Drive circuit basics

For a given size of a stepper motor, a limited space is available for the windings. In the process of optimizing a stepper motor drive system, an efficient utilization of the available winding space as well as a matching of driver and winding parameters are of great importance.

This chapter discusses the basic electrical characteristics of a stepper motor winding. Special attention is given to driving configurations and current control methods.

Figure 1. Winding of a typical Permanent Magnet stepper motor.

Winding resistance and inductance

The windings of a stepper motor are made up of several turns of copper wire. The wire is wound on plastic bobbin, which allows separate manufacturing of the winding, the stator and other mechanical parts. At a final stage of production the bobbin is mounted around the stator poles. Resistance and inductance and are two inherent physical properties of a winding, or any coil. These two basic factors also limit the possible performance of the motor.

The resistance of the windings is responsible for the major share of the power loss and heat up of the motor. Size and thermal characteristics of the winding and the motor limit the maximum allowable power dissipated in the winding. The power loss is given by:

$$P_R = R \cdot I_M^{\,2}$$

It is important to note that a motor should be used at its maximum power dissipation to be efficient. If a motor is running below its power dissipation limit, it means that it could be replaced by a smaller size motor, which most probably is less expensive
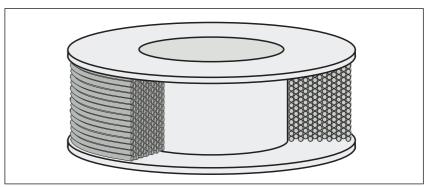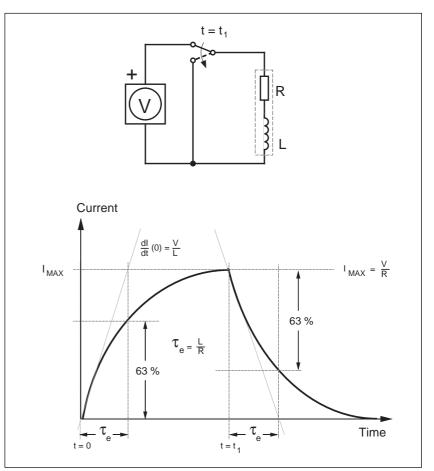

Figure 2. Current wave form in an inductive–resistive circuit.

How are the motor winding parameters affected by the number of turns and the wire diameter?

The crosssectional area of the winding is A. The resistance of the winding as a function of the number of turns is found by the following idealized calculation:

$R = \rho \cdot l / a$ where:

$a = A / n$, the cross-sectional area of the wire;
wire length $l = 2 \cdot \pi \cdot r \cdot n$; ρ is the resistivity of copper.

$R = \rho \cdot 2 \cdot \pi \cdot r \cdot n / (A / n) = 2 \cdot \pi \cdot \rho \cdot r \cdot n^2 / A \approx n^2$

The resistance is proportional to the square of the number of wire turns.

Inductance is calculated as (simplified):

$L = 2 \cdot \pi \cdot r^2 \cdot n^2 \approx n^2$

The inductance is proportional to the square of the number of wire turns.

To calculate the current rating we use the condition of constant power disspation:

$P_R = R \cdot I_M{}^2$
which leads to:

$I_M = \sqrt{ P_R / R } \approx \sqrt{ P_R / n^2 } \approx 1 / n$

Current is inversely proportional to the number of turns.

Torque is proportional to the flux F, which is proportional to the number of ampereturns in the winding:

$T \approx \Phi \approx n \cdot I_M \approx n \cdot (1 / n) = $ constant.

Torque is constant at a constant power dissipation level, regardless of the number of turns.
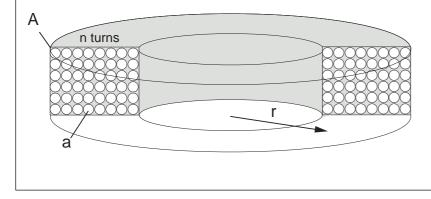
Rated voltage is:

$V_M = R \cdot I_M \approx n^2 \cdot (1 / n) \approx n$

Rated voltage is proportional to the number of turns.

