Analysis of the Commutation Torque Ripple Effect for BLDCM fed by HCRPWM - VSI

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ABSTRACT -- This paper presents an analytical study of the torque ripple due to the phase commutation in a BLDCM(Brushless DC Motor) fed by HCRPWM - VSI(Hysteresis Current Regulated Pulse Width Modulation - Voltage Source Inverter). In order to show the duration of the phase commutation and the torque ripple during the phase commutation, the instantaneous trapezoidal waveform of BEMF and the amplitude of the phase current are considered. The simulation and experimental results indicate that the duration of the phase commutation and the current ripple during the phase commutation vary with speed and depend on the amplitude of the phase current. Also the effect on the motor speed due to the torque ripple during the phase commutation is studied.

I. INTRODUCTION

Theoretically, if a BLDCM(Brushless DC Motor) has the trapezoidal BEMF waveform with a 120^0(electrical) constant plateau for a half cycle, and is fed with rectangular stator currents in the portion of the 120^0 constant plateau of BEMF, the torque produced is constant. However, in practice, the torque ripple may exist due to the motor itself but also to the feeding system. The causes of the torque ripple coming from the motor itself are cogging torque and BEMF waveform imperfections, and those coming from the feeding system are the current ripple resulting from PWM or HCR(Hysteresis Current Regulator) and from the phase commutation[1], [2].

Some methods to attenuate cogging torque or BEMF waveform imperfections were proposed, mainly by slots or magnets skewing[3], [4], or by changing the magnets dimensions and positioning[5], [6]. Also, many studies of the torque ripple due to the feeding system have shown that the torque ripple due to the phase commutation can introduce significant effect on the motor speed rather than one due to the ripple current resulting from PWM or HCR[7] - [13]. It is because that the torque ripple during the phase commutation is larger than the torque ripple resulting from PWM or HCR and the duration of the phase commutation is also longer.

A few ways were proposed to analyze the torque ripple during the phase commutation and to overcome them. However, they did not consider the instantaneous trapezoidal waveform of BEMF during the phase commutation as well as the amplitude of the phase current[12] - [13]. But, the duration of the phase commutation and the current ripple during the phase commutation are affected by the BEMF waveform and by the amplitude of the phase current.

So, we will study the phase commutation phenomena taking into the instantaneous BEMF waveform of the phase with decaying current during the phase commutation and the amplitude of the phase current. All the possible configurations of HCR will be derived and the possibility for the current control of HCR during the phase commutation will be simulated. Also the effect on the motor speed due to the torque ripple during the phase commutation will be studied.

II. DESCRIPTION OF THE DRIVE SYSTEM

As shown in Fig. 1 a), the drive system consists of a BLDCM fed by HCRPWM - VSI (Hysteresis Current Regulated Pulse Width Modulation - Voltage Source Inverter), a commutation sensor mounted on the rotor, and the hall effect current sensors placed in the input stage of the motor.

The mathematical model and conventions of the BLDCM are shown in Fig. 1 b). The rotor is cylindrical type hence the inductances are constant, and the magnets are radially magnetized yielding a trapezoidal BEMF shown in Fig. 2. The electrical and mechanical equations of the motor are given in (1) - (3).

The voltage source inverter is composed of

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

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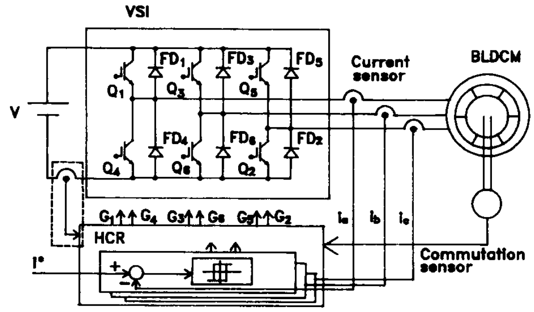
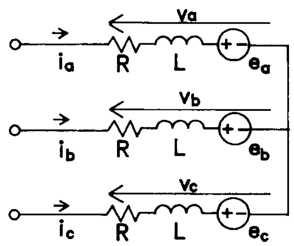


