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RADIO FREQUENCY WATTMETER

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This invention relates to electrical power measuring devices, and particularly to a radio frequency wattmeter.

Meters for measuring electrical energy at commercial power frequencies are well known. The commercial wattmeter, however, is not suitable for the measurement of radio frequency power. It is, therefore, the principal object of this invention to provide an improved radio frequency wattmeter.

One essential characteristic of a radio frequency wattmeter is that it produces a negligible effect on the circuit to which it is connected. Where a given radio transmitter, for example, is connected by a plurality of transmission lines to a number of radiators comprising a directive antenna array, it is desirable to be able to insert a wattmeter in the transmission lines successively without detuning or otherwise affecting the system. It is, therefore, a further object of this invention to provide a radio frequency wattmeter having a negligible series impedance and a high shunt impedance so that it may be inserted in and removed from a radio circuit whenever necessary without unbalancing the circuit.

Other desirable features which are provided by the wattmeter of the present invention are: that it is direct reading; that it utilizes a direct current indicator which may be located at a considerable distance from the meter itself; that it may be readily calibrated without reference to another radio frequency meter; that its calibration is independent of frequency; that it operates without appreciable error with a current having a substantial leading or a lagging power factor; that it is conveniently adapted for use over a wide range of frequencies, which range may easily be extended by changing several coils; that it is extremely economical to build; that no external power supply is required as it uses no vacuum tubes; and that it consumes a minimum of power from the line.

The foregoing objects are accomplished by energizing a pair of serially connected current responsive devices by two radio frequency currents. The first current is proportional in amplitude and phase to the current which is supplied to a load, while the second current is similarly proportional to the voltage across the load. The two currents are combined so as to produce an indication which is proportional to the power delivered to the load. This invention is a modification of the wattmeter disclosed in a copending application of George H. Brown and Jess Epstein, Serial No. 312,058, filed January 2, 1940.

This invention will be better understood from the following description when considered in connection with the accompanying drawing, in which Figure 1 is a schematic diagram of the invention; Figures 2 and 3 are schematic diagrams illustrating the method of calibrating the meter; and Figures 4, 5 and 6 are vector diagrams for explaining the operation and calibration of the meter. Similar reference numerals refer to similar parts throughout the several drawings.

Referring to Fig. 1, the wattmeter is provided with input terminals 9 and output terminals 11. One input and one output terminal is shown grounded, but it is to be understood that this is not necessarily actual ground, but may be the ground of the system. By means of these terminals the meter is inserted in the transmission line supplying power to a load. A conductor 13 is connected between the ungrounded input and output terminals. The conductor is preferably a copper tube or other low resistance conductor, and is bent so as to form two suitably spaced single turn line current coils 15 and 17 through which the entire line current flows. The reactance of these coils is negligible at the operating frequency, and the series resistance of the conductor is also negligible, so that the power loss in the meter is likewise negligible.

A pair of current pick-up coils 19 and 21 are connected in series and adjustably coupled to the two line current coils 15 and 17, respectively. The size of the current pick-up coils is not critical and may be, for example, approximately 10 turns. The outer terminals of the two current pick-up coils 19, 21 are connected through the heater elements 27, 29 of a pair of current responsive vacuum thermocouples 31, 33, respectively, to ground. The circuit described so far is the line current responsive portion of the wattmeter. The line voltage responsive portion will now be described.

A connection is made from any convenient point on the conductor 13 to the high potential side of a parallel circuit comprising an inductor 35 and a variable capacitor 37, the low potential sides of which are grounded. A voltage pick-up coil 39 is adjustably coupled to inductor 35. One terminal of this coil is connected to ground through a series capacitor 41 and the other terminal of the coil is connected to the electrical mid-point between current pick-up coils 19 and 21 through a resistor 57 and a meter 45. It is to be understood that these elements may be connected in this circuit in any desired order.

The terminals of the output elements of the

vacuum thermocouples are connected in series opposition, that is, the negative D. C. output terminals, are connected together and a suitable D. C. meter 47 is connected between the two positive terminals. Both terminals of the D. C. meter are preferably by-passed to ground by a pair of capacitors 49, 51. As a result, the meter deflection is proportional to the difference between the currents flowing through the two thermocouple heaters.