Finally, the electrical time constant is:

$\tau_e = L / R \approx n^2 / n^2 = $ constant

The time constant is not affected by the number of turns.

Inductance makes the motor winding oppose current changes, and therefore limits high speed operation. Figure 2 shows the electrical characteristics of an inductive–resistive circuit. When a voltage is connected to the winding the current rises according to the equation

$I(t) = (V / R) \cdot (1 - e^{- t \cdot R / L })$

Initially the current increases at a rate of

$\delta I / \delta t \, (0) = V / L$

The rise rate decreases as the current approaches the final level:

$I_{MAX} = V / R$

The value of $\tau_e = L / R$ is defined as the electrical time constant of the circuit. τ_e is the time until the current reaches 63% ($1 - 1/e$) of its final value.

When the inductive–resistive circuit is disconnected and shorted at the instant $t = t_1$, the current starts to decrease:

$I(t) = (V / R) \cdot e^{- (t-t_1) \cdot R / L}$

at an initial rate of

$I(t) = - V / L$

When a square wave voltage is applied to the winding, which is the case when fullstepping a stepper motor, the current waveform will be smoothed. Figure 3 shows the current at three different frequencies. Above a certain frequency (B) the current never reaches its maximum value (C). As the torque of the motor is approximately proportional to the current, the maximum torque will be reduced as the stepping frequency increases.

To overcome the inductance and gain high speed performance of the motor two possibilities exist: Increase the current rise rate and/or decrease the time constant. As an increased resistance always results in an increased power loss, it is preferably the ratio V / L that should be increased to gain high speed performance.

To drive current through the winding, we should:

• use as high voltage as possible

• keep the inductance low.

Accordingly, a low inductance/resistance motor has a higher current rat-

ing. As the maximum current is limited by the driver, we find that high performance is highly dependant on the choice of driver.

The limiting factor of the motor is the power dissipation, and not the current itself. To utilize the motor efficiently, power dissipation should be at the maximum allowed level.

Basic winding parameters and dimensioning
Under the conditions of a constant maximum allowable power dissipation P_R and a given winding space, i. e. a given copper volume, the only parameter that could be altered is the number of wire turns, or correspondingly, the wire diameter. See the fact box, *"How are the winding parameters affected by the number of turns and the wire diameter?"* on previous page.

Drive circuit schemes

The stepper motor driver circuit has two major tasks:

- To change the current and flux direction in the phase windings

- To drive a controllable amount of current through the windings, and enabling as short current rise and fall times as possible for good high speed performance.

Flux direction control
Stepping of the stepper motor requires a change of the flux direction, independently in each phase. The direction change is done by changing the current direction, and may be done in two different ways, using a bipolar or a unipolar drive. Figure 4 shows the two schemes. Only one of the two phases is shown as the two phases are identical.

Bipolar drive
Bipolar drive refers to the principle where the current direction in one winding is changed by shifting the voltage polarity across the winding terminals. To change polarity a total of four switches are needed, forming an H-bride.

