Commutatorless Motor of Armature-field Perpendicular Type

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Commutatorless Motor of Armature-field Perpendicular Type

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One of the greatest problems in widely used commutatorless motors is that their instantaneous torque contains considerable pulsation. This paper proposes a new method to eliminate the torque pulsation in principle by providing a q-axis field winding in addition to a usual d-axis one; besides, the commutation and the starting at no commutation angle of advance become possible, in this method, without any forced commutation circuit in the inverter.

1. Introduction

A combination of a three phase inverter and a three phase synchronouse motor is the most popular system in commutatorless motors because of the simplicity of the inverter circuit and the high utilization of the armature winding[1]. In this system, however, as the armature current is commutated at intervals of $\pi/3$ rad, the phase difference between the active armature winding and the field winding axis (d-axis) variates periodically, and the torque pulsation, the frequency of which is six times the rotating frequency of the motor, is brought about. For commutatorless motors with induced voltage commutation, which are the most distinctive ones, the commutation angle of advance must be set high to obtain a high load capacity. The torque pulsation, therefore, is extremely large and the mean torque also decreases.

So far, several method to decrease torque pulsation have been proposed; multiphase method[2],[3], modulation control method of armature current[4], or constant control method of commutation margin in which the minimum commutation margin is maintained in any operating condition[5],[6]. However, there are following problems in these methods; (1) complicated devices are required for the purposes, (2) operating range is limitted to low motor speed.

An armature-field perpendicular type commutatorless motor proposed in this paper must be provided with a q-axis field winding in addition to conventional d-axis one. The equivalent axis of resultant field winding due to these two field windings is shifted synchronously maintaining perpendicular relation with the active armature winding during each commutation cycle, so that the torque pulsation can be eliminated in principle. Furthermore, the commutation and the starting of the commutatorless motor without any forced-commutation circuit in the inverter can be realized by aid of the transformer EMF in the commutating armature winding, even though the commutation angle of advance equals zero.

In this paper the principle construction of the motor is first illustrated, the torque pulsation and commutation characteristics are then analyzed. Some testing results to demonstrate the improvement are also described.

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2. Basic Principle

Figure 1 shows the basic principle of the commutatorless motor of armature-

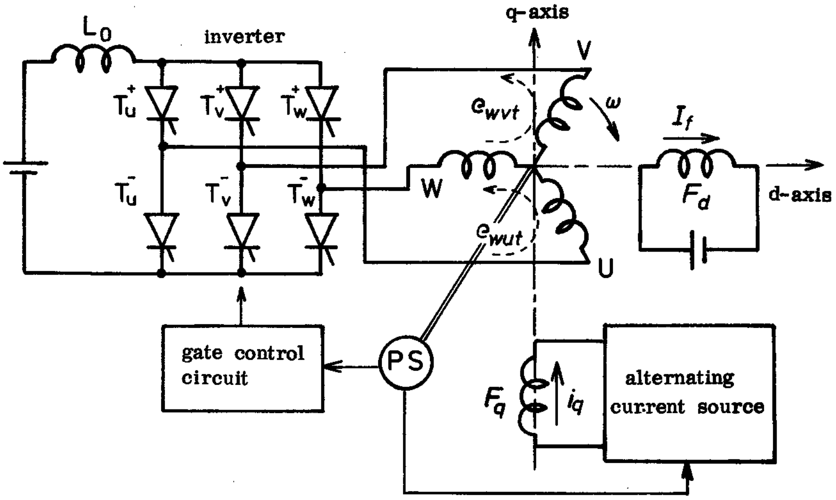


Fig. 1 Basic principle of armature-field perpendicular commutatatorless motor.

