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High-Current DC Motor Drive Uses Low On-Resistance Surface Mount MOSFETs

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INTRODUCTION

Surface mount technology has been utilized for small disk drive motors with peak currents during spin up of one or two amps. Now the availability of low on-resistance, surface mount power MOSFETs has increased the current handling capability of surface mount technology. This application note presents a 5 amp DC motor drive using all surface mount components with the exception of the filter capacitor. The system is controlled directly by a microcontroller and features a cycle-by-cycle current limit.

The term DC Motor generally refers to a brushed DC motor with permanent magnets. These motors have a fixed stator with permanent magnets and a wound rotor with a brushed commutator. Other motors which are also considered DC machines are Shunt-Wound DC, Series-Wound DC and Brushless DC motors. Although the basic motor characteristics are quite similar for these motors, the control circuitry is quite different. The motor control circuitry presented here will deal exclusively with brushed permanent magnet DC motors (hereafter called simply DC motors).

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Figure 1. 5 Ampere Surface Mount DC Motor Drive

SIMPLE DC MOTOR CONTROL

DC Motor Basics

DC motors are the best choice for many variable speed applications. A DC motor is the most simple motor to control electronically. Brushless DC, Stepper, AC induction and switched reluctance motors all require more complex control circuitry and more switching devices. Small low cost DC motors are available off-the-shelf for many low volume applications where a custom designed motor would be too expensive. The reliability of brushed motors is adequate for most applications, although the brushes will eventually wear out and require servicing.

A simple electrical model for a DC motor is shown in Figure 2. The back Electromotive Force (EMF) generator is a variable voltage source which is a linear function of motor speed. The series resistance is usually very low and is the only factor limiting the current under a locked rotor condition. The inductance is very important to the operation of PWM motor controls. The higher the inductance the lower the ripple current at a given frequency.

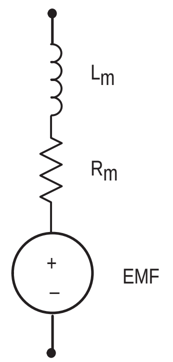

Figure 2. Electrical Model of a DC Motor

DC motor controls can be classified by the quadrants of operation referring to the torque versus speed plot (see Figure 3). Single-quadrant controls only operate in the first quadrant with positive speed and positive torque. A single quadrant drive usually consists of a single transistor and a single clamp diode (see Figure 4). This type of control can only move the motor in one direction and cannot generate any braking forces.

