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A new dc-CT utilizing the skin effect of a conducting current in a small magnetic pipe

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This paper proposes a new method for noncontact measurement of the dc current. This device utilizes the skin effect of an ac current flowing in a ferromagnetic pipe with an amorphous-tape wound structure. The dc current controls the skin depth of the ac current. This dc-current transformer (CT) has no winding and outputs the difference between the terminal voltage of the pipe and the induced voltage in a one-turn coil. The ac current does not affect the dc line because of axis symmetry. A linear relation between the output and dc current is obtained when an appropriate ac drive frequency is selected. Improvement of gain can be attained by reducing the diameter. It is clarified that the magnetic pipe is applicable for a dc-CT with a small size.

I. INTRODUCTION

Noncontact measurements of the dc current are widely used in the area of power systems and electronic circuits.[1] Recently it has become necessary to develop a dc current sensor having no windings in order to meet a need to miniturize the sensors.

We developed a new dc current sensor utilizing a magnetic pipe[2–4] with an amorphous-tape wound structure. This device is easily assembled without winding and is applicable for dc-CT. The operating principle is based on controlling the skin depth of the ac current applied directly to the pipe. This paper reports on the operating principle and performance of the device.

II. STRUCTURE AND OPERATING PRINCIPLE

Figure 1 shows the structure and circuit connection for the dc-CT. The pipe is made of Co-base zero magnetostrictive amorphous tape with a width of 20.8–21.8 mm and a thickness of 21–27 μm. Copper tape with a thickness of 30 μm is placed on each edge of the amorphous tape and wound together in order to form electric contacts. The dc line is placed on the axis of the pipe. A high-frequency current $\dot{I}$ is fed directly to the pipe along the axial direction by a sinusoidal power source $\dot{e}_a$. $\dot{V}_{\rm diff}$ is the output voltage which is easily obtained by passing one of the lead lines for the terminal voltage through the inside of the pipe. $\dot{V}_{\rm diff}$ represents the difference between the terminal voltage $\dot{V}_d$ and induced voltage $\dot{V}_s$ in a one-turn coil, as explained in Fig. 2:

$$\dot{V}_{\rm diff} = \dot{V}_d - \dot{V}_s. \quad (1)$$

Figure 2(a) explains the operation of the device when the dc current I_d is zero. The tape-wound structure of the pipe is approximated by the bulk structure having the same length and cross-sectional area.[3] The current density on the inner surface is almost zero because of the skin effect. If the end effect of the ac current is neglected and if the radial component of the ac current is very small, the terminal voltage $\dot{V}_d$ of the pipe becomes independent of the distance r from the axis of the pipe[2,3]:

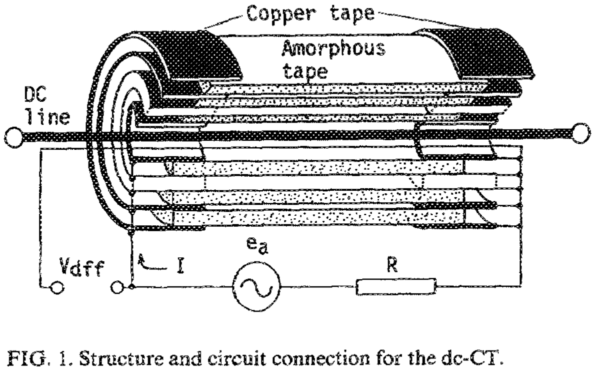

FIG. 1. Structure and circuit connection for the dc-CT.

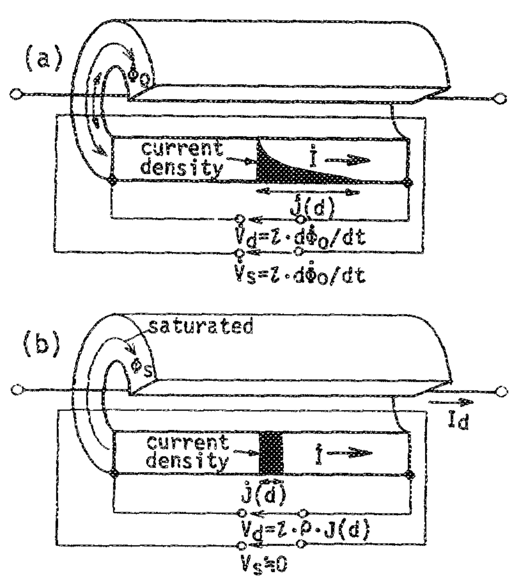

FIG. 2. Explanation of the operating principle: (a) dc current equals zero; (b) dc current is large enough to saturate the flux.

