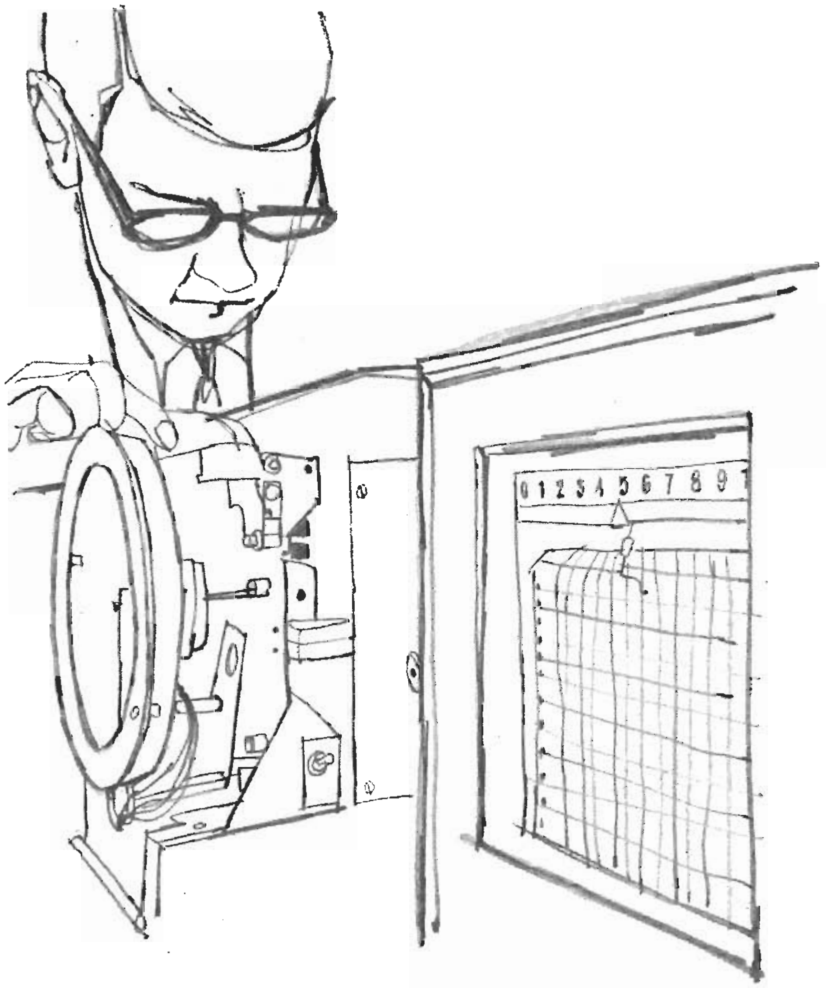
SELF-BALANCING POTENTIOMETERS

By ROBERT MEEM



Electronics technicians who fill industrial jobs encounter few devices more frequently than these.

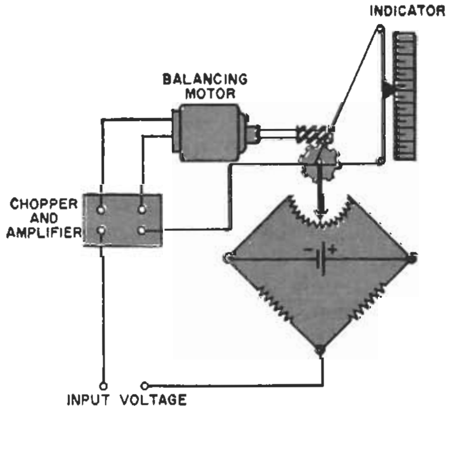
VISIT almost any industrial plant and you are likely to find a battery of recorders, such as the instrument shown in Fig. 2, keeping track of temperature, humidity, pressure, *p*H, tension, viscosity, or whatever other variables may be of interest to the process at hand.