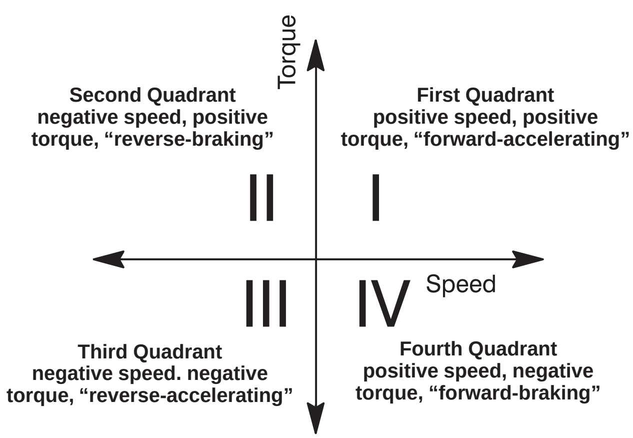

Figure 3. Torque/Speed Quadrants of Operation

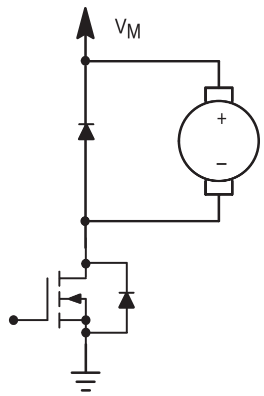

Figure 4. Single-Quadrant DC Motor Drive Circuit

Two-Quadrant PWM Strategy

Reversing capability requires the use of an H-bridge in order to reverse the motor current. There are many different ways to drive the H-bridge. A two-quadrant motor control is the most popular. In a two-quadrant system, one transistor is turned on and the diagonally opposite transistor is Pulse Width Modulated (PWM). Usually the bottom transistors are modulated, however pulse width modulating the top transistors works equally well. If the bottom transistors are used for PWM, the top transistors are used for steering. In order to reverse the direction of the motor, the active “steering” transistor is turned off, the other steering transistor is turned on. Again, the diagonally opposite transistor is PWM’ed. A simplified circuit for two-quadrant motor control is shown in Figure 5. In this circuit a single PWM signal is used to PWM either lower transistor, while a second signal “FWD” is used to control direction. This topology is ideally suited for microprocessor control, as it requires a single, high-speed PWM signal, and the direction signal may be a single, general I/O pin.

Two-Quadrant Operation

The two-quadrant control in Figure 5 cannot generate any braking forces. The motor can only operate in quadrant I (forward accelerating) and quadrant III (reverse accelerating). In order to reverse directions the motor must coast down to zero before reversing directions. If the pulse width is decreased to allow the motor to slow, the peak current through the switching transistor decreases. If the average applied voltage is less than the back EMF of the motor, the motor current will decrease to zero and the motor will coast. Referring to Figure 3, the operating point will first move down vertically to the speed axis (as the torque decreases to zero), and then move left along the speed axis. If there was no friction the motor would spin forever.

Many loads, such as fans or pumps, are mostly frictional. These systems can easily utilize a two-quadrant drive. The two-quadrant circuit usually has better speed regulation, acceleration and efficiency than a four-quadrant system. An additional advantage of the two-quadrant system is that it cannot regenerate.

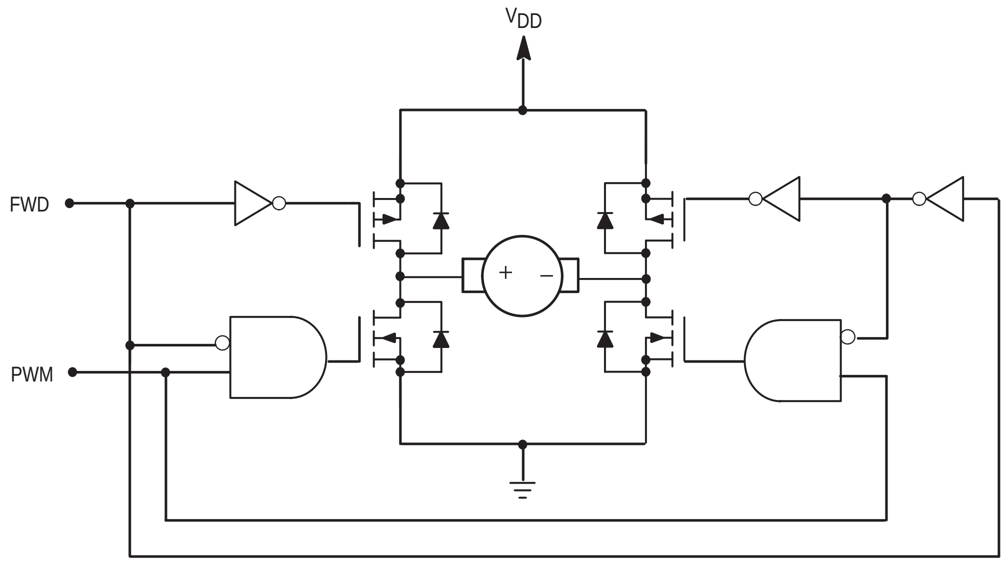

Figure 5. Two-Quadrant DC Motor Drive Circuit

CURRENT CONSIDERATIONS

Because the power devices have finite current carrying capability, one must consider the effects of motor operation on the power devices. Motor current usually depends on load torque and the commanded acceleration. The most demanding conditions on the power electronics are usually a stalled or locked motor, or maximum acceleration with an inertia load.

