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Modified Self-Saturated Magnetic Amplifier with Half-Wave Output

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In this paper, the modified circuit of the self-saturated magnetic amplifier with the half-wave output, which consists of two cores, is described. The steady state operations of this circuit with resistive load under the d-c voltage control are analysed on the assumption that the core has an ideal parallelogram-shaped dynamic hysteresis loop. Moreover, some experimental results of the steady state operation are illustrated. In this circuit, the higher gain is obtainable(1) compared with the self-saturated magnetic amplifier with single core, since the control winding may have the large number of turns in the modified circuit. The modified dircuit is simpler than the multistage self-saturated magnetic amplifier.

1. Introduction

The half-wave output is required in order to control some sorts of vibrator.(2) Therefore, thyratron, SCR or the half-wave self-saturated magnetic amplifier are available. Authors attempted to control it by the half-wave circuit and, for this purpose, devised a modified circuit of the self-saturated magnetic amplifier.

Originally, the self-saturated magnetic amplifier has the high gain, and so the half-wave circuit is suitable in order to obtain the half-wave output. However, in the half-wave circuit, the considerable higher impedance should be connected in the control circuit to prevent the effect of the a-c voltage induced from the output winding (winding is abbreviated wdg. hereafter), during the exciting interval. Consequently, it is impossible to take a large number of turns for the control wdg.

Fig. 1 shows the modified circuit. As shown in Fig. 1, in the modified circuit, two

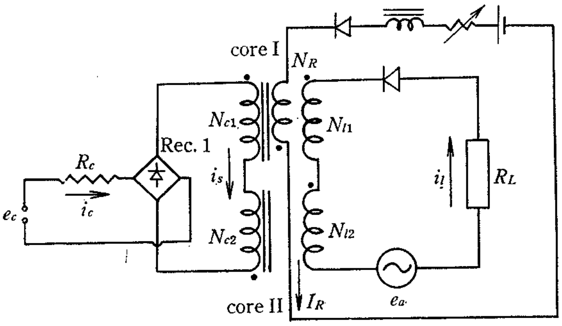

Fig. 1 Circuit diagram of the modified self-saturated magnetic amplifier.

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control wdgs. are connected in series oppositely and closed through the rectifier Rec. 1. Therefore, it is possible to take a large number of turns for the control wdg., so the high gain is obtainable.

2. Principle of Operation

The cores I and II have the identical magnetic characteristics. With respect to the number of turns, the output wdgs. N_{l1} and N_{l2} have the relation of $N_{l1}=N_{l2}=N_l$, and, in the same manner, the control wdgs. N_{c1} and N_{c2}, also, have the relation of $N_{c1}=N_{c2}=N_c$. From Fig. 1, the induced a-c voltage in the control side does not appear during the exciting interval. Since the constant reset current from the d-c source flows in the reset wdg. N_R through very high impedance, any interferrance can not appear during the transient interval. Let us explain the principle of the operation of the circuit shown in Fig. 1. First of all, it is assumed that the magnetic characteristics of the cores have the parallelogram-shaped dynamic hysteresis loop shown in Fig. 2. The ampere-turns required at the point 1, 2, 3,…………on the loop are designated AT_{a1}, AT_{a2}, AT_{a3},………… respectively.

When both the control voltage e_c and the a-c source voltage e_a are zero, the flux of core I is reset to the point 0 by means of the reset ampere-turns $I_RN_R=2AT_{a1}$, while the flux of core II is assumed to remain at the point 2.

