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High CMR Isolation Amplifier for Current Sensing Applications

Application Note 1059

Introduction

One of the more difficult problems that designers may face is trying to isolate precision analog signals in an extremely noisy environment. A good example is monitoring the motor phase current in a high-performance motor drive. A typical 3-phase induction motor drive (Figure 1) first rectifies and filters the 3-phase ac line voltage to obtain a high-voltage dc power supply; the output transistors then invert the dc supply voltage back into an ac signal to drive the 3-phase induction motor. The transistor inverter commonly uses pulse-width modulation (PWM) to generate a variable voltage, variable frequency drive signal for the motor. High performance motor drives usually incorporate

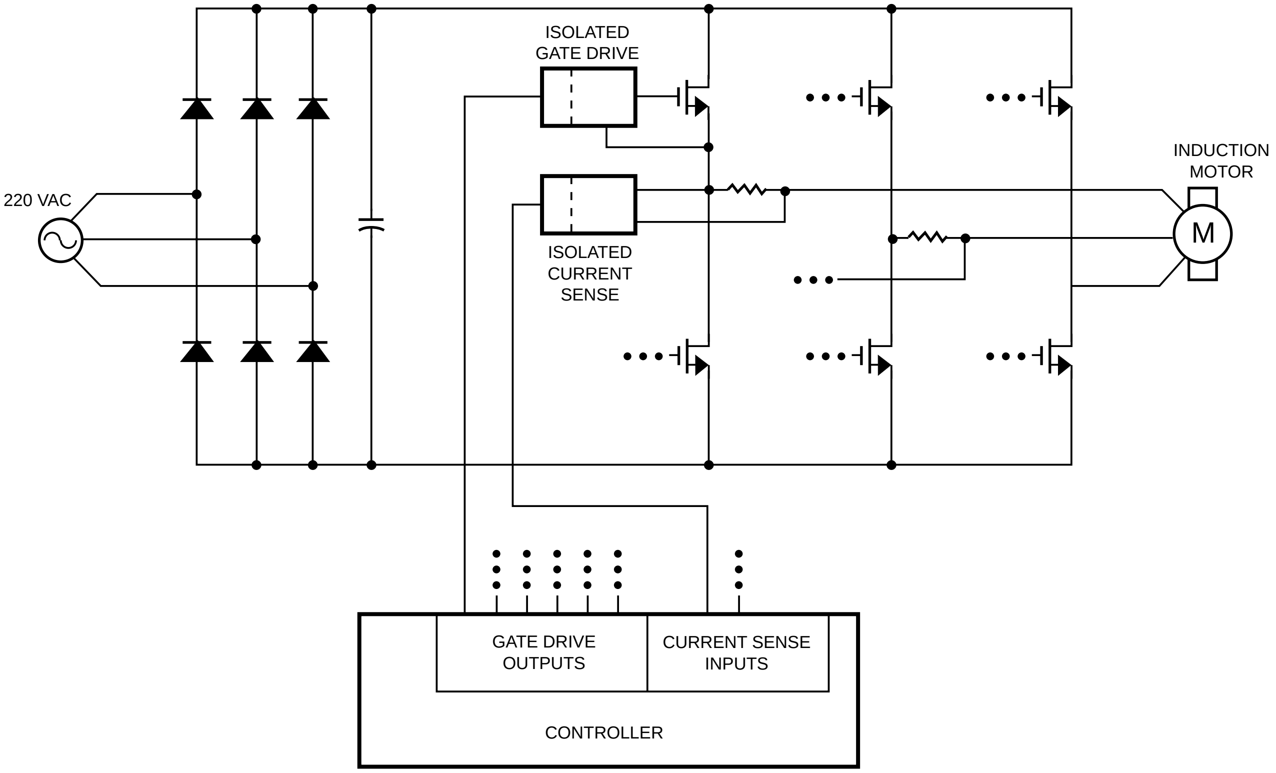

Figure 1. Typical 3-Phase AC Induction Motor Drive.

some form of current sensing in their design. The difficulty in isolating precision analog signals arises from the large voltage transients that are generated by the switching of the inverter transistors. These very large transients (equal in amplitude to the dc supply voltage) can exhibit extremely fast rates of rise (greater than 10 kV/µs), making it extremely difficult to sense the current flowing through each of the motor phases.

Developed as a compact low-cost solution for just this type of design problem, the HCPL-7800 High CMR Isolation Amplifier allows designers to sense current in extremely noisy environments while maintaining excellent gain and offset accuracy. It exhibits outstanding stability over both time and temperature, as well as unequaled common-mode transient noise rejection (CMR). To achieve such a high level of performance, the HCPL-7800 combines several different technologies, including a state-of-the-art sigma-delta (ΣΔ) analog-to-digital converter (ADC), chopper-stabilized internal amplifiers, a fully differential circuit topology fabricated on a 1 µm standard-cell CMOS process, an edge-triggered level-sensitive data encoder/decoder circuit, a high-efficiency, high-speed AlGaAs LED, an advanced photo-detector noise shield, and an efficient “light-pipe” packaging technology. The HCPL-7800 is available in a small 8-pin DIP package, making it the world’s smallest isolation amplifier.