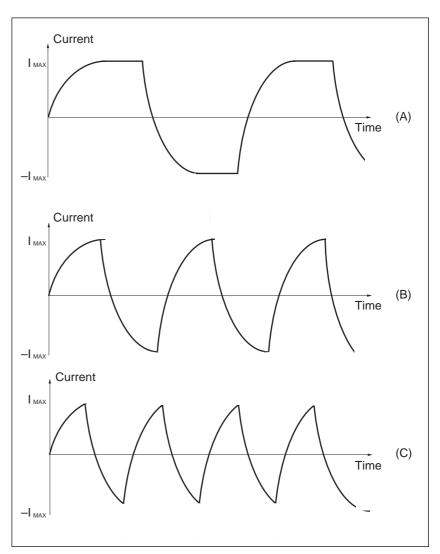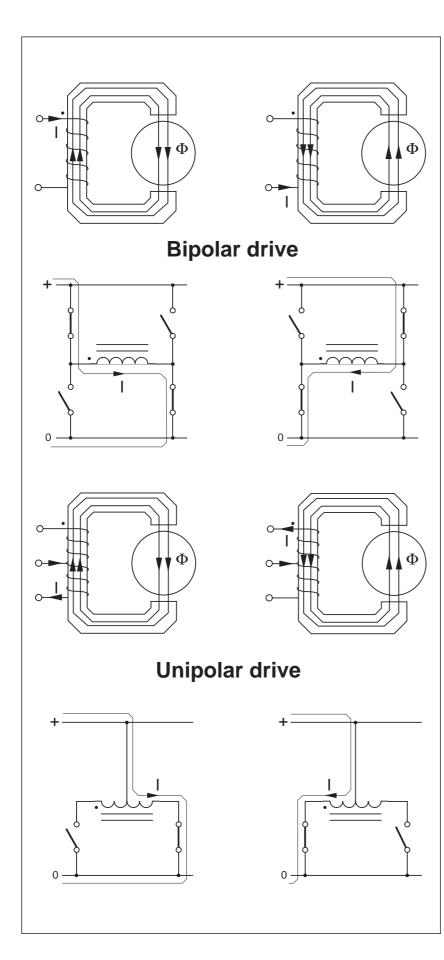The bipolar drive method requires one winding per phase. A two-phase

Figure 3. Current wave form in an inductive–resistive circuit.

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Bipolar drive

Unipolar drive

Figure 4. Bipolar and unipolar drive schemes to control the current and the flux direction in the phase winding.

motor will have two windings and accordingly four connecting leads.

Unipolar drive
The unipolar drive principle requires a winding with a center-tap, or two separate windings per phase. Flux direction is reversed by moving the current from one half of the winding to the other half. This method requires only two switches per phase. On the other hand, the unipolar drive utilizes only half the available copper volume of the winding. The power loss in the
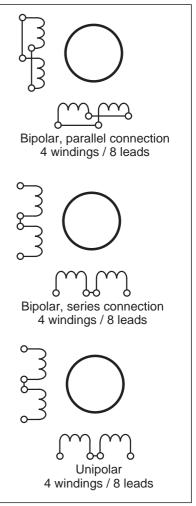

Bipolar, parallel connection
4 windings / 8 leads

Bipolar, series connection
4 windings / 8 leads

Unipolar
4 windings / 8 leads

Figure 5. Different winding configurations for bipolar and unipolar drive using an 8-lead motor.

winding is therefore twice the loss of a bipolar drive at the same output power.

The unipolar, centerttapped motor has three leads per phase, totally six leads for a two-phase motor. A motor having two separate windings per phase is usually referred to as an 8-lead motor. It may be connected both as a unipolar or a bipolar motor, see figure 5.

Current control

To control the torque as well as to limit the power dissipation in the winding resistance, the current must be controlled or limited. Furthermore, when half stepping a zero current level is needed, while microstepping requires a continuously variable current.

Two principles to limit the current are described here, the resistance limited drive and the chopper drive. Any of the methods may be realized as a bipolar or unipolar driver.

Resistance limitation of the current (L/R drive).
In this basic method the current is limited by supply voltage and the resistance of the winding, and if necessary, an additional external resistance (dropping resistor):

$$I_M = V_{supply} / (R + R_{ext})$$

If the nominal motor voltage is the same as the supply voltage, R_{ext} is excluded.