The adjustment and calibration of the wattmeter requires three distinct operations. First, the thermocouple unit is adjusted; second, the current coils are adjusted; and third, the voltage coils are adjusted. These adjustments will now be described.

The thermocouple adjustment and calibration is accomplished with the thermocouple unit 53 disconnected from the remainder of the apparatus. The thermocouple heaters are connected in series to any available source of direct or alternating current, preferably of the operating radio frequency, and the output meter connected between the two positive output terminals, as described above. If the two thermocouples are exactly equal the meter reading will be zero for all values of applied current. This is not likely to be the case at first, however, and so it is necessary to adjust one or the other thermocouple until the output is reduced to zero. This is accomplished by connecting a resistor across the couple which is delivering the greater voltage. Such a resistor, 53, is shown in Fig. 1. The unit may then be calibrated to determine its deflection constant K by energizing one of the thermocouples, the meter still being connected across the output of both couples, and determining the ratio between the energizing current and the deflection. It will also be useful to determine the meter constant K' when the meter is connected to the output of only one thermocouple and that thermocouple is energized. The unit is then reconnected to the wattmeter.

The current adjustment is accomplished by disconnecting the voltage line inductor 35 from the line and passing an alternating current through the current coils as shown in Fig. 2. The output terminals 11 are short circuited, or connected to a given load, and a source of current 55, whose frequency is within the desired operating range, is connected to the input terminals 9. The amplitude of current I_L flowing through the line current coils 15 and 17 is adjusted to some value which is within the desired operating range of the meter, with reference to the probable load impedance of the device whose power consumption is to be measured. For example, assume the meter is to read 1 kw. at mid scale. With the output short-circuited, the line current is adjusted to that value which will flow when 1 kw. is being consumed by the assumed load. Then the coupling between the line current coils 15, 17 and the pickup coils 19, 21 is adjusted until the current I_2 in the two thermocouples is equal to a value which is determined from Equation 7, which is derived below, assuming any convenient ratio between I_1 and I_2 and unity power factor. Preferably, I_1 and I_2 are made equal. This operation is facilitated by means of a switch 57 which connects the meter across either one of the thermocouples. The current and voltage coils should be mounted at right angles to each other, or otherwise shielded.

The voltage calibration is made by applying the source 55 to the line voltage coil as shown in

Fig. 3. No current flows through the conductor 13 during the voltage adjustment. The line voltage is determined for the assumed load impedance and power, and the generator 55 is adjusted to this value. A certain current will flow through inductor 35 to ground which will induce a voltage in the secondary 39 of the voltage transformer. The transformer secondary, in series with the two current pick-up coils 19 and 21 in parallel, constitutes a link circuit which is tuned to resonance by capacitor 41. Keeping this circuit tuned to resonance, the coupling between the voltage transformer primary 35 and secondary 39 is then adjusted with the meter connected to one of the thermocouples until its deflection is equal to the value for I_2 previously determined from Equation 7. In using Equation 7 for the voltage and current calibrations described above, the meter constant K' must be used, as the meter is connected to only one thermocouple. The same meter reading should then be obtained when the meter is connected to the other thermocouple. The path of the current $2I_1$ produced by the line voltage is shown in Fig. 3. Since the current $2I_1$ divides equally between two equal current paths to ground, no resultant voltage is induced in the line current inductors 15 and 17. Consequently, the meter currents produced by the line current and the line voltage are independent.

The line voltage inductor 35 is preferably tuned to resonance at the operating frequency to increase the shunt impedance of the meter, but this adjustment will not affect the calibration of the instrument. The meter is then connected as shown in Fig. 1 and it is ready for use.

The phase relation between the line current I_L and the circulating current I_2 is illustrated in Fig. 4, to which reference is now made. The line current I_L is shown leading the line voltage E_L by an angle ϕ . The voltage E_2 induced in the line pick-up coils 19 and 21 is made to lead the line current I_L by 90° , by suitably phasing the transformer secondary. The resultant current I_2 that flows through the thermocouples and inductors 19 and 21 is inductive and therefore lags the voltage E_2 by 90° . Consequently, the induced current I_2 is in phase with the line current I_L , a condition which is required.

