AC Motor Drive Using Integrated Power Stage

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Abstract

The AC induction motor is the workhorse of modern industry. Worldwide about 50 million motors are installed every year that have greater than 1/2 hp. Today only a small percentage of these motors utilize variable speed drives. Almost half of the variable speed AC drives sold today are in the 1 to 5 hp range. Companies producing this range of drives are under a great deal of pressure to reduce costs. Lower system cost will result in higher volumes as more applications use variable speed. The power semiconductors are a significant portion of the cost of these drives. A new module called an Integrated Power Stage may be used to reduce the cost and complexity of the power semiconductors. A functional demo board has been developed using this module for a 1 to 2 hp AC motor drive.

INDUCTION MOTOR SYSTEM

A systems approach can be taken to reduce the overall cost of an AC drive in the 1 to 3 hp power range. The system can be partitioned by semiconductor technologies and power dissipation requirements. A block diagram of a basic AC drive system is shown in Figure 1.

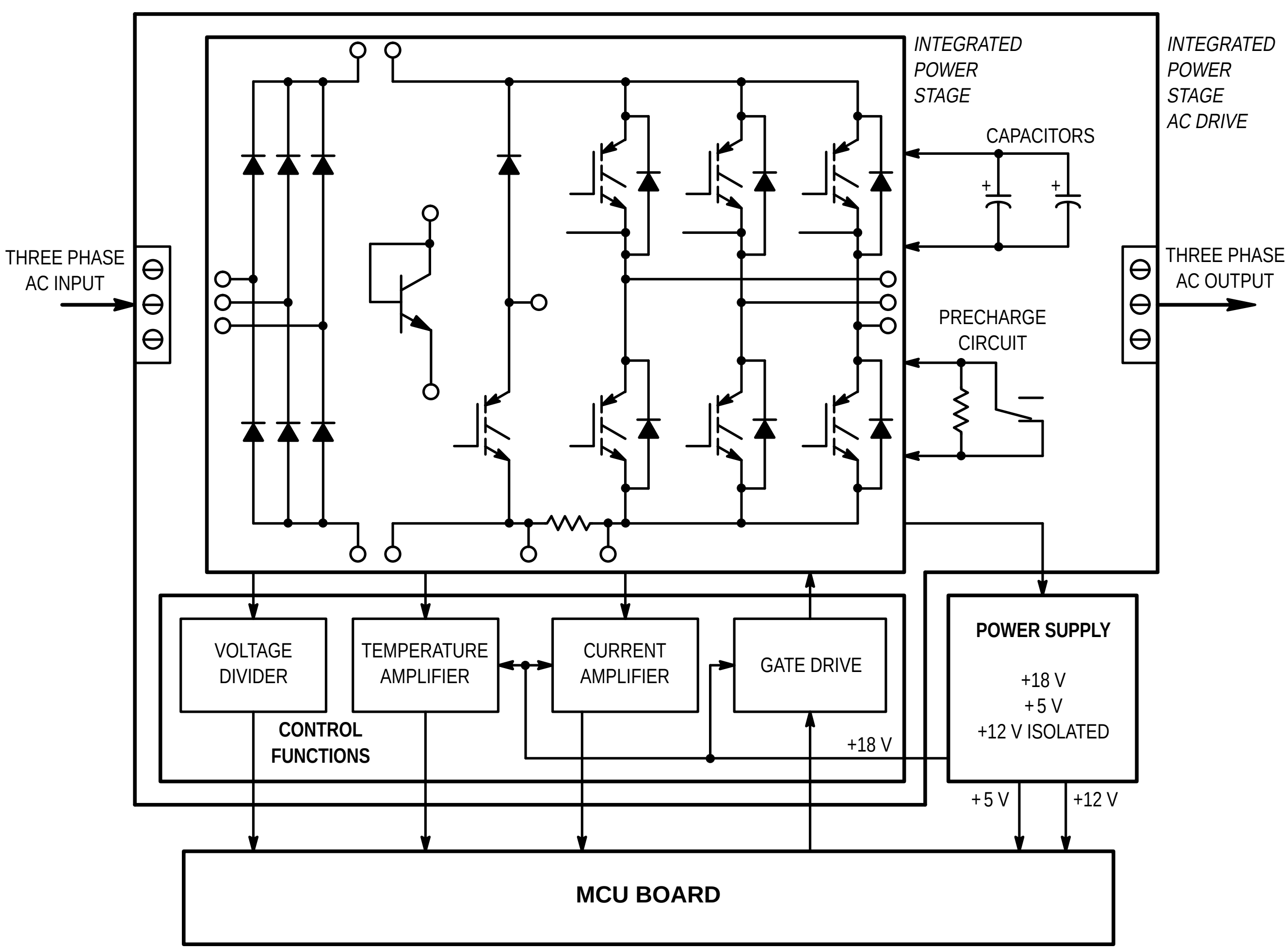


Figure 1. System Block Diagram

REV 1

The power semiconductors for an AC drive consist of a three phase rectifier and a three phase inverter. The three phase rectifier converts a three phase AC power source into a DC supply. A single phase power source may also be connected to any two of the three inputs. Electrolytic capacitors are used to provide energy storage for the DC supply.

A three phase inverter consisting of six IGBTs and six soft recovery diodes is used to drive the motor. Three phase AC is then generated by using sine wave pulse width modulation. The voltage and frequency of the AC output can be easily controlled using an embedded microcontroller unit. The most common constant V/F (volts per hertz) drives provide sine frequencies of 1 to 120 Hz and voltages of 0 to 240 VAC or 480 VAC. The three phase inverter is very flexible and can also be used for most three phase motors and modulation or commutation schemes. This includes brushless DC motors.

Because AC motors under sine wave excitation are also capable of generating, a dynamic brake circuit is often used. When the speed command is reduced in an AC drive, the motor will regenerate. The real part of the three phase power flows from the motor to the inverter. This results in current flowing from the inverter into the DC buss capacitors. Because this energy cannot flow back into the AC supply it must be stored in the capacitors or dissipated. If too much energy is pumped into the capacitors the voltage will rise to unacceptable levels. A dynamic brake resistor and a seventh IGBT are often used to dissipate this energy. Because large resistors used for dynamic braking are inductive, a clamp diode is used to limit the transistor voltage during turnoff.

INTEGRATED POWER STAGE MODULE

There are a total of 20 power semiconductor devices in this AC drive system. Using single transistor discrete packages is very cumbersome. Often a rectifier module and IGBT six pack is used with a discrete transistor for the brake. This simplifies matters a little, reducing the number of components that must be mounted to a heatsink and soldered to three.

The "Integrated Power Stage" Module is a comprehensive solution for small motor drives. A schematic of the Integrated Power Stage is shown in Figure 2 and the module is illustrated in Figure 3. These modules contain all the power electronics for an AC drive. By combining all the power devices into a single package mounting use is greatly simplified. A single module is fewer parts than two modules. This should reduce manufacturing cost and improve reliability. The Integrated Power Stage also contains a 1% sense resistor and a temperature sense diode. These components can be used to provide status and control functions as well as protection features.

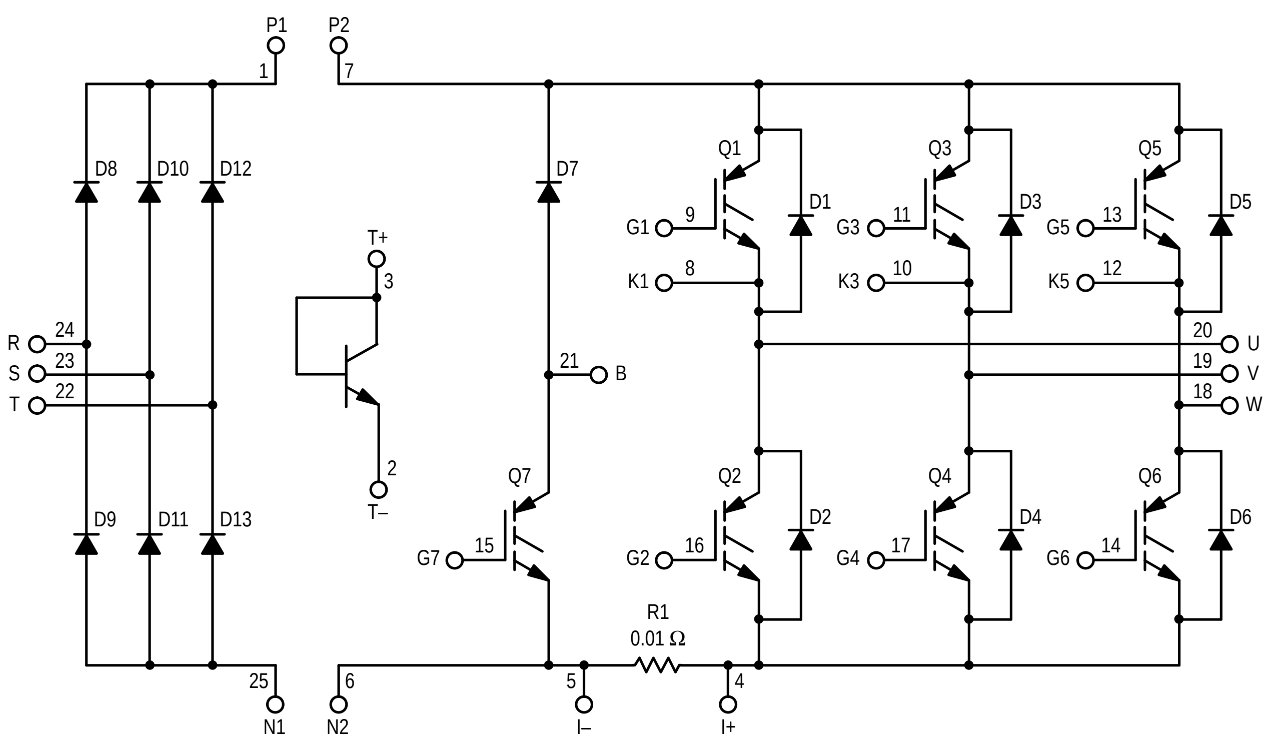


Figure 2. Integrated Power Stage Schematic

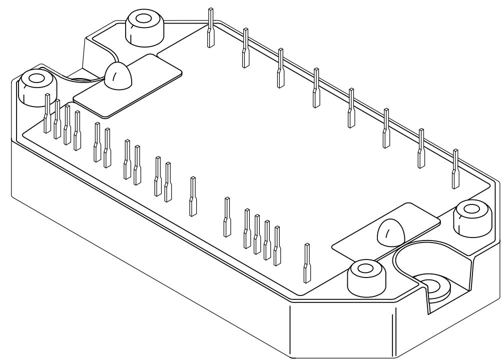


Figure 3. Integrated Power Stage Module Illustration

There is a family of six modules for 1, 2 and 3 hp motor drives for both low voltage (up to 240 VAC) and high voltage (up to 480 VAC). Table 1 contains the part numbers and the voltage and current ratings for the Integrated Power Stage modules.

