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Analog Power USA Applications Department

Brushless DC Motor Control Using Surface Mount MOSFETs

Brushless DC Motors typically require six MOSFETs for the power switching and yet have significant size constraints for the electronics. However a new generation of MOSFETs and surface mount packages provide extremely low RDS in small packages, allowing the miniaturization of motor drive circuits and elimination of heatsinks. In this design example we will make an 18V 10A speed control using a Microchip MIC4607-1 MOSFET driver. This driver is rated at 85V maximum allowing this design to be adapted for use up to 60V operating voltage.

The basic powertrain circuit is shown in Figure 1. N-Channel MOSFETs are used for both high side and low side due to the lower RDS and the availability of driver ICs to drive them. The low side FETs provide speed control PWM, and the upper FETs are used for commutation steering. During the PWM off-time, the current freewheels through the applicable off MOSFET’s diode. This plus the high inductances found in motors results in diode reverse recovery when the bottom FET turns on for the next PWM on-period which can create electrical noise.

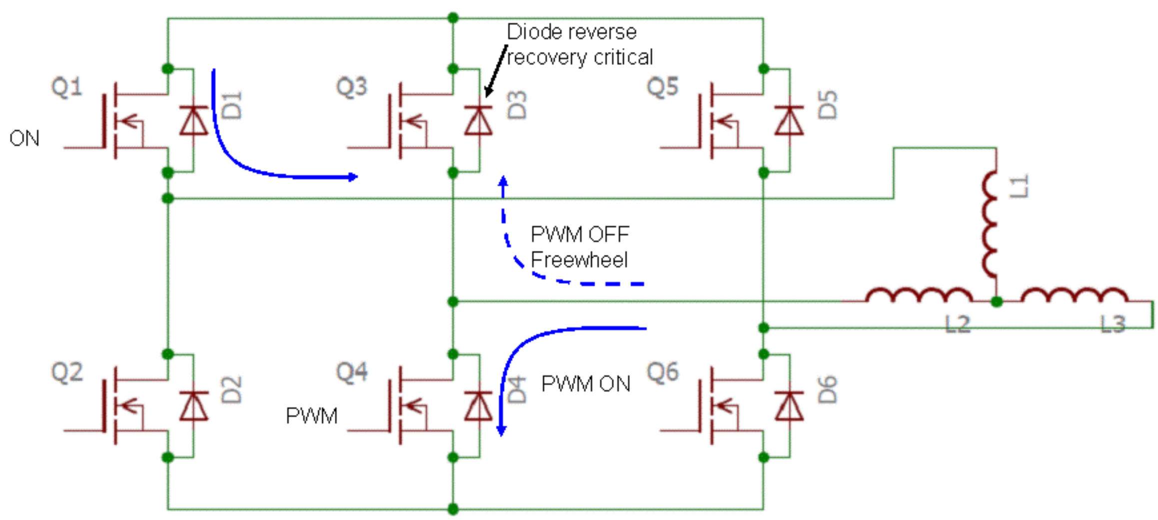

Figure 1. Three phase motor drive circuit showing diode conduction and recovery during PWM

The use of the diodes and their reverse recovery means that the gate drive of the top and bottom MOSFETs needs careful consideration. The top MOSFETs are used for steering/commutation only and therefore have a switching frequency an order of magnitude or more lower than the PWM low side MOSFETs. This means that at first pass, the top MOSFETs could tolerate higher gate series resistance, but these MOSFETs also see high dv/dt as the diode recovers. This dv/dt can turn on the MOSFET, increase losses dramatically and even cause device failures, so it should be minimized as much as possible. A simple answer is to insert a significant resistance in series with the bootstrap capacitor so it provides a slower turn on and yet it does not hinder a fast turn off and a strong Gate-Source clamp to ensure the MOSFET stays off. No such flexibility is available for the low side FETs as the gate drive voltage is not typically available phase by phase. A series resistance is the only simple variable and its value has to be a compromise between ensuring soft turn on, limiting the reverse recovery current in the top MOSFETs and providing good off-state pull down. However the addition of a diode and extra resistor allows tailoring of turn on and turn off speeds separately.

