A Wide-Band Active Current Transformer and Shunt

Guang-qiu Tong and Xiu-ye Xu

Abstract—**An active current transformer and shunt with high accuracy and wide frequency range is described in this paper. The new transformer which uses two three-stage core transformers with two two-stage feedback amplifiers can be used in the audio frequency band. It has a wide range of current ratio (0.01–1) and can dissipate 10 W in the external burden. If the external burden of the transformer is an ac standard resistor, it becomes an ac current to voltage transducer that can be used in many electrical measurements. The relative uncertainty (3σ) in the current ratio of the new transformer is between $(1 + j1)$ ppm to $(8 + j8)$ ppm over the frequency range from 40 Hz to 10 kHz.**

I. Introduction

It is well known that the low frequency error (γ) of a transformer is caused by internal burden error (γ_{mi}), produced by the stray capacitance and the series copper winding resistance, and the external burden error (γ_{mo}). Therefore, the low frequency error is approximately

$$\gamma \approx \gamma_{mi} + \gamma_{mo}. \tag{1}$$

Usually, to reduce γ_{mi}, multi-core techniques have been adopted to constitute a multi-stage transformer. There are a number of methods to reduce γ_{mo} [1]. These can be divided generally into a passive method and an active method. In the passive method, an additional current transformer, T, is used to produce an out-of-phase voltage, which offsets the burden voltage across Z_0, as shown in Fig. 1. Because the circuitry in Fig. 1 is passive, this method of compensating the transformer is very stable. However, in usage and calibration, the out-of-phase voltage produced across impedance Z_1 often needs to be adjusted so that the voltage across winding N_2 becomes zero. Therefore, the process of maintaining the performance of the transformer by the passive method is complicated and time consuming.

In the active method, the output voltage of an amplifier is used to offset the voltage of the burden [2], [3]. The main characteristics of this method are given below:

1. This method involves simple circuitry, lightweight and low cost.
2. The voltage of the burden can be offset automatically by the output voltage of the amplifier without any adjustment.

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G.-Q. Tong is a guest scientist in the Electricity Division, National Institute of Standards and Technology, Gaithersburg, MD 20899 from the National Institute of Metrology, Beijing, China.

X.-Y. Xu is with the National Institute of Metrology, Beijing, China.

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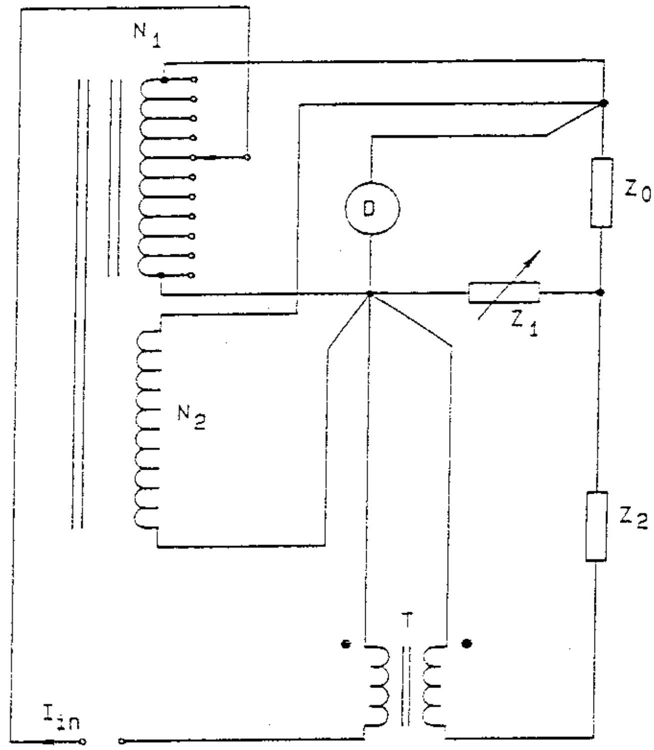

Fig. 1. Two-stage transformer with an additional current transformer, T, used to reduce the burden.

3. Unwanted oscillations may occur if the amplifier circuit is not properly designed.
4. Low frequency errors due to dc drift in the amplifier output cannot be easily controlled.

Problems in the latter two characteristics have been solved in the new active transformer introduced in this paper. The circuitry and parameters of this new transformer are designed so that it is not only stable (i.e., no oscillations) but also has very small dc drift. Also, the error in the current ratio caused by temperature change is essentially negligible over a wide temperature range (0°–35°C).

