A PRECISION CURRENT INTEGRATOR

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by

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RESUMO

Desenvolvemos um integrador digital de corrente de precisão, transistorizado, capaz de medir correntes desde 10^{-7} A a 2.10^{-5} A dentro de ± 0,2%.

Apresentamos também projetado com semicondutores e com diagramas eletrônicos completos, um medidor da corrente integrada e uma unidade de comando para instrumentação nuclear. A finalidade de todo o sistema é o comando de arranjos de contagem, prefixando-se a quantidade de carga fornecida pela corrente proveniente do feixe de um acelerador eletrostático ou de uma câmara de ionização acoplada a um reator nuclear.

ABSTRACT

A solid state digital precision current integrator was developed for measuring current as low as 10^{-7} A with a precision within ± 0,2%. The dynamic range is of 10^{-7} A to 2.10^{-5} A.

Associate semiconductors instruments, an integrator current meter and a command circuit for nuclear instrumentation, are described also with complete electronic diagram. The aim of the system as a whole is the command of counting arrangements, by preseting an amount of charge furnished by the current from the beam of an electrostatic accelerator or an ionization chamber coupled at a nuclear reactor.

RESUMÉ

On a dévélopé un intégrateur digital de courant de précision transistorisé, pour mesurer des courants de 10^{-7} A jusqu'à 2.10^{-5} A, avec une précision de ± 0,2%.

Des instruments à semiconducteurs associés, un mesureur de courant intégré et un circuit de commande pour l'instrumentation nucléaire sont exposés avec des schémas électroniques complets. Le but de tout le système est la commande des arrangements de comptage, en préfixant la quantité de charge donnée par le courant qui vient du faisceau d'un accelérateur electrostatique ou d'une chambre d'ionization localizé dans un réacteur nucléair.

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Introduction:

The current integrator problem has been the subject of many papers from several authors. This instrument is of fundamental importance in measurements made with reactors and accelerators because it is used to determine the incident flux. In the accelerators the beam current is the integrated variable, while in reactors it is the neutron flux level, converted to current by ionization chambers.

There are many types of integrators according to the applications. Some are used with direct currents from a few nA to hundreds of μA and others with current bursts varying in wide ranges. But in every case the precision is the most important characteristic which is needed in an increasingly higher degree.

Among the existing schemes the most commom is based on the use of a precision capacitor and a high gain high impedance DC amplifier. Using these components two basic configurations are possible:

1) The amplifier input is connected to the current collector and the capacitor between this point and ground. The volt-

age change due to the accumulated charge is measured by means of the DC amplifier with negative voltage feedback.

2) The amplifier input is connected to the current collector and the capacitor between this point and the output of the amplifier. This is the well known Miller integrator.

In both cases the output signal is of low impedance and proportional to the capacitor charge. It can be read on a meter and used to trigger other circuits.

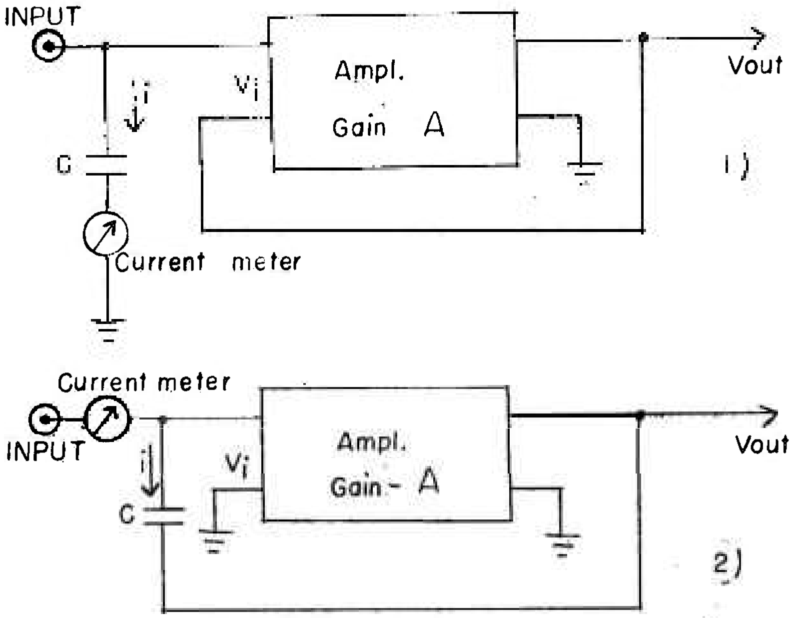

Fig. 1 - Integrator Configurations

The current being integrated must be monitored with a current indicator to follow the operation of the machine.