The periods of diode conduction and hence recovery are not always obvious and therefore we will look at them and the appropriate gate drive one by one. The most obvious case is the PWM of the low side switch. During the power stroke, Q1 and Q4 are on. During the PWM freewheel period the inductive-driven current flows through D3. Then for the next power stroke Q4 turns on and commutates D3. Q3/D3 is therefore subject to reverse recovery current which increases with the turn-on speed of Q4 and also dv/dt as the diode recovers. Q3 must therefore be held off via a stiff gate drive and a reasonable di/dt for Q4 turn on will reduce the reverse recovery current. The best way to control gate drive for Q1, Q3, and Q5 is therefore to place a resistor in series with the bootstrap capacitor shown as R1 in Figure 2. A typical value can be 10 to 20 Ohms.

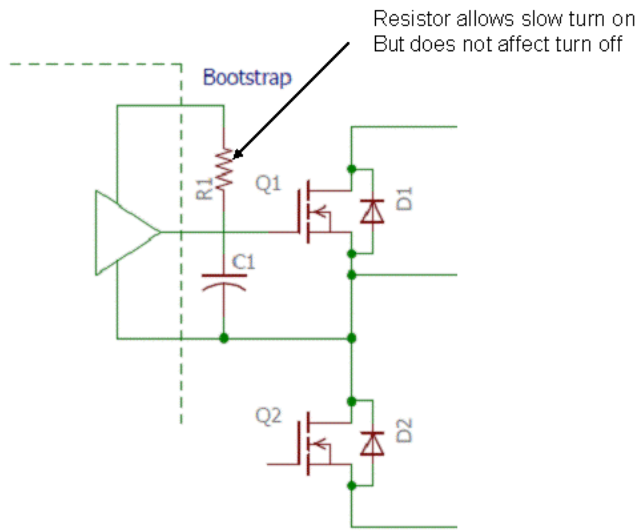

Figure 2. Resistance used in series with the Bootstrap capacitor slows down turn on but still provides a strong pull down gate drive to protect against dv/dt turn on in Q1/D1

The di/dt for a top side diode commutation is set by the turn on speed of the bottom FET. A slow turn on will produce a lower peak IRR. However due to inevitable dv/dt voltage ramps, a low resistance pull down from gate to source is always recommended. This can be implemented using two resistors and a diode as shown. R1 can be ~10 Ohm and R2 ~2 Ohm.

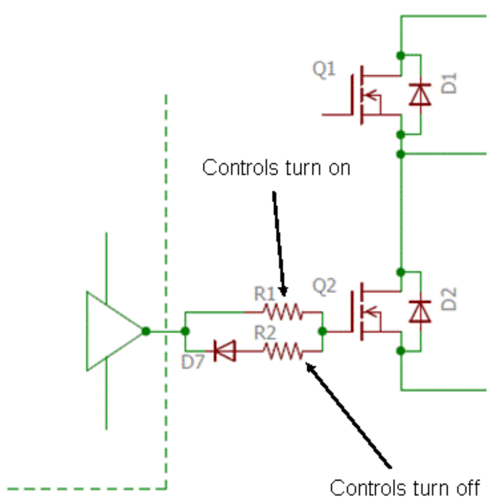

Figure 3. Low side gate drive allowing slow turn on, yet strong pull down for low side MOSFETs.

A less obvious case of diode conduction is when the steering (top) MOSFET is turned off, just prior to another winding being turned on. Assume current is freewheeling when a steering MOSFET is turned off: Before turn off, current is flowing through Q1 and free wheeling D3. When Q1 is turned off, since no MOSFET is on, the current has to flow via a bottom side diode and top side diode back into the supply i.e. the current flows through D2 and D3. This condition also causes the Drain/Source motor node to go below ground due to the diode drop over D2.