II. The New Active Transformer

The new active transformer is composed of two similar decade transformers. Each decade transformer is itself an active transformer, which consists of a passive transformer and a voltage follower, as shown in Fig. 2. In this passive transformer, a three-stage core has been used to reduce the low frequency error caused by internal burden error (γ_{mi}), and a magnetic shield (not shown in Fig. 2) has been used to reduce the leakage flux. The voltage fol-

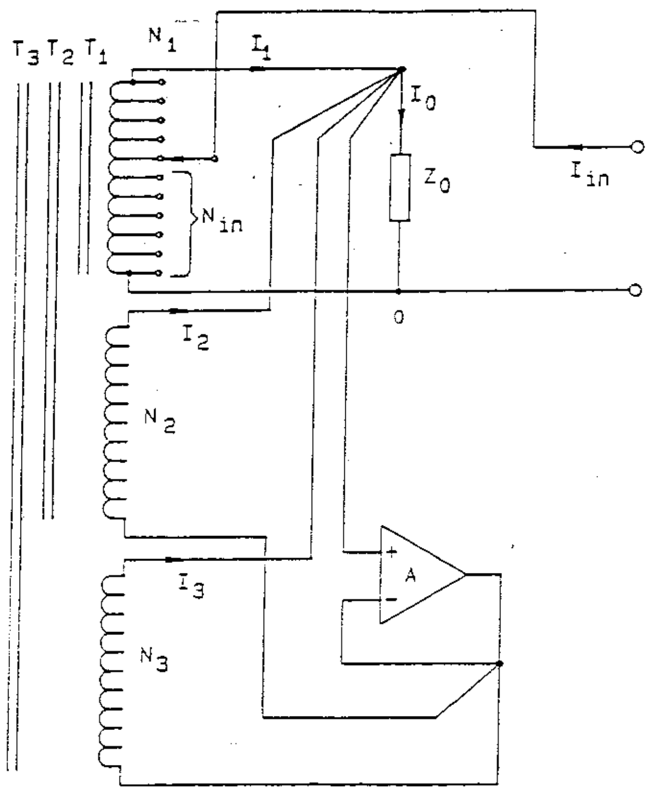

Fig. 2. The decade transformer circuit.

lower (A) is a two-stage feedback amplifier (see Appendix I, for details). It has high input impedance (> 100 MΩ) and very small dc drift (about 1 μV/°C and 10 μV/year). Because the main component of the burden current I_0 is supplied by winding N_1, the voltage follower is only required to supply the magnetizing and loss current components.

The complete circuit of the new active transformer is shown in Fig. 3. The first decade transformer is composed of three cores (T_1, T_2, T_3), three windings (N_{11}, N_{12}, N_{13}), and a voltage follower (A). The second decade transformer is also composed of three cores (T_4, T_5, T_6), three windings (N_{21}, N_{22}, N_{23}), and a voltage follower (A). The rated burden current I_0 of the transformer is 0.1 A (rms). The rated input current I_{in} has a range of 0.1 A to 1 A for the first decade transformer and 1 A to 10 A for the second decade transformer. The total current ratio of the active transformer can be expressed by

$$K = (K_1)(K_2) \tag{2}$$

where $K_1, K_2 = 0.1, 0.2, \cdots, 0.9, 1$. So that the range of the current ratio is 0.01 to 1.00. To avoid unwanted low frequency oscillations, the precaution is to properly increase the dc resistance in the circuits of windings N_{12}, N_{13}, N_{22}, and N_{23} independently.

III. The Low-Frequency Error of the Active Transformer

Analyzing the low frequency errors in the circuit of Fig. 2, the burden current is

$$I_0 = I_1 + I_2 + I_3 \tag{3}$$

where I_1, I_2, and I_3 are the output currents of the three windings N_1, N_2, and N_3, respectively. Since

$$N_1 = N_2 = N_3 \tag{4}$$

and the main component of the low frequency error is caused by the magnetizing and loss currents, the three winding currents can be expressed as

$$\begin{cases} I_1 = \dfrac{N_{in}}{N_1} I_{in} - I_{m1} \\ I_2 = I_{m1} - I_{m2} \\ I_3 = I_{m2} - I_{m3} \end{cases} \tag{5}$$

where I_{m1}, I_{m2}, and I_{m3} are the magnetizing and loss (error) currents of the three windings N_1, N_2, and N_3, respectively, and I_{in} is the input current applied to the transformer. Equations (3) and (5) combine to give

$$I_0 = \frac{N_{in}}{N_1} I_{in}(1 + \gamma) \tag{6}$$

and

$$\gamma = -\frac{N_1}{N_{in}} \frac{I_{m3}}{I_{in}} \tag{7}$$

where γ is the low frequency error of the transformer.

