Low-cost current-shunt monitor IC revives moving-coil meter design

By Thomas Kugelstadt (Email: tk@ti.com)
Senior Systems Engineer, Industrial Systems

Despite their lack of resolution and accuracy in comparison to digital meters, analog moving-coil meters remain the display of choice when it comes to tracking a reading's trend or drawing information upon a measurement's rate of change. For low-level current measurements, however, the meter current for a full-scale deflection usually exceeds the current to be measured, and a separate supply driving the meter is required. Analog meters of the past, such as the Multavi-10 from Hartmann & Braun, solved this problem by implementing a rechargeable accumulator as the meter supply. Manually selectable shunt resistors in combination with a high-precision chopper amplifier allowed the user to choose from thirteen different current ranges between 1 µA and 1 A.

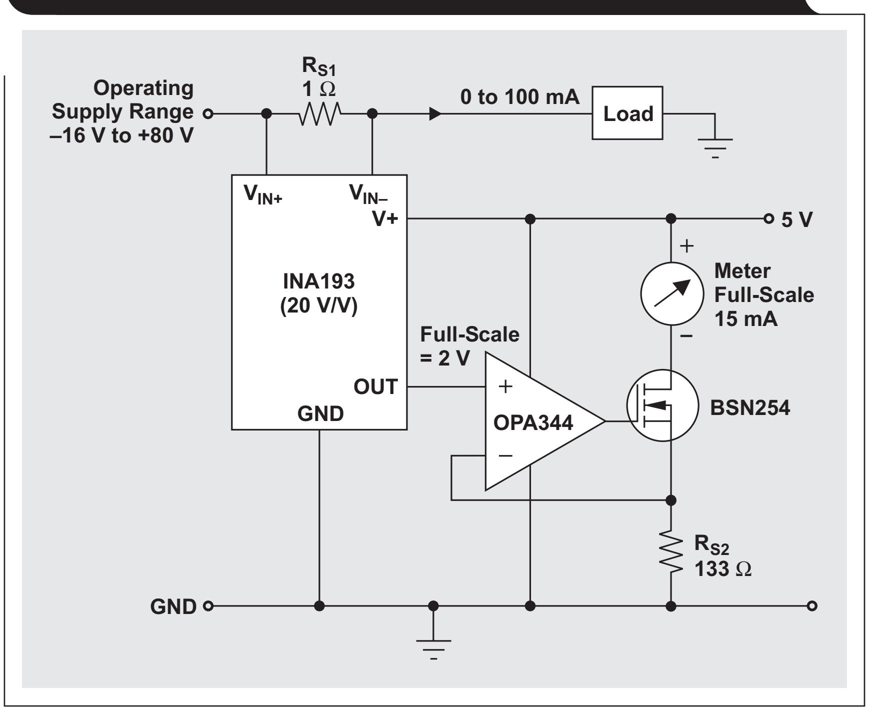
With the introduction of modern current-shunt monitor ICs such as the INA19x family, the amplifier design of moving-coil meters has been drastically simplified. Figure 1 shows the drive circuit of an 8-inch moving-coil meter measuring a current range from 0 to 100 mA. The meter current for a full-scale deflection is 15 mA. The current-shunt monitor, INA193, senses the voltage drop across the 1-Ω shunt resistor, R_{S1}. At a maximum current of 100 mA, the voltage across R_{S1} is 100 mV.

The value chosen for R_{S1} depends on the application and is a compromise between small-signal accuracy and maximum permissible voltage drop in the measurement line. High values of R_{S1} provide better accuracy at lower currents by minimizing the effects of offset, while low values of R_{S1} minimize voltage loss in the supply line. For most applications, the best performance is attained with an R_{S1} value that provides a full-scale shunt voltage range of 50 to 100 mV. The maximum input voltage for accurate measurements is 500 mV.

In this example, the INA193 amplifies the 100-mV full-scale input by a gain factor of 20 V/V, thus providing a full-scale output of 2 V. The succeeding operational amplifier, OPA344, possesses rail-to-rail inputs and outputs; it operates in conjunction with the N-channel MOSFET, BSN254, as a voltage-controlled current source.

