



AN235

Application note

Stepper motor driving

By Thomas Hopkins

Introduction

Dedicated integrated circuits have dramatically simplified stepper motor driving. To apply these ICs, designers need little specific knowledge of motor driving techniques, but an understanding of the basics helps in finding the best solution. This note explains the basics of stepper motor driving and describes the drive techniques used today.

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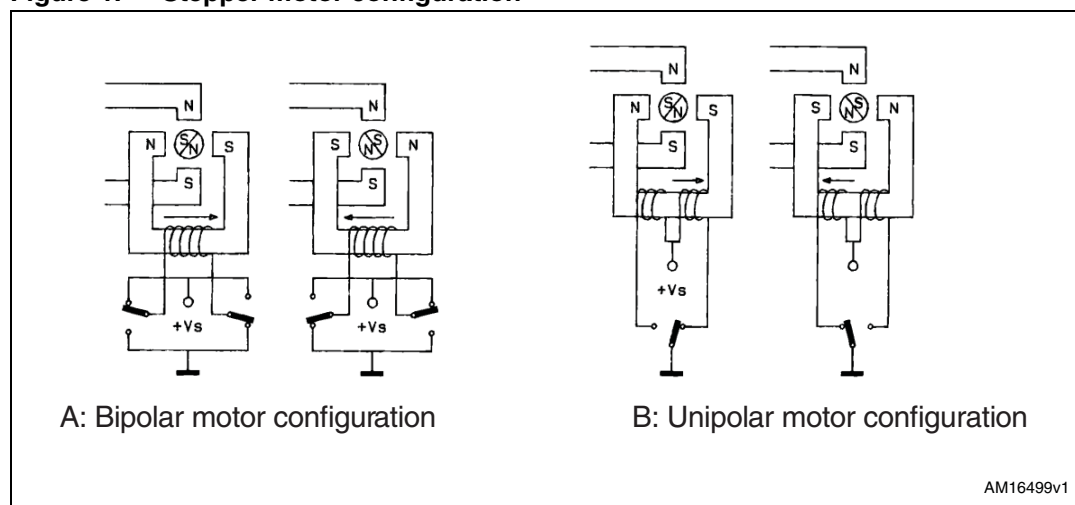
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1 Motor configurations

From a circuit designer's point of view stepper motors can be divided into two basic types: unipolar and bipolar. A stepper motor moves one step when the direction of current flow in the field coil(s) changes, reversing the magnetic field of the stator poles. The difference between unipolar and bipolar motors lies in the way that this reversal of the magnetic field is achieved ([Figure 1](#)). The bipolar motor has one coil per phase and needs two changeover switches, or a full-bridge, for each phase. The switches reverse the direction of current flow in the coil. The unipolar motor has a center tapped coil on each phase and needs one changeover switch, or two transistors to ground, for each phase. The switches select which half of the coil current flows through.

Figure 1. Stepper motor configuration

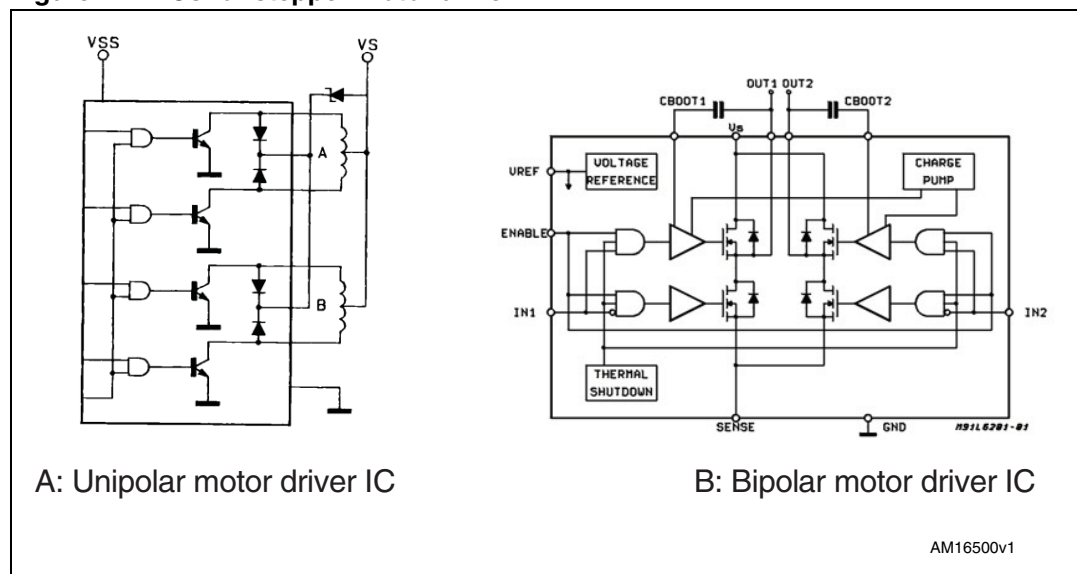


The advantage of the bipolar circuit is that there is only one winding, with a good bulk factor (low winding resistance). The main disadvantage is the more complex drive circuit needing the two changeover switches for each phase. This is implemented as a full H-bridge for each phase and requires more transistors than the unipolar configuration.

The unipolar circuit needs only one changeover switch, implemented as two transistors to ground, for each phase. Its enormous disadvantage is, however, that a double bifilar winding is required. This means that at a specific bulk factor the wire is thinner and the resistance is much higher. The problems involved are going to be discussed in this application note. Unipolar motors are still popular today for low performance applications because the drive circuit is simpler when implemented with discrete devices. However, with the integrated circuits available today, bipolar motors can be driven with no more components than the unipolar motors.

[Figure 2](#) compares integrated unipolar and bipolar driver ICs. The unipolar driver integrates the four transistors to ground and the four freewheeling diodes. The bipolar driver integrates two full H-bridges and the 8 freewheeling diodes.