Table 1. Integrated Power Stage Ratings

		I_C (Amps)				
		8	12	15–16	20	30
V_{CES} (Volts)	600			MHPM7A15A60A	MHPM7A20A60A	MHPM7A30A60B
	1200	MHPM7A8A120A	MHPM7A12A120A	MHPM7A16A120B		

IPS AC MOTOR DRIVE DEMO BOARD CIRCUITRY

A demo board has been developed for the Integrated Power Stage family of modules. A photograph of this demo board is included at the end of the text as shown in Figure 13. The purpose of this demo board is to provide a vehicle for evaluating the performance of these modules and to enable customers to rapidly develop proof of concept systems. The board contains the integrated power stage module, passive power components and gate drive. It also contains a current amplifier, temperature amplifier and voltage divider for monitoring drive status. Over–current, over–voltage comparators and a programmable logic device provide instantaneous fault protection.

Power Circuit

The power electronics for the demo board is shown in Figure 4. Three phase or single phase AC power is connected to the input terminals R, S, and T. The order of the input connections makes absolutely no difference. The Integrated Power Stage (U1) rectifies the AC and provides a DC output at P1 (1) and N1 (25). Negative temperature coefficient thermistors (R1 and R2) are used to limit the inrush current and protect the rectifier diodes from excessive surge current. Two thermistors with a cold resistance of 1 Ω are sufficient to protect the low voltage systems. Alternatively, a relay and precharge resistor could be used to limit inrush current. Both upper and lower branches of the DC buss are split between the rectifier and brake for flexibility.

Capacitor C1 is a polypropylene capacitor for high frequency performance. Capacitors C2 and C3 are the DC buss capacitors. Jumpers are provided to configure these capacitors in series or parallel. The PC board is designed for both high voltage and low voltage systems. All the values shown are for the low voltage configuration.

The output terminals U, V, and W are connected to the motor. Exchanging the order of the connections will reverse the direction of the motor rotation. The motor rotation can also be reversed by software control. A connector is also provided for dynamic brake connection.

The heatsink of U1 is earth grounded using a small screw through one of the module standoffs. The heatsink should be earth grounded for safety reasons. The clearance and creepage distances for the printed circuit board are designed to meet the spacing requirements of UL 840 and IEC 335 for 480 VAC drives. The AC drive standards UL 508, UL 508C, VDE 0110, and VDE 0160 refer to these standards or use similar clearance tables.

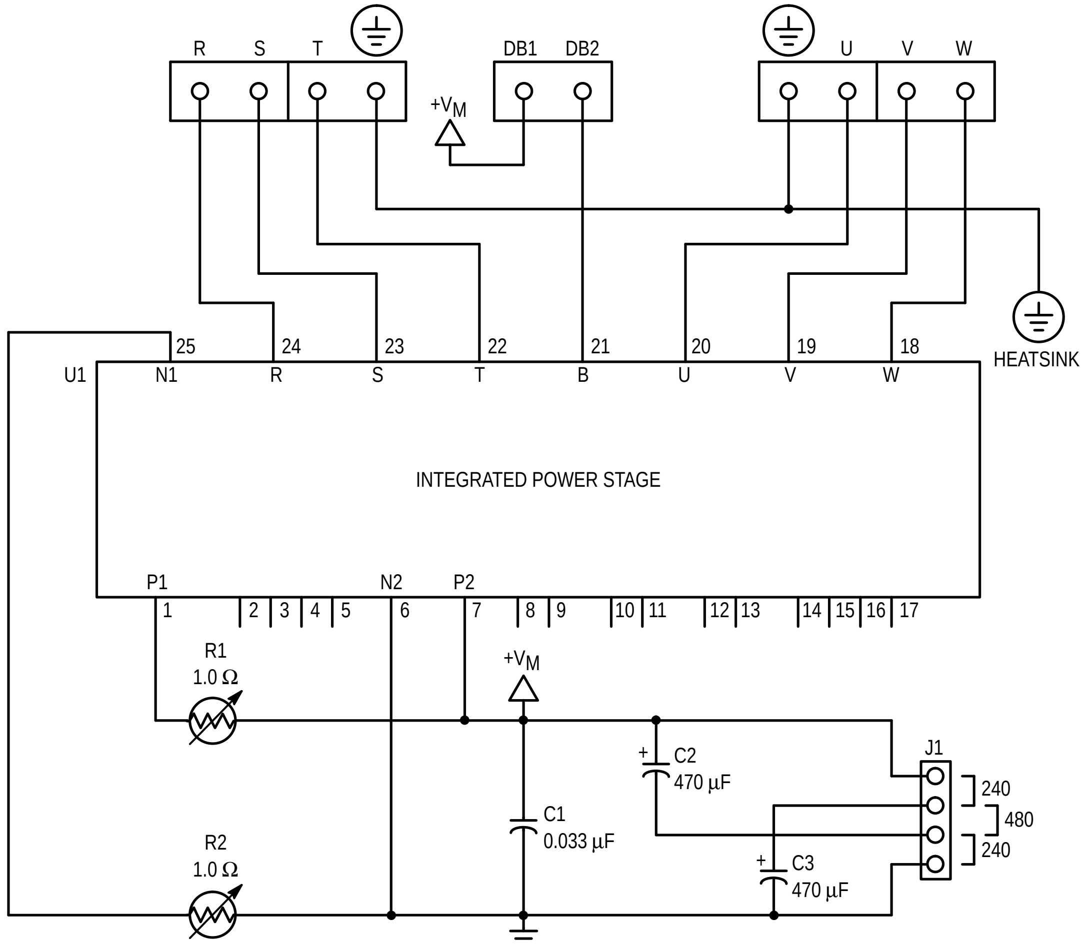


Figure 4. Power Electronics

Gate Drive

The gate drives for the high side IGBTs use optocouplers for level shifting. The circuit is shown in Figure 5. The HCPL0453 optocoupler (U8) was chosen for its high dv/dt capability and speed of operation. The 480 VAC drives must operate with DC link voltages as high as 850 volts under regeneration conditions. Thus, a 600 volt HVIC solution is not suitable for 480 VAC drives. It is estimated that high voltage drives account for more than 1/3 of 1 hp drives and about three–fourths of the 5 hp drives. Optocouplers provide a universal solution for both voltage ranges.

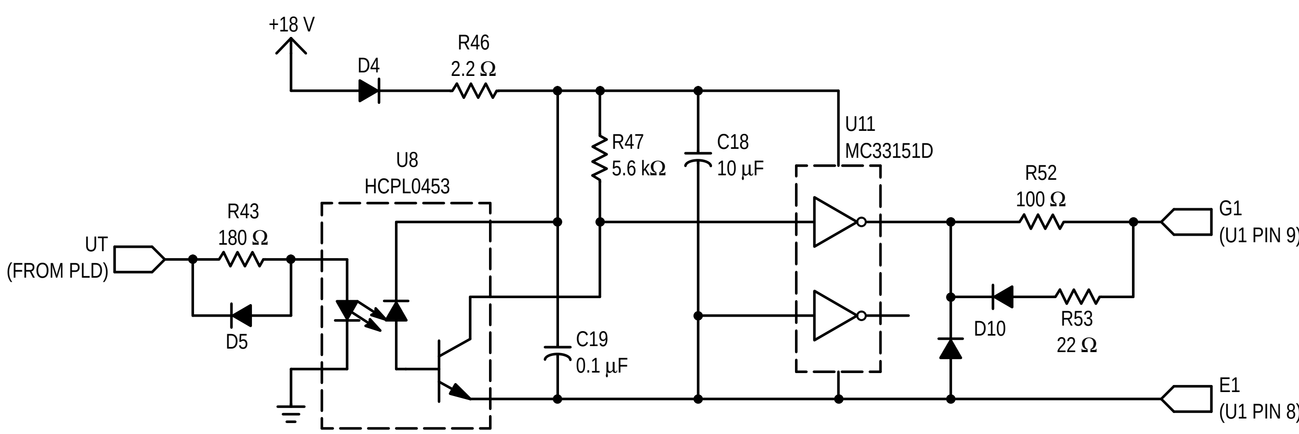


Figure 5. High Side Gate Drive

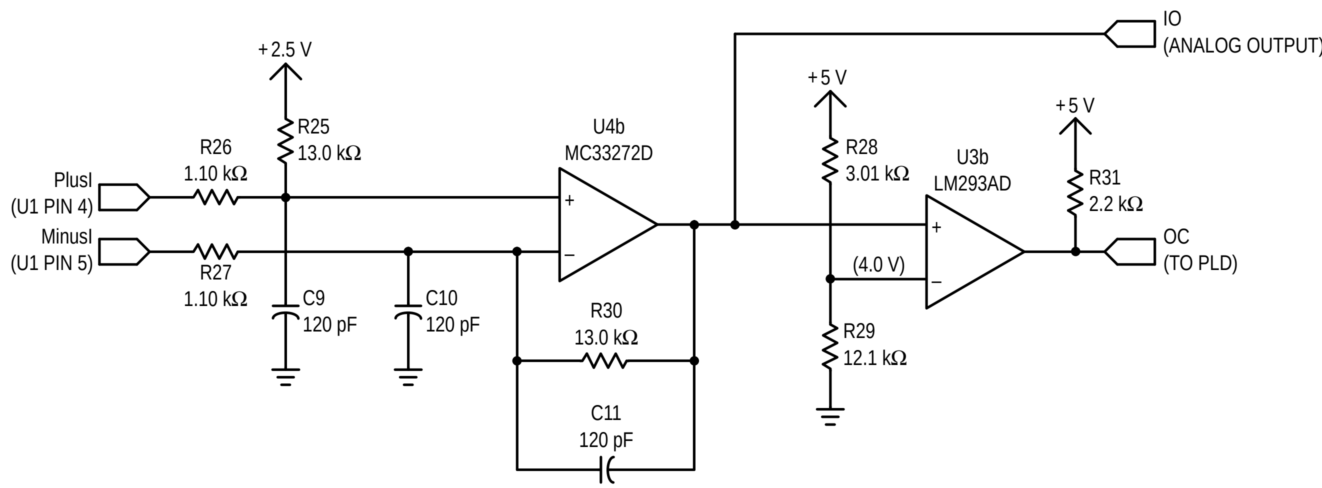


Figure 6. Current Amplifier and Over–Current Comparator

Power is supplied by a bootstrap circuit consisting of a high voltage diode (D4), a small resistor (R46), and capacitor (C18). When the lower IGBT is turned on, the capacitor charges through the diode and resistor. The lower transistor is then turned off and the upper transistor is turned on. The charge stored in the capacitor supplies the gate drive energy. Actually, the bias current of the IC and optocoupler pull–up resistor are the primary current drains on the bootstrap capacitor. The 10 µF capacitor can provide a holdup time of several milliseconds. An 18 volt supply is recommended because about 3 volts are lost in the lower transistor on voltage and the bootstrap diode. The small resistor limits the peak current under transient conditions.

