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Speed Control of D. C. Moter by Ultra Low Frequency Signal

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Abstract

It is reported in this paper that by the application of thyratron amplifier with phanotron to the speed control of d. c. motor followed after ultra low frequency signal, its controlling characteristics indicate such excellent results that are never obtained by the other methods.

In this new controlling system, the series motor driven by the thyraton amplifier shows especially successful operations due to its series characteristics.

1. Introduction

In recent years, the electronic d. c. motor control, due to its high efficiency and precise control at reasonable cost, has been developed for increasing use in industrial applications and automatic control systems. The output voltage of the grid-controlled rectifier tube such as the thyratron or the ignitron, depends upon the motor speed in the case of the motor control by means of varying the output voltage of the tube. Contrarily, for the conventional motor-generator set, known as the Ward-Leonard system, the output voltage of the generator does not depend upon the motor speed. This is one of the important differences between the Ward-Leonard system and the electronic control system.

The thyratron amplifier circuit for controlling the d. c. motor is suggested in the present paper, in which the output voltage of the thyratron, independently of motor speed, can be controlled proportionally to the signal voltage fed into the grid circuit, by making use of the phanotron. The speed control of the d. c. motor by ultra low frequency signal was carried on satisfactorily.

2. Shunt motor control by ultra low frequency signal

(1) Circuit of a thyratron amplifier for a shunt motor control. The rotating armature of a d. c. motor with shunt excitation is generally represented by a series circuit consisting of a resistance R, an inductance L, and an e. m. f. e_c generated in the armature winding and acting as a counter voltage, which tends to oppose the flow of current resulting from an external voltage applied to the armature terminals. This counter e. m. f. is proportional to speed of motor n, under the assumption of a constant operating flux. Therefore it can be expressed by

$$e_c = cn \tag{1}$$

where c is a proportional constant.

The motor controlling circuit employing the thyratron amplifier with the phanotron

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is illustrated in Fig. 1, in which the motor is represented by the equivalent circuit mentioned above. In Fig. 1 $e=E_m \sin\theta$ represents the instantaneous a. c. plate voltage of the thyratron. The grid circuit of the thyratron is composed of the specified bias voltage $-A(1+\cos\theta)$ and a signal voltage e_s serves for controlling the angle of ignition. The thyratron starts to fire at that instant when the resultant grid voltage gets to the value of zero, neglecting the critical grid voltage. Therefore the angle of ignition θ_i is given by

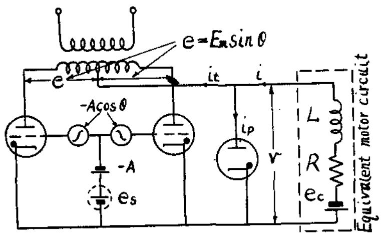


Fig. 1. Single-phase full-wave thyratron amplifier-motor circuit.

$$e_s = A(1+\cos\theta_i) \tag{2}$$

(2) **Output voltage of the thyratron amplifier circuit.** Fig. 2 represents the time functions of the anode supply voltage and of the armature current consisting of the thyratron current and the phanotron current. For simplification of the diagrams, the arc-voltage drop of the rectifier tube is neglected. In Fig. 2, e_c represents the counter e. m. f. generated in the armature-winding. The thyratron current i_t starts to conduct at the point θ_i, the angle of ignition. At the point θ_2, where the a. c. supply voltage intersects the line of e_c, the thyratron ceases to conduct due to the e. m. f. $-Ldi/dt$ induced in the inductance. On the other hand, the phanotron current i_p starts to flow at this instant and ceases to conduct at the point θ_p where the e. m. f. induced in the inductance reaches to zero.

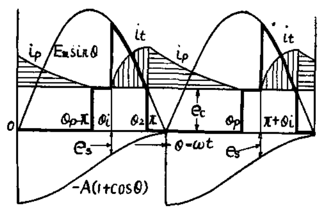


Fig. 2. Time functions of output voltage in thyratron amplifier and motor current.