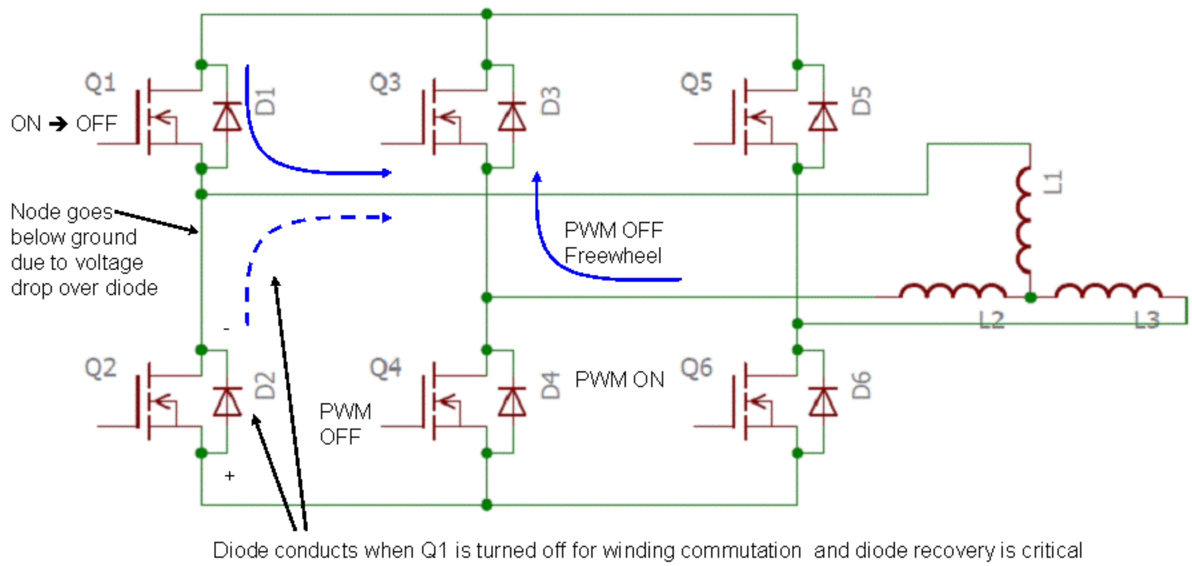

Figure 4. Diode D2 conduction when a top side FET is turned off

The IC may be sensitive to excessive negative voltages and can be protected by clamping the IC motor winding pin to ground using a Schottky diode and a resistor. This resistance is in series with the turn off gate drive and therefore a low value should be used. A one or two Ohm resistor will limit the current through the diode clamp sufficiently to allow a low forward drop. This resistor is in series with the turn off gate drive and therefore its addition means that there is no need to add a resistor in series with the Gate drive IC output because this resistor is in the same loop. Turn on speed can be controlled separately as shown in Figure 2.

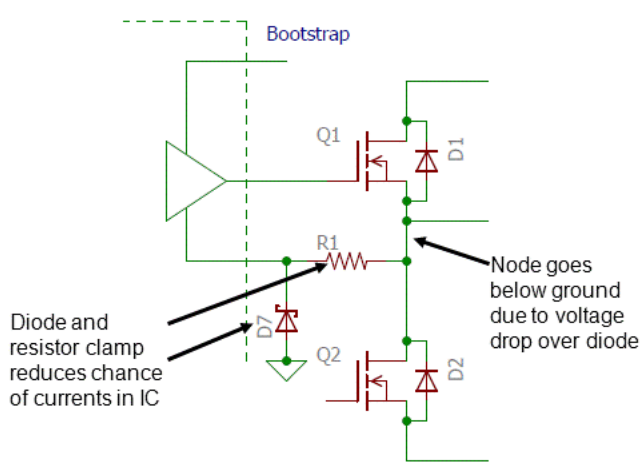

Figure 5. Addition of a clamp to ensure that the IC does not see excessive negative voltages on the center node pin

As well as ensuring that the IC is not affected by the negative voltage, the conduction and recovery of the low side diodes will cause both a reverse recovery current spike and dv/dt when they recover that must be taken into account. The di/dt is set by the supply voltage and the inductance of the windings and is therefore not controllable using gate resistance. The strong pull down resistance discussed will ensure the MOSFETs do not begin to turn on due to the dv/dt.

Combining all these techniques with a Microchip MIC4607-1 three phase driver IC gives the schematic shown in Figure 6.