Referring now to Figs. 3 and 5, the phase relation between the mesh current I_1 and the line voltage E_L will be determined. The current I_1 flowing through the inductor 35 lags the line voltage E_L by 90° . This current I_1 induces a quadrature voltage E_3 across the pickup coil 39 and since the link circuit is tuned to series resonance by the capacitor 41, it has unity power factor and the link current $2I_1$ is in phase with the induced voltage E_3 . The mesh current I_1 , therefore, is also in phase with the line voltage E_L . Consequently, it will be seen that the two mesh currents I_1 and I_2 are respectively in phase with the line voltage E_L and line current I_L .

It now remains to be shown that the meter deflection is proportional to $E_L I_L \cos \phi$, which is the power supplied to the load. The mesh equations may be stated as follows:

$$I_1 + I_2 = I_1 + I_2 \cos \phi + j I_2 \sin \phi \quad (1)$$

squaring both sides:

$$(|I_1 + I_2|)^2 = I_1^2 + I_2^2 \cos^2 \phi + I_2^2 \sin^2 \phi + 2 I_1 I_2 \cos \phi \quad (2)$$

and since $\sin^2 \phi + \cos^2 \phi = 1$

$$(|I_1 + I_2|)^2 = I_1^2 + I_2^2 + 2 I_1 I_2 \cos \phi \quad (3)$$

and similarly for the other mesh:

$$(|I_1 - I_2|)^2 = I_1^2 + I_2^2 - 2I_1I_2 \cos \phi \quad (4)$$

The meter deflection is equal to the product of the meter constant K and the thermocouple current squared. Consequently, the deflection D_A , due to the current in one mesh, when the meter is connected across both thermocouples, is:

$$D_A = K(|I_1 + I_2|)^2 = K(I_1^2 + I_2^2 + 2I_1I_2 \cos \phi) \quad (5)$$

while the deflection D_B , due to the current in the other mesh, is:

$$D_B = K(|I_1 - I_2|)^2 = K(I_1^2 + I_2^2 - 2I_1I_2 \cos \phi) \quad (6)$$

The total deflection, D_T is equal to the difference, that is:

$$D_T = D_A - D_B = 4KI_1I_2 \cos \phi \quad (7)$$

Equation 7 indicates that the resultant meter deflection is proportional to the product of the currents I_1 and I_2 and their phase angle $\cos \phi$. Since these currents are respectively in phase with and proportional to the line current and line voltage, the total deflection is proportional to power, as required.

It will be appreciated that the calibration of the meter is independent of frequency; the only adjustment required to shift from one frequency to another is to tune the link circuit to resonance, for which purpose the meter 45 is provided. The mesh currents are independent of frequency changes since any increase in coupling due to an increase in frequency is exactly equalized by a like increase in the mesh impedance. That is:

$$I_2 = \frac{I_L \omega M_1}{\omega L} = \frac{I_L M_1}{L} \quad (8)$$

where M_1 is the mutual coupling between the line current and line pick-up coils, and L is the mesh circuit inductance, and

$$I_1 = \frac{E_L}{\omega L_A} \times \frac{\omega M_R}{R} \times \frac{\omega M_C}{\omega L_C} \quad (9)$$

or

$$I_1 = \frac{E_L M_R M_C}{L_A R L_C}$$

where M_R and M_C are the mutual coupling of the voltage transformer and link circuit transformers; L_A is the inductance of the voltage coil 35; R is the resistance of the link circuit; and L_C is the mesh inductance. It will be noted that the ω term cancels out of the two equations 8 and 9.

It will be noted that the present invention is similar to that disclosed in the above identified application of George H. Brown and Jess Epstein. The difference lies in the elimination of the second coupling transformer 25 in the link circuit of the prior device, and the inclusion of resistor 57 in the simplified link circuit. Fewer parts are required in the present arrangement than in the earlier device, and, in addition, there are fewer adjustments to make and fewer to get out of adjustment. Thus the stability of the instrument is also better than that of the more complicated arrangement.