The gate drive current is supplied by an MC33151D (U11) high current MOSFET driver. This is an economical LVIC with 1.5 amps of source and sink capability. Separate resistors are used for turn–on and turn–off. A low turn–off impedance is essential to minimize turn–off losses and shoot–through current. The turn–on resistor is selected to limit the turn–on dv/dt to an acceptable level. The values for R52 and R53 thus vary according to the specified power module/development system.

The dv/dt limitations necessitate some additional power losses in the IGBTs, particularly for the high voltage drives. The dv/dt applied to the motor is also a consideration as this stresses the motor insulation. The typical dv/dt measured on the demo board is 5 to 10 V/ns during IGBT turn–on. This value can be lowered by adding output filter inductors or using larger gate drive resistors. However, using larger gate drive resistors will greatly increase power dissipation in the IGBTs.

The low side gate drive uses a similar circuit without the optocoupler. Two non–inverting MC33152Ds are used for the three low side transistors and the brake transistor.

Status Circuitry

The sense resistor in the integrated power stage is placed between the brake and inverter. This allows the resistor to sense both positive motor current and dynamic braking currents. A resistor placed between the rectifier and brake transistor would not sense the regenerative current when the brake is turned on. The DC link current may be used in many different control and protection schemes. The DC current in this resistor multiplied by the DC voltage gives the real power output of the inverter. The real power divided by 3 and divided by the output phase voltage gives the real output phase current. Unfortunately, the output power factor is not known. However, the peak current in the resistor is indicative of the peak phase current. Thus, a DC measurement and a peak over current detect provides a cost effective means of control and protection.

The current amplifier and over–current comparator are shown in Figure 6. A differential amplifier senses current in both directions. A 2.5 volt reference provides an offset for the differential amplifier. The conditioned output varies from 0 to 5 volts with 2.5 volts representing zero current. The over–current comparator trips at 12.7 amps.

The temperature amplifier is shown in Figure 7. The circuit consists of an inverting amplifier with a 0.69 volt offset. The output provides a temperature signal of approximately 26.5 mV/°C. The compensation capacitor is essential to avoid oscillations with such a large feedback resistor. Resistor R20 biases the temperature sense diode at 1 mA. The bias current can be increased if necessary to minimize noise problems. However, the gain will have to be readjusted.

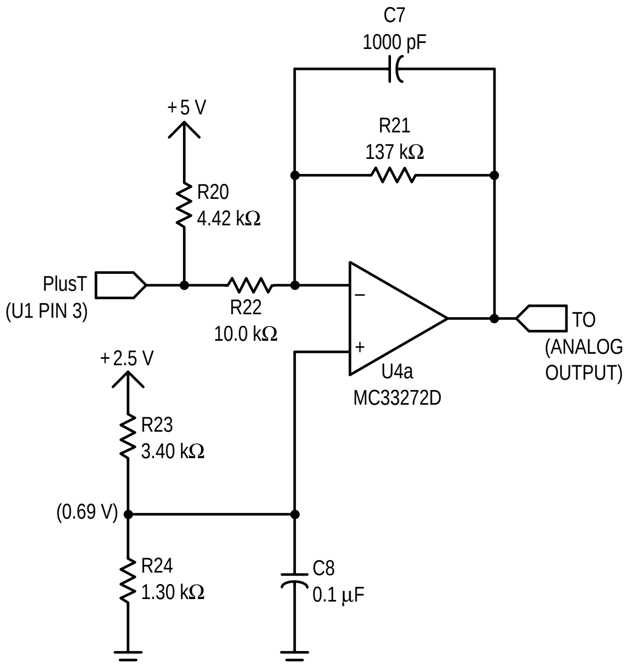


Figure 7. Temperature Amplifier

The voltage divider and over–voltage comparator are shown in Figure 8. The voltage divider provides a 0 to 5 volt signal, 1 volt per 100 volts on the DC buss. Four resistors in series are used to ensure the voltage rating of the resistors is not exceeded for the high voltage system. The over–current comparator trips at 4.25 volts. Some hysteresis is also provided to prevent the brake from oscillating between the on and off states. The resistive divider also serves as a bleeder resistor to slowly discharge the buss capacitors. The high voltage drive uses resistors twice the value shown for R11–14.

Logic Circuit

The input logic of the demo board uses a programmable logic device for flexibility, see Figure 9. The 22V10 PLD has 12 input pins and 10 I/O pins. Seven of the outputs are dedicated to the seven IGBT gate drives. Seven of the inputs are configured for use with the seven transistor inputs. Seven resistors are connected to the inputs and may be configured as pull–up or pull–down resistors. The polarity of the input signals may be changed by modifying the device equations and setting the polarity jumper. One of the inputs is dedicated as a hardware enable. The three remaining I/O pins are available as programmable I/O signals to the ribbon connector.

Complete Schematic & Bill of Materials

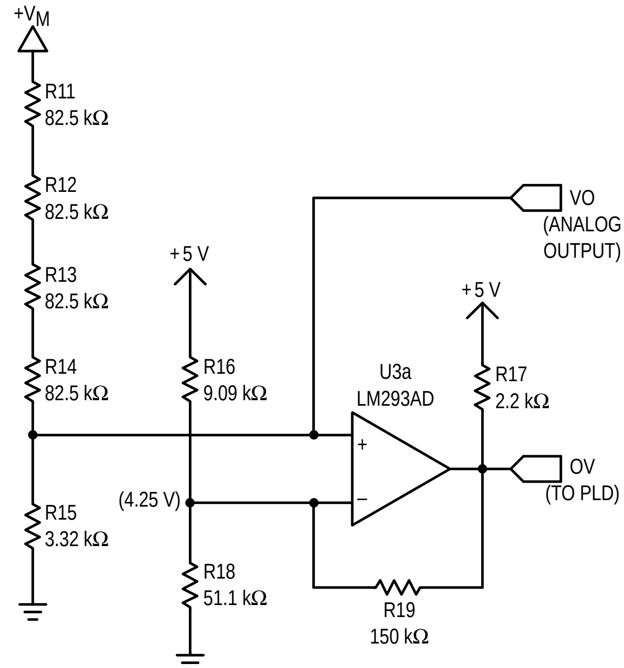


Figure 8. Voltage Divider and Over–voltage Comparator

Appendix I contains a complete board level schematic of the demo board. All of the component values listed in the schematic are for the 1 hp 240 VAC configuration. Appendix II is a bill of materials for the demo board. Again the values listed are for the 1 hp 240 VAC configuration. The 2 hp 240 VAC configuration requires changing several resistor component values. The 1 & 2 hp 480 VAC configurations require changing J1 and using 1000 volt bootstrap diodes, in addition to changing several resistor values. Alternate bill of materials are available on special request.

USING THE IPS AC MOTOR DRIVE DEMO BOARD

PWM Signals

The demo board requires a PWM signal source. The PWM signals can be generated by a microcontroller. Two microcontrollers suitable for this purpose are the MC68332 and the MC68HC16Y1. Basic code for PWM AC motor control has been written for the MC68332[1] and the MC68HC16Y1[2]. Both of these microcontrollers include a Time Processor unit. The Time Processor unit is an autonomous timer which may be micro–programmed for various time functions. A special microcode primitive has been written called Multi–Channel PWM[3] that can generate center aligned PWM signals with dead time. A motor control development system has been developed for the 'HC16Y1. The integrated power stage demo board was designed specifically to interface directly to the 'HC16Y1 motor control development system. However, the PLD provides added flexibility for use with different microcontrollers.