The armature winding is short-circuited with the phanotron during the conductive periods of the phanotron. Therefore the output voltage of the thyratron amplifier will follow the anode supply voltage during the conducting periods of the thyratron ($\theta_i \sim \theta_2$), and it will be zero during the conducting periods of the phanotron ($\theta_2 \sim \theta_p$). Again it maintains the value equal to e_c during the non-conducting periods ($\theta_p \sim \pi+\theta_i$). These circumstances are shown in Fig. 2.

The average value of output voltage v can be derived directly from Fig. 2. In the case of the discontinuous conduction ($\theta_p < \pi+\theta_i$),

$$v = \frac{1}{\pi}\left[\int_i^{\theta_2} E_m \sin\theta d\theta + (\pi+\theta_i-\theta_p)e_c\right] = \frac{E_m}{\pi}[(\cos\theta_i - \cos\theta_2) + (\pi+\theta_i-\theta_p)a] \tag{3}$$

where $a=e_c/E_m$. An angle of extinction of the phanotron can be calculated from the following equation.

$$\theta_p = \theta_2 + \tan\phi \log\frac{1}{a}[\cos\phi\sin(\theta_2-\phi) - \{\cos\phi\sin(\theta_i-\phi)-a\}\exp\{(\theta_i-\theta_2)/\tan\phi\}] \tag{4}$$

where

$$\phi = \tan^{-1}\omega L/R.$$

Next, in the case of the continuous conduction, $(\theta_p=\pi+\theta_i)$

$$v=\frac{E_m}{\pi}(\cos\theta_i-\cos\theta_2)\simeq\frac{E_m}{\pi}(1+\cos\theta_i) \tag{5}$$

where

$$\cos\theta_2\simeq-1 \text{ at } a=\sin\theta_2\leq 0.25\,.$$

It is readily seen from equations (2) and (5) that the output voltage of the thyratron amplifier is proportional to the signal voltage being applied to the grid circuit of thyraton.

(3) **Effects of a phanotron in the thyratron amplifier circuit.** The ordinary rectifier-motor circuit which has no phanotron is first discussed in order to explain the effects of phanotron in the thyratron amplifier circuit. Fig. 3 represents the wave form of the anode voltage and of the armature current in the ordinary rectifier-motor circuits.

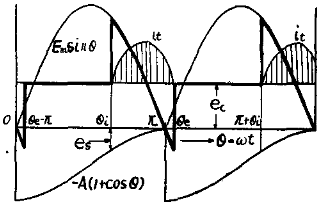


Fig. 3. Time functions of output voltage in thyratron rectifier and motor current.

In this case, the inductance of the armature circuit, which prevents the thyratron current from rising sharply at the point of igaition θ_i, does the curreut from dying out at the point θ_2 where the external voltage causing the current flow is equal to zero. The e. m. f. of the inductance keeps the current flowing up to the point θ_e. During the conductive periods of the thyratron $(\theta_i\sim\theta_e)$ the voltage at the armature terminals will, of course, follow the anode supply voltage. On the other hand, during the non-conducting periods $(\theta_e\sim\pi+\theta_i)$, the voltage at the armature terminals will be equal to the counter e. m. f. The average value of the thyratron output voltage v can be derived directly from Fig. 3.

In the case of the discontinuous conduction, $(\theta_e<\pi+\theta_i)$

$$v=\frac{1}{\pi}\left[\int_{\theta_i}^{\theta_e}E_m\sin\theta\,d\theta+(\pi+\theta_i-\theta_e)e_c\right]=\frac{E_m}{\pi}[(\cos\theta_i-\cos\theta_e)+(\pi+\theta_i-\theta_e)a] \tag{6}$$

An angle of extinction of the thyratron θ_e can be calculated from following equation.

$$[a-\cos\phi\sin(\theta_e-\phi)]=[a-\cos\phi\sin(\theta_i-\phi)]\exp[(\theta_i-\theta_e)/\tan\phi] \tag{7}$$

Next, in the case of the continuous conduction, $(\theta_e=\pi+\theta_i)$

$$v=\frac{2E_m}{\pi}\cos\theta_i \tag{8}$$

For this rectifier circuit, it is evident from equations (2), (6) and (8) that the output voltage is not preportional to the signal voltage.