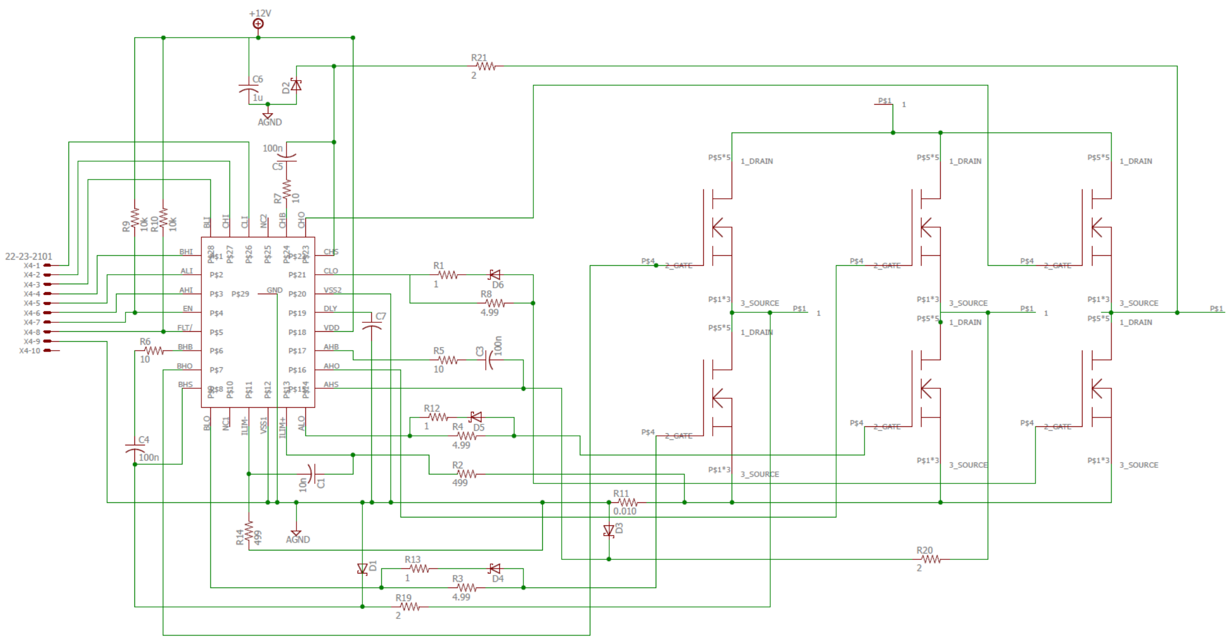

Figure 6. Motor drive circuit using the techniques outlined in Figures 2 through 5.

Looking at the actual operation of the circuit shown in Figure 6, we can see the various conditions occurring in the actual circuit. A 12V Quadcopter motor was used as a load with a Microchip microcontroller responsible for sensor-less commutation.

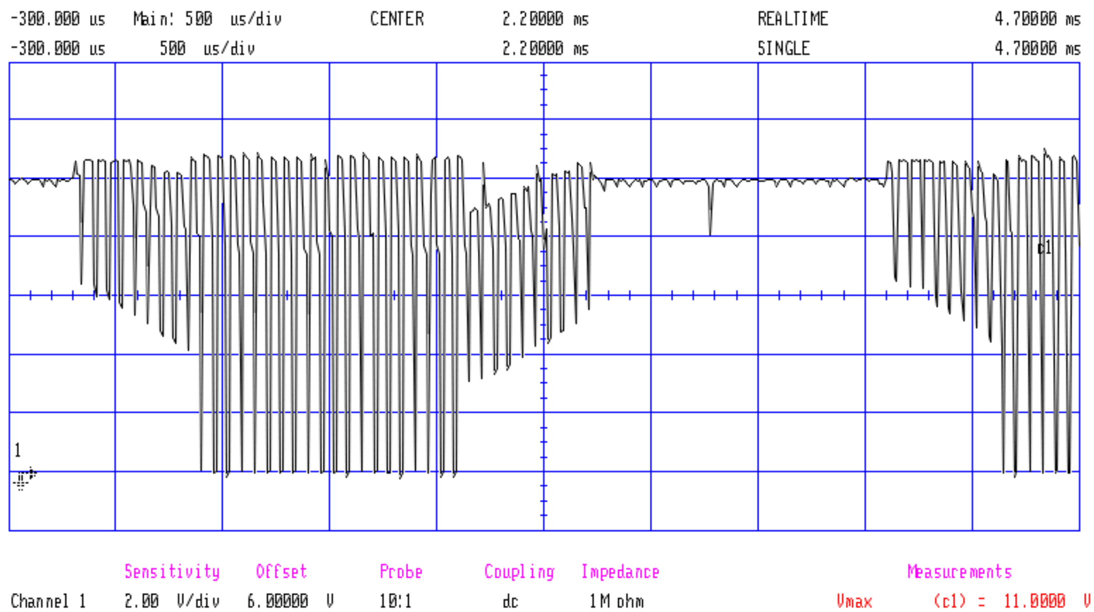

Figure 7. Motor node for a complete motor cycle showing all stages of operation

Figure 7 shows a complete motor cycle for one phase: 1) High side on, 2) high side and low side off, 3) Low side PWM, high side off followed by high side and low side off and then high side on. Note that the node is going above the rail voltage (10V here).