Compared to Hall-effect sensors, another commonly used current-sensing device, the HCPL-7800 has excellent gain and offset characteristics, including very low drift over temperature. In addition, the HCPL-7800 exhibits superior common-mode transient noise immunity; it is not affected by external magnetic fields; and it does not exhibit residual magnetization effects that can affect offset. It is also easily mounted on a printed circuit board and is very flexible for designers to use, allowing the same circuit and layout to be used to sense different current ranges simply by substituting different current-sensing resistors. These features make the HCPL-7800 an excellent choice for sensing current in many different applications.

Theory of Operation

Before discussing how to use the HCPL-7800 in a typical application, a brief discussion of the primary functional blocks inside the HCPL-7800 (Figure 2) will be useful. At the input of the isolation amplifier, a sigma-delta (also known as delta-sigma, oversampling, or 1-bit) ADC converts

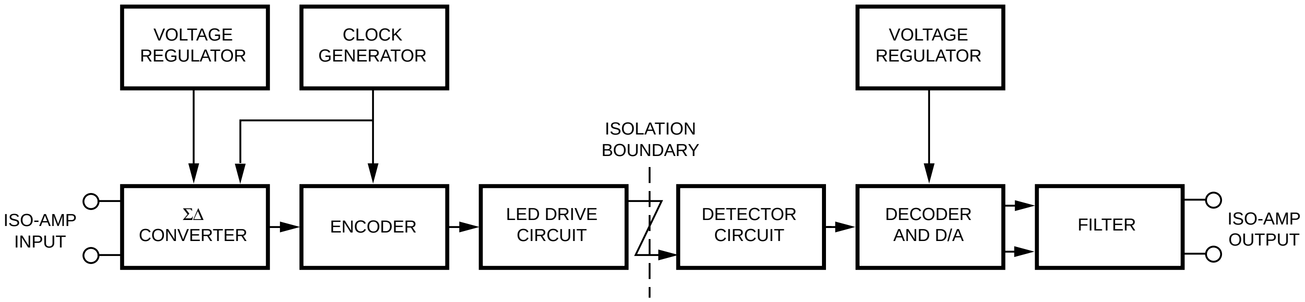

Figure 2. HCPL-7800 Block Diagram.

the analog input signal into a high-speed serial bit stream, the time average of which is directly proportional to the input signal (Figure 3). The sigma-delta converter has a fully-differential, second-order, switched-capacitor topology (Figure 4). The differential circuitry helps to minimize offset and offset drift and improve power-supply rejection, while the switched-capacitor circuitry is well suited to the high-speed CMOS IC process used. The sigma-delta converter is comprised of two op-amp integrators and a clocked comparator, driven by a high-frequency non-overlapping two-phase clock at about 6 MHz. The high sampling speed (6 MSPS) inherent in the operation of the sigma-delta converter eliminates the need for input sample\hold or track\hold circuits.

The encoder and decoder circuits play a key role in the operation of the isolation amplifier; they ensure accurate transmission of the sigma-delta data across the isolation boundary by using an edge-triggered, level-sensitive coding scheme. The analog signal information is contained in the time average value of the output pulses of the sigma-delta converter. Therefore, if the sigma-delta data were not encoded, any pulse-width distortion of that data during transmission across the isolation boundary would directly affect the average value of the data and introduce errors into the transmitted signal. The encoder circuit, however, eliminates the effects of pulse-width distortion by generating one pulse for every edge (both rising and falling) of the converter data to be transmitted, essentially converting the *widths* of the sigma-delta output