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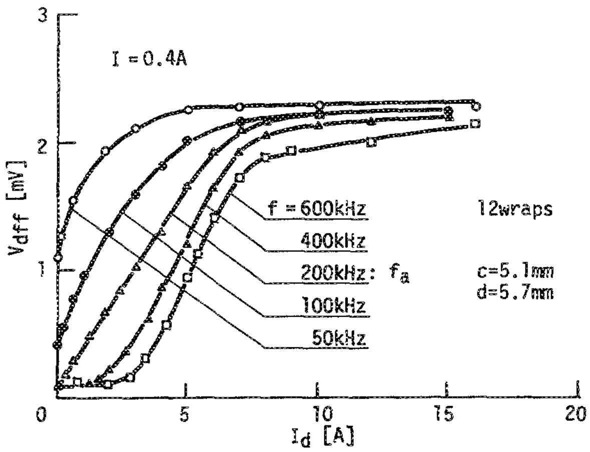

FIG. 3. Frequency dependence of operating characteristics.

$$\dot{V}_d = l\left(\rho\,\dot{J}(r) + \frac{d\dot{\Phi}(r)}{dt}\right), \tag{2}$$

where l is the length of the pipe, ρ is the resistivity, and $\dot{\Phi}(r)$ is the interlinkage flux with the supposed cylinder of radius r and of unit length. $\dot{\Phi}(r)$ exists outside the supposed cylinder. $\dot{J}(r)$ is the current density on the supposed cylinder. Equation (2) represents the balance between current density and flux.

Let the inner radius and outer radius of the pipe be c and d, respectively. When the dc current is not applied, Eq. (2) becomes as follows on the inner surface:

$$\dot{V}_d = l\,\frac{d\dot{\Phi}_0}{dt}, \tag{3}$$

where Φ_0 is the sum of the flux in the pipe. Since the induced voltage $\dot{V}_s$ in a one-turn coil is identical to Eq. (3), the voltage difference $\dot{V}_{\rm diff}$ becomes zero.

When the dc current is large enough to saturate the flux, the ac current distributes uniformly in the pipe owing to the decrease of permeability as shown in Fig. 2(b). In this case, the induced voltage $\dot{V}_s$ becomes zero while the terminal voltage $\dot{V}_d$ is proportional to the dc resistance of the pipe. Then the voltage difference $\dot{V}_{\rm diff}$ is

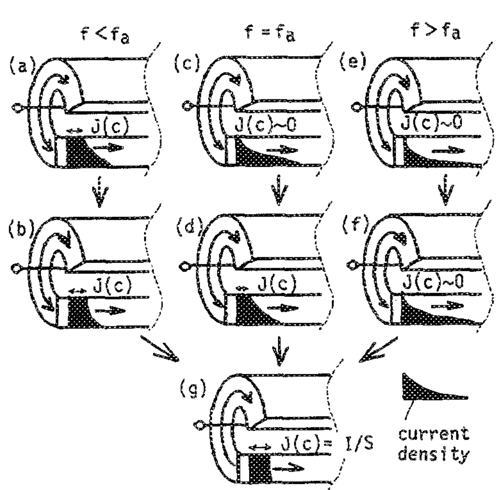

FIG. 4. Influence of drive frequency on ac current distribution.

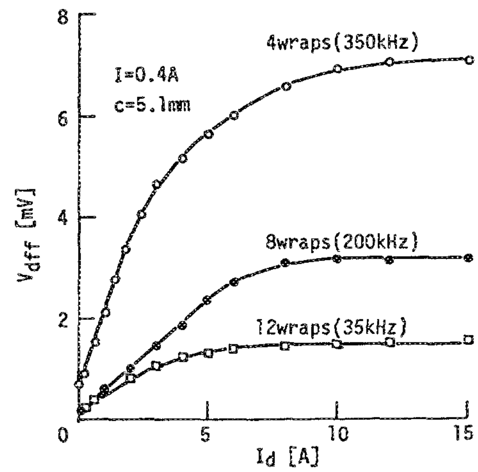

FIG. 5. Relation between output and number of wraps of the amorphous tape.

$$\dot{V}_{\rm diff} = l\rho\dot{J}(d) = (l\rho/S)\dot{I}, \tag{4}$$

where S is the cross-sectional area of the pipe.

From the above considerations, the voltage difference $\dot{V}_{\rm diff}$ can be utilized as the output for dc-CT since the voltage increases with the increase of the dc current.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows relations between dc current I_d and output voltage $V_{\rm diff}$ obtained for a pipe with 12 wraps of amorphous tape. The waveform for $\dot{V}_{\rm diff}$ was almost sinusoidal.[5] The linear relation between I_d and $V_{\rm diff}$ is obtained up to $I_d = 6$ A for 200 kHz. When the dc current is zero, the output voltage decreases with the increase of drive frequency and then reaches a minimum at 200 kHz. Therefore, the appropriate drive frequency f_a for this pipe is 200 kHz.

Figure 4 illustrates the ac current distribution models in the pipe. When the drive frequency equals f_a, the current density $J(c)$ on the inner surface increases with the increase of dc current from a very low level, as shown in Figs. 4(c), 4(d), and 4(g).

