{ce(sat)}$ with very short turn-off times, and drastically reduce both turn-on and turn-off switching losses.
Fast rectifiers	Available at 300V and 600V, Turboswitch™ diodes feature ultra-fast recovery while maintaining a low drop voltage. They significantly cut losses in both the diode and transistor at turn-on.
Thyristors	The thyristor (or SCR) delivers both rectification and motor voltage adjustment. A sensitive device ( $I_{gt} < 200\mu A$ ) simplifies the gate drive and reduces overall control circuit dissipation.
AC switches	Triac and ACST switches are suited to this type of drive, offering high surge current and low conduction loss. ST's Snubberless™, logic level triacs require a low gate-triggering current (10mA and 35mA) and run safely without requiring a turn-off aid snubber. The new ACST switches are designed with intrinsic over-voltage robustness and safely suppress the mains voltage surges described in IEC61000-4-5.

The rotor of the brush DC motor includes a winding which is fed by a DC voltage source through carbon brushes. The stator circuit comprises a permanent magnet structure (PMDC motor) or a winding. If the stator includes a winding, the latter can be connected to the rotor winding in series or parallel, or can be driven separately. Brush DC motors can be driven in voltage mode, since motor speed is proportional to supply voltage when the load is constant. However, to control motor torque, a current control loop is usually added in higher performance systems. For bi-directional operation, the rotor current must be inverted, taking into account the stator magnetic field.

### Typical application parameters

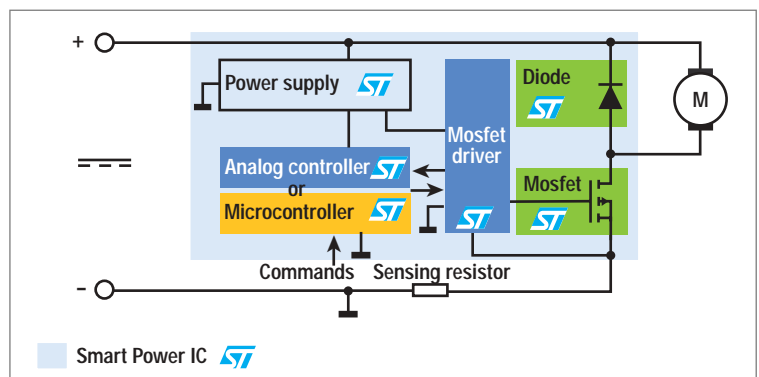
Voltage	Motor power	Speed range
6 to 320Vdc	Up to 20,000W	0 to 30,000 RPM

### Main applications

- Consumer audio/video
- Shavers
- Toys
- Cordless tools
- Automotive body functions
- Traction
- Servomechanisms
- Factory automation
- Machine tools

## Single-switch choppers

For the unidirectional operation of a PMDC motor, only one power switch is needed. In case of PWM control, a freewheeling diode is connected across the motor.

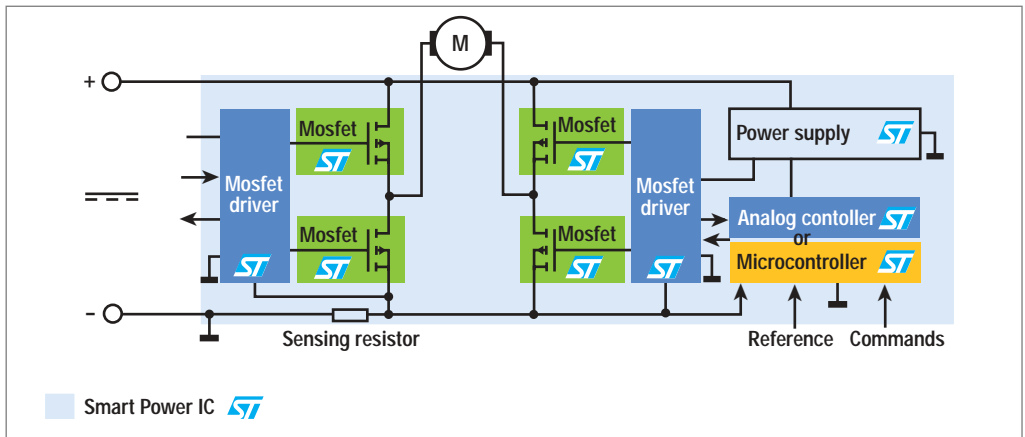


Unidirectional brush DC motor drive

# Brush DC motor

## Full-bridge converter

This configuration enables the bi-directional operation of PMDC motors.