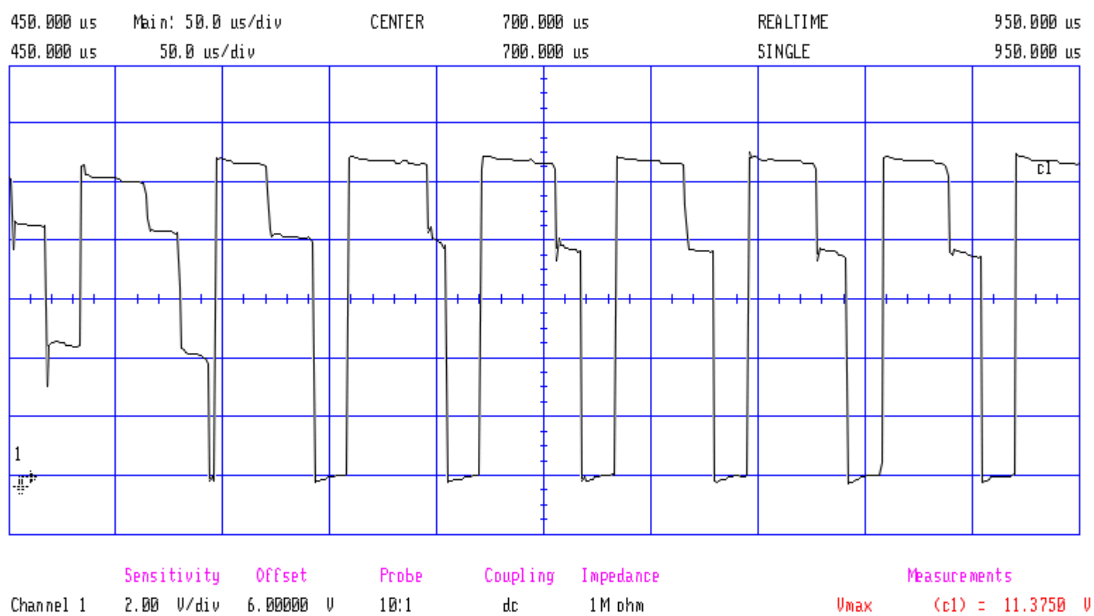

Figure 8. Low Side PWM waveform

Figure 8 shows the N channel PWM operation. At this low duty cycle the freewheeling current decays to zero during the free wheel period and the diode is not commutated by the low side MOSFET, I.E. it is discontinuous.