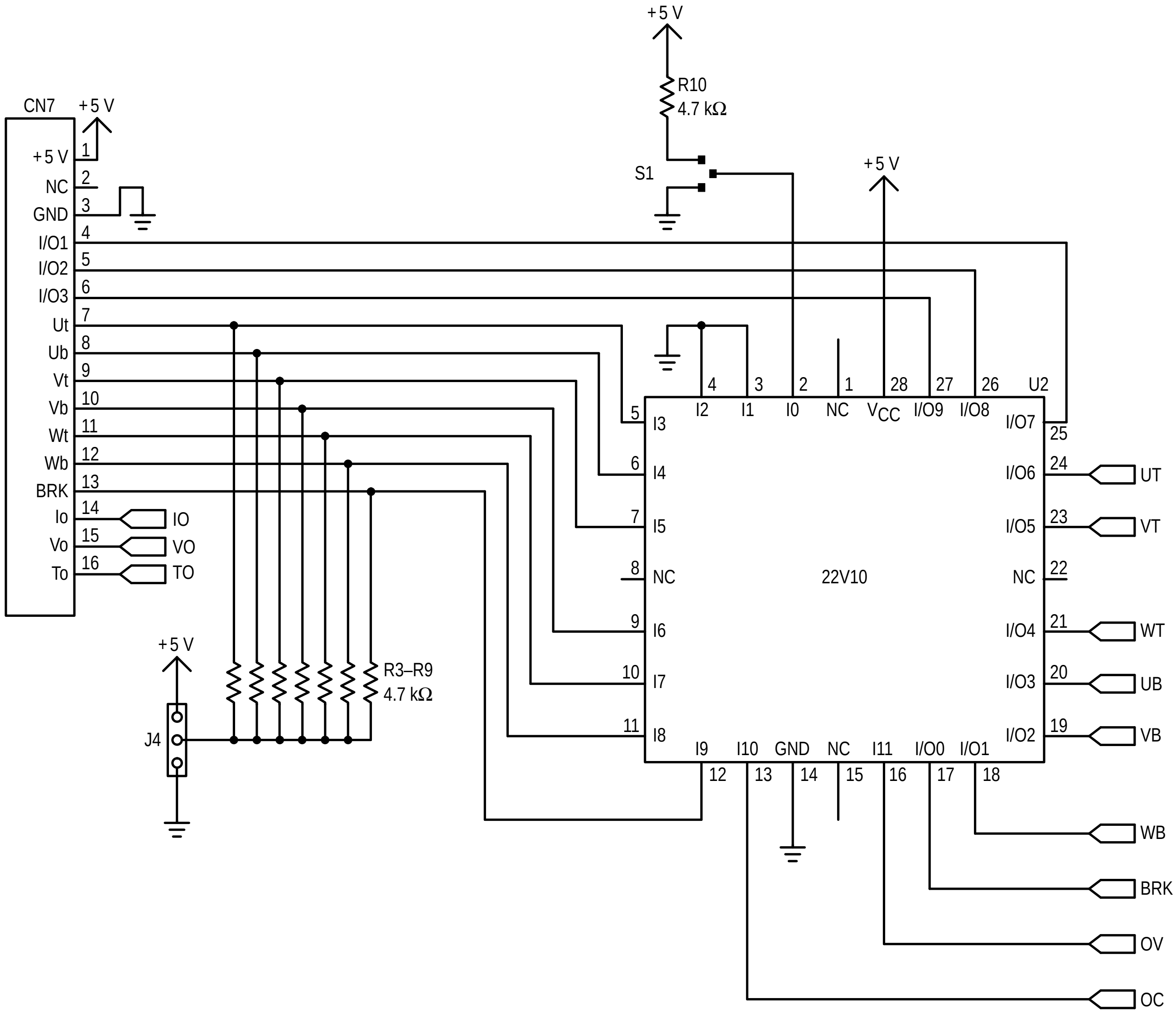


Figure 9. Input Logic

The PWM signals should be center aligned with dead time. The demo board does not provide any dead time. The microcontroller can provide accurate digitally generated dead time far better than an analog circuit. Appropriate PWM signals are illustrated in Figure 10.

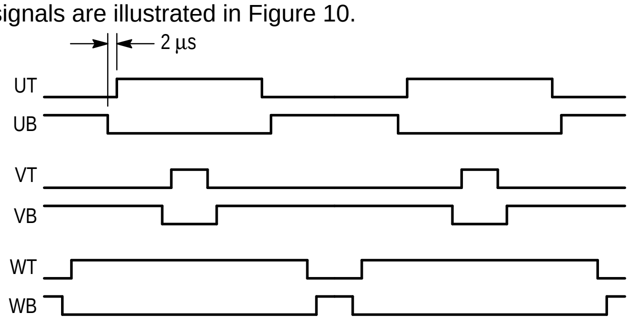


Figure 10. PWM Timing

The recommended dead time for the demo board is at least 2 µs. Less than 2 µs of dead time will allow some shoot through current during switching, resulting in higher switching losses. Inadequate dead time may also result in damage to the power transistors.

PLD Programming

The demo board is shipped with a preprogrammed PLD. This PLD provides only two basic essential functions, half–bridge lockout and a master enable. A half–bridge lockout ensures that both upper and lower transistors are not simultaneously turned on. The master enable function enables or disables all six PWM signals according to the position of SW1 (U2 pin I0).

The standard PLD is programmed for active high logic signals. Therefore jumper J1 should be positioned to configure the input resistors as pull downs. The three general purpose I/O pins are programmed for compatibility with the HC16Y1 development system. Connector CN7 pin 6 (I/O3) is connected to the active low fault pin of the development system. It is set high to enable the PWM signals. The other two I/O pins are tri–stated. The logic equations for the standard PLD were compiled using ABLE. The PLDs were programmed using a Data I/O 2900 programmer. The actual ABLE code is included in Appendix III.

Additional functions may be implemented by changing the logic equations, recompiling the ABLE code and programming a new PLD. In an AC motor drive system many of the functions are a combination of hardware and microprocessor software. The PLD provides the flexibility of being able to easily change the hardware to implement new functions.

The standard PLD does not directly disable the PWM signals under overcurrent conditions. This was intentionally done to enable easy setup and testing of the drive system. Once the system is setup and running, an overcurrent latch may be added by changing the PLD. An overcurrent latch is very sensitive to noise and may result in too many false trips in some systems.

The brake transistor can be configured to turn on automatically when the over voltage comparator detects an over voltage. The micro should monitor the regeneration current to protect the inverter, brake transistor and brake resistor.

When used with a different microprocessor, it may be desirable to invert the PWM polarities. This can easily be accomplished by simply changing the logic equations and moving jumper J1. Also included in Appendix III are ABLE examples of using the brake for overvoltage and inverted inputs.

Laboratory Setup

The demo board is intended to be used only in a power laboratory. The high voltage levels present in any AC drive system represent a serious shock hazard. The demo board should only be used by engineers and technicians who are experienced in power electronics.

A complete laboratory setup consists of an isolated AC supply, the IPS AC Motor Drive demo board, an AC induction motor, a dynamometer or motor load, a microprocessor board and isolated lab supplies for +18 V and +5 V. A block diagram of the lab setup is shown in Figure 11.

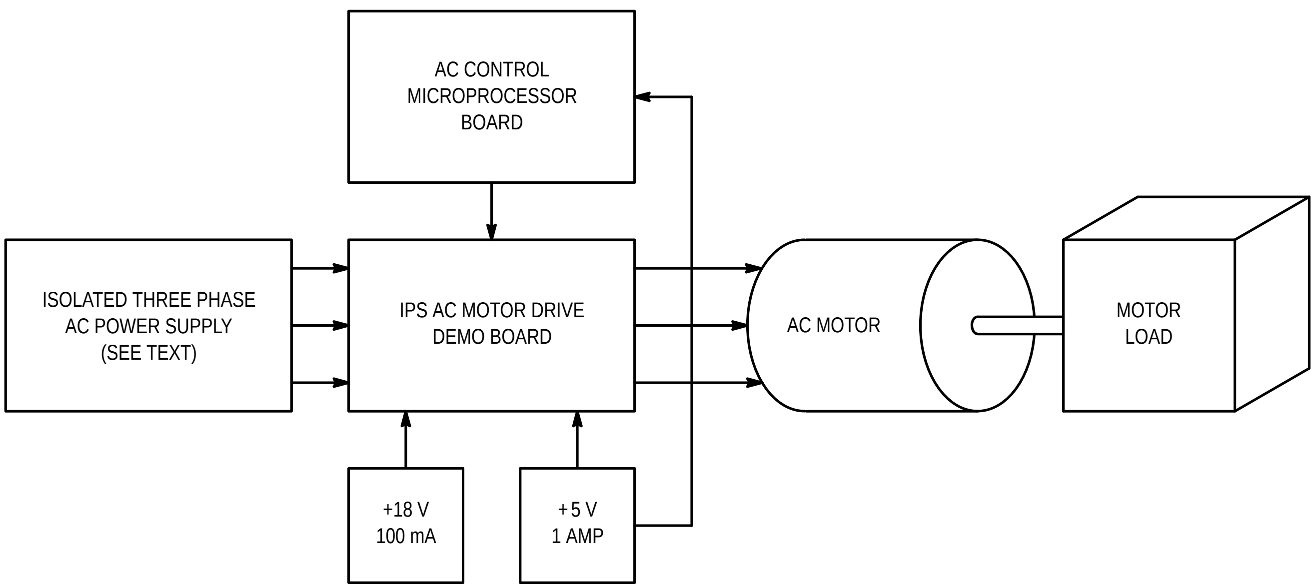


Figure 11. Laboratory Set–up Block Diagram

The motor drive demo is not electrically isolated from the AC mains. This topology is very common in low cost AC drives. The microprocessor is grounded on the negative supply of the high voltage DC buss. Thus, the micro and associated circuitry are hot and must be isolated from user controls and serial interfaces in final product form.

In the laboratory it is safest to isolate the AC supply, auxiliary power supplies and oscilloscopes. This prevents a shock from touching any single point in the circuit. This does not, however, prevent shocks when touching two or more points in the circuit. If absolutely necessary, one point in the circuit (the micro ground for example) may be earth grounded. However, this establishes all high voltage nodes at dangerously high voltages.

An isolated AC power supply can be constructed using an isolation transformer and a variable transformer (variac). A schematic of the recommended AC power source is shown in Figure 12. Fast semiconductor grade fuses should be used directly up line of the AC drive. The transformer should be fused with slower fuses to prevent blowing a fuse when energizing the transformer. The demo board contains thermistors to prevent excessive inrush current. However, it is advisable to use a variac when first powering up the system.