During the interval of the positive half cycle of e_a, let the flux of core I reach at the point 4 on the loop when the phase angle $\omega t=\theta$. At $\omega t=\theta$, the exciting current i_{lx} can flow through N_{l1} and N_{l2}, and the circular current i_{sx} will flow through the circular circuit which consists of N_{c1}, N_{c2} and Rec. 1. Under this condition, the ampere-turns acting on the cores are given in the following relations

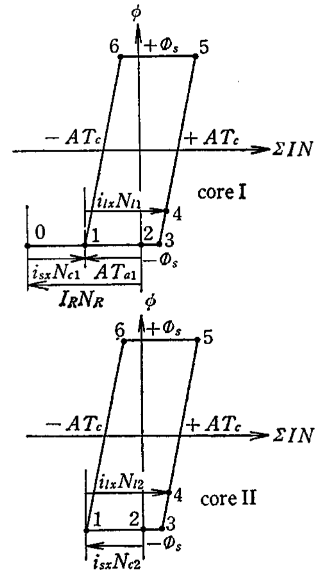


Fig. 2 Magnetic characteristics of the cores.

on the core I

$$-I_RN_R+i_{sx}N_{c1}+i_{lx}N_{l1}=AT_{a4} \tag{1}$$

on the core II

$$-i_{sx}N_{c2}+i_{lx}N_{l2}=AT_{a4} \tag{2}$$

Combining eqs. (1) and (2), the following equations are obtained

$$i_{sx}N_{c2}=I_RN_R-i_{sx}N_{c1}=\frac{1}{2}I_RN_R \tag{3}$$

$$i_{sx}=\frac{1}{2}\frac{N_R}{N_c}I_R \tag{4}$$

According to eq. (3) and Fig. 2, by giving the ampere-turns $i_{sx}N_{c2}$ to the core II, the flux of core I is reset to the point 1, while the flux of core II is also reset to the point 1. The reset ampere-turns $1/2 \times I_R N_R$ is maintained constant during the entire one cycle. Consequently, the cores I and II are always given the constant magnitudes of the reset ampere-turns. The circular current i_{sx} must flow always through the circular circuit and is given by eq. (4). Under this condition, in order that the fluxes of cores change from the negative saturation flux $-\Phi_s$ to the positive one $+\Phi_s$ during the positive half cycle of e_a, the magnitude of e_a is determined as follows

$$E_a = 4\pi f N_l \Phi_s \tag{5}$$

where $e_a = E_a \sin \omega t$ [V]

f : supply source frequency [c/s]

Φ_s : saturation flux [Wb]

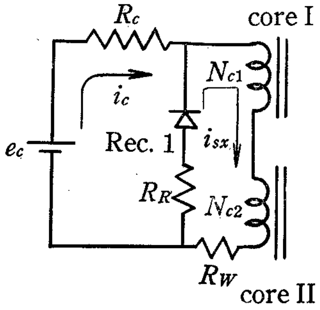


Fig. 3 Equivalent circuit of the control side.

During the negative half cycle of e_a, since the current flows through the output circuit, the fluxes of cores decrease by means of e_a. At the end of this interval the fluxes of cores returned to the point 1 of the loop by the voltage given by eq. (5).

Now, e_c is impressed. Under this condition the equivalent circuit of the control side is as shown in Fig. 3. It is assumed that the control-circuit resistance R_c is large enough. In case of $i_c < i_{sx}$, the great majority of the control current i_c flows through the circuit which consists of R_c, Rec. 1, R_R and e_c, in order that the rectifier forward resistance R_R is smaller than the control winding resistance R_W, and that i_c can not flow through the control wdgs. In case of $i_c \geq i_{sx}$, since the Rec. 1 blocks only for the current difference component i_c' between i_c and i_{sx}, i_c' flows through the control wdgs.

During the exciting interval, at the phase angle $\omega t = \theta$ when i_{lx} flows, the ampere-turns on the cores I and II are given as follows, respectively, from Fig. 4 on the core I

$$-I_R N_R + i_{sx} N_{c1} + \left(i_c' N_{c1} - \frac{1}{2} i_c' N_{c1} \right) + i_{lx} N_{l1} = AT_{a4} + i_c' N_{c1} \tag{6}$$

on the core II

$$-i_{sx} N_{c2} + \left(\frac{1}{2} i_c' N_{c2} - i_c' N_{c2} \right) + i_{lx} N_{l2} = AT_{a4} \tag{7}$$