In case the drive frequency is lower than f_a, the ac current flows through the inner surface regardless of the dc current as shown in Figs. 4(a), 4(b), and 4(g). Accordingly, the terminal voltage $\dot{V}_d$ differs from an induced voltage $\dot{V}_s$ at any amplitude for dc current as seen from Eq. (2).

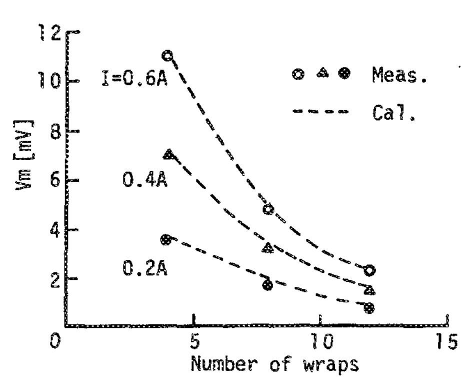

FIG. 6. Calculation of the maximum output voltage.

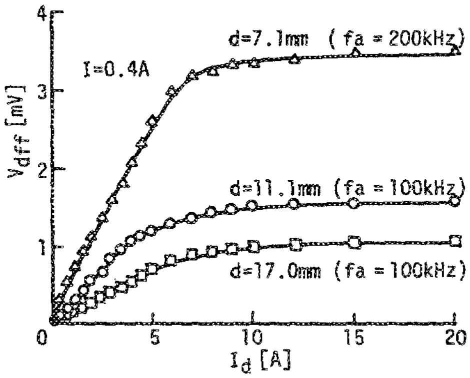

FIG. 7. Relation between the diameter of the pipe and the output voltage.

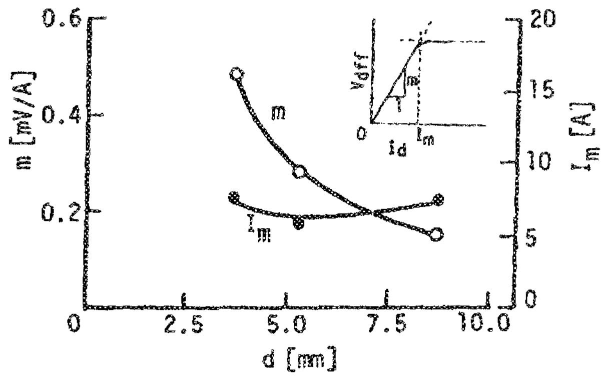

FIG. 8. Comparison of gain and maximum range of measurable dc current against the diameter of the pipe.

When the drive frequency is higher than f_a, the skin depth is reduced as compared with that when $f=f_a$. Therefore, the current density $J(c)$ on the inner surface remains zero although the dc current is increased to a certain value as explained in Figs. 4(e), 4(f), and 4(g).

In the case of another pipe with a different number of wraps, the appropriate frequency increases with the reduction of the wraps, as shown in Fig. 5. This is because a thinner skin depth is required for a thinner pipe. In Fig. 5 the maximum output voltage increases with a decrease in the number of wraps of the amorphous tape.

Figure 6 shows a comparison of the measured maximum output voltage V_m with the ones calculated by Eq. (4). The calculated values explain well the measured results. Therefore, it is seen that the maximum output voltage is proportional to the product of the dc resistance of the pipe and amplitude of the ac current.

IV. OPERATING PERFORMANCE

The above discussion indicates that the measurable dc current is limited by flux saturation in the pipe and that the ratio of the output voltage to dc current is concerned with the ratio of field strength to dc current in the pipe. Therefore, the diameter of the pipe effects the performance of the device.

Figure 7 shows the influence of the diameter on the output voltage. Each pipe is 21.8 mm in length with eight wraps of amorphous tape. The pipes are driven with appropriate frequencies. We defined the gain m and the maximum amplitude I_m for measurable dc current as inserted in Fig. 8.

Readout values of the gain m and the maximum amplitude I_m of measurable dc current are summarized in Fig. 8. With the reduction of diameter, the gain increases while the maximum amplitude for measurable dc current is almost independent of the diameter. Therefore, we can obtain a small dc-CT having a good performance without winding.

V. CONCLUSION

A new concept for dc-CT proposed here utilizes the change of ac current distribution against dc current in an amorphous tape-wound pipe. This device outputs the difference between the terminal voltage of the pipe and induced voltage in a one-turn coil. Such a voltage difference can be easily obtained by passing one of the lead lines for the terminal voltage through the inside of the pipe. This device has no winding. The ac current does not affect the dc line because of its axis symmetry.

The linear relation between output and dc current is obtained when the appropriate ac drive frequency is selected. From these results, it clarified that the magnetic pipe is applicable for a dc-CT with a small size.

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