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STEPPER MOTOR DRIVER CONSIDERATIONS
COMMON PROBLEMS & SOLUTIONS

by Thomas L. Hopkins

This note explains how to avoid same of the more common pitfalls in motor drive design. It is based on the author's experience in responding to enquiries from the field.

INTRODUCTION

Over the years while working with stepper motor users, many of the same questions keep occurring from novice as well as experienced users of stepper motors. This application note is intended as a collection of answers to commonly asked questions about stepper motors and driver design. In addition the reference list contains a number of other application notes, books and articles that a designer may find useful in applying stepper motors.

Throughout the course of this discussion the reader will find references to the L6201, L6202 and L6203. Since these devices are the same die and differ only in package, any reference to one of the devices should be considered to mean any of the three devices.
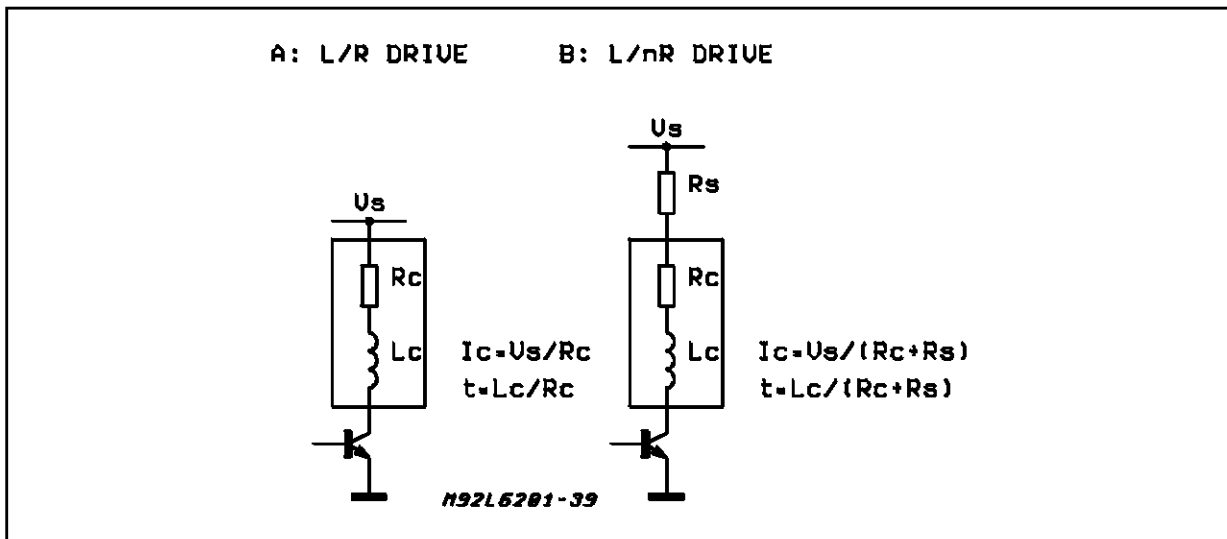
Motor Selection (Unipolar vs Bipolar)

Stepper motors in common use can be divided into general classes, Unipolar driven motors and Bipolar driven motors. In the past unipolar motors were common and preferred for their simple drive configurations. However, with the advent of cost effective integrated drivers, bipolar motors are now more common. These bipolar motors typically produce a higher torque in a given form factor [1].

Drive Topology Selection

Depending on the torque and speed required from a stepper motor there are several motor drive topologies available [5, chapter3]. At low speeds a simple direct voltage drive, giving the motor just sufficient voltage so that the internal resistance of the motor limits the current to the allowed value as shown in Figure 1A, may be sufficient. However at higher rotational speeds there is a significant fall off of torque since the winding inductance limits the rate of change of the current and the current can no longer reach it's full value in each step, as shown in Figure 2.
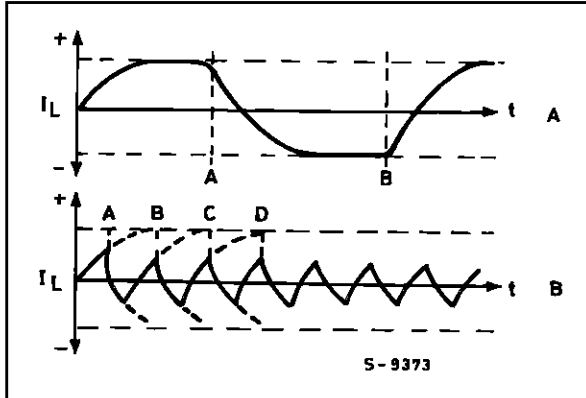
Figure 1: Simple direct voltage unipolar motors drive.

Figure 2: Direct voltage drive.
       A - low speed;
       B - too high speed generates fall of
       torque.

One solution is to use what is commonly referred to as an L/nR drive (Fig. 1B). In this topology a higher voltage is used and the current limit is set by an external resistor in series with the motor winding such that the sum of the external resistance and the internal winding resistance limits the current to the allowed value. This drive technique increases the current slew rate and typically provides better torque at high rotational speed. However there is a significant penalty paid in additional dissipation in the external resistances.

To avoid the additional dissipation a chopping controlled current drive may be employed, as shown in Figure 3. In this technique the current through the motor is sensed and controlled by a chopping control circuit so that it is maintained within the rated level. Devices like the L297, L6506 and PBL3717A implement this type of control. This technique improves the current rise time in the motor and improves the torque at high speeds while maintaining a high efficiency in the drive [2]. Figure 4 shows a comparison between the winding current wave forms for the same motor driven in these three techniques.