If the pulse width is increased abruptly to quickly accelerate the motor, very high currents may flow. This will cause an undesirable jerk on the motor and the mechanical system. Worse, it could exceed the current rating of the power devices. Limiting the rate of acceleration is a fairly simple task for a microprocessor. However, a simple rate limit does not protect the MOSFETs under a locked motor or shorted condition. A simple cycle-by-cycle current limit will limit the current and indirectly limit acceleration. This allows full utilization of the power devices. In two-quadrant systems a single-sense resistor may be used. Pulse width modulating the lower transistors allows the current sense resistor to be conveniently located at the bottom. SENSEFET™ transistors can be used for lossless current sensing in two-quadrant systems by connecting the mirrors together and using a single current mirror resistor. A diagram with cycle-by-cycle current limit is shown in Figure 6.

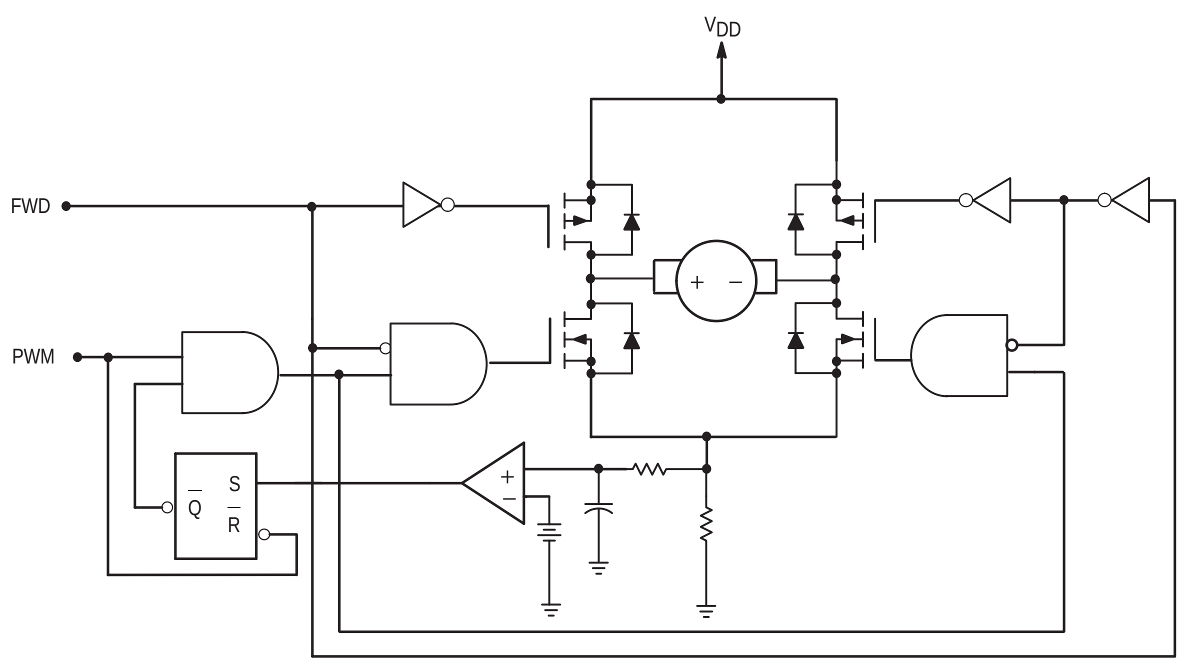

Figure 6. Two-Quadrant DC Motor Drive Circuit with Current Limit

Referring to Figure 6, when the voltage across the sense resistor exceeds the reference voltage, the comparator output will switch high. This will set the Reset-Set latch, disabling the PWM signal and turning the lower transistor off. When the PWM input is switched low the latch will be reset and the PWM signal will be enabled to turn on the transistor on the next cycle. The effect is to limit the peak current on a cycle-by-cycle basis. This current limit will permit sub-harmonic currents to flow, which can create some audible noise.

The maximum average motor current will depend on the motor inductance and back EMF. When the motor is under a stalled condition, the back EMF will be zero and a large voltage will appear across the internal inductance and resistance of the motor. A low inductance motor will have higher peak-to-peak ripple current, resulting in lower current during the valleys between peaks and consequently a lower average current. This may cause a small motor with high inductance to actually generate more stall torque than a larger motor with low inductance.