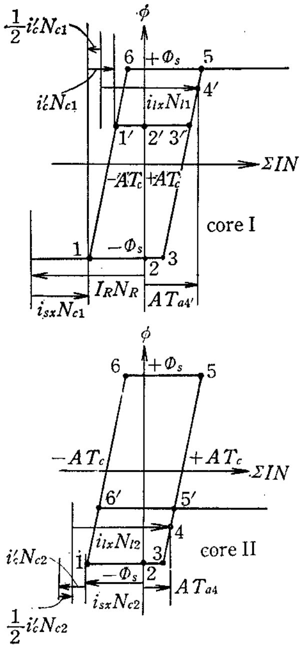


Fig. 4 Ampere-turns relations of the cores for $i_c \geq i_{sx}$.

Thus, the following current flows through the control-circuit resistance R_c

$$i_c = i_{sx} + \frac{1}{2} i_c' \tag{8}$$

The decreasing of i_c is caused by the exciting current in the output circuit.

As the phase angle of e_a advances, the flux of core I reaches the saturation point 5, resulting in collapse of the output wdg.-reactance of the core I. Consequently, since the control side resistance referred to the output circuit is nearly zero, e_a impressed across the load resistance R_L at θ_f.

During the negative half cycle of e_a, the current given by eq. (8) exists, because of the identical current through the output wdgs.

In Fig. 5, the wave shapes of the voltage and the current in some parts of the circuit are illustrated.

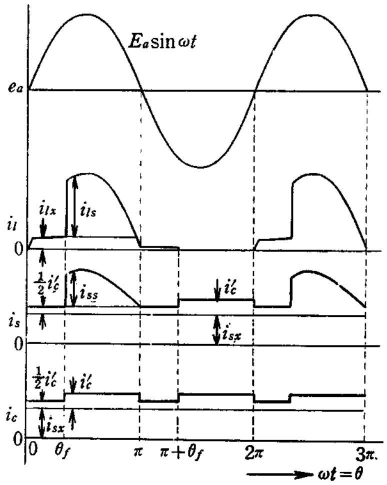


Fig. 5 Wave shapes of the voltage and the current in some parts of the circuit.

3. Analysis of Steady State Operation

3.1 For $i_c < i_{sx}$

In this case, i_c can not flow through the control wdgs. At $\omega t=\theta$, during the positive half cycle of e_a, the exciting current given by the equation below exists

$$i_{lx} = \frac{1}{N_l} \left\{ \frac{I_R N_R}{2} + AT_{a4} \right\} \tag{9}$$

Since the cores can not saturate, only the exciting current flows during the entire cycle of e_a. Employing AT_a (θ) which is the time function of ampere-turns AT_a acting on the core at $\omega t=\theta$, we obtain the average exciting current I_{lx} as follows

$$I_{lx} = \frac{1}{2\pi} \frac{1}{N_l} \left\{ \int_0^{2\pi} \frac{I_R N_R}{2} \, d\theta + \int_0^{2\pi} AT_a(\theta) \, d\theta \right\} \tag{10$'$}$$

The second term of above equation is equal to zero, so that I_{lx} becomes

$$I_{lx} = \frac{1}{N_l} \frac{I_R N_R}{2} \tag{10}$$

3.2 For $i_c \geq i_{sx}$

3.2.1. Control Current

In this case, i_c' the current difference between i_c and i_{sx}, flows through the control wdgs. and is concerned in the control of the core flux. $(AT_{a5} - AT_{a3})$, the ampere-turns difference between two ampere-turns which correspond to $+\Phi_s$ and $-\Phi_s$, is presented by ΔAT_a in Fig. 2.