*Bi-directional brush DC motor drive*

## Product highlights

Controllers	Depending on the application, either analog controllers or microcontrollers can be used. Analog controllers are more compact and basic, whereas microcontrollers are more flexible and allow complex control algorithms to be implemented.
Power transistors	VIpower devices are suitable for low-voltage brush DC motors in automotive or Industrial applications. Low-side and high-side drivers are available, including a new single-package full bridge driver. With unrivalled low $R_{ds(on)}$ , STripFET MOSFETs are ideal for higher power applications such as cordless tools.
Smart Power ICs	Monolithic motor drivers can be used conveniently in applications where the input voltage does not exceed a few dozen volts and the current feeding the motor windings is limited to a few amps. These devices may include just the power stage or the control section. ST has developed several types of Power IC, suited to different application requirements, working in linear or switch mode.
Gate drivers	Monolithic full-bridge and half-bridge gate drivers are available and include protection, dead time and supply circuits.

The single-phase induction motor is a brushless motor designed either with a single stator coil plus a “shaded pole” coil, or two stator coils and a phase-shift capacitor. The rotor is usually made of an aluminum squirrel cage. Speed is controlled either by varying the motor voltage or by changing the number of motor poles.

### Typical application parameters

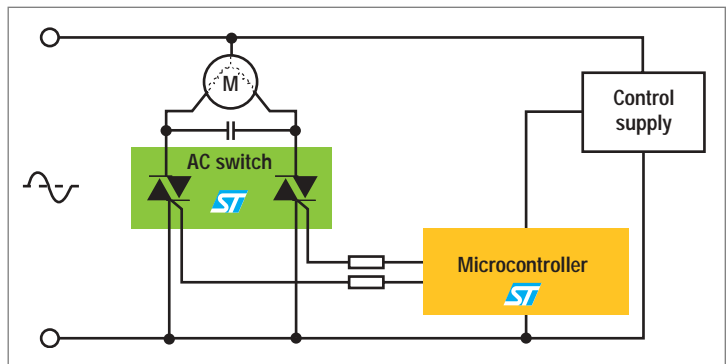
Voltage	Motor power	Speed range	Features
100 to 240Vac	10 to 2,000W	0 to 3,000 RPM	Robust, low starting torque

## Bi-directional induction motor drive

When a motor with a phase-shift capacitor is used, the direction of rotation can be reversed by means of two AC switches which connect the phase-shift capacitor in series with either of the two stator windings.

### Main applications

- Washing machines
- Window and door openers



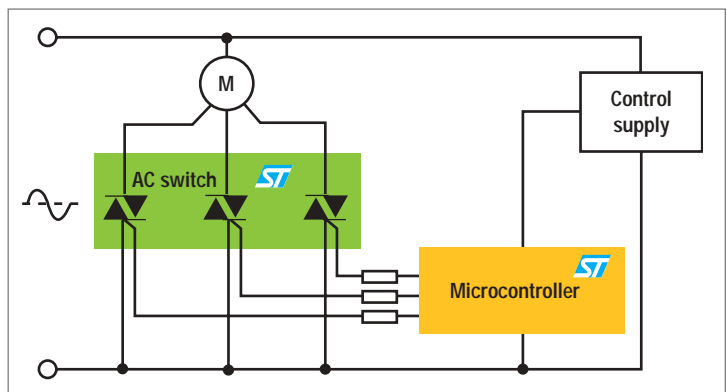
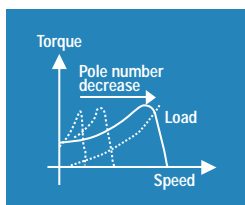
Direct-reverse speed induction motor drive

## Multi-winding on/off induction motor drive

Here the stator coil is divided into 3 or 4 pairs of windings. The speed is adjusted stepwise by connecting different combinations of these windings to the mains through AC switches in order to change the number of active stator poles and the base speed.