In this respect the first scheme has the advantage that a low impedance meter can be inserted in the ground branch of the condenser, whereas in the second it must be in series with the integrator input, which requires high insulation. In the first case the input voltage is the voltage developed on the capacitor itself which can be as high as one hundred volts or more. Thus extreme care is required in the insulation of the current collector and in the connecting cable, and there is also the inconvenience of a changing voltage on the collector electrode. In the second type due to the negative feedback the input voltage is very small minimizing the above effects. There are three ways of using and integrator:

1) For the measurement of accumulated charge, when the integrator and the counting system are connected and disconnectet simultaneously, during an arbitrary time interval.

2) For the measurement of the total charge accumulated in an experiment with the integrator and the counting system connected all the time. In this case the current must be zero at the beginning and at the end of the experiment.

3) The integrator initiates the counting cycle and terminates it when a preselected accumulated charge is reached.

The second method is used when the current is generated in sharp bursts as in some types of accelerators. The third is the most convenient in general, since it normalizes the yield with no need of reading the integrator.

When the maximum charge is reached the integration can be repeated discharging the capacitor, as many times as needed. This recycling is convenient since one can integrate larger charges with the same capacitor; it can be done automatically and many schemes to do this have been proposed in the literature. (1-5)

OPERATION:

This method of repeating the integration many times, which we can call quantization is used in this instrument. The number of cycles is counted with a binary counter with preselected count. The integrator circuit is of the Miller type and a second precision capacitor C1 switched by a sensitive relay R1 discharges the integrator capacitor C2 at each cycle, in this way quantizing the charge. This principle of quantization is similar to the one presented by Lewis and Collinge. (1)

The integrator circuit (see block diagram fig. 2 and fig. 4) is formed by the electrometer tube CK 5886, the four transistors T1 to T4 and the feedback capacitor C2. It receives the current and furnishes at the output a voltage proportional to the integrated charge, keeping the input at essentially zero potencial because of the negative feedback.

The output changes from -1.5 V to -11 V and the input changes by about 6 mV since the amplifier a gain of about 2000.

The output signal is fed to a Schmitt trigger T5, T6; this circuit triggers when the signal reaches -1.5 V triggering in turn a monovibrator T8, T9 which activates the relay

R1. This relay in the normal condition connects one side of the quantizing capacitor C1 to the reference voltage of -85 V through a 10 KΩ resistor. The other side is kept fixed near zero volts by the diode D1.

When R1 is activated the capacitor C1 is switched from -85 V to integrator input during a time interval of about 15 ms. During this time it removes from the integrator a charge $Q = 15 \times 10^{-9} F \times 85 V \approx 1 \mu C$ since the capacitor voltage changes from -85 V to nearly zero which is the input potential. In this way the output voltage rises from -1.5 to -11 V, from where it starts dropping again while the integration proceeds until -1.5 V is again reached, and the cycle is repeated.

The discharge of C1 is done at almost constant current of obout 1 mA, through the 200 KΩ resistor connected to the -150 V. The diode D1 opens due to the positive transient at its cathode when the relay switches (see waveform on the block diagram). When this discharge of the condenser is complete the diode starts conducting again and the potential at this side of the capacitor quickly returns to its previous potential.

This arrangement has the advantage of wasting much less time ($<$ 2ms) than the simple RC circuit because the discharging current must be limited to avoid overloading the amplifier.

The count and stop comands are generated by two different flip-flops: T10, T11 which is called Count F.F. and T12, T13 called Stop F.F.. The Count F.F. controls the data accumulation of the experiment by means of external gates or relays