Note that the entire meter circuit, including the INA193, operates from a single 5-V supply, which also limits the maximum output voltage swing of the OPA344 to 5 V. It therefore is necessary to choose a MOSFET with a low gate-source threshold voltage, V_{GS}, since this voltage subtracts from the amplifier output swing. The BSN254 has a maximum threshold voltage of 2 V, which satisfies the

Figure 1. Moving-coil meter with separate supply using INA193



low-V_{GS} requirement. Because the voltage at the non-inverting OPA344 input equals the one at the inverting input, the full-scale output of 2 V lies across R_{S2}. To allow for the maximum deflection current to flow, R_{S2} is calculated via

$$R_{S2} = \frac{V_{OUT(FS)}}{I_{Meter(FS)}} = \frac{2\ \text{V}}{15\ \text{mA}} = 133\ \Omega.$$

R_{S2} can be adjusted to calibrate the meter or to change its full-scale current range. R_{S1} can be adjusted to increase low-current measurement accuracy or to extend the measurement range to higher current values. Another benefit of the circuit is that the meter can be separated from the point of measurement. Because moving-coil meters are not intended for high-precision measurements, the designer can use relaxed-accuracy resistors. Bypassing the instrument supply with decoupling capacitors is necessary to avoid stray pickup from the electrical-noise environment.

About the INA19x current-shunt monitor

The INA193 is just one member of a family of current-shunt monitors. The INA194 and INA195 are members that have the same pinout but provide different gains of 50 V/V and 100 V/V, respectively. Three other current-shunt monitors, the INA196, INA197, and INA198, are functionally identical but come in a different pinout.

The INA19x family uses a new, unique internal circuit topology that provides a common-mode range extending from –16 V to +80 V while operating from a single power supply. The common-mode rejection in a classic instrumentation amplifier approach is limited by the requirement for accurate resistor matching. By converting the induced input voltage to a current, the INA19x provides common-mode rejection that is no longer a function of closely matched resistor values, providing the enhanced performance necessary for such a wide common-mode range.

The simplified diagram in Figure 2 shows the basic circuit function. When the common-mode voltage is positive, amplifier A2 is active. The differential input voltage, $V_{IN+} – V_{IN–}$ applied across R_S, creates the voltage potentials v_N and v_P at A2's inputs:

$$v_N = V_{IN+} - I_S R_S \text{ and } v_P = V_{IN+}.$$

To make $v_P = v_N$, A2 must drive the transistor so that its collector current, I_C, causes a voltage drop across the 5-kΩ resistor that equals the differential input voltage:

$$v_P = v_N$$
$$V_{IN+} - I_C \times 5\ \text{k}\Omega = V_{IN+} - I_S R_S$$
$$I_C \times 5\ \text{k}\Omega = I_S R_S$$

