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An Accurate Current Integrator

in the Range of

10^{-5} to 10^{-9} Amperes

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Abstract

A current integrator has been constructed having the following specifications: accuracy 0.3% or better over the range from 4×10^{-5} amperes to less than 10^{-9} amperes, with leakage current less than 5×10^{-14} amps. Positive or negative input currents can be integrated with a duty cycle as low as 0.25%. The unit has a temperature coefficient of 0.03%/°C and is relatively insensitive to external shunt capacity at the input.

Introduction

After a fairly extensive literature survey, it became obvious that integrators constructed to date fell into two distinct classes. The first of these stored the incoming charge on a known and stable capacitor, which was then discharged by a shorting switch when the voltage exceeded some set level. The accuracy of this type of integrator is dependent upon the stability of the discriminator setting, and upon the duty cycle.

The second class of integrators use feedback of charge of opposite polarity to the input charge, and is the basis of current (or voltage) to frequency convertors. The charge fed back can be gated to the input through diodes or by a relay. Leakage currents become excessively high in the diode method, of the order of 10^{-11} amperes. The accuracy of this type of integrator is dependent solely upon the stability of a reference voltage or current, and the voltage drift of the input to an amplifier, if the gain of the amplifier is sufficiently high.

Basic Configuration

It was decided to use the method of charge feedback to the input of the integrator using a relay as the switch. A block diagram of the integrator is given in Fig. 1. The incoming

current, i , is integrated in a Miller amplifier. When the output of the amplifier exceeds a certain level, relay RL2 is operated causing a known charge of opposite polarity to that of the input to be injected. The number of relay operations is then proportion to the charge fed to the integrator.

A simplified schematic of the integrator is given in Fig. 2. It can readily be shown that the Laplace transform of the output voltage of the amplifier is given by

$$\begin{aligned}\bar{V}_o &= \frac{-\bar{i}}{p^2 \frac{T_2}{A} (c_1 + c_f) + p \left(\frac{T_2}{R_1 A} + \frac{c_1}{A} + c_f + \frac{c_f}{A} \right) + \frac{1}{AR_1}} = \\ &= \frac{-R_1 A \bar{i}}{(1 + pT_a)(1 + pT_b)}\end{aligned}\quad (1)$$

assuming all initial conditions are zero.

For a step function of input current $\bar{i} = \frac{i_o}{p}$ and hence

$$V_o = -R_1 A i_o \left[1 + \frac{1}{T_a - T_b} (T_a e^{-\frac{t}{T_a}} - T_b e^{-\frac{t}{T_b}}) \right] \quad (2)$$

If $R_1 \rightarrow \infty$, as one would hope:

$$\bar{V}_o = \frac{-\bar{i}}{\left[c_f \left(\frac{1+A}{A} \right) + \frac{c_1}{A} \right] \left[p \frac{T_2 (c_1 + c_f)}{c_f (1+A) + c_1} + 1 \right] p} \quad (3)$$

and for $\bar{i} = \frac{i_o}{p}$

$$V_o = \frac{-i_o T_c}{c_f \left(\frac{1+A}{A} \right) + \frac{c_1}{A}} \left[e^{-\frac{t}{T_c}} + \frac{t}{T_c} - 1 \right] \quad (4)$$

$$\text{where } T_c = T_2 \frac{c_1 + c_f}{c_f(A+1) + c_1} \quad (5)$$

When the reference capacitor is discharged into the input of the integrator, a current $i = \frac{-V_R}{R_R} e^{-\frac{t}{T_r}}$ flows, as the input to the amplifier is a virtual ground. The Laplace transform is

$$\bar{i}_{\text{ref}} = \frac{-V_R c_R}{1 + pT_r} \quad T_r = R_R c_R \quad (6)$$

and hence, again assuming $R_1 \rightarrow \infty$

$$\bar{V}_o = \frac{V_R c_R}{\left[c_f \left(\frac{1+A}{A} \right) + \frac{c_1}{A} \right] [pT_c + 1] [pT_r + 1] p} \quad (7)$$

$$\text{Hence } V_o = \frac{V_R c_R}{\left[c_f \left(\frac{1+A}{A} \right) + \frac{c_1}{A} \right]} \cdot \left[1 + \frac{1}{T_c - T_r} (T_c e^{-\frac{t}{T_c}} - T_r e^{-\frac{t}{T_r}}) \right] \quad (8)$$

Accuracy Considerations

Accuracy is affected by the following, each of which will be considered in detail.

- 1) drift at the input to the amplifier
 - 2) variation of stray capacity and cable capacity at input to integrator
 - 3) variation of amplifier gain
 - 4) leakage resistance across input to integrator
 - 5) grid current of the amplifier input electrometer tube
 - 6) stability of the reference capacitors
 - 7) stability of the reference voltage
- 1) Drift at the input to the amplifier.

