Method for Automatic Compensation of the Loading Effect for High-Precision Buffer Amplifiers and Voltage Dividers

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Abstract
To reduce errors due to loading effects, an automatic compensation circuit (ACC) for the loading effect is developed. The concept of the ACC is quite simple. The ACC generates a current in relation to the difference between the input and load voltages. The ACC compensates for the errors automatically with only a connection to the buffer amplifier in parallel. The errors due to loading effects were compensated to nearly zero with the ACC. Furthermore, to confirm the function of the ACC, we used an inductive voltage divider (IVD) that has known load characteristics. The errors of the in-phase components reach $100 \times 10^{-6}$ owing to loading effects, but the errors are compensated to nearly zero with the ACC. Similarly, the errors of the quadrature components are compensated by the ACC automatically.

Keywords: Loading Effect, Buffer Amplifier, Voltage Divider, Compensation, Measurement

1. Introduction
The buffer amplifiers used in the field of electrical standards must have high-precision specifications.[1] One of the key issues is to reduce the loading effects of the buffer amplifier. A voltage divider is constituted by the output impedance of the buffer amplifier and load when the load is connected. The error due to loading effects can be compensated, for example, by using voltage or current injection in the bridge circuit.[2, 3] These methods are very accurate and useful, but the measurement setup is complicated and not easy to operate. Therefore, buffer amplifiers are more useful if they have an automatic compensation function for loading effects.[4] There are many technologies for compensation of the loading effect in the field of power circuit such as AC-DC converter and DC-DC converter.[5, 6] However, the technologies are realized by using switching circuit and the accuracy of signal is not high because of the ripple due to the switching. Therefore, to realize the accurate automatic compensation function without switching circuit, an automatic compensation circuit (ACC) is developed. The main aim of the ACC is the accurate measurement of current/voltage at power frequency to 50th harmonics with 1 kΩ load for international comparison of accurate measurement of current. This paper describes in detail the concept of the ACC, and its application to a buffer amplifier and a voltage divider.

2. Compensation of Loading Effects
The simple concept of the ACC is shown in Fig. 1. The output impedances of the buffer amplifier $Z_o$ and the load $Z_L$ form a voltage divider. This means that the voltage $V_L$ across $Z_L$ differs from the voltage under unloaded conditions, and a current $i_L$ flows through $Z_L$. Therefore, the ACC plays a role in keeping $i_L = i_c$. Then, the current $i_0$ from the buffer amplifier will be zero.

A schematic diagram of the ACC is shown in Fig. 2. The ACC consists of a differential amplifier, voltage amplifier, buffer amplifier, and constant voltage-to-current converter. The ACC generates a current in relation to the voltage difference $V_D = V_s - V_L$. When $V_L$ approaches $V_s$, the relationships between currents become $i_c = i_L$ and $i_0 \approx 0$.

![Fig. 1 Concept of the ACC. A relationship between the voltage and the current is present when the ACC is connected.](image-url)
3. Evaluation of a Buffer Amplifier with ACC

3.1 Measurement setup

Figure 3 shows the measurement setup for evaluation of a buffer amplifier with the ACC. The input voltage is 1 V in the frequency range from 45 Hz to 3 kHz. The basic operation is to measure the difference between the input voltage and the output voltage with a polarity reversing operation to cancel the deviation derived from the lock-in amplifier (“D” in Fig. 3) and signal path. Basically, a sinewave voltage $V_{in}$ and the output voltage by the buffer amplifier with respect to the input voltage are fed to the differential lock-in amplifier D, and the voltage difference is measured for the in-phase and quadrature components. The measurements were performed by the following procedure. First, the switch in Fig. 3 was connected to the side without load. In this state, the sine-wave voltage was input, and the frequency was swept from 45 Hz to 3 kHz. Then the switch was changed, and the frequency was swept again from 45 Hz to 3 kHz. Thus, results were subtracted from the measured data of the buffer amplifier to provide the correction. The influence of input signal accuracy as well as noise of the cables and other components is eliminated by this procedure.

