A Device for Audio-Frequency Power Measurement

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***Abstract*—A new device for the measurement of audio-frequency power is introduced. This device can also be used to measure audio-frequency voltage and current. The full range of power factors are accomodated (cos ϕ = 0 to 1). Voltage and current measuring ranges are 15–600 V and 0.1–10 A, respectively. When cos ϕ = 1, the permissible error of the power measurement is from 50 to 150 ppm over the frequency range of 40 Hz to 10 kHz (including the line power frequency).**

I. Introduction

SINCE THE beginning of the 1960's, an accurate device (XF-1) for calibrating instruments and meters of current, voltage, and power at dc and audio-frequencies was produced in China, and the technology of electric measurement at audio-frequency was developed. However, the accuracy of power measurements above 1 kHz over the audio-frequency range had not been improved since that time because of leakage between the current and voltage input loops, and because of the difficulties in developing an audio-frequency amplifier with high accuracy and low phase shift, simultaneously. Therefore, until the new device had become available, the accuracy of power measurements made by the XF-1 had not been determined above 1 kHz. Hence, some design approaches for a new device were suggested by the authors as follows.

1) Technical problems in performing power measurements at high frequency and low power factor must be overcome, so that the accuracy of these measurements can be improved.

2) The means for making automatic measurements with the new device will be provided to fill the requirements for automatic calibration of digitial wattmeters.

3) The measuring principle and circuit designs of the new device should suit the manufacturing process. The adjustment and the compensation of each component in the new device should be simple, and each component can be calibrated and used independently.

II. The Key Problems in the Measurement of Power at High Audio-Frequencies

Through analysis of the data obtained using the XF-1, the following two aspects have been found to be the key problems in making power measurements at high audio-frequencies and low power factor.

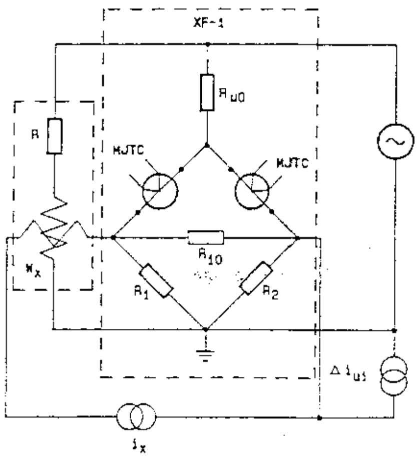

Fig. 1. The power measurement circuit of the XF-1.

1) Interference Between the AC Voltage Input Loop and the AC Current Input Loop: Electric power is a function of the corresponding voltage and current. When an instrument for measuring single phase power has four input terminals, the power must be supplied by a separate voltage source and a separate current source. The two sources have four output terminals to connect to the power meter. According to the theory of network analysis, a power meter with four input terminals is affected by three independent signals. Therefore, the power meter is sensitive to an interference signal besides the voltage and current input signals. The interference signal is a voltage between the voltage and current input loops of the power meter when the two input loops are insulated from each other in the instrument; otherwise, the interference is a leakage current between the two input loops when the two input loops are connected in the instrument, as for the example in the model XF-1, which is shown in Fig. 1. The current Δi_{ui} is the leakage current between the two input loops, and the accuracy of the power measurement is seriously decreased by Δi_{ui} at high frequencies and lower power factors. In addition, when the voltage and current sources are supplied by the main supply using two power supply transformers, a leakage current at the power frequency is produced through the power measurement circuit of the instrument by leakage admittances between primary and secondary coils. Therefore, a beat frequency signal, caused by the two signals and the leakage current near the power frequency, will create an undesired increase in the power measurement.