### Main applications

- Fans in home appliances



Multi-winding on/off induction motor drive

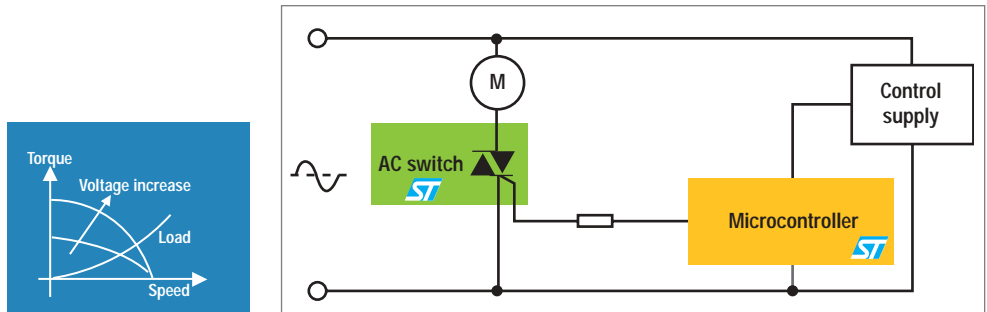
# Single-phase induction motor

## Phase-controlled induction motor drive

ST can offer a silent and cost-effective variable speed drive with an innovative topology to control speed. A simple phase-control switch can then be used to vary speed by changing the motor torque profile. (See also the *AC Universal Motor Drive* page 6)

### Main applications

- Fans in home appliances
- Ice makers
- Domestic water pumps
- Industrial fans and pumps



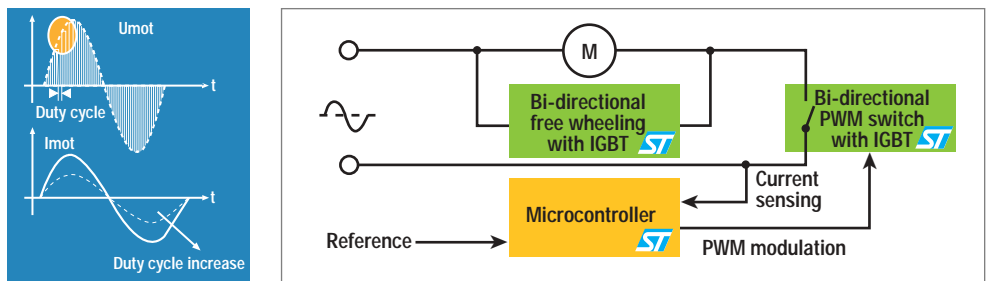
Phase-controlled induction motor drive

## High-frequency PWM induction motor drive

The induction motor is driven in high-frequency mode by an innovative single-switch topology, which delivers a silent and cost-effective variable speed drive. The speed is controlled by the motor voltage: the power switch runs in PWM mode and its duty cycle changes linearly to control the speed according to torque.

### Main applications

- Heating, ventilation and air conditioning
- Industrial blowers and compressors



High-frequency controlled induction motor drive

## Product highlights

Microcontrollers	An 8-bit low-cost microcontroller with proven EMC behaviour and low power consumption is ideal for this application. ST7, ST6 and ST52 family MCUs have an on-chip clamping diode for zero crossing detection through a resistor, and a high current sinking capability for direct triac drive and PWM generation. In addition they offer multiple, external interrupts and analog inputs, and fully configurable I/Os.
Power transistors	The IGBT is the best 600V rated device for PWM induction motor drives. The PowerMESH™ IGBTs combine low $V_{ce(sat)}$ with very short turn-off times and drastically reduce switching losses.
AC switches	With high commutation performance, Snubberless™ triacs, ACS™ and ACST switches are the best choice. In addition, the latest ACS and ACST switches offer an outstanding over-voltage robustness enabling equipment to comply with the IEC6100-4-5 standard. The 500V ACS, also available in array configuration, is suitable for fan drives while the 700-800V ACST is intended for medium power motor drives in washers, dryers and refrigerators.

The three-phase induction motor is a brushless motor. Its stator is copper wound and the rotor is typically an aluminum squirrel cage. The motor is supplied with three alternating voltages which produce a rotating stator field while speed varies with the field frequency. The rotor follows this field with a lag called the *slip*.

### Typical application parameters

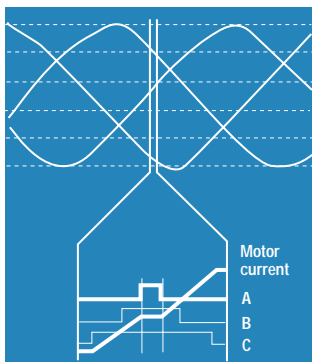
Voltage	Motor power	Speed range	Features
100 to 240Vac	50 to 2,200W	0 to 20,000 RPM	Robust, silent and reliable

