Electronic Integrator for Micrometeorological Data[1]

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ABSTRACT

A transistorized, battery-operated integrator suitable for obtaining the time average of fluctuating electrical analogue signals in the field with relative errors of about 0.1 to 0.2 per cent is described.

A solid state operational amplifier is used in an R-C integrator circuit. Continuous integration is accomplished by reversing the polarity of the input signal each time a fixed time-integral has occurred. The addition of a resistor to the ordinary R-C integrating circuit reduces the error resulting from the finite switching time. The integral is obtained by counting the input polarity reversals which are registered on a counter (mechanical or electronic) to be automatically recorded at desired intervals.

The use of transistor converters allows the complete circuit as well as additional equipment to be operated several days from one 12V automobile battery.

1. Introduction

Time integration often is required for processing data (e.g., net or solar radiation). If measurements are recorded on a strip-chart, considerable time and effort are usually expended in chart reading although methods for simplifying the integration of single-channel strip-chart records have been reported (Russell, 1960; Brown and Harvey, 1961). Single-channel recorders with either ball and disc or switch-adder integrators for each of several measurements are expensive, but the cost per channel is decreased where multichannel integrators on recorders are feasible (King and Graham, 1959).

Several types of integrators have been proposed that do not require recorders. We have been particularly concerned with types designed for battery operation or that can be modified for battery operation in the field. Most of the commercially available integrators such as electronic R-C network types require 110v ac main power. Direct-current integrating motors (e.g., Electro Methods Ltd.[3]) have been used separately or in systems designed to improve their performance (Trickett *et al.*, 1957; Schoffer and Suomi, 1961). Several chemical devices are also available: these include low cost mercury coulometers[4] (Tanner, *et al.* 1963), gas coulometers (Trickett, *et al.*, 1957) and Solion integrators.[5] Thermal systems also have been used and include distillation (latent heat) integrators (Monteith and Sceicz, 1960; Trickett *et al.*, 1957), heat storage units (Draper, McKay and Lees, 1955), and thermal transducers utilizing transient heat flow in homogeneous materials (Kovarik, 1958). Several integrating systems incorporating galvanometers have been proposed (Funk, 1960; Rider and Bradley, 1962) which appear useful for many field applications.

We wanted a battery-operated integrator with sufficient resolution to be useful for integrals over periods as short as a few minutes and yet with low power drain so that it could be operated for several days and could record time-integrals in digital form. We accordingly chose the transistorized R-C network analogue integrators as best suited for our purpose.

2. R-C analogue integrators

Basic analogue integrating circuits, Fig. 1, are very common and will not be discussed in detail. In this circuit the rate at which the capacitor C_1 is charged is proportional to the value of the input signal $E(t)$. Thus the total charge placed on this capacitor during any given period of time is proportional to the time integral of $E(t)$.

Continuous integration with these integrators requires periodic measurement and removal of the charge accumulated on the integrating capacitor. If the same amount of charge is removed each time, then the number of times charge is removed is a measure of the integral. The charge removal can be accomplished in three general ways: firstly, the capacitor can be shorted with a mechanical (or electronic) switch each time it reaches a fixed reference potential and allowed to discharge to

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[3] Electro Methods Ltd., Claxton Way, Stevenage, Herts, England.

[4] Curtis Instruments, Inc., 45 Kisco Avenue, Mount Kisco, N.Y.

[5] Texas Research and Electronic Corporation, 6612 Denton Drive, Dallas 35, Tex.

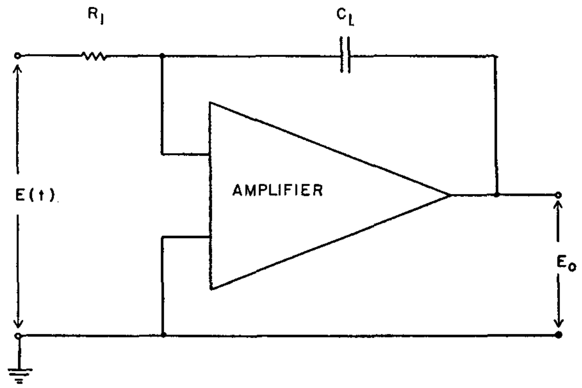

Fig. 1. R-C analogue integrator.