For a given motor, high speed performance is increased by increasing the supply voltage. An increased supply voltage in the resistance limited drive must be accompanied by an additional resistor (R_{ext}) in series with the winding to limit the current to the previous level. The time constant:

$$\tau_e = L / (R + R_{ext})$$

decreases, which shortens the current rise time. See figure 6. The penalty using this method is the power loss in the additional external resistors. Usually several watts has to be dissipated - and supplied. Spacious power resistors, heat removal considerations and a space consuming power supply reduce costeffectivenes and limits L/R drive scheme to small motors, rated around 1- 2 Watts.
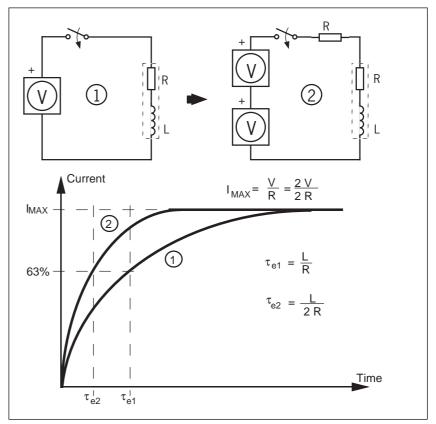
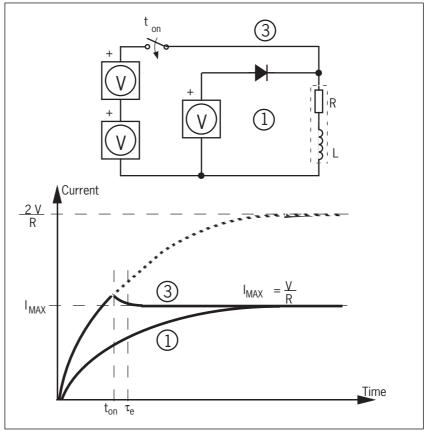

Figure 6. Resistance limitation of the current.

$$I_{MAX} = \frac{V}{R} = \frac{2 V}{2 R}$$

$$\tau_{e1} = \frac{L}{R}$$

$$\tau_{e2} = \frac{L}{2 R}$$

Figure 7. The bilevel drive.

$$I_{MAX} = \frac{V}{R}$$

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The bilevel L/R-drive
The bilevel L/R-drive provides a solution to the power waste using dropping resistors. In the beginning of the current build-up period, the winding is connected to a secondary high voltage supply. After a short time, when the current has reached its nominal level, the second level supply is disconnected. Figure 7 explains further. The disadvantage of bilevel drive is the need of a second level power supply. In some applications where 5 V and 12 V/24 V are available, it may be a cost effective solution, but, if not available, it is a costly method. It is possible to use voltage doubling techniques as well.

Current paths
Another very important consideration is current paths at turn-off and at phase shift. The inductive nature of the winding demands that a current path always exists. When using transistors as switches, diodes have to be added to enable current flow in both directions across the switch. For the bipolar driver four diodes, one for each switch, provide current paths according to figure 8. Note that there are two ways to turn the current off, either by turning all transistors off (path 3), or turn just one of the two conducting transistors off (path 2). The former gives a fast current decay as the energy stored in the winding induc-

tance is discharged at a high voltage, V_{supply}. The latter gives a slow current decay as the counter voltage is only two diode voltage drops and the resistive voltage drop across the winding resistance. At phase shift the current will decay rapidly as both conducting transistors are turned off. For high speed halfstepping a rapid decay to zero in the half step position is important.

The unipolar driver is somewhat more complicated when it comes to current paths. The reason being the full coupling between the two halves of each phase winding, except for a small amount of leakage inductance. Figure 9 shows some possible
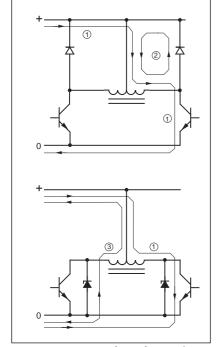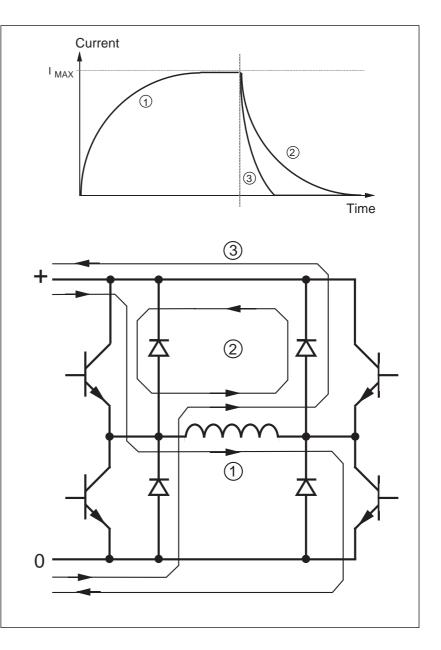

