Control of Actual Rectifying Period in Commutatorless Motor

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This paper describes the utilization factor of armature winding and a speed control method of the commutatorless motor. The commutatorless motor has only a few numbers of thyristor commutator segments. Therefore, in order to employ the armature winding as effectively as possible, a method, in which the armature winding is made to act near the q-axis and its acting period is controlled, is brought up. This method improves the utilization factor of armature winding especially for the commutatorless motor with a few numbers of commutator segments. Judging from the utilization factor together with the torque ripple and the cost of the thyristor segments, the desirable numbers of the commutator segments may be concluded to be 2 or 3 pairs. From the experimental results, the advantages of this method are shown sufficiently.

1. Introduction

Mechanical Commutator wihch is one of the most important components of the D-C motor has many problems associated with the commutation. Such problems may be solved by the commutatorless motor (say, C-L motor) using thyristor commutator instead of mechanical commutator. With the development of semiconductor controlled rectifier, the use of the C-L motor in applications required for the wide range contral of motor speed or the precise control of output, is extending steadly. The thyristor commutator, as a matter of course, has no troubles in the commutation, so it does not require so many pairs of the commutator segments as compared with those of the mechanical commutator. Considering the cost of producing the thyristor commutator, the desirable numbers of the commutator segments may be generally regarded to be less than three pairs. But, in the case of these very small numbers of commutator segments, the characteristics and efficiency of the motor are greatly differ from those of the ordinary D-C motor. This paper first deals with the utilization factor of armature winding (say, U-factor) in the C-L motor generally, and examines the effect of the numbers of commutator segments. It also leads to most suitalbe voltage control method associated with the U-factor. At last, the results of these experiments are shown.

2. Control of actual rectifying period

There are $2n$ rectifications per revolution in the case of n pairs of commutator segments

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and one rectifying period is π/n. Like the D-C motor, the speed control of the C-L motor can be done easily by the method of the armature voltage control or the field exciting control. The field exciting control is seldom used for automatic control systems, because it lacks about quick response and has no wide range of speed control. When the wide range speed control is required, the armature voltage control should be used whether it is manual or automatic control. The examples of the armature voltage control are shown in Fig. 1.

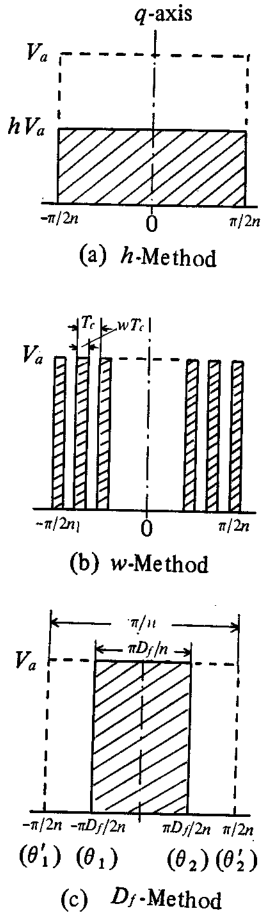


Fig. 1. Methods of armature voltage control.

In Fig. 1-(a), the armature voltage can be controlled by the applied voltage hv_a kept all the rectifying period π/n through. Same results also may be brought out by random pulse wide control wT_c, shown in Fig. 1-(b). These methods are called h- and w-method hereafter. As mentioned before, the C-L motor has only a few pairs of thyristor commutator segments. In order to employ the armature winding as effectively as possible, the armature winding would have better to act near the q-axis like the D-C motor. The method of the armature voltage control based on above idea is shown in Fig. 1-(c) and the model of the mechanical commutator motor, which is equivalent to the thyristor commutator motor driven in this method, is shown in Fig. 2. The positoins of the armature wind-