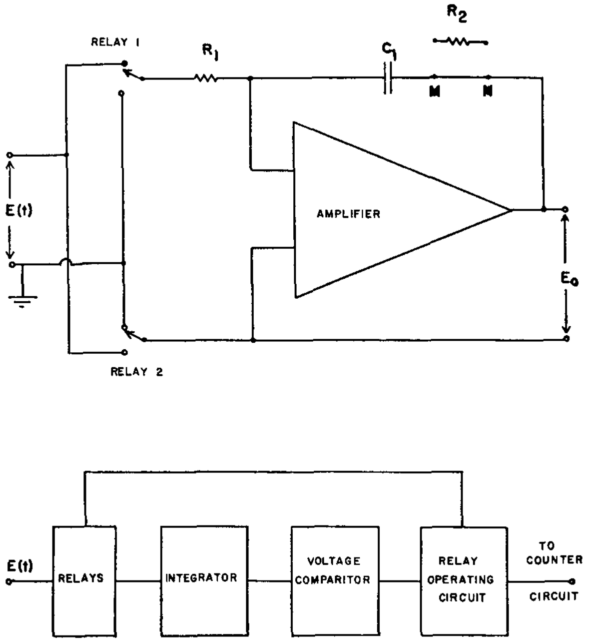

Fig. 2. (A, top) Integrator with relays for reversing input signal polarity. Resistor, R_2, compensates for finite polarity switching time. (B, bottom) Block diagram of complete circuit.

some other known potential, usually zero (Seddon, 1960). This method introduces errors since the integrating circuit is inoperative during the clamping time—the time required for the capacitor to discharge plus the operating time of the relay. Secondly, each time the capacitor becomes charged to a fixed reference potential, a known quantity of charge is removed (Mobley, 1962). This method has the advantage that the charge is removed from the capacitor without interrupting the integration, but the circuitry is more complicated. Thirdly, the polarity of the input signal can be reversed; this is the method we have chosen and is shown in Fig. 2.

A voltage comparison circuit senses the potential E_0 at the output and when this potential reaches a predetermined value (corresponding to a given time integral) the polarity of the input signal is reversed. This reverses the current charging the integrating capacitor and the capacitor discharges. When the capacitor has reached a similar potential but of opposite polarity, the polarity of the input signal is once again reversed. This procedure is continued for the period of time for which the integral is desired, each cycle of polarity reversal being recorded on a counter. Thus the number of counts registered is proportional to the integral of the input signal $E(t)$ and the integration process is only interrupted for very short periods of time.

Reversing the integrator input polarity, as used in our circuit, allows the capacitor to be charged over a much wider potential range than does the clamping method, and the circuitry is simpler than the second approach. Polarity reversal also decreases zero drift which can be serious in transistorized dc operational amplifiers under conditions of changing ambient temperature. The switching time introduces some error (less than first method of charge removal), and we show how this can be minimized.

3. General description

The block schematic of the integrator is shown in Fig. 2B. We used a transistorized operational amplifier[6] (one of several available commercially) and solid state circuitry throughout in order to minimize power requirements and increase portability. The complete circuit is powered by one 12v automobile battery, with a current drain of 135 ma in addition to the power required to operate the counter. Voltages other than the 12V supplied by the battery are required. To eliminate the need for additional batteries, transistor converters (not shown) have been used to supply the required power.[7] Thus the instrument is suited to field operation where power mains are not available. The unit can be modified easily to use other amplifiers.

In this circuit two unijunction transistors sense the integrator output voltage and produce pulses when this voltage has reached the value at which polarity switching should occur. The stable characteristics of these transistors make them well suited to this application. The pulses generated are used to fire silicon controlled rectifiers which operate and latch two polarized, single-pole, double-throw relays[8] which control the polarity of the input signal. The relays can be either latching or non-latching but must have a center-tapped (double) coil and should be high speed; if available, one DPDT relay could be used. A record of the number of integration cycles must be made; since each silicon-controlled rectifier is fired once per cycle, a pulse is taken from one of these rectifiers and used to trigger the counter circuit.[7]

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[6] George A. Philbrick Researches, Inc., 285 Columbus Ave., Boston 16, Mass. (Model P-2).

[7] Schematics of our power supply and counter circuits are available upon request.

[8] C. P. Clair and Co., 3101 Pratt Blvd., Chicago 45, Ill.

Any mechanical or electronic counter can be used. We found a Sodeco[9] printing counter quite satisfactory up to 10 counts per second.

4. Polarity switching and integrator circuits

Ideally the relays reversing the input polarity should operate with infinite speed because a delay in switching results in part of the integral not being recorded. The nature of this error is illustrated in Fig. 3A. The solid lines GCE represent the ideal situation where the switch reversing the input signal operates with infinite speed. The dashed lines represent the actual situation where switching time is composed of t_a, the time required for activation of the contacts plus t_0, the time of transit when the input is open. It can be seen that a cumulative error corresponding to time interval t_e results in this case, and makes the number of counts registered non-linear with respect to the input signal.