Few devices are more valuable or more necessary to modern industrial operations. Few are more likely to be encountered by electronics technicians in industrial roles. They provide a history of process performance which is essential for duplicating previous results, studying process efficiency, correcting unfavorable conditions, and planning future operations. Trends are readily detected from the record of past and present conditions, so that corrective measures can be taken at an early stage.

Instruments of this kind will record any variable that can produce an electrical signal—and just about any variable can. In operation, a pen is positioned on a horizontal carriage in response to the input voltage, and its position is recorded continuously as a chart revolves beneath it. At speeds of ¾-inch to 2 inches per hour, a single rolled chart will hold a continuous record of about 30 days of operation. Other recorders use circular charts which revolve beneath the pen, much as a phonograph record revolves under the needle. These charts are usually designed for 24-hour coverage and are replaced each day.

While simple galvanometers are adequate for most noncontinuous measurements, they are almost useless for continuous recording, since they are too delicate to move a recording pen over a chart without seriously affecting their sensitivity. For this reason, industrial recorders contain synchronous motors, which are powerful enough to drive the pen easily and which, through the use of amplifiers, respond to minute changes in the input signal. A typical instrument with a full-scale range of 10 millivolts will be sensitive to a change in input signal of less than 2 microvolts.

Fig. 1. How the self-balancing potentiometer works. Functional blocks are shown.



Basic Elements

A unit called a self-balancing potentiometer is the heart of a pen recorder. Potentiometer, in this connection, refers to a circuit for balancing an input voltage against an internal reference voltage. It has little to do with the familiar "pot" or variable resistor widely used in radio and television circuits.

The elements of a self-balancing potentiometer are shown in Fig. 1. The input voltage may be supplied by a ther-

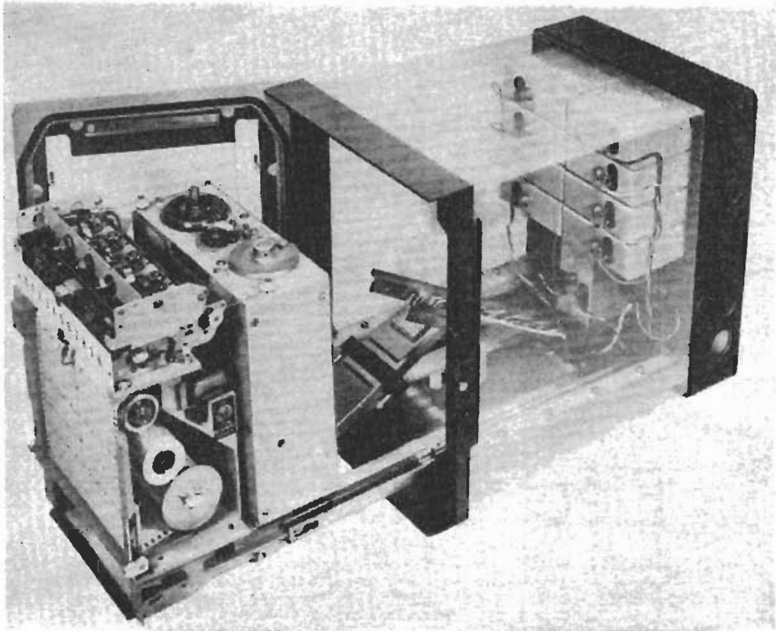


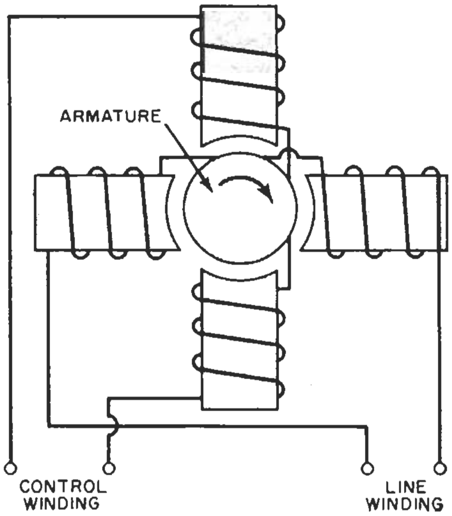
Fig. 2. A self-balancing potentiometer by Minneapolis-Honeywell, opened for detail. Drive mechanism is at the front (left). Behind it (to the right) is the amplifier enclosure. Modules at the rear (extreme right) are power-supply and control units.