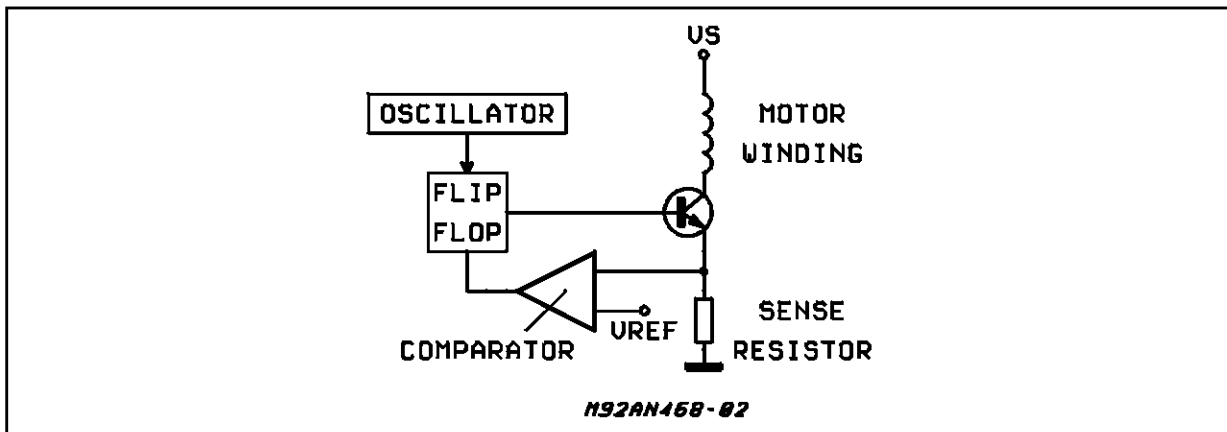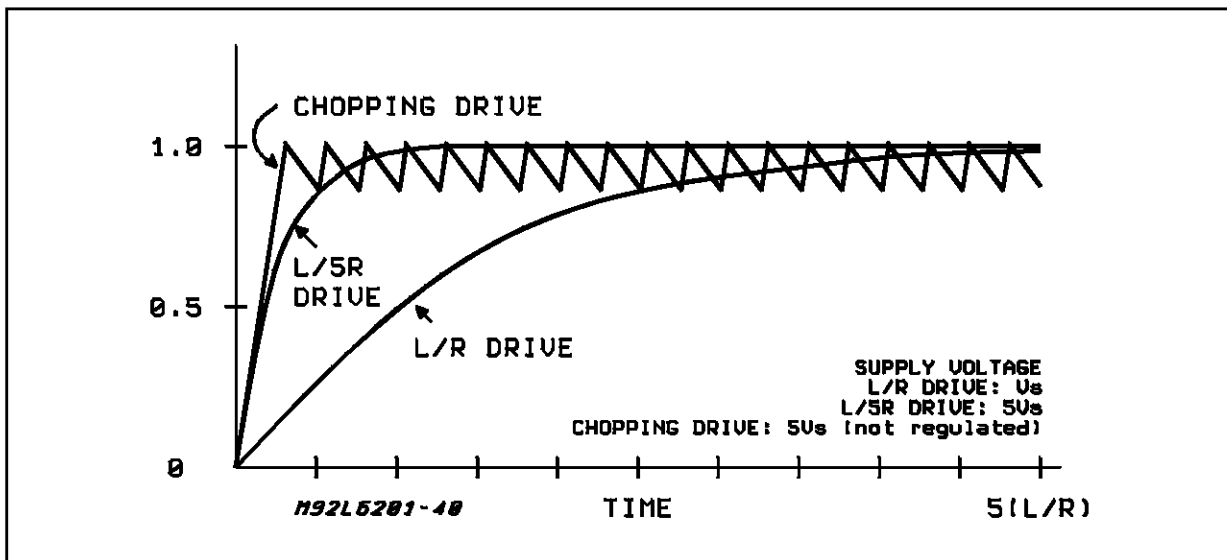**Figure 3:** Chopper drive provides better performance.

Figure 4: Motor current using L/R, L/5R and chopper constant current drive.

In general the best performance, in terms of torque, is achieved using the chopping current control technique [2]. This technique also allows easy implementation of multiple current level drive techniques to improve the motor performance. [1]

Driving a Unipolar Motor with the L298N or L6202

Although it is not the optimal solution, design constraints sometimes limit the motor selection. In the case where the designer is looking for a highly integrated drive stage with improved performance over previous designs but is constrained to drive a unipolar wound (6 leaded) motor it is possible to drive the motor with H-Bridge drivers like the L298N or L6202. To drive such a motor the center tap of the motor should be left unconnected and the two ends of the common windings are connected to the bridge outputs, as shown in Figure 5. In this configuration the user should notice a marked improvement in torque for the same coil current, or put another way, the same torque output will be achieved with a lower coil current.
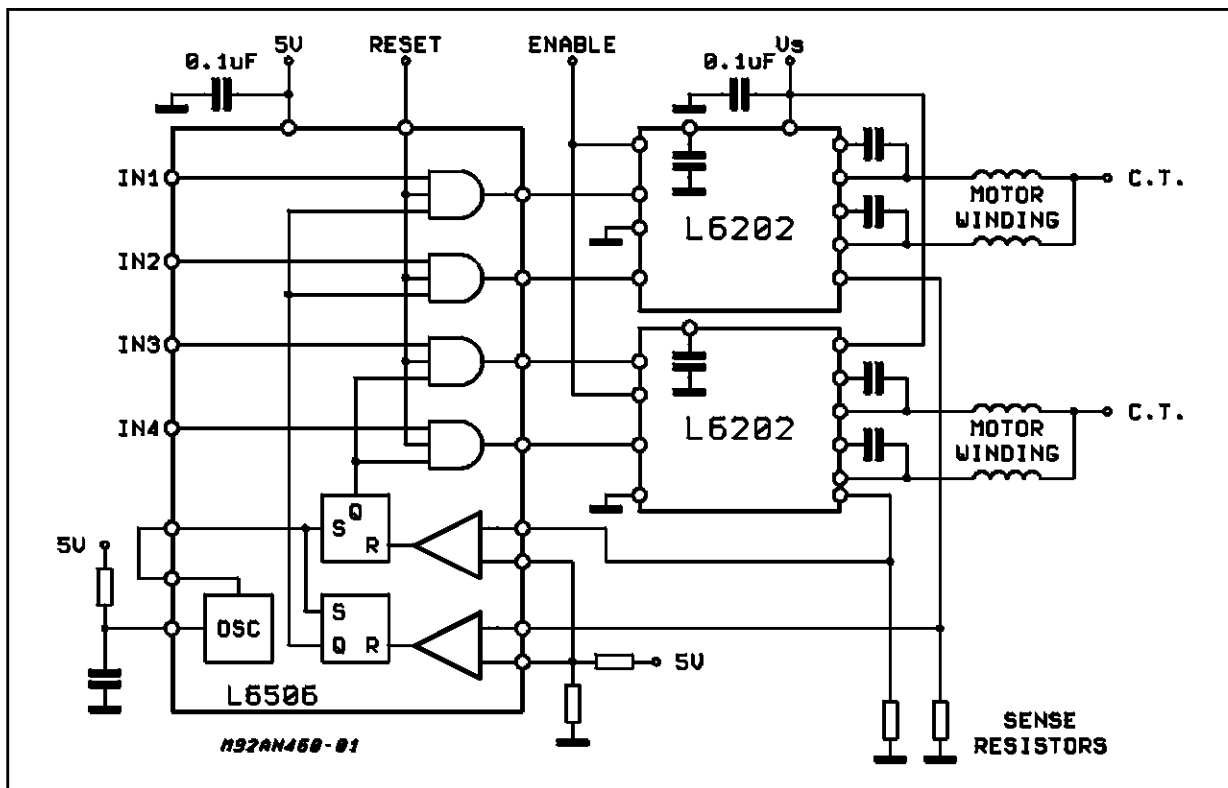
A solution where the L298N or L6202 is used to drive a unipolar motor while keeping the center connection of each coil connected to the supply will not work. First, the protection diodes needed from collector to emitter (drain to source) of the