The equivalent circuit including amplifier drift is shown in Fig. 3.

$$\text{Again } \bar{V}_o = \frac{A\bar{v} [p R_1 (c_1 + c_f) + 1]}{p\{c_f(1 + A) + c_1\}R_1 + 1}$$

If the input drift voltage is considered a step function $\bar{v} = \frac{v}{p}$

$$V_o = Av \left[1 - \frac{c_f}{c_f \left(\frac{A+1}{A} \right) + \frac{c_1}{A}} e^{-\frac{t}{R_1 [c_1 + (1+A)c_f]}} \right]$$

In other words, a current flows through R_1 and is integrated.

$$\text{Now, if } R_1 \rightarrow \infty \quad \bar{V}_o \rightarrow \frac{\bar{v}(c_1 + c_f)}{c_f \left(\frac{A+1}{A} \right) + \frac{c_1}{A}}$$

That is, the drift voltage is not integrated, but causes a change in voltage at the output which is a time independent

function of the drift voltage. It could be minimized if c_1 was made small, but other practical considerations limit the lower value of c_1 .

Zero drift has one other direct effect on accuracy: the reference capacitor containing the known charge fed back to the input via RL1 discharges to the input voltage of the amplifier. If this is not zero there is an error of $\frac{v}{v_{\text{ref}}} \times 100\%$. The reference voltage is of the order of 10V and thus for 0.1% accuracy the input drift must be less than 10 mv. The state of the art for electrometer tubes is of the order of 1 mv/hr drift.

2) Variation of stray capacity and input cable capacity.

From equation (4) when the initial transient has died out.

$$v_o = \frac{-i_o \cdot (t - 1)}{c_f \left(\frac{1 + A}{A} \right) + \frac{c_1}{A}} \quad (9)$$

Hence the effect of the cable capacity is reduced by the gain of the amplifier. The smallest value of c_f used, on the 10^{-9} coulomb range, is 200 pf. The minimum gain of the amplifier system used is 20,000. Hence for 0.1% accuracy

$$\frac{\Delta c_1}{A} = 2 \times 10^{-13} \text{ F}$$

$$\therefore \Delta c_1 = 4000 \text{ pf.}$$

If the beam monitoring device plus cable is of larger capacity than say 5000 pf the readings on the lowest current

range would need correction.

3) Variation of amplifier gain.

By differentiation of equation (9) it can be shown that

$$\frac{dV}{V_o} = \frac{c_f + c_1}{c_f(1 + A) + c_1} \frac{dA}{A}$$

This expression has a maximum value when c_f is smallest, i.e. 200 pf for the 10^{-9} ampere range. If A is assumed to be 20,000, and $dA = 10,000$

$$\frac{dV}{V_o} = \frac{2 \times 10^{-10} + 10^{-8}}{2 \times 10^{-10}(2 \times 10^4) + 10^{-8}} \times .5 \times 100\% \approx .125\%$$

This is largely due to the effect of c_1 , which is shown to be 0.01 μ f to prevent excessive grid current being drawn by the electrometer tube on the lowest current ranges, when a positive charge is injected from the reference capacitor.

4) Leakage resistance across the input to the integrator.

As shown by equation (9), if there is a shunt resistance across the input, and an amplifier offset voltage exists, current will flow and be integrated. Hence the source impedance must be high, and leakage paths to ground reduced to a minimum. In practice it has been possible to achieve leakage currents of 5×10^{-14} amps. without great effort.

5) Grid current of amplifier input electrometer tube.

This should be of the order of 10^{-14} amps, or less if the electrometer is properly biased, and appears as a leakage current.

6) Stability of the reference and feedback capacitors.

The capacitors chosen for use have polystyrene dielectric, with dielectric absorption of less than 0.01%. There is no evidence as to change of capacitance with time; temperature coefficient of capacitance is 75 ppm/ $^{\circ}$ C. These are negligible errors.

The time allowed for discharge of the reference capacitor must be greater than $7R_{\text{ref}}C_{\text{ref}}$ in order that the reference capacitor will discharge to less than 0.1% of the reference charge.

7) Stability of the reference voltage.

The reference voltage is generated across a temperature compensated zener which, when biased at 7.5 ma, has a temperature coefficient of less than 0.01%/ $^{\circ}$ C. The current through the zener diode must be held within 0.1 ma, achieved by the use of a constant current source.