mocouple or any number of other devices. It is introduced to the amplifier through a bridge arrangement which is powered by a dry-cell battery. Within the range of the instrument, there will be a setting of the slidewire contact at which the battery voltage picked off by the contact will exactly balance the input voltage, so that no current will flow through the input circuit.

At any other setting, there will be current which is amplified and used to power the motor, which in turn drives the slidewire contact to a new position. The motor will stop only when it has moved the contact to the proper balance point. Thus, the instrument works on the null-balance principle.

Since most inputs are d.c., a chopper is used to convert them to a.c. before amplification. In this way, drift problems associated with d.c. amplifiers are avoided. It is obvious that the unbalance voltage—that is, the difference between the input signal and the reference voltage—may be either positive or negative, depending on whether the input signal is increasing or decreasing. The polarity is of the utmost importance; if it were disregarded, the motor might turn in the wrong direction and never succeed in balancing the bridge. To prevent this, the chopper — which resembles the vibrator used in an auto radio—is polarized by attaching a small, permanent magnet to its vibrating reed. The reed is driven back and forth by an electromagnet powered by the line voltage. Thus the output of the chopper will always maintain a constant phase relation to the a.c. line voltage.

Fig. 3. Two-phase, reversible induction motor used to provide automatic balance.



The amplifier is conventional. In the *Leeds and Northrup* "Speedomax H" recorder, for example, two type 12AX7 twin triodes provide four stages of voltage amplification. A single type 12BH7 twin triode is used for power amplification.

The balancing motor (which will be described in detail below) drives the slidewire contact by means of a worm gear. It may have either a ratio of 100:1 for 5-second response, or 16-2/3:1 for 1-second response. Faster response is usually unnecessary and would be entirely useless where the slow chart speed would offset any advantage that might otherwise be gained.

The pen is moved back and forth by an arrangement not unlike the dial cord found on some radios. The pen is connected to the cord, and the cord is wrapped around the gear

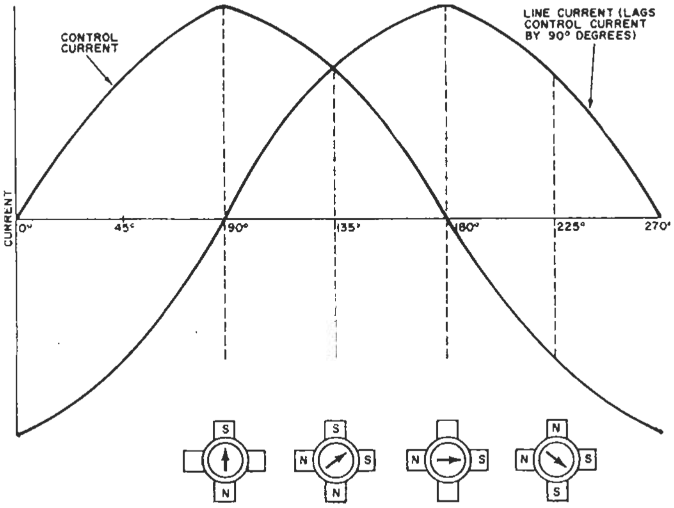


Fig. 4. Relationship between line and control currents, showing the instantaneous position of the rotor at various moments.

wheel which is driven by the worm gear. Whenever the gear wheel turns, therefore, the pen also moves.