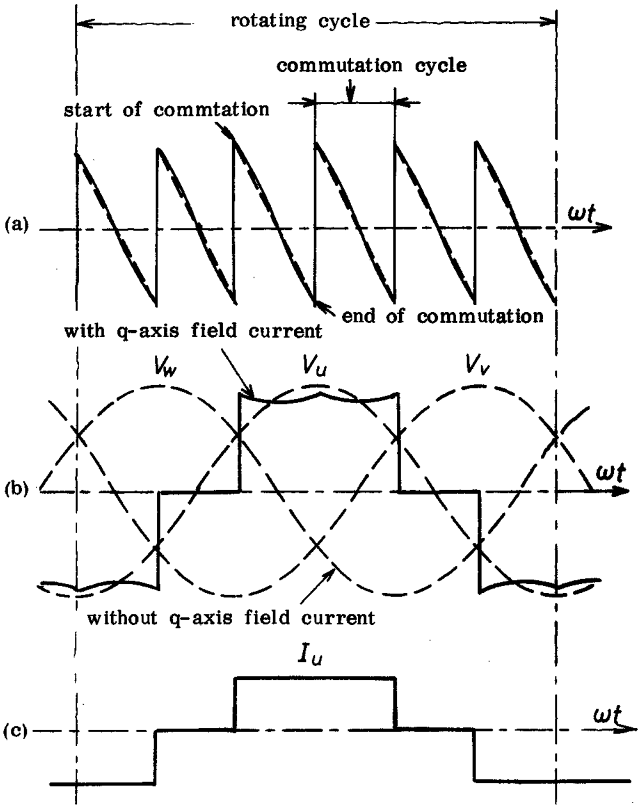


Fig. 2 Voltage and current wave forms.
(a) Q-axis field current. (b) Armature EMF. (c) Armature current.

field perpendicular type. In addition to conventional d-axis field winding, it provides a q-axis field winding, through which an alternating current i_q, whose frequency is six times the rotating one of the motor, is supplied by another field current source. i_q is desirable to be a positive maximum value at starting of every commutation cycle ($\theta=0$), 0 at middle point ($\theta=\pi/6$), and a negative maximum value at the end ($\theta=\pi/3$) as shown in Fig. 2(a), respectively, that is, i_q is given by

$$i_q=I_q \sin(\theta+5\pi/6) \tag{1}$$

In view of the experimental results, the current of sawtooth waveform as shown in dotted line in Fig. 2(a) has almost a similar effect.

Now, if the following relation between d-axis field MMF $F_q(\theta=0)$ is satisfield by adjusting I_q, its resultant MMF F_a+F_q will be shifted with θ in every commutation cycle as shown in Fig. 3.

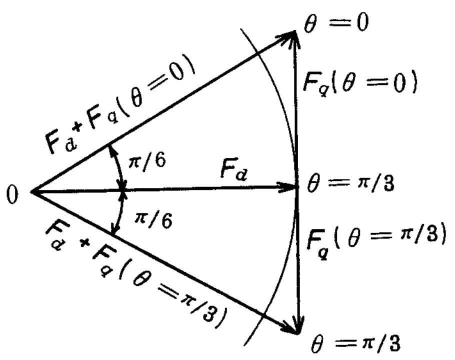


Fig. 3 Resultant MMF.

$$\frac{F_q(\theta=0)}{F_a}=\tan\pi/6=0.577 \tag{2}$$

With the commutation angle of advance $\beta=0$, therefore, the resultant field winding axis rotates synchronously with the active armature winding axis, keeping with it the right angle. Then the motor generates the maximum mean torque as well as one without pulsation, and the improvement of motor efficiency can be also expected.

3. Performance Analysis

To ease the understanding of the essential feature of this system, the following matters are assumed.

(1) The motor is of nonsalient revolving armature type.

(2) The DC reactor has so large an inductance that the DC input current I_a is ripple free.

(3) The commutation is ideal and the commutation over lapping angle u equals zero.

3.1 Equivalent Armature Winding

Paying attention to the active armature winding, the equivalent armature winding in a commutation cycle can be represented as shown in Fig. 4. The mutual

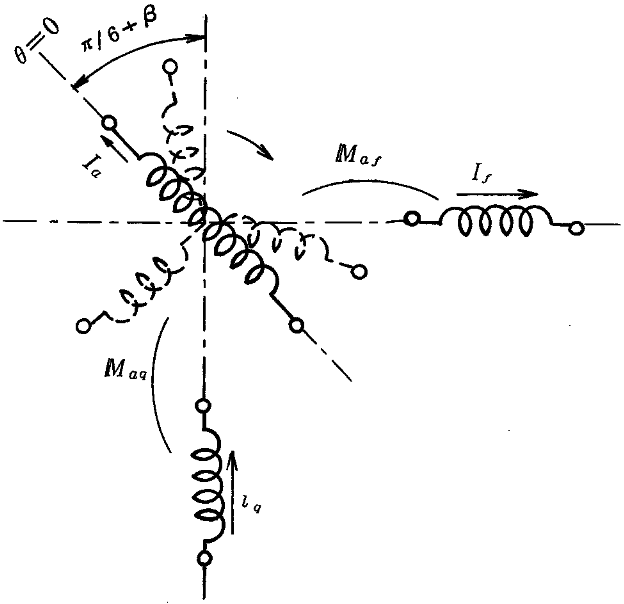


Fig. 4 Equivalent armature winding in commutation cycle.

