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1903 Proc. Phys. Soc. London 19 173

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XVIII. *On a Hot-Wire Ammeter for the Measurement of very small Alternating Currents.* By J. A. FLEMING, D.Sc., F.R.S., Professor of Electrical Engineering in University College, London*.

THERE are many occasions on which it becomes necessary to measure a small alternating current of the order of one-hundredth of an ampere.

In taking the magnetizing currents of small transformers of one kilowatt size or less for the determination of the power-factor on the high-tension side, say, at 2000 volts, the magnetizing current to be measured may be at most about 0.02 of an ampere, or less in proportion to the size of the transformer.

The capacity of a small condenser or short length of cable or wireless telegraph aerial can be measured by means of a simple harmonic electromotive force, if we have the means of measuring a small alternating current and a high voltage. For if a simple harmonic electromotive force of frequency $n=2\pi/p$, and R.M.S. value V , is applied to a condenser of capacity C microfarads, then the alternating current (R.M.S. value) flowing into it has a value of $CpV/10^6$ amperes, *provided there is no sensible resonance*.

If the frequency is about 80 so that $p=500$ and if $V=2000$ volts, then a capacity as small as $1/500$ of a microfarad can be measured in this manner, provided we have the means of measuring the voltage V and an alternating current of the above-named magnitude. This can of course be done by any form of electro-dynamometer adapted for measuring very small currents, but the hot-wire ammeter here described is much simpler to construct.

The following form of hot-wire ammeter can be so made as to measure currents as small as two milliamperes, and is easily calibrated at the time of using it.

The ammeter consists of a wooden box (A B, see fig. 1) 10.4 cms. in length, 8 cms. in height, and 6 cms. in width.

* Read March 25, 1904.

The top of this box opens on hinges, and in the centre is fixed an achromatic convex lens l having a focal length of 10 cms. The front of the box is cut down to form a window, W , which is glazed with a sheet of thin transparent mica (see fig. 1). In the box is fixed a square rod of well-seasoned pine, a metre

Fig. 1.

in length and 2.5 cms. in width and breadth. To each end of this rod are fixed two small brass uprights to which terminal screws are attached and also small spring pieces of brass, $p p$, which are pressed in by screws passing through the uprights (see figs. 1 and 2).

To these springs at each end of the rod are attached fine wires, either of pure silver or of some high resistance alloy, such as constantan, platinoid, &c., according to the use to which the instrument is to be placed.

In the instrument I have already constructed, these wires are of platinoid, the length of the wires being one metre and the diameter 0.05 of a millimetre. The distance apart of these wires is about 5 millimetres. The extremities of these wires are soldered to the two spring pieces at the ends of the wooden rod, and the tension of these wires can be adjusted by means of the screws passing through the small uprights and pressing against the spring pieces.

To the centre of the wooden rod carrying the above-mentioned fine wires are fastened two very delicate spiral springs, s , which have their other ends looped over the long straight wires. These spiral springs are made of extremely fine platinoid wire, and they serve to keep the ammeter wires tight (see fig. 2).

If one of the wires is heated by passing a current through it, it sags down slightly. This sag is indicated in the following manner:—The two wires are embraced by an exceedingly small loop of paper *m* made from a strip of paper a couple of millimetres in width and about 12 or 15 millimetres in length.

To this loop of paper is attached with a touch of shellac a fragment of silvered microscopic glass about a couple of millimetres in width and 5 millimetres in length.

Fig. 2.

The tension of one of the wires is so adjusted that when no current is passing through either of them one wire sags more than the other, and this little loop of paper and its attached mirror sets itself at an angle of about 45 degrees to the horizontal. This is attained by slightly relaxing the tension on one of the wires. Upon the lid of the containing box is carried an incandescent lamp, having a straight or horseshoe-shaped filament, and in front of the box is placed (see fig. 1) a vertical strip of ground glass *S*, carried in a brass grooved frame which can be adjusted to any height on a vertical metal rod. The height of the incandescent lamp is so adjusted that the lens forms a clear image of the filament or of one leg of the filament upon the ground glass in the form of a horizontal line of light. With a good lens this image can be made very sharp. The lens actually used was the objective of an old opera-glass. A hood of metal or asbestos placed over the lamp prevents the direct rays of the lamp falling on the ground-glass screen. The screen can be conveniently placed about a metre from the wire box.

If, then, a small current is passed through the slacker of the two measuring wires, its sag will increase and the small mirror attached to the two wires will be tilted, and

the image of the filament on the ground glass will move down, but return again to its original zero, as soon as the current is removed.

