Brief communication

RMS voltmeter based power and power-factor measuring system

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Many standards laboratories do not have the capability to calibrate their standard power meters used for low frequencies (50–60 Hz). It is difficult to refer them to DC standards because in general, they only respond to AC signals. This paper shows a new system, based on known equations, that permits the calibration of AC wattmeters. The precision of this method depends only on the precision of one resistor and a RMS voltmeter. Both can easily be traced to DC standards.

1. Introduction

Power and energy are important magnitudes for electrical utilities. Usually, class 0·2 watt-hour meters are used by large consumers or in interconnection points between different companies. Class 0·05 (or better) standard meters are needed for calibrating such instruments. It is difficult to maintain these because it is not generally possible to refer them to DC standards (DC resistors and DC voltage). This is due to, their principles of operation, the input transformers and the phase-shift compensation of their electronic circuits. So, many laboratories have to regularly send their power standards to other countries, which is costly and time consuming.

This paper describes the development of a calibrating system for power standards based only on the precision of one resistor and a true RMS voltmeter. The latter are usually maintained by official laboratories. The basic equations of this method have been known for a long time, and many electronic power-meters use them (Erard *et al.*. 1987, Schuster 1980). However, the proposed system has the advantage that it is easily traceable to DC standards.

2. Description of the method

The method employed is similar to the method shown by Goffin and Marchal (1946), based on the following equations

$$\langle (X-Y)^2 \rangle = \langle X^2 \rangle + \langle Y^2 \rangle - 2\langle XY \rangle \quad (1)$$

$$\langle (X+Y)^2 \rangle = \langle X^2 \rangle \langle Y^2 \rangle + 2\langle XY \rangle \quad (2)$$

where $\langle \ \rangle$ is the average value, and X, Y are voltages proportional to the input voltge v and input current i of the power meter.

$$X = v/A \quad Y = Ri/B \quad (3)$$

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A, B and R are constants. From (1) and (2) and noting that $\text{RMS}^2(X) = \langle X^2 \rangle$, we obtain

$$4\langle XY \rangle = \text{RMS}^2(X+Y) - \text{RMS}^2(X-Y) \quad (4)$$

The power P is $\langle vi \rangle = \langle XY \rangle AB/R$, and $L_1 = \text{RMS}(X+Y)$, $L_2 = \text{RMS}(X-Y)$, $L_3 = \text{RMS}(X)$, $L_4 = \text{RMS}(Y)$ are the measurements of the voltmeter. Thus, the power is

$$P = (L_1^2 - L_2^2)AB/(4R) \quad (5)$$

For computing the power factor (PF) we use the definition of this magnitude.

$$PF = P/[\text{RMS}(v)\text{RMS}(i)] \quad (6)$$

then

$$PF = (L_1^2 - L_2^2)/(4L_3\, L_4) \quad (7)$$

It should be noted that (7) does not depend on A, B or R, so the errors of the power factor only depend on the voltmeter errors.

3. Proposed system

Figure 1 shows the proposed measuring system. It performs the measurements and the computation mentioned above. The voltage and current generators are based on commercial sources. They have a short-term stability in power measurements which is better than 10 ppm of the apparent power. The shunt resistor R, used for measuring the current is a broadband resistor (bandwidth greater than 1 MHz). The uncertainty of its value is lower than 5 ppm. It is the only resistor where value needs to be known.

The voltmeter is a Fluke 8506A with a thermal RMS converter. It has an internal thermal transfer that takes only 6 s for each measurement. According to the manufacturer the basic errors are below 120 ppm.

The summing device (shown in Fig. 2) performs the adding or subtracting of the input signals. A personal computer controls the whole system via an IEEE 488 interface. All the switches are controlled by the computer via the IEEE 488. Thus the

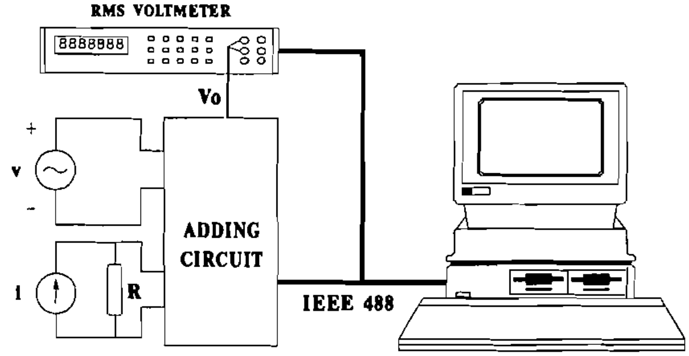

Figure 1. Block diagram of proposed measuring system.

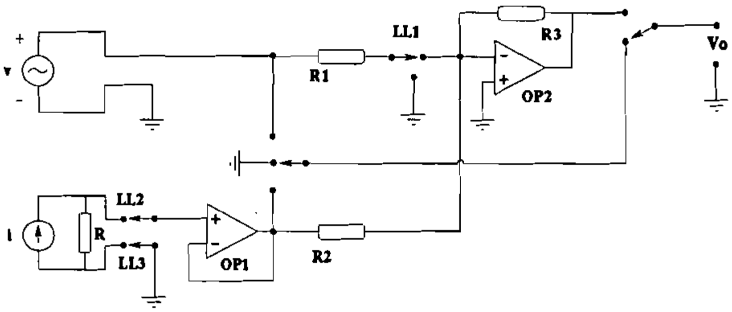

Figure 2. Electronic circuit of summing device.

voltmeter measures the different signals sequentially, they are: v, Ri, X, Y, $X+Y$ and $X-Y$. The operational amplifiers are of high precision (gain greater than 120 dB, noise lower than 0·1 μV). Resistors R_1-R_3 perform well in high frequencies (time constant lower than 50 ns) and have a low thermal coefficient (lower than 0·6 ppm/°C). All the switches are relays with a stable low-contact resistance. The buffer OP1 in the current branch, diminishes the errors coming from the variation of the contact resistances of LL_2 and LL_3. It should be noted that this was not necessary in the voltage branch, because the value of R_1 is much higher than the contact resistance of LL_1.