inductances between the active armature winding and d-, q-axis field windings M_{af}, M_{aq} are given as follows, respectively,

$$M_{af}=M_{af}\sin(\theta-\pi/6-\beta) \tag{3}$$

$$M_{aq}=M_{aq}\cos(\theta-\pi/6-\beta) \tag{4}$$

Besides, it is assumed that the current described previously by Eq. (1) flows through the q-axis field winding.

3.2 Instantaneous Torque

Considering the equivalent armature winding in Fig. 4, the instantaneous torque is given by

$$\tau=I_fI_a\frac{d}{d\theta}M_{af}+i_qI_a\frac{d}{d\theta}M_{aq} \tag{5}$$

where, the first term represents the essential active torque produced by the d-axis field and the second term represents the torque due to the q-axis alternating field. Substituting Eqs. (1), (2) and (3) into Eq. (5), the following equation is obtained.

$$\tau=M_{af}I_fI_a\cos(\theta-\pi/6-\beta)+\frac{1}{2}M_{aq}I_aI_q\{\cos(2\theta+2\pi/3-\beta)+\cos\beta\} \tag{6}$$

The calculated results of the normalized instantaneous torque $\tau^N(=\tau/M_{af}I_fI_a)$ during commutation cycle $(\theta=0\sim\pi/3)$ are shown in Fig. 5, where it is seen that there is little torque pulsation on proper q-axis field current $(M_{aq}I_q/M_{af}I_f=0.5\sim0.6)$. The torque pulsation ratio can be defined by the following equation, as the fluctuating curve of the instantaneous torque is smooth.

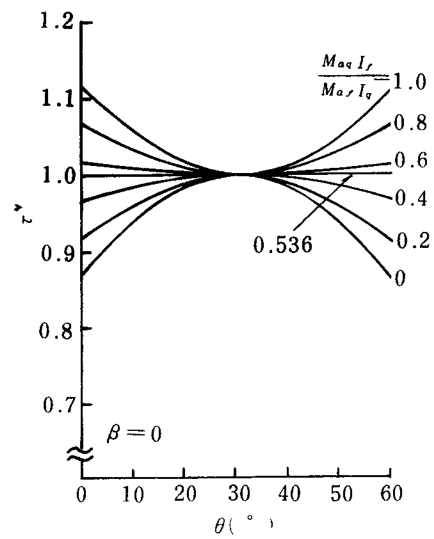


Fig. 5 Instantaneous torque.

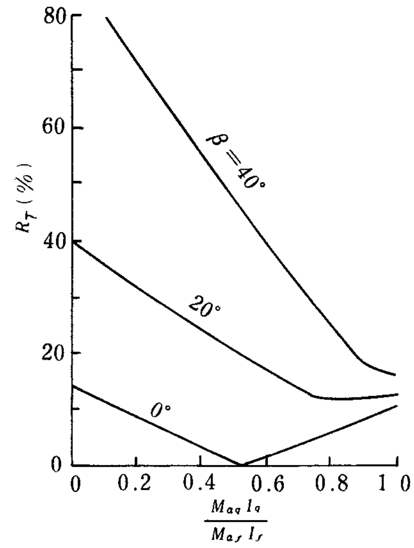


Fig. 6 Torque pulsation ratio.

$$R_T=\frac{\tau_{(max)}-\tau_{(min)}}{\tau_{(mean)}}\times 100(\%) \tag{7}$$

Figure 6 shows the calculated results of the torque pulsation ratio. With the commutation angle of advance $\beta=0$, some value of $M_{aq}I_q/M_{af}I_f$ at which $R_T=0$ exist. On the other hand, the condition that the instantaneous torques at three instants $\theta=0$, $\pi/6$, $\pi/3$ are equal gives the following value about the q-axis field current, from Eq. (6) with $\beta=0$.

$$\frac{M_{aq}I_q}{M_{af}I_f}=0.536 \tag{8}$$

This value agrees approximately with the result shown in Fig. 6. The values of F_q at $\theta=0$ and $\pi/3$ are 53.6 percent of that of F_d, which are smaller than 57.7 percent shown in Eq. (2), and the swinging angle of the resultant field axis is also a little smaller than $\pi/6$ as shown in Fig. 7, that is, the active armature and the resultant field winding get out of somewhat of the perpendicular relation.