As a preliminary step, both the wires must be aged by sending intermittently a small current through them for a considerable time, this current being continually interrupted.

In the instrument actually made, the platinoid wires have a resistance of about 168 ohms each; hence, if an electromotive force of 2 volts is applied to the ends of the wires, a current of about $1/84$ of an ampere passes through them.

The instrument is calibrated in the following manner:—A secondary cell having a measured electromotive force, say, of about 2 volts, is connected in series with one of the working wires through a resistance-box of the usual plug pattern. By varying this resistance, different currents are passed through the wire and the position of the spot of light on the screen corresponding to the different currents is noted.

If the wire employed is of platinoid or of constantan, its resistance will not be altered appreciably by different small currents passed through it, and hence the resistance of the wire can be determined once for all, with a sufficient degree of approximation for practical purposes, by means of a potentiometer. When this has once been done, a few observations taken with a cell of known electromotive force and a plug resistance-box used as above, enable the observer to mark off on the ground-glass strip with a pencil the position of the line of light for various known currents lying within a certain range. The strip of ground glass may then be removed and applied to a sheet of squared paper, and a curve plotted down showing the deflexions in terms of the actual currents. This curve proves to be a parabola (see fig. 3) because, if we plot the logarithms of the deflexions and the logarithms of the currents, we have a straight line delineated, making an angle with the horizontal, the tangent of which is equal to 2. If, then, we replace the ground-glass screen in its original position and pass through the ammeter wire any current, continuous or alternating, lying within the range of the graduation, the resulting deflexion of the line of light on the screen can be at once marked off on the ground glass, and from the curve of calibration obtained

as above described the ampere value of this current becomes at once known.

In the instrument actually used the deflexion of the line of light on the scale placed at a distance of about 80 cms. from the mirror, produced by an application of two volts to the wire, is about 3 centimetres, and 4 volts produce about

Fig. 3.

12 centimetres deflexion: hence, current of about $1/100$ of an ampere or 10 milliamperes produces a deflexion which can be accurately read to within 2 or 3 per cent., and a current of as small as 5 milliamperes thus can be measured.

The particular class of wire with which the instrument should be strung depends on the uses to which it is to be put. If the object is to read a current of as small a value as possible, then the wire must be as fine as possible and made of a material of high specific resistance, such as constantan.

Messrs. Hartmann & Braun of Frankfurt have recently given attention to the production of very fine wires drawn from different pure metals and alloys, and they are able to furnish wires of pure metals and high-resistance alloys drawn down to diameters varying between 0.05 mm. and 0.02 mm. The resistance of a constantan wire of the latter size per metre is about 1350 ohms, whilst a wire of pure silver of the larger size has a resistance of only 8 ohms per metre.

The sag of the wire used in the above described instrument depends essentially upon its temperature, and its temperature depends upon the rate at which energy is being expended in it, per unit of its surface. Accordingly, for the measurement of the smallest currents the wires must be of high-resistance material and as small as possible in diameter, whilst for the measurement of small voltages the wire must be made of a material like silver with high conductivity.

The resistance R of the ammeter wire corresponding to different currents A through it can be determined as follows:—The ammeter wire is joined in series with a plug-resistance R_1 , and also with a constant resistance R_2 which may be either 20 or 40 ohms.

Fig. 4.

The ammeter wire is also shunted by a divided resistance R' (see fig. 4), and from a section of this resistance and from the terminals of the resistance R_2 wires are taken to a potentiometer. A battery of 100 volts is connected up, so as to send a small current through the ammeter wire, and this is

adjusted until the terminal potential-difference of the ends of the ammeter wire is either 2, 4, or 6 volts as required. Let this last potential-difference be called V , and the P.D. down the resistance R_2 be called V_2 . Also let the resistance of the ammeter wire under the working circumstances be R . Then V/R is the current through the ammeter wire and V/R' the current through the divided resistance, and the sum $V/R + V/R'$ is equal to V_2/R_2 which is measured. Hence R can be determined corresponding to various values of V/R .

In the case of the actual calibration of the hot-wire ammeter already made, the resistance R' was 497 ohms, and hence the resistance R was obtained from the equation

$$\frac{V}{R} + \frac{V}{497} = \frac{V_2}{R_2}.$$

The following table gives the observed values of V , V_2 , R_2 , and R_1 , and the calculated values of the wire-resistance R and current A for the two platinoid wires (1) and (2) in the instrument already made.

TABLE I.