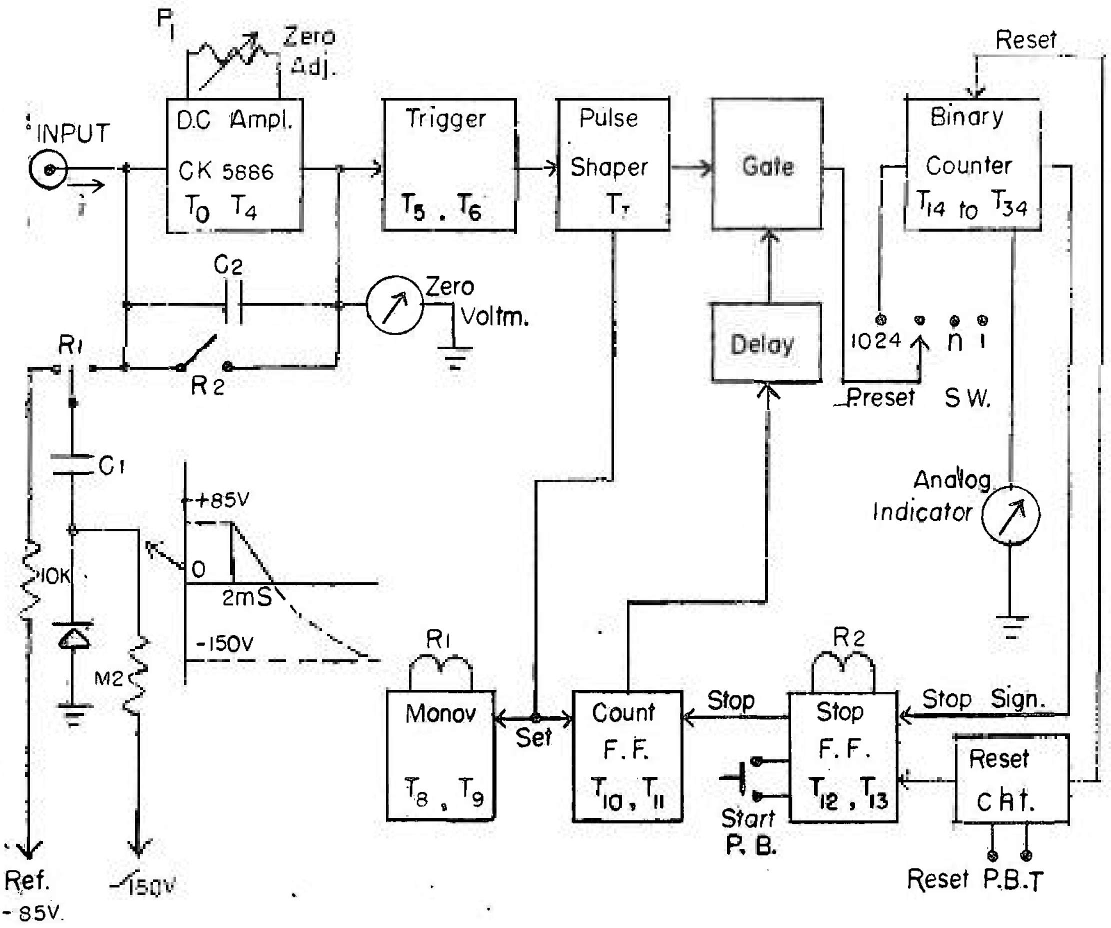

Fig. 2 - Current Integrator Block Diagram

through T14. Thus it controls the start and the stop of the counting. The Stop F.F. controls relay R2 which opens and closes the integrator.

Before starting, the integrator is blocked by relay R2 which short-circuits the output with the input, keeping the output near 0V. This potential can be read with the null galvanometer and adjusted by means of the zero adj. Potenciometer P1. In this situation the trigger is in the normal condition since there is still 1.5 V to go from 0 V to -1.5 V. The input current is by-passed from the capacitor C2 by R2, while the counting system controlled by the Count F.F. is off.

When starting, the relay R2 controlled by the Stop F.F. opens, allowing C2 to accumulate charge and the output potential starts lowering to -1.5 V at which point the trigger fires. Only this first firing actuates the Count F.F. turning on the external instrumentation, and simultaneously activating the Relay R1 by the monovibrator. From this moment on the integration itself proceeds, the following triggers being counted in the binary counter.

Since the counting system opens only at the first trigger any drift affecting the triggering level is automatically compensated, except for the drift occuring between the first and last trigger of the run.

The first trigger must not be counted in the binary counter to have the proper number of cicles, so there is a gate in the path of the trigger pulse to the counter that opens when the Count F.F. opens. This gate is delayed so that the first trigger does not pass.

In order to force the first triggering to occur within a reasonable time when the input current is very small, the diode OA202 injects a currente of 0.1 μA at the input of the integrator.

At the first triggering the Count F.F. turns off this current by removing the forward voltage. It is a selected silicon diode for a reverse current of less than 10^{-10}A at

50 mV reverse and is kept shielded from light. To minimize the residual current its bias when off is adjusted to be less than ± 10 mV by the potentiometer P3, and care must be taken in not allowing the input voltage adjusted by the potentiometer P1 to go beyond ± 10 mV.

BINARY COUNTER:

The binary counter has 10 stages T15, T16 to T33 , T34. It counts the number of cycles and gives a Stop signal when the preselected number is reached. The Stop signal is taken from the last stage and the preselected number is set in the Preset switch by routing the trigger pulse to the appropriate stage. The stop signal is a positive pulse that appears when the last stage flips from state 1 to state 0 and actuates the Stop F.F.. This in turn resets the Count F.F. at the same time closing relay R2, terminating the integration.

When one wants to stop the integration for some time and proceed without loosing the previous information the Hold-Normal switch is used. When it is in the Hold position a circuit is set up that directs the next trigger pulse to the Stop F.F. having the same effect as the Stop Siganl. Thus the integration is interrupted as soon as the first cycle is completed. Throwing the switch to the Normal position generates a Start pulse initiating the integration which then continues until the preselected number of cycles is reached.