bridge transistors will be forward biased by the transformer action of the motor windings, providing an effective short circuit across the supply. Secondly the L298N, even though it has split supply voltages, may not be used without a high voltage supply on the chip since a portion of the drive current for the output bridge is derived from this supply.

Selecting Enable or Phase chopping

When implementing chopping control of the current in a stepper motor, there are several ways in which the current control can be implemented. A bridge output, like the L6202 or L298N, may be driven in enable chopping, one phase chopping or two phase chopping, as shown in Figure 6. The L297 implements enable chopping or one phase chopping, selected by the control input. The L6506 implements one phase chopping, with the recirculation path around the lower half of the bridge, if the four outputs are connected to the 4 inputs of the bridge or enable chopping if the odd numbered outputs are connected to the enable inputs of the bridge. Selecting the correct chopping mode is an important consideration that affects the stability of the system as well as the dissipation. Table 1 shows a relative comparison of the different chopping modes, for a fixed chopping frequency, motor current and motor inductance.

Figure 5: Driving a unipolar wound motor with a bipolar drive

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Table 1: Comparative advantages of chopping modes

Chopping Mode	Ripple Current	Motor Dissipation	Bridge Dissipation *	Minimum Current
ENABLE	HIGH	HIGH	HIGH	LOWER
ONE PHASE	LOW	LOW	LOWEST	LOW
TWO PHASE	HIGH	LOW	LOW	Ipp/2

(*) As related to L298N, L6203 or L6202.

Figure 6a: Two Phase Chopping.

Figure 6b: One Phase Chopping.

Figure 6c: Enable Chopping.

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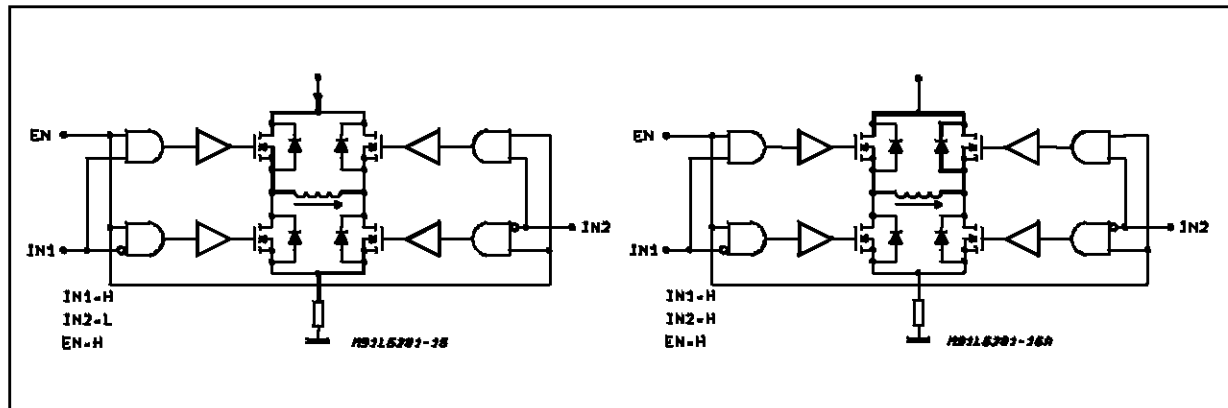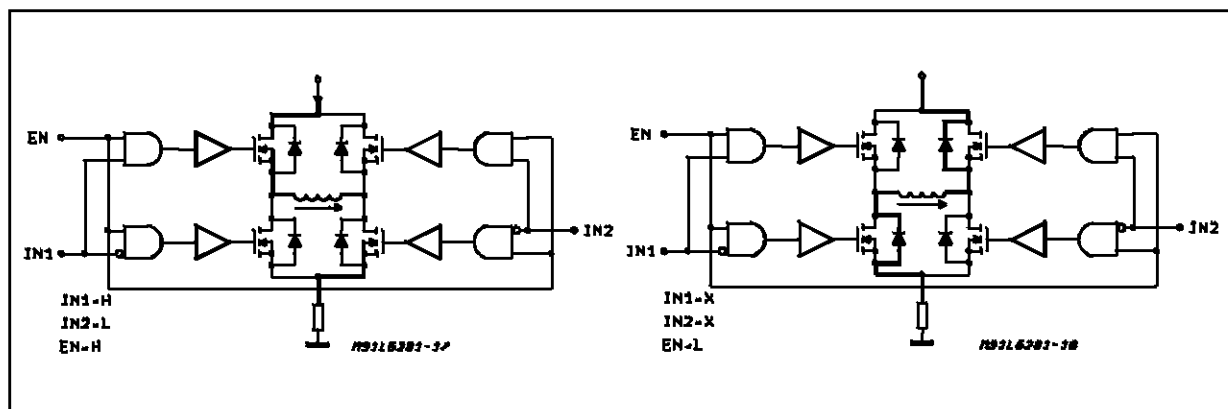**MICROELECTRONICS**

RIPPLE CURRENT

Since the rate of current change is related directly to the voltage applied across the coil by the equation:

$$V = L \frac{di}{dt}$$

the ripple current will be determined primarily by the chopping frequency and the voltage across the coil. When the coil is driven on, the voltage across the coil is fixed by the power supply minus the saturation voltages of the driver. On the other hand the voltage across the coil during the recirculation time depends on the chopping mode chosen.

When enable chopping or two phase chopping is selected, the voltage across the coil during recirculation is the supply voltage plus either the V_F of the diodes or the RI voltage of the DMOS devices (when using the L6202 in two phase chopping). In this case the slope of the current rise and decay are nearly the same and the ripple current can be large.

