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A NEW TECHNIQUE FOR REMOVING CHARGE FROM THE
STORAGE CAPACITOR IN DIRECT CURRENT ANALOG-TO-PULSE-RATE CONVERTERS*

F. M. Glass

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ABSTRACT

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A new all-solid-state direct-current integrator integrates currents as low as 10^{-11} amp with an accuracy of 1%. Currents as low as 10^{-12} amp can be integrated with approximately the same accuracy when fast response is not a necessity. This integrator features solid-state current switches that have sufficient speed for single-range, recycling ionization detectors to cover four decades. These switches are complementary silicon planar transistors that operate in the inverted-mode with both their base-emitter and base-collector junctions reverse biased. The individual leakage currents in the quiescent state total about 10^{-13} amp. When matched complementary pairs are used, the algebraic sum of the leakage current can be less than 10^{-14} amp. Recycling rates of 20 kHz are easily obtainable.

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INTRODUCTION

The recycling ionization chamber has been considered for many years as a possible answer to the OCD's need for a reliable wide-range radiation monitor having essentially flat response to gamma and x-ray energies in the range of 100 kev to 1 Mev. The CDV-781 aerial survey meter is an instrument that might be improved by employing the recycling ionization chamber principle. The design of such an instrument is made complicated because the response time must be short even when the current is as low as 10^{-12} amp, if the instrument is to be useful at ground speeds of 100 mph. The relays and solid-state switches that have been employed to remove charge from integrating capacitors either have been too slow or their leakage resistances have been too low to be dependable in this application. Because of these considerations existing techniques of current integration were surveyed and a search was made for a better low-current switch.

Techniques of Current Integration

Figure 1 illustrates four operating principles that have been successfully employed in current integrator circuits. A distinguishing operating principle common to all four circuits is that the voltage across a storage capacitor is monitored by an electrometer type operational amplifier, the output of which triggers a discriminator at a given voltage level. The discriminator generates a reset pulse which removes a fixed charge from the integrating capacitor and supplies a signal to a scaler.

The technique for removing charge from the storage capacitor is different for each of the four integrators illustrated. The integrator in Fig. 1a employs the time-proven diode pump. The charge removed is $Q = CV$, where C is the coupling capacitor C_c , and V is the amplitude of the reset pulse less the forward voltage drop across the diode. Accuracy is therefore independent of the amplifier gain, the trigger level of the discriminator, and the temperature coefficient of the integrating capacitor C_i . Two good examples of instruments of this type are the ORNL vacuum-tube integrator, model Q-1259, which has given excellent service since 1950, and the more recent solid-state version by Landis and Goulding.¹ The most serious limitation of these instruments is diode leakage which limits their sensitivity to about 10^{-10} amp.

The principle illustrated in Fig. 1b is employed in an integrator designed by Brenner.² The technique is to charge a capacitor C_s to a given reference voltage of opposite polarity to the charge on the integrating capacitor and then to transfer this charge to the integrating

¹D. A. Landis and F. S. Goulding, "A New Type of Beam Integrator," Nucl. Chem. Div. Ann. Rept. 1964, UCRL-11828, Jan. 1965, pp. 222-23.

²Roul Brenner, A Precision Current Integrator, Instituto de Energia Atomica, Publication No. 67, March 1964.

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Fig. 1. Charge Dumping Techniques of Current Integrators.

capacitor C_i by means of a high-quality relay. The charge removed from C_i is dependent only on the value of C_s and the reference voltage, provided $C_i \gg C_s$, as it normally is. The leakage can be made quite small in this instrument; however, the reset frequency is limited by the relay to a few hundred Hertz.

The oldest of the four techniques illustrated in Fig. 1 is shown in Fig. 1c. This technique removes the charge from the integrating capacitor by shorting it with a relay or electronic switch. Since the charge is completely removed from the integrating capacitor with each relay closure, a good stable integrating capacitor C_i , a high-gain operational amplifier, and good trigger stability in the discriminator are essential for good accuracy. The linearity of an instrument incorporating this technique is poor, because the input is shorted while the charge is being removed from the storage capacitor. The only significant feature of this integrator is that the leakage current can be made quite low if a high-quality relay is used.

The principle of operation for the circuit shown in Fig. 1d is that when the integrating capacitor C_i charges sufficiently to trigger the upper-level discriminator, the current generator is triggered on, which quickly discharges C_i to the voltage level at which the lower level discriminator triggers. The lower-level discriminator then turns the current generator off. The charge removed with each reset cycle is $Q = C(E_2 - E_1)$, where E_2 and E_1 are the voltage levels at which the two discriminators trigger.

The accuracy of this circuit, for currents of sufficient magnitude to be negligibly affected by diode leakage, is limited only by the accuracy with which each discriminator can sense a voltage level. This statement requires qualification: the current being integrated should also be smaller by at least two orders of magnitude than the reset current; i.e., the reset duty cycle must be very short for the highest current measured if the instrument is to be linear. In addition, the operational amplifier must have an extremely high gain-bandwidth product.