a) drive system



b) mathematical model

Fig. 1. Schematic of a BLDCM drive system and a mathmatical model of BLDCM

$$+\begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

$$i_a + i_b + i_c = 0 \qquad (2)$$

$$T_q = (e_a\, i_a + e_b\, i_b + e_c\, i_c)/\omega_m \qquad (3)$$
$$= J_r\,(d\omega_m/dt) + D\,\omega_m + F + T_{qL}$$

where,

R : phase resistance
$L = L_s - M$: synchronous inductance per phase
L_s : self inductance per phase
M : mutual inductance between phases
i_a, i_b, i_c : phase currents
v_a, v_b, v_c : phase voltages
e_a, e_b, e_c : phase BEMFs
T_q : developed torque
ω_m : mechanical rotor angular speed
J_r : rotor inertia
D : damping coefficient
F : friction torque
T_{qL} : load torque

IGBTs(Insulated Gate Bipolar Transistors) and diodes. HCR is used because of its simplicity of implementation, fast response and inherent peak current limiting capability. The current control

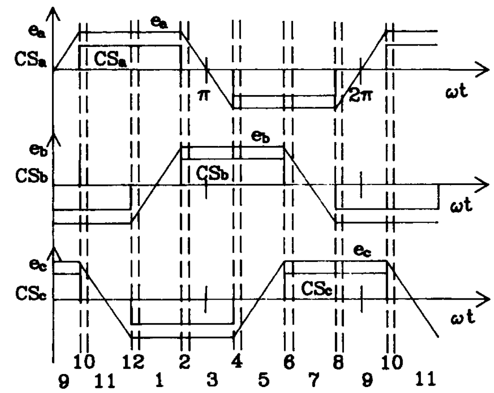


Fig. 2. Waveforms of BEMF and commutation sensor signal

is made by the comparison between the reference current and the actual one which is the phase currents or the inverter input current.

HCR commands the conduction of IGBT taking into account the actual current and the hysteresis window. When the actual current is lower than the lower limit of the hysteresis window, IGBTs are switched on and the current rises until it reaches the upper limit of that; then IGBTs are turned off and the current flows across the freewheeling diodes and decreases until to attain lower limit. So the phase current is basically bounded within the hysteresis window.

There exist two schemes of HCR according to the sensing of the actual current. One of the scheme is that the current control of HCR is made by the comparison between the inverter input current and the reference one. The other scheme can be performed by the comparison between the each phase current and the reference one.

The commutation sensor commands the inverter to conduct or not in order to produce the stator currents in adequate phases. Its signals are also shown in Fig. 2. Considering the period 2 and 3 of Fig. 2, the phase currents are commutated from phase a to phase b. So, the phase a is switched off by the commutation sensor signal CS_a and its current begins to decay. The phase b is switched on by CS_b and its current begins to rise. But, the current of the phase c isn't involved on the phase commutation. In this case the phase a, b and c are the phase with decaying, with rising, with uncommutating current, respectively.

Also, among the current control by HCR with sensing the phase current, there may exist three methods. One of the method is that HCR of the phase b commands the conductions of IGBTs for its own phase and the phase c during the period 2 and 3 which is 60^{o}(electrical): This method will be called the current control by HCR of the phase with rising current because the phase currents are controlled according to the HCR status of the phase with rising current. Another method is that HCR of the phase c commands the conductions of IGBTs for its own phase and the phase b during 60^{o}(electrical): This method will be called the current control by HCR of the phase with uncommutating current. The third method is that HCR of the each phase during 120^{o}(electrical) commands the conductions of IGBTs for their own phases independently: This method will be called the independent current control by HCR of the each phase. In section Ⅲ, these three methods will be examined.