Figure 2. INA19x simplified circuit diagram

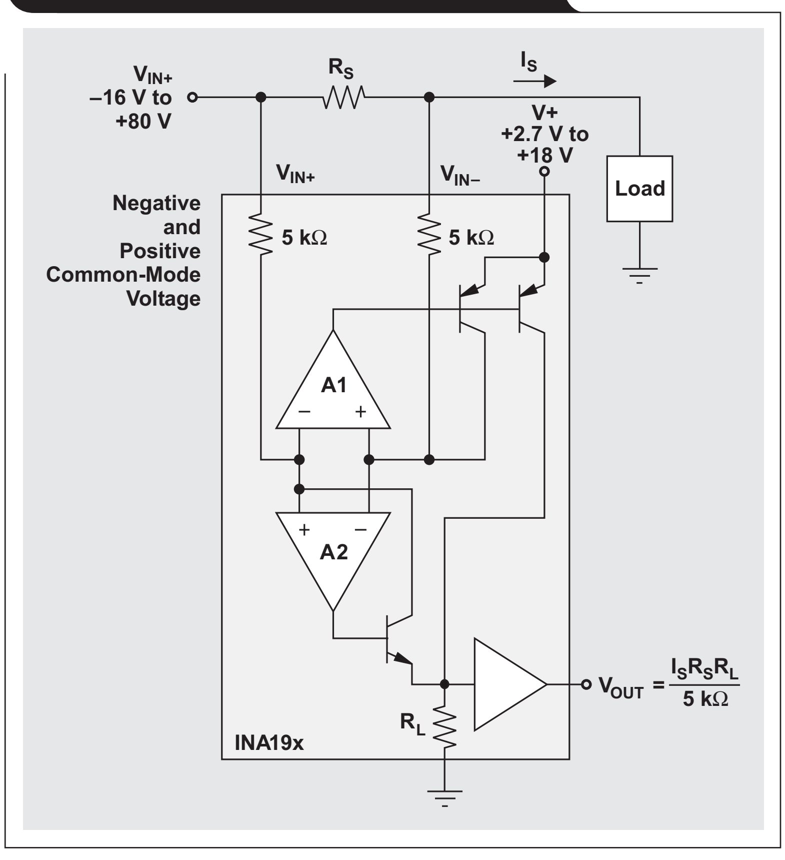
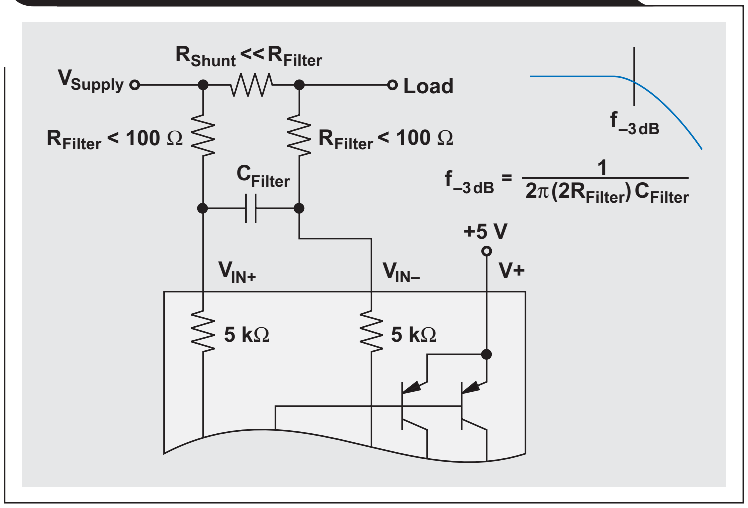


Figure 3. Input filter (gain error = –1.5% to –2.2%)



Expressing I_C through the ratio of output voltage to load resistor,

$$I_C = \frac{V_{OUT}}{R_L},$$

defines the output voltage as

$$V_{OUT} = \frac{I_S R_S R_L}{5\ k\Omega}.$$

When the common-mode voltage is negative, amplifier A1 is active. The differential input voltage, $V_{IN+} - V_{IN-}$ dropped across R_S, is converted to a current through a 5-kΩ resistor. A1 then drives a precision current mirror whose output through R_L provides the signal voltage to the output buffer amplifier. Patent-pending circuit architecture ensures smooth device operation, even during the transition period when both amplifiers A1 and A2 are active.

The input pins, V_{IN+} and V_{IN-}, should be connected as closely as possible to the shunt resistor to minimize any resistance in series with the shunt resistance. Power-supply bypass capacitors are required for stability. Applications with noisy or high-impedance power supplies may require additional decoupling capacitors to reject power-supply noise. Bypass capacitors should be connected close to the device pins.

The input circuitry of the INA19x can accurately measure beyond its power-supply voltage, V+. For example, the V+ power supply can be 5 V, whereas the load power-supply voltage is up to +80 V. The output voltage range of the OUT terminal, however, is limited by the voltages on the power-supply pin.

The output of the INA19x is accurate within the output-voltage-swing range set by the power-supply pin, V+. This is best illustrated by the INA195 or INA198 (both of which use a gain of 100), where a 100-mV full-scale input from the shunt resistor requires an output voltage swing of +10 V and a power-supply voltage sufficient to achieve +10 V on the output.

An obvious and straightforward location for filtering is at the output of the INA19x series; however, this location negates the advantage of the internal buffer's low output impedance. The only other option for filtering is at the input pins of the INA19x, which is complicated by the internal input impedance of 5 kΩ + 30% (see Figure 3). Using the lowest possible resistor values minimizes both the initial shift in gain and the effects of tolerance. The effect on initial gain is given by

$$\text{Gain Error }\% = 100 - \left(100 \times \frac{5\ k\Omega}{5\ k\Omega + R_{Filter}}\right).$$

Total effect on gain error can be calculated by replacing the 5-kΩ term with 5 kΩ – 30% (or 3.5 kΩ) or 5 kΩ + 30% (or 6.5 kΩ). The tolerance extremes of R_{Filter} can also be inserted into the equation. If a pair of 100-Ω 1% resistors is used on the inputs, the initial gain error will be 1.96%. Worst-case tolerance conditions will always occur at the lower excursion of the internal 5-kΩ (3.5-kΩ) resistor, and at the higher excursion of R_{Filter} – 3% in this case.