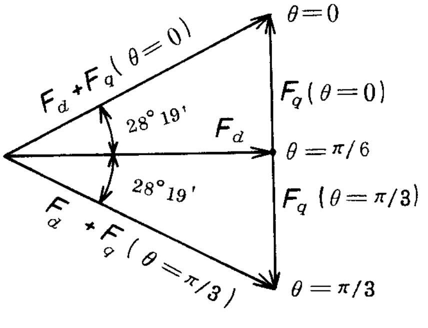


Fig. 7 Resultant field MMF at $R_T=0$.

3.3 Average Torque

From Eq. (6), the average torque becomes

$$T=\frac{3}{\pi}\int_{0}^{\pi/3}\tau\,d\theta$$

$$=M_{af}I_fI_a\cos\beta\left\{0.955+0.0865\frac{M_{aq}I_q}{M_{af}I_f}\right\} \tag{9}$$

The second term in Eq. (9) represents the increase of average torque brought about by the q-axis field winding. With $M_{aq}I_q/M_{af}I_f=0.536$, the value in { } is

$$0.955+0.0865\frac{M_{aq}I_q}{M_{af}I_f}=1.001$$

which equals the maximum instantaneous torque of the conventional system without the q-axis field winding.

3.4 Instantaneous Induced Voltage in Active Armature Winding

The instantaneous induced voltage in the active armature winding is represented by the following equation.

$$e_a=v_a-R_aI_a$$

$$=I_f\frac{d}{dt}M_{af}+i_q\frac{d}{dt}M_{aq}+M_{aq}\frac{d}{dt}i_q \tag{10}$$

where, the first and second terms mean speed EMFs and the third term means a transformer EMF due to the q-axis field alternating current. Substituting Eqs. (1), (3) and (4) into Eq. (10), the following equation is obtained.

$$e_a=\omega M_{af}I_f\cos(\theta-\pi/6-\beta)+\omega M_{aq}I_q\cos(2\theta+2\pi/3-\beta) \tag{11}$$

The calculated results of the normalized instantaneous voltage in the active armature winding $e_a^N(=e_a/\omega M_{af}I_f)$ are shown in Fig. 8. Under the influence of the transformer

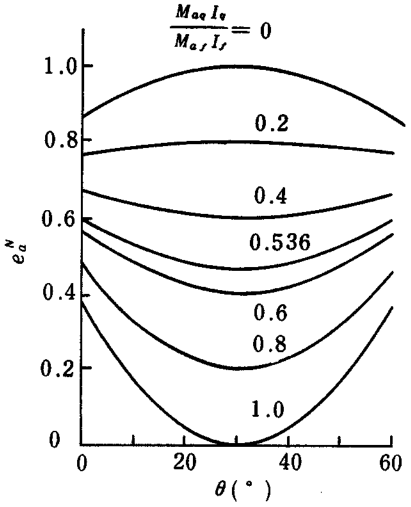


Fig. 8 Normalized instantaneous armature EMF.

EMF, the instantaneous induced voltage at the condition $R_T \doteqdot 0$ (or $M_{aq}I_q/M_{af}I_f = 0.536$) becomes small at the middle of the commutation cycle, unlike the instantaneous torque shown in Fig. 5. The condition of the smallest voltage pulsation may be achieved by smaller q-axis compensation than that of the torque.

3.5 Commutation by q-axis Alternating Field Current

It is impossible to give the q-axis field alternating current whose rising period is zero as shown in Fig. 2(a), because of the large inductance of the field winding. In practice, a q-axis alternating current with rising period as shown in Fig. 9 is given by an alternating current source.