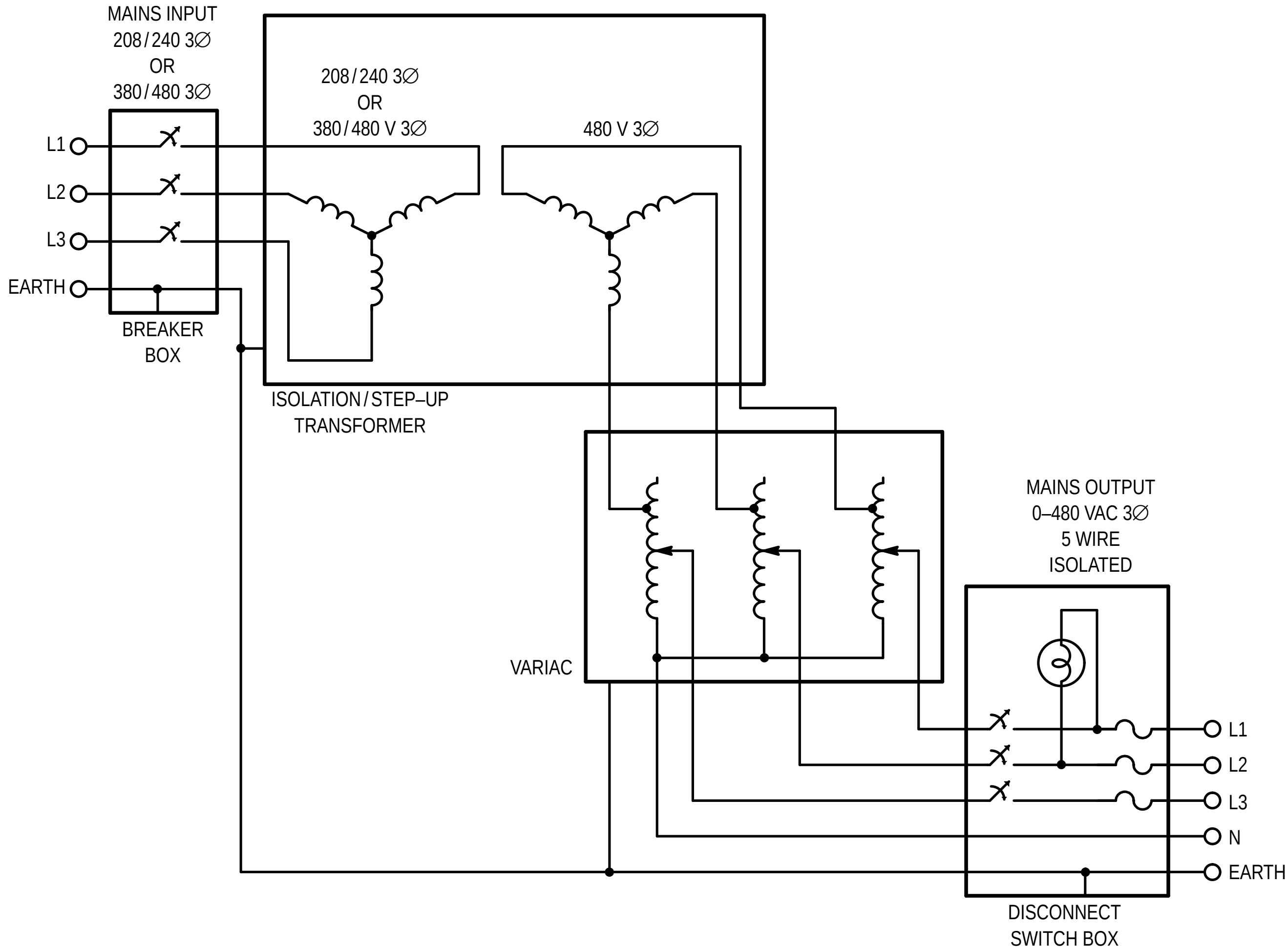


Figure 12. Isolated Three Phase AC Supply

Use the following procedure the first time the system is powered up. Check all connections twice. First turn on the +5 and +18 volt supplies. Then check all the gate drive signals with an oscilloscope. Once you are confident the micro and gate drives are functioning properly, proceed to power up the AC line. Set the inverter output frequency to about 15 Hz. Set the load torque to zero or disconnect the motor load. First turn down the variac all the way. Then energize the isolation transformer. Monitor the DC link voltage. Slowly increase variac output voltage. The motor should start turning before the DC buss reaches 100 volts. Once the motor is turning, it should be safe to turn up the variac to full voltage.

SUMMARY

The Integrated Power Stage greatly simplifies the design and assembly of an AC drive. A demo board has been developed for the integrated power stage module. The demo board has been tested and is fully operational. This board may be used to evaluate module performance and facilitate rapid product development.

REFERENCES

1. *Using the MC68332 Microcontroller for AC Motor Control,* J. Baum and K. Berringer, Motorola Application Note AN1310
2. *M68MCD16Y1 Motion Control Development Board Users Manual,* M68MCD16Y1/D
3. Multi–Channel PWM TPU Function, TPUPN05/D

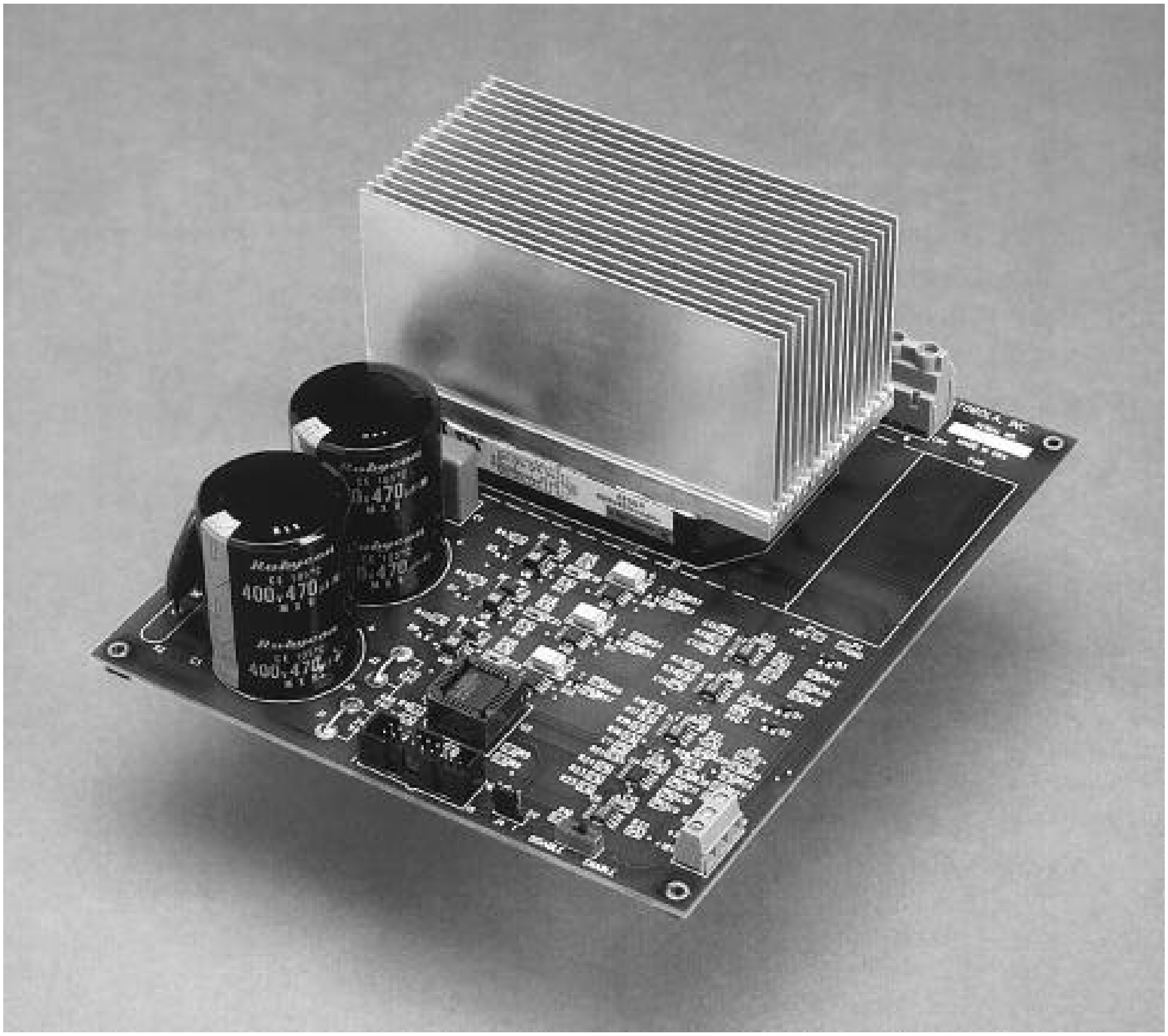
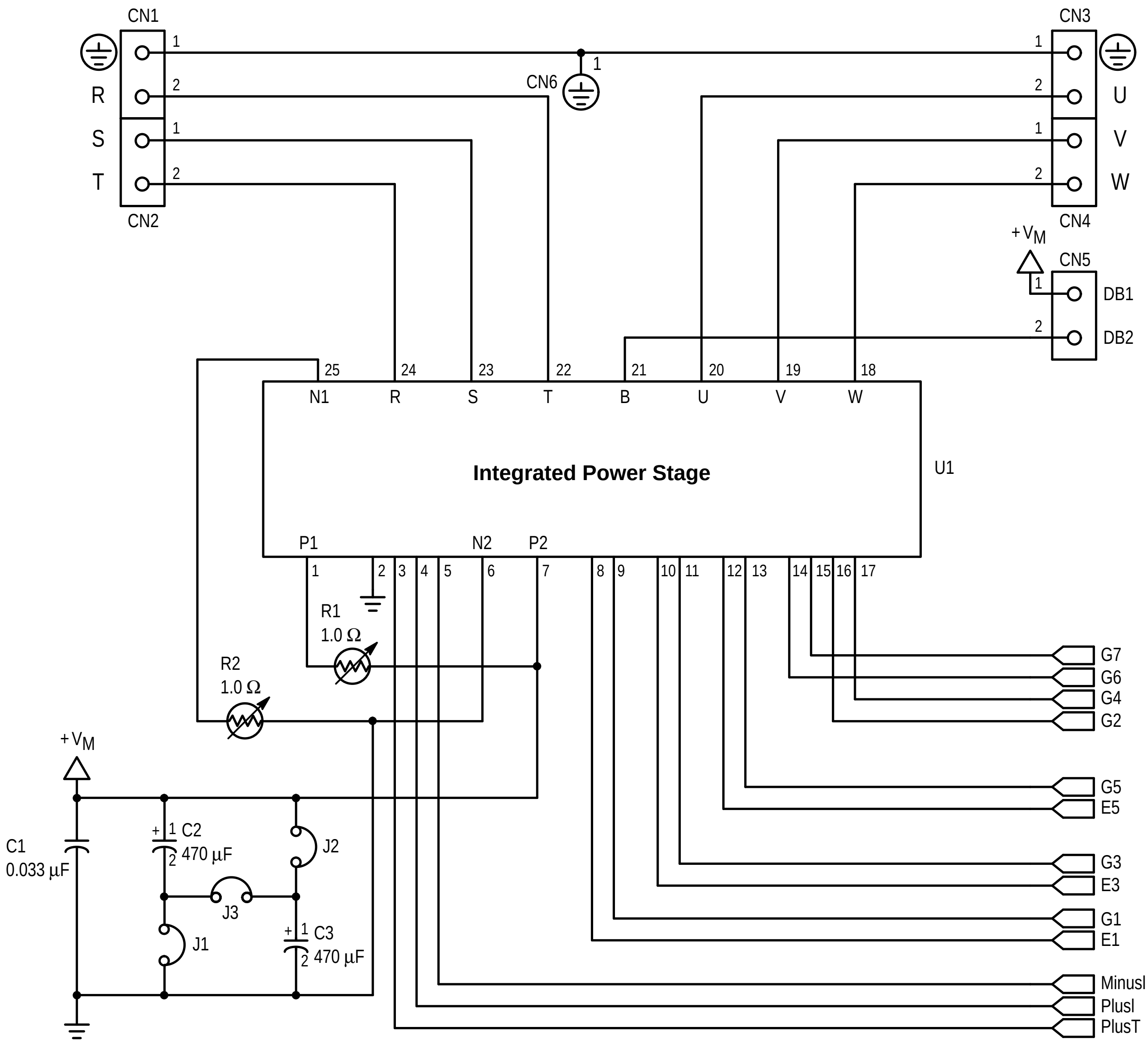