The advantages and disadvantages of the different schemes illustrated in Fig. 1 can be summed as follows. The diode pump system is fast, and excellent accuracy and long-term stability can be achieved with minimum critical circuitry. The range easily achieved with good accuracy and perfect linearity is from 10^{-9} to 5×10^{-4} amp. However, the diode pump circuit is limited in sensitivity by the leakage of the diodes. The voltage-sensing and current-switching technique shown in Fig. 1d is also fast and has the same range limitations as the diode pump circuit, but the circuitry required to achieve the same degree of accuracy that is easily obtainable with the pump circuit is comparatively complicated and sophisticated. The Brenner circuit is very slow, but it can have excellent leakage characteristics if constructed from quality components. Linearity is perfect up to the cycling limitations of the reed relay. The shorting method illustrated in Fig. 1c is slow and nonlinear. No one instrument described previously can fill all the needs of an experimenter whose experiments include the integration of very small currents from ion chambers

as well as beam currents. An ideal instrument would have the speed and accuracy obtainable with the diode pump circuit and the current leakage as low as the best reed relay, and would be capable of dumping charges as small as 10^{-12} coulomb.

The Transistor as a Current Switch

Solid-state operational amplifiers with input current leakages of less than 10^{-14} amp became a reality with the development of insulated-gate field-effect transistors. It became apparent that it might be possible to design a wide-range solid-state current integrator having a lower leakage current than existing designs if a fast, low-leakage solid-state switch could be found. At the present time, leakage currents of 10^{-12} amp for silicon diodes reverse biased at 1 v is about the best that can be achieved by the state of the art. Although a leakage current of this magnitude is good enough for beam current measurements, it precludes the use of the diode pump circuit in instruments intended for use with ion chambers. Therefore, the possibility of using silicon planar bipolar transistors as current switches was investigated.

Several types of silicon transistors have a typical reverse-biased collector-to-base leakage current I_{CBO} as low as 1×10^{-10} amp at a collector-to-base voltage V_{CB} of 20 to 30 v. It was determined experimentally that four types of bipolar transistors had I_{CBO} values ranging from 1×10^{-13} to 4×10^{-12} amp when biased at a V_{CB} of 0.1 v. However, the leakage current can be made much lower than the I_{CBO} if the transistor is operated in the "inverted mode," i.e., with the collector and emitter leads interchanged. In the inverted-mode operation the leakage current through the emitter terminal is, from the equations of Ebers and Moll,³

$$I_E \approx I_{CBO} \left(\frac{h_{FEI}}{h_{FEN}} \right) \left(1 - e^{-\left| \frac{qV}{kT} \right|} \right),$$

where h_{FEN} and h_{FEI} are the normal and inverted current gains respectively, q is the charge of the electron, v is the junction bias, k is the Boltzmann constant, and T is the absolute temperature in $^{\circ}K$. In this relationship it is assumed that (1) the only voltage drops are at the junction, and the injected current densities are low; (2) the "Early" space-charge layer widening effect is negligible; (3) the emitter and collector junctions, individually, have a $V - I$ characteristic of the form

$$I = I_s \left(e^{\frac{qV}{kT}} - 1 \right);$$

³J. J. Ebers and J. L. Moll, "Large-Signal Behavior of Junction Transistors," Proc. IRE, December 1954, pp. 1761-72.

Table I. Comparison of I_{CBO} with I_E^a

Type	Sample	I_{CBO} (amp $\times 10^{-12}$)	I_E (amp $\times 10^{-13}$)	h_{FEN}	h_{FEI}	$\approx I_{CBO}/I_E$
2N4338 npn Silicon Planar Epitaxial	1	1.7	-1.00	150	2.0	17
	2	50	-1.30	280	2.4	384
	3	0.47	-0.32	285	5.0	14.7
	4	2.1	-1.70	470	1.5	12.3
	5	0.68	-0.10	330	4.0	68
	6	1.87	-0.17	1100	3.4	110
2N4250 pnp Diffused Silicon Planar	1	-4.6	1.6	315	1.8	29
	2	-2.5	0.17	300	0.2	147
	3	-0.063	0.085	380	3.0	7.4
	4	-0.102	0.28	350	3.0	3.6
	5	-0.21	0.20	430	3.5	10
	6	-0.215	0.085	300	3.0	25

^aTest conditions for current gain were $V_{CE} = 0.6$ v and $I_B = 1$ μ a; for I_{CBO} , $V_{CB} = 0.1$ v; and for I_E , V_B and $V_C = 0.1$ v reverse bias.

and (4) no drift fields exist in the base except at the junctions. Even though the equations by Ebers and Moll were based on the behavior of junction transistors, Verster⁴ verified that the agreement between theory and experiment is very good for silicon planar transistors. Although the experimental data in Table I for twelve transistors picked at random does not agree very well with theory, it does point out the advantage of inverted-mode switching. It is possible that some of the disagreement between theory and experiment is due to surface leakage on the substrate and encapsulation leakages. The experimental data do indicate, however, an average ratio of I_{CBO}/I_E equal to 68 for the twelve samples tested; and that most of these transistors, if properly matched in complementary pairs, are usable as current switches. The ORNL model Q-2895 current integrator was designed to provide experience with transistors in this application.