The average current through the power MOSFETs and diodes will also be a function of the motor parameters. The worst case average diode current is for a low inductance motor since the current will free-wheel most of the time. The N-channel transistor current is the opposite of the diode current and will also be worst for a high inductance motor. The P-channel steering transistor current is the same as the motor current and will be worst for a high inductance motor. If the motor drive circuit will be used with a variety of motors, both transistors and the free-wheel diode should be chosen to handle the cycle-by-cycle current limit value on a continuous basis.

REVERSING HAZARDS

The reversing capability of this two-quadrant system is limited to static reversal. That is, the direction cannot be changed while the motor is still moving. Figures 7 and 8 illustrate what occurs during dynamic reversal. Both of these figures use the simple model for the DC motor. Take the case in Figure 7 where the FWD signal is initially high. Transistor Q1 is on and transistor Q4 is PWM'ing. Current is flowing from right to left in the motor, and the back EMF of the motor is positive on the left and negative on the right. When Q4 is turned off, current will free-wheel through the diode of Q3.

Now suppose the back EMF is quite high and the FWD signal is toggled low as in Figure 8. Q3 will turn on holding the negative side of the back EMF generator high. The effective voltage on the positive side of the EMF voltage source is then the supply voltage plus the back EMF voltage. The motor current will first decrease to zero and then change directions and flow as shown in Figure 8. When Q2 is off, the back EMF of the motor will cause current to flow downward through Q3, through the motor, up through the diode of Q1 and back into the motor supply voltage. The current will increase in this direction at the rate determined by the back EMF and will be limited only by the motor resistance. If the back EMF energy is large enough it could easily destroy the P-channel transistors.