The current control of HCR is divided into two stages such as the conduction stage and the commutation stage[12]. In Fig. 2, the period with the odd number shows the conduction stage, and one with the even number shows the commutation stage.

A. Conduction stage

There are two phases in series conducting current during 60^{o}(electrical) while the other is open circuited: the period 1 in Fig. 2, for example. When HCR switches IGBTs on, the current rises, and when it turn them off, the current decreases remaining within the hysteresis window. So, during this stage the inverter input current and the phase currents are kept within the hysteresis window. For the conduction stage the general equation taking into account the current control of HCR is:

$$di_m/dt = (SW_m\ V - 2\ R\ i_m - CS_a\ e_a - CS_b\ e_b - CS_c\ e_c)/(2\ L) \quad (4)$$

where,

V : input DC voltage of the inverter

subscript m : indicates the phase a, b, or c

CS_m : status of commutation sensor,

$i_m > 0 \Rightarrow CS_m = 1$,

$i_m = 0 \Rightarrow CS_m = 0$,

$i_m < 0 \Rightarrow CS_m = -1$

SW_m : status of HCR,

$i_m^* > 0,\ i_m \le i_m^* - \Delta i_{HW}/2$

$\Rightarrow SW_m = 1$(upper IGBT ON),

$i_m^* > 0,\ i_m \ge i_m^* + \Delta i_{HW}/2$

$\Rightarrow SW_n = -1$(upper IGBT OFF),

$i_m^* < 0,\ i_m \le i_m^* - \Delta i_{HW}/2$

$\Rightarrow SW_m = -1$(lower IGBT OFF),

$i_m^* < 0,\ i_m \ge i_m^* + \Delta i_{HW}/2$

$\Rightarrow SW_m = 1$(lower IGBT ON)

Δi_{HW} : hysteresis window

B. Commutation stage

At the end of the conduction stage of each 60^{o}(electrical), a conducting IGBT is turned off and another one is turned on as commanded by the commutation sensor: the period 2 in Fig. 2, for example. While they are commutating, the third phase is kept with the current. The rising and decaying of the currents during the phase commutation does not occure instantaneously to reach their final values due to the time constant of the stator winding. Thus, there are three conducting currents until the decaying one reaches zero. The general equations of this stage are:

$$\begin{aligned} di_r/dt &= [CS_r\ V\ (1.5\ SW_r + 0.5) + (-3\ R\ i_r - 2\ e_r + e_d + e_u)]/(3\ L) \\ di_d/dt &= [-CS_d\ V + (-3\ R\ i_d + e_r - 2\ e_d + e_u)]/(3\ L) \\ di_u/dt &= [CS_u\ V\ (1.5\ SW_u - 0.5) + (-3\ R\ i_u + e_r + e_d - 2\ e_u)]/(3\ L) \end{aligned} \quad (5)$$

where,

subscripts r, d, and u : indicate the phase with rising, decaying, and uncommutating current, respectively

Ⅲ. ANALYSIS OF THE TORQUE RIPPLE DURING THE PHASE COMMUTATION

For the analysis of the phase commutation phenomena, the commutation from phase a to phase b is considered, from period 1 to 2 in Fig. 2. The circuit configuration before this commutation is shown in Fig. 3 a). Solid line represents the circuit configuration of flowing current. The circuit configuration immediately after the phase commutation is that of Fig. 3 d).

