High-tension Electrostatic Wattmeters

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XXIV. *High-tension Electrostatic Wattmeters.* By ERNEST WILSON.

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IT is well known that the quadrant electrometer can be used as a wattmeter on alternating-current circuits, and various methods have been devised for connecting it to the mains. The usual method is to impress upon the quadrants an E.M.F. proportional to the current in the main circuit, and to impress upon the needle either the voltage of the mains or a voltage proportional thereto. This is accomplished by passing the main's current through a non-inductive shunt and connecting the quadrants thereto, and using a potential transformer when the voltage of supply has to be subdivided. The drawback to this method is that usually about 1 volt is required across the shunt, and when very large currents have to be dealt with the energy dissipated becomes large. As an alternative, "series" or "current" transformers can be employed, in which case the drop between the terminals of the primary coil can be very much reduced; but when considerable accuracy is required, especially on low power factors, this method is not reliable.

The use of a quadrature transformer whose primary winding is in the main circuit has been successfully developed by Dr. W. E. Sumpner in connection with iron-cored instruments.* It has also been developed in connection with electrostatic wattmeters,† and a diagram of one set of the connections is given in Fig. 1. In this diagram Q is the electrometer, whose moving system is connected to the ends of a non-inductive resistance, R, which is in series with a condenser, K, across the supply mains. The quadrants of the electrometer are connected to the terminals of the secondary circuit of a quadrature transformer, QT.

The action of this instrument depends upon the equation

$$\frac{(2\pi f)^2}{T} \int_0^T V A dt = \frac{1}{T} \int_0^T \left(\frac{dV}{dt} \cdot \frac{dA}{dt} \right) dt, \dots \quad (1)$$

in which V is the voltage of the supply mains, A the amperes

* "Journal" Institution Electrical Engineers, 1908, Part 191, Vol. XLI. p. 227.

† British Patent Specifications 26,512, 1905, and 2,707, 1904.

FIG. 3.

FIG. 2.

FIG. 1.

in the work circuit, f the frequency of supply and T the periodic time.

In Fig. 2 the condenser is replaced by an inductive resistance L , and in this case the action depends up the equation

$$\frac{1}{T} \int_0^T V A dt = \frac{1}{T} \int_0^T \left(\int_0^t V dt \right) \frac{dA}{dt} dt, \quad (2)$$

in which the differential $\frac{dV}{dt}$ is replaced by the integral $\int_0^t V dt$.

The arrangement shown in Fig. 1 has the advantage that the condenser K can be designed to withstand very high voltages, but it is only strictly accurate on sine curves, and equation (1) shows that its action involves the frequency f squared. A number of experiments were made with varying wave-forms, and they show that it is fairly reliable with approximately sine curves. The arrangement shown in Fig. 2 has the disadvantage that it involves an inductive resistance, L , capable of withstanding very high voltages. Equation (2) shows that it is independent of variation in wave-form. Each of these types is, of course, afflicted with the error arising from the proportion of the total voltage V to the voltage across the non-inductive resistance R , which on very high voltage systems becomes very small.

Fig. 3 shows in diagrammatic form a high-tension wattmeter whose moving system is directly connected to, and experiences the full voltage of, supply.* The quadrants are connected to a small air-cored generator, G , which rotates in a magnetic field produced by and proportional to the current A in the work circuit. This generator is driven at known speed by a small motor, which can be either direct or alternating current. It was found that when the voltage V impressed upon the moving system is of the order 20,000 volts or more, the quadrants require a considerable voltage in order that accuracy and stability may be secured. In addition, the brushes of the generator have to be carefully adjusted so as to eliminate transformer action. The following are a few particulars of one form of generator which has yielded good results: The armature is of the two-pole type, and is wound with 100 sections, each having 50 turns and an area for magnetic flux of 130 square cms. The commutator has 100 parts. The field coil is built up of copper strip 2 in. deep by $\frac{1}{2}$ in. thick, and has

* British Patent Specifications 5,582, 1904, and 27,201, 1904.

four sections connected to blocks in such wise that they can be used in parallel or series or parallel-series groupings. The number of turns per section is 10. The speed of rotation is 3,600 revs. per min., and is registered by a Hartmann & Braun speed counter, capable of detecting a variation in speed of 0.3 per cent. The curve of voltage between the generator brushes was determined for various positions of a rotating contact-maker fixed to the shaft of the alternator and compared with the curve of current in the field coil. If the generator is to be reliable, these curves should be identical. The curve shown in Fig. 4 and the observation points thereon can

○ Denotes Volts. × Denotes Amperes. Frequency, 4. Speed of Generator, 3,000.]