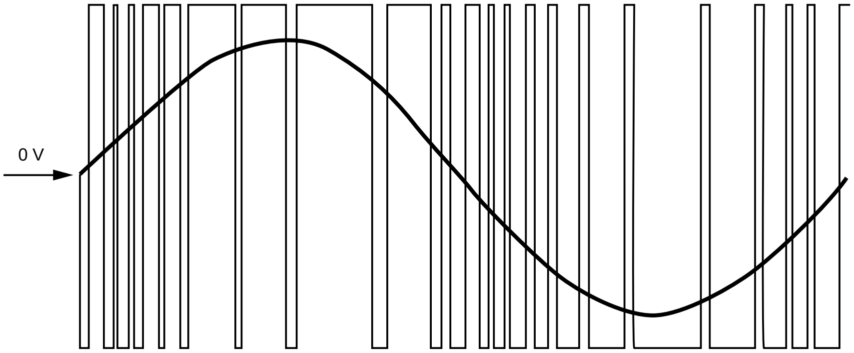

Figure 3. Example ΣΔ Conversion

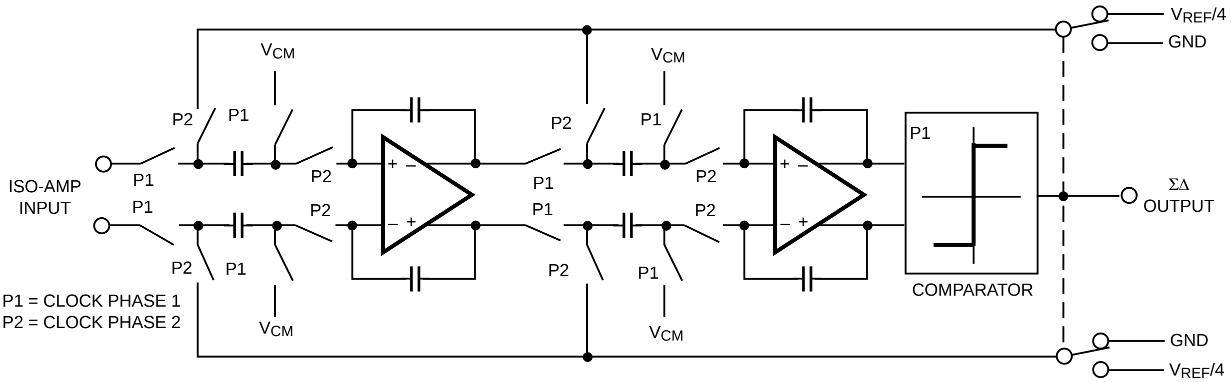

Figure 4. Second-Order Switched-Capacitor Sigma-Delta Converter.

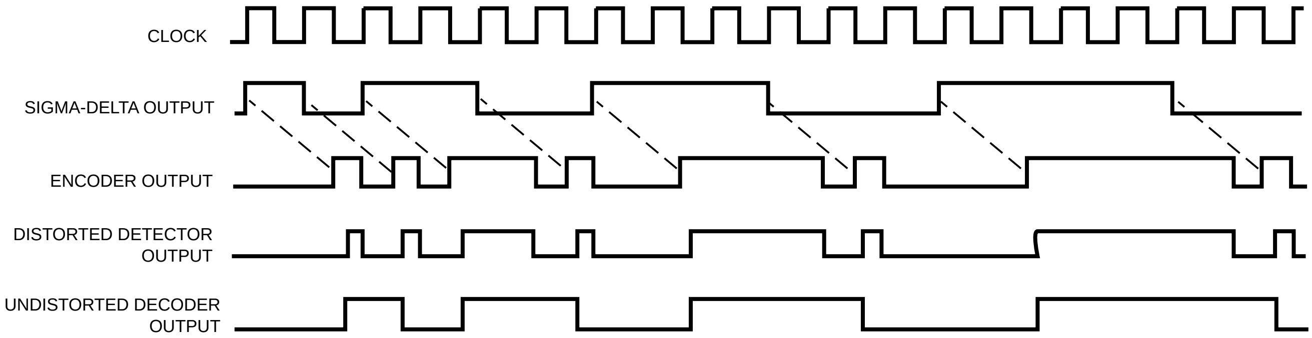

Figure 5. Encoder/Decoder Timing Diagram.

pulses into the *positions* of the encoder output pulses (Figure 5). The decoder circuit then recovers the original data by simply inverting its output whenever a rising edge of the encoded signal is detected. Any pulse-width distortion that occurs during optical transmission will not affect the relative positions of the encoded pulses; therefore, the distortion will have no effect on the recovered sigma-delta data, nor on the accuracy of the isolation amplifier. To aid in the decoding of the signal, the widths of some of the pulses are lengthened. A significant benefit of this coding scheme is that any non-ideal characteristics of the LED (such as nonlinearity and drift over time and temperature) have little, if any, effect on the performance of the HCPL-7800.

The encoded signal is sent optically across the isolation boundary using the same low-cost high-volume opto-electronic and packaging technology developed for the high-speed HCPL-7101, 50 MBd CMOS Optocoupler. The LED drive circuit and the optical detector circuit of the HCPL-7800 are nearly identical to those used in the HCPL-7101, with slight modifications to optimize performance in motor drive applications. The LED drive circuitry was re-designed to reduce the amount of power-supply noise generated by the switching of the LED, thereby increasing the accuracy of the isolation amplifier. On the detector side, an improved CMR noise shield allows the device to achieve levels of common-mode transient rejection not previously attainable by isolation amplifiers.

After the encoded signal is received by the detector circuit, it is sent to the decoder circuit (Figure 6), which is comprised of a pair of toggle flip-flops with two additional time-out circuits that maintain the flip-flops in the correct state. By using two matched but oppositely-phased flip-flops, the single-ended encoded signal is converted back to a differential decoded signal with very high accuracy. The decoded signal is then sent to the digital-to-analog converter (DAC) circuit, which simply converts the output of the decoder into very precise analog voltage levels.