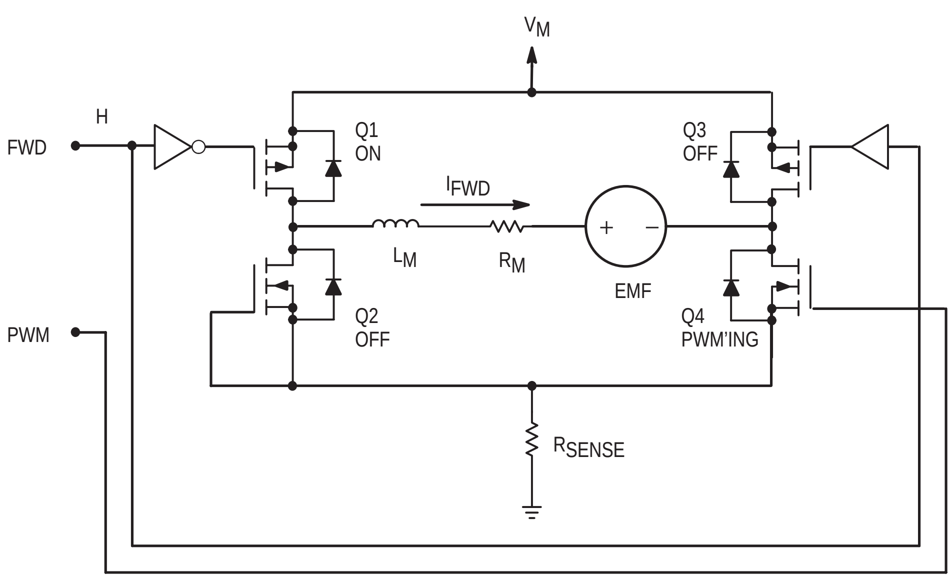

Figure 7. Normal Forward Operation

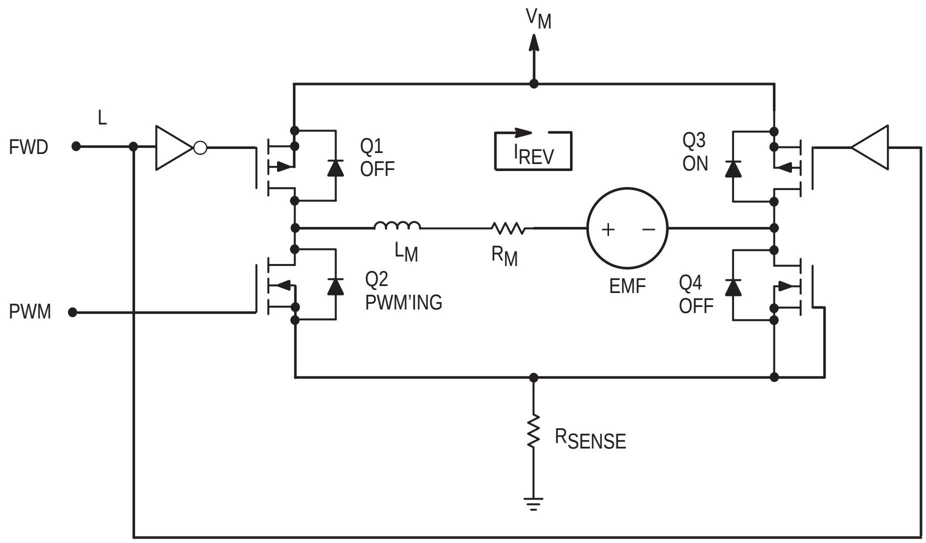

Figure 8. Motor Currents After Reversal

The simple current limit circuit shown in Figure 6 will not limit the current during reversal because the current is not flowing through the sense resistor. Even if the over current condition could be detected, the upper P-channel devices must be PWM'ed off in order to reduce the current. If the P-channels must be PWM'ed, a four-quadrant control should be considered. Since the two-quadrant system does not normally generate any braking forces, slewing the pulse period to zero and reversing directions does not ensure the motor has stopped, and may again result in a large current peak. Three-phase brushless DC motor drives often have the same difficulty in dynamic reversal.

Programming a short time delay sufficient to allow the motor to stop may permit safe dynamic reversal. Another alternative is to turn off the PWM signal, monitor the phase voltages and wait until the average voltage across the motor decreases to zero. This will indicate the motor has stopped and may safely be reversed. If the application has a large inertia load, requires fast reversal and current limit operation, then a four-quadrant system should be used. However, most applications can benefit from the more cost effective, two-quadrant system. Four-quadrant systems should be reserved for the more demanding applications such as servo-positioning.

IMPLEMENTATION USING SURFACE MOUNT DEVICES

The cycle-by-cycle current limit shown in Figure 6 may be implemented using standard logic devices, standard linear devices and power MOSFETs. A complete circuit using surface mount components is shown in Figure 9. A photograph of the board is shown in Figure 1 and a complete list of the components used is listed in Table 1.

Two-quad NAND gates are used to implement the control logic and over-current latch. The NAND latch is RESET dominant and will ignore any glitches while the input is low. The LM393 comparator is a dual linear comparator and was chosen for single-ended operation near ground. The TL431 provides a 2.5 volt reference which is divided down to 250 mV by R7 and R10. Capacitor C3 and resistors R6 and R7 provide a 1.0 µs time constant. The time constant must be large enough to filter out most of the diode reverse recovery current, but small enough to detect peak currents under a stalled condition.

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Table 1. List of Components

Designators	Quantity	Description	Manufacturer	Part Number
C1,C2,C10	3	100nF Capacitor, Z5U dielectric		
C3	1	220pF 10% Capacitor, X7R dielectric		
C4,C5,C6,C7,C8,C9	6	10nF Capacitor, Z5U dielectric		
C11	1	1000µF 16V Electrolytic Capacitor	Illinois Capacitor	108RZS016M
CON1,CON2	1	3 pin Connector	Phoenix Contact	MKDS 1/3 3.81mm
CON3	1	2 pin Connector	Phoenix Contact	MKDS 1/2 3.81mm
D1,D2	2	3A 40V Schottky Diode	Motorola	MBRS340T3
D3,D4	2	Small Signal Diode	Motorola	MMBD6050L
D5	1	Small Signal Diode	Motorola	MMBD7000L
IC1,IC2	2	Quad 2-input NAND gate	Motorola	MC74HC00D
IC3,IC4	2	Dual High-Speed TMOS Driver	Motorola	MC33151D
IC5	1	Dual Comparator	Motorola	LM393AD
IC6	1	Voltage Reference	Motorola	TL431ACD
Q1,Q3	2	120mΩ P-ch TMOS MOSFET	Motorola	MTB23P06E
Q2,Q4	2	40mΩ N-ch TMOS MOSFET	Motorola	MTB36N06E
R1,R3	2	47Ω Resistor		
R2,R4	2	100Ω Resistor		
R5	1	0.05Ω 1.5W Wirewound Resistor	Ohmite	W1S5JR05
R6,R7,R9,R11	4	2.4kΩ Resistor		
R8	1	10kΩ Resistor		
R10	1	22kΩ Resistor		

1. All capacitors are 50V 20% ceramic chip capacitors with a 1206 footprint unless noted.
2. All resistors are 1/8 W 5% carbon film chip resistors with a 1206 footprint unless noted.