Figure 13. Integrated Power Stage AC Motor Drive Board

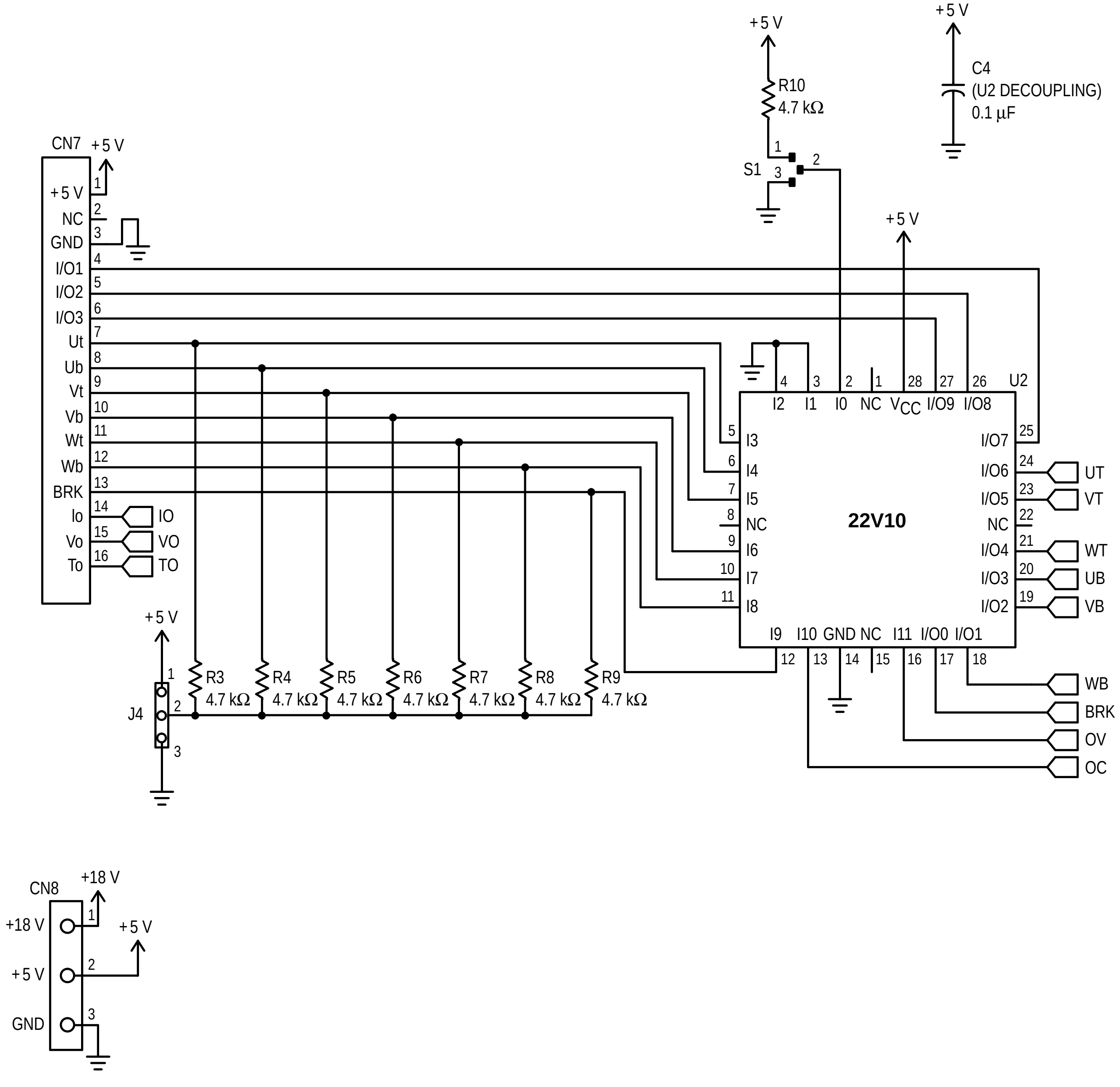
Appendix I

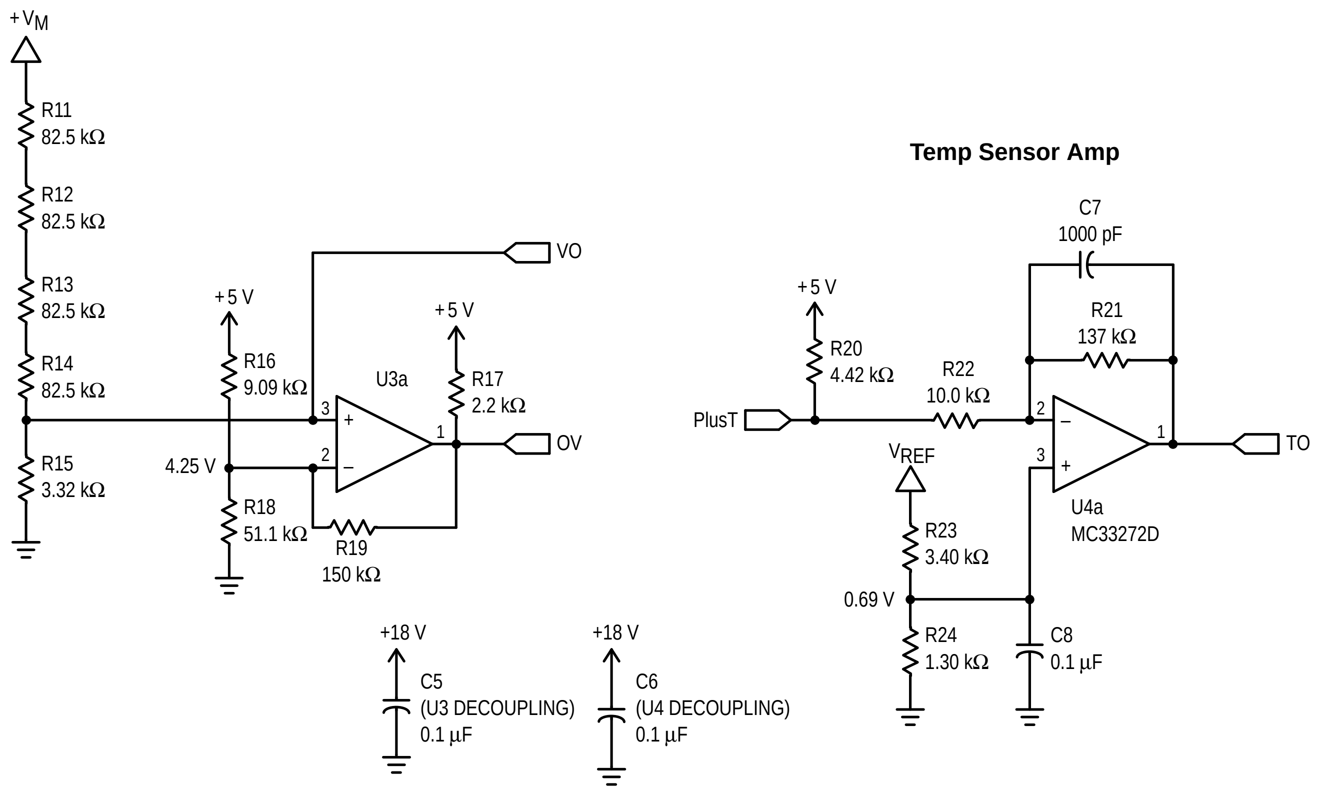
Board Schematic

IPS AC Motor Drive
Power I/O

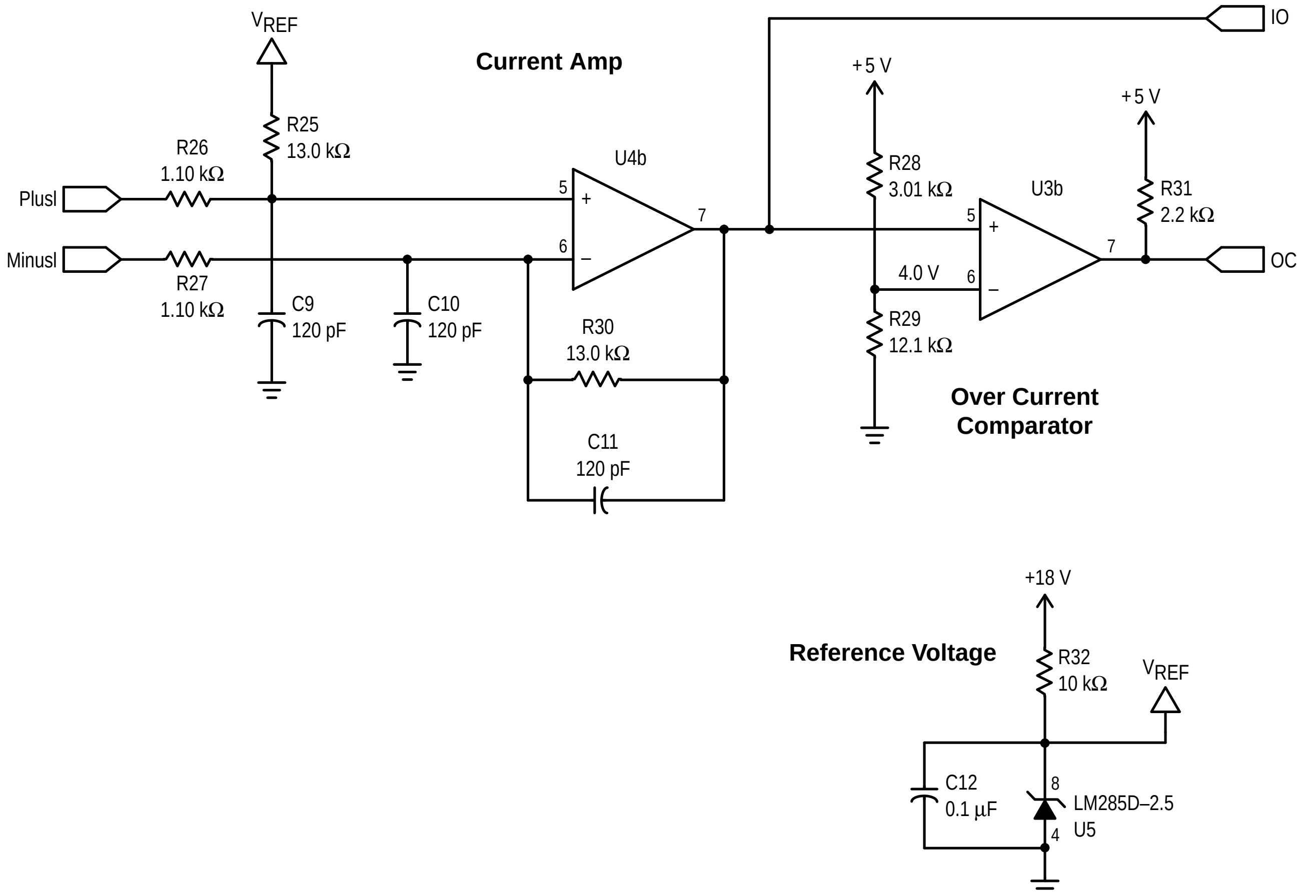


IPS AC Motor Drive
Logic I/O

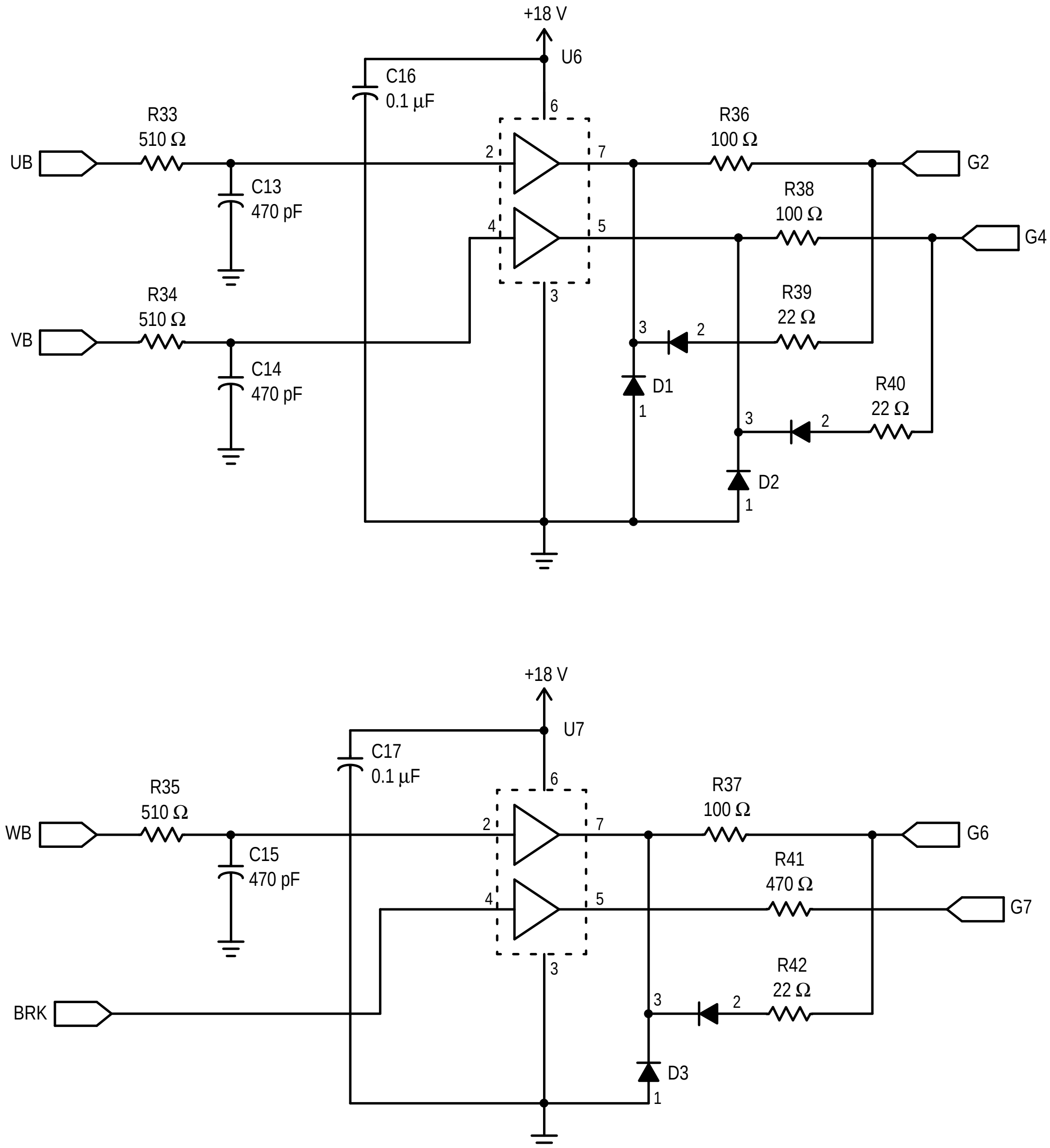



+VM
R11
82.5 kΩ
R12
82.5 kΩ
R13
82.5 kΩ
R14
82.5 kΩ
R15
3.32 kΩ
+5 V
R16
9.09 kΩ
4.25 V
R18
51.1 kΩ
VO
U3a
+5 V
R17
2.2 kΩ
OV
R19
150 kΩ
+18 V
C5
(U3 DECOUPLING)
0.1 µF
+18 V
C6
(U4 DECOUPLING)
0.1 µF
Temp Sensor Amp
C7
1000 pF
R21
137 kΩ
+5 V
R20
4.42 kΩ
R22
10.0 kΩ
PlusT
VREF
TO
U4a
MC33272D
R23
3.40 kΩ
0.69 V
R24
1.30 kΩ
C8
0.1 µF