When one phase chopping is used, the voltage across the coil during recirculation is V_{on} (V_{sat} for Bipolar devices or $I \cdot R_{DSon}$ for DMOS) of the transistor that remains on plus V_F of one diode plus the voltage drop across the sense resistor, if it is in the recirculation path. In this case the current decays much slower than it rises and the ripple current is much smaller than in the previous case. The effect will be much more noticeable at higher supply voltages.

MOTOR LOSSES

The losses in the motor include the resistive losses (I^2R) in the motor winding and parasitic losses like eddie current losses. The latter group of parasitic losses generally increases with increased ripple currents and frequency. Chopping techniques that have a high ripple current will have higher losses in the motor. Enable or two phase chopping will cause higher losses in the motor with the effect of raising motor temperature. Generally lower motor losses are achieved using phase chopping.

POWER DISSIPATION IN THE BRIDGE IC.

In the L298N, the internal drive circuitry provides active turn off for the output devices when the outputs are switched in response to the 4 phase inputs. However when the outputs are switched off in response to the enable inputs all base drive is removed from output devices but no active element is present to remove the stored charge in the base. When enable chopping is used the fall time of the current in the power devices will be longer and the device will have higher switching losses than if phase chopping is used.

In the L6202 and L6203, the internal gate drive circuit works the same in response to either the input or the enable so the switching losses are the same using enable or two phase chopping, but would be lower using one phase chopping. However, the losses due to the voltage drops across the device are not the same. During enable chopping all four of the output DMOS devices are turned off and the current recirculates through the body to drain diodes of the DMOS output transistors. When phase chopping the DMOS devices in the recirculation path are driven on and conduct current in the reverse direction. Since the voltage drop across the DMOS device is less than the forward voltage drop of the diode for currents less than 2A, the DMOS take a significant amount of the current and the power dissipation is much lower using phase chopping than enable chopping, as can be seen in the power dissipation graphs in the data sheet.

With these two devices, phase chopping will always provide lower dissipation in the device. For discrete bridges the switching loss and saturation losses should be evaluated to determine which is lower.

MINIMUM CURRENT

The minimum current that can be regulated is important when implementing microstepping, when implementing multilevel current controls, or anytime when attempting to regulate a current that is very small compared to the peak current that would flow if the motor were connected directly to the supply voltage used.

With enable chopping or one phase chopping the only problem is loss of regulation for currents below a minimum value. Figure 7 shows a typical response curve for output current as a function of the set reference. This minimum value is set by the motor characteristics, primarily the motor resistance, the supply voltage and the minimum duty cycle achievable by the control circuit. The minimum current that can be supplied is the current that flows through the winding when driven by the minimum duty cycle. Below this value current regulation is not possible. With enable chopping the current through the coil in response to the minimum duty cycle can return completely to zero during each cycle, as shown in figure 8. When using one phase chopping the current may or may not return completely to zero and there may be some residual DC component.

When using a constant frequency control like the L297 or L6506, the minimum duty cycle is basically the duty cycle of the oscillator (sync) since the set dominance of the flip-flop maintains the output on during the time the sync is active. In constant off time regulators, like the PBL3717A, the minimum output time is set by the propagation delay through the circuit and it's ratio to the selected off time.