Now, the output voltage in both cases shown in Fig. 2 and Fig. 3 may be calculated as a function of the signal voltage on the basis of the given values of the counter e. m. f. e_c and the impedance angle of the armature circuit ϕ, by the aid of the equations (2), (3), (5), (6) and (8). This is given the graph shown in Fig. 4; curves (I) and (II) show the output voltage in the ordinary rectifier-motor circuit $(\cos\phi=0.6)$ and they deviate greatly each other by the counter e. m. f. e_c or the motor speed n. On the other hand, curves (III) and (IV) show the output voltage in the amplifier-motor circuit in which the effect of phanotron is more confirmed by connecting a reactor in series with the armature winding. Then, the power factor of the armature circuit is equal to 0.1. It is evident from the part of the straight line which is common with the curves (III) and (IV) that the output voltage of the amplifier circuit is proportional to the signal voltage independently of the counter e. m. f. e_c or the motor speed n.

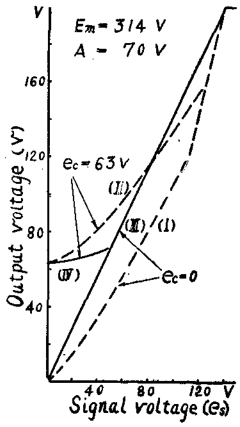


Fig. 4. Characteristic curves of thyratron amplifier and rectifier for shunt motor control.

(4) The speed control of a shunt motor by ultra low frequency signal. A d. c. shunt motor is directly coupled mechanically to a load, as shown in Fig. 5, and is operated with constant field excitation and variable armature voltage impressed. The voltage impressed across the motor is equal to the sum of the voltage drops through the inductance and resistance, and the counter e. m. f. Thus v is given by the following equation

$$v = L\frac{di}{dt}+Ri+cn \tag{9}$$

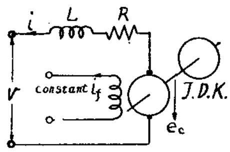


Fig. 5. Motor-load circuit.

The torque developed by a shunt motor is proportional to the armature current under the constant field excitation, that is,

$$\tau = ki \tag{10}$$

where k is a proportional constant. As the motor and load are drived by this torque, the following relation ban be written:

$$\tau = J\frac{dn}{dt}+Dn+K \tag{11}$$

where J: combined inertia of motor and load, D: damping coefficient, K: constant torque.

If the variation Δv appears in the voltage impressed across the motor which is operating under the steady state condition at voltage V_a and speed N_a, the speed variation Δn will be followed. Then Δn can be derived from equations (9), (10) and (11) as follows:

$$\Delta n = \Delta v/(p^2F+pG+H) = \Delta v/Z_n \tag{12}$$

$$Z_n = p^2F+pG+H \tag{13}$$

where p: operator of Heaviside

$$\left.\begin{aligned} &F = JL/k,\ G = (DL+JR)/k, \\ &H = (DR+ck)/k \end{aligned}\right\} \tag{14}$$

In the case of the sinusoidal variation of the voltage at angular frequency α,

$$\Delta v = V_a \sin\alpha t \tag{15}$$

Then Δn and Z_n may be expressed as the functions of α

$$\Delta n = N_a \sin(\alpha t-\varphi_n) \tag{16}$$

$$Z_n = (H-\alpha^2F)+j\alpha G \quad (17)$$

In the equations (16), the magnitude N_a and the phase angle φ_n of the speed variation can be expressed by

$$N_a = V_a/\sqrt{(H-\alpha^2F)^2+(\alpha G)^2} \quad (18)$$

$$\varphi_n = \tan^{-1}\alpha G/(H-\alpha^2F) \quad (19)$$

The effect of changing the frequency of the supply voltage on the motor-load circuit is to produce a change in the magnitude and the phase angle of the output speed with respect to the input voltage. Although the speed Δn is practically in phase with the sinusoidally varying voltage Δv at very low values of α, for higher values of frequency the maximum speed obtained is reduced in magnitude and occurs at the time (that is, phase) different from that when the voltage is a maximum. It is therefore concluded that the speed of a d. c. motor can be controlled following after the ultra low frequency voltage, that is, ultra low frequency signal supplied to grid circuit of thyratron amplifier.