A. Current control by HCR of the phase with the rising current

In order to determine the duration of the phase commutation and the torque ripple during the phase commutation, we will consider that the BEMF waveform of the phase with decaying current during the phase commutation does not remain constant but has a linear slope, as period 2 in Fig. 2. Its waveform is expressed as (6) during the period 2 and 3. And in these analysis we will neglect the winding resistance in order to achieve the analytical formations. Also the initial value of the decaying current and the final value of the rising current are assumed to be equal to the reference value i^* of HCR. The reference value i^* of HCR becomes the mean value of the phase currents during the conduction stage.

$$e_d = E(1 - t/T_s) \quad ; (5/6)(10\ k_e/E) \le t \le (7/6)(10\ k_e/E) \tag{6}$$

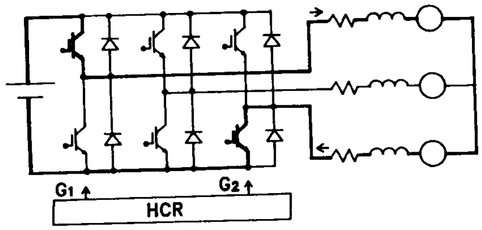
where,

E : amplitude of the plateau of BEMF

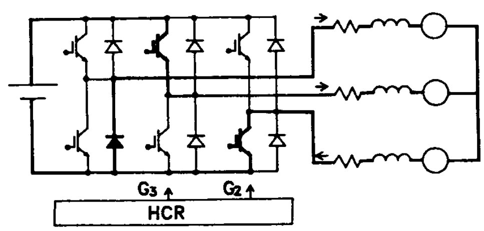
$T_s = (10\ k_e)/(6\ E)$: time corresponding 30°(electrical)

k_e : BEMF constant

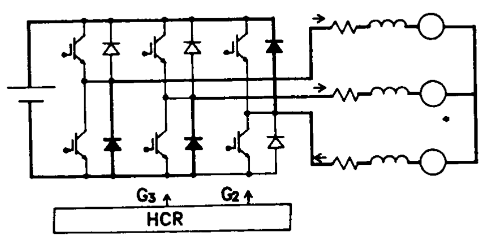
Three different cases of the phase commutation which depend on the operating conditions can be found[13], and the duration of the phase commutation and the torque ripple during the phase commutation for each case are obtained from (3) - (6), as follows. Also, the current waveforms are simulated using (4) - (6) and the motor parameters in Table I. They are shown in Fig. 4.



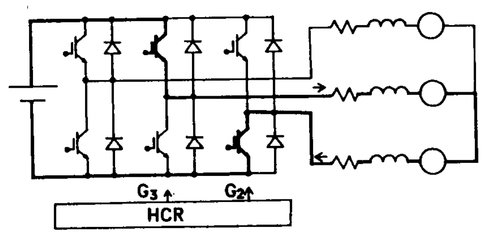
a) before commutation



b) during commutation : two IGBTs and one diode conducting



c) during commutation : three diodes conducting



d) after commutation

Fig. 3. Circuit configurations

1) Commutation case 1 : As shown in Fig. 4 a), the current i_a vanishes and at the same time the current i_b reaches its final value $i^*(0 < t \le t_c)$. The next sequence of Fig. 3 b) is then Fig. 3 d) and the phase commutation is finished. The duration and the torque ripple for this case can be summarized as follows:

duration :

$$t_c = (10\ k_e)/(3\ E)\ [2\ (2\ ev - 1)/ev] \tag{7}$$

where,

$ev = (2\ E)/V$

torque ripple :

$$\Delta T_q = (T_{qc} - T_{qn})/T_{qn} = 0 \tag{8}$$

where,

T_{qc} : peak torque in commutation stage which is obtained from (3)

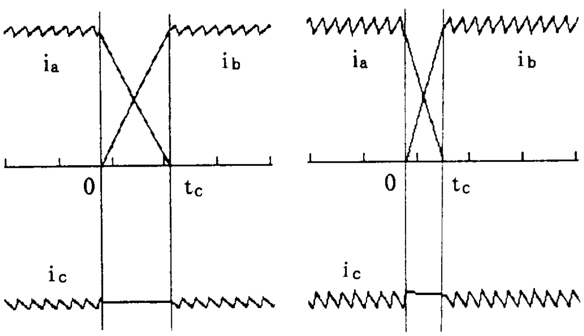
$T_{qn} = 2\ E\ i^*$: mean torque in conduction stage

2) Commutation case 2 : As shown in Fig. 4 b), the current i_b reaches the upper limit of the hysteresis window $i^* + \Delta i_{HW}/2$ before current i_a vanishes; the next sequence of Fig. 3 b) is Fig. 3 c) where Q_3 and Q_2 are switched off. So until i_a vanishes, there is a sequence which two IGBTs and one diode conduct or a sequence which three diodes conduct.