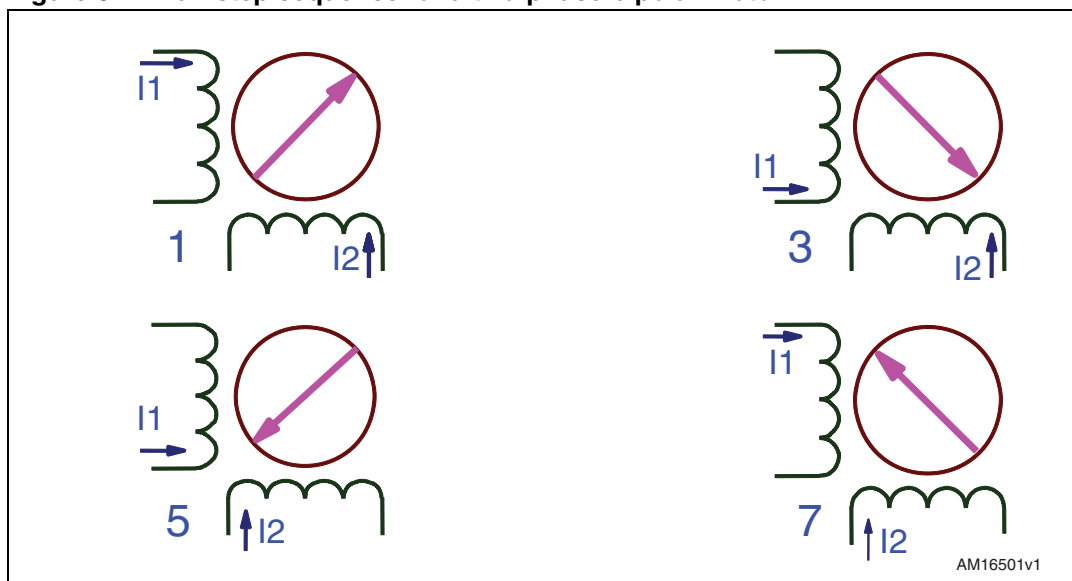
Figure 2. ICs for stepper motor drive



2 Step sequence

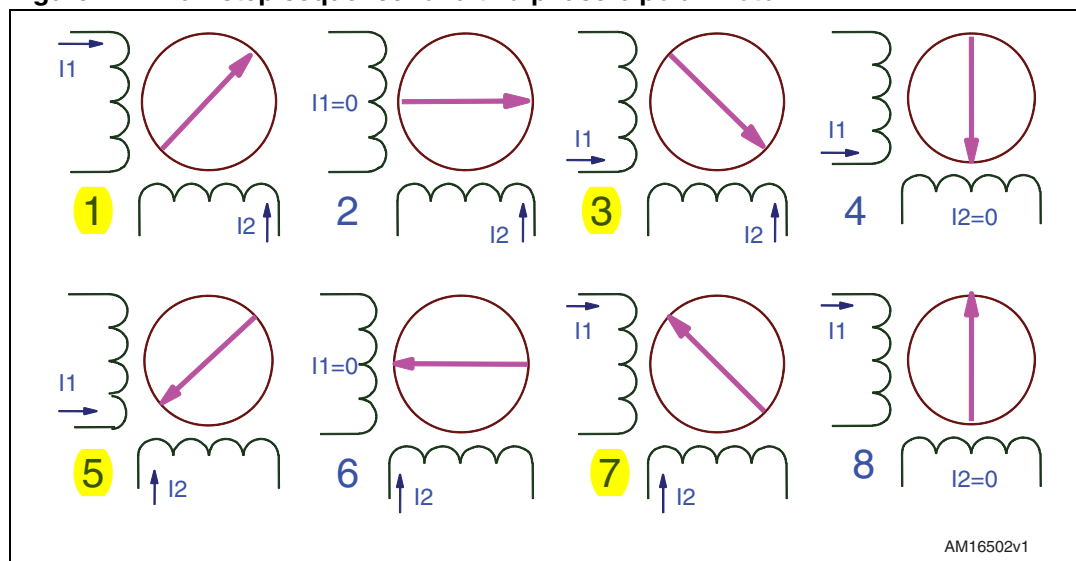
With either motor configuration, the motor makes one step each time the polarity of the current in the stator winding changes. For a motor with one pole pair on the rotor, this corresponds to 4 steps per electrical cycle. [Figure 3](#) shows the step sequence and idealized current waveform for a two-phase bipolar stepper motor. In [Figure 3](#), each time the current in one of the windings is reversed, the motor makes one step of 90° . Of course no stepper motors would want to use such a coarse step. Typical stepper motors are 1.8° or 7.5° per step corresponding to 200 or 48 steps per rotation. A 200 step per rotation motor would have 50 pole pairs on the rotor and need 50 electrical cycles per mechanical rotation.

Figure 3. Full-step sequence for a two-phase bipolar motor



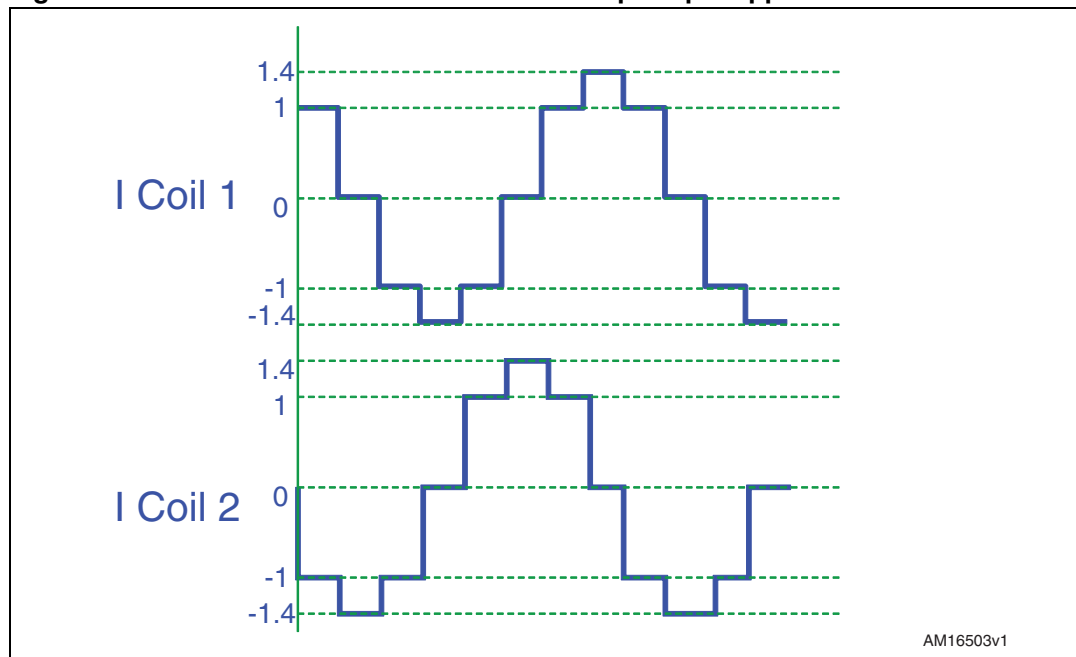
In [Figure 3](#) the current is reversed to make each step. However it is possible to have an intermediate, half-step, position by simply switching the current in one coil off before switching it on in the reverse direction. [Figure 4](#) shows the sequence for half-step drive and the idealized current waveform for a two-phase bipolar stepper motor. In half-step we now have 8 half-steps per electrical cycle and have doubled the effective resolution of the stepper motor.

Figure 4. Half-step sequence for a two-phase bipolar motor



The main advantage of half-step is the increased resolution. The main disadvantage of half-step operation is that in the half-step state the motor has only about 70% of the torque as when driven to the full-step state. This is the direct result of lower flux density in the stator. In the full-step state the magnetic vector generated by the stator is the vector sum of the magnetic vectors of the two coils. When both coils are excited evenly, the vector sum of the two is at a 45° angle and has a magnitude of $\sqrt{2}$ times the magnitude of each individual vector. When only one coil is driven, as in the half-step states, the total magnetic vector is only the vector for one coil. This results in a 30% reduction in torque for the half-steps. The reduction in torque can be compensated for by increasing the current in the one driven coil for the half-steps. If the current is increased by $\sqrt{2}$ when only one coil is driven, as shown in [Figure 5](#), the torque is essentially equal for both full-step and half-step states.