## Three-phase induction motor in scalar control mode

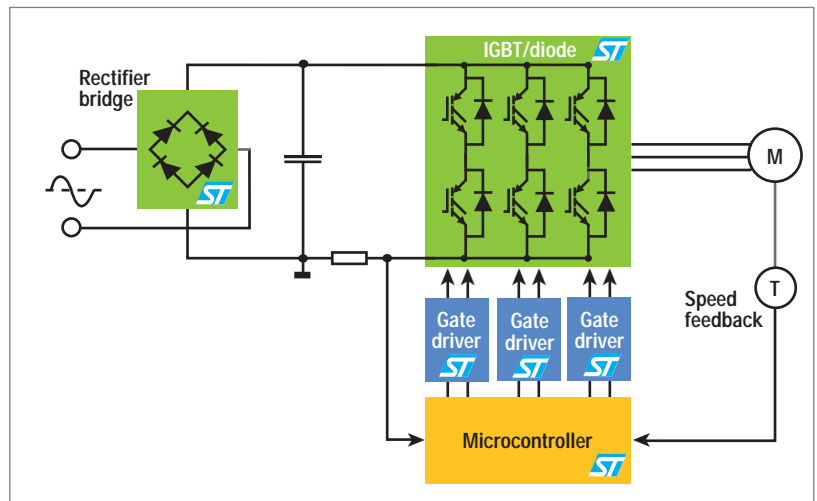
Scalar control is typically achieved by controlling the voltage-to-frequency ratio in an open or closed loop. Optimized motor efficiency can be achieved by implementing slip regulation.

### Main applications

- Washing machines
- Heating, ventilation and air conditioning
- Blowers, fans and pumps
- Industrial control



Centered pattern switching



High-frequency scalar three-phase induction motor drive

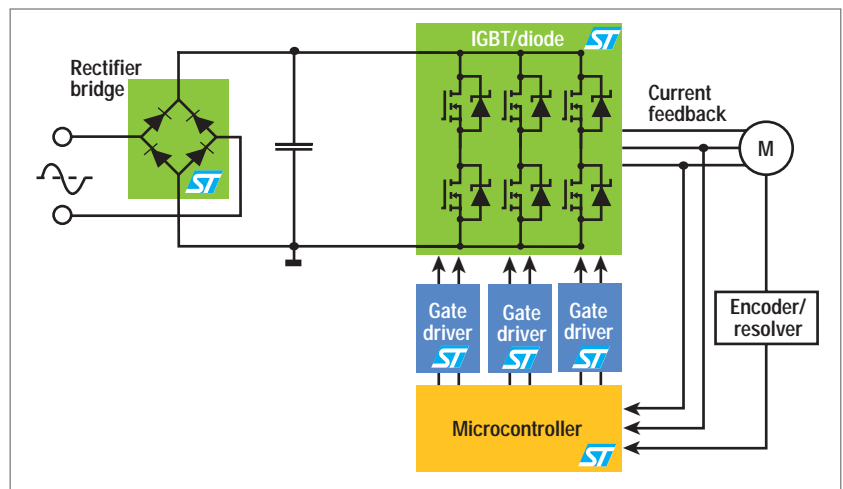
# Three-phase induction motor

## Three-phase induction motor in vector control mode

Vector control provides real-time processing of the stator phase current and rotor position. It provides four-quadrant operation, and excellent dynamic behaviour, to maintain optimum efficiency and speed response time.

### Main applications

- Robotics
- High-end industrial control
- Servo drives



High-frequency vector three-phase induction motor drive

## Product highlights

Scalar drive microcontrollers	The ST7MC embeds a dedicated macrocell generating two complementary sets of three sinusoidal PWM outputs, using edged patterns and single/double update centered pattern with a 12-bit resolution and automatic dead time insertion. Multiple sensor input is available, such as tachogenerator, hall, encoder and dedicated speed acquisition hardware.
Vector drive microcontrollers	The ST10F269 is a 16-bit MCU with pipelined architecture targeting applications demanding high computing performance at low system cost. The processor frequency can be up to 40Mhz, where most instructions are executed in 50ns, allowing the running of computational-intensive vector control on AC motors. The 256KByte embedded flash along with the 12KByte internal RAM offers high flexibility to single chip solution.
Power transistors	Available at 600V, the PowerMESH™ IGBTs range from 3 to 50A. To reduce component count on the board, they can be provided with a built-in Turboswitch™ freewheeling diode. The low $V_{ce(sat)}$ combined with very short fall times drastically reduces both on and switching losses while the fast-recovery diode further reduces the IGBT turn-on losses.
Fast rectifiers	Available at 300 and 600V, the Turboswitch™ diodes feature ultra-fast recovery while maintaining a low drop voltage. They significantly cut losses in both the diode and the transistor at turn-on.
Gate drivers	Half-bridge gate drivers are 600V monolithic circuits which may include a bootstrap diode for the floating driver, dead time circuitry, two UVLO circuits and an uncommitted comparator for protection functions. Signal and power grounds are separated to ensure high noise immunity.