	Wire (1).			Wire (2).		
V (in volts)	2	4	6	2	4	6
V_2 "	0.639	1.277	0.9575	0.634	1.2675	0.9500
R_2 (in ohms)	6372	3191	2070	6415	3212	2088
R_1 "	40	40	20	40	40	20
V_2/R_2 (in amperes) ..	0.0159	0.0319	0.0478	0.0158	0.0317	0.0475
A "	0.0119	0.0238	0.0357	0.0118	0.0236	0.0354
R (calc.) in ohms ...	168.3	167.8	167.8	169.8	169.1	169.3

Between the above limits of current 0.01 and 0.04 ampere the resistance of wire (1) may be taken as 168 ohms and that of wire (2) as 169.4 ohms.

As an instance of the use of this ammeter and also of the precautions necessary in using it, the following measurements of the capacity of leyden-jars taken with it may be given.

Two leyden-jars were employed which will be called respectively no. 1 and no. 2. A small alternating current transformer having a transformation ratio of 1 to 118 was employed to step up the voltage of an alternator having an electromotive force curve of nearly simple sine form.

The jar to be measured was connected across the high-tension terminals of the transformer, and the hot-wire ammeter inserted so as to measure the alternating current taken by the jar. The high and low tension voltages were measured by Kelvin electrostatic voltmeters. The capacity of the jar or jars was calculated from the condenser-current A , as read on the ammeter from the expression $A = CpV/106$, where V is the reading of the electrostatic voltmeter across the high-tension terminals of the transformer. The following Table II. gives the observations :—

TABLE II.

Condenser.	Terminal Voltages of Transformer.		Frequency used = n .	p = $2\pi n$.	Observed Condenser Current = A .	Calculated Capacity in Microfarads = C .
	L.T.	H.T.				
Jar no. 1 ...	97.5	13,750	73.7	463	0.0112	0.00176
	101.8	14,400	76.7	483	0.0121	0.00174
Jar no. 2 ...	97.0	13,650	73.7	463	0.0107	0.00169
	101.7	14,250	76.7	483	0.0110	0.00159
Jars nos. 1 & 2 in parallel.	97.0	15,300	73.7	462	0.0204	0.00287
	101.8	16,350	76.7	483	0.0226	0.00285

The capacities of the jars as measured by the rotating commutator described by the author and Mr. Clinton (see Proc. Phys. Soc. Lond. vol. xviii. p. 386, also Phil. Mag. May 1903, p. 493) were as follows:—Jar no. 1 = 0.00154 mfd., Jar no. 2 = 0.00124 mfd., Jars nos. 1 & 2 in parallel = 0.0028 mfd.

Hence it will be seen that the hot-wire ammeter gave a capacity in close approximation to that given by the commutator method for the joint capacity of the jars, but that there was an apparent increase of capacity when the jars were measured separately by the ammeter method. This is clearly due to resonance. The changes in the transformation ratio of the transformer due to the addition of the capacity are apparent from the figures in Table II. Hence, in using this method, the precaution must always be taken of having sufficiently large capacity in parallel with the one to be

measured to destroy resonance, but the current into the capacity, which it is desired to measure, is alone measured by the hot-wire anmmeter.

In connexion with this subject, I have had occasion to notice the manner in which even the small capacity of a Kelvin high-tension voltmeter will, in conjunction with the inductance of some transformers of high inductance, produce a marked alteration of the change ratio of transformation, by reason of resonance, when the transformer is used at various voltages. The small capacity of a high-tension electrostatic voltmeter across the high-tension terminals of a transformer, will, as shown by the figures in Table III. below, sensibly affect the change-ratio.

The transformer tested was worked at a frequency of about 80, and the voltage of the high-tension and low-tension terminals measured by electrostatic voltmeters over a certain range of voltage, no other load being on the high-tension side.

The change-ratio is far from constant, as shown by the figures in Table III., and this is clearly due to the resonance produced by the capacity of the high-tension voltmeter. Under such circumstances, when brush-discharges are taking place in the interior of the voltmeter it possesses a spurious and increased capacity, and hence, in using electrostatic voltmeters, a single reading should not be accepted too readily as giving the change-ratio of a transformer.

TABLE III.