Figure 5. Current waveform to reduce half-step torque ripple



3 The bipolar motor produces more torque

The torque of the stepper motor is proportional to the magnetic field intensity of the stator windings, which is proportional to the number of turns and the current in the winding, so torque is proportional to $N \cdot I$. A natural limit against any current increase is the danger of saturating the iron core, though this typically isn't the major factor for stepper motors. Much more important is the maximum temperature rise of the motor, due to the power loss in the stator windings. The dissipation in the windings is equal to the square of the current times the winding resistance. Since the resistance is proportional to the number of turns, dissipation is proportional to $N \cdot I^2$. This gives an advantage to the bipolar configuration which better uses the copper in the windings compared to a unipolar motor.

Consider the motor shown in [Figure 1 B](#). When it is driven as a unipolar motor, current flows from V_s to ground in one half of the center tapped winding through N turns. The power dissipation and torque for the unipolar configuration are:

Equation 1

$$P_d \sim N \cdot I_u^2 \quad \text{and} \quad T_u \sim N \cdot I_u$$

If the same motor is driven as a bipolar motor, from the ends with the center tap left unconnected, the current flows through both halves or $2N$ turns and the dissipation and torque are:

Equation 2

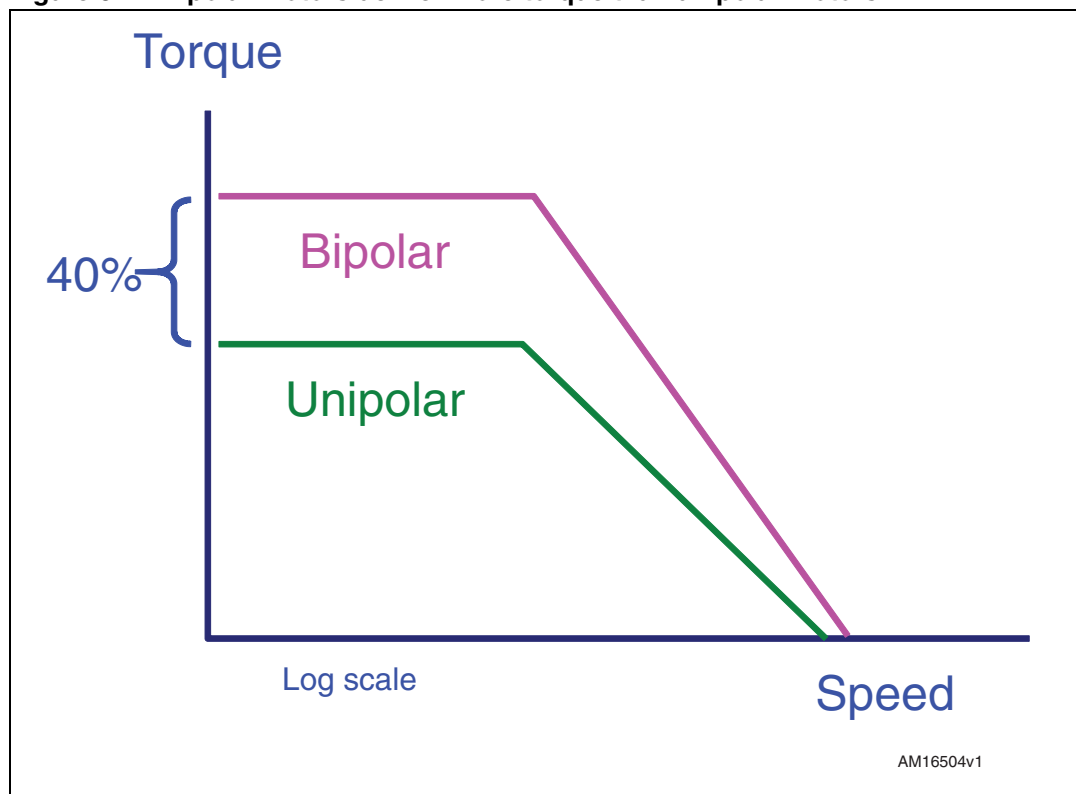
$$P_d \sim 2N \cdot I_b^2 \quad \text{and} \quad T_b \sim 2N I_b$$

If P_d is set to be the same for both drive conditions, substituting one equation into the other shows that

Equation 3

$$I_b = I_u \frac{1}{\sqrt{2}} \quad \text{and} \quad T_b = \sqrt{2} \cdot T_u$$

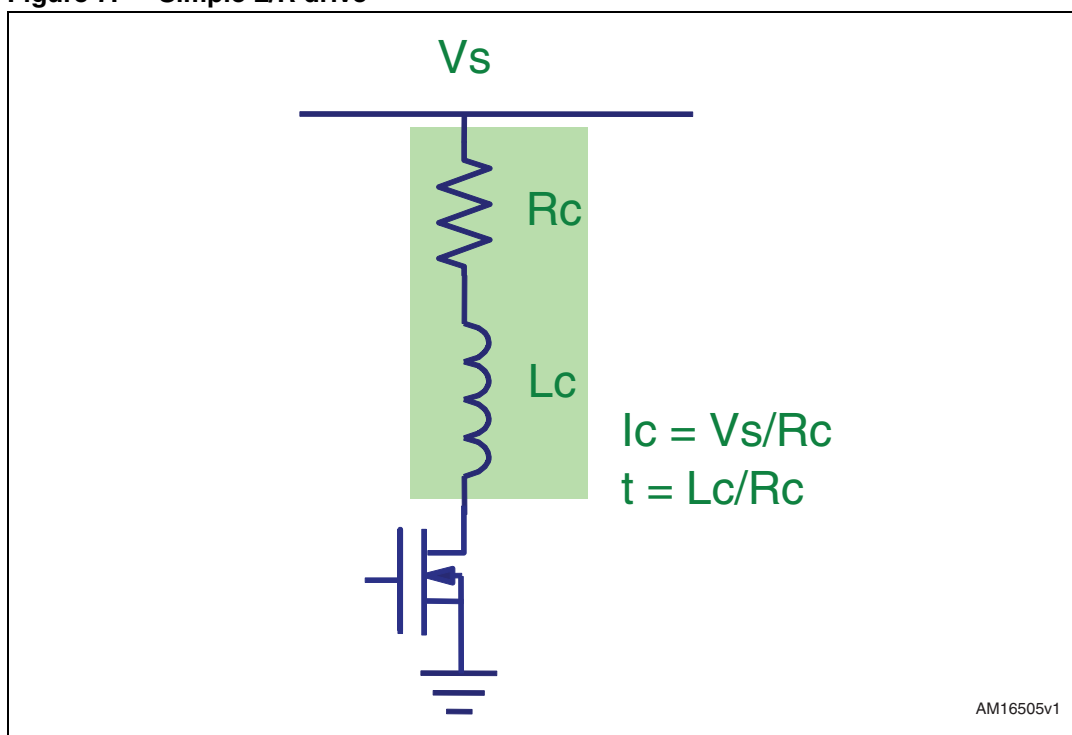
Since the bipolar driven motor better uses the copper in the windings it can deliver more torque with the same dissipation in the windings than a unipolar motor built on the same frame. Another way to look at it is that the bipolar motor has less dissipation to produce the same torque.