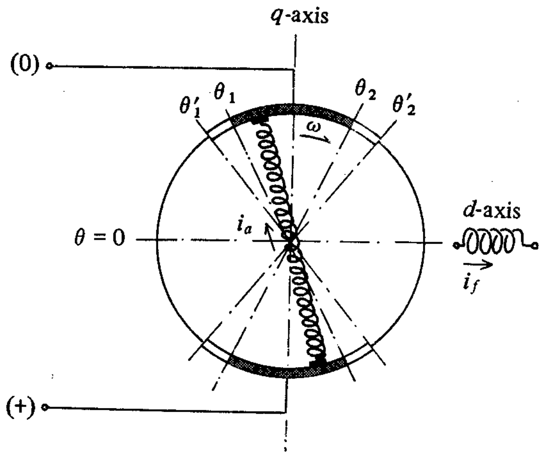


Fig. 2. Equivalent commutation model of C-L motor.

ing axis at the beginning and the end of the rectifying period are, respectively,

$$\theta_1 = \pi/2 - \pi D_f/2n$$

$$\theta_2 = \pi/2 + \pi D_f/2n$$

3. U-factor of armature winding[1)]

Since the D-C motor and the C-L motor act on the same principle relating to the commutation, if it is assumed that the copper losses and the machine sizes are the same in both motors, the U-factor is defined as "the ratio of the output of the C-L motor to that of the ideal D-C motor with infinit numbers of commutator segments at rated supplied voltage". The instantaneous applied voltages for the armature and the field circuit are

$$\left.\begin{aligned} [v] &= [R][i] + \frac{d}{dt}[L][i] \\ [v] &= [R][i] + [L]\frac{d}{dt}[i] + \omega[G][i] \end{aligned}\right\} \qquad (1)$$

writing in eq. (1)

$$\left.\begin{aligned} &[v] = \begin{bmatrix} v_f \\ v_a \end{bmatrix} \qquad [v] = \begin{bmatrix} i_f \\ i_a \end{bmatrix} \\ &[R] = \begin{bmatrix} R_f & 0 \\ 0 & R_a \end{bmatrix} \\ &[L] = \begin{bmatrix} L_f & M_{af} \\ M_{af} & L_a \end{bmatrix} = \begin{bmatrix} L_f & -M\cos\theta \\ -M\cos\theta & L_{a0} + L_{a2}\cos 2\theta \end{bmatrix} \\ &\theta = \omega t \\ &[G] = \frac{d}{d\theta}[L] = \begin{bmatrix} 0 & M\sin\theta \\ M\sin\theta & -2L_{a2}\sin 2\theta \end{bmatrix} \end{aligned}\right\} \qquad (2)$$

where v_f and v_a are the terminal voltages, i_f and i_a are the currents, R_f and R_a are the winding resistances of the field and the armature circuit, respectively, and L_f, L_a and M_{af} are the self-inductance and the mutual-inductance. Connecting all the armature coils always, the self- and mutual-inductances have the same values for any pairs of the commutator segments.

The instantaneous powers are then

$$\begin{aligned}[p] &= [i]_t[v] \\ &= [i]_t[R][i] + [i]_t[L]\frac{d}{dt}[i] + \omega[i]_t[G][i]\end{aligned} \tag{3}$$

where $[i]_t$ is the transposed current matrix. The first term on the right hand side of eq. (3) is the copper losses p_r of the windings and the half value of third term represents the mechanical output p_m, then

$$\begin{aligned}[p_m] &= \frac{1}{2}\omega[i]_t[G][i] \\ &= \omega M i_f [\sin\theta - \frac{L_{a2} i_a}{M i_f} \sin 2\theta]\end{aligned} \tag{4}$$

For simplification, it is assumed that the armature current is rectangular like the applied voltage as shown in Fig. 1-(c) and the field current is constant. With the apparent rectifying period π/n $(=\theta_2' - \theta_1')$ and the actual rectifying period $\pi D_f/n (=\theta_2 - \theta_1)$, the mean mechanical output becomes

$$\begin{aligned}P_m &= \frac{E_a I_a}{\theta_2' - \theta_1'}\int_{\theta_1}^{\theta_2}[\sin\theta - \frac{L_{a2} I_a}{M I_f}\sin 2\theta]d\theta \\ &= \frac{2n}{\pi} E_a I_a \sin(\pi D_f/2n)\end{aligned} \tag{5}$$