2) High Accuracy, Wide Frequency Band Amplifiers: Many kinds of feedback amplifiers have been used in power measurement circuits in the last several years,

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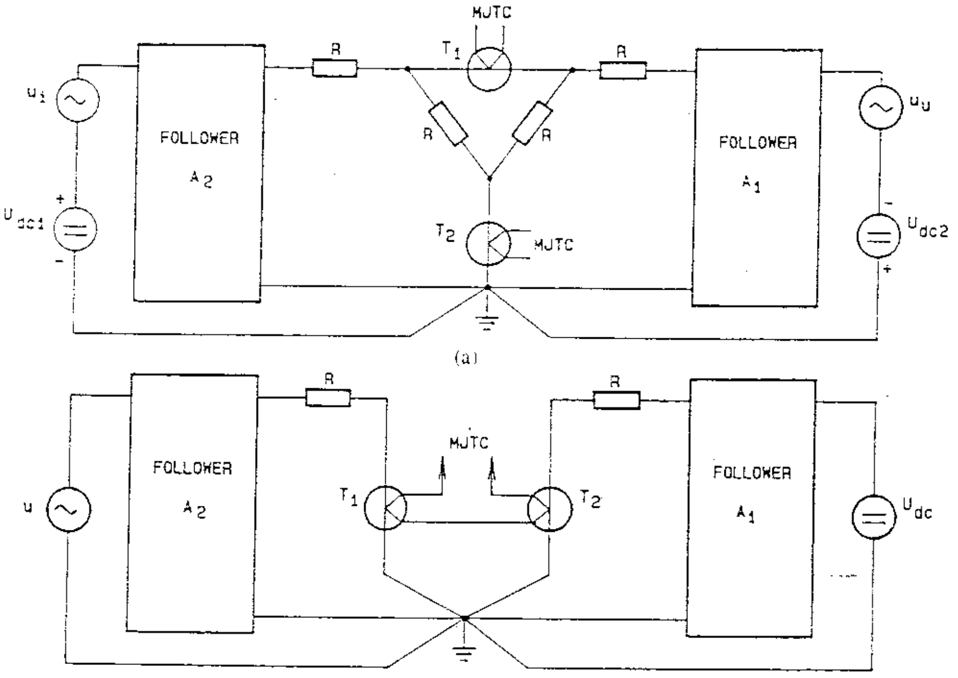

(a)

(b)

Fig. 2. (a) The power measurement circuit of the new device. (b) The voltage or current measurement circuit of the new device.

and have mainly been applied to the amplification of voltage and power. Because the gain bandwidth product of feedback amplifiers has been restricted, the operating frequency range of a single feedback-loop amplifier has also been limited to less than 1 kHz when the gain accuracy of the amplifier is about 100 ppm. The closed-loop phase error will be increased, and the amplitude error will approximate the square of the phase error, when the amplifier is operated at the high end of its operating frequency range. Therefore, when the power meter has been constructed using a single feedback-loop amplifier, the power measurement error is quite large at low power factor and high frequency. For the error in power measurement caused by the amplifier to be negligible, the closed-loop gain error of the amplifier should be less than 10 ppm over e whole operating frequency range. To realize an amplifier error of less than 10 ppm, some additional work was needed on the theory and circuits of feedback amplifiers.

III. A Voltage Follower of High Accuracy

The theory of the combined feedback amplifier was introduced in [1] and verified in practice over the last ten years. When a new device for audio-frequency power measurement was being studied, a high quality follower amplifier was developed. The input impedance of this amplifier is more than 10 MΩ, the output impedance is less than 0.001 Ω, and the input noise is less than 0.5 μV (in a 1-Hz band). The dc drift of the input is about 2 μV/day, and the error in the closed-loop gain is less than ±10 ppm over the frequency range from dc to 10 kHz. The amplifier is direct coupled, needs only a dc power supply, and is not sensitive to the voltage fluctuations of the supply. An isolation transformer with three-stage cores (the ratio of voltage is 1 : 1) has also been employed. Its voltage ratio error is less than 2 ppm (40 Hz to 10 kHz). This isolation transformer and the voltage follower have been combined to connect the three key parts of the new device (see Fig. 5) so that all of the error caused by the interconnections can be neglected, as illustrated in Fig. 3 (connecting circuit).

