Research on Overall Efficiency Improvement of Electric Vehicles by MTHDPAM Control Method

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Abstract - In this paper, I propose the Minimum Total Harmonic Distortion Pulse Amplitude Modulation control method. This control method is beforehand calculating the switching pattern to minimize THD by adding a redundant pulse. This is attributed to increase of the motor iron loss depending on harmonic voltage.

Keywords - Pulse Amplitude Modulation, Total Harmonic Distortion, Permanent Magnet Synchronous Motor

I. INTRODUCTION

The global environmental issue pushes to shift the use of internal combustion engine vehicles to the hybrid and pure electric vehicles. One of the key technologies in this area is the energy saving as a total system. It is desirable if the Permanent Magnet Synchronous Motor (PMSM) is driven by a pure sinusoidal voltage, but it is not realistic for EV application. Therefore, motor control is generally used Pulse Width Modulation (PWM) control method, which transform from AC voltage to equivalent DC voltage using inverter switching. However, the PWM voltage inevitably contains harmonics. Additionally, the PM motor iron loss depends on these harmonics.

In this paper, I propose the Minimum Total Harmonic Distortion Pulse Amplitude Modulation (MTHDPAM) control method. This control method is beforehand calculating the switching pattern to minimize Total Harmonic Distortion (THD) by adding a redundant pulse. This strategy is based on voltage waveform analysis for reduce harmonics compared with the Pulse Amplitude Modulation (PAM) control method. Several kinds of Pulse Width Modulation (PWM) pattern generation methods are compared in this paper. For example, a single PAM control method, MTHDPAM control method, Quasi-PAM control method are investigated. And using these PWM pattern, the dq equations of PM motor are solved by numerical approach and the motor efficiency is compared each other.

Fig. 1. Three-phase uvw -axis stationary coordinate system

Fig. 2. Two-phase dq -axis rotating coordinate system

Fig. 3. d -axis equivalent circuit

Fig. 4. q -axis equivalent circuit

II. EQUIVALENT IRON LOSS OF PM MOTOR

A. PMSM dq -axis equivalent circuit[5]

Three-phase uvw -axis PMSM in Fig. 1 can be transformed into two-phase dq -axis model as shown in Fig. 2 after three-phase to two-phase transformation and also stationary reference frame to rotating reference frame transformation. The equivalent dq equations become as follows.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -\omega L_q \\ \omega L_d & R_a + pL_q \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \Psi_a \end{bmatrix} \quad (1)$$

where p is differential operator, ω is angular velocity, Ψ_a is Flux linkage and motor movement equation is defined as:

$$J \frac{d\omega}{dt} = T_e - T_L - B\omega \quad (2)$$

where J is Inertia, T_e is motor torque, T_L is load torque, B is viscous friction coefficient, P_n is logarithmic pole and T_e is expressed by the following equation.

$$T_e = P_n \{ \Psi_a I_q + (L_d - L_q) I_d I_q \} \quad (3)$$

In general for PM motor analysis, the model shown in Fig. 2 is used. However, this model is not considering motor iron loss. Therefore, when the efficiency is investigated, the equivalent circuits including equivalent iron loss resistance R_c in Fig. 3 and 4 are often used.

B. Basic voltage equation

Fig. 3 and Fig. 4 indicate dq -axis equivalent circuit considering the motor iron loss. Equivalent circuit considering the motor iron loss can obtain basic voltage equation, which is expressed as follows.

$$\begin{bmatrix} V_{od} \\ V_{oq} \end{bmatrix} = \begin{bmatrix} pL_d & -\omega L_q \\ \omega L_d & pL_q \end{bmatrix} \begin{bmatrix} I_{od} \\ I_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \Psi_a \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_a & 0 \\ 0 & R_a \end{bmatrix} \begin{bmatrix} I_{od} \\ I_{oq} \end{bmatrix} + \left(1 + \frac{R_a}{R_c}\right) \begin{bmatrix} V_{od} \\ V_{oq} \end{bmatrix} \quad (5)$$

where current equation is expressed as follows.

$$I_{od} = I_d - I_{cd} \quad (6)$$

$$I_{cd} = \frac{-\omega L_q I_{oq} + pL_d I_{od}}{R_c} \quad (7)$$

$$I_{oq} = I_q - I_{cq} \quad (8)$$

$$I_{cq} = \frac{\omega(\Psi_a + L_d I_{od}) + pL_q I_{oq}}{R_c} \quad (9)$$

C. Efficiency calculation

The iron loss W_i [W], copper loss W_c [W], mechanical output P_m [W] and efficiency η [%] are defined as:

$$W_i = \frac{V_{od}^2 + V_{oq}^2}{R_c} \quad (10)$$

$$W_c = R_a(I_d^2 + I_q^2) \quad (11)$$

$$P_m = \omega T_e \quad (12)$$

$$\eta = \frac{P_m}{P_m + W_i + W_c} \times 100 \quad (13)$$

where iron loss is represented by power consumption of equivalent iron loss resistance, and copper loss is represented by power consumption of armature winding resistance.

III. WAVEFORM ANALYSIS

In general, inverter output voltage waveform is non-sinusoidal. Therefore, it is contained harmonic components. Thus, we need to analyze waveform to measure the amount of harmonic components. In addition, harmonic components obtained by Fourier series expansion.