The final analog output voltage is recovered by filtering the DAC output with a differential four-pole filter (Figure 7). The filter was designed to maximize bandwidth while minimizing quantization noise generated by the sigma-delta conversion process. The overall gain of

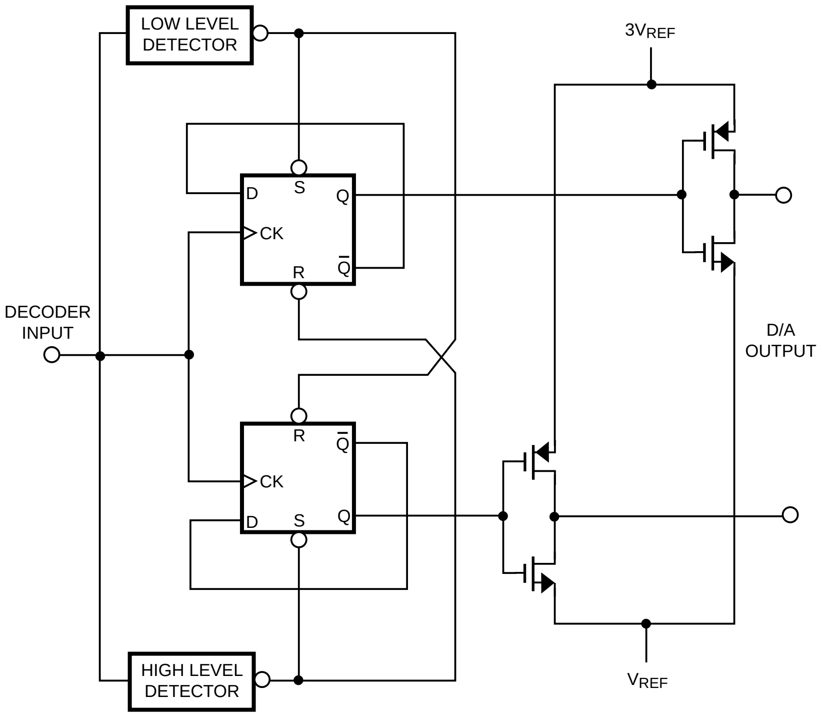

Figure 6. Decoder and Digital-to-Analog Converter.

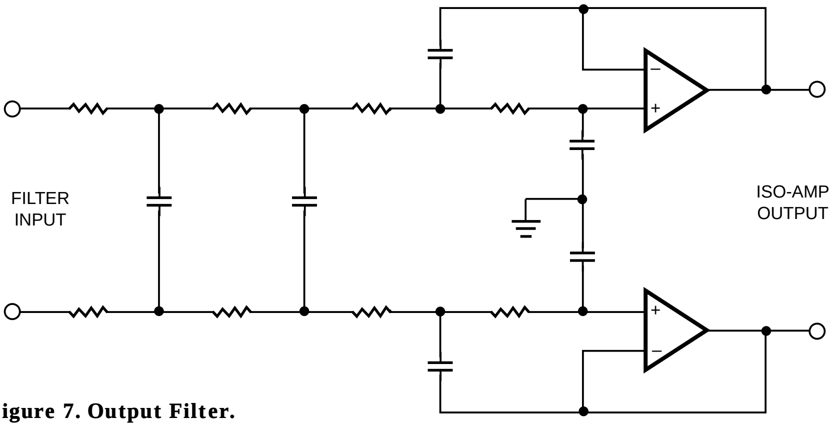

Figure 7. Output Filter.

the isolation amplifier is determined primarily by matched internal temperature-compensated bandgap voltage references, resulting in very stable gain characteristics over time and temperature.

The HCPL-7800 incorporates some unique features specifically designed to improve its performance in current-sensing applications, particularly in motor drives. Chopper stabilization of all critical internal amplifiers and a fully differential circuit topology allow the HCPL-7800 to operate with small full-scale input voltages while maintaining excellent input offset and offset drift performance. Small input voltages help to minimize power dissipation in the external current sensing resistor. In addition, a unique input circuit allows accurate sensing of input signals below ground, using only a single +5V supply and eliminating the need for split supplies for the input circuit.

Application Information

The recommended application circuit (Figure 8) is relatively straight forward. A floating power supply (which in many applications could be the same supply that is used to drive the high-side power transistor) is dropped to 5 V through a simple three-terminal voltage regulator. The voltage from the current sensing resistor is applied directly to the input of the HCPL-7800 without the need for a pre-amplifier. Finally, the differential output of the isolation amplifier is converted to a ground-referenced single-ended output voltage with a simple differential amplifier circuit. Because the isolation amplifier has a differential output voltage, the polarity of the circuit can easily be changed by reversing the connections to the differential amplifier circuit.

Although the application circuit is relatively simple, a few recommendations should be followed to ensure optimal performance. Common mode transient noise rejection of the isolation amplifier is extremely important in designing a current sensing circuit for use in motor drives. To obtain optimal CMR performance, good design and layout practices should be observed. An example printed circuit board (PCB) layout illustrates how to minimize any stray parasitic capacitive coupling by maintaining the maximum possible distance between the input and output sides of the circuit and by ensuring that any ground plane on the PCB does not pass directly below the HCPL-7800 (Figure 9). The parts placement diagram shows where the different components are located and how to make external connections to the PCB. Note that the layout is the mirror image of what you would use to generate an actual PCB; this was done to make it easier to match up the layout with the schematic.