Then, the relation between i'_c and θ_f is determined. From Fig. 4, the relation between the magnitude of the reset flux and corresponding ampere-turns becomes as follows

$$\frac{\dfrac{1}{\omega N_l}\displaystyle\int_{\pi}^{2\pi}\frac{E_a}{2}\sin\theta d\theta}{\Delta AT_a}=\frac{\dfrac{1}{\omega N_l}\displaystyle\int_{\pi}^{\pi+\theta_f}\frac{E_a}{2}\sin\theta d\theta}{\Delta AT_a-i'_cN_c}$$

$$\therefore\ i'_c=\frac{1}{2}\frac{\Delta AT_a}{N_c}(1+\cos\theta_f) \tag{11}$$

I'_c denotes the average value of i'_c and is given by the following equation as can be seen from Fig. 5

$$I'_c=\frac{1}{4\pi}\frac{\Delta AT_a}{N_c}(2\pi-\theta_f)\ (1+\cos\theta_f) \tag{12}$$

As i_{sx} flows already through the control circuit, taking account of $I_{sx}=i_{sx}$, the total average control current I_c is as follows

$$I_c=\frac{1}{4\pi}\frac{\Delta AT_a}{N_c}(2\pi-\theta_f)\ (1+\cos\theta_f)+\frac{1}{N_c}\frac{I_RN_R}{2} \tag{13}$$

3.2.2 Load Current

During the exciting interval, it is assumed that e_a is entirely impressed across the output wdgs., and therefore the exciting current i_{lx} flows through the output circuit. From eqs. (6) and (7), the exciting current i_{lx} at $\omega t=\theta$ becomes

$$i_{lx}=\frac{1}{N_l}\left\{\frac{I_RN_R}{2}+AT_{a4}+\frac{i'_cN_c}{2}\right\} \tag{14}$$

Employing AT_c (the coercive ampere-turns) and ΔAT_a, eq. (14) yields the next relations during the positive half cycle

$$i_{lx}=\frac{1}{N_l}\left\{\frac{I_RN_R}{2}+\frac{i'_cN_c}{2}+AT_c-\frac{1}{2}\Delta AT_a\cos\theta\right\} \tag{15}$$

during the negative half cycle

$$i_{lx}=\frac{1}{N_l}\left\{\frac{I_RN_R}{2}+\frac{i'_cN_c}{2}-AT_c-\frac{1}{2}\Delta AT_a\cos\theta-\frac{1}{2}\Delta AT_a(1+\cos\theta_f)\right\} \tag{16}$$

During the positive half cycle, after the saturation of core I, it is recognized that the constant ampere-turns remain in core II. Thus, combining eqs. (15) and (16), the average exciting current I_{lx} is calculated as follows

$$I_{lx}=\frac{1}{2\pi}\frac{1}{N_l}\left\{\frac{I_RN_R}{2}(\pi+\theta_f)+AT_c(\pi-\theta_f)+\frac{1}{4}\Delta AT_a(\pi-\theta_f)(1-\cos\theta_f)\right\} \tag{17}$$

After the saturation of the core I, the saturation component i_{ls} of the output current flows through N_{l2}, and consequently, through N_{c2}, the saturation component i_{ss} of the circular current must flow by the current-transformer action from N_{l2} into N_{c2}. The equivalent circuit for this case is illustrated in Fig. 6. Then, for the cases of $R_R \ll R_c$ and $R_W \ll R_c$ in Fig. 6, the following equations are obtained

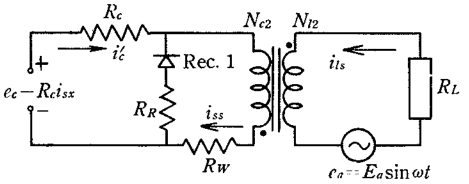


Fig. 6 Equivalent circuit during the saturation interveal.

$$\left.\begin{aligned} i'_c &\doteqdot \frac{e_c - R_c i_{sx}}{R_c} \\ i_{ls} &\doteqdot \frac{e_a}{R_L} \end{aligned}\right\} \tag{18}$$

The average value I_{ls} of i_{ls} is given by the following

$$I_{ls} \doteqdot \frac{1}{2\pi}\frac{1}{R_L}\int_{\theta_f}^{\pi} e_a d\theta = \frac{1}{2\pi}\frac{E_a}{R_L}(1+\cos\theta_f) \tag{19}$$

Thus, from eqs. (17) and (19), total average output current I_l becomes approximately

$$\begin{aligned} I_l \doteqdot & \frac{1}{2\pi}\frac{1}{N_l}\left\{\frac{I_R N_R}{2}(\pi+\theta_f) + AT_c(\pi-\theta_f) + \frac{1}{4}\Delta AT_a(\pi-\theta_f)(1-\cos\theta_f)\right\} \\ & + \frac{1}{2\pi}\frac{E_a}{R_L}(1+\cos\theta_f) \end{aligned} \tag{20}$$

From eqs. (13) and (20), the control characteristics are obtained theoretically and shown in Fig. 7.