On the other hand, the instantaneous copper losses are given from eq. (3)

$$p_r = i_f^2 R_f + i_a^2 R_a \tag{6}$$

The mean copper losses are given with the effective current $\sqrt{D_f} I_a$

$$P_r = I_f^2 R_f + (\sqrt{D_f} I_a)^2 R_a \tag{7}$$

Substituting $n=\infty$ and $D_f=1$ in eqs. (5) and (7), the mean copper losses and the mechanical output of the ideal D-C motor become

$$\left.\begin{aligned}P_r &= I_f^2 R_f + I_{ad}^2 R_a \\ P_m &= E_a I_{ad}\end{aligned}\right\} \tag{8}$$

where I_{ad} is the armature current of the ideal D-C motor. If the mean copper losses of the C-L motor are equal to those of the ideal D-C motor, the mean armature current of the C-L motor is given from eqs. (7) and (8)

$$I_a = I_{ad}/\sqrt{D_f} \tag{9}$$

Substituting eq. (9) in eq. (5), the mean mechanical output of the C-L motor is given by

$$P_m = \frac{2n\, E_a I_{ad}}{\pi\sqrt{D_f}} \sin\left(\pi D_f / 2n\right) \tag{10}$$

Consequently, from eqs. (8) and (10) the U-factor f_n is

$$f_n = \frac{2n}{\pi\sqrt{D_f}} \sin\left(\pi D_f / 2n\right) \tag{11}$$

It is seen that the U-factor can be shown as function of n and D_f. The values of the U-factor at $D_f = 1$ are given in table 1. Moreover, the values for the so-called "120 or

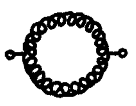
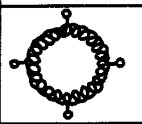
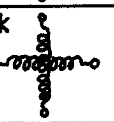
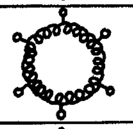
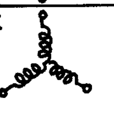
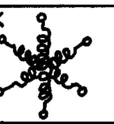
n	Motor connection	U-factor	(at $D_f = 1$)
1		f_{11}	0.637
2		f_{21}	0.900
	* 	$f_{2\frac{1}{2}}$	0.900
3		f_{31}	0.955
	* 	$f_{3\frac{2}{3}}$	1.013
	* 	$f_{3\frac{1}{3}}$	0.827

Table 1. U-factor on various motor connection.

180 degree conducting", C-L motor etc.[2] are also given in it, considering the armature winding in the actual rectifying period. For $n=1$, the U-factor is considerably smaller than that of the ideal D-C motor. But for $n \geqq 2$, these U-factors are only a slightly smaller than that of the D-C motor. Judging from the torque ripple and the cost of the thyristor commutator, the desirable numbers of commutator segments may be concluded to be 2 or 3 pairs. Fig. 3 shows the relations between the U-factor and the mean voltage controlled by various kinds of methods. In h- or w-method, the U-factor is quite proportional to the mean voltage. On the other hand, in D_f-method, according as the mean voltage reduces, the U-factor is not so much decreased as that in h- or w-