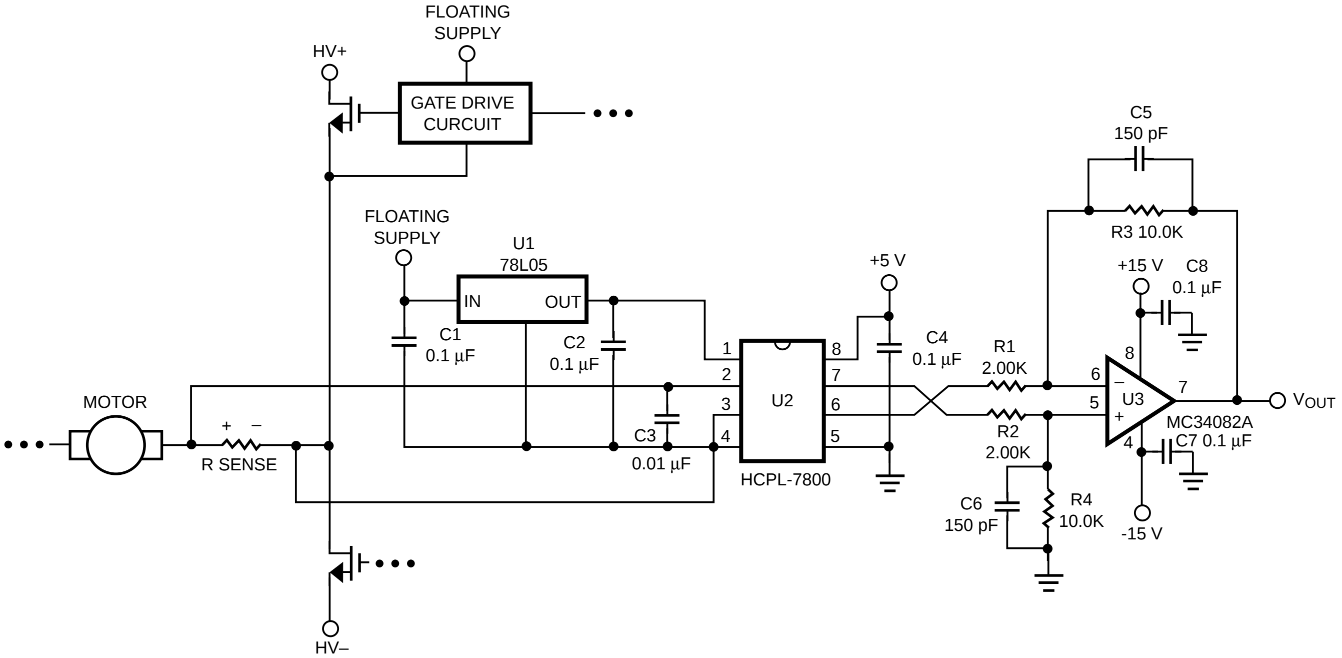

Figure 8. Recommended Application Circuit.

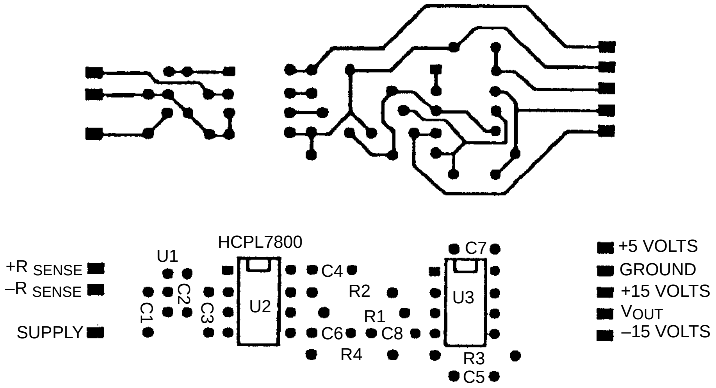

Figure 9. Example PCB Layout and Parts Placement Diagram.

Another important consideration is how to connect the input-circuit “ground” or common to the current-sensing resistor. Kelvin-type grounding techniques should be used, with the input circuit having a single-point common connection as close as possible to pin 4 of the HCPL-7800, including the connection from the negative terminal of the sense resistor. This is important because the large load currents flowing through the motor drive, along with the parasitic inductances inherent in the wiring of the circuit, can generate both noise spikes and offsets that are relatively large compared to the very small voltages that are being measured across the current-sensing resistor. By referencing the input circuit to the negative side of the sense resistor (Figure 8), the current-induced noise transients are seen as a common-mode signal and will not interfere with the transmission of current-sense signal. If the same power supply is used both for the gate drive circuit and for the current sensing circuit, it is very important that the Kelvin connection from pin 4 of the HCPL-7800 to the sense resistor be the ONLY return path for supply current to the gate drive power supply in order to eliminate potential “ground loop” problems. The only connection between the isolation amplifier circuit and the gate drive circuit should be the positive power supply line.