IV. New Voltage Multiplier

A new kind of voltage multiplier, as shown in Fig. 2(a), has been adopted for the input circuit in order to remove electrical leakage between the voltage input loop and the current input loop of the power meter. When the thermoelectric potential of thermal converter T_1 is equal to that of thermal converter T_2, we have

$$u_u \, u_i \cos\phi = -U_{\mathrm{dc1}} \, U_{\mathrm{dc2}} \tag{2}$$

where ϕ = phase difference of two ac input voltages (u_u, u_i) and u_i is the output voltage from a current shunt. Thus power measurements can be realized with the circuit of Fig. 2(a). A similar circuit can be used to measure ac voltage and current, as shown in Fig. 2(b), where u is the output voltage from a voltage divider or a current shunt. When the thermal EMF of the two thermal converters is balanced, we have

$$u = U_{\mathrm{dc}} \tag{3}$$

where the thermoelectric potential is about 10 mV when u and U_{dc} are the rated values.

The characteristics of the new voltage multiplier are described in the following.

1) The new multiplier is composed of some resistors and two multijunction thermal converters (MJTC's). Because all resistance values of the resistors and heaters of

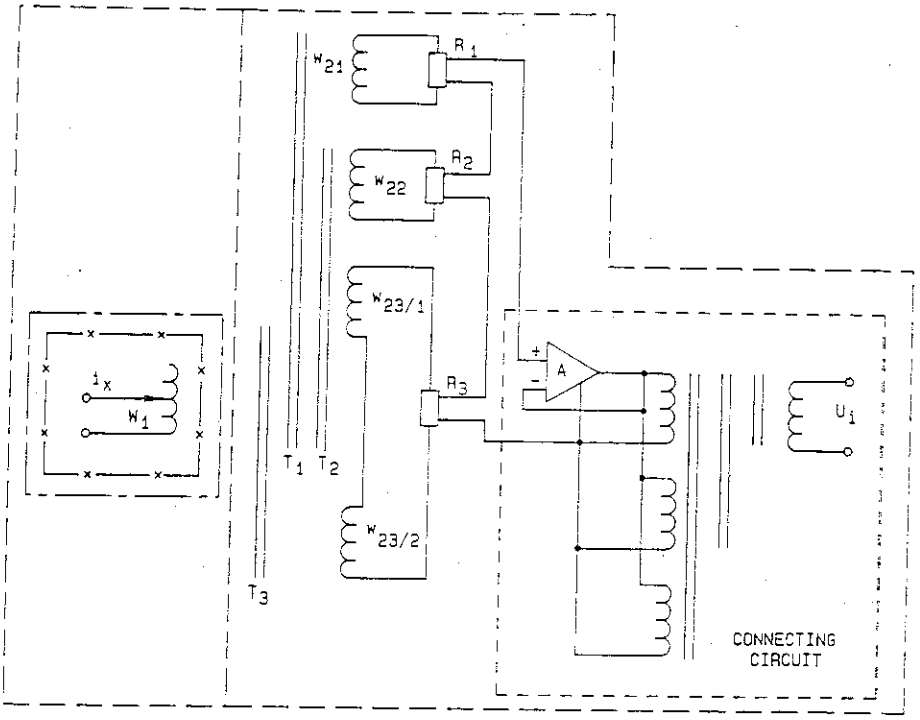

Fig. 3. Schematic diagram of the inductive shunt.

the two thermal converters are of a median value of 77 Ω, the multiplier frequency response is very good (i.e., time constants are about 0.1–1.0 ns). Also, the heaters of the MJTC have been designed to operate in a power-matching state, so that the high and low frequency error of the thermal converters has been reduced sharply [2].

2) The phase angle error of the multiplier can be self-calibrated because its two inputs are symmetrical. This phase calibration is accomplished by determining the residual phase error when applying quadrature input signals to the multiplier [3]. The amplitude error of the multiplier at cos $\phi = 1$ can be calibrated independently with an ac-dc voltage transfer standard and a high accuracy inductive divider whose turns-ratio is 1 : 1; therefore, a higher accuracy standard is not required for calibrating the multiplier.