A Reset push-button resets all the binaries to the zero condition and also the Stop F.F. to the Stop condition . This push-button can also be used to stop the integrator, but destructively.

For the visual indication of the integration process a meter is used which gives an indication proportional to the number of cycles stored in the last five stages of the counter. This binary analog conversion is done by summing five currents from the five binaries whose values are proportional to 1,2,4,8, and 16 respectively, starting from the last. Each binary generates the current when in the state one, and by combining these five currents 32 steps of deflection can be generated.

The null galvanometer, with a series resistor reads the output voltage of the integrator during integration, and can be used to interpolate when for some reason the charge does not reach the preselected value.

Error Evaluation:

Let us consider the possible causes of error in this system.

In the first place the standard charge that is withdrawn from the integrator after each trigger pulse is the product of C1 by the potential change between its terminals during the time the relay R1 makes contact with the integrator input. The potential of C1 in the side of the diode changes during the discharge but returns exactly to the same level before the relay contact breaks. The potential on the other side changes from -85 V to the input potential. The input potential changes approximatelly 6 mV from the beginning to the end of the discharge, since the amplifier gain is about 2000. ($6\text{mV} = \frac{12\text{ V}}{2000}$). If for instance the gain decrease 30% there will be a change of about 3 mV in this signal.

Before operating the input potential is normalized through the zero Adj. potentiometer and the null galvanometer.

A drift of about 5 mV in this potential is expected during the run due to bias changes in the electrometer tube.

The changes that can be expected from these effects amount to 8 mV which corresponds to $\frac{8\text{ mV}}{85\text{ V}} = 0{,}01\%$. Except for this error the precision of the standard charge will depend on the reference voltage and on the stability of the precision capacitor. The reference is given by a 85A2 tube which has a stability better than 0,1%.

In the second place let us consider the trigger. The triggering levels may change but only the change between the first and the last trigger contributes to the error. If the circuit returns to the same initial conditions, and no charge were lost by leakage the charge that passed through the system is exactly what was withdrawn, that is nq, n being the number of cycles and q the standard charge. When there is a change in trigger level between the first and the last trigger, caused by temperature changes or amplifier noise there will be an error equal to the difference in level multiplied by the capacitance C2 of the integrator. An exagerated change of 10 mV gives an error of $\frac{10\text{ mV}}{12\text{ V}} = 0{,}1\%$ of one standard change. This error does not depend on the number of cycles so the relative error reduces with large integrated charges.

The "soakage" effect in the dieletric when a polystyrene capacitor is used is very low. In C1 its contribution is negligible because this capacitor is connected to the input for constant time (15 mS). In C2 this effect causes a small loss of charge, which is independent of the number of cycles, reducing the error with increasing number of cycles.

Another possible source of error is the delays in actuation of the relays. The relay R1 cannot contribute to the error because only the number of quanta of charges withdrawn between the first and last triggers is important and not the exact timing of the discharges. The relays R2 and R3 also do not contribute, because they open before the first trigger and close after the last.

In case an external relay is used to control the counting system, there will be delays which generate error. Let us suppose that there is an initial current i_1 and a final current i_2. In the beginning of the integration there will be a charge $q_1 = i_1 \times T_1$ integrated before starting the counting and at the end a charge $q_2 = i_2 T_2$ lost before stopping the counting. The error will be the difference $q_1 - q_2 = i_1 T_1 - i_2 T_2$. Suppose that $T_1 = T_2 = 10$ ms and $i_1 - i_2 = 1\,\mu$A there will be an error of $q_1 - q_2 = 1 \times 10^{-6}$ A x 10 x 10^{-3}s = 10^{-8}C which for one cycle of integration amounts to 1%.

This result demonstrates the need for electronic gates for controlling the counting in high precision work, because of their negligible delays. This problem is discussed further in another section.

Finally there is the problem of current leakage. Since we use an electrometer tube in the input, polistyrene capacitors and high insulation relays ($> 10^{12}\,\Omega$) the total leakage can be kept below 10^{-10}A, which corresponds to 0,1% for currents of 0,1μ A.

The low input voltage reduces the requirements of insulation in the charge collector, and in the current meter.

For a leakage of 10^{-10}A and 10 mV on the input we need an insulation of $\frac{10 \times 10^{-3}\,V}{10^{-10}} = 100\ M\,\Omega$.

POWER SUPPLY AND CONSTRUCTION: (Fig. 6)

The circuit requires power supply of -20 V, +20 V and -150 V regulated within ± 0.5%. The current is 20 mA for the -20 V and +20 V supplies. The -150 V furnishes 5 mA for the reference tube 85A2. The ripple should be kept low (< 1 mV). The circuit is mounted in a dust tight box and ditributed in three plug-in cards and the power supply. Because of the low consumption(5 mV) no ventilation is needed.