The first stage equivalent circuit of the transformer is shown in Fig. 4 (the equivalent circuits for the second and third stages can be similarly represented). From these equivalent circuits, neglecting second-order terms, we obtain

$$\begin{cases} \dfrac{I_{m1}}{I_1} \simeq \dfrac{I_{m1}N_1}{I_{in}N_{in}} \simeq \dfrac{Z_{s1}}{Z_{m1}} + \dfrac{Z_0}{Z_{m1}} = \gamma_{m1} + \dfrac{Z_0}{Z_{m1}} \\ \dfrac{I_{m2}}{I_{m1}} \simeq \dfrac{Z_{s2}}{Z_{m2}} + \dfrac{\gamma_A Z_{02}}{Z_{m2}} = \gamma_{m2} + \dfrac{\gamma_A Z_{02}}{Z_{m2}} \\ \dfrac{I_{m3}}{I_{m2}} \simeq \dfrac{Z_{s3}}{Z_{m3}} + \dfrac{\gamma_A Z_{03}}{Z_{m3}} = \gamma_{m3} + \dfrac{\gamma_A Z_{03}}{Z_{m3}} \end{cases} \tag{8}$$

where γ_A is the error of the voltage follower A. Z_{s1}, Z_{s2}, and Z_{s3} are the internal burdens of the three windings; Z_{m1}, Z_{m2}, and Z_{m3} are the equivalent magnetizing impedances of the three windings; Z_0 is the external burden, and $\gamma_A Z_{02}$ and $\gamma_A Z_{03}$ are the equivalent external burdens seen by windings N_2 and N_3, respectively; and γ_{m1}, γ_{m2}, and γ_{m3} are the low frequency errors caused by the internal burdens of the three windings N_1, N_2, and N_3. In the three-stage design, error currents I_{m1} and I_{m2} are compensated by I_2 and I_3. The remaining error current, I_{m3}, is given by

$$I_{m3} \simeq \frac{N_{in}}{N_1} I_{in} \left(\gamma_{m1} + \frac{Z_0}{Z_{m1}}\right) \left(\gamma_{m2} + \frac{\gamma_A Z_{02}}{Z_{m2}}\right) \cdot \left(\gamma_{m3} + \frac{\gamma_A Z_{03}}{Z_{m3}}\right). \tag{9}$$