Deciding how to connect the input pins of the isolation amplifier to the current-sensing resistor is also important. The simplest alternative is to connect pin 2 (V_{IN+}) to the positive terminal of the sense resistor on the motor side, pin 4 (GND1) to the negative terminal of the sense resistor, and pin 3 (V_{IN-}) directly to pin 4 (Figure 8). Connected this way, the power-supply return line also functions as the negative sense line for the current-sensing resistor, and a single pair of conductors can be used to connect the isolation amplifier circuit to the sense resistor. In some applications, however, supply currents flowing through the power-supply return line may cause offset or noise problems. In this case, better performance may be obtained by connecting pins 2 and 3 (V_{IN+} and V_{IN-}) directly across the sense resistor with two conductors and connecting pin 4 to the sense resistor with a third conductor. By connecting the amplifier in this manner, induced voltages on the power-supply return line are seen as common-mode signals at the input of the isolation amplifier and are reduced by the input common-mode rejection of the amplifier. In either case, to minimize electromagnetic interference of the sense signal, the conductors used to connect the isolation amplifier to the sense resistor should be either twisted pair wire or closely spaced traces on a printed circuit board.

A final layout consideration is proper bypassing of the circuit. Notice that both the power supply pins and the input pins are bypassed. Power supply bypassing is required because of the high-speed digital nature of the signal transmission inside the isolation amplifier. Bypassing of the input pin(s) is recommended to help reduce some of the input offset voltage that can be caused by the combination of long input leads and the switched-capacitor nature of the input circuit. All bypass capacitors should be located as close as possible to the appropriate pins of the HCPL-7800. Because proper layout and bypassing of the applications circuit is essential for optimal circuit operation, it is recommended that any prototype circuits be constructed using a printed circuit board or point-to-point wiring techniques; the use of white plug-in prototype boards is not recommended because their large parasitic capacitances and inductances may not yield accurate test results.

The recommended application circuit includes a post-amplifier that serves three functions: to reference the output signal to ground, to amplify the signal to appropriate levels, and to filter any output noise. Because the isolation amplifier has a differential output, any common-mode noise at the output of the isolation amplifier will be attenuated by the common-mode rejection of the post-amplifier circuit, resulting in lower overall output noise. Selecting a particular op-amp for use as the post-amp is not that critical. However, it should have adequate precision and bandwidth for the application. The op-amp should be of sufficiently high precision so that it does not contribute a significant amount of offset or offset drift relative to the contribution from the isolation amplifier.

In addition to having enough precision, the op-amp should also have enough bandwidth and slew rate so that it does not adversely affect the overall response of the circuit. The bandwidth of the post-amplifier circuit should be at least twice the minimum bandwidth of the isolation amplifier, or about 100 kHz. To obtain a large-signal bandwidth of 100 kHz with a gain of 5, the op-amp should have a gain-bandwidth product of at least 500 kHz and a slew rate of at least 3 V/µs. Sometimes, however, bandwidths lower than those limited by the gain-bandwidth of the op-amp are desirable. The post-amplifier circuit includes a pair of capacitors (C5 and C6) that form a single-pole low-pass filter; these capacitors allow the bandwidth of the post-amp to be adjusted independently of the gain and are useful for reducing the output noise from the isolation amplifier. The components shown in the application circuit form a differential amplifier with a gain of 5 and a cutoff frequency of approximately 100 kHz.

Because it is common to have more than one current-sensing channel, op-amps packaged as duals or quads can reduce the total required board space and component count. The op-amp shown in the application circuit is a relatively inexpensive dual device that has excellent offset and offset drift specifications, as well as good bandwidth and slew rate. Many different op-amps could be used in the circuit, including: MC34082A (Motorola, shown in schematic), TL052A (Texas Instruments), LF412A (National Semiconductor), and OP-42 (Analog Devices).

The gain-setting resistors in the post-amp should have a tolerance of 1% or better to ensure adequate CMRR and gain tolerance for the overall circuit. Thick film resistor networks can be used which have much better ratio tolerances than can be achieved using discrete resistors. In addition to offering good gain tolerance, a resistor network also reduces the total number of components for the circuit as well as the required board space.