Figure 6. Bipolar motors deliver more torque than unipolar motors

4 Motor drive topologies

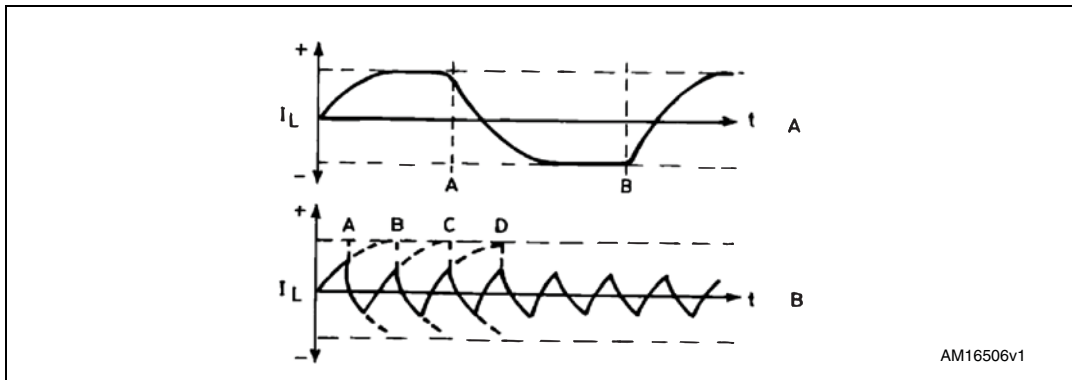
For a stepper motor, the motor current is determined primarily by the drive voltage and the motor impedance (resistance and inductance). A simple and popular drive topology is to supply only as much voltage as needed, utilizing the resistance (R_L) of the winding to limit the current as shown in [Figure 7](#). For simplicity, the single FET in [Figure 7](#), [Figure 9](#) and [Figure 10](#) represents either a FET and clamping diode for the unipolar motor drive or a composite of the two diagonal switches of a full-bridge the bipolar drive. A typical motor with 5 V and 1 A on its name plate means that with a 5 V drive the resulting current is 1 A, corresponding to having a 5 Ω coil resistance.

Figure 7. Simple L/R drive



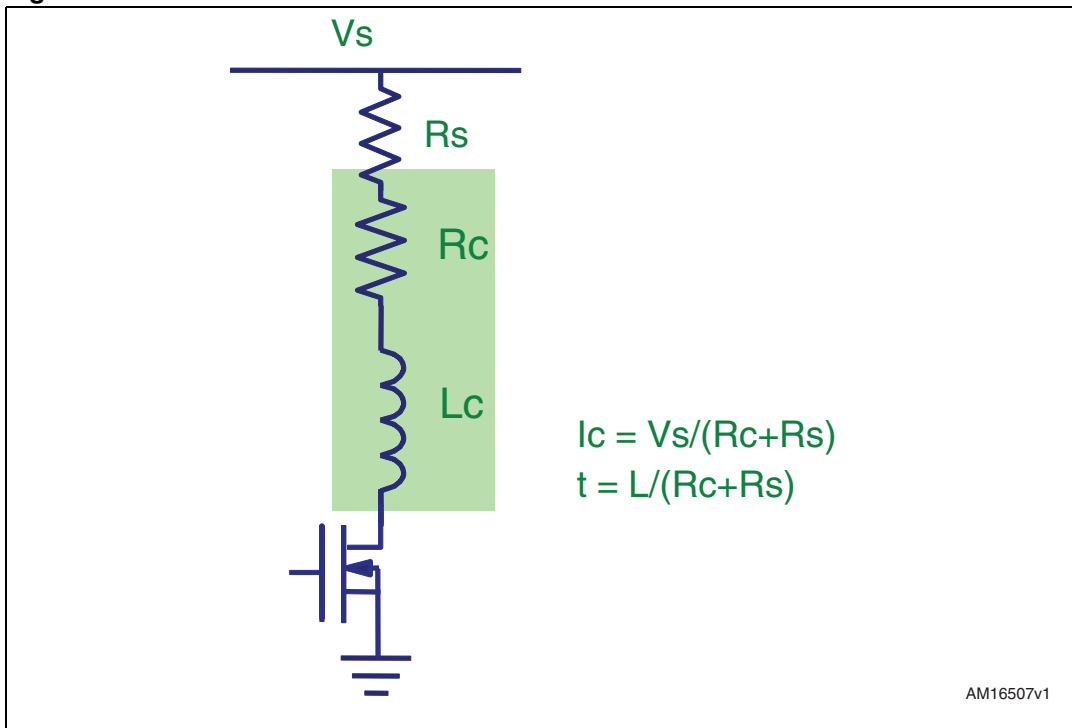
As already discussed, the torque of the motor is, among others, proportional to the winding current. In the full-step sequence, the motor changes the polarity of the winding current in the same stator winding every two steps. The rate at which the current changes its direction, in the form of an exponential function, depends on the winding inductance, the coil resistance and drive voltage. [Figure 8 A](#) shows that at a low step rate the winding current I_L reaches its nominal value V_L/R_L before the direction is changed at the next step. However, at higher speeds, the polarity of the stator current is changed more often and the current no longer reaches its saturating value because of the limited change time. Clearly, the peak and the area under the current waveform diminish with increasing step rate, reducing torque and power. This is shown in [Figure 8 B](#).

Figure 8. Peak winding current decreases at higher speed, limited by motor inductance



The only way to have the current rise more quickly is to have a higher drive voltage or a lower inductance. One method used to get better performance is to increase the drive voltage and use an external resistance to limit the current to the original value as shown in [Figure 9](#). The exponential time constant is L/R so increasing the resistance reduces the rise time. Since the asymptotic current is set by the resistance, the time constant and current can be set by selecting the drive voltage and the external resistance. This topology, referred to as L/nR drive, was commonly used in early printers. Its significant disadvantage is the very significant dissipation in the external resistance. For the 1 A motor the dissipation in the external resistance is around 20 W.