Figure 7: The transfer function of peak detect current control is nonlinear for low current values.
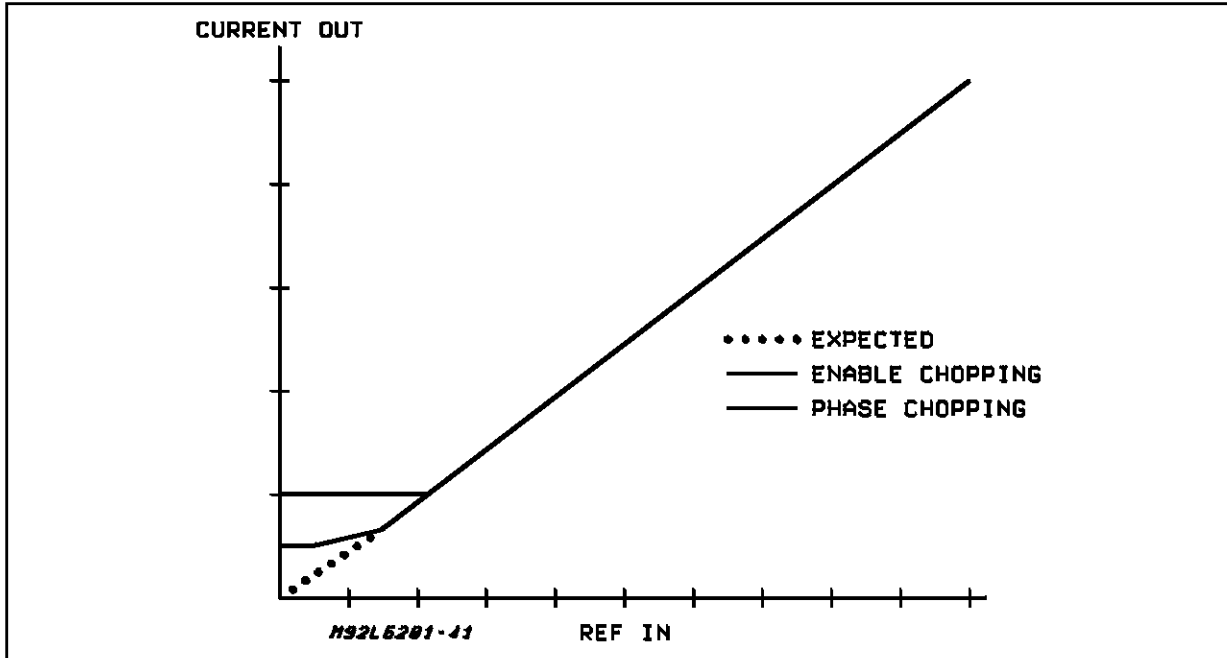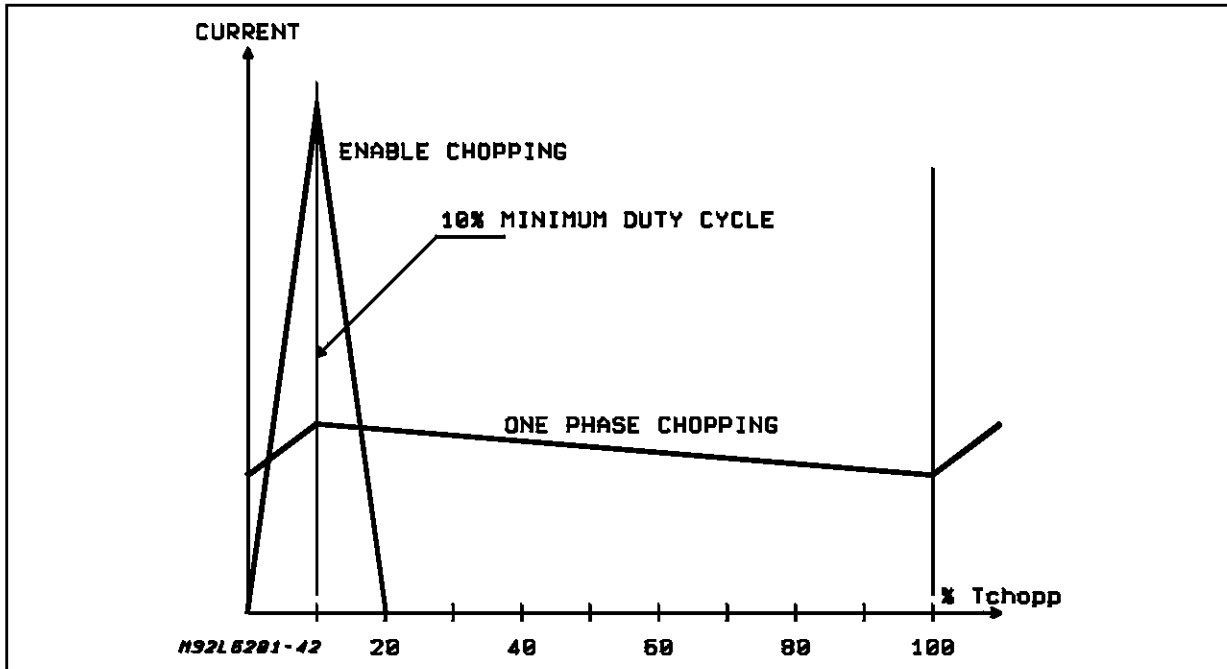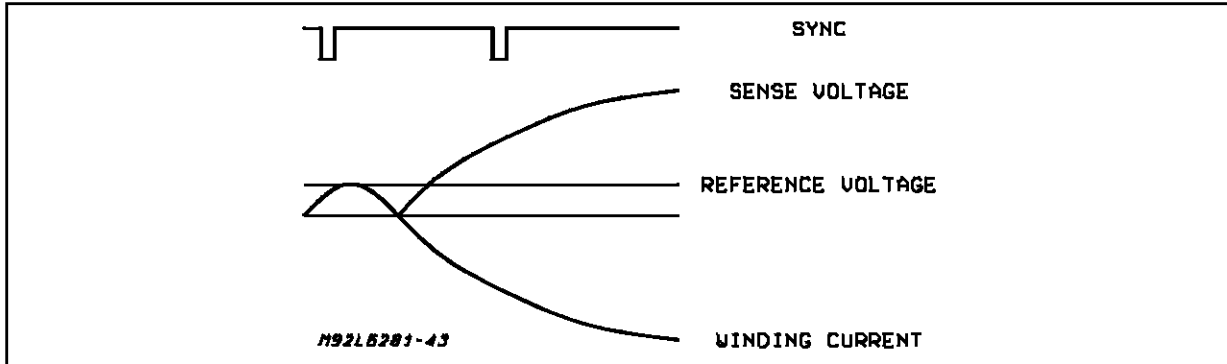

Figure 8: A Minimum current flows through the motor when the driver outputs the minimum duty cycle that is achievable.

For two phase chopping the situation is quite different. Although none of the available control chips implement this mode it is discussed here since it is easy to generate currents that can be catastrophic if two phase chopping is used with peak detecting control techniques. When the peak current is less than 1/2 of the ripple (I_{pp}) current two phase chopping can be especially dan-gerous. In this case the reverse drive ability of the two phase chopping technique can cause the current in the motor winding to reverse and the control circuit to lose control. Figure 9 shows the current wave form in this case. When the current reaches the peak set by the reference both sides of the bridge are switched and the current decays until it reaches zero. Since the power transistors

Figure 9: Two phase chopping can loose control of the winding current..

are now on, the current will begin to increase in a negative direction. When the oscillator again sets the flip-flop the inputs will then switch again and the current will begin to become more positive. However, the effect of a single sense resistor used with a bridge is to rectify current and the comparator sees only the magnitude and not the sign of the current. If the absolute value of the current in the negative direction is above the set value the comparator will be fooled and reset the flip-flop. The current will continue to become more negative and will not be controlled by the regulation circuit.

For this reason two phase chopping is not recommended with bridge circuits like the L298N or L6203 and is not implemented in any of the currently available driver IC's. The problem can be avoided by more complex current sense techniques that do not rectify the current feedback.

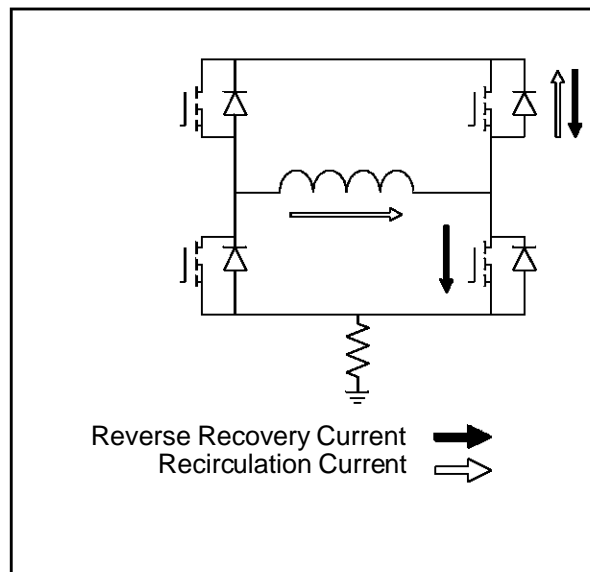**Chopper Stability and Audio Noise.**

One problem commonly encountered when using chopping current control is audio noise from the motor which is typically a high pitch squeal. In constant frequency PWM circuits this occurrence is usually traced to a stability problem in the current control circuit where the effective chopping frequency has shifted to a sub-harmonic of the desired frequency set by the oscillator. In constant off time circuits the off time is shifted to a multiple of the off time set by the monostable. There are two common causes for this occurrence.