Gate drive is supplied by two MC33151 high-speed MOSFET drivers. These drivers provide logic level inputs, under-voltage lockout and high current outputs. Twelve volt applications may utilize a single gate resistor for each transistor. The P-channel gate resistors are chosen to provide optimum reverse recovery characteristics. The low output impedance of the MC33151 insures the P-channel devices remain off under commutation stresses. Applications that require higher motor supply voltages would need a more complex gate drive. (See *Interfacing Microcomputers to Fractional Horsepower Motors,* Application Note AN1300/D.)

Complementary surface mount power MOSFETs are used for simplicity. Both the N-channel MTB36N06E and the P-channel MTB23P06E are in a new surface mount package called the D^{2}PAK. This package is similar to a TO-220 but does not have the tab and is leadformed for surface mounting. A special leadframe is used to allow tab removal without stressing the die. Shearing the tab off a standard TO-220 is not recommended because stresses on the tab can easily crack the die.

The P-channel transistor has an on-resistance specification of 120 mΩ. At 5 amps of continuous current this transistor will dissipate a maximum of 3.0 watts. The package is rated at 2.5 watts with a minimum specified pad area. By using a large heat-spreading copper area the power dissipation can be increased. The N-channel device has a low on-resistance of only 40 mΩ, which will cause only 1.0 watt of power dissipation at 5 amps. A smaller N-channel transistor might be used. However, due to the 3:1 ratio of the mobility of holes in a P-type material and electrons in an N-type material, an N-channel transistor is much smaller than a P-channel device of the same on-resistance. The N-channel transistor is a comparative bargain for minimizing the total on-resistance losses. Due to the cost difference between the N and P-channel devices, the P-channel on-resistance to N-channel on-resistance ratio of 2:1 is optimum in order to minimize total cost versus conductance (cents per mho). Thus, the MTB36N06E is a good economical complement for the MTB23P06E.

The internal diode of the P-channel transistors has a very high forward voltage drop and a reverse recovery time of about 200 ns. The reverse recovery time is fast enough to provide operation at 20 kHz; however, the forward voltage is much too high to operate at 5 amps. The maximum forward voltage of 2 volts at a current of 5 amps would create an unacceptable 10 watts of power dissipation. By putting a Schottky diode in parallel with the P-channel the on-voltage is decreased to about 500 mV. The MBRS330T3 is a 3 amp, 30 V Schottky in the surface mount SMC package. This diode can be operated at 5 amps as long as the copper temperature does not exceed 85°C. An additional benefit in using the Schottky is a dramatic reduction in diode clearing losses and a reduction in switching noise. Figure 10 shows the N-channel drain current during turn-on with the P-channel internal diode alone, while Figure 11 shows the effect of adding the Schottky.

V_{GS} (5V/div)

V_{DS} (5V/div)

I_D (1A/div)

(100 ns/div)

Figure 10. N-Channel Turn-On Waveform

V_{GS} (5V/div)

V_{DS} (5V/div)

I_D (1A/div)

(100 ns/div)

Figure 11. N-Channel Turn-On Waveform with Schottky Diode

The output of each half-bridge is common to the drain of the N-channel, drain of the P-channel and the anode of the Schottky diode. Therefore, a single, large copper area may be used to provide a heatsink for each half-bridge. Using many through-hole vias to the back side of the board provides additional heatsinking.