Figure 9. L/nR drive

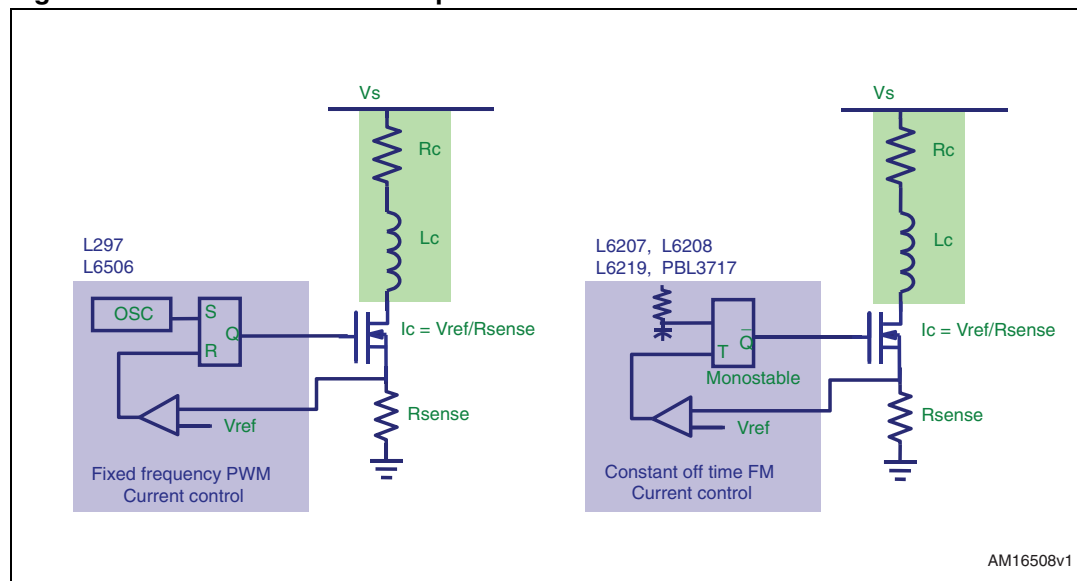


What is really needed is a low dissipation drive circuit that would give the fast rise times of a higher drive voltage and limit the current to the desired value without the high dissipation associated with the external resistance in the L/nR drive configuration. Such a drive can be implemented using switch mode techniques as show in [Figure 10](#). Here the peak current is

set by the voltage reference and the value of the sense resistor so that each time the current reaches the set peak value the switch is turned off for the remainder of the period. Since the only losses in this technique are the saturation loss of the switch and the resistive loss in the sense resistor and coil resistance, the total efficiency is very high.

The average current drawn from the power supply is less than the winding current due to the chopping. When the transistor is on, current is being drawn from the supply, however, during the off-time the current is recirculating locally and there is no current from the power supply. This type of phase current control, that has to be done separately for each motor phase, leads to the best ratio between the supplied electrical and delivered mechanical energy.

Figure 10. Switch mode drive implementations



It would make no sense to apply the same principle to a current controlled unipolar circuit, as additional switches for each phase would be necessary for the shortening out of the windings during the off-time and thus the number of components would be similar to the bipolar drive. Moreover, there would be the previously discussed torque disadvantage.

Figure 11. Current waveforms for L/R, L/nR and switch mode drive

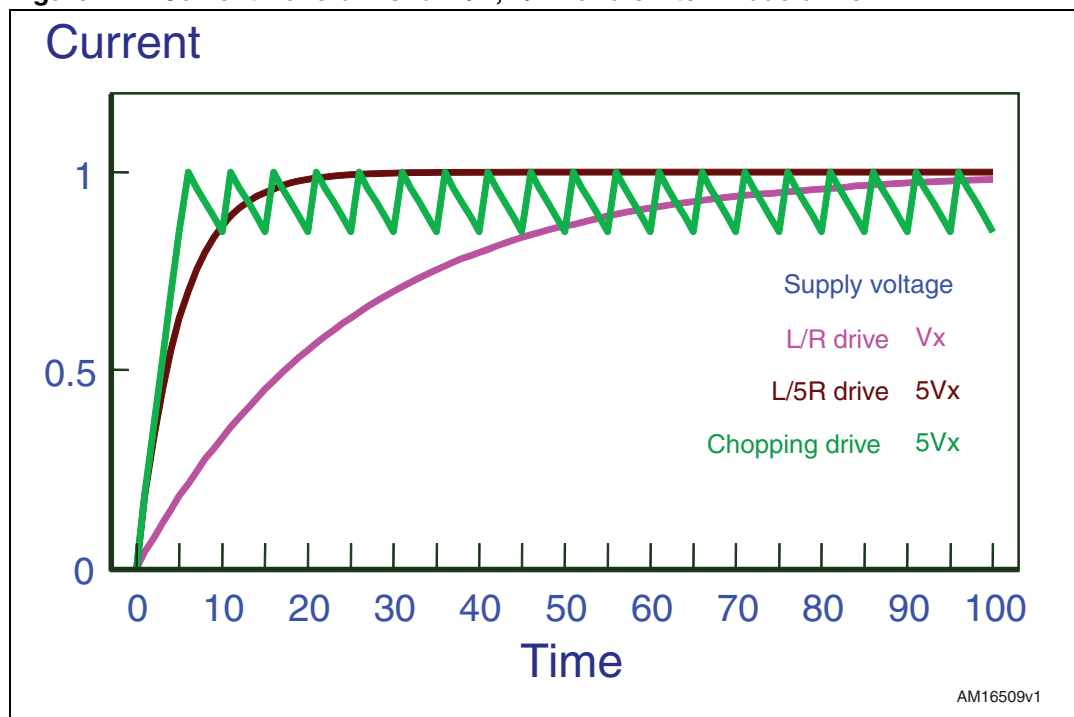
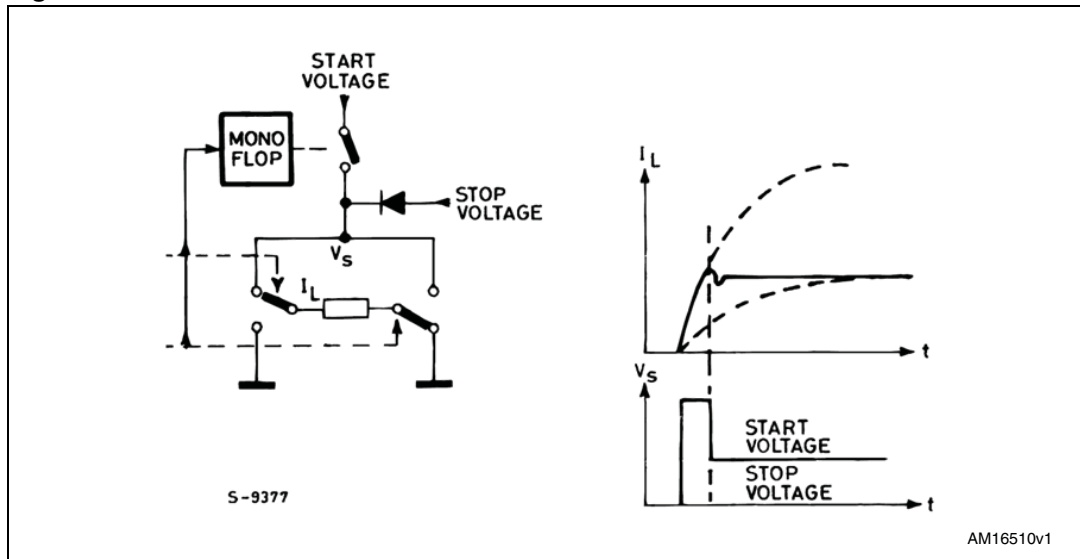


Figure 11 compares the current rise time for the three drive topologies. The comparison is done for a 5 V, 1 A motor. The L/R drive uses the motor's rated voltage, the L/nR uses five times the motor rated voltage and an external resistor equal to four times the winding resistance and the switch mode drive uses a supply voltage five times the motor rated voltage with the peak current set equal to the motor rated voltage divided by the winding resistance (1 A). In each case the final current reaches 1 A but the figure clearly shows the faster rise time of the higher voltage drives. This faster rise significantly improves the torque at higher step rates.