If a resistor R_2 is added to the circuit between points M and N as shown in Fig. 2A, E_0 becomes equal to E_c+E_{R2}, the sum of the voltages across the capacitor C_1 and resistor R_2, respectively. At time t_s shown in Fig. 3B, E_0 equals the reference potential E_s and the relays are activated. If the charging current remains constant during the time interval t_a, the integrating capacitor charges linearly from A to B. During the time interval t_0 the charging current goes to zero and E_c remains constant from B to D as shown. If the point D is to lie on the line CE corresponding to ideal operation, E_R must be equal, at time t_s, to the potential change the capacitor C_1 would experience when charging from A to C if R_2 were not in the circuit. The line AC corresponds to the time interval $t_a+t_0/2$ and so

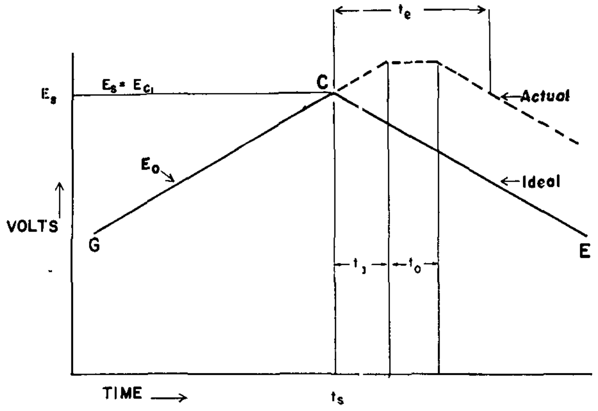
$$E_R=\int_{t_s}^{t_s+(t_a+t_0/2)} \frac{idT}{C}, \qquad (1)$$

where i is the charging current. Thus

$$R_2=\frac{t_a+t_0/2}{C}, \qquad (2)$$

since it has been assumed that the charging current remains constant for the switching period.

The error introduced can be made small by the selection of high speed relays. R_2 depends only on C_1 and t_a+t_0 does not depend on the value of the input resistor R_1. Thus the value of the input resistor R_1 can be changed to adjust the counting rate. If the value of R_2 is properly chosen the instrument will be linear provided the assumption holds that the instantaneous value of $E(t)$ at the moment of switching is equal to the average value of $E(t)$ during the time required for the switching operation.



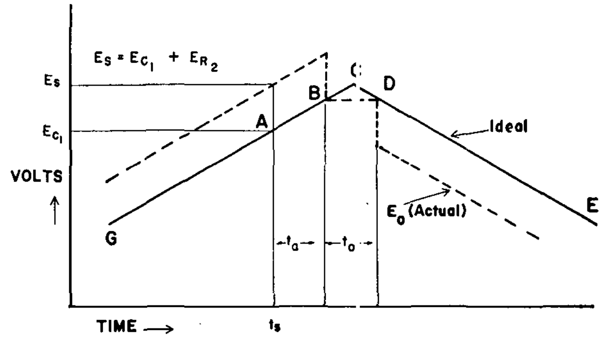


FIG. 3. (A, top) Error in output voltage E_0 due to finite time required for switching polarity at input. (B, bottom) Output voltage when compensated by resistor R_2.

The voltages at which the unijunction transistors activate the relays are determined by isolated voltages (12.4 v in our circuit) supplied between points $A(+)$ and B and between $C(+)$ and D (Fig. 4) by the unijunction transistor power supply. Any change in this voltage results in a change in the reference potential E_s. These voltages are regulated by zener referenec diodes. The temperature coefficient of integration (less than 0.01 per cent per deg C in our circuit) could be contributed partly to the temperature coefficient of these voltage regulating diodes and partly to changes in the integrating capacitor. The latter was a polystyrene capacitor with a stated maximum temperature coefficient of capacitance of 0.008 per cent per deg C.

The value of the integrator input resistor R_1 is determined from the equation

$$E_0=(1/C_1R_1)\int_{t_1}^{t_2} E(t)dt, \qquad (3)$$

and the conditions that the maximum expected input voltage $E(t)$ (including a fixed bias voltage at the input, if one is used) will give about 10 counts per second for best accuracy. In our circuit the output voltage E_0,

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[9] Landis and Gyr, Inc., 45 West 45th Street, New York 36, N. Y.