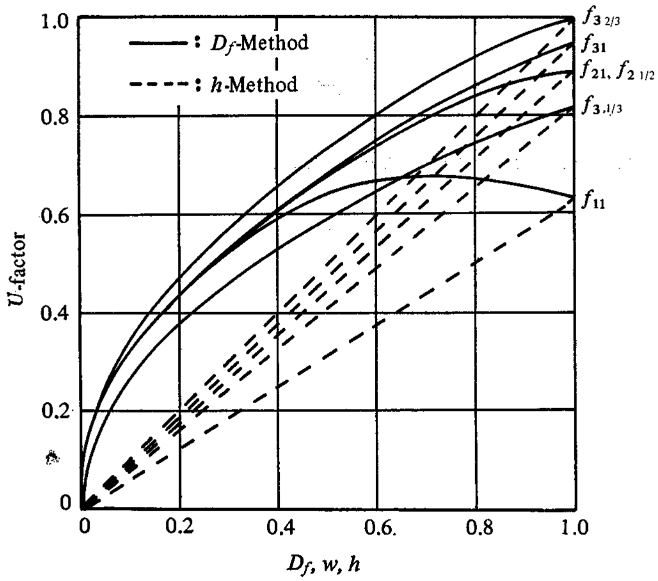


Fig. 3. Theoretical values of U-factor.

method, because the armature winding acts effectively in the actual rectifying period near the q-axis. Consequently, the D_f voltage control greatly improves the U-factor especially for $n=1$, in which the U-factor takes maximum value at a point of $D_f<1$.

4. Experimental circuit

As above mentioned, the D_f voltage control has an advantage for the U-factor. This article deals with the circuit which is able to perform such D_f voltage control. Fig. 4 shows a experimental circuit for $n=2$. The bridge inverter consists of the four outside main thyristors, S_{ac+}, S_{ac-}, S_{bd+} and S_{bd-} and the four auxiliary thyristors S'_{ac+}, S'_{ac-}, S'_{bd+} and S'_{bd-}[3]. The main thyristors are turned off forcedly by the action of the auxiliary thyristors, the inductances L, the capacitances C and feedback diods D. The

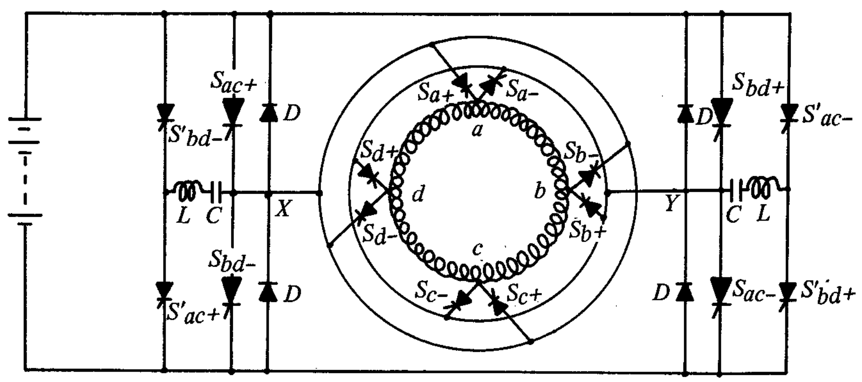


Fig. 4. Experimental circuit ($n=2$)

eight inner thyristors, S_{a+}, S_{a-}, etc., connected directly to the armature winding, manage the commutating action by the aid of the inverter circuit. They require the appropriate gate signals to perform a perfect commutation, and for that, it needs to detect the rotor position. As shown in Fig. 5, the disk with four $\pi/4$ slits, is mounted at the end of rotor shaft, and the two pick-ups which detect the rotor position through the slit, are fixed at the stator frame. The beginning and the end of rectifying period are given by P_1 and P_2 pick-ups, respectively. Referring to Figs,. 4, 5 and 6, let's explain how to control the D_f method. If P_1 is shifted in clockwise direction and P_2 counter clockwise from reference position by α degree, respectively, then the signals from P_1 is lagged and that of P_2 leaded. Then the duty factor D_f becomes

$$D_f=(90-2\alpha)/90 \tag{12}$$

The gate signals of pick-ups P_1 and P_2 are shown in Fig. 6-(a), and Fig. 6-(b) shows the potentials at X and Y points controlled by the right and left bridge inverter arms in Fig.