(5) **Experimental results.** A symmetrical single-phase full-wave amplifier circuit is used for the shunt motor control, as shown in Fig. 1. The experimental results obtained by driving the shunt motor with constant field excitation and variable armature voltage which is proportional to the signal valtage linearly, are shown in oscillogram I. In this oscillogram, (I) : ultra low frequency signal, (II) : output voltage of thyratron amplifier, (III) : motor speed.

3. Series motor control by ultra low frequency signal

(1) **Circuit of a thyratron amplifier for a series motor control.** For series motor, the counter e. m. f. e_d generated in the armature winding is propotional to the product of motor speed n and motor current i, neglecting saturation of the field. Therefore it can be expressed by

$$e_d = dni = R_d i\,, \ R_d = dn \quad (20)$$

where d is proportional constant and R_d is the equivalent resistance which is proportional to the speed. Then a d. c. motor with series excitation, as shown Fig. 6, is represented by a series circuit of an inductance L and a resistance R consisting of resistances R_m and R_d, where L and R_m represent the resultant inductance and resistance in the windings of armature and field, respectively. Therefore a series motor can be considered as a shunt motor, in which the value of the counter e. m. f. e_c equals to zero, and R is variable resistor.

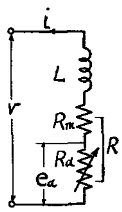


Fig. 6. Equivalent circuit of series motor.

(2) **Output voltage of the thyratron amplifier circuit.** As the value of e_c is equal to zero in the series motor, θ_2 becomes to π in Fig. 2. Then the average value of output voltage can be readily derived from Fig. 2, and is gived by

$$v = \frac{1}{\pi}\int_{\theta_i}^{\pi} E_m \sin\theta \, d\theta = \frac{E_m}{\pi}(1+\cos\theta_i)\,. \quad (21)$$

Accordingly, a continuous flow of the motor current is obtained in the series motor. It is also concluded from equations (2) and (21) that the output voltage of the thyratron amplifier is proportional to the siganl voltage being applied to the grid circuit of the thyratron.

(3) **Output voltage of the ordinary thyratron rectifier circuit.** For series motor control, an extinction angle of the thyratron θ_e, can be calculated from equation (7) by putting $a=e_c/E_m=0$, and is given by

$$\sin(\theta_e-\phi) = \sin(\theta_i-\phi)\exp[(\theta_i-\theta_e)/\tan\phi] \tag{22}$$

The average value of the thyratron output voltage can be derived from Fig. 3. In the case of discontinuous conduction $(\theta_e<\pi+\theta_i)$

$$v = \frac{1}{\pi}\int_{\theta_i}^{\theta_e} E_m \sin\theta d\theta = \frac{E_m}{\pi}(\cos\theta_i-\cos\theta_e) \tag{23}$$

Next, for continuous conduction $(\theta_e=\pi+\theta_i)$, v is represented by equation (8).

Fig. 7 shows the graph of output voltage versus signal voltage for several different values of impedance angle (that is, motor speed). It is readily seen from Fig. 7 that the output voltage of thyratron rectifier will increase greatly in accordance with the increase of power factor of the motor circuit (or speed). In case that the motor circuit is purely resistive, that is, the motor speed gets to infinite value, output voltage of thyratron rectifier may be shown by a straight line ($\cos\phi=1.0$) in Fig. 7.

This characteristics represented by the straight line also correspond to the output voltage characteristics of the thyratron amplifier with phanotron, as represented by equation (21). It is thus evident that the output voltage of thyratron amplifier is linearly proportional to the signal voltage independently upon the motor speed.

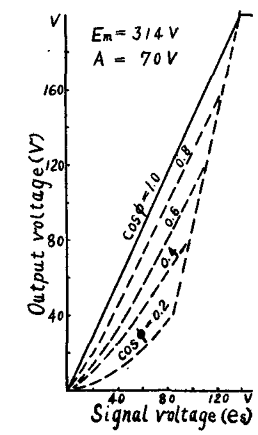


Fig. 7. Characteristic curves of thyratron amplifier and rectifier for series motor control.