Note that the specified accuracy of the INA19x must then be combined in addition to these tolerances. While this discussion has handled accuracy worst-case conditions by combining the extremes of the resistor values, it is appropriate to use geometric mean or root-sum-square calculations to total the effects of accuracy variations.

Related Web sites

amplifier.ti.com
www.ti.com/sc/device/*partnumber*
Replace *partnumber* with INA193, INA194, INA195, INA196, INA197, INA198, or OPA344

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products	
Amplifiers	**amplifier.ti.com**
Data Converters	**dataconverter.ti.com**
DSP	**dsp.ti.com**
Interface	**interface.ti.com**
Logic	**logic.ti.com**
Power Management	**power.ti.com**
Microcontrollers	**microcontroller.ti.com**
Applications	
Audio	**www.ti.com/audio**
Automotive	**www.ti.com/automotive**
Broadband	**www.ti.com/broadband**
Digital control	**www.ti.com/digitalcontrol**
Military	**www.ti.com/military**
Optical Networking	**www.ti.com/opticalnetwork**
Security	**www.ti.com/security**
Telephony	**www.ti.com/telephony**
Video & Imaging	**www.ti.com/video**
Wireless	**www.ti.com/wireless**

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page
support.ti.com

TI Semiconductor KnowledgeBase Home Page
support.ti.com/sc/knowledgebase

Product Information Centers

Americas

Phone	+1(972) 644-5580	Fax	+1(972) 927-6377
Internet/Email	support.ti.com/sc/pic/americas.htm		

Europe, Middle East, and Africa

Phone			
Belgium (English)	+32 (0) 27 45 54 32	Netherlands (English)	+31 (0) 546 87 95 45
Finland (English)	+358 (0) 9 25173948	Russia	+7 (0) 95 363 4824
France	+33 (0) 1 30 70 11 64	Spain	+34 902 35 40 28
Germany	+49 (0) 8161 80 33 11	Sweden (English)	+46 (0) 8587 555 22
Israel (English)	180 949 0107	United Kingdom	+44 (0) 1604 66 33 99
Italy	800 79 11 37		
Fax	+(49) (0) 8161 80 2045		
Internet	support.ti.com/sc/pic/euro.htm		

Japan

Fax			
International	+81-3-3344-5317	Domestic	0120-81-0036
Internet/Email			
International	support.ti.com/sc/pic/japan.htm		
Domestic	www.tij.co.jp/pic		

Asia

Phone			
International	+886-2-23786800		
Domestic	Toll-Free Number		Toll-Free Number
Australia	1-800-999-084	Malaysia	1-800-80-3973
China	800-820-8682	New Zealand	0800-446-934
Hong Kong	800-96-5941	Philippines	1-800-765-7404
India	+91-80-51381665 (Toll)	Singapore	800-886-1028
Indonesia	001-803-8861-1006	Taiwan	0800-006800
Korea	080-551-2804	Thailand	001-800-886-0010
Fax	+886-2-2378-6808	Email	tiasia@ti.com
Internet	support.ti.com/sc/pic/asia.htm		ti-china@ti.com

C120905

Safe Harbor Statement: This publication may contain forward-looking statements that involve a number of risks and uncertainties. These "forward-looking statements" are intended to qualify for the safe harbor from liability established by the Private Securities Litigation Reform Act of 1995. These forward-looking statements generally can be identified by phrases such as TI or its management "believes," "expects," "anticipates," "foresees," "forecasts," "estimates" or other words or phrases of similar import. Similarly, such statements herein that describe the company's products, business strategy, outlook, objectives, plans, intentions or goals also are forward-looking statements. All such forward-looking statements are subject to certain risks and uncertainties that could cause actual results to differ materially from those in forward-looking statements. Please refer to TI's most recent Form 10-K for more information on the risks and uncertainties that could materially affect future results of operations. We disclaim any intention or obligation to update any forward-looking statements as a result of developments occurring after the date of this publication.

Trademarks: All trademarks are the property of their respective owners.

Mailing Address: Texas Instruments
Post Office Box 655303
Dallas, Texas 75265

© 2006 Texas Instruments Incorporated