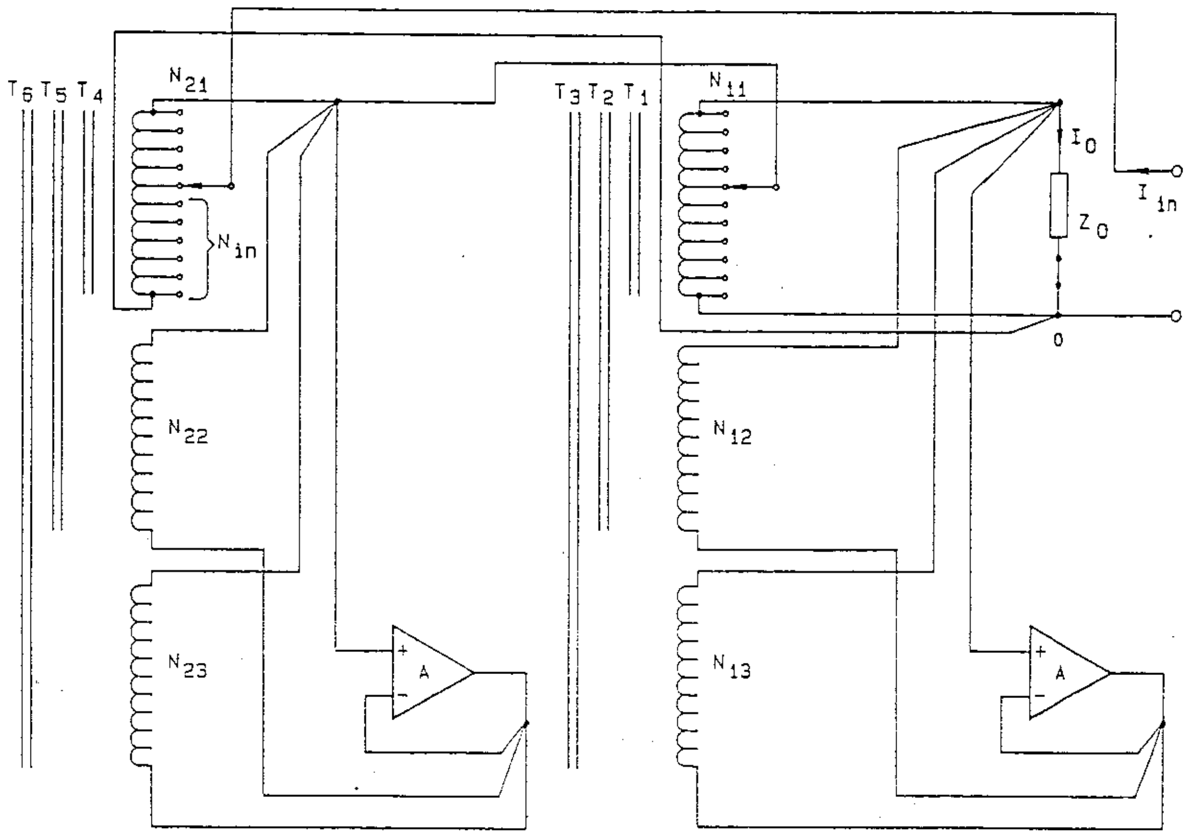

Fig. 3. The complete circuit of the active transformer.

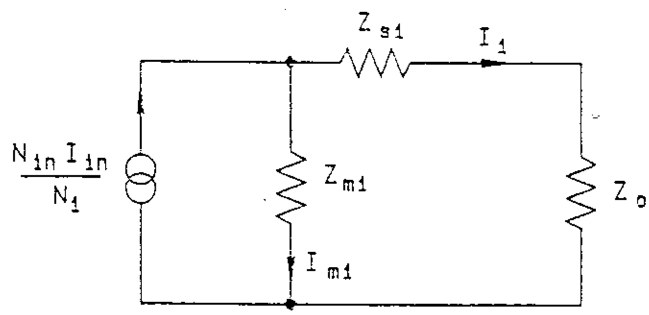

Fig. 4. Equivalent circuit of the transformer.

Assuming the following approximations:

$$\begin{cases} \gamma_{m1} \simeq \gamma_{m2} \simeq \gamma_{m3} \simeq \gamma_m & \text{(magnetizing error)} \\ \gamma_A \ll \gamma_m & \\ Z_{m1} \simeq Z_{m2} \simeq Z_{m3} \simeq Z_m & \text{(magnetizing impedances)} \\ Z_{02} = \dfrac{I_0 Z_0}{I_2} \simeq Z_{m1} & \text{(see Appendix)} \\ Z_{03} = \dfrac{I_0 Z_0}{I_3} \simeq \dfrac{Z_m}{\gamma_m} & \text{(see Appendix)}, \end{cases} \tag{10}$$

and combining (7), (9), and (10) we obtain

$$\gamma = -\left(\gamma_m^3 + \gamma_m \gamma_A + \gamma_m^2 \gamma_A + \gamma_A^2 + \gamma_m^2 \frac{Z_0}{Z_m} + \gamma_A \frac{Z_0}{Z_m} + \gamma_m \gamma_A \frac{Z_0}{Z_m} + \frac{\gamma_A^2 Z_0}{\gamma_m Z_m}\right). \tag{11}$$

At low frequency, the following values are easily achieved:

$$\begin{cases} \gamma_m < 0.3\% \\ \gamma_A < 0.001\% \\ \dfrac{Z_0}{Z_m} < 5\%. \end{cases} \tag{12}$$

Thus,

$$\gamma \simeq -\left(\gamma_m^2 \frac{Z_0}{Z_m} + \gamma_A \frac{Z_0}{Z_m}\right). \tag{13}$$

Therefore, it is possible to obtain a low frequency error of the shunt in Fig. 2 (and, therefore, in Fig. 3) of about 1 ppm.