FIG. 4.

be taken as an example of the agreement obtained. The agreement is as close as can be demonstrated by the method of test.

The generator verifies the theory underlying its action. In the case before us the armature rotates in a short solenoid having a length of $4\frac{3}{4}$ in.—i.e., there is a distance between the upper and lower sections of $\frac{3}{4}$ in. Under these conditions the armature which has a diameter of 4.5 in. rotates in a field which has not uniform strength, but is denser at the centre of the solenoid than near its ends. A field coil has been constructed having its conductors wound on the surface of a cylinder concentric with the armature, and fulfilling the condition that

the ampere-turns per unit length of an axis normal to the plane of the windings are constant. The field inside this winding is constant in strength and has the value $\frac{8\pi^2 a^2 n x}{3}$,* where the total turns are $2na$, n being the turns per unit length of the axis, and x the current. This theoretically perfect method of winding is difficult to accomplish when currents of 200 amperes have to be carried, as was the case in the generator first alluded to. It would appear that strip copper $\frac{1}{2}$ in. thick gives at ordinary frequencies an unobservable error due to eddy currents.

As regards the electrometer, it may be mentioned that in its first form† it resembled Lord Kelvin's quadrant electrometer. The suspension was made of phosphor-bronze strip, and the vanes, two in number, were each $10\frac{3}{4}$ in. long by about 4 in. broad at their widest part. In a later form of the instrument‡ the quadrant pairs are the moving system, and are suspended by phosphor-bronze strip between two fixed sectors, which are heavily insulated and capable of withstanding several fold the normal voltage of the instrument. The suspended quadrants are $9\frac{1}{2}$ in. in diameter, and are $1\frac{3}{4}$ in. from the fixed sectors, the instrument being designed for 15,000 volts. The instrument obeys the straight line law, is accurate on low power-factor, and has a sensibility such that on a scale 50 in. distant from the mirror, the kilowatts per millimetre deflection are 1.82 when the generator field coils are four series.

A further piece of apparatus, depending upon the charging of condensers in parallel and the placing of them in series, has been used for multiplying a small voltage produced by the passage of the main's current through a low resistance shunt.§

ABSTRACT.

When using the Electrometer as a wattmeter it is necessary (in order to secure accuracy) that the voltage impressed upon the quadrants shall not be less than a certain minimum depending upon the voltage to be impressed upon the moving system. When the latter voltage is of the order 10,000, the quadrants require a voltage larger than can economically be provided by a shunt. One is led, therefore, to consider intensifying devices.

The "series" or "current" transformer, whose secondary winding is closed on a non-inductive resistance, can be used to give

* Maxwell's "Electricity and Magnetism," Vol. II., §675, Edition 1873.

† British Patent Specification 2,707, 1904.

‡ British Patent Specification 27,201, 1904.

§ See British Patent Specification 2,850 of 1905.

fairly good results, but it is not accurate at all frequencies and is dependent upon wave form.

The author's quadrature transformer is a very simple piece of apparatus which can be relied upon to give for electrostatic wattmeters an electromotive force which is strictly the differential of the current in the primary winding. When so used it is necessary, for accuracy, at all frequencies and on all wave forms, that the integral of the mains voltage shall be impressed upon the moving system, although for sine curves only the differential need be impressed instead of the integral.

The best device to impress on the quadrants a suitable voltage in phase with the currents is a generator with an air-cored magnetic circuit as described in the Paper. The mains current is passed through the field coil of the generator and produces a magnetic field proportional to the current; the armature is driven at known speed in this field, and is provided with a commutator and brushes. The brushes when set accurately have a voltage between them proportional to, and having the same wave form as, the mains current.