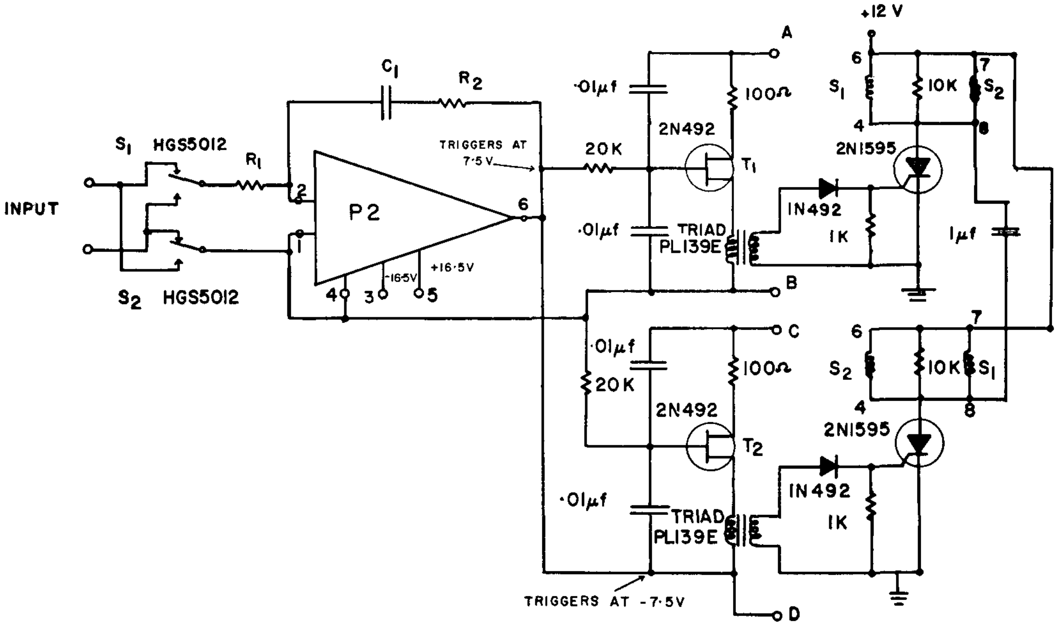

Fig. 4. Schematic circuit of integrator with voltage comparitor and relay operating circuit.

swings from $(+7.5\rightarrow -7.5\rightarrow +7.5)=(15+15)=30$ v for each count. If (t_2-t_1) is 0.1 sec, and an integrating capacitor of 0.075 μf is used, Eq (3) reduces to

$$R_1=\frac{E_{\max}(0.1\text{ sec})}{(0.075\times10^{-6}\,\mu\text{f})(30\text{ volts})}$$

$$=E(4.45\times10^4\text{ amp}^{-1}). \quad (4)$$

Thus, if R_1 is 100K, a 2.4 volt input signal will cause 10 counts per second to be registered. As an example, the ±1.0 volt output signal of a preamplifier could be superimposed upon a +1.4 volt constant bias at the integrator input terminals; the signal being integrated would then vary between the extremes of 0.4 volts and 2.4 volts so that the corresponding counting rate would vary between 1.67 counts per second and 10 counts per second and zero input signal would be represented by 5.83 counts per second.

If smaller signals than those used in the above example are to be integrated, the value of the input resistor R_1 may be reduced to increase the counting rate; however, the signal cannot be too small if accuracy is to be maintained. The accuracy of small signals is limited mainly by the amplifier. For example, the specifications for the Philbrick P2 operational amplifier indicate a possible drift of 5 mv corresponding to a temperature change from 20C to 45C; thus the smallest signal suited to this integrator should be many times this value. As an example, a bias voltage of 125 mv is suitable for use with a ±100 mv full scale input signal. If the 100 mv signal does not change in polarity, a smaller bias of 25 mv can be used. If the bias is too small the minimum counting rate becomes so slow that the zero drift of the operational amplifier is not effectively removed by the polarity-reversing feature of this circuit. If the bias is much larger than the input signal, the accuracy of the integration is decreased since the relative change in counting rate as the input signal goes from zero to full scale is reduced. Errors due to drift that arise when small signals are measured can be decreased if an operational amplifier having less zero drift is used (some are now commercially available). Another solution is to use a signal preamplifier as indicated in the example above; we have used this method when integrating the low level signal from a net radiometer with 0.5 ly min^{-1} mv^{-1} output.

The counting circuit used is not shown.[7] It was designed for use with a Sodeco printing counter and produced a pulse of approximately 12 v at 1 amp with a duration of 40 millisec. Electronic binary and decimal counter circuits can be used if needed for either punch-tape or magnetic-tape recording.

This integrator (with power supplies and counting circuits) was used intermittently, accumulating a few weeks' operation and then was used continuously in the field for 3 months during the summer of 1963. For use in the field the complete circuit, including Philbrick operational amplifier and integrator circuits, the power converters, and the counting circuit for the Sodeco counter, was mounted in one 9×11×6 inch aluminum carrying case.

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