3) Two ac and two dc voltage signals are simultaneously applied to the multiplier with the two thermal converters working at the same temperature; therefore, this operating mode can reduce the error due to deviation from the quadratic response to a negligible level. Moreover, the ac voltage automatically tracks the dc voltage through the thermoelectric potential difference of the two thermal converters. This EMF difference is then amplified.

4) There are only three input terminals to the multiplier, and a common point for two input loops; therefore, there is no interference between the two voltage input loops of the multiplier.

V. Isolating Inductive Shunt and AC Current Input Loop

The principle circuit of the inductive shunt is shown in Fig. 3. The nominal value of the resistor R_3 is 20 Ω. The error of its resistance value is less than 10 ppm after adjustment, the time constant is less than 3 ns before compensation, and the temperature coefficient is less than 2 ppm/°C. The rated current of resistor R_3 is 50 mA, and the resistance change in R_3 effected, by operating current, is about 1 ppm. The operating current of R_3 is supplied by secondary winding w_{23}, which consists of two series windings $w_{23/1}$ and $w_{23/2}$. The nominal value of resistors R_2 (having an error of about $\pm 2 \cdot 10^{-4}$) and R_1 (having an error of about $\pm 1 \cdot 10^{-3}$) is also 20 Ω. These two resistors (and the associated secondary winding) are used to reduce the magnetizing error of the inductive shunt at low frequency; therefore, the magnetizing error is less than 10 ppm. The ratio and phase angle errors of the inductive shunt have been compensated so that the ratio error is less than 10 ppm and the time constant is less than 1 ns. In order for the output of the inductive shunt to support a burden, a connecting circuit has been adopted as shown in Fig. 3. An output transformer is used to provide isolation, thereby permitting flexible connections. The error of the voltage transformer ratio (1 : 1) is less than 2 ppm. The ranges of the input current of the inductive shunt are 0.1, 0.25, 0.5, 1, 2.5, 5, and 10 A. When the input currents are at their rated values, the output voltage is 1 V. The total uncertainty (3σ) specification of the inductive shunt is less than

$$\pm((1 + 0.4F) \pm j(1 + 0.5F)) \cdot 10^{-5}$$

over the frequency range of 40 Hz to 10 kHz, where F is in kilohertz. This expression for the total uncertainty was obtained experimentally, and included one year of stability data.

The ac voltage and current inputs of the new device must be connected like the measured wattmeter W_x in Fig. 1, in order to calibrate the device, XF-1. Hence, the ac