Figure 9. Current paths in the unipolar driver.

Figure 8. Current paths in the bipolar driver.

schemes. Because of the coupling, large voltage transients—at least twice the supply voltage—occurs when switching on and off. The transistor switches must be rated at a much higher voltage than the supply voltage. The leakage inductance will also cause transients. Therefore the switching transistors has to be protected by snubber networks or zener diodes.

Chopper control
The chopper driver provides an optimal solution both to current control and fast current build-up and reversal. The basic idea is to use a supply voltage which is several times higher than the nominal voltage of the motor. The current rise rate, which initially is V/L, is thereby possible to increase substantially. The ratio V_M/V_{supply} is called the overdrive ratio. By controlling the duty cycle of the chopper, an average voltage and an average current equal to the nominal motor voltage and current are created. The chopper is usually configured for constant current regulation, see figures 10 - 12.

Constant current regulation is achieved by switching the output current to the windings. This is done by sensing the peak current through the winding via a current-sensing resistor, effectively connected in series with the motor winding. As the current increases, a voltage develops across the sensing resistor, which is fed back to the comparator. At the predetermined level, defined by the voltage at the reference input, the comparator resets the flip-flop, which turns off the output transistor. The current decreases

until the clock oscillator triggers the flip-flops, which turns on the output transistor again, and the cycle is repeated.

The advantage of the constant current control is a precise control of the developed torque, regardless of power supply voltage variations. It also gives the shortest possible current build-up and reversal time. Power dissipation is minimized, as well as supply current. Supply current is not the same as the motor current in a copper drive. It is the motor current multiplied by the dutycycle, at standstill typically

$$I_{supply} = I_M \cdot (V_M / V_{supply})$$

Figure 12 shows an H-bridge configured as a constant current chopper. Depending on how the H-bridge is switched during the turn-off period, the current will either recirculate through one transistor and one diode (path 2), giving the slow current decay, or recirculate back through the power supply (path 3). The advantage of feeding the power back to the power supply is the fast current decay and the ability to quickly reduce to a lower current level. One example is when microstepping at a negative slope, which may be impossible to follow if the current decay rate is lower than the slope demands. The disadvantage with fast current decay is the increased current ripple, which can cause iron losses in the motor. Further discussion about the concept of fast/slow current decay can be found in the Half-stepping Techinques and Microstepping chapters.
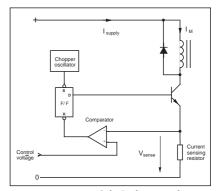
Figure 10. A simplified schematic shows the principle of constant current chopper regulation.
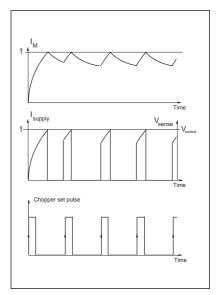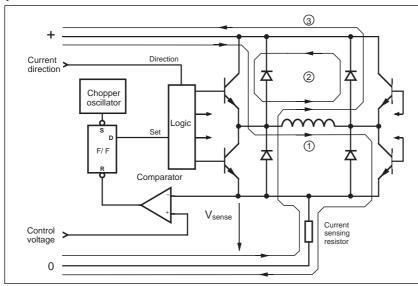
Figure 11. Current waveform in the basic chopper circuit.

Figure 12. An H-bridge configured as a constant current chopper.