Another drive topology that may be used is a bilevel drive, where a higher voltage is applied during the transition and then the supply voltage is dropped back down to the lower voltage to maintain the current. The circuit shown in Figure 11 applies a high voltage, without the additional limit resistor, during the time set by the monostable for each transition. When the monostable times out, the switch is opened and the voltage is reduced to the lower voltage that is just enough to maintain the current.

Figure 12. Bilevel current drive

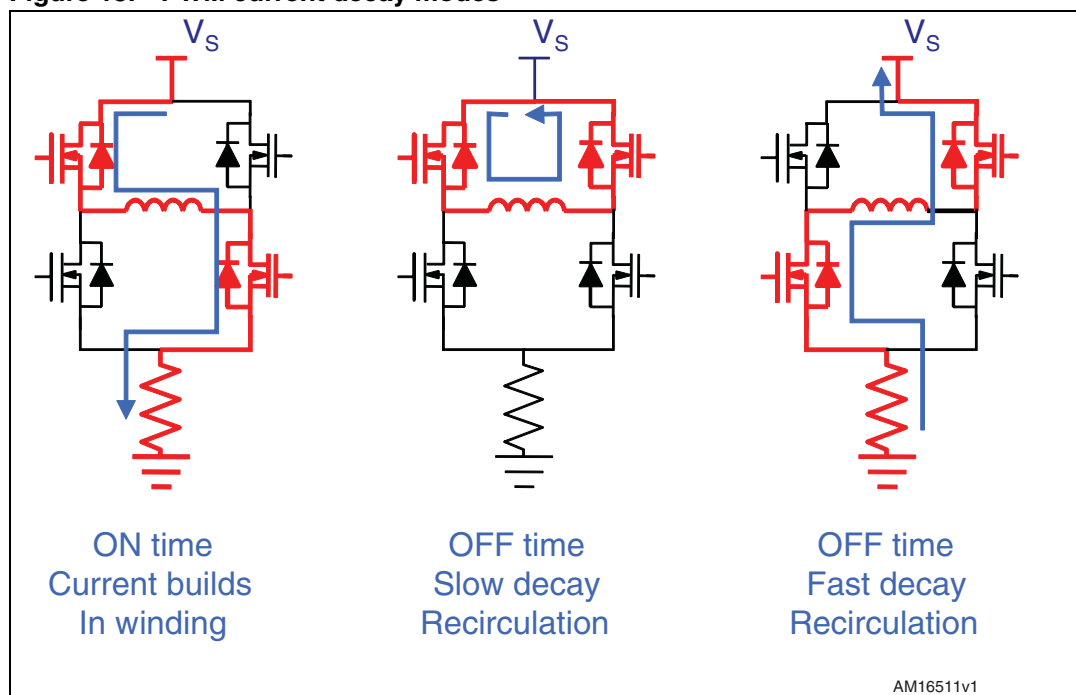


This configuration requires additional power components to switch the supply voltage that are not needed with the switch mode technique and is not often used.

5 Slow versus fast decay

When implementing current controlled motor drives, the designer has a choice of the recirculation path the current flows in during the "off" time. [Figure 12](#) shows the two recirculation options implemented in the L6208, or the L6203. Applying the chopping to only one side of the bridge allows the current to recirculate around a low voltage loop, in the upper transistors within the bridge. Since the rate of change of the current is controlled primarily by the L/R time constant of the motor, the current decays relatively slowly, hence the designation of slow decay mode. Applying the chopping signal to both sides of the bridge results in a higher voltage across the coil since the current is recirculating back through the power supply. The higher voltage across coil forces a faster decay of current, hence a fast decay mode.

Figure 13. PWM current decay modes



The selection of the decay mode influences the operation of a drive in several ways. The most obvious is the magnitude of the ripple current. Drives implemented using the fast decay mode have, for the same off-time or chopping frequency, a higher ripple current than drives implemented using a slow decay mode, as shown in [Figure 13](#). This difference in itself is not significant for most stepper motor drives. Issues with the stability of the current control loop are discussed elsewhere [1]. Generally for full-step and half-step drives the slow decay mode is preferred since it reduces the current ripple and, for many driver ICs, the dissipation in the device.