Selecting an appropriate current-sensing resistor is also important; it should have a low value of resistance to minimize power dissipation, a low value of inductance to accurately reflect high-frequency signal components and reduce the amount of induced noise, and a reasonably tight tolerance to maintain overall circuit accuracy. Although decreasing the value of the sense resistor decreases power dissipation, it also decreases the full-scale output voltage applied to the isolation amplifier. If the sense resistor is too small, the input offset of the HCPL-7800 can become a large percentage of full scale. These two conflicting considerations must, therefore, be weighed against each other in selecting an appropriate sense resistor for a particular application. In general, select the lowest value resistor that does not substantially impact overall circuit accuracy. Locating the sense resistor and the isolation amplifier close to each other will also help to minimize electro-magnetic interference and maintain circuit accuracy. Although it is possible to buy current-sensing resistors from established vendors (IRC, Dale, Ultronix, Isotek, and K-tronics are just a few vendors who manufacture resistors suitable for current-sensing applications), it is also possible to make a sense resistor using various materials, including a short piece of wire or even a trace on a PC board. For a discussion of very low value current sensing resistors, see “Precision Low-Ohmic Resistors Provide Accurate Current Sensing” in the June 1992 issue of PCIM. Sometimes, input voltages larger than ±200 mV are desired due to limitations associated with extremely low value resistors. In this case, a resistor divider can easily be added to the input of the HCPL-7800. A resistor network can also be used here to achieve good gain tolerance and minimize board space.

As mentioned earlier, the power supply for the input of the isolation amplifier can be the same supply used to power the gate drive circuit of the high-side transistor. An inexpensive 78L05 three-terminal regulator is shown in the recommended application circuit; it is more than adequate to regulate the input supply and also draws less power supply current than a shunt-type regulator circuit would. With the isolation amplifier circuit referenced to the sense resistor, the supply from the gate-drive circuit may have a large amount of noise on it. A resistor or inductor in series with the input of the regulator can be used to form a low-pass filter with C1, reducing the supply noise to an acceptable level. Because the performance of the isolation amplifier can be affected by changes in the power supply voltages, using regulators with tighter output voltage tolerances will result in better overall circuit performance. Many different regulators that provide tighter output voltage tolerances than the 78L05 are available, including: TL780-05 (Texas Instruments), LM340LAZ-5.0 and LP2950CZ-5.0 (National Semiconductor). If an isolated supply is required, a simple ac-powered supply made from a transformer, a rectifier and filter capacitor would be adequate; a simple dc-dc converter made from some CMOS gates, a transformer, a rectifier and a filter capacitor could also do the job. In either case, a three-terminal voltage regulator should still be used if the regulation of the isolated supply is not adequate.

The overall isolation amplifier circuit exhibits a fast, well-behaved response without overshoot or ringing (Figure 10). The figure shows the response of the application circuit to a ±200 mV 20 kHz square wave input.

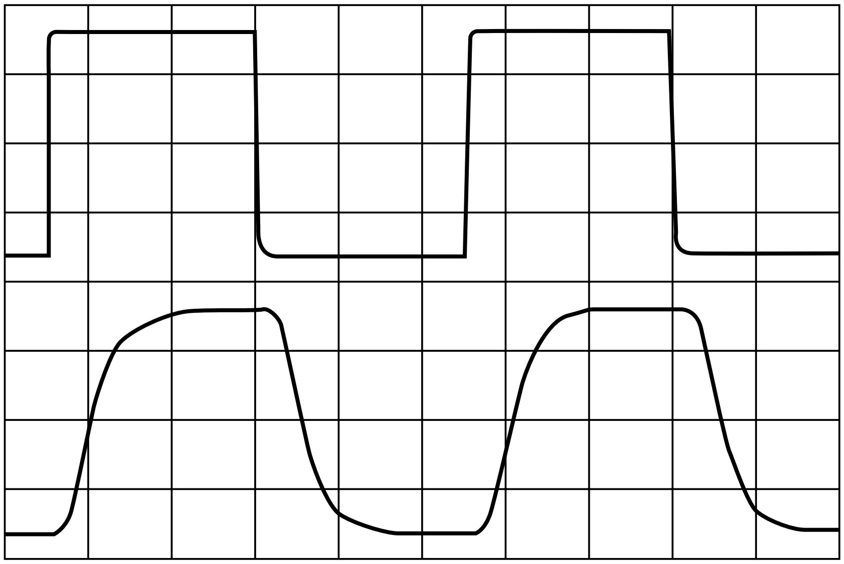

Figure 10. Application Circuit Time Response.

To aid in designing circuits using the HCPL-7800, a SPICE macro-model was developed (Figure 11, Listing 1) that correctly models the primary characteristics of the isolation amplifier, including: gain, offset, bandwidth and response time, linearity, average input current, power supply currents, and output resistance.

The HCPL-7800 high CMR isolation amplifier provides a unique combination of features ideally suited for motor control designs. The product provides the precision and stability needed to accurately monitor motor current in the high-noise environment found in motor drives. It can also be used for general analog isolation applications requiring accuracy and stability under similarly severe noise conditions.