Balancing Motor

The function of the balancing motor is to position the recording pen according to changes in the input voltage. To do this, it must be able to rotate in either direction, in response to increases or decreases in that voltage. This is accomplished by means of a two-phase, reversible induction motor, shown in Fig. 3.

The motor has four poles and two sets of stator windings. The *line windings,* which carry the line current, are on the horizontal poles. The *control windings,* which carry the current resulting from the amplified unbalance voltage, are on the vertical poles. A necessary condition for the operation of the motor is that there be a 90-degree phase difference between the line current and the control current. When this phase difference exists, the poles will become magnetized in turn and will produce continuous rotation of the armature, as illustrated in Fig. 4.

When the control current leads the line current, as in this instance, the armature will rotate in a clockwise direction. If the control current should lag the line current by 90 degrees, however, counterclockwise rotation would result. Thus, with a constant line current, the direction of the armature rotation can be reversed by shifting the phase of the control current 180 degrees.

The method of obtaining the necessary phase shift in the control current is shown in Fig. 5. The type 12BH7 in the power-amplifier stage is connected so that the plate voltage for the two triodes is supplied from opposite ends of a center-tapped, high-voltage power transformer. The control winding of the balancing motor is connected to the transformer center-tap and to the junction of the two cathodes. A capacitor is shunted across the winding of the proper value to balance inductance, so that impedance is almost purely resistive.

The three possible conditions are illustrated in Fig. 6. When the system is balanced, no signal voltage is applied to the grids of the power-amplifier triodes. The plate of triode 1 goes positive on one half of the cycle, and current flows through the motor control winding. At the same time, the plate of triode 2 goes negative and no current flows through it on that half cycle.

During the next half cycle, the plate voltages are reversed. No current is drawn by triode 1, but current flows through triode 2 and, of course, through the control winding. The result is a pulsating direct current (Fig. 6A) with 120 pulses-per-second. Since this yields a fundamental frequency of 120 cycles while the motor is designed for 60 cycles, the rotor will not move.

When the system is not in balance, the unbalance voltage (E_G) will be converted to a.c., amplified, and applied to the grids of the power amplifier. Depending on whether the unbalance voltage is positive or negative, the grid voltage will always be in-phase with the plate voltage of either triode 1 or triode 2.

In the first instance, we assume that the grid voltage is in-phase with the plate voltage of triode 1. On the half cycle when the plate voltage is positive the grid will also be positive, and the output will be greater than when the grid voltage was zero. At the same time, however, the plate of triode 2 will be negative and the latter will not conduct. On the next half cycle, the plate of triode 1 will be negative. The plate of triode 2 will be positive, but its grid will be negative, so little or no current will flow.

The result of this situation is shown in Fig. 6B. It is apparent that, despite the irregularity of the waveform, the basic frequency in this case will be 60 cycles. This control

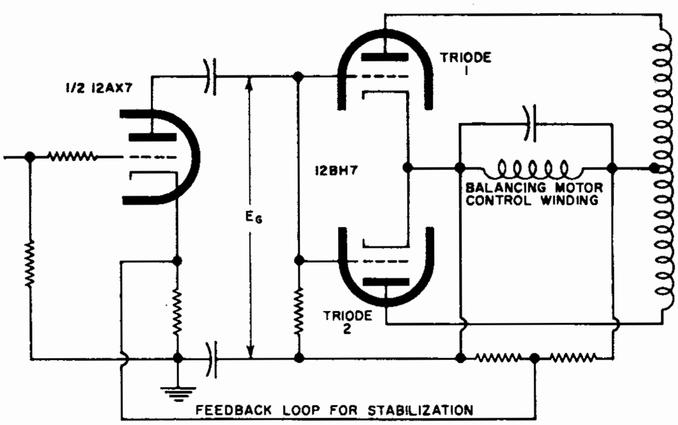


Fig. 5. The output section of the amplifier. The control winding of balancing motor is incorporated in this circuit.

current leads the line current by 90 degrees, and the rotor of the balancing motor will revolve in a clockwise direction.