The stator of the brushless DC motor is copper wound with a rotor featuring a number of permanent magnets. The motor is supplied with three further waveforms which produce a rotating stator field. The rotor runs synchronously, and optimum motor efficiency occurs when the current in the motor and the back-EMF are in phase.

### Typical application parameters

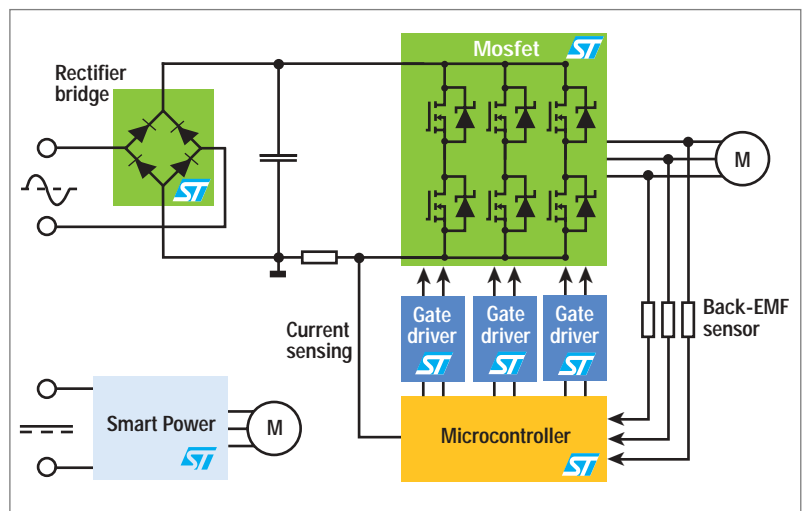
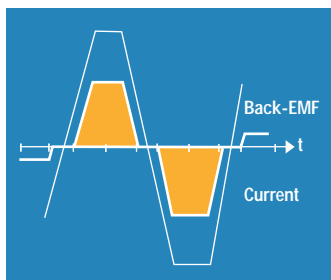
Voltage	Motor power	Speed range	Features
Up to 60Vdc; 100 to 240Vac	5 to 2,200W	0 to 30,000 RPM	High torque capability at start-up and low-speed Highly efficient and compact

### Main applications

- Heating, ventilation and air conditioning
- Refrigerators
- Medical equipment
- Robotics
- Fans
- Pumps
- Hard disk drives
- CD/DVD drives

## Brushless DC motor in 6-step mode

The motor is supplied by three trapezoidal 6-step waveforms. During each step, two phases are active. In sensorless mode, the inactive phase is monitored to read the back-emf.

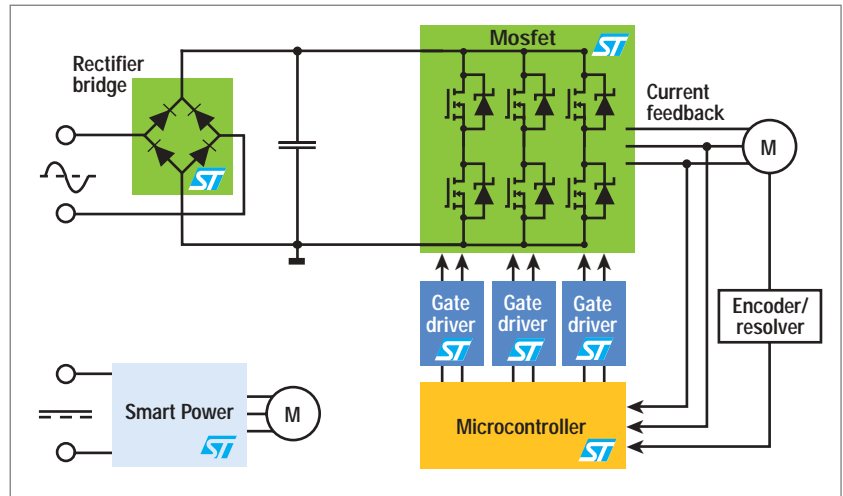


High-frequency three-phase brushless DC motor drive

# Three-phase brushless DC motor

## Brushless DC motor in sinusoidal mode

This brushless DC motor is supplied by three sinusoidal waveforms. This control mode delivers low levels of acoustic and electromagnetic noise while a resolver and current sensors are normally needed for high-performance operation.