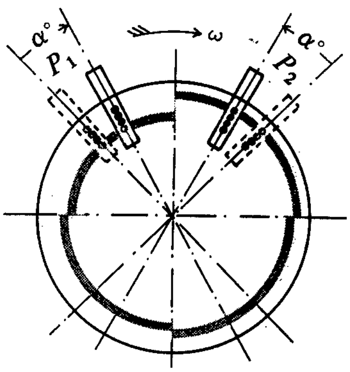


Fig. 5. Detector of rotor position.

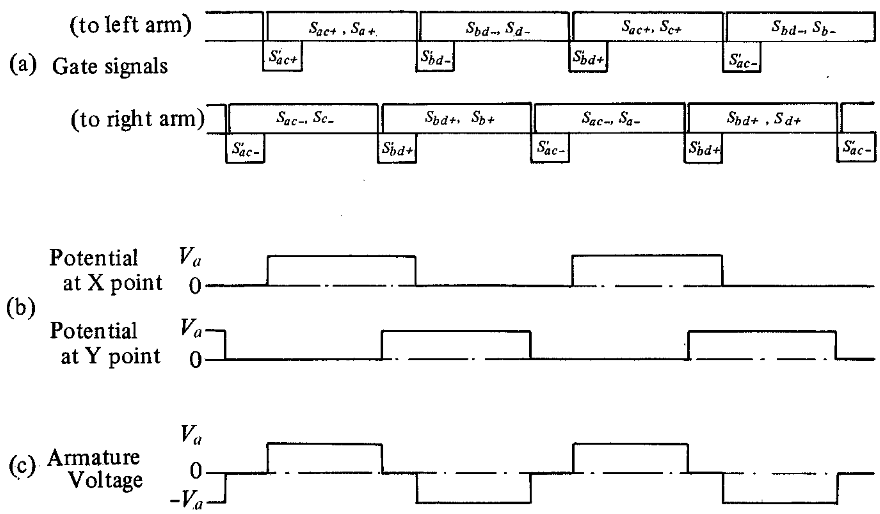


Fig. 6. Gate signals and armature voltage.

4, in which those thyristors are turned on and off by those signals, and in Fig. 6-(c) the armature voltage is given as the potential difference between X and Y points.

5. Experimental results

A 1*kW*, 100-*volt*, 4-poles, revolving field type motor employed the experiment, has the following constants;

$$R_a = 0.705\ ohms, \qquad M = 0.265\ henry$$
$$L_{a0} = 0.00365\ henry, \qquad L_{a2} = 0.00109\ henry$$

The armature current wave forms for $D_f=1$ and 0.8 are shown in Fig. 7. They sink near the q-axis under the influence of the counter *emf*.. Typical steady state speed-ampere characteristics are shown in Fig. 8. Like the ordinary D-C motor, the C-L motor becomes nearly a constant speed motor at large D_f. But, its characteristics become to droop so much so that the value of D_f decrease, because the pulsating armature current with the same time width as the actual rectifying period brings out the large equivalent armature resistance. In Fig. 9, the speed-D_f characteristics are shown. It is seen that

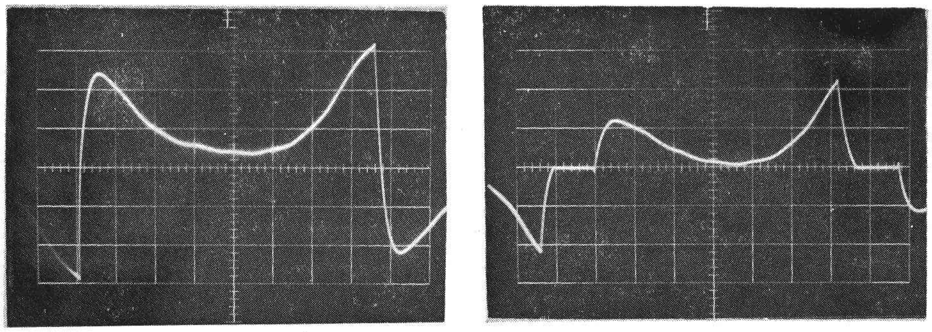


Fig. 7. Current wave forms.