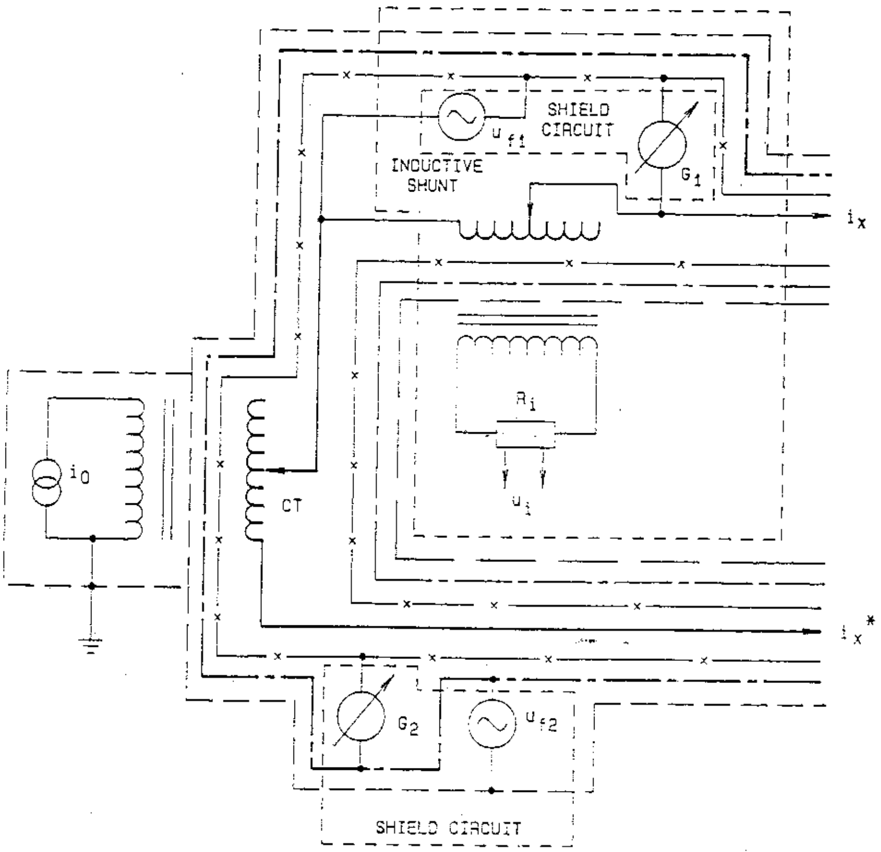

Fig. 4. The ac current input loop and three-layer shields of the new device.

voltage loop (supplying the ac voltage signal u_x) and the ac current loop (supplying the ac current signal i_x) should be isolated; in addition, leakage current Δi_{ui} should be very small so that the error caused by Δi_{ui} in Fig. 1 is negligible. Because the low potential terminal of the ac voltage u_x is generally grounded, isolation between the two loops must be established in the ac current input loop. If such isolation can be realized, then the ac current input connections of the wattmeter being measured can be flexible when using the new device.

The ac current loop can be isolated as shown in Fig. 4. There are three-layer shields in the inductive shunt and the isolating current transformer in Fig. 4. The current transformer is only required to have high efficiency for power transfer, but the inductive shunt is required for high transfer ratio accuracy from input current i_x to output voltage u_i. When the indication of the ac null detector G_2 becomes zero, by adjusting u_{f2} the leakage current between the current input loop and ground will be minimized. And when the indication of detector G_1 is zero, by adjusting u_{f1} the measurement terminal of the input current loop will be shielded from any interference current. In actual operation, the null indications of G_1 and G_2 are read automatically using voltage followers.

VI. AC RESISTANCE DIVIDER

A resistance divider similar in principle to the divider described in [4] has been used to expand the ranges of input voltage. If only accuracy is considered, an inductive voltage divider (IVD) is most suitable. However, an IVD has some disadvantages: large volume, weight, input current at low frequency, and high input voltage. To overcome these disadvantages, a new high accuracy resistance divider with multisection shielding has been adopted in the new device. The same connecting circuit as described above has also been employed to reduce the output impedance of the resistance divider and to isolate it from other circuits. The resistance divider has been constructed of thin-film resistors, with a current rating of 2 mA. Its shielding circuit consists of some mica capacitors, and its ratio error at high frequency has been compensated as described in [4].

The ranges of input voltage of the resistance divider are 15, 30, 75, 150, 300, 450, and 600 V. When the input voltages are at their rated values, the output voltage is 1 V. The ratio and phase angle total uncertainties of the resistance divider (3σ) are less than

$$\pm\left((2 + 0.3F) \pm j(0.5 + 1F)\right) \cdot 10^{-5}$$

over the frequency range of 40 Hz to 10 kHz, where F is in kilohertz. This expression for the total uncertainty was obtained experimentally, including one year of stability data.