Brushless DC motor in sinusoidal mode

## Product highlights

6-step mode microcontrollers	The ST7MC carries out sensorless control of the motor. The back-EMF zero crossing is recognized by the MCU, using a resistor set of ST-patented method or the classical industry-standard approach. The 6-step mode is provided by six dedicated PWM outputs. Current regulation or limitation is implemented by an on-chip op amp and comparator MCU. There is also an emergency function for switching off the inverter.
Power transistors	Power MOSFETs in STripFET technology are ideal PWM switches for 5V and 12V drives. They come as a single package complementary p- and n-channel pair, an SO-8 package double-die n- or p-channel solution, and in a large variety of SMD packages. For the 600V range, PowerMESH™ IGBTs cover all power ratings, both in single configuration or associated with a Turboswitch™ fast rectifier.
Fast rectifiers	Available at 300V and 600V, the Turboswitch™ diodes feature ultra-fast recovery while maintaining a low drop voltage. They drastically cut losses in both the diode and the transistor at turn-on.
Smart Power ICs	Monolithic motor drivers can be conveniently used in applications where the input voltage does not exceed a few dozen volts and the current feeding the motor windings is limited to a few amps. These parts may include just the power stage or include the control section. ST has developed several types of Power ICs, suited to different application requirements. Some operate in linear and some in switch mode.
Gate drivers	Half-bridge gate drivers are high-voltage monolithic circuits which include a bootstrap diode for the floating driver, dead time circuitry, two UVLO circuits and an uncommitted comparator for protection functions. Signal and power grounds are separated to ensure high noise immunity.

The stepper motor has windings only on the stator, while the rotor usually features permanent magnets. The stepper motor converts digital pulses into fixed angular steps and, for this reason, are normally used in an open loop configuration and are the most cost-effective solution in many positioning applications.

There are two basic types of stepper motor: unipolar and bipolar. In a unipolar motor, the current is allowed to flow in one direction through the motor windings, while in a bipolar motor it will flow in both directions. A stepper motor driver typically works in switch mode and includes a current control circuit allowing the current in the windings to be controlled in such a way that it follows a predetermined profile. In half and full-step modes, the current profile is rectangular, while in micro step mode it is nearly sinusoidal. A power bridge is needed to drive bipolar stepper motors, but an array of switches is sufficient to drive unipolar stepper motors.

### Typical application parameters

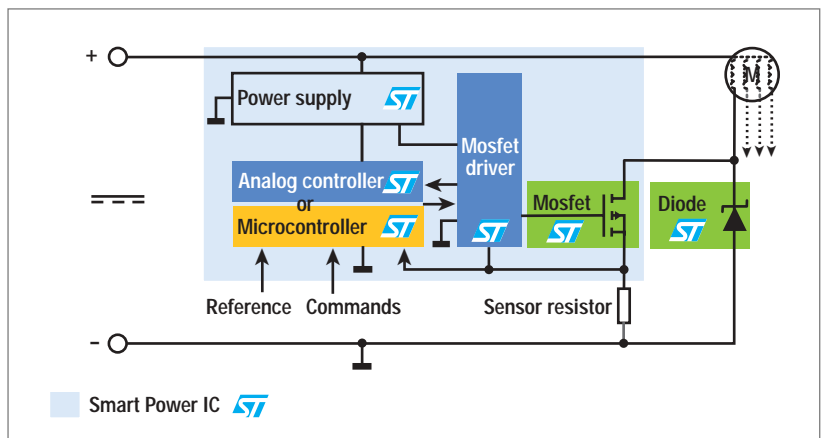
Voltage	Motor power	Speed range	Angular resolution	Features
12 to 180Vdc	Up to 300W	0 to 1,000 RPM	0.1 to 45 degrees	High torque at rest position Accuracy

### Main applications

- Printers
- Automotive
- Air conditioning louver
- Factory automation
- Machine tools

## Driver for unipolar stepper motors

All stator windings share a common terminal and the free terminal of each winding is connected to a separate power switch. Diodes are used for clamping the voltage across the switches at turn-off.