IV. Calibration [4]

The new active transformer has been calibrated by an absolute method such as the bootstrap method using the IVD. T_x is the transformer to be calibrated, T_f is the bootstrap transformer, I_s is a stable current source produced by a current transformer with a nominal turns ratio of 0.1, and ΔI is the output current of a ratio error set. Based on this calibration relative uncertainties (3σ) of the new active transformer are found to be as follows:

1. When the current ratio $K = 0.1$ to 1 ($I_{in} = 0.1$ A to 1 A and $Z_0 = 10\ \Omega$)

$$\gamma < (1 + j1) \text{ ppm} \qquad (40 \text{ Hz} - 1 \text{ kHz})$$

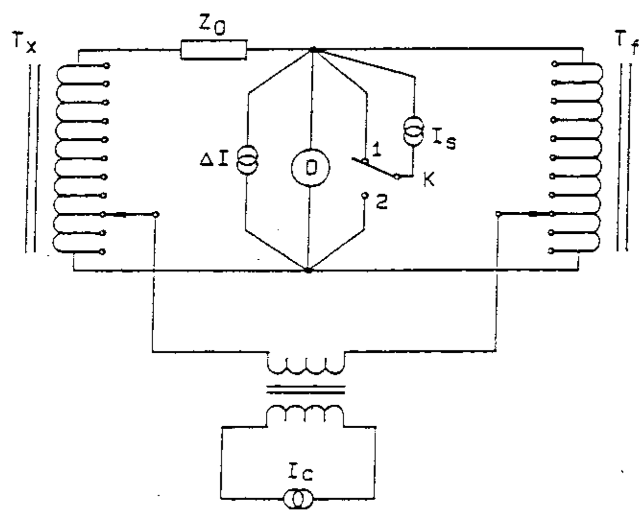

Fig. 5. Schematic circuit for calibrating the transformer.

and

$$\gamma < (1 + j1) \text{ ppm to } (8 + j8) \text{ ppm}$$
$$(1 \text{ kHz} - 10 \text{ kHz}).$$

2. When $K = 0.01$ to 0.1 ($I_{in} = 1$ A to 10 A and $Z_0 = 10\ \Omega$)

$$\gamma < (3 + j3) \text{ ppm} \qquad (40 \text{ Hz} - 1 \text{ kHz})$$

and

$$\gamma < (3 + j3) \text{ ppm to } (8 + j8) \text{ ppm}$$
$$(1 \text{ kHz} - 10 \text{ kHz}).$$

The temperature coefficient of the current ratio of the new active inductive shunt is less than 0.1 ppm/°C (not including the temperature coefficient of Z_0).

V. Conclusion

The new active transformer described in this paper can be used in the frequency range of 40 Hz to 10 kHz. The rated current ratio is 0.01 to 1. The relative uncertainty (3σ) of the current ratio is $(1 + j1)$ ppm to $(8 + j8)$ ppm over the frequency band of 40 Hz – 10 kHz. The external burden referred to in this paper is a 10-Ω ac resistor that can be transformed to an equivalent 0.1-Ω resistor to produce an audio-frequency current-to-voltage transducer. It should be noted that the burden could also be reactive in order to produce quadrature or complex current-to-voltage relationships.

Appendix I

A detailed circuit diagram of the two-stage voltage follower (A) is shown in Fig. 6, where A_1 is the first stage amplifier that drives the common of A_2 (point V), and A_2 is the second stage amplifier that corrects for the remaining difference between V and V_{in}. Amplifiers A_5 and A_6 provide the dc power required for A_2. If the open-loop gains of A_1 and A_2 are G_1 and G_2, respectively, the output voltage of A can be represented by

$$V_{out} = V_{in}\left(1 - \frac{1}{G_1 G_2}\right) = V_{in}(1 - \gamma_A) \qquad (14)$$

where

$$\gamma_A \approx \frac{1}{G_1 G_2}. \qquad (15)$$

Appendix II

Derivation of the fourth and fifth equations in (10).