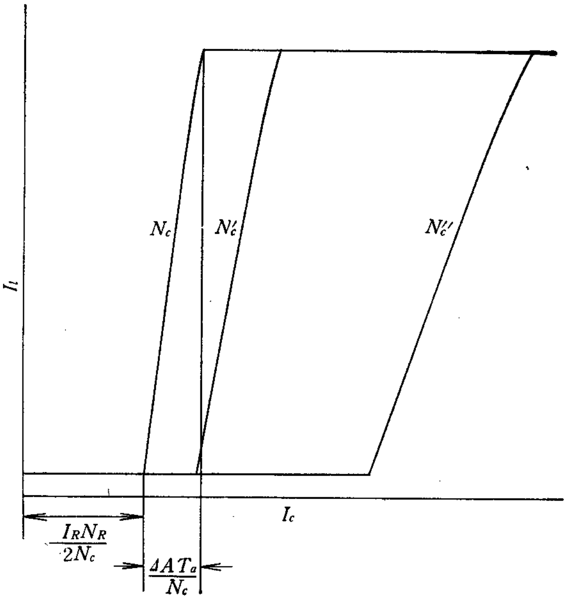


Fig. 7 Theoretical control characteristics.

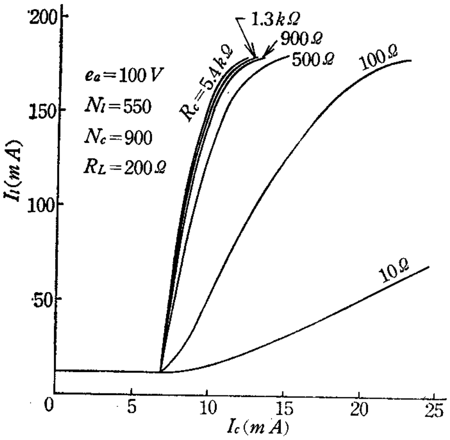


Fig. 8 Experimental control characteristics for various values of R_c.

4. Experimental Results

The circuit used in experiment is the same as is shown in Fig. 1. The cores are Sendelta of 0.1×20×80×110mm ; $N_l=550$, $N_R=70$. The reset current I_R equals 208mA. Fig. 8 demonstrates the effects of the control-circuit resistance variation on the control characteristics. In this case, little difference of the control characteristics exists for more than $R_c=900\Omega$. The effects of the value of N_c are shown in Fig. 9. The current gains are, in the linear portion of the curves in Fig. 9, about 70,55 and 30 correspondingly to the control wdg. of 900,600 and 300 turns, respectively. The major reason why the current gains differ from the experimental results will be that N_c is more effective than R_c as the number of turns increases.

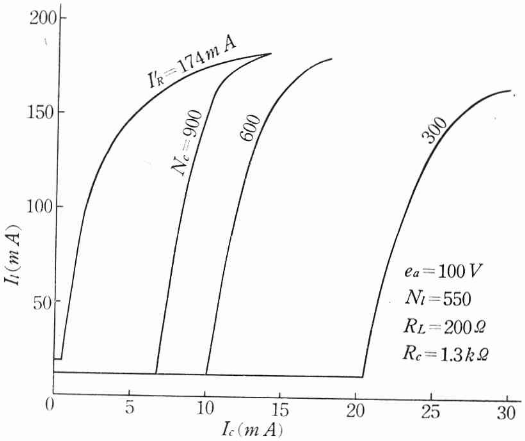
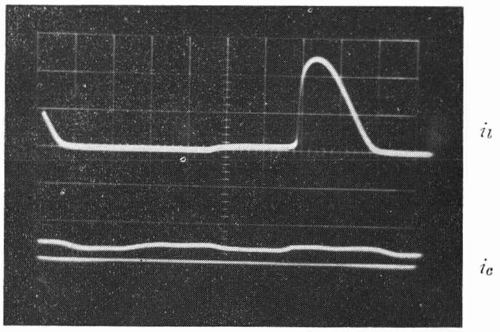