The highly insulated part of the input is mounted on a teflon plate supported on grounded terminals to guard it against leakage currents. The relay soquets are ceramic or preferably teflon and kept entirely free from dirt.

COMMANDS FOR THE EXTERNAL INSTRUMENTATION:

By means of T14 the Count F.F. controls a current of about 2 mA through a 10 K resistor that can be used to control the external instrumentation. This instrumentation may consist of several scalers, analizers etc, that must be switched on and off by this signal. This can be done by multi-contact relays or eletronic gates wired in a convenient form for each case. For these controls and its power supply a separate chassis is needed which can be conveniently adapted for every counting system used. An example of a transistorized command circuit is shown in fig. 7.

INTEGRATOR CHARACTERISTICS:

Current limits: 0,1 μA to 20 μA for 0,1% error.

Integrated charge: From 1 μC to 1024 μC in 10 range factors of two.

Charge polarity: Positive

Input drift: ± 5 mV/hour after a one hour warmup.

Leakage current: 10^{-10} A

Visual analog indication of the integration.

Front panel meter for cycle interpolation and a push-button for zero checking. The push-button increases sensitivity to 100 mV full scale.

Control Signal: 2 mA through a 10 KΩresistor connected to -20 V and clamped to ground by a control transistor (T14). The clamp is open when integrating.

The integrator was tested using a constant current generator. For currents from 0.1 to 3 μA the precision was within ± 0,2%.

INTEGRATOR CURRENT METER:

Normally it is necessary to have a meter to monitor the current in order to follow the operation of the machine. It maybe of low accuracy but preferably of fast response.

Frequently a D.C. current amplifier is used with negative feedback inserted in the current path.

The introduction of such a circuit has two important effects:

1) Leakage currents and ripple that come from the line through the power transformer may disturb the integrator. It is specially serious in the Miller integrator (2nd configuration) requiring high insolation and special shielding in the power transformer as well as precautions to avoid accidental leakage currents (knobs and external meters).

2) The input potential of the current amplifier is not zero and changes with time. In the case of the integration capacitor grounded (1st configuration) the meter circuit should be inserted in the ground branch of the capacitor. In this case the input potential will add or subtract from the capacitor voltage causing an error.

Because of these problems the following scheme was adopted; (see figs. 3 and 5):

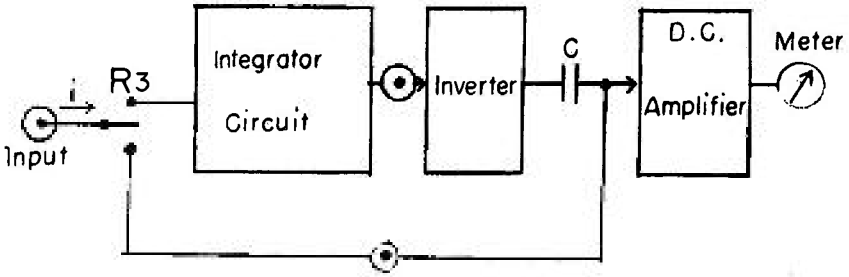

Fig. 3 - Current meter block diagram

At the integrator input a relay (R3) directs the current to the current meter circuit when it is not integrating , and switches it to the integrator input when integrating. In this case the output signal of the integrator amplifier is differentiated by a capacitor C exactly equal to the integrating capacitor C2 thus giving a current equal to the input current. The relay is comanded by the Stop F.F. of the integrator. Since a Miller type integrator is used an inverter is needed for the output signal in order to have the differentiated current with the same polarity of the input current.

This scheme has the imediate advantage of leaving the integrator input free of disturbances capable of affecting the precision . The relay is of course of high insulation. However this circuit has small qualitative inconveniences:

Every time a discharge takes place at the end of a cycle there is a strong negative current in the amplifier, which is of short duration. Using a low leakage silicon diode in the feedback loop and a storing capacitor the resulting meter jump is reduced to about 5% of the reading.

Also when the stop push button is pressed a transient is observed

The current amplifier has negative feedback and uses an electrometer tube associated to transistors in a similar arrangement to that used in the integrator. The linearity was found to be very good in all ranges.

The inverter and the DC amplifier were mounted on a separate chassis with the stabilized power supply. It has two inputs: the direct current and the integral signal from the integrator amplifier.