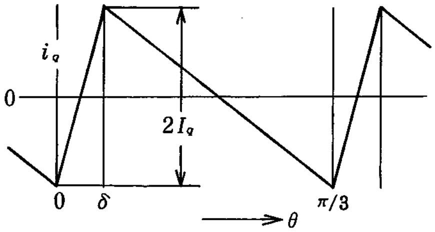


Fig. 9 Q-axis altenating current.

Now, we will discuss the commutation from T_u^- thyristor to T_v^- thyristor in Fig. 1. While i_q is rising sharply during the period δ, the transformer EMFs e_{wut} and e_{wvt} in W-U and W-V phase armature windings are induced in adition to the speed EMFs. These transformer EMFs may be considered as the reverse voltage divided into two halves and impressed upon T_w^+, T_u^- and T_w^+, T_v^-, respectively. The transformer EMFs are, moreover, considerably greater than the speed EMFs, and so the turn offs of every thyristors are assured if δ exceeds the commutation angle of overlap u. Accordingly, all the thyristors in the inverter are turned off at the same time, i.e. this method belongs to the current intermittent commutation. It is also possible the starting without any additional means.

By the way, the problems in this system are as follows.

(1) If the condition of no torque pulsation ($F_{q(\theta=0)}/F_d = 0.577$) is satisfied, the transformer EMF becomes excessively great, and I_q must be restricted within smaller value, so that the perfect cancellation of torque pulsation becomes impossible.

(2) The DC input current is intermitted at every commutation, and the feedback diode must be connected in parallel with the smoothing reactor (which may be fairly small by the addition of q-axis field).

4. Experimental Results

The motor used in the test was a 6 poles, three phases wound type induction motor, rated at 1 KW, 100 V; It's air gap was especially enlarged to 2 mm in order to give it characteristics similar to that of synchronous motor. Two stator windings connected in series are used for d-axis field winding and the remaining one for q-axis field winding.

4.1 Commutation

The conventional commutatorless motor with induced voltage commutation has no commutation voltage on the condition $\beta=0$. In order to obtain a stable commutation, therefore, β must be set to a large value as shown in Fig. 10. But, as mentioned above section, our proposed system is possible to have a stable commutation by the transformer EMF even if $\delta=0$. Fig. 10(b) shows a voltage waveform of inverter thyristor. As seen in the figure, the reverse voltage due to the transformer action appears at the commutation.

4.2 Starting

Because the armature current can be commutated by the transformer EMF alone, the motor becomes possible to start by itself. Fig. 11 is an oscillogram which shows a starting characteristics at $\beta=0$, the applied voltage being adjusted to 20% of the rated voltage. It is seen that the system can be commutated for the input

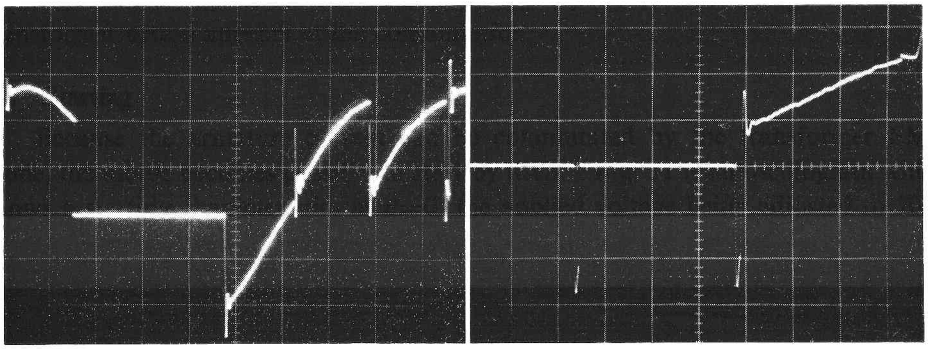

(a) natural commutation type ($\beta=45°$) (b) armature perpendicular type ($\beta=0$)

Fig. 10 Voltage wave forms of thyristor.