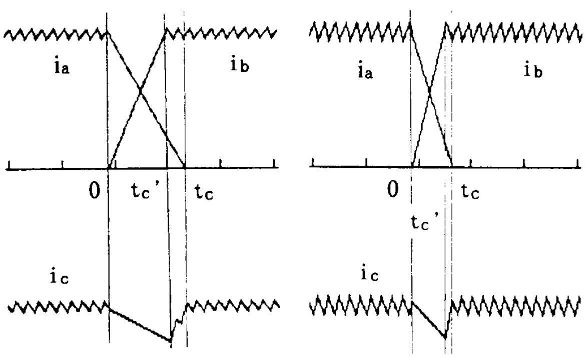
In order to simplify the analysis of this case, it is assumed that the first sequence of the phase commutation corresponds to that the current i_b reaches its final value i^* before current i_a vanishes($0 < t \le t_c'$) and the second one to that the current i_b remain its final value i^* where three diodes conduct until i_a vanishes(t_c'

TABLE I
MOTOR PARAMETERS

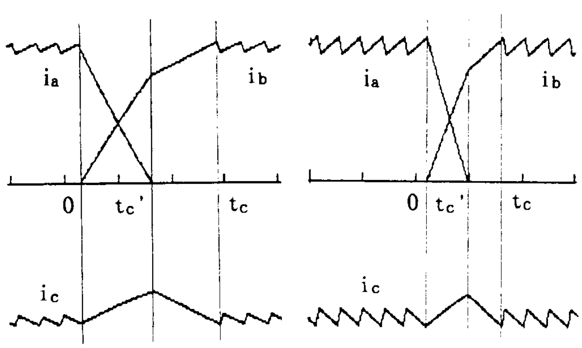
rated power, P_r	2.2 [kW]
rated speed, N_r	3000 [rpm]
rated torque, T_r	6.96 [Nm]
No. of pole pairs, P_p	3
DC link voltage, V	250 [V]
rated current, I_r	16.5 [A]
phase resistance, R	0.48 [Ω]
phase inductance, L	4.4 [mH]
BEMF constant, k_e	5.8 [V/krpm]
torque constant, k_t	0.54 [Nm/A]
rotor inertia, J_r	0.42 [kg-cm^2]
static friction, F	0.29 [Nm]



a) commutation case 1(2100 [rpm])



b) commutation case 2(1200 [rpm])



c) commutation case 3(3000 [rpm])

Fig. 4. Simulation results on commutation cases (the current control by HCR of the phase with rising current, left: 1[pu], right: 1/2[pu] load, x axis: 2[ms]/div.)

$\leq t \leq t_c$). The natural end of the phase commutation occurs when the decaying current reaches zero. The duration and the torque ripple for this case are:

duration :

$$t_c = (10\ k_e)/(6\ E)\ [(1 + ev)/ev]$$

$$\cdot \left[1 \pm \sqrt{1 - \frac{18\ L\ i^*}{10\ k_e} \left(\frac{ev}{1 + ev} \right)^2} \right] \quad (9)$$

torque ripple :

$$\Delta T_q = [1 - (3\ E)/(10\ k_e)]\ i_d(t_c')/i^* \quad (10)$$

where,

$$i_d(t_c') = (2\ E^2)/(10\ k_e\ L)\ t_c'^2 - V\ (1 + ev)/(3\ L)\ t_c' + i^*$$

$$t_c' = (10\ k_e)/(3\ E)\ [(2 - ev)/ev] \cdot \left[1 \pm \sqrt{1 - \frac{9\ L\ i^*}{10\ k_e} \left(\frac{ev}{2 - ev} \right)^2} \right]$$