3.2 Evaluation results

The measurements were carried out in three conditions (open load, 1 kΩ load, and 1 kΩ load with ACC). Figure 4 shows the in-phase and quadrature deviations of the buffer amplifier. The voltage error $\varepsilon$ in Fig. 4 were defined as follows:

$$V_{BUF} = V_{in}(1 + \varepsilon)$$  \hspace{1cm} (1)

Using the in-phase component $\varepsilon_i$ and the quadrature component $\varepsilon_q$, this can be expressed as follows:

$$\varepsilon = \varepsilon_i + j\varepsilon_q = \frac{V_{BUF} - V_{in}}{V_{in}}$$  \hspace{1cm} (2)

With an open load, the voltage error of the in-phase component is very small up to 400 Hz and increases above 1 kHz. The voltage error of the quadrature component increases with frequency. The voltage difference of the in-phase component with a 1-kΩ load decreases because of the voltage drop by the output impedance of the buffer amplifier and the load.

The frequency characteristics of the buffer amplifier with ACC are flat with frequency for both the in-phase and quadrature components. In other words, the ACC contributes by compensating the voltage drop derived from the load and output impedance of the buffer amplifier. The ACC compensates for the errors automatically with only a
connection to the buffer amplifier in parallel. The errors due to loading effects were compensated to nearly zero with the ACC.

4. Application to Voltage Dividers

The ACC worked well for automatic compensation of the loading effect of a buffer amplifier. This means the ACC can be applied to similar situations that need automatic compensation of the loading effect. One of these situations is that of a voltage divider. Therefore, we used an inductive voltage divider to test the ACC.

Two-stage inductive voltage dividers (IVDs)[2] play an important role in several research areas where accurate impedance or power measurements are necessary, for example, the evaluation of the transformer ratio of a bridge circuit for precise impedance measurements, such as for capacitance and inductance standards. In addition, a precision IVD is an important component of sinusoidal and nonsinusoidal power standards.[7] Although the output impedance of a two-stage IVD is practically quite small, the effect of the output impedance is significant when an extremely small measurement uncertainty is required for the IVD calibration, e.g., less than $10^{-8}$. Therefore, IVD calibration using the build-up method[8] based on Thompson’s method[9, 10] uses unloaded conditions. However, the IVD ratio error may deviate from the calibrated values when calibrated IVDs are used in some applications because of the relationship between the IVD output impedance and the loads. Thus, evaluation of the loading effects on IVDs is an important issue. Therefore, load-characterization results of two-stage IVDs with resistive loads up to 10 kHz were evaluated. In addition, an ACC for the loading effects of IVDs is applied to reduce the errors due to loading effects.

4.1 Calibration of voltage ratio of IVD

The IVD is calibrated using the build-up method based on Thompson’s method, as shown in Fig. 5.[9] The build-up method provides precise calibration results because the potentials at each IVD tap are kept constant. The important features of the system are the measurement of small voltage differences and the measurement under unloaded conditions. Therefore, the calibration system includes a voltage comparator that operates based on the coaxial difference transformer, detector windings, an injection transformer, and shielded switching system called special connectors to achieve more accurate measurements.[3] The switches and injection current sources are used to reduce the leakage current due to the capacitance of the cable.

![Fig. 5 IVD calibration using the build-up method. IVD1 is the device under test (DUT), IVD2 is used for voltage adjustment, and CalT is a transformer designed such that the ratio between the secondary and primary values is about 1:N. Using the voltage difference $V_x - V_y$ on the secondary side of the transformer CalT (between taps x and y) as a reference, the voltage difference between every two adjacent taps, $V_n - V_{n+1}$, in IVD1 can be successfully measured to determine the voltage ratio of each tap of IVD1.[9]](image)

The switch is turned on, and the injection transformer is adjusted such that the detector shows 0 (null), after that, the switch is turned off, and the current source is adjusted such that the detector shows 0 again. If these adjustments are repeated, the detector finally shows a constant value that is independent of the switch mode. It means the current derived from the IVD is zero, even if the switch is ON because the potentials at nodes a and b are the same at this time. In this way, the unloaded conditions are realized for precise IVD calibration.

Figure 6 shows the calibration results of an IVD both in-phase and quadrature components at 1 kHz and 10 kHz under unloaded conditions. The ratio errors are the deviations of the voltage ratio from the nominal ratios of the IVD.