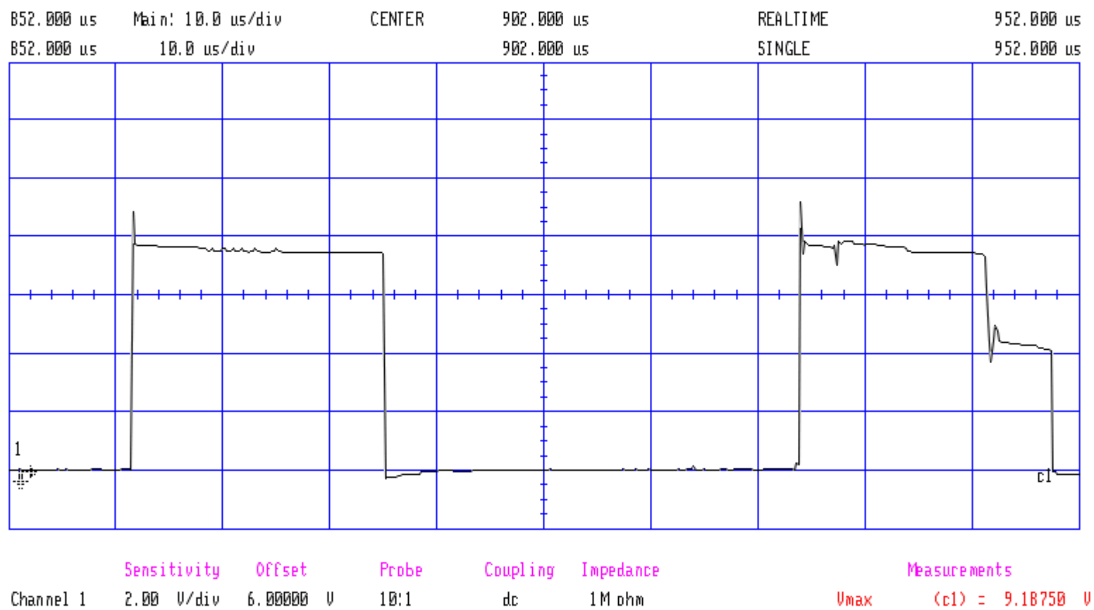

Figure 9. PWM with continuous diode conduction for one cycle

Figure 9 shows continuous conduction for Vrail = 6.5V. The center node is going above the rail by a diode drop. Negative going spikes at low side turn on are not visible. However spikes at PWM MOSFET turn off are visible.

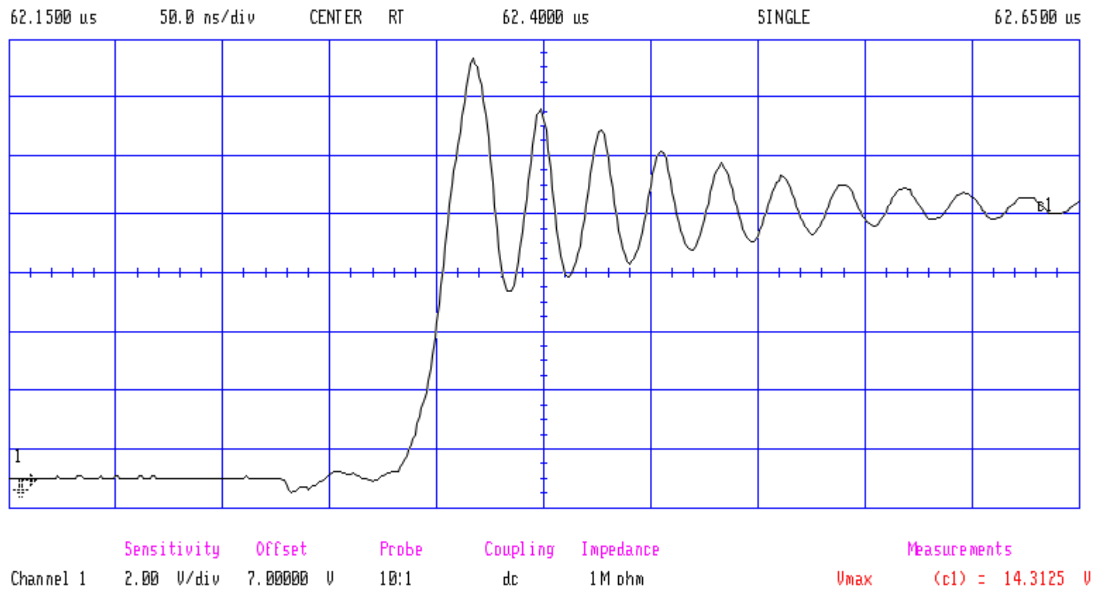

Figure 10. Ringing on motor node at bottom FET turn off, VDS = 8V

Figure 10 shows the ringing in detail. At a rail voltage of 8V, the peak voltage is 14V and the peak dv/dt is 0.3V/ns. The high dv/dt is due to the inevitable snappy diode turn on which cannot be controlled. The ringing is probably due to some degree of VGS oscillations as the MOSFET VGS is still above the threshold voltage at this point. Adjusting the value of the turn off series resistance can usually minimize this spike. Note that in theory this spike cannot happen as the diode should clamp the node to a diode drop above the rail. It is caused by parasitic inductance in the rails and the high currents and di/dt that can occur when switching in half bridges, emphasizing the need to keep loop inductance low and the input rail capacitors close to the MOSFETs.