A. Fourier series expansion

Any periodic waveform $f(\omega t)$ can expand in Fourier series as follows.

$$f(\omega t) = A_0 + \sum_{n=1}^{\infty} (A_n \cos n\omega t + B_n \sin n\omega t) \quad (14)$$

where A_0 , A_n and B_n are defined as:

$$\begin{cases} A_0 = \frac{1}{2\pi} \int_0^{2\pi} f(\omega t) d\omega t \\ A_n = \frac{1}{\pi} \int_0^{2\pi} f(\omega t) \cos n\omega t d\omega t \\ B_n = \frac{1}{\pi} \int_0^{2\pi} f(\omega t) \sin n\omega t d\omega t \end{cases} \quad (15)$$

B. Total Harmonic Distortion

THD represents the ratio of the rms sum of harmonics with the rms of fundamental of the waveform.

Therefore, THD is defined as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} (A_n^2 + B_n^2)}}{\sqrt{A_1^2 + B_1^2}} \times 100\% \quad (16)$$

High THD causes an increase of copper loss and iron loss. In addition, the overheating, equipment vibration, noise and other adverse effects are generated.

IV. PWM AND PAM CONTROL METHODS

A. PWM control method[1]

The PWM control method controls the pulse width by comparing the carrier signal that is proportion to the time such as triangular or sawtooth wave with the modulated signal. It is well known that the iron loss of motor and the switching loss of inverter increase due to the carrier harmonics of the PWM inverter. Moreover, the typical and widely used the PWM control method power train for EV is battery-inverter-motor combination as shown in Fig. 5.

B. PAM control method[2][3]

While the PWM control method controls the pulse width of the applied DC voltage of the inverter, depending on the size of the average output voltage, PAM control method controls the pulse amplitude of the applied DC voltage of the inverter, depending on the size of the average output voltage by using a chopper. Therefore, the PAM control method power train for EV is battery-DC-DC chopper-inverter-motor combination as shown in Fig. 6.

Fig. 5. PWM control method power train

Fig. 6. PAM control method power train

Fig. 7. PWM waveform

Fig. 8. PAM waveform

C. Quasi-PAM control method[4]

The Quasi-PAM control method changes the pulse amplitude similarly PAM control method. However, it changes the pulse amplitude for efficiency improvement. Therefore, it controls the pulse width by comparing the carrier signal with the modulated signal similarly the PWM control method. Accordingly, this control method does not need to consider the time delay at chopper unlike the PAM control method. Namely, this control method is simple compared with the PAM control method, however, the prospects for improving the efficiency compared with PAM control method is small.

D. Comparison of PWM and PAM control methods

The applied voltage of the PWM control method inverter is fixed battery output voltage as shown in Fig. 7. In contrast, the applied voltage of the PAM control method inverter is changing according to the motor speed using a chopper as shown in Fig. 8.

In addition, the inverter switching loss P_{sw} [W] is defined as:

$$P_{sw} = \frac{V_{inv} \times I_{ave}}{6} \times (T_r + T_f) \times f_{sw} \quad (17)$$

where V_{inv} [V] is inverter DC link voltage, I_{ave} [A] is average current of flow the switching device, T_r [S] is turn-on rising time, T_f [S] is turn-off falling time and f_{sw} [s] is switching frequency.

Moreover, motor iron loss is expressed by sum of hysteresis loss p_h [W] and eddy current loss p_e [W], and these losses are defined as:

$$p_h = \frac{k_h \cdot k_m^\beta}{S^\beta} \times \frac{V_m^\beta}{f^{\beta-1}} \quad (18)$$

$$p_e = \frac{k_e \cdot k_m^2}{S^2} \times V_m^2 \quad (19)$$

where V_m [V] is harmonic voltage, S [m²] is sectional area of iron core and β is Steinmetz constant depending on material. From equation (18) and (19), it is estimated that the iron loss is proportional to the applied voltage amplitude of the motor. The absolute value of harmonic voltage of the PAM control method can be less than that of the PWM control method. Therefore, the iron loss can be decreased and the motor efficiency can be improved. However, the PAM control method is using two-way chopper. Therefore, the chopper efficiency affects the total efficiency.

Moreover, motor copper loss P_{copper} [W] is defined as:

$$P_{copper} = R_a I_1 + R_a I_m \quad (20)$$

where R_a [Ω] is Armature winding resistance, I_1 [A] is primary current, I_m [A] is harmonic current. In case of the PAM control method, 6th harmonic torque pulsation is generated. This is due to 5th and 7th harmonics of output frequency. In addition, torque pulsation causes an increase of harmonic current. Thus, copper loss is increased as shown in equation (20). By contrast, in case of the PWM control method, torque pulsation is rarely occurs. This is due to high frequency switching of inverter, and harmonics are migrated to the higher frequency. Thus, harmonic current and copper loss are reduced. From these results, by using the PAM control method compared with the PWM control method, reduction of the motor iron loss and the inverter switching loss can

Fig. 9. MTHDPAM (9 pulses per half cycle) voltage waveform

Fig. 10. Harmonics comparison of PAM and MTHDPAM (9 pulses per half cycle) voltage waveforms

be expected, however, the motor copper loss is increased. Therefore, if the harmonics of the PAM control method can be suppressed, the reduction of the motor copper loss and iron loss can be expected. In next section, the