ACKNOWLEDGMENT

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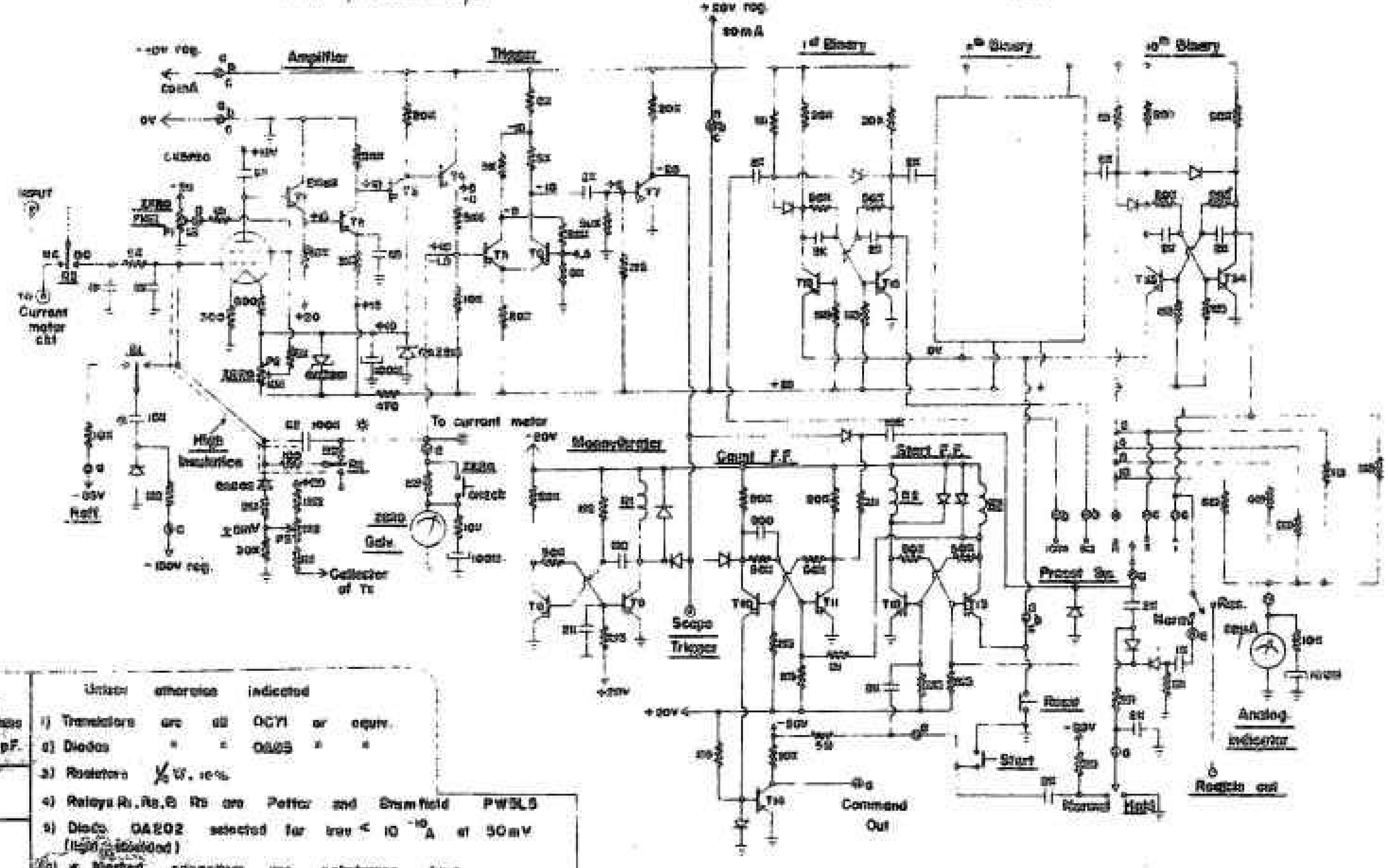
FIGURE CAPTIONS

Fig. 4 : Detailed diagram of current integrator
Fig. 5 : Current meter diagram
Fig. 6 : Power supply for current integrator
Fig. 7 : Command circuit diagram

Current : From 1 to 50μA
Capacity : 1μC x 1024 = 1024μC

PRECISION CURRENT INTEGRATOR

Raul [illegible] [illegible] 4, 1960



Conventions

Resistors in Ohms
Capacitors in pF.