In order for the power MOSFETs and diodes to self-align during the reflow process, the solder mask should be fairly tight, about 20 mils larger than the component on all sides. The pad size should be designed for the best alignment and thermal characteristics for the application. The copper heatsink was designed such that a large rectangle of copper is covered by the solder mask around the transistors and diodes, and tinned copper is exposed around the perimeter through-holes for best thermal transfer. This may be accomplished in many CAD systems by putting a minimal footprint (20 mils larger than the device) for the power devices on the top pad layer, and placing the large rectangle on the top and bottom trace layers. The through-holes are spaced around the perimeter on the common pad layer. A detail of one of the heatsinks is shown in Figure 12.

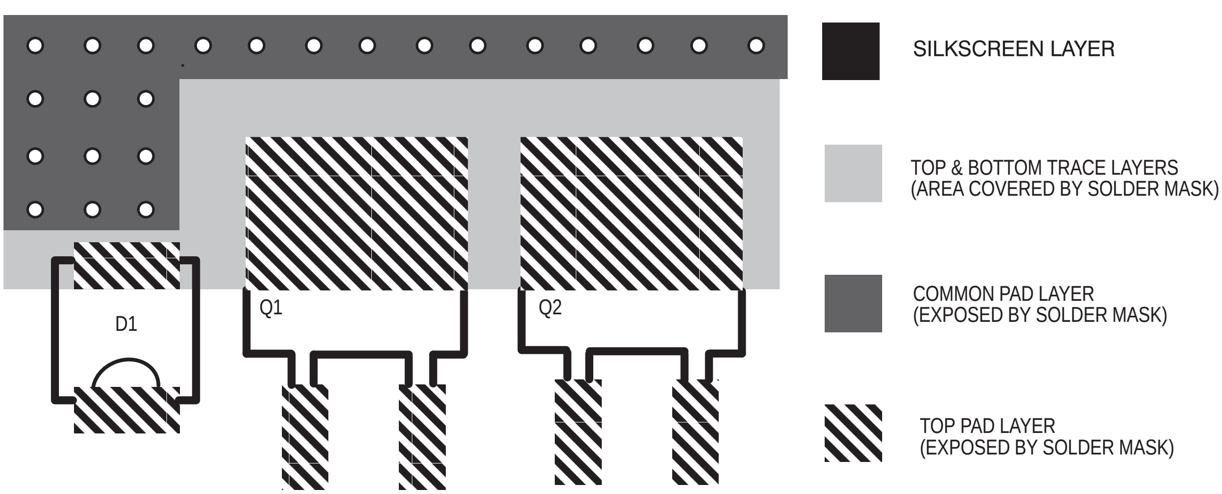

Figure 12. PCB Heatsink Detail

The sense resistor is a wirewound resistor repackaged in a surface mount body. Although the resistor is not specifically a low-inductance resistor, typical units measured only 20 nH. This inductance causes some voltage spikes of a few volts in the N-channel during turn-on and turn-off. Diodes D3 and D4 protect the MC33151's from the negative portions of these transients. The soft recovery of the Schottky diodes helps minimize any ringing during turn-on due to the source inductance.

CONCLUSION

The two-quadrant topology with a current limit works well with different motors in a large variety of applications. This topology is well suited for direct microprocessor control. The current limit provides protection from a stalled or locked motor but does permit some audible noise during current limit. The major limitation of this type of system is the potential problems during a quick motor reversal.

Using low on-resistance complementary MOSFETs, a surface mount DC motor drive can handle currents as high as 5 amps. A Schottky diode in parallel with the P-channel transistor will allow higher diode currents as well as greatly reducing the reverse recovery losses. Special layout techniques allow higher power dissipation and can easily be implemented on many CAD layout packages. The surface mount motor drive still requires a large through-hole electrolytic capacitor to supply the necessary ripple current.

When the cost of mounting and heatsinking the through-hole devices is included, the surface mount solution compares favorably with both discrete and modular solutions. The cost of the low on-resistance devices is more expensive than using a smaller transistor; however this additional cost is more than made up by the elimination of a heatsink. Overall, the surface mount solution appears practical for many low-cost, high-volume applications.

REFERENCES

Interfacing Microcomputers to Fractional Horsepower Motors, Warren Schultz, Motorola Application Note AN1300/D

ACKNOWLEDGMENTS

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