Another device depending upon the charging of condensers in parallel and the placing of them in series has also been used for multiplying a small voltage produced by the passage of the mains current through a low-resistance shunt.

DISCUSSION.

Dr. SUMPNER pointed out that the reason why a fairly high voltage was needed on the quadrants together with a strong control on the needle when a very high voltage was applied to the latter, was because of the action between the needle and the case; unless the case was quite symmetrical about the axis of the needle.

Dr. RUSSELL inquired whether the author was troubled about brush discharges at the edges of the needle.

Mr. E. H. RAYNER remarked that he had been using a quadrant electrometer for measuring the energy losses in insulating materials with a sensitiveness 1,000,000 times as great as Prof. Wilson's, giving 0.5 mm. scale deflection per microwatt. The use of a high inductance would introduce errors with low power factors owing to its resistance. The method of working the needle at half the main voltage, having the effect of eliminating the correction for the current resistance, has such advantages that it is in many cases the natural one to use. If a dividing resistance is employed, it will be found that when high voltages and resistances are used the capacity and current of the needle will be comparable with that in the resistance, and at low power factors the error may be serious. The best way to avoid it is to connect the needle to the middle point of the high-voltage transformer, when such is used; the resistance of its winding is much less than that of any practicable dividing resistance. If a high-voltage transformer is not used for obtaining the potential, a potential divider may be made by connecting two similar switchboard voltage transformers in series across the mains, and connecting the needle to the middle point. There is another error when using a high resistance of the order of 50,000 ohms in the "current" circuit when measuring a watt or less. This is caused in a similar manner to the above. The capacity current between quadrants and needle, in the case of one set of quadrants (assuming one pole of the supply is earthed), has to traverse the current resistance. This causes a deflection on open circuit which is proportional to the resistance used. Like the previous error it may become quite important at low power factors.

Mr. C. C. PATERSON drew attention to the serious limit of accuracy imposed by not being able to keep the speed constant.

Mr. W. DUDDELL asked if the voltage could not be reduced by means of another quadrature transformer in series with a high resistance, instead of being applied direct to the needle.

Prof. C. H. LEES drew attention to the advisability of reducing the voltage by some means before applying it to the needle.

The AUTHOR, in reply, stated that Dr. Sumpner's remarks were very interesting, as they bore out the statement in the Paper about the minimum voltage to be impressed upon the quadrants. In the case of the instrument exhibited, the *moving* system was at *low* potential relatively to the case. This reversal of the ordinary arrangement helped matters in the above connection, and gave greater accessibility to the moving parts. Dr. Russell raised the question of brush discharge. The author found that brush discharge gave rise to unsteadiness. It could be discovered by observing the instrument in the dark with the high voltage impressed, and where found the radius of curvature could be then increased and thus remove the discharge. The author was glad to hear from Mr. Rayner that he had an electrostatic wattmeter of such great sensibility. The suspension used in the case of the instrument exhibited was of very stout phosphor bronze. If necessary the sensibility could be greatly increased.

When charging the needle, by aid of a non-inductive ratio, at half the voltage of the mains the author could very well believe that when the latter was of the order of 10,000 the capacity current would be large compared with the current in the reducing ratio due to its resistance. This would then give rise to inaccuracy. In Figs. 1 and 2 the voltage on the needle was about 100 when the voltage of the mains was 10,000. It was no doubt a very difficult thing to build an inductive resistance, L , with an air core whose CR component was small enough to render correction negligible. Replying to Mr. Paterson, he wished to say that the speed need not be regulated to any exact figure. All that was necessary was to be able to regulate it so that it came within the range of the speed meter, and then to apply a correction if necessary. Mr. Duddell suggested *two* quadrature transformers—one for the needle in series with a high non-inductive resistance, and one for the quadrants. This would only give accuracy on sine curves. Non-inductive resistances for 10,000 volts or more were very expensive, and the author had avoided their necessity. Potential transformers as a means for reducing voltage were not strictly reliable when great accuracy was desired.