The frequency characteristics of an IVD (0.1 tap, 0.4 tap, and 0.8 tap) at frequencies from 60 Hz to 10 kHz (Fig. 7) show that the in-phase errors remained constant up to 1 kHz but maximum error reached approximately $1 \times 10^{-6}$ at 10 kHz. However, the quadrature errors varied with frequency, maximum error is reaching $1.5 \times 10^{-6}$ at 10 kHz. As you can see, this method can provide very accurate measurements of voltage ratios. However, these values were obtained using the build-up method under approximately unloaded conditions.
4.2 Loading effect of voltage divider

The IVD load characteristics were evaluated by comparing the measured values with resistive and capacitive loads and without a load. Figure 8 shows the evaluation system of the IVD load characteristics. The output voltage difference between IVD1 and IVD2 was measured. To detect the very small variation with loads, IVD2 was used to obtain an output voltage similar to that of IVD1. The differences between the voltage without a load $V_s$ and the voltage with a load $V_L$ are measured by the evaluation system. Then, the error due to the loading effects $\epsilon_L$ is expressed as follows:

$$\epsilon_L = \frac{V_L - V_s}{V_{IN}}$$  \hspace{1cm} (3)

where $l_s$ is the calibrated ratio of IVD1 by the build-up method and $V_{IN}$ is the input voltage of the IVDs.

Further, the switching system in Fig. 8 eliminated the influence of the cables and connectors. The input impedance of the detector affected the evaluation of the IVD load characteristics. Therefore, we first evaluated the effect of the detector input impedance with a simulated impedance of 10 MΩ // 50 pF. The ratio errors due to the IVD input impedance at 10 kHz were $0.38 \times 10^{-6}$ and $-0.53 \times 10^{-6}$ for the in-phase and quadrature components, respectively. The measurement uncertainties of the in-phase and quadrature components were estimated to be $0.04 \times 10^{-6}$ and $0.03 \times 10^{-6}$, respectively (coverage factor: $k = 2$).

We evaluated the load characteristics of IVD1 and IVD2. The positions of IVD1 and IVD2 were swapped when IVD2 was evaluated. Figure 9 shows the frequency characteristics of the IVD with resistive load. The error in Fig. 9 means the deviation from the calibrated voltage ratio of an IVD. The error in the in-phase components with resistive load did not vary considerably with the frequency. The quadrature components with resistive load were proportional to the frequency. IVD2 also exhibited load characteristics similar to IVD1. The loading effects largely affected both the IVD in-phase and quadrature components.\[11\]
The ratios of the IVDs were calibrated under unloaded conditions; therefore, these frequency characteristics of the loading effects are useful for estimating the error with other loads.

4.3 Compensation of loading effect with ACC

The error due to loading effects can be compensated by using voltage or current injection in the bridge circuit,\[2, 3\] for example. These methods are very accurate and useful, but the measurement setup is complicated and not easy to operate. Therefore, the IVDs are quite useful if they have an automatic compensation function for loading effects. To realize the automatic compensation function, an automatic compensation circuit (ACC) for IVDs is developed. The concept of the ACC is shown in Fig. 10.

The IVD load characteristics were evaluated for 1-kΩ loads with the ACC, as shown in Fig. 11.

Figure 12 shows the evaluation results of the load characteristics of IVD1 with the ACC up to 3 kHz. The errors of the in-phase components reach $100 \times 10^{-6}$ owing to the loading effects, but the errors are compensated to nearly zero with the ACC. Similarly, the errors of the quadrature components are compensated by the ACC automatically. As shown in Figs. 12(c) and (d), the ACC worked well, even though the output voltage of the IVD increased (tap 0.8).

In addition, we evaluated the load characteristics of IVD2 with the ACC. The positions of IVD1 and IVD2 were swapped when IVD2 was evaluated with the ACC. The errors of both the in-phase and quadrature components of IVD2 are also compensated well with the ACC. Therefore, the ACC can automatically compensate for the loading effects of IVDs.

5. Conclusion

To reduce the errors due to loading effects, an ACC was developed for the buffer amplifier. The frequency charac-
Characteristics of the buffer amplifier with ACC were flat with frequency for both the in-phase and quadrature components. The ACC compensates for the errors automatically with only a connection to the buffer amplifier in parallel. The errors due to loading effects were compensated to nearly zero with the ACC.

Furthermore, the load-dependence characteristics of two-stage IVDs were evaluated. To reduce the errors due to the loading effects of IVDs, an ACC was applied to the IVDs. The ACC compensates for the errors automatically with only a connection to the output terminal of the IVDs. The errors due to loading effects were compensated to nearly zero with the ACC.

Our future work will extend the range of the voltage, frequency, and load value for many power applications.

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