Figure 14. Ripple current with slow decay and fast decay mode drive

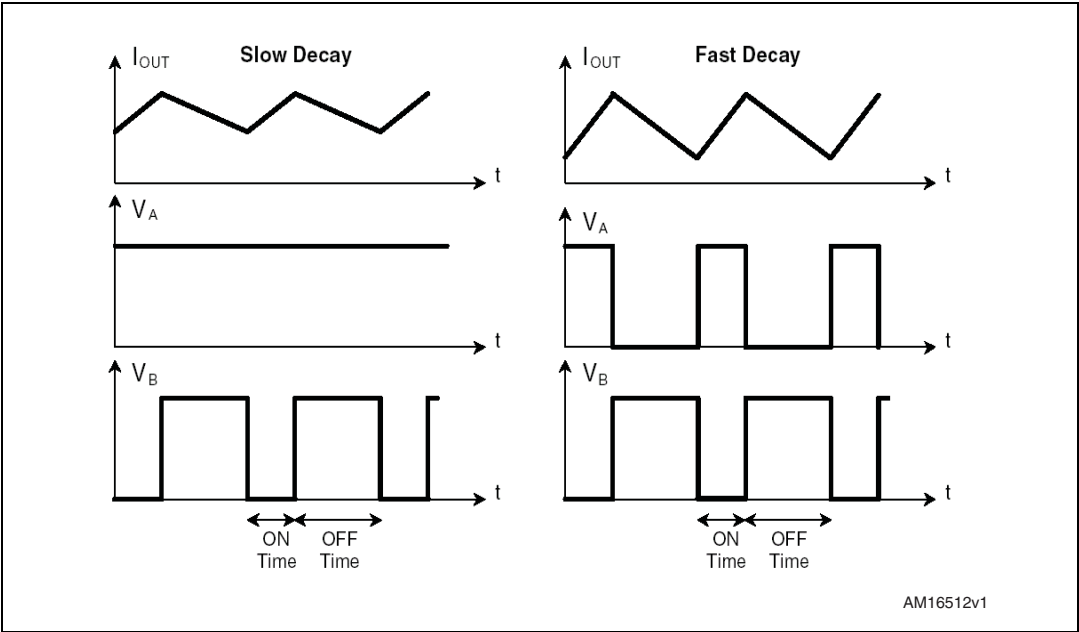
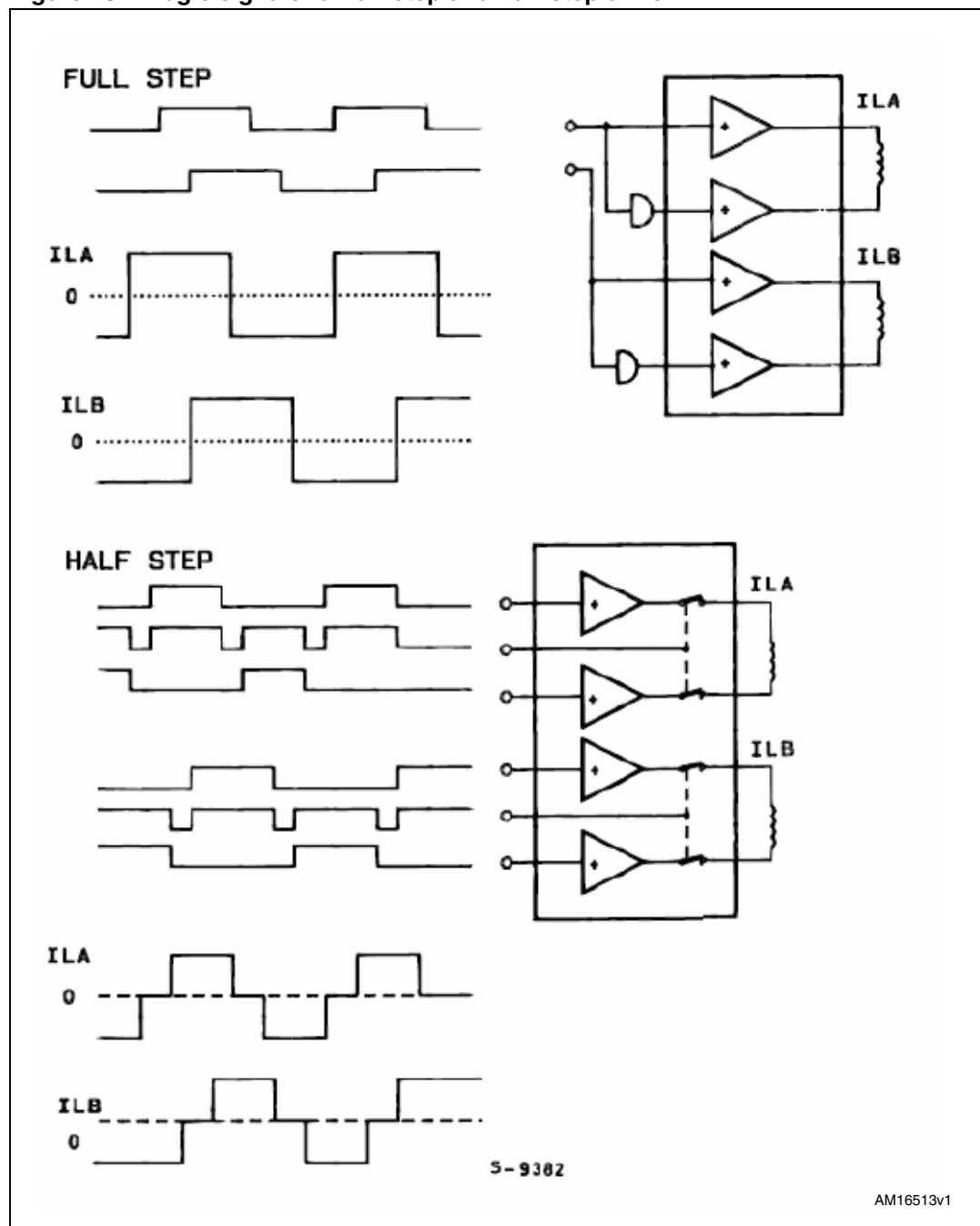


Figure 15. Logic signals for full-step and half-step drive

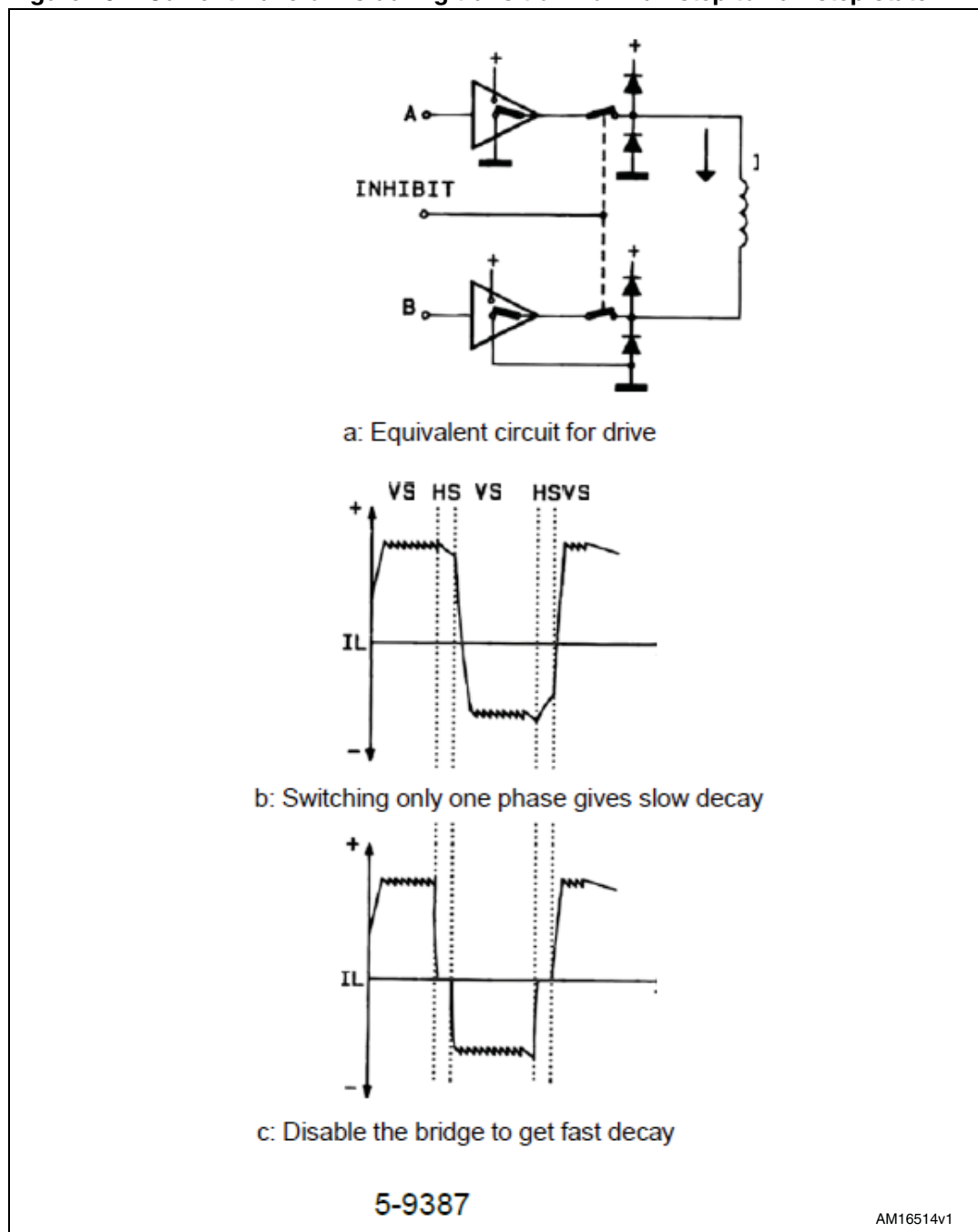


6 Control signals

In most applications the stepper motor driver IC is controlled by a microcontroller that generates the commutation sequence for the motor. [Figure 15](#) shows the typical control signals from the microcontroller for operating in full-step and half-step modes. In the simplest form, a full-step drive needs two square waves in quadrature to drive the motor. The rotational direction is determined by which of the two phases is leading the other and the rotational speed is directly proportional to the clock frequency. More often, since the switch mode current control signals are ANDed with the phase control, four signals to the drive IC are actually required, one for each half-bridge.