The first cause is related to the electrical noise and current spikes in the application that can fool the current control circuit. In peak detect PWM circuits, like the L297 and L6506, the motor current is sensed by monitoring the voltage across the sense resistor connected to ground. When the oscillator sets the internal flip flop causing the bridge output to turn on, there is typically a voltage spike developed across this resistor. This spike is caused by noise in the system plus the reverse recovery current of the recirculating diode that flows through the sense resistor, as shown in

Figure 10. If the magnitude of this spike is high enough to exceed the reference voltage, the comparator can be fooled into resetting the flip-flop prematurely as shown in Figure 11. When this occurs the output is turned off and the current continues to decay. The result is that the fundamental frequency of the current wave form delivered to the motor is reduced to a sub-harmonic of the oscillator frequency, which is usually in the audio range. In practice it is not uncommon to encounter instances where the period of the current wave form is two, three or even four times the period of the oscillator. This problem is more pronounced in breadboard implementations where the ground is not well laid out and ground noise contributes makes the spike larger.
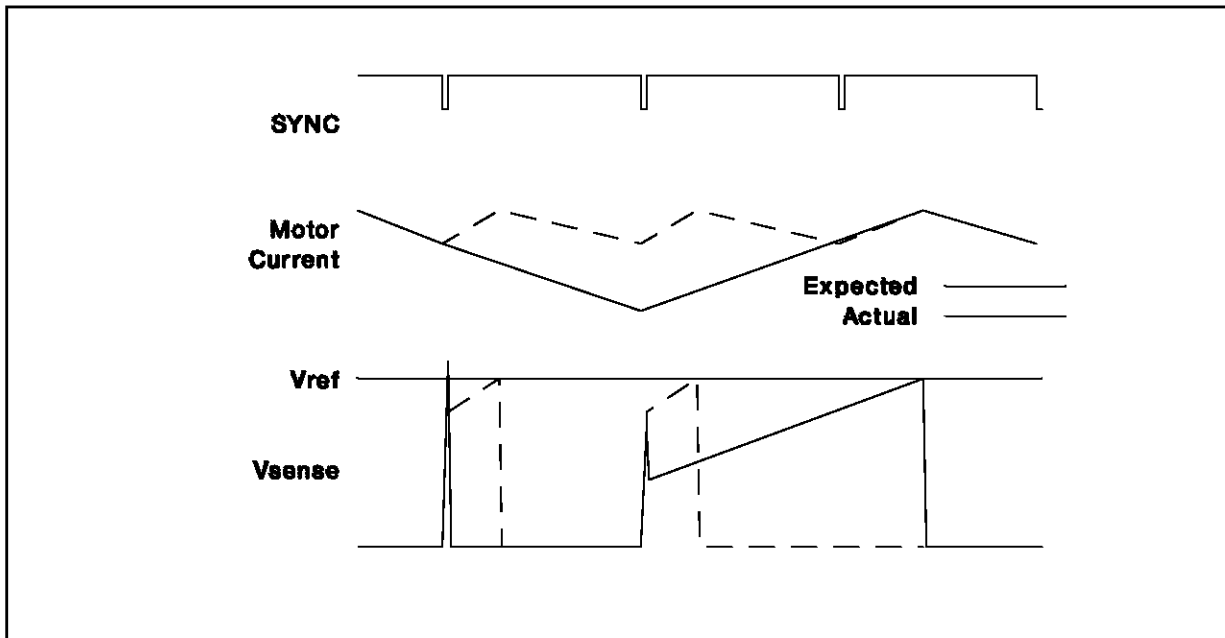
When using the L6506 and L298N, the magnitude of the spike should be, in theory, smaller since the diode reverse recovery current flows to ground and not through the sense resistor. How-

Figure 10: Reverse recovery current of the recirculation diode flows through the sense resistor causing a spike on the sense resistor.

Reverse Recovery Current ➡
Recirculation Current ⇨

Figure 11: Spikes on the sense resistor caused by reverse recovery currents and noise can trick the current sensing comparator.

ever, in applications using monolithic bridge drivers, like the L298N, internal parasitic structures often produce recovery current spikes similar in nature to the diode reverse recovery current and these may flow through the emitter lead of the device and hence the sense resistor. When using

DMOS drivers, like the L6202, the reverse recovery current always flows through the sense resistor since the internal diode in parallel with the lower transistor is connected to the source of the DMOS device and not to ground.

In constant off time FM control circuits, like the

CALCULATING POWER DISSIPATION IN BRIDGE DRIVER IC'S

The power dissipated in a monolithic driver IC like the L298N or L6202 is the sum of three elements: 1) the quiescent dissipation, 2) the saturation losses and 3) the switching losses.

The quiescent dissipation is basically the dissipation of the bias circuitry in the device and can be calculated as $Vs \cdot Is$ where Vs is the power supply voltage and Is is the bias current or quiscent current from the supply. When a device has two supply voltages, like the L298N, the dissipation for each must be calcualted then added to get the total quiescent dissipation. Generally the quiescent current for most monolithic IC's is constant over a vide range of input voltages and the maximum value given on the data sheet can be used for most supply voltages within the allowable range.

The saturation loss is basically the sum of the voltage drops times the current in each of the output transistors. For Bipolar devices, L298N, this is $Vsat \cdot I$. For DMOS power devices this is $I^2 \cdot R_{DSon}$.

The third main component of dissipation is the switching loss associated with the output devices. In general the switching loss can be calculated as:

$$Vsupply \cdot Iload \cdot tcross \cdot fswitch$$

To calculate the total power dissipation these three compnents are each calculated, multipled by their respective duty cycle then added togther. Obviously the duty cycle for the quiescent current is equal to 100%.

PBL3717A, the noise spike fools the comparator and retriggers the monostable effectively multiplying the set off time by some integer value.