(4) **The speed control of a series motor by ultra low frequency signal.** The torque developed by the series motor is proportional to the square of the motor current, but it can be written approximately as follows,

$$\tau = l'i^2 \simeq l(i-I_0) \tag{24}$$

where l', l, and I_0 are constants determined by the motor. The voltage impressed across the motor, as shown in Fig. 6, is expressed by

$$v = L\frac{di}{dt}+R_m i+dni\,. \tag{25}$$

Similarly to the previous section [2-(4)], speed variation Δn of the series motor followed after voltage variation Δv can be derived from equations (24), (25) and (11). In this case, the coefficients in the equation (13) are represented as follows,

$$\left.\begin{aligned} F &= JL/l,\ G = (DL+R_mJ+2dJN_d)/l, \\ H &= [DR_m+2dDN_d+d(K+lI_0)]/l \end{aligned}\right\} \tag{26}$$

(5) **Experimental results.** A single-phase half-wave thyratron amplifier circuit (thyratron, TX-920 is used) is employed for a series motor control as shown in Fig. 8. Universal motor on the free market having the capacity of 50 W (100 V, 1.1 A), is employed for the experiments. In general, the speed corresponding to the signal voltage,

$e_s = E_{sd}+E_{sa}\sin\alpha t$ is given by $n = N_d+N_a\sin(\alpha t-\varphi_n)$.

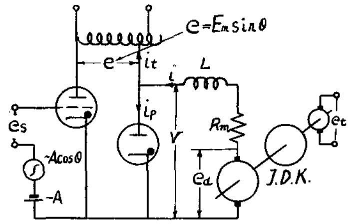


Fig. 8. Single-phase half-wave thyratron amplifier-motor-load circuit.

Experimental values of the speed variation with respect to the signal voltage are tabulated in Table 1. For comparison, the calculated values are also given in the table. It is readily recognized that magnitude of speed variation N_a decreases according as the increase of signal frequency α.

Table 1. Magnitudes of speed variation

No.	E_{sd} (V)	N_d (rpm)	E_{sa} (V)	$\frac{\alpha}{2\pi}$ (cps)	N_a		$\frac{CV-EV}{CV}$ (%)
					EV(rpm)	CV(rpm)	
1	85	1850	23	0.11	550	585	6
2	85	1850	23	0.29	250	285	12
3	74	1500	13	0.11	330	340	3
4	74	1500	13	0.29	190	180	−5

EV: Experimental value
CV: Calculated value

Oscillogram 2 shows experimental results, in which curves (I), (II) and (III) are explained as follows:

(I): The signal voltage of $e_s=74+13\sin 1.8t$ [V], which is too small in magnitude to operate the electro-magnetic oscillograph, and pulses are employed as the indicator at the instant of its maximum point.

(II): Motor speed $n = 1500+190\sin(1.8t-71°)$ [rpm]

(III): Motor current $i = 0.79+0.11\sin(1.8t+20°)$ [A]

