Method for the Measurement of Small Direct Currents

By E. J. HARRIS, Ph.D.*

ECENTLY a direct current amplifier has been described[1] which employs a commutator to ert the direct current into an mating current to permit of amplition by A.C. coupled circuits. It y be of interest to describe an mative system which was used in many to amplify the output from mo-couples and low resistance to-voltaic cells. It makes use of fact that potential energy can be ed up in an inductance over a iod of time, and then used to set a ring, or damped oscillation, in ned circuit. The initial amplitude the ring may be many times the F. applied to the primary coil use the ring can be set up in a ndary coil of high inductance. direct current is fed via an interter through the primary coil, and successive rings which appear ss the secondary can be amplified n A.C. amplifier. Fig. 1 shows the eforms of the primary current and secondary E.M.F. It is convenient actuate the interrupter from the ns, in which case the interruption s place at 50 c/s., and most gns of interrupter give approxiely equal "on" and "off" iods. The natural frequency of secondary circuit is made about c/s.

fter amplification the output can rectified, but the direct current ined in this way is not a linear tion of the input current. A er method is to take some easily surable E.M.F. and divide it down known ratio and finally feed it

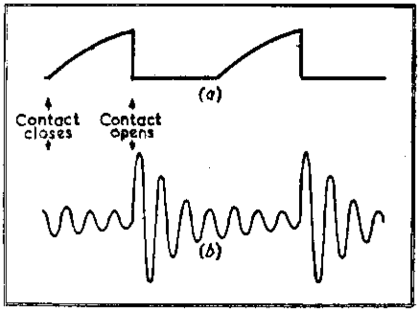

Fig. 1. (a) Primary current (b) secondary e.m.f. The 'ring' when the contact closes is due to contact e.m.f. and the residual energy in the circuit. Only the ring set up when the contact opens is of significance.

back into the input of the apparatus in opposition to the unknown E.M.F. The instrument is then used as a null indicator and the known current is adjusted until the ring waveform is a minimum. It has proved very convenient for making spectroscopic measurements in conjunction with a thermo-couple.

The signal to noise ratio attainable depends on the band-width of the amplifier following the input circuit. The German amplifiers had a pass band of several kilocycles, but it is considerably better to work with a band width of a few hundred cycles centred on the frequency of maximum intensity of the spectrum of the repeated ring waveform. Fig. 2 shows the form of the spectral distribution, and it appears that the best frequency band is centred at 0.8-0.9 of the natural ring frequency. There is nothing to be gained by reducing the band width below a few hundred cycles because the closing of the contact sets up some spurious ring, and this would interfere with the ring from the unknown current if the time constant of the amplifier were made greater than, say, 0.005 second. The sensitivity of the German instruments for signal equal to noise was found to be 0.1 microvolt from a 10 ohm source, but the noise did not originate in the source, as was found by shorting the input.

The design of the German apparatus was not complete, and the models which were brought to this country had a number of defects. It is therefore only possible to give an outline of the considerations which lead to best performance.

Fig. 3 shows schematically the input circuit. It consists of the "transformer" T, a resistance network to provide a small, calculable E.M.F. in the primary circuit to balance against the unknown, and the interrupter. The German transformers were wound on ordinary laminations, and had a turns ratio of 1 : 250 when operating from a 20-ohm source. The primary resistance was 42 ohms, and the Q of the secondary was about 0.5. These transformers were very prone to magnetic pick-up and it was found that improved performance was obtained by the use of toroidal coils wound on mu-metal strip cores. In this way the magnetic circuit was made more nearly perfect, and in addition the Q of the secondary was increased to 5. The amplitude ($\hat{V}$) of the first half-cycle of the ring is related to the circuit constants and the applied E.M.F. E, by the equation :

$$\hat{V} = E\sqrt{\frac{TR}{C}} \cdot \frac{1}{R+R_1} \cdot \left(1 - \varepsilon^{-\frac{T_1}{T}\left(1+\frac{R_1}{R}\right)}\right)\varepsilon^{-\frac{R\tau}{L}}$$