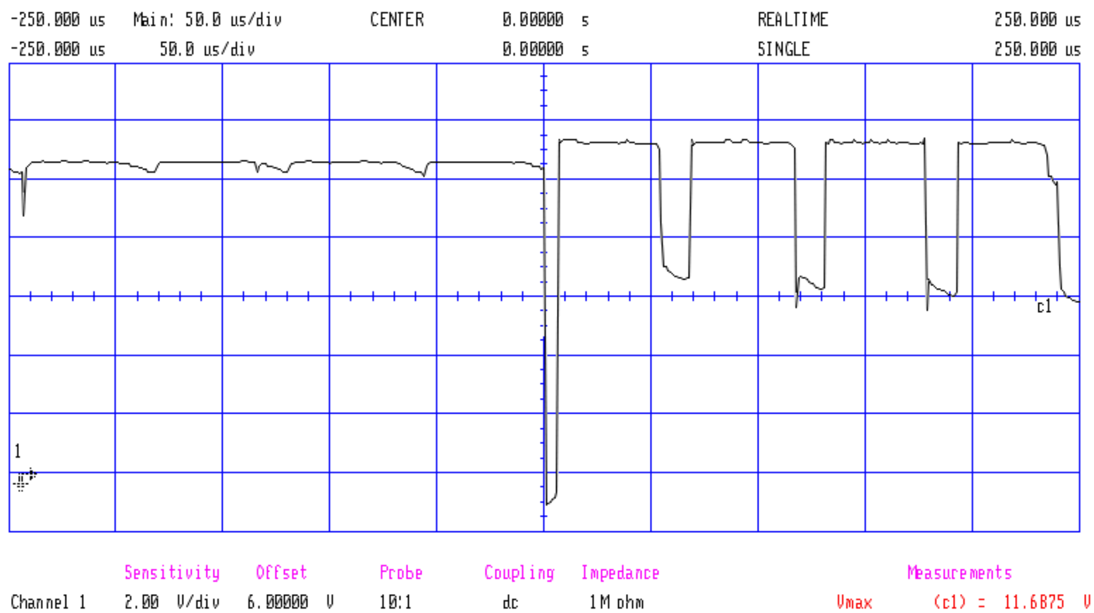

Figure 11. Motor node going negative with respect to ground

Figure 11 shows the motor/center node going negative with respect to ground by about a volt when the top MOSFET is commutated.

MOSFET Selection

As we have seen, the stresses and waveforms in a low voltage motor drive circuit can be higher stress than at first thought, mainly due to high inductances and diode commutation. Key MOSFET parameters to consider are:

- 100% UIS testing to help guarantee ruggedness during diode commutation
- High CISS/CRSS ratio to help keep MOSFETS off when high dv/dt is applied
- Soft (as opposed to snappy) recovery of the MOSFETs diodes, I.E. diode recovery causes as low di/dt as possible which in turn keeps a voltage spike as low as possible.
- Low internal RG MOSFETs to ensure that a low external VGS clamp is not negated by a high internal series resistance.
- High threshold voltage to reduce the chance of dv/dt turn on. This assumes that >6V VGS is applied for the on state, which is good practice in motor drives to allow use of MOSFETs with higher threshold voltages.
- Low inductance packages such as DFN3x3 and DFN5x6.
- High IDM and low thermal impedance at short pulses (~ms) to ensure survival of start up and locked rotor surges.

The voltage rating of the MOSFET should be at least 1.5 X the rail voltage and the external gate series resistance of the N channel MOSFET tuned to ensure minimal ringing or otherwise a higher voltage may be required.

Since the switching period of even the bottom MOSFETs is quite long, super-low figure of merit MOSFETs (I.E. leading edge technology) will have no improvement in performance over more generic technology. In fact super-low figure of merit MOSFETs will require higher values of series resistance to slow them down to the speeds of less esoteric MOSFETs, and therefore they are harder to design with..

The RDS and current rating required is somewhat hard to quantify. Each MOSFET only conducts for a duty cycle of about 50% maximum, but the high side MOSFETS can see higher power dissipation than expected due to diode as opposed to MOSFET conduction depending on whether it is turned on during its diode conduction.
The circuit shown in Figure 6 used six AM7302N:

Part	Configuration/ polarity	V_{DS} Max V	V_{GS} Max V	$R_{DS(on)}$ m Ohm @ V_{GS} = 10V	4.5V	2.5V	1.8V	I_D Max A	Q_G C	P_D W	Package
AM7302N	Single N	30	20	4	6	-	-	24.2	32	3.5	DFN3X3

The board was tested with currents up to 8A with minimal temperature rise observed on the MOSFETs. Designing for 2W maximum dissipation at a DC current equal to the maximum motor full load current using the hot RDS or 1W using the data sheet RDS is a reasonable conservative approximation. Looking at the AM7302N, that would suggest the maximum motor rating would be :

I_{MOTOR}, max = (1W / 0.004) ^ 0.5
= 16A

Another simple method would be to say that the current rating of the MOSFET should be about 1.5 X the maximum motor current.