Two easy solutions to this problem are possible. The first is to put a simple RC low pass filter between the sense resistor and the sense input of the comparator. The filter attenuates the spike so it is not detected by the comparator. This obviously requires the addition of 4 additional components for a typical stepper motor. The second solution is to use the inherent set dominance of the internal flip-flop in the L297 or L6506 [1][3] to mask out the spike. To do this the width of the oscillator sync pulse is set to be longer than the sum of the propagation delay (typically 2 to 3µs for the L298N) plus the duration of the spike (usually in the range of 100ns for acceptable fast recovery diodes), as shown in figure 12. When this pulse is applied to the flip-flop set input, any signal applied to the reset input by the comparator is ignored. After the set input has been removed the comparator can properly reset the flip-flop at the correct point.
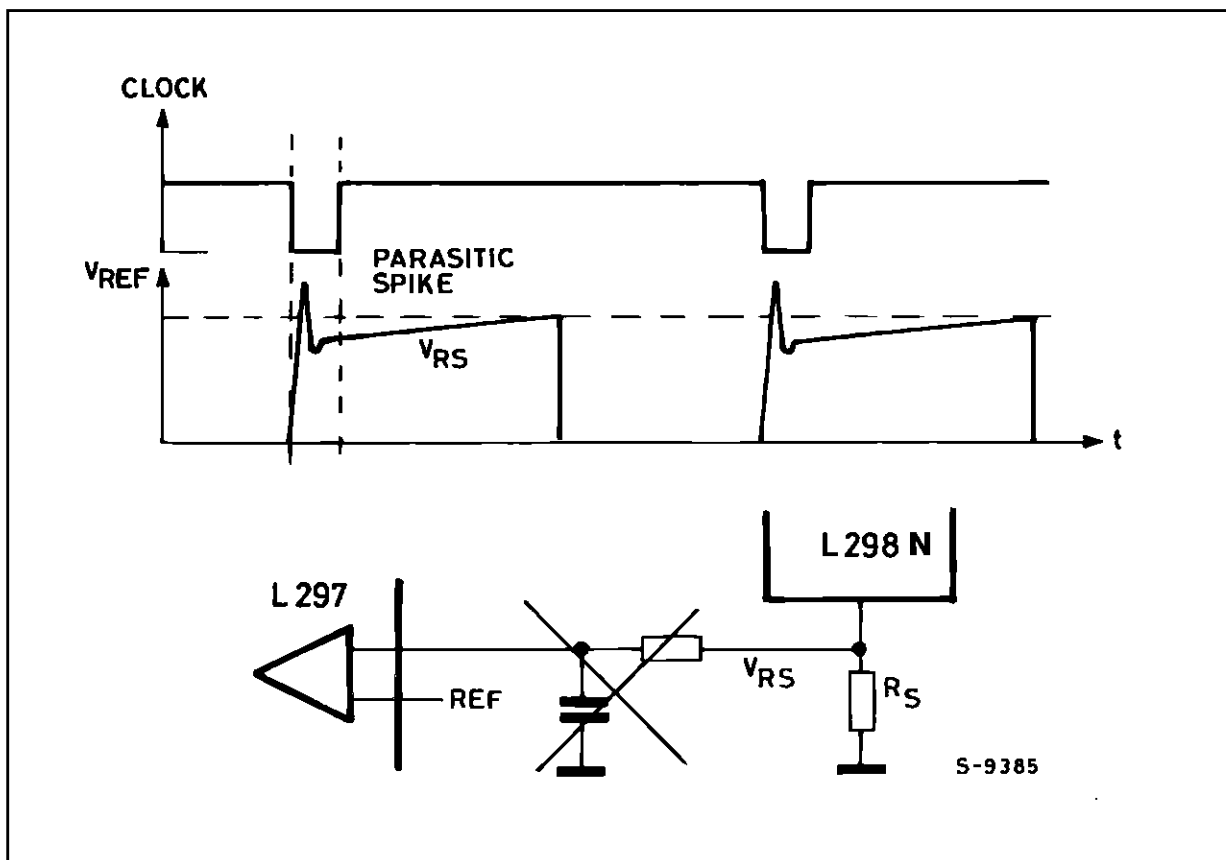
The corresponding solution in frequency modulated circuits, is to fix a blanking time during which the monostable may not be retriggered.

The best way to evaluate the stability of the chopping circuit is to stop the motor movement (hold the clock of the L297 low or hold the four inputs constant with the L6506) and look at the current wave forms without any effects of the phase changes. This evaluation should be done for each level of current that will be regulated. A DC current probe, like the Tektronix AM503 system, provides the most accurate representation of the motor current. If the circuit is operating stability, the current wave form will be synchronized to the sync signal of the control circuit. Since the spikes discussed previously are extremely short, in the range of 50 to 150 ns, a high frequency scope with a bandwidth of at least 200 MHz is required to evaluate the circuit. The sync signal to the L297 or L6506 provides the best trigger for the scope.

The other issue that affects the stability of the constant frequency PWM circuits is the chopping mode selected. With the L297 the chopping signal may be applied to either the enable inputs or the four phase inputs. When chopping is done using the enable inputs the recirculation path for the current is from ground through the lower recirculation diode, the load, the upper recirculation diode and back to the supply, as shown in Figure 6c. This same recirculation path is achieved using two phase chopping, although this may not be im-

Figure 12: The set-dominant latch in the L297 may be used to mask spikes on the sense resistor that occur at switching.

plemented directly using the L297 or L6506. In this mode, ignoring back EMF, the voltage across the coil during the on time (t_1) when current is increasing and the recirculation time (t_2), are:

$$V_1 = V_s - 2\ V_{sat} - V_{Rsense}$$

and

$$V_2 = V_{ss} + 2\ V_F$$

The rate of current change is given by (ignoring the series resistance):

$$V = L\frac{di}{dt}$$

Since the voltage across the coil (V_2) during the recirculation time is more than the voltage (V_1) across the coil during the on time the duty cycle will, by definition, be greater than 50% because t_1 must be greater than t_2. When the back EMF of the motor is considered the duty cycle becomes even greater since the back EMF opposes the increase of current during the on time and aides the decay of current.