Transformer Terminal Voltages measured by Kelvin Electrostatic Voltmeters.		Transformation Ratio. Frequency = 80.
H.T.	L.T.	
16,350	515	31·7 : 1
16,650	503	33·1 : 1
16,850	460	36·6 : 1
16,900	435	38·8 : 1
16,750	415	40·3 : 1
15,000	360	41·6 : 1
12,000	303	39·6 : 1

As an instance of the application of this hot-wire ammeter in measuring the magnetizing currents of small transformers, the following figures may be given :—A transformer of 1 K.W. size had the hot-wire ammeter above described placed in series with its primary circuit, and as a check and test of accuracy a known high resistance R of 3450 ohms was also put in series with the hot-wire ammeter, and a Kelvin electrostatic voltmeter was connected to the terminals of this high resistance. The following readings were then taken :—The voltage V at the primary terminals of the transformer, the voltage V' at the terminals of the high resistance R , and the deflexion of the hot-wire ammeter, were found to be as follows :—

$$R=3450 \text{ ohms, } V'=114.5 \text{ volts. } V=2000 \text{ volts.}$$

Hence the magnetizing current of the transformer was $114.5/3450=0.033$ ampere.

The hot-wire ammeter was calibrated as above described, and the reading of the magnetizing current taken with it was found to be 0.034 of an ampere. Hence the value of the same current as determined by the electrostatic voltmeter, and the high resistance by the ratio V/R and that determined by the hot-wire instrument were in very fair agreement.

The hot-wire ammeter has, however, the advantage over the high-resistance and electrostatic voltmeter method, that it is easier to calibrate and also involves a less drop in voltage, the more so as the current to be measured is smaller.

This form of hot-wire ammeter has many uses. It can be employed as a relay operated by small alternating currents to set in action appliances only workable with continuous currents. In this case the sagging wire is made to drop a steel needle on to a mercury surface and thus close the circuit required.

As a research instrument, it may be useful because it appears that the deflexion of the ray of light created by the sag of the wire within useful limits of working is almost exactly proportional to the square of the current passing through the wire, and hence standardization is effected by

passing one current of known value through the instrument, whilst if a suitable wire is employed, it can be calibrated with sufficient accuracy for most technical purposes by applying to the ends of the ammeter wire 2, 4, or 6 volts obtained from 1, 2, or 3 secondary cells, if need be a suitable resistance being interposed. For measuring alternating currents of a few milliamperes for electromedical purposes, it should also be useful.

When currents larger than a few milliamperes have to be measured, it can easily be accomplished by the same fine wire ammeter, by shunting the terminals with a resistance either equal to or one-half, one-third, or one- n th of that of the wire resistance. Thus, if the above described ammeter is shunted with 168 ohms, or with 84 ohms, or 42 ohms, then the ammeter readings have to be multiplied by 2, by 3, or by 5, to evaluate the whole current, and if shunted by a shunt of one- n th of its own resistance, then the readings have to be multiplied by $n + 1$.

The above described ammeter has been skilfully made for me by my assistant, Mr. A. Blok, who has also carried out for me the measurements described.

DISCUSSION.

Mr. W. DUDELL expressed his interest in the paper and said it was difficult to make a satisfactory instrument. The author had said that with a fine constantin wire it was possible to measure currents as small as 2 milliamperes. He asked if this was calculated or observed. There should be a standard method of comparing these instruments, and he suggested using the current necessary to give a deflexion equal to one-quarter of the scale-distance. Mr. Duddell pointed out that many dynamometers were more sensitive than the instrument shown, and asked the author the order of magnitude of the currents which it was necessary to measure in aerial conductors.

Dr. W. WATSON exhibited and described a form of ammeter for small alternating currents. The current to be measured flows through a piece of fine iron wire bent into

the form of a right angle. This is linked with a similar shaped piece of nickel wire forming part of a galvanometer circuit. The thermo-E.M.F. at the junction, produced by the heating effect of the current, sends a current through the galvanometer which can be measured in the usual way. The current to be measured is practically proportional to the deflexion of the galvanometer.

Mr. A. CAMPBELL described a form of ammeter by Rubens; and Mr. W. A. PRICE referred to an instrument similar to that shown by the author, in which the sag of the wire is measured by the movement of an aluminium pointer.

Dr. FLEMING said he was quite aware that electrodynamometers had been designed for measuring very small alternating currents, but they were more difficult to make and calibrate than the simple form of hot-wire instrument he now exhibited. He had no doubt that the use of a constantin wire of 0.02 mm. diameter would greatly increase the sensitiveness of the instrument, though he had not actually tried it for want of time. As regards Mr. Duddell's question about the magnitude of the currents flowing into a Wireless Telegraph aerial, that of course depended upon the size of the aerial. In the case of an ordinary 180 foot single aerial the average value was about 0.5 to 1 ampere, but that depended of course on the frequency of the groups of oscillations. The author said that although in the ammeter he exhibited the sag of the working wire was indicated by a mirror, yet he had also used an index-needle, and he had no doubt a good commercial instrument might be made on this plan.