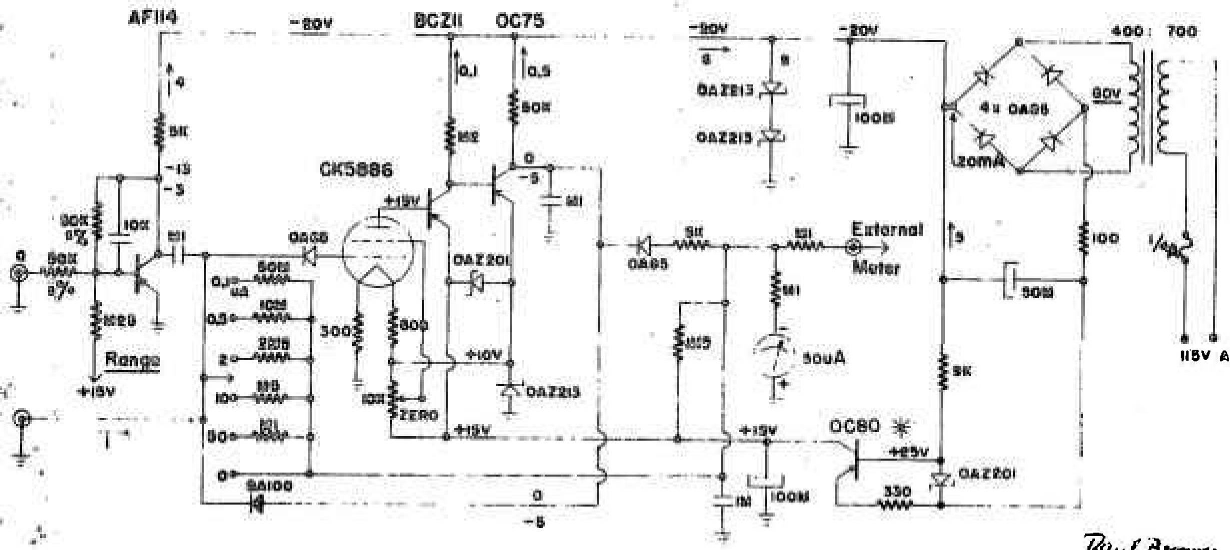
k = 10^3
M = 10^6

The letter replaces the decimal point

Unless otherwise indicated

1) Transistors are all OC71 or equiv.
2) Diodes " " OA85 " "
3) Resistors ¼ W, 10%.
4) Relays R1, R2, R3 R5 are Pettor and Bromfield PW5L5
5) Diode OA202 selected for Irev < 10^{-10}A at 50mV (high insulation)
6) * Marked capacitors are polystyrene type all other ceramic or paper.