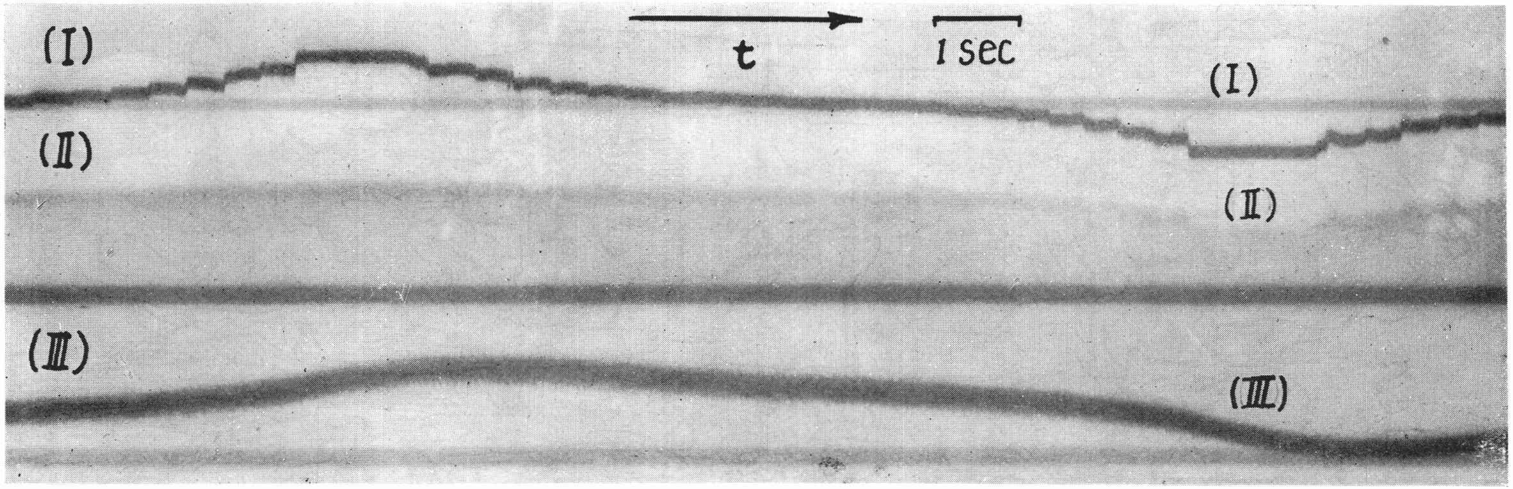
4. Conclusions

The methods of motor speed control followed after the ultra low frequency signal are described above. The phanotron and reactor in thyratron amplifier-motor circuit not only serve the linear power amplification but moderate the a. c. ripple and secure the continuous flow of motor current. It prevents also the over load of thyratron. The application of the series motor to the above-mentioned follower speed control has the following merits:

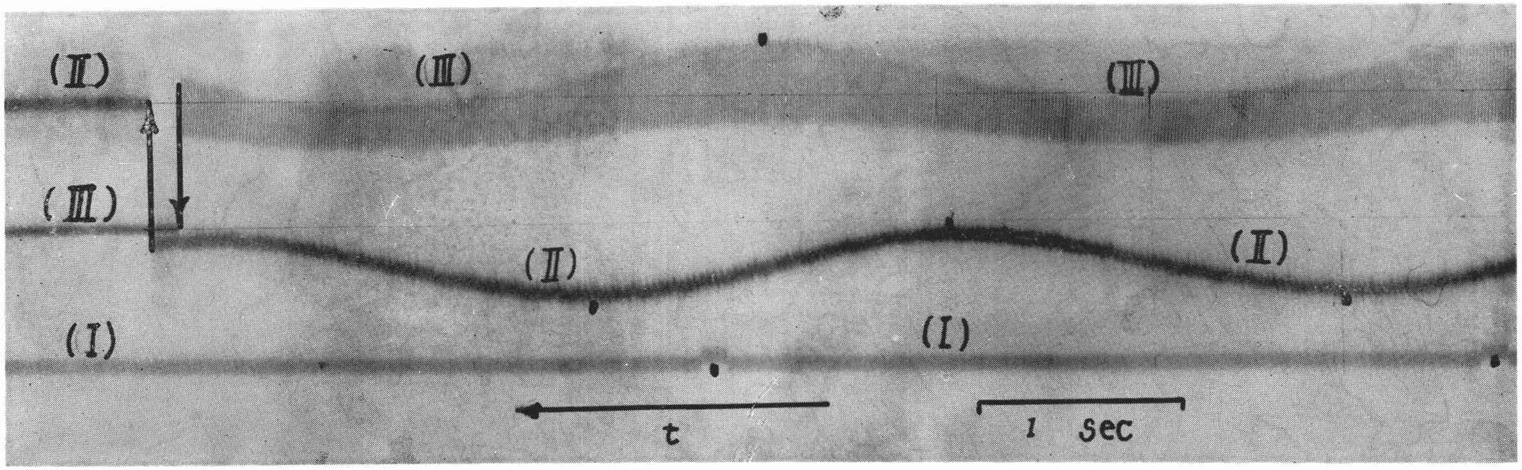
(1) It enables to make use of the surpassing characteristics of the series motor which develops the large torque at low speed.

(2) As there is no necessity of d. c. source for field excitation, the controlling circuit becomes very simple.

(3) The series field winding of the motor serves as a reactor, which confirms the effect of phanotron.



Oscillogram I



Oscillogram II