The control program operates as follows. At the beginning or during the autocalibrating mode, it calculates the coefficients A and B using (3). Then, according to (5) it calculates the power, and according to (7) the power factor (R must be known).

4. Error analysis

The first error comes from the variation of the voltage and current during the time required for performing a measurement. This is an important point. Equation (5) has been known for a long time, but only with new fast digital RMS voltmeters can the proposed method be implemented with high precision. With a conventional thermal transfer, each measurement would take more than 10 min, so the method would become very cumbersome and the stability of the source would be a problem.

To reduce this source of error, the computer shows the mean value of the last three measurements. On the other hand, when a large difference appears between the last measurement and the stored average, the computer assumes that an intentional change has occurred and only the last value is displayed. In our case, the error due to the variation of the sources is around 10 ppm of the apparent power.

A second error source comes from the voltmeter itself. The used voltmeter has a maximum error of 120 ppm, according to the manufacturer. However, it has excellent stability and linearity. In each range, the linearity error is less than 5 ppm (from 30% to 120% of the range). According to the manufacturer the 24 h stability is better than 25 ppm. Other improvements can be made, disregarding the first measurement and taking the second into account. This reduced the dispersion of this measurement by about three times, in the instrument tested. So, it is possible to diminish the voltmeter error by adjusting one point of each range during the recalibration work, or using a short table of corrections with the actual errors determined in a recent calibration. This correction is done automatically by the computer.

We define the power error E_p as the ratio between the absolute power error and the apparent power. It is easy to see, using (5), that

$$E_p = \alpha - \beta + (\alpha + \beta) \cos(\phi) \tag{8}$$

where α and β are the relative voltmeter errors when measuring L_1 and L_2, respectively, and $\cos(\phi)$ is the power factor. It is assumed that $X \approx Y$. The worst case error would be twice the maximum of the voltmeter error. However, at low power factors the error decreases because the voltmeter measures nearly the same value and errors tend to cancel ($\alpha \approx \beta$) as shown in Fig.3. The vectors $X + Y$ and $X - Y$ have nearly the same module.

The absolute value of the resistors is not important (except R). In the auto-calibrating mode the coefficients A and B (R_1/R_3 and R_2/R_3) are determined. Note that only the product AB is necessary for computing the power. For calculating the value of AB, it is better to use direct current sources and the DC mode in the voltmeter (errors lower than 5 ppm). This method has lower errors than the method using AC. This work can be done automatically via the IEEE interface, with suitable sources.

Another source of error is the phase shift of the input signals caused by stray capacitors and inductors. Although these power meters are mainly used in 50 Hz or 60 Hz frequency networks, small phase shifts produce large errors when low power factors are measured. The four resistors used in the summing device were tested at 1 MHz. The theoretical effect of their stray elements on the power error is lower than 10 ppm of the apparent power. A complete phase shift test for all the system is needed to corroborate its behaviour at low power factors. This was done, using a zero power generator (two signals in quadrature). This device, developed in our laboratory, is based on a low dissipation capacitor and an electronic-compensated current transformer. The overall error of the system at zero power-factor was lower than 50 ppm of the apparent power, including all the error sources.

The value of the resistor R is also a source of errors. This error is lower than 5 ppm if the value of a recent calibration is used.

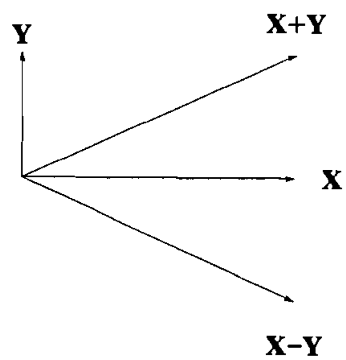

Figure 3. Vector diagram of signals $X + Y$ and $X - Y$, corresponding to a measurement with zero power factor.

5. Experiments

The proposed system was compared with a Zera power standard meter which had a recent calibration with 0·01% uncertainty. The measured power differences were around 0·01%. The lowest power factor used was 0·25, because this was the lowest power factor of the calibration certificate. The errors are of the same order of measurement uncertainty. So, for analysing the performance of the proposed system in more detail, lower power factors and lower uncertainties must be achieved for the reference wattmeter.

6. Future work

A comparison between the proposed system and the power standards of the Physikalisch-Technische Bundesantalt (Brauschweig, Germany) will be carried out to confirm the precision of all the system. Sinusoidal waveforms as well as non-sinusoidal currents and voltages will be used to analyse the behaviour of this system under such conditions. The harmonic contents of the voltage and the current will be correlated by a Thévenin model of the source (see Slomovitz 1991). The effect of non-sinusoidal waveforms is a very important point, as many real tests are done under these conditions (Slomovitz 1989).

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