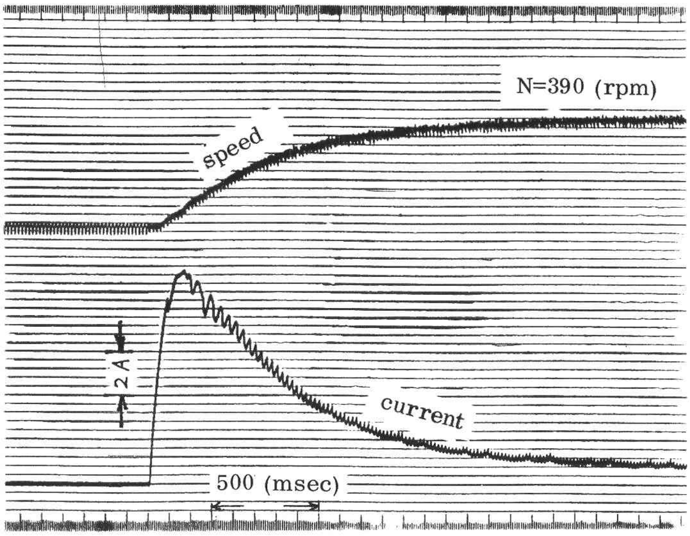
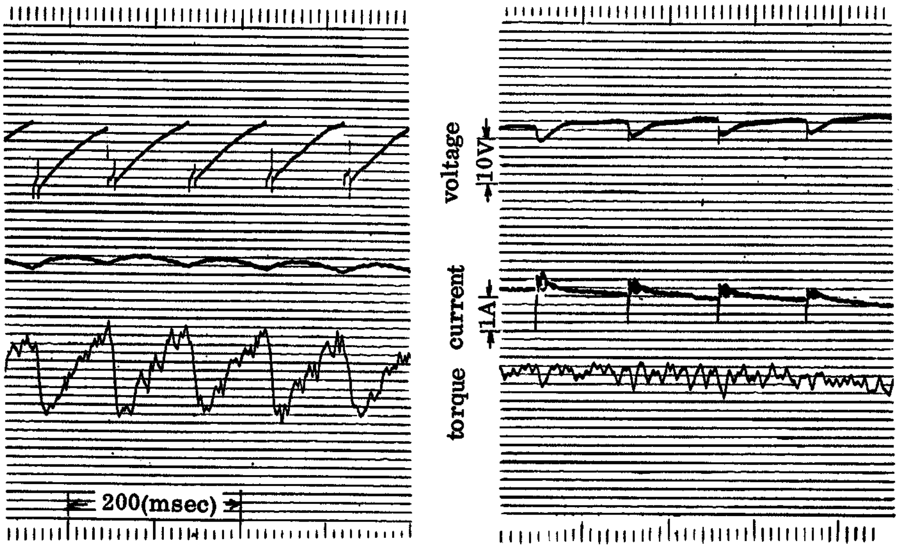


Fig. 11 Starting characteristics.

current of as large as about 10A.

4.3 Torque Pulsation

The strict measurement of instantaneous torque is very difficult, because of the following reasons; (1) the rotor of motor has a moment of inertia in itself, (2) the natural oscillation caused by the torsion of the motor and its load is superposed. In the test, we used a magnetic strain type torque meter, eliminated natural frequency component by a notch-filter, and measured at extremely low motor speed (about 20 rpm). Strictly speaking, the torque pulsation is to be compared with that of the forced commutation system at $\beta=0$. However, because the measurement of the accurate torque is difficult, we will now present two typical examples for the comparison. The terminal voltage and the input current at DC side of the inverter, and the instantaneous torque of the conventional natural commutation type commutatorless motor operated at $\beta=60°$ is shown in Fig. 12(a). Fig. 12(b) shows them in the case providing the q-axis field. Though the optimum compensation of the q-axis field current could not be realized because the motor speed is very low, the waveforms of voltage and current are nearly flat, and so, merely very small pulsation is contained in the instantaneous torque waveform.



(a) natural commutation type **(b) armature perpenducular type**

Fig. 12 Terminal voltage, input current and torque wave forms in steady state.

5. Conclusions

As described above, by conducting an alternating current of suitable waveform and amplitude through the q-axis field winding of a commutatorless motor, the torque pulsation can be eliminated in principle, and the average torque approaches to the muximum instantaneous value of the conventional system. Furthermore, the commutation and starting become possible even at commutation angle of advance

$\beta=0$. Experimental results perfectly prove clearly that the torque pulsation and the starting characteristics can be improved by our proposed system.

We expect to report on next chance a system utilizing *d*-axis damper current, in addition to this basic construction.

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