3) Commutation case 3 : As shown in Fig. 4 c), the current i_a vanishes before current i_b reaches its final value $i^*(0 < t \leq t_c')$; the next sequence is also Fig. 3 d), but in this case the phase commutation will be achieved only when current i_b reaches the final value $i^*(t_c' \leq t \leq t_c)$. The duration and the torque ripple for this case are:

duration :

$$t_c = (2\ L)/[V\ (1 - ev)] \cdot \left[\frac{E^2}{10\ k_e\ L} t_c'^2 - \frac{V\ (1 + ev)}{6\ L} t_c' + i^* \right] \quad (11)$$

where,

$$t_c' = [(10\ k_e)/(6\ E)]\ [(1 + ev)/ev] \cdot \left[1 \pm \sqrt{1 - \frac{18\ L\ i^*}{10\ k_e} \left(\frac{ev}{1 + ev} \right)^2} \right]$$

torque ripple :

$$\Delta T_q = i_r(t_c')/i^* - 1 \quad (12)$$

where,

$$i_r(t_c') = V\ (2 - ev)/(3\ L)\ t_c' - E^2/(10\ k_e\ L)\ t_c'^2$$

In the commutation case 1, the uncommutating current i_c remains constant as shown in Fig. 4 a). So the case 1 does not introduce the torque ripple because the phase with uncommutating current does not involve the current ripple.

As shown in Fig. 4 b) and Fig. 4 c), during the phase commutation, the phase with uncommutating state presents a current ripple that can not be kept within the hysteresis window. The current ripple has the peak value at t_c'. It is due to the fact that two IGBTs and one diode conduct in the first sequence of the phase commutation because the rising current is lower than the upper limit of the hysteresis window. These results of simulation introduce an important fact that HCR of the phase with rising current can not control the uncommutating current in the commutation case 2 and 3. The characteristics of current control by HCR of the phase with rising current are the same as those of the current control by sensing the inverter input current mentioned in [12], [13].

Comparing the left and right figures in Fig. 4, it shows that the duration and the current ripple increase at the heavy load condition. But the phase commutation phenomenon for each case is the same for any load condition.

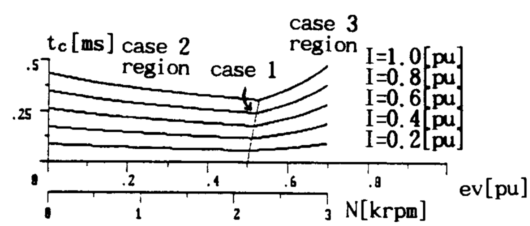
The duration and the torque ripple are simulated as Fig. 5 using (7) - (12). The duration decreases slightly as the speed increases in a low speed range and it increases rapidly as the speed increases in a high speed range. The duration is minimum for the speed of the commutation case 1. At a low speed the maximum of the torque ripple reaches +0.5 [pu] for any load condition and at a high speed it reaches about -0.25 [pu]. And it is zero for the speed of the case 1. Also the duration and the torque ripple depend on the mean value of the phase currents. That is, as the amplitude of the phase current increases, the duration and the torque ripple increase.