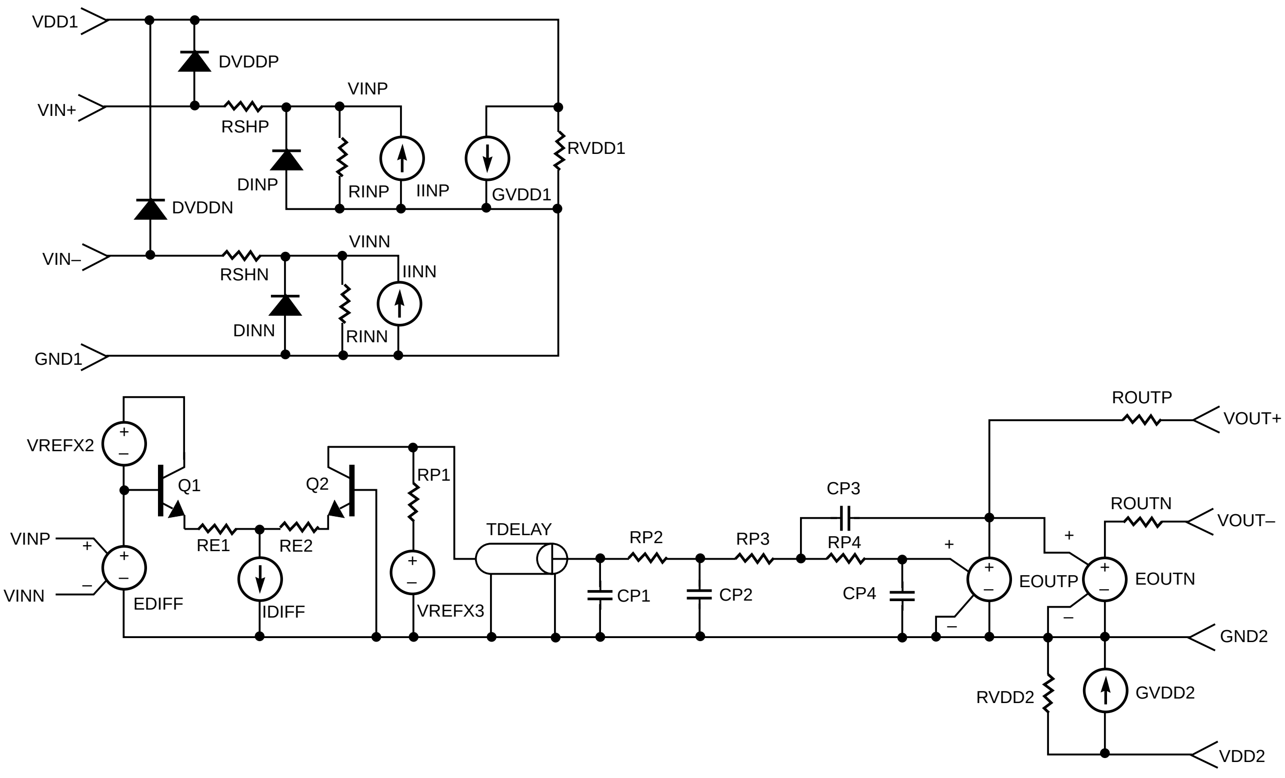

Figure 11. HCPL-7800 SPICE Macro-Model.

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* HCPL-7800 SPICE MACRO-MODEL
*
*                  VDD1
*                  I   VIN+
*                  I   I   VIN-
*                  I   I   I   GND1
*                  I   I   I   I   GND2
*                  I   I   I   I   I   VOUT-
*                  I   I   I   I   I   I   VOUT+
*                  I   I   I   I   I   I   I   VDD2
                   I   I   I   I   I   I   I   I
.SUBCKT HCPL7800   1   2   3   4   5   6   7   8

DVDDP 2 1 DMOD
DVDDN 3 1 DMOD
RSHP 2 9 530
RSHN 3 10 530
DINP 4 9 DMOD
DINN 4 10 DMOD
RINP 4 9 530K
RINN 4 10 530K
IINP 4 9 670N
IINN 4 10 670N
GVDD1 1 4 POLY(1) (22,23) 4.37M 0 -445U 0 69.1 U 0 -6.34U
RVDD1 1 4 790
EDIFF 11 5 POLY(1) (9,10) -3.6M 4
VREFX3 12 5 3.61
VREFX2 13 11 2.395
Q1 13 11 14 QMOD
Q2 17 5 16 QMOD
RE1 14 15 31 K
RE2 15 16 31K
IDIFF 15 5 37.356U
RP1 12 17 65.7K
TDELAY 17 5 18 5 Z0=65.7K TD=970N
CP1 18 5 6.3P
RP2 18 19 65.7K
CP2 19 5 6.3P
RP3 19 20 52.7K
CP3 20 22 15.2P
RP4 20 21 52.7K
CP4 21 5 6.52P
EOUTP 22 5 21 5 1
EOUTN 23 5 POLY(1) (22,5) 4.79 -1
ROUTP 22 7 11
ROUTN 23 6 11
RVDD2 8 5 2.2K
GVDD2 8 5 POLY(1) (22,23) 8.71 M 145U 189U -1.22U -15.8U -127N 1.43U
.MODEL DMOD D IS=8E-13
.MODEL QMOD NPN
.ENDS HCPL7800
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Listing 1. HCPL-7800 SPICE Macro-Model.

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