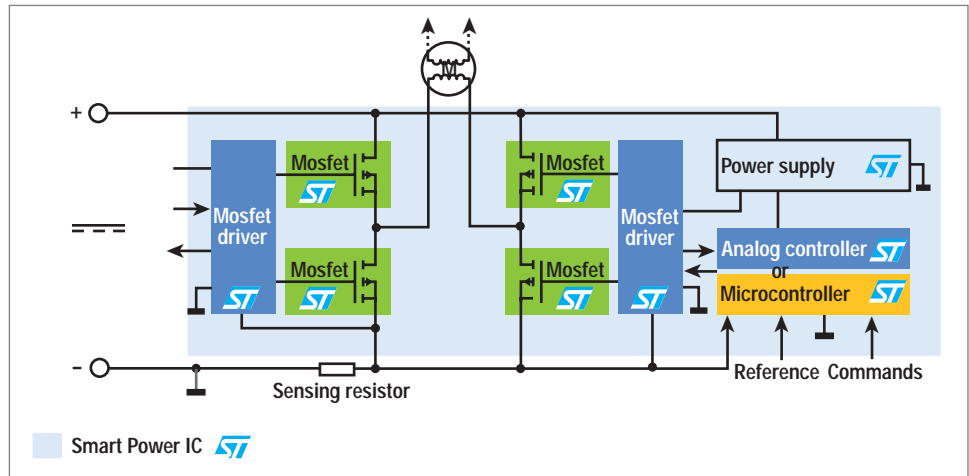


Multi-phase unipolar stepper motor drive

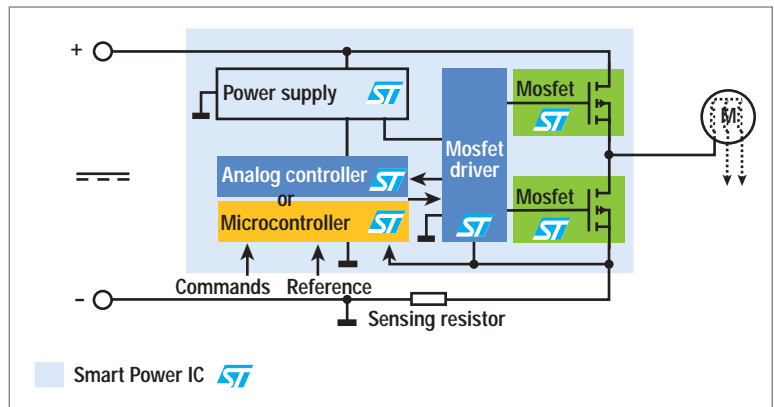
# Stepper motor

## Driver for bipolar stepper motors

A full-bridge converter is required to drive each of the two windings of a two-phase motor, whereas a three-phase inverter is needed to drive a three-phase motor.



Two-phase bipolar stepper motor drive



Multi-phase bipolar stepper motor drive

## Product highlights

Controllers	Analog controllers are often used for controlling stepper motors whereas microcontrollers are required in high-end systems for user interface, communication and timer capability.
Power transistors	VIpower devices are suitable for a low-voltage stepper motors in automotive and industrial applications. Low-side and high-side drivers are available, including a new single package full bridge driver. With its unrivalled low $R_{ds(on)}$ , the STripFET MOSFET is ideal for higher power applications such as printers.
Smart Power ICs	Monolithic motor drivers can be conveniently used in applications where the input voltage does not exceed a few dozen volts and the current feeding the motor windings is limited to a few amps. These parts may include just the power stage or include the control section. ST has developed several types of Power IC, which suit different application requirements; some work in half/full step and some in micro stepping mode.
Gate drivers	Half-bridge gate drivers are high-voltage monolithic circuits which include a bootstrap diode for the floating driver, dead time circuitry, two UVLO circuits and an uncommitted comparator for protection functions. Signal and power grounds are separated to ensure high noise immunity.

The switched reluctance (SR) motor is a brushless motor, consisting of a salient pole-wound stator and an iron salient pole rotor. Motor torque is generated by using the magnetic forces between rotor and stator salient poles and the motor is supplied by current which is switched synchronously with the rotor pole position.

### Typical application parameters

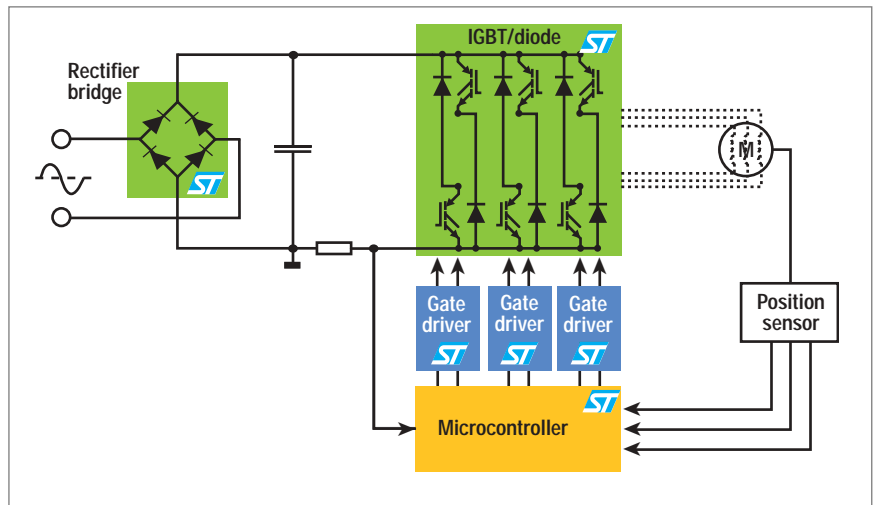
Voltage	Motor power	Speed range	Features
12 to 180Vdc	Up to 2,000W	0 to 100,000 RPM	Very high torque at low speed