Fig. 9 Experimental control characteristics, illustrating effects of variation of N_c turns.

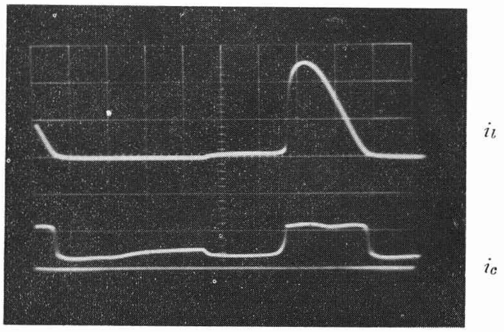
The oscillograms showing the wave shapes of i_l and i_c are presented in Photo. 1. Practically, during the negative half cycle of e_a, the flux of core I changes very gradually by means of the ampere-turns $1/2\times I_RN_R$, even after the flux of core II reached saturation. When R_c is low, the flux change during this interval prevents the control current from increasing.

Fig. 10 shows the control characteristics taken with the variety of e_a.

The characteristic curve which corresponds to $I'_R=174_{mA}$ in Fig. 9 is one for the case that the reset ampere-turns $I'_RN_R=174_{mA}\times70_T$ are given to the core II on which the new reset wdg. N_R is arranged, while the ampere-turns on core I remains by $I_RN_R=208_{mA}\times70_T$.



$R_c=1.3k\Omega$



$R_c=100\Omega$

Photo. 1 Wave shapes of i_l and i_c.

5. Comparison with Self-Saturated Magnetic Amplifier

If one compares with the self-saturated circuit, first, the comparison with the half-wave circuit having a single core must be done. The current gain equals 25, in the half-wave circuit (the control wdg. of 900 turns, the output wdg. of 550 turns, the load resistance 100Ω, the control circuit choke coil of 30H, the control-circuit resistance 350Ω, the source voltage 50V) ; while, in this circuit, it is equal to 70, corresponding to $N_c=900$ in Fig. 9. As this circuit consists of two cores, it is necessary to compare with the two-stage half-wave circuit. This circuit, however, is simple, taking account of the difficulty of the multistage circuit.3)

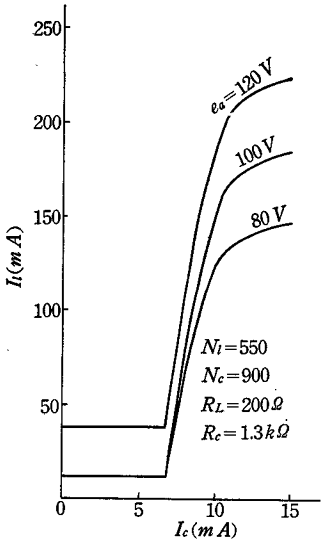


Fig. 10 Effects of e_a on the experimental control characteristics.

6. Conclusion

The steady state operation of the modified circuit has been analysed on the assumptions that the cores have the ideal parallelogram-shaped dynamic hysteresis loop and other circuit elements are also ideal. The usual cores, however, have a magnetic characteristic differed from the assumed one, and especially the minor loop has the complicated forms.4) Thus, the experimental results differ from the theoretical values.

It is found that the current gain of this modified circuit is higher than that of the half-wave circuit. In this modified circuit, it is possible to take the large number of turns for the control wdg., and consequently, the current gain increases.

This circuit gives the same results for the a-c control voltage, but the details are now under discussion.

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