The effect on the motor speed due to the torque ripple can be defined as the peak value of the speed ripple as follows:

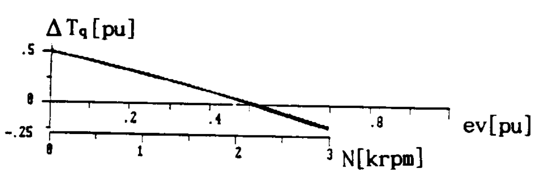
$$\Delta \omega_m = \frac{1}{J_r} \int_0^{t_c'} (T_{qc} - T_{qn})\, dt \qquad (13)$$

where,

$\Delta \omega_m$: peak value of the speed ripple



a) duration



b) torque ripple

Fig. 5. Duration of the phase commutation and the torque ripple during the phase commutation

From (13), the speed ripple is simulated as shown in Fig. 6. It atracts more attention that the speed ripple is conspicuous in a low and high speed range and in a large current where the duration and the torque ripple is large. The amplitude of the speed ripple reaches about 1.25 [rpm] at the very low speed and large current. It could be serious in the fine control applications such as the mill drive and the capstan drive.

B. Current control by HCR of the phase with uncommutating current and the independent current control by HCR of the each phase

For the commutation case 1 and 3 mentioned before, the characteristics of these schemes are the same as those of the current control by HCR of the phase with rising current. But they are not the same as those of the case 2. As shown in Fig. 7 a), the uncommutating current in the case 2 is kept within the hysteresis window although the duration is longer because there exists some freewheeling state in the phase with rising current. It is due to the fact that while one diode is conducting in the first sequence of the phase commutation, the switching state of two IGBTs is determined by HCR of the phase with uncomutating current. The decaying current flowing across the freewheeling diode does not depend on the HCR status.

The characteristics of the independent current control by HCR of the each phase are similar to those of the current control by HCR of the phase with uncommutating current. But, as shown in Fig. 7 b), the rising current continues to be switched on during the first sequence of the phase commutation, while the uncommutating current is switched on or off. It is because that the current control for the each phase is made independently by three HCRs.

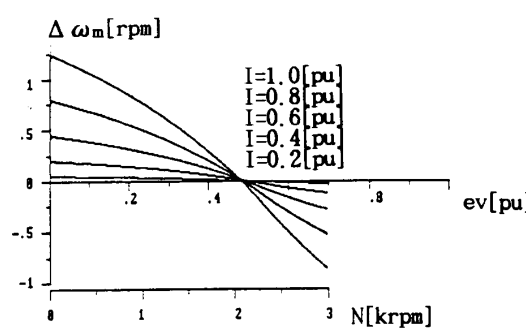
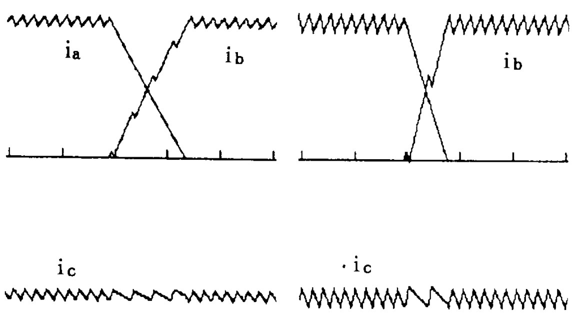
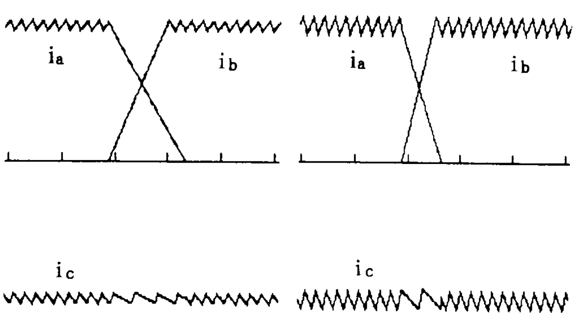


Fig. 6. Amplitude of the speed ripple



a) the current control by HCR of the phase with uncommutating current



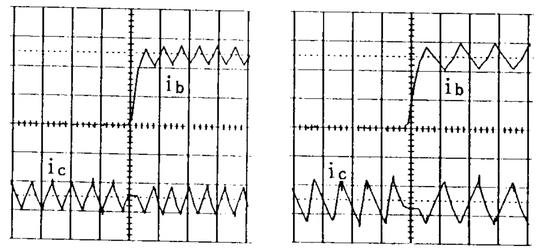
b) the independent current control by HCR of the each phase