Looking at the 10ms maximum rating for the AM7302N we see a value of 50W, which corresponds to a current of approximately 80A. The IDM rating for this device is 100A. Using these two ratings we can see that the device can handle start up currents without exceeding the capabilities of the MOSFET.

The 1 s thermal impedance is approximately 30K/W, giving a 1 second maximum current of about 25A, sufficient for locked rotor and overload conditions assuming a reasonable overload protection circuit.

For higher current 12V to 20V motor drives the following MOSFETs could be used:

Part	Configuration Polarity	V_{DS} Max V	V_{GS} Max V	$R_{DS(on)}$ m Ohm @ V_{GS} = 10V	4.5V	I_D Max A	Q_G C	P_D W	Package
AMR438N	Single N	30	20	1.9	2.4	42	55	5	SOIC-8PP
AM7426N	Single N	30	20	2.8	4.8	35	35	5	SOIC-8PP
AM4832N	Single N	30	20	3	4.2	27	59	3.1	SO-8
AM90N03-03P	Single N	30	20	3.5	4.6	90	36	300	TO-220
AM90N03-03B	Single N	30	20	3.8	4.6	90	70	300	TO-263
AM160N03-03D	Single N	30	20	3.9	-	93	36	50	TO-252

The driver IC used here, the MIC4607-1 has an operating voltage rating of 85V and the circuit can be used at rail voltages higher than used for this design. The following MOSFETs could be used for a 48V nominal rail for example:

Part	Configuration Polarity	V_{DS} Max V	V_{GS} Max V	$R_{DS(on)}$ m Ohm @ V_{GS} =		I_D Max A	Q_G C	P_D W	Package
				10V	4.5V				
AM90N06-02PF	Single N	60	20	2.6	3	90	110	60	TO-220CFM
AM320N06-02P	Single N	60	20	2.9	3.5	230	112	300	TO-220
AM90N06-03B	Single N	60	20	3	3.3	90	140	300	TO-263
AM90N06-04D	Single N	60	20	4	5	92	64	50	TO-252
AMR462N	Single N	60	20	4.3	4.9	28	60	5	SOIC-8PP
AM90N06-04m2B	Single N	60	20	4.6	5.9	90	57	300	TO-263
AM90N08-04B	Single N	80	20	4.5	6	90	113	300	TO-263
AM90N08-05P	Single N	80	20	5.9	-	90	112	300	TO-220
AM7484N	Single N	80	20	6.9	9	22	51	5	SOIC-8PP
AM290N10-02FP	Single N	100	20	4.6	6.6	290	260	430	TO-247
AM200N10-05B	Single N	100	20	5.5	7	200	159	300	TO-263
AM180N10-04m5P	Single N	100	20	6.5	8.5	180	78	300	TO-220
AM90N10-07B	Single N	100	20	7	9	90	114	300	TO-263
AM90N10-07I	Single N	100	20	7	9	60	51	50	TO-251
AM90N10-07P	Single N	100	20	7.4	9.8	130	114	300	TO-220
AM90N10-08m5PCFM	Single N	100	20	8.5	-	69	114	60	TO-220CFM
AM190N10-04B	Single N	100	20	9	10.5	190	140	300	TO-263
AMR416N	Single N	100	20	10	12	18	51	5	SOIC-8PP

Conclusions

Low voltage motor drive circuits may seem low stress due to the low switching speeds involved. However due to the high inductances involved, the circuit should be designed to ensure slow turn on and yet have a low-resistance Gate to Source pull-down to ensure the MOSFET is held off when it sees a high dv/dt due to diode reverse recovery.

MOSFETs such as the Analog Power AM7302N in a DFN3x3 package prove to be ideal for motors up to approximately 16A and 20V operating. The small size yet excellent thermal impedance and package maximum current makes it ideal for motors such as ~12A maximum Quadcopter motors. For higher currents and or higher voltages, other low on resistance MOSFETs are available and can be driven in the same manner as shown here.