Fig. 6C shows the comparable situation when the grid voltage is in-phase with the plate of triode 2. On the first half cycle, triode 1 will not conduct because its grid will be negative. On the next half cycle, the plate and grid of triode 2 will be in-phase and will produce a large output. The resulting 60-cycle wave will be 180 degrees out-of-phase with the wave shown in Fig. 6B. Since it lags the line current by 90 degrees, the direction of the motor will be reversed, as explained above.

Whether the control current is supplied by triode 1 or 2, it is essential that it be 90 degrees out-of-phase with the current in the motor line winding. This is accomplished primarily by placing a 2.3-microfarad capacitor in series with the line winding. There is some mechanical lag in the chopper circuit and some phase shift in the power output stage, however, and while the result of these various effects is a phase difference of about 90 degrees, it may be necessary

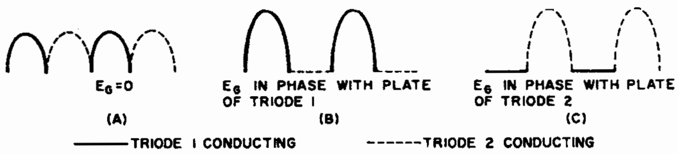


Fig. 6. Output-current waveforms of the amplifier in Fig. 5 for the three possible conditions of input voltage in Fig. 1.

to make small adjustments to obtain proper phase relation.

Other Features

When a dry cell is used as the source of power for the bridge, its output will vary with age, and this may cause inaccuracy. This factor is overcome by inserting a rheostat in series with the battery and periodically reducing the resistance in the circuit so that the output to the bridge remains substantially constant.

A standard cell having a constant voltage of 1.0195 volts is incorporated in many circuits and connected so that, when a switch is thrown, it will oppose the bridge voltage through a resistive network. The rheostat is then adjusted until there is no current flow. In many instruments the calibration is automatic. The standard cell is switched into the circuit at regular intervals, and the rheostat is driven to the null position by the same balancing motor that operates the slidewire contact. When the rheostat is at one extreme leaving more resistance in the line, the dry cell is replaced.

Some instruments employ a zener-diode voltage supply (Fig. 7) instead of a dry cell. Zener diodes have the unique property that, when connected in the reverse direction, the voltage remains constant despite changes in current drain. Since their characteristics do not change with use, periodic calibration is unnecessary.

Not all instruments use a slidewire device to achieve balance. A bridge made by the *Foxboro Company*, for example, operates on a.c. and employs a center-tapped variable capacitor as the balancing mechanism. The unbalance signal is amplified in the usual manner and drives the rotor of the capacitor to a balance position.

The *Minneapolis-Honeywell* recorder (Fig. 2) uses a strain gage as the balance mechanism. Four pre-stressed, looped, wire strands enclosed in an *I*-shaped frame form the variable resistance legs of a Wheatstone-bridge circuit. Their resistance varies in proportion to the tension applied to them, in accordance with the principle of the strain gage.

When the horizontal torsion pivot to which the wires are fastened is at zero position, the wires are under equal torsion and have equal resistance. Any movement of the balancing motor causes a torsional movement of the pivot, however, so as to increase the tension and thus the resistance on two of the wires and reduce it on the other two. This changes the electrical resistance of the wires and continues to change it until the bridge is electrically rebalanced. At this point the motor will stop turning.

Movement of the wires, which act like rubber bands, is extremely slight but precisely proportional to the degree of shaft rotation. The pen carriage is linked to the balancing motor, and the same movement that balances the bridge also positions the pen. This strain-gage arrangement has the advantages of infinite resolution and low mechanical wear. ▲

Fig. 7. Establishing the reference voltage with a zener diode. Voltage-current characteristic of the diode is at the right.