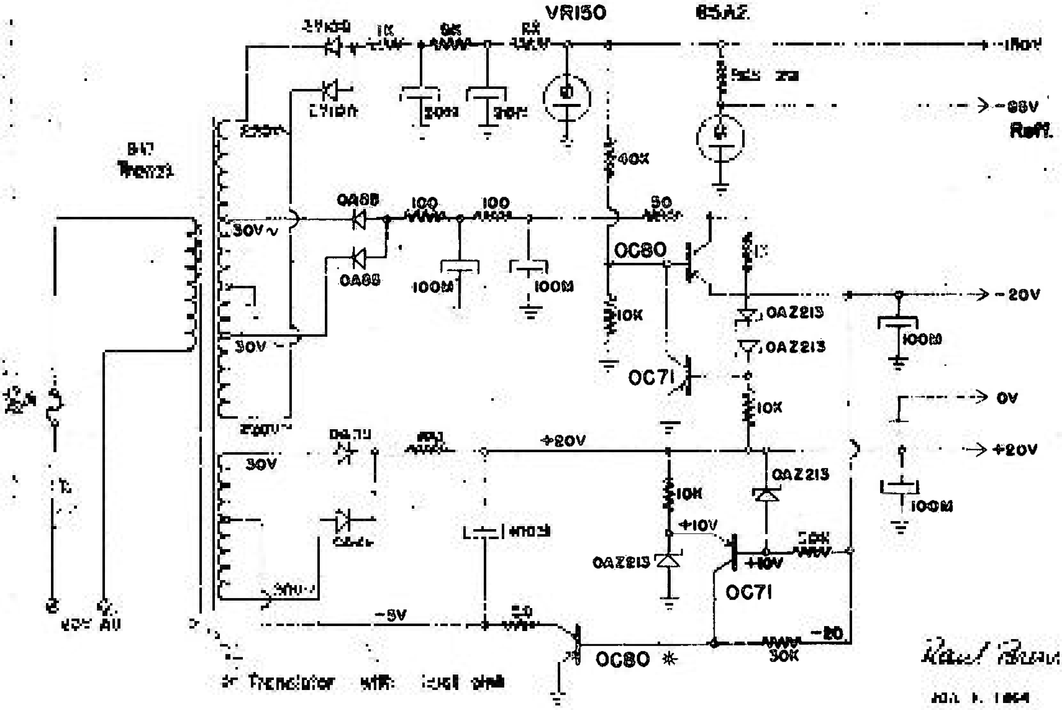
Fig. 4



✳ Transistor with heat sink

Raul Bramer
jan. 7. 1964

Fig. 5



✳ Transistor with heat sink

Raul Bramer
jan. 7. 1964

Fig. 6

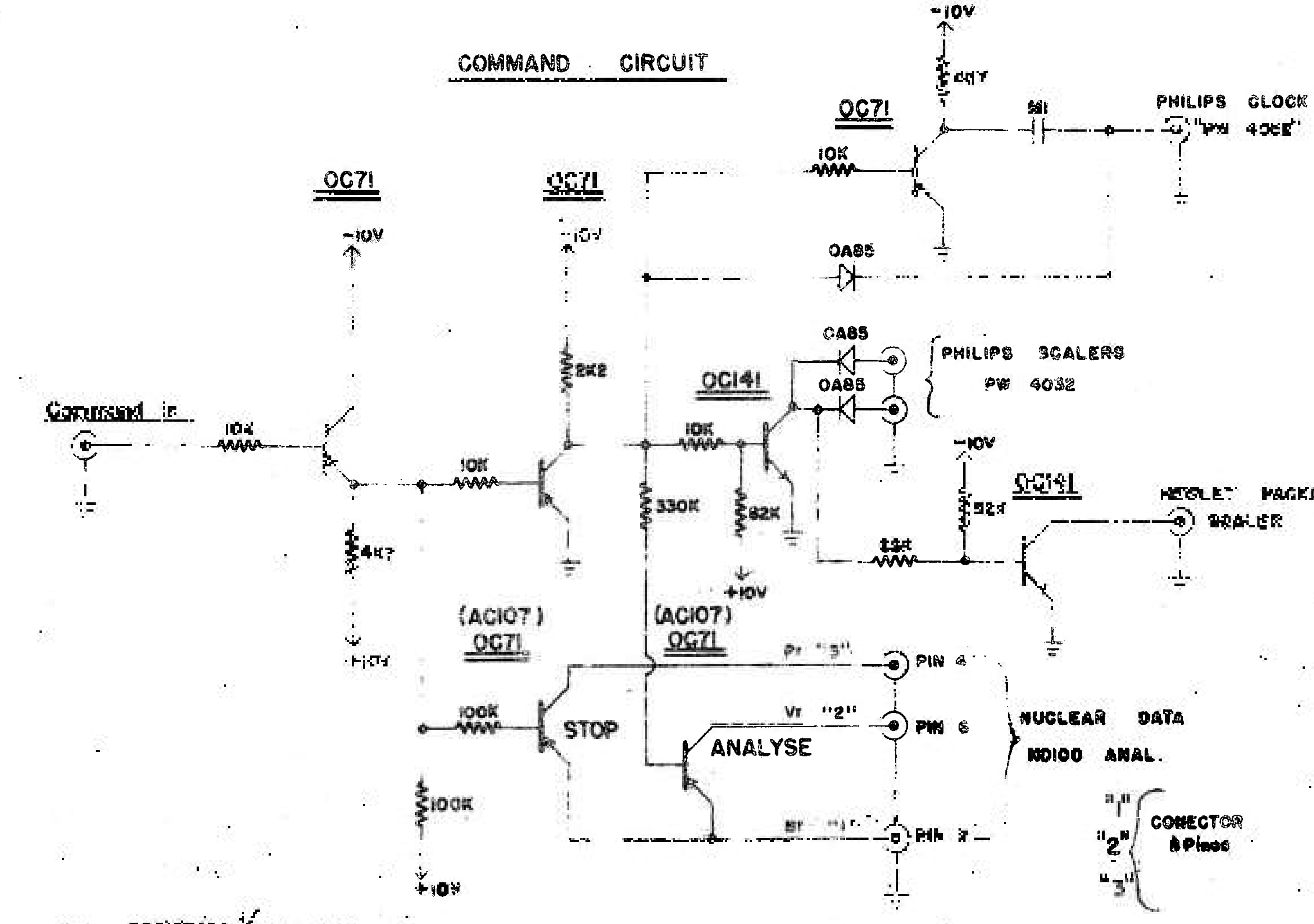

COMMAND CIRCUIT
OC71
OC71
OC71
OC141
OC141
(AC107) OC71
(AC107) OC71
Command in
10K
10K
10K
10K
100K
100K
4K7
2K2
330K
82K
4K7
82K
22K
M1
OA85
OA85
OA85
-10V
-10V
-10V
-10V
+10V
+10V
+10V
STOP
ANALYSE
PHILIPS CLOCK "PW 4062"
PHILIPS SCALERS PW 4032
HEWLETT PACKARD SCALER
Pr "3"
Vr "2"
Br "1"
PIN 4
PIN 6
PIN 7
NUCLEAR DATA ND100 ANAL.
"1"
"2"
"3"
CONECTOR 8 Pines
ALL RESISTORS 1/4W 10%

Fig. 7