VII. AC SIGNAL SOURCE AND MEASURING SYSTEM

The complete power measuring system is shown in Fig. 5. The ac power signal source, frequencies, phases, amplitudes, and ranges all can be automatically controlled through the IEEE-488 bus. The differential thermal EMF of the voltage multiplier (see Fig. 2(a)) is amplified to

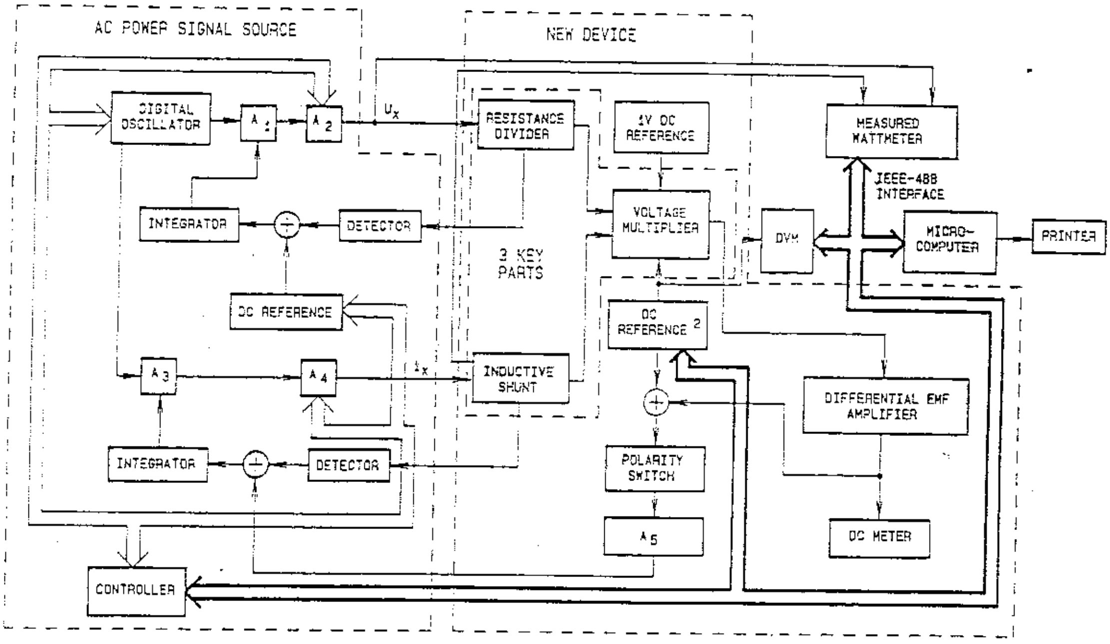

Fig. 5. Complete power measurement system.

control the output power of the ac power signal source; hence, the automatic measurement level of the system is increased. The stability of this ac power measuring system is better than 30 ppm/3 min (40 Hz to 10 kHz, including the line power frequency). This device can also be used as an ac voltage measuring system and an ac current measuring system. The stability is better than 20 ppm/3 min for ac voltage and current measurement (40 Hz to 10 kHz, including the line power frequency).

A microcomputer is used to sample and process the data of the DVM and the measured wattmeter. The results of the measurements can then be corrected automatically with the calibrated values of the resistance divider, the inductive shunt, and the voltage multiplier. The calibrated results can also be printed automatically.

VIII. TECHNICAL SPECIFICATIONS

The main technical specifications of the new device are shown as follows.

1) Measuring range:
   - a) ac input voltage 15–600 V,
   - b) ac input current 0.1–10 A,
   - c) frequency band 40 Hz to 10 kHz,
   - d) range of the power factor $\cos\phi = 0 - 1$.

2) Permissible relative error (γ_p) of the power measurements:

$$\gamma_p = \frac{\Delta P_x}{i_h \, u_h \cos\phi} \le \pm\left((5 + F) \pm (2 + 2F)\tan\phi\right) \cdot 10^{-5}$$

where F is in kilohertz:

i_h rated values of the current ranges,
u_h rated values of the voltage ranges,
ϕ phase difference of the ac voltage to current,
ΔP_x permissible measurement error of the input power.

When $\cos\phi = 1$, the permissible error of the power measurement is from 50 to 150 ppm over the frequency band of 40 Hz to 10 kHz.

3) Measurement accuracies of ac voltage and current are better than 35–100 ppm over the frequency range of 40 Hz to 10 kHz.

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