An additional advantage is found in the improved accuracy over a wide range of frequencies which is made possible by the change. In the original arrangement, it was necessary to maintain a link current I_B of the order of 3 amperes in order to insure sufficient mesh current without having unduly tight coupling at the transformer 25. It was found that the constancy

of calibration between different operating frequencies depended upon the resistance of the link circuit remaining constant. The radio frequency resistance of this link circuit was quite low, varying from 0.5 ohm at 550 kc. to 0.6 ohm at 1500 kc. This meant that if the instrument was calibrated at 1000 kc. it would read 10 percent high at 550 kc. and 10 percent low at 1500 kc. While several ohms of fixed resistance could be inserted in this circuit to reduce the percent change of resistance, it is apparent that for each ohm inserted the power loss in the meter would be increased by 9 watts.

In the present circuit, however, the link current is only about 0.3 ampere. The added power loss is less than one-tenth of a watt for each ohm added. Sufficient resistance may, therefore, be added to reduce the percent change of resistance with frequency, so that the calibration of the instrument is constant throughout the broadcast frequency range.

I have thus described a radio frequency wattmeter which is accurate and reliable, which has a negligible effect on the circuit with which it is used, which is operable over a wide range of frequency, and which requires no external source of power.

I claim as my invention:

1. A radio frequency wattmeter comprising a coupling means for connection in series with a power circuit energizing a load, a pair of pick-up coils coupled to said coupling means, a pair of current responsive devices connected in series with said pick-up coils, a tuned circuit connected in parallel with said power circuit, an inductor coupled to said resonant circuit, means effectively connecting said inductor between a point intermediate said pick-up coils and ground, and means for tuning said inductor and said pick-up coils to resonance at the operating frequency.

2. A radio frequency wattmeter comprising a coupling means for connection in series with a power circuit energizing a load, pick-up coil means coupled to said coupling means, a pair of current responsive devices connected in series with said pick-up coil means, means for grounding a point intermediate said series connected devices, high impedance coupling means connected in parallel with said power circuit, and means coupling said high impedance coupling means between a point intermediate the ends of said pick-up coil means and at the electrical center thereof and said ground.

3. A device of the character described in claim 1 in which said pair of current responsive devices comprise a pair of thermocouples connected in series opposition and a meter.

4. A device of the character described in claim 1 which is further characterized by the inclusion of a resistor in said means effectively connecting said inductor between a point intermediate said pick-up coils and ground.

5. A radio frequency wattmeter comprising inductor means adapted to be connected in series with a power circuit energizing a load, a pair of pick-up coils coupled to said inductor means, a pair of current responsive devices, connections from said devices to said pick-up coils, means coupled to said power circuit for deriving a current in phase with the voltage of said line, and means including a resistor connected effectively between a point intermediate said pick-up coils and a point intermediate said current responsive devices for passing said derived current through said responsive devices.

6. A radio frequency wattmeter comprising coupling means for connection in series with a power circuit energizing a load, a pair of pick-up coils coupled to said coupling means, a pair of current responsive devices, said pick-up coils and said devices being connected in series so that first currents are induced in said pick-up coils corresponding to currents in said circuit flow in a given direction through said devices, and means connected to said power circuit and including a series resonant circuit connected to said pick-up coils for deriving from currents flowing in said coupling means a second current which is in phase with the voltage of said line, said second current passing through said responsive devices so as to add to said first current in one of said devices and to oppose said first current in the other of said devices.

7. A radio frequency wattmeter comprising coupling means for connection in series with a power circuit energizing a load, pick-up coil means coupled to said coupling means, a pair of thermocouples having their heater elements connected in series with said pick-up coil means, resonant impedance means including a first inductor connected between a point intermediate said elements and a point intermediate said pick-up coil means, a second inductor connected across said power circuit and coupled to said first inductor, and a meter connected across the output elements of said thermocouples.

8. A device of the character described in claim 7 in which said resonant impedance means also includes a resistor.

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