General Description of the Instrument

The integrator is constructed in two sections: the integrator proper and the control unit. A schematic of the integrator section is given in Fig. 5. When input current is

not being integrated RL6 is closed preventing charge accumulating on the input cable, and RL4 is open. RL1 is normally open, being closed momentarily for manual reset of the integrator to zero. RL3 is normally closed, causing the reference capacitor to be charged to a preset voltage; and RL2 is open. When the integrator "START" button is pushed RL6 opens, and RL4 closes. A ramp is generated at the output of the amplifier which at a preset level actuates the discriminator. This causes RL3 to be opened, and RL2 then closes, discharging the reference capacitor into the input of the integrator. After about 100 msecs. RL2 and RL3 revert to their original positions. This cycle then repeats until the STOP button is operated, and the number of times the discriminator fires is counted by a SODECO register. This number is proportional to the integral of the input current and an interpolation between counts is obtained by monitoring the voltage at the output of the amplifier on a meter, the full scale reading of which corresponds to the charge stored in the reference capacitor.

The integrator has five ranges, 10^{-5} , 10^{-6} , 10^{-7} , 10^{-8} , and 10^{-9} coulombs/count controlled by the range switch. This switch selects appropriate reference capacitors, reference voltages and feedback capacitors. Each range is calibrated, by adjusting the reference voltage, to indicate an integral number of coulombs $\times 10^{-n}$ per count. This simplifies use of the instrument.

The control chassis contains the discriminator and the control logic. The discriminator is a conventional circuit using a tunnel diode. The control logic is constructed from DEC modules such that if several integrators are used simultaneously one unit can be the master unit (locally or remotely controlled) and the remainder slaved to it. All inputs and outputs are standard DEC levels or pulses.

The integrator may be started, stopped or reset by pushing the appropriate button on the front panel, or operated remotely by means of the BNC connectors on the rear of the unit. Remote control inputs should be standard DEC +ve pulses of $0.4\mu\text{s}$ duration or positive edges of 3V amplitude and $0.2\mu\text{s}$ rise time into a 100 pf load. The start, stop and reset outputs give zero volts to assert the state and -3V to negate at 500Ω impedance. The integrator may be reset whether integrating or not, and after the reset cycle, will return to the state it was in.

The Sodeco register reads full scale of the interpolation meter: i.e. when the integrator is set for the 10^{-8} range 2 counts on the register implies 2×10^{-8} coulombs. A second register allows preset operation. A preset count is set in the register before operating the integrator, which is then counted down to zero. At this point integration is stopped. The preset feature can be disabled by a front panel switch.

Zeroing and Calibration

The range switch has two extra positions labelled "Zero" and "Balance". These positions facilitate adjustment of the integrator. When set to the "Balance" position the amplifier feedback loop is opened and the input shorted. The "Balance" potentiometer is then adjusted to zero the output of the amplifier as indicated on the interpolation meter. This adjustment is very sensitive due to the high open loop gain of the amplifier. The range switch is then set to "Zero", which position is identical to that of the 10^{-9} range except that a 100meg.Ω resistor is connected from the amplifier input to ground. Thus any offset voltage will cause integration, which is then reduced to zero by use of the "Zero" control.

If the resistors between the anodes of the electrometer tubes and the input to the P75 amplifier were matched, and the amplifier had infinite common mode rejection then these two controls would be orthogonal. In practice this is not so, but usually the "Balance" control should only need setting when the instrument is calibrated.

The integrators are calibrated using the equipment shown in Fig. 4. An adjustable reference voltage source is used to generate the required current into the integrator. The current is measured by setting S2 so that the current flows through the GR decade box, which is set to have a resistance $10^n \Omega$ such that with the current flowing 10 mv will be the resultant

voltage across it.

$$\text{i.e. } R = \frac{10^{-2}}{1} = 10^n \Omega$$

After the appropriate range resistor has been selected, the voltage source is adjusted to give 10 mv across the GR resistor as measured by the Medistor voltmeter. This method eliminates the requirement of accurate calibration of very high value resistors, which are notoriously unstable.

Accuracies, resolution, and temperature coefficient of the various instruments is listed in Table 1. After calibration of the Dymec amplifier for linearity, the input current should be known to 0.05%. There will be a slight current change when S2 is thrown to feed current into the integrator as the decade box is removed from the circuit. It should be remembered that the input impedance to the integrator is very small. If a 1000 V source is used, the change is of the order of +0.01%.

When 1×10^{-n} amperes is flowing into the integrator set to the appropriate range, the discriminator should fire exactly once per second. If an oscilloscope is triggered at exactly once per second by a crystal-controlled source, the drift of the discriminator pulse in terms of msec/sec is a measure of the accuracy of calibration of that range of the integrator in units of 0.1%. The resistor controlling the reference voltage for that particular range can then be adjusted for best

accuracy. The accuracy for opposite polarity input current is then checked.