In the half-step state one of the motor phases is off with zero current. When moving from the full-step state to the half-step state the current must fully discharged to reach zero current. Although simply taking the input that was high to a low-state would eventually cause the current to decay to zero, it leaves the bridge in a slow decay mode with the current circulating around the two low transistors in the bridge. For high step rated, the current may not decay to zero during the step, as shown in [Figure 16 b](#).

Figure 16. Current waveforms during transition from full-step to half-step state

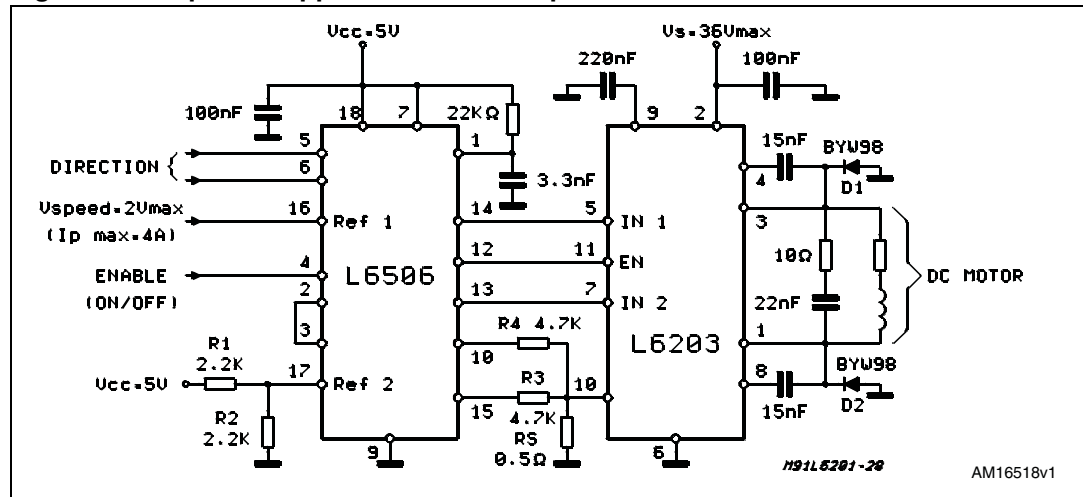


To get the fastest decay from a full-step to a half-step state the bridge should be disabled so that both of the transistors that were on are switched off. This puts the bridge in a fast decay mode and the current decays more quickly, as shown in [Figure 16 c](#). For half-step operation an additional two signals are required to inhibit the bridge and put it in tristate during the steps when there is no current in that phase. [Figure 15](#) shows the drive signals required for a driver like the L298 or L6203.

The six commutation signals can easily be generated from a microcontroller, but the current control is typically implemented in circuitry that is added between the microcontroller and

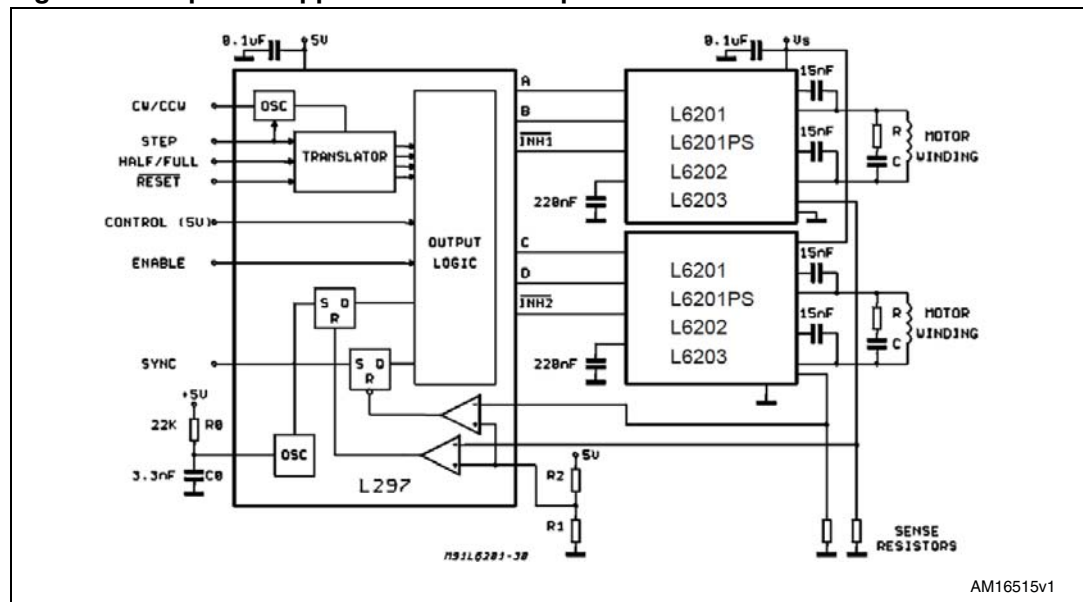
the driver IC, as shown in [Figure 17](#). Here a dedicated current control IC, the L6506, combines the commutation signals with the current control signals and then passed the 6 lines to the driver IC. Some driver ICs, like the L6219 or the L6207, have the current control built into the driver IC.

Figure 17. Bipolar stepper motor drive implemented with the L6506 and the L6203



Alternatively, logic circuitry or a dedicated IC like the L297 can generate the control signals from a step clock and direction signal. [Figure 18](#) shows a drive circuit using the L297 and the L6203. In this circuit the microcontroller needs to supply only the STEP and the CW/CCW signals. Since most applications do not switch between full-step and half-step, the HALF/FULL signal can usually be hard wired to the desired operation condition.

Figure 18. Bipolar stepper motor driver implemented with the L297 and the L6203



As discussed earlier the torque ripple in half-step can be decreased by increasing the current in the winding during the half-step states. The circuit in [Figure 19](#) detects when one of the inhibit lines is low and increased the voltage at the REF input of the L297 to increase the current during the half-step.

7 References

1. Stepper motor driver considerations, common problems and solutions, AN460.

8 Revision history

Table 1. Document revision history

Date	Revision	Changes
02-Jul-1988	1	Initial release.
14-Nov-2012	2	Changed: Figure 3 , Figure 4 , Figure 5 , Figure 6 , Figure 7 , Figure 9 , Figure 10 , Figure 11 , Figure 13 , Figure 14 and Figure 17 . Added: Section 2 . Updated: drive configuration topic. Removed: microstepping section. Minor text changes.

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