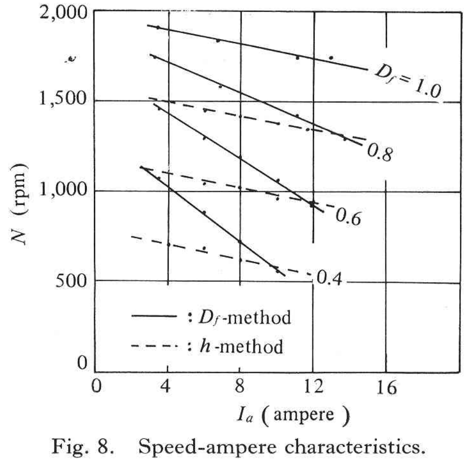


Fig. 8. Speed-ampere characteristics.

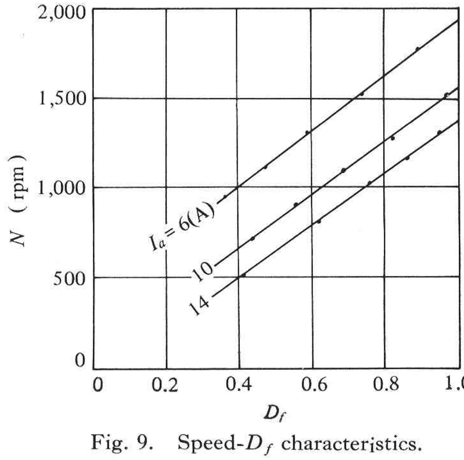


Fig. 9. Speed-D_f characteristics.

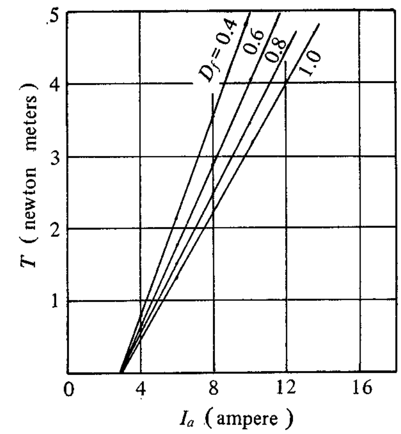


Fig. 10. Torque-ampere characteristics.

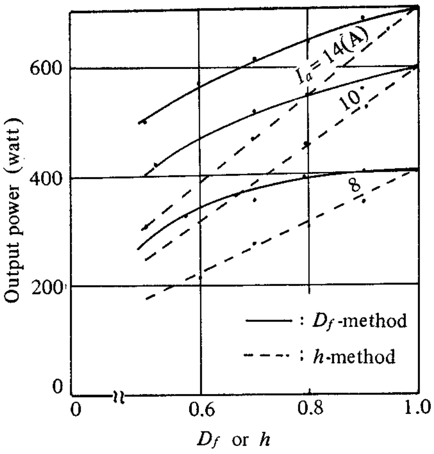


Fig. 11. Ouptut-D_f or-h characteristics.

the motor speed is controlled easily by the D_f method. Fig. 10 represents the torque-ampere characteristics. In the same average current, the decrease of D_f causes the increase of the torque. Moreover, the output-D_f or -h characteristics are shown in Fig. 11. From these experimental results, the advantage of the D_f control method may be fairly explained.

6. Conclusion

The general formula for the U-factor is derived as the function of the number of commutator segments and the coefficient of the actual rectifying period, and the armature voltage control method is brought up. From the derived formula and experimental results, the following interesting conclusions are summarized,

(1) The desirable numbers of commutator segments are 2 or 3 pairs.

(2) D_f-voltage control method on the small numbers of commutator segments improves the U-factor, especially for $n=1$.

(3) The motor speed may be controlled efficiently by D_f over a wide range.

References

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