Summary of Performance

Range: 10^{-5} - 10^{-9} amperes

Accuracy: Better than 0.3%, probably 0.1%

Temperature coefficient: less than .025%/°C, not accurately determined

Maximum input current: four times full scale reading, i.e.

4×10^{-8} amperes on the 10^{-8} range

Current Integrator Calibration and Test Procedure

- 1) Determine whether or not Start, Stop and Reset buttons are operating properly.
- 2) Short circuit the inputs to the P75A amplifier, (pins 2 and 3) and adjust the P75A offset potentiometer. Remove the short circuit.
- 3) Reset the integrator with input open (on any range) and adjust the Balance and Zero pots. until the interpolation meter reads zero.
- 4) Place range switch on BAL and set the Balance control at the point where the interpolation meter switches from one polarity to the other.
- 5) Set range switch on Zero and adjust Zero control until interpolation meter remains stationary.
- 6) Set range switch to 10^{-9} and let integrator stand for about ten minutes. If leakage is greater than 5×10^{14} amperes check for source. Common sources of leakage are dirt and leaky 2.0Mf or 0.2 μ f feedback capacitors.
- 7) Set up test equipment as shown in Fig. 4. Any oscilloscope having a delayed timebase facility is suitable.
- 8) Set range switch to 10^{-5} . Set the calibrator to 10^8 and the GR decade box to 1K Ω . Check zero of Dymec amplifier. Vary the voltage of the EDC supply about 1000V so that the Medistor reads 10.000mv.

- 9) Switch S2 to INTEGRATE. The integrator should now be counting at a rate of exactly once per second if correctly calibrated and the discriminator pulse displayed on the scope should be stationary. If this is not so, adjust the 10^{-5} range reference calibrating potentiometer until the discriminator pulse is stationary, or drifts less than 25 milliseconds in 25 seconds.
- 10) Note reference voltage.
- 11) Reverse polarity of input current and polarity switch on integrator. Reset the EDC supply voltage to get 10mv across the GR decade box if necessary.
- 12) Check calibration. It should be within 0.1%. Note reference voltage.
- 13) Repeat (9), (10), (11), and (12) for all ranges using suitable calibrator resistors.
- 14) Check to see whether or not RL7 operates when the START button is pushed, and releases when the STOP button is pushed.
- 15) Determine whether STOP, START and RESET inputs can be driven be standard DEC levels or pulses
- 18) Check START, STOP and RESET outputs for proper levels (0V true, -3V false).

NOTE: A standard calibration sheet should be completed for each instrument whenever it is calibrated. These are filed in the Instrument Lab.

INTEGRATOR CALIBRATION SHEET

Integ. Range	Hi Meg Resistor	G. R. Standard Resistor	Medistor Standard Voltage	d/t x 100 = 0/0 Error	Dial Settings of VS 1000N	Reference Voltage (V)
-----------------	-----------------------	-------------------------------	---------------------------------	--------------------------	---------------------------------	-----------------------------

+	10^8	1K	B.			
			A.			
-	10^8	1K	B.			
			A.			
+	10^9	10K	B.			
			A.			
-	10^9	10K	B.			
			A.			
+	10^{10}	100K	B.			
			A.			
-	10^{10}	100K	B.			
			A.			
+	10^{11}	1M	B.			
			A.			
-	10^{11}	1M	B.			
			A.			
+	10^{12}	10M	B.			
			A.			
-	10^{12}	10M	B.			
			A.			

Leakage Test

A=Coul./Sec.= _____

Integrator No. _____

Calibration Check _____

Final Calibration _____ Date Cal. _____

FIG 1

Notes:

- R_1 = Source Impedance in Parallel with Leakage Impedances to Ground
- C_1 = Sum of Cable Capacity, Source Capacity and Permanently Connected Capacity from Summing Junction to Ground
- R_2 C_2 = To the Major Lag in the Amplifier, in the Plate Circuit of the Input Electrometer Tube
- C_f = Miller Feedback Capacitor

FIG 2

Symbols have same meaning as Fig. 2. V is the voltage drift at the input of the amplifier.

FIG 3

FIG 4

Table 1

GR Decade Box Dymec Amplifier Medistor Voltmeter

Model Number	1432Y	2411A	A71-RB
Accuracy	$\pm .05\%$	$\pm .002\%$	.01% absolute
Resolution	1000	—	1 μ V useable
Temp. Coeffi.	± 20 ppm/ $^{\circ}$ C	$< .005\%/^{\circ}$ C	—
Drift	—	$< 1\mu$ V/week $< .5\mu$ V/ $^{\circ}$ C	—
Input impedance	—	$10^{10}\Omega$	$10^9\Omega$ at .01% off null.
Output impedance	—	$< 1.5\Omega$	—
Linearity	—	.001% of 10 V	—

B

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