(A) Because

$$Z_{02} = \frac{I_0 Z_0}{I_2}$$
$$I_0 \approx I_1$$
$$I_2 \approx I_{m1}$$

and

$$\gamma_{m1} \ll \frac{Z_0}{Z_{m1}}$$

Therefore

$$Z_{02} \approx \frac{I_1 Z_0}{I_{m1}} \approx \frac{Z_0}{\gamma_{m1} + \dfrac{Z_0}{Z_{m1}}} \qquad (16)$$

and

$$Z_{02} \approx Z_{m1} \approx Z_m. \qquad (17)$$

(B) By similar reasoning as in 2(A) above

$$Z_{03} = \frac{I_0 Z_0}{I_3} \approx \frac{I_1 Z_0}{I_{m2}} = \frac{I_{m1}}{I_{m2}}\left(\frac{I_1 Z_0}{I_{m1}}\right).$$

From (16) and (17)

$$Z_{03} \approx \frac{I_{m1}}{I_{m2}} Z_m \approx \frac{Z_m}{\gamma_{m2} + \dfrac{\gamma_A Z_{02}}{Z_{m2}}}.$$

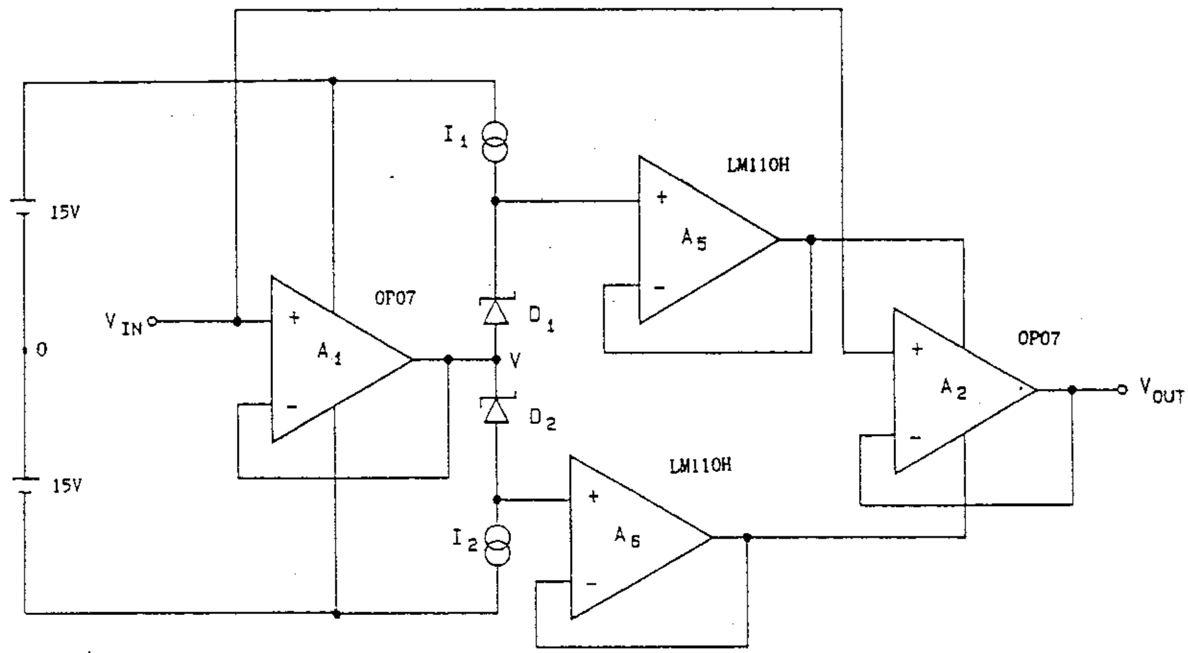

Fig. 6. Detailed circuit diagram of the two-stage voltage follower.

Since

$$\frac{\gamma_A Z_{02}}{Z_{m2}} \ll \gamma_{m2}$$

therefore

$$Z_{03} \simeq \frac{Z_m}{\gamma_{m2}} \simeq \frac{Z_m}{\gamma_m}. \tag{18}$$

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References

[1] Z.-T. Qian, "Principle of inductive voltage dividers," in Symposium of NIM. 1976.

[2] Geoffrey E. Beard, "Single-stage amplifier-aided current transformers prossessing small ratio error at 60 Hz," *IEEE Trans. Instrum. Meas.*, vol. IM-28, pp. 141–146, June 1979.

[3] G. E. Beard, "100:1 step-up amplifier-aided two-stage current transformer with small ratio errors at 60 Hz," *IEEE Trans. Instrum. Meas.*, vol. IM-28, pp. 146–152, June 1979.

[4] W. C. Sze, "An injection method for self-calibration of inductive voltage dividers," *J. Res. NBS*, vol. 72C, no. 1, 1968.