### Main applications

- Traction
- Industrial and automotive actuators
- Home appliances

## Asymmetrical half-bridge PWM control

This inverter topology leverages the motor's best features. An independent current loop is implemented for each motor phase so that some phase current overlap is possible for attaining higher speeds.

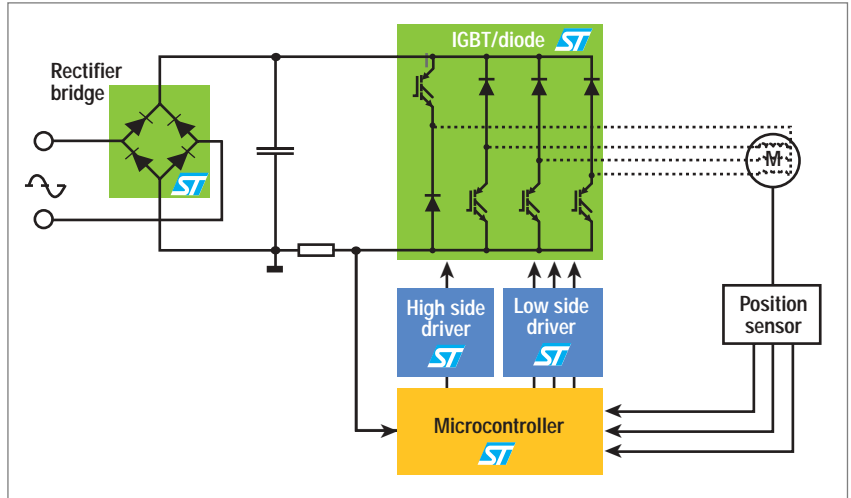


*Asymmetrical half-bridge PWM control*

# Switched reluctance motor

## Simplified asymmetrical half-bridge PWM control

This inverter topology is cost-effective and well adapted to medium speed operation (20,000 RPM).



*Simplified asymmetrical half-bridge PWM control*

## Product highlights

Microcontrollers	The ST7MC performs current loop reference regulation, position sensor decoding and motor phase commutation. Phase commutation delays and phase angle are managed by the motor control peripheral timers.
Power transistors	Available at 600V, PowerMESH™ IGBTs are offered in a high-frequency version for the PWM switch and a low drop version for the phase control switch. This combination will optimize total losses of each inverter bridge leg.
Fast rectifiers	Available at 300V and 600V, the Turboswitch™ diodes have ultra-fast recovery characteristics while maintaining a low drop voltage. They drastically cut losses in both the diode and transistor at turn-on.
Gate drivers	Half-bridge gate drivers are high-voltage monolithic circuits which include a bootstrap diode for the floating driver, dead time circuitry, two UVLO circuits and an uncommitted comparator for protection functions. A triple low-side gate driver can also be conveniently used in this application.

# Auxiliary blocks

## Power factor corrections

Used to reduce the low-frequency AC harmonics of the motor drive, power factor correction (PFC) circuits now use boost topologies and run in either continuous or discontinuous PWM conduction modes. Covering the 20 to 1,500W range, ST offers a comprehensive semiconductor kit to deliver this functionality. This consists of continuous or discontinuous PWM control ICs (L4981 & L6561), PowerMESH™ or MDmesh MOSFETs and Turboswitch™ rectifiers.

## Auxiliary supply

As a standalone system, the motor drive typically requires a supply of up to 10W to feed the controller and the power switch drive. ST offline monolithic circuits, such as the VIPer and FIPS PWM regulator, address this function with compact, reliable and low standby power solutions.

## Protection devices

Transil™ diodes are designed to protect against over-voltage by clamping against electrostatic discharge (ESD) and electrical overstress (EOS). They protect the DC line power bus from 5V to 200Vdc or force triac triggering or FET transistor clamping against any over-voltage. Uni- or bi-directional Transil™ diodes are available as axial and surface mount devices, with a power range of up to 5,000W (10/1000µs pulse) and stand-off voltages from 3.3 to 376V.



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Selnì 3-phase induction motor picture by courtesy of Selnì Motors

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