In this condition the control circuit may be content to operate stability at one half of the oscillator frequency, as shown in Figure 13. As in normal operation, the output is turned off when the current reaches the desired peak value and decays until the oscillator sets the flip-flop and the current again starts to increase. However since t_1 is longer than t_2 the current has not yet reached the peak value before the second oscillator pulse occurs. The second oscillator pulse then has no effect and current continues to increase until the set peak value is reached and the flip-flop is reset by

the comparator. The current control circuit is completely content to keep operating in this condition. In fact the circuit may operate on one of two stable conditions depending on the random time when the peak current is first reached relative to the oscillator period.
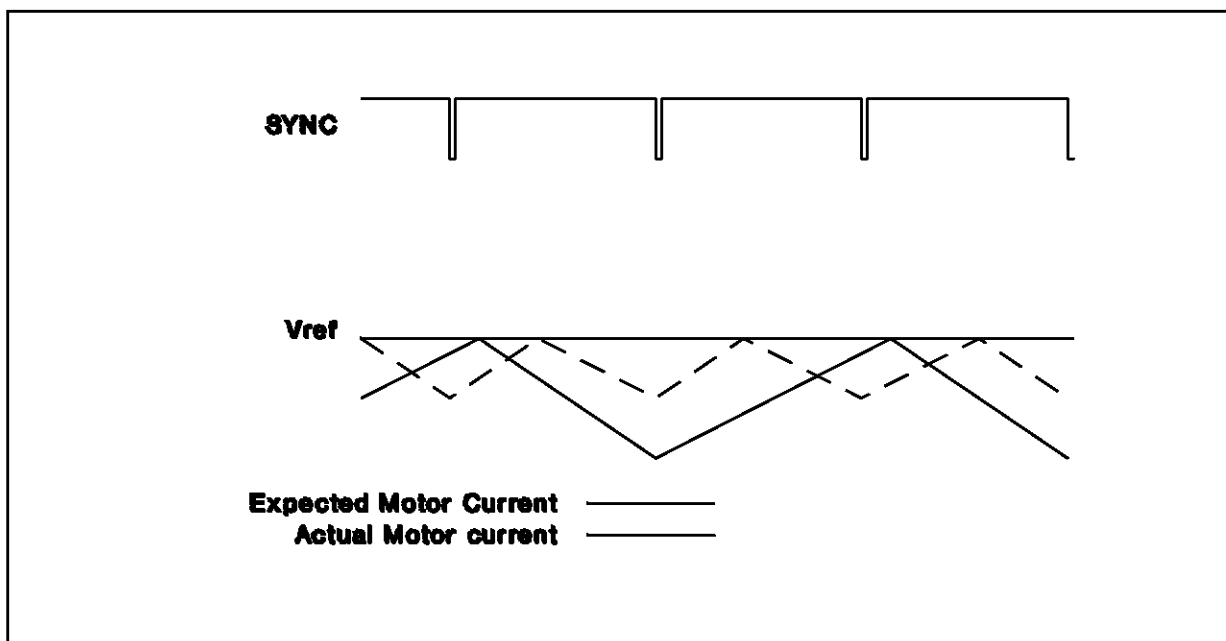
The easiest, and recommended, solution is to apply the chopping signal to only one of the phase inputs, as implemented with the L297, in the phase chopping mode, or the L6506.

Another solution that works, in some cases, is to fix a large minimum duty cycle, in the range of 30%, by applying an external clock signal to the sync input of the L297 or L6506. In this configuration the circuit must output at least the minimum duty cycle during each clock period. This forces the point where the peak current is detected to be later in each cycle and the chopping frequency to lock on the fundamental. The main disadvantage of this approach is that it sets a higher minimum current that can be controlled. The current in the motor also tends to overshoot during the first few chopping cycles since the actual peak current is not be sensed during the minimum duty cycle.

EFFECTS OF BACK EMF

As mentioned earlier, the back EMF in a stepper motor tends to increase the duty cycle of the chopping drive circuits since it opposes current increased and aids current decay. In extreme, cases where the power supply voltage is low compared to the peak back EMF of the motor, the duty cycle required when using the phase chopping may exceed 50% and the problem with the

Figure 13: When the output duty cycle exceeds 50% the chopping circuit may sinchronize of a sub-harmonic of the oscillator frequency.

stability of the operating frequency discussed above can occur. At this point the constant frequency chopping technique becomes impractical to implement and a chopping technique that uses constant off time frequency modulation like implemented in the PBL3717A, TEA3717, TEA3718, and L6219 is more useful.

Why Won't the motor move

Many first time users of chopping control drives first find that the motor does not move when the circuit is enabled. Simply put the motor is not generating sufficient torque to turn. Provided that the motor is capable of producing the required torque at the set speed, the problem usually lies in the current control circuit. As discussed in the previous section the current sensing circuit can be fooled. In extreme cases the noise is so large that the actual current through the motor is essentially zero and the motor is producing no torque. Another symptom of this is that the current being drawn from the power supply is very low.

Avoid Destroying the Driver

Many users have first ask why the device failed in the application. In almost every case the failure was caused by electrical overstress to the device, specifically voltages or currents that are outside of the device ratings. Whenever a driver fails, a careful evaluation of the operating conditions in the application is in order.

The most common failure encountered is the result of voltage transients generated by the inductance in the motor. A correctly designed application will keep the peak voltage on the power supply, across the collector to emitter of the output devices and, for monolithic drivers, from one output to the other within the maximum rating of the device. A proper design includes power supply filtering and clamp diodes and/or snubber networks on the output [6].

Selecting the correct clamp diodes for the application is essential. The proper diode is matched to the speed of the switching device and maintains a V_F that limits the peak voltage within the allowable limits. When the diodes are not integrated they must be provided externally. The diodes should have switching characteristics that are the same or better than the switching time of the output transistors. Usually diodes that have a reverse recovery time of less than 150 ns are sufficient when used with bipolar output devices like the L298N. The 1N4001 series of devices, for example, **is not** a good selection because it is a slow diode.

Although it occurs less frequently, excess current can also destroy the device. In most applications the excess current is the result of short circuits in the load. If the application is pron to have shorted loads the designer may consider implementing some external short circuit protection [7].

Shoot through current, the current that flows from supply to ground due to the simultaneous conduction of upper and lower transistors in the bridge output, is another concern. The design of the L298N, L293 and L6202 all include circuitry specifically to prevent this phenomena. The user should not mistake the reverse recovery current of the diodes or the parasitic structures in the output stage as shoot through current.

SELECTED REFERENCES

[1]Sax, Herbert., "Stepper Motor Driving" (AN235)

[2]"Constant Current Chopper Drive Ups Stepper-Motor Performance" (AN468)

[3]Hopkins, Thomas. "Unsing the L6506 for Current Control of Stepping Motors" (AN469)

[4]"The L297 Steper Motor Controller" (AN470)

[5]Leenouts, Albert. The Art and Practice of Step Motor Control. Ventura CA: Intertec Communications Inc. (805) 658-0933. 1987

[6]Hopkins, Thomas. "Controlling Voltage Transisnts in Full Bridge Drivers" (AN280)

[7]Scrocchi G. and Fusaroli G. "Short Circuit Protection on L6203". (AN279)

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