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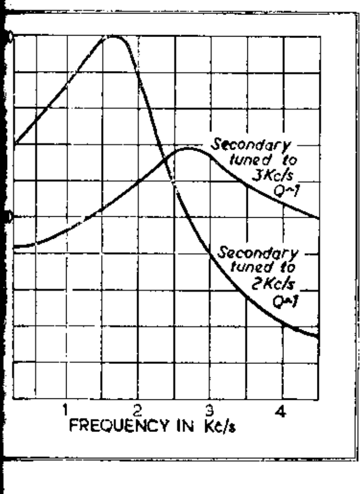
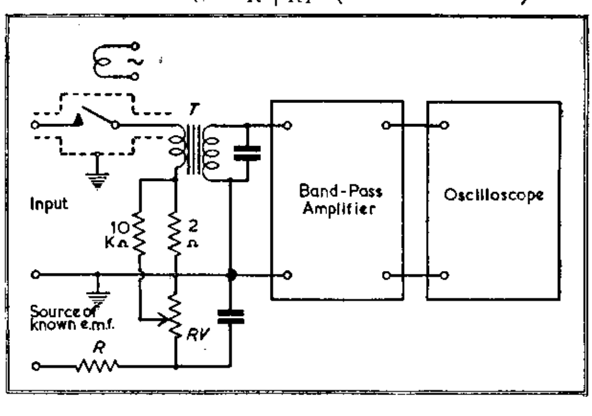


Fig. 2. Spectral distribution of energy equivalent to the repeated 'ring' wave form of Fig. 1 (b). Recurrance 50c/s.

Fig. 3. (right) Input circuit.



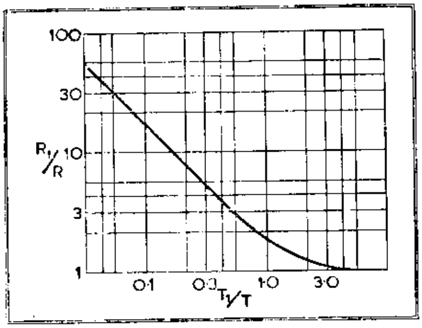


Fig. 4. Relation between $\frac{R_1}{R}$ and $\frac{T_1}{T}$ for optimum performance.

in which R_1 is the source resistance, R the primary resistance, C is the effective capacity across the primary, L the primary inductance, τ is the time between the contact opening, and $\hat{V}$ reaching its maximum, T_1 is the time during which the contact remains closed (usually 0.01 sec.) and $T = L/R$. Fig. 4 shows a plot of R_1/R against T_1/T for optimum $\hat{V}$. For example, with L equal to 0.1 H, R equal to 10 ohms, and T 0.01 sec., the constants suit a source resistance of 20 ohms. The amplitude of $\hat{V}$ is only reduced by 10 per cent. if R is twice or a half of the optimal value. The turns ratio should be the highest attainable consistent with the secondary becoming self-resonant at the ring frequency. Thorough magnetic screening of the input coil is essential. A double mu-metal box was used, and the inter-space was filled with pitch in order to preclude mechanical vibration.

A diagram of the interrupter is shown in Fig. 5. The soft iron armature (A) is supported on a phosphor bronze spring (S) between the poles of an alternating current electromagnet. The armature is polarised by a direct current field applied by the centre pole, and consequently it vibrates at the same frequency as the alternating current. The magnetic fields are applied through a thin aluminium diaphragm in order to reduce pick-up in the input circuit. The contacts of the vibrator are best made of material with a low contact E.M.F. with respect to copper (gold-silver alloy) and soldering should be carried out with the bismuth-tin alloy recommended in the reference. The whole interrupter is screened magnetically. In order to reduce loops in the wiring, which pick up stray magnetic fields, the interrupter and transformer are best mounted one over the other.