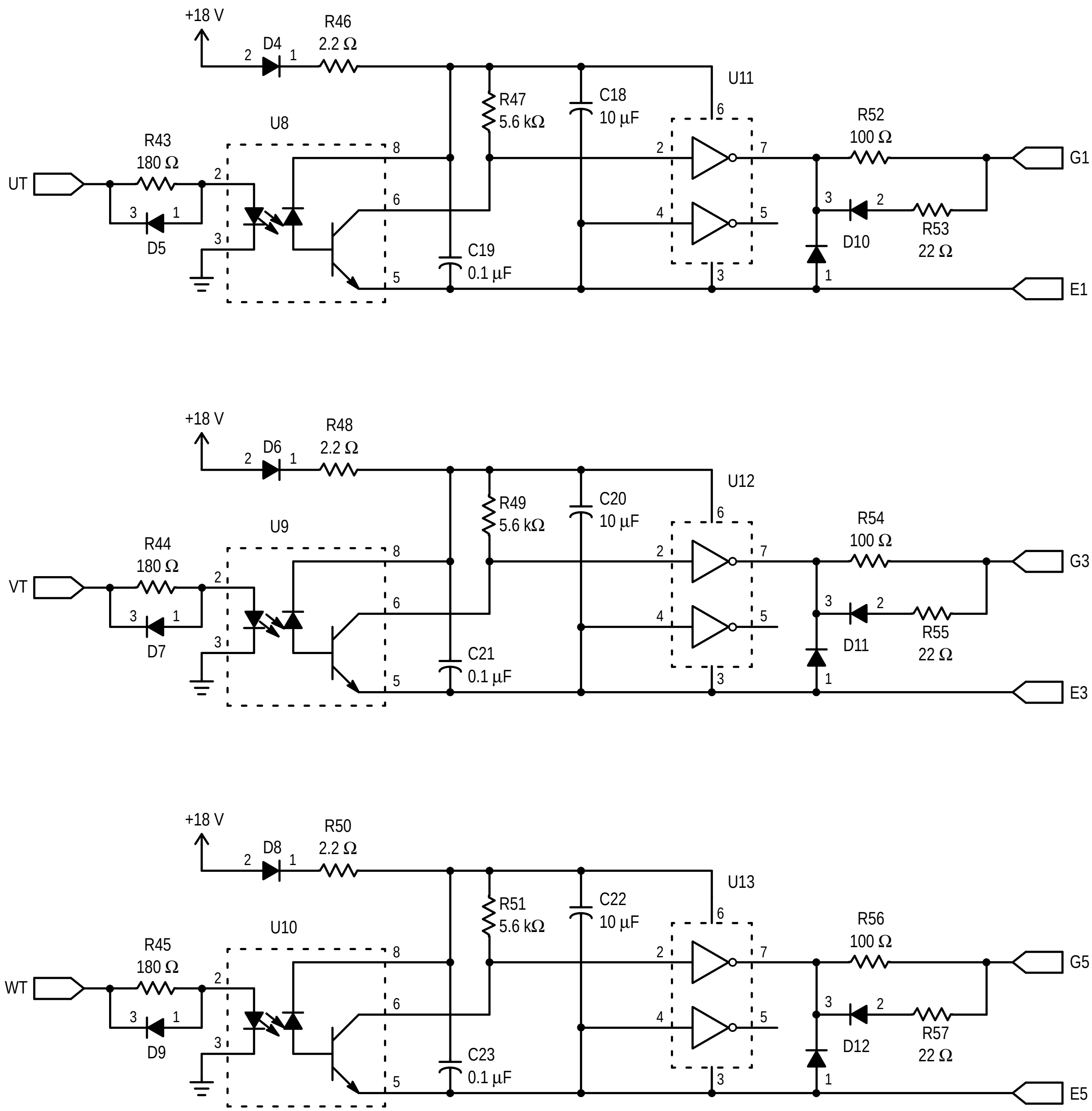
IPS AC Motor Drive
Current Limit



IPS AC Motor Drive
Low Side Gate Drive



IPS AC Motor Drive
High Side Gate Drive



Appendix II

Bill of Materials

Item #	Designators	Qty	Part Number	Value	Description	Rating	Tol.	Package	Comp.	Manufacturer	Allow Subs.
1	C1	1	FKP1 0,033 1000	0.033 μF	Capacitor	1000 V	±10%	#WIM22p5	Poly.	Wima	no
2	C2,C3	2	LGQ2W471MHSC	470 μF	Electrolytic Capacitor	450 V	±20%	#SNAP35	Alum.	Nichicon	yes
3	C4,C5,C6,C8,C12, C16,C17,C19,C21, C23	10		0.1 μF	Capacitor	50 V	±10%	1206	X7R	Panasonic	yes
4	C7	1		1000 pF	Capacitor	50 V	±5%	805	NPO	Panasonic	yes
5	C9,C10,C11	3		120 pF	Capacitor	50 V	±5%	805	NPO	Panasonic	yes
6	C13,C14,C15	3		470 pF	Capacitor	50 V	±5%	805	NPO	Panasonic	yes
7	C18,C20,C22	3	PCT5106–ND	10 μF	Capacitor	25 V	±20%	#PAND	Tant.	Panasonic	no
8	CN1,CN2,CN3, CN4,CN5	5	17 14 97 1		Connector 2x0.375″			#PNX2x375		Phoenix Contact	no
9	CN6	1			Screw hole			#SCRW440			yes
10	CN7	1			Header 2x8 0.1″			#HDR8x2			yes
11	CN8	1	17 29 13 1		Connector 3x0.2″			#PNX3x200		Phoenix Contact	no
12	D1,D2,D3,D10, D11,D12	6	MMBD6100LT1		Dual Diode			SOT23		Motorola	yes
13	D4,D6,D8	3	MURS160T3		Diode			#SMB		Motorola	no
14	D5,D7,D9	3	MMBD914LT1		Diode			SOT23		Motorola	yes
15	J1,J2,J3	3			Jumper 18AWG			#J400			yes
16	J4	1			Jumper 3x0.1″			#HDR3x1			yes
17	R1,R2	2	SG405	1.0 Ω	Thermistor	30 A	±25%	#THRM310		Ketema	no
18	R3,R4,R5,R6,R7, R8,R9,R10	8		4.7 kΩ	Resistor	1/10 W	±5%	805		Panasonic	yes
19	R11,R12,R13,R14	4		82.5 kΩ	Resistor	1/8 W	±1%	1206		Panasonic	yes
20	R15	1		3.32 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
21	R16	1		9.09 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
22	R17,R31	2		2.2 kΩ	Resistor	1/10 W	±5%	805		Panasonic	yes
23	R18	1		51.1 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
24	R19	1		150 kΩ	Resistor	1/10 W	±5%	805		Panasonic	yes
25	R20	1		4.42 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
26	R21	1		137 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
27	R22	1		10.0 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
28	R23	1		3.40 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
29	R24	1		1.30 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
30	R25,R30	2		13.0 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
31	R26,R27	2		1.10 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
32	R28	1		3.01 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
33	R29	1		12.1 kΩ	Resistor	1/10 W	±1%	805		Panasonic	yes
34	R32	1		10 kΩ	Resistor	1/10 W	±5%	805		Panasonic	yes
35	R33,R34,R35	3		510 Ω	Resistor	1/10 W	±5%	805		Panasonic	yes
36	R36,R37,R38, R52,R54,R56	6		100 Ω	Resistor	1/10 W	±5%	805		Panasonic	yes
37	R39,R40,R42, R53,R55,R57	6		22 Ω	Resistor	1/10 W	±5%	805		Panasonic	yes
38	R41	1		470 Ω	Resistor	1/10 W	±5%	805		Panasonic	yes

Bill of Materials — continued

Item #	Designators	Qty	Part Number	Value	Description	Rating	Tol.	Package	Comp.	Manufacturer	Allow Subs.
39	R43,R44,R45	3		180 Ω	Resistor	1/10 W	±5%	805		Panasonic	yes
40	R46,R48,R50	3		2.2 Ω	Resistor	1/10 W	±10%	SG73		KOA	no
41	R47,R49,R51	3		5.6 kΩ	Resistor	1/10 W	±5%	805		Panasonic	yes
42	S1	1	SS–12SDP2		Subminiature Switch			#SW1		NKK	no
43	U1	1	MHPM7A15A60A		Int. Power Stage			#HPM1		Motorola	no
44	U2	1	22V10		PAL			PLCC20		TI	yes
45	U3	1	LM293AD		Dual Comparator			SO8		Motorola	yes
46	U4	1	MC33272D		Dual Op Amp			SO8		Motorola	no
47	U5	1	LM285D–2.5		Voltage Reference			SO8		Motorola	no
48	U6,U7	2	MC33152D		MOSFET Driver			SO8		Motorola	no
49	U8,U9,U10	3	HCPL0453		High Speed Opto			SO8		HP	no
50	U11,U12,U13	3	MC33151D		Dual MOSFET Driver			SO8		Motorola	no
51		1	4200 02 U 2 0450		Heatsink					Aavid	no
52		1	FS24B3		2 1/2″ Box Fan (opt.)					ComAir	yes
53		4		1/2″	4–40 Metal Standoffs						yes
54		4		1/4″	4–40 Screws						yes
55		4		7/8″	4–40 Screws						yes
56		2		3/8″	6–32 Screws						yes
57		2			6–32 Lock Washer						yes

Appendix III

ABLE Code Listing

```
module IPS_PAL

title   'IPS demo board PAL'

IPS_PAL device 'P22V10C';

"This is the ABLE code for the preprogrammed PLD which comes in the demo"

"inputs"

        OE          pin 2;
        UT_in       pin 5;
        UB_in       pin 6;
        VT_in       pin 7;
        VB_in       pin 9;
        WT_in       pin 10;
        WB_in       pin 11;
        Brk_in      pin 12;
        OC_in       pin 13;
        OV_in       pin 16;
        IO1         pin 25;
        IO2         pin 26;


"       VCC         pin 28;"
"       GND         pin 14;"
"       NC          pin 1, 8, 15, 22;"

"outputs"

        UT_out      pin 24;
        UB_out      pin 20;
        VT_out      pin 23;
        VB_out      pin 19;
        WT_out      pin 21;
        WB_out      pin 18;
        Brk_out     pin 17;
        IO3         pin 27;

equations

        UT_out  =   UT_in & !UB_in & !OE;
        UB_out  =   UB_in &          !OE;
        VT_out  =   VT_in & !VB_in & !OE;
        VB_out  =   VB_in &          !OE;
        WT_out  =   WT_in & !WB_in & !OE;
        WB_out  =   WB_in &          !OE;
        Brk_out =   0;
        IO3     =   1;

end IPS_PAL
```

```
module IPS_PAL

title   'Inverted Inputs'

IPS_PAL device 'P22V10C';

"This ABLE code provides inverted inputs. Configure J1 for pull up resistors."

"inputs"

        OE          pin 2;
        UT_in       pin 5;
        UB_in       pin 6;
        VT_in       pin 7;
        VB_in       pin 9;
        WT_in       pin 10;
        WB_in       pin 11;
        Brk_in      pin 12;
        OC_in       pin 13;
        OV_in       pin 16;
        IO1         pin 25;
        IO2         pin 26;

"       VCC         pin 28;"
"       GND         pin 14;"
"       NC          pin 1, 8, 15, 22;"

"outputs"

        UT_out      pin 24;
        UB_out      pin 20;
        VT_out      pin 23;
        VB_out      pin 19;
        WT_out      pin 21;
        WB_out      pin 18;
        Brk_out     pin 17;
        IO3         pin 27;

equations

        UT_out  =   !UT_in & UB_in & !OE;
        UB_out  =   !UB_in &          !OE;
        VT_out  =   !VT_in & VB_in & !OE;
        VB_out  =   !VB_in &          !OE;
        WT_out  =   !WT_in & WB_in & !OE;
        WB_out  =   !WB_in &          !OE;
        Brk_out =   0;
        IO3     =   1;

end IPS_PAL
```

```
module IPS_PAL

title   'Auto Brake'

IPS_PAL device 'P22V10C';

"This is the ABLE code with automatic braking under overvoltage"

"inputs"

        OE          pin 2;
        UT_in       pin 5;
        UB_in       pin 6;
        VT_in       pin 7;
        VB_in       pin 9;
        WT_in       pin 10;
        WB_in       pin 11;
        Brk_in      pin 12;
        OC_in       pin 13;
        OV_in       pin 16;
        IO1         pin 25;
        IO2         pin 26;

"       VCC         pin 28;"
"       GND         pin 14;"
"       NC          pin 1, 8, 15, 22;"

"outputs"

        UT_out      pin 24;
        UB_out      pin 20;
        VT_out      pin 23;
        VB_out      pin 19;
        WT_out      pin 21;
        WB_out      pin 18;
        Brk_out     pin 17;
        IO3         pin 27;

equations

        UT_out  =   UT_in & !UB_in & !OE;
        UB_out  =   UB_in &          !OE;
        VT_out  =   VT_in & !VB_in & !OE;
        VB_out  =   VB_in &          !OE;
        WT_out  =   WT_in & !WB_in & !OE;
        WB_out  =   WB_in &          !OE;
        Brk_out =   OV_in;
        IO3     =   1;

end IPS_PAL
```

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