DESIGN CONSIDERATIONS

Reset or Charge-Dumping Circuit

Resetting is accomplished in the ORNL model Q-2895 current integrator in the following manner. Complementary silicon planar transistors of the type described in the preceding section serve as current switches (see Q_1 and Q_2 in Fig. 2). In their normal quiescent state they are in the inverted-mode condition with both junctions reverse biased by 100 mv. Under these conditions the effective leakage contributed by the switches is the algebraic sum of the two emitter currents. From Table I, complementary pairs can be picked that will give an effective leakage of less than 10^{-14} amp. Reset pulses switch these transistors from the reversed-biased state to the active state for a precise time during which a constant current flows to or from the integrating capacitor. Use of the transistors in this manner has the advantages of both normal and inverted modes of operation. The current that flows for the duration of the reset pulse is

$$I = \frac{V_R - V_{BE} + V_D}{R_E},$$

where V_R is the reference voltage, V_D is the forward drop across the diode clamp, and V_{BE} is the base-to-emitter voltage for the transistor in the active, or on, state. Since V_{BE} and V_D have opposite signs, almost perfect

⁴T. C. Verster, "Silicon Planar Epitaxial Transistors as Fast and Reliable Low-Level Switches," IEEE Trans. Electron Devices ED-11, May 1964, pp. 228-37.

Fig. 2. DC Current Integrator, ORNL Model Q-2895.

temperature compensation can be achieved by matching the diode current of the clamp with the emitter current of the switching transistor. Since the base-driving impedance is the low dynamic impedance of the diode and the input always remains at essentially ground potential, the switching transistors and R_E provide a current source that has essentially the same stability as R_E . The charge removed from the storage capacitor by each reset pulse is

$$Q = I\tau + C(V_R - V_B + V_D) \quad ,$$

where τ is the width of the reset pulse in seconds and C is the capacitance from the emitter terminal to ground (note: the capacitance from the emitter to the base and collector is degenerated by unity gain). If C is small (about 1 pf) and the product of τ and I is large (greater than 10^{-8} coulomb), the effect of C can be neglected. Unfortunately this condition cannot always be obtained, and the capacitance C therefore determines the

lower limit of the charge that can be reliably and accurately dumped. It is extremely difficult to remove charges smaller than 10^{-10} coulomb when range switching is employed unless a compromise is made in the reference voltage V_R that determines the reset-pulse amplitude. By using a reed relay in a very unorthodox manner, one can have two ranges, with the most sensitive range being 10^{-10} coulomb (see Fig. 3). This technique keeps the total capacitance in the emitter circuit at less than 2 pf. The high range is 10^{-7} coulomb; it is intended for integrating beam currents.

Amplifier

The calibration of the integrator is independent of amplifier drift and gain, provided the sum of the error voltage due to the signal and the drift voltage as referred to the input remains less than the reverse bias on Q_1 and Q_2 . Hence, little effort was made to design a superior operational

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Fig. 3. Current Switch with Range Switching.

amplifier. The amplifier is a differential type employing both common-mode feedback to the current source for the input pair and voltage feedback to the unused input. It has both inverted and noninverted outputs, either of which can be selected by the polarity switch, depending on the sign of the current being integrated. A matched pair of 2N3608 insulated-gate field-effect transistors in the input stage provides a high input impedance with a leakage current less than 1×10^{-14} amp. The overall gain is designed for 100 with a gain-bandwidth product of 1.9 MHz.

Discriminator

The discriminator consists of two trigger pairs. The function of the first pair, which is capable of free running when its dc threshold voltage is exceeded, is to prevent "lock out" and to provide a reasonably constant trigger pulse for the second pair. The function of the second trigger pair is to generate a reset pulse τ that is extremely constant in width. Methods for generating accurate timing pulses have been covered in the literature and will not be discussed here.

Rate Meter

The rate meter covers the range of 1 to 2000 counts/sec in four ranges. It is a duty-cycle type having excellent stability and linearity. Although its intended use is only as an indicator to aid the operator in adjusting the beam, its accuracy is limited only by the panel meter linearity and the accuracy with which the individual ranges have been calibrated.

CONCLUSIONS

The 10^{-10} coulomb minimum charge range of the ORNL model Q-2895 direct-current integrator is much too large to be of practical use in the aerial survey meter. To cover four decades, the recycling rate should be from 1 Hz to 10 kHz to be compatible with the flying speeds of the aircraft and the desired resolution. Since the current from an ion chamber with an acceptable size (400 cc) and filled with a mixture of Freon-216, xenon, and krypton produces an ionization current of only 1.3×10^{-12} amp in a 10-mr/hr field of 100-kev x rays, the charge removed with each recycle will have to be 1.3×10^{-12} coulomb. Further investigation will be required to determine if this can be accomplished reliably over the wide temperature range in which this instrument must operate. If it can be done reliably, the instrument would have the advantage of four decades of coverage in a single range with simple read-out-capabilities.

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