Fig. 7. Simulation results on commutation case 2(the current control by HCR of the phase with uncommutating current and the independent current control by HCR of the each phase at 2100[rpm], left: 1[pu], right: 1/2 [pu] load, x axis: 2[ms]/div.)

shown in Fig. 7 b), the rising current continues to be switched on during the first sequence of the phase commutation, while the uncommutating current is switched on or off. It is because that the current control for the each phase is made independently by three HCRs.

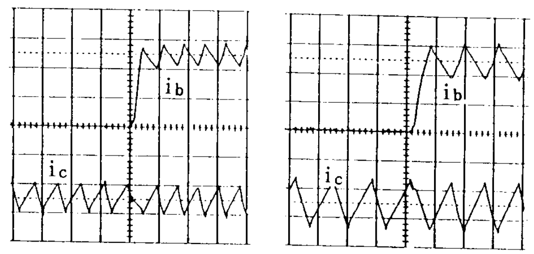
For the case 3, however, the uncommutating current can not be kept within the hysteresis window by the three methods of the current control mentioned before. The reason is that the decreasing current flows in the phase with uncommutating current although its own HCR commands the IGBT to switch on.

So in a speed range of the case 1 and 2,



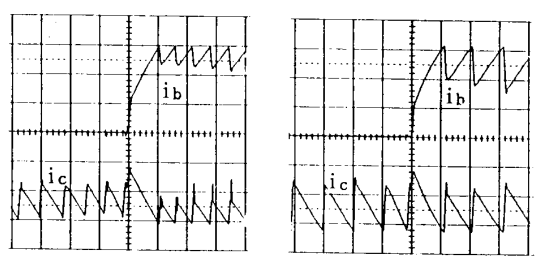
x axis : 0.1 [ms/div] x axis : 0.2 [ms/div]

a) commutation case 1(1800 [rpm])



x axis : 0.05 [ms/div] x axis : 0.1 [ms/div]

b) commutation case 2(1000 [rpm])



x axis : 0.5 [ms/div] x axis : 1 [ms/div]

c) commutation case 3(3000 [rpm])

Fig. 8. Experimental results on commutation cases(the independent currnt control of HCR of the each phase, left: 1/3 [pu], right: 1/8 [pu] load)

when the phase currents are controlled by the HCR of the phase with uncommutating current and by the independent current control by HCR of the each phase, the torque ripple and the speed ripple are not sensitive to the duration. And they are bounded within a value corresponding to the hysteresis window because the phase currents are kept within the hysteresis window. On the other hand, in a speed range of the case 3, both the duration and the torque ripple in the right portion in Fig. 5 affect seriously to the motor speed. So there exist the speed ripple in a high speed range, as shown in the right portion in Fig. 6.

For the independent current control by HCR of the each phase, the current waveforms are validated by the experiments under 1/3 [pu] and 1/8 [pu] load condition, respectively, as shown in Fig. 8. For each case, it can be seen that the duration and the current ripple increase as the amplitude of the phase current increases. This is the same as the results deduced from the simulations, as Fig. 4 a), 7 b) and 4 c), respectively. Also, the uncommutating current in the case 2 remains within the hysteresis window.

Ⅳ. CONCLUSION

The phase commutation was analyzed taking into account the possible configurations of the hysteresis current regulator.

The simulation and experimental results indicate that the duration of the phase commutation and the current ripple during the phase commutation vary with speed and depend on the amplitude of the phase current. The torque ripple during the phase commutation and the speed ripple due to the torque ripple are conspicuous in a low and high speed range and in a large current where the duration and the current ripple is large. The method by the independent current control allows to eliminate the torque ripple during the phase commutation and the speed ripple in a low speed range.

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