If the output is to be used only for null indication it is easy to arrange part of a sinusoidal time base, derived from the mains through a phase-shifting network, so that the first few half-cycles of the ring are spread across the screen. This increases the ease of the balancing operation.

It is possible to use the output waveform to control an apparatus. The sign of the first half-cycle of the ring is determined by the direction in which the primary current flows. By making a switch circuit sensitive to the polarity of the ring it becomes possible to operate relays or a motor. Thyratrons provide the most convenient sign sensitive circuit (*see* Fig. 6), the waveform is applied via a split secondary transformer to their grids, and in correct phase relation to the 50 c/s. A.C. applied to the anodes. The common cathode resistor R_0 ensures that only one valve fires, the other being held off. Each operation of the interrupter in the input circuit leads to the triggering of one of the two thyratrons. The anode loads R_1, R_2 are either relay coils for direct switching, or can be the coils of a reversible A.C. motor, in which case the direction of rotation depends on the sign of the off-balance at the input. If the motor is coupled to the potentiometer P a self-balancing system is obtained, which can be made recording by fitting a pen on the potentiometer shaft. The self-balancing principle can also be applied to a variable outside the apparatus itself. For example, if the input E.M.F. is produced by a thermocouple (Th) measuring an oven temperature the oven heating can be switched on or off according to the difference in E.M.F.s between Th and P. Additional to the function of ordinary thermostats, it is possible to make the reference E.M.F. from P vary in time by driving the potentiometer from a clock, so that the oven temperature can be controlled in time. This could be a valuable feature in a number of chemical and metallurgical processes.

[1] *Rev. Sci. Inst.*, 1946, 17, 194.

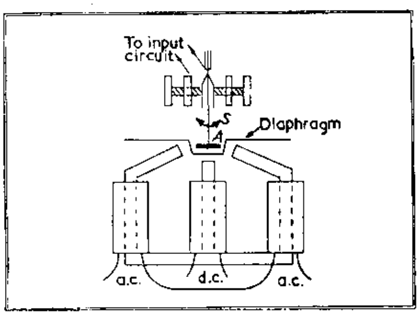


Fig. 5. (above) Diagram of Interrupter.

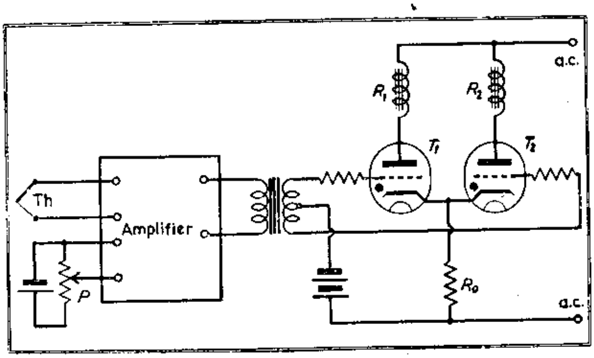


Fig. 6 (left). Arrangement to control oven by use of the off-balance between a thermocoupled (Th) and a motor driven source of reference potential (P).

Another Calculating Machine

In the isssue of December 1946 (p. 3 mention was made of the Autom Electric Computer now under construct at the N.P.L.

A report appears in Science Today* work started on a similar machine at Princeton Institute of Advanced Stu under the direction of Dr. J. von Neuman

The "memory" portion of the chine will be provided by special C tubes known as "Selectrons," each which will be able to store up more 4,000 binary digits. The beam p through a control mesh consisting of sets of parallel wires, 65 wires in direction, the potential of each wire separately controlled. The screen far side of the mesh is thus divided 4,096 squares, into which the beam only penetrate if each of the four of the mesh through which is pa suitably charged.

As successive pulses or "non-pu arrive for storage the control funct passed from one square of the m the next, and the electrons are to pass or held back according succession of pulses separated in thus recorded as a succession of on the screen separated in space.

The apparatus should be more than the A.C.E. machine, whic mercury tubes in its memory secti

* A weekly newsletter, published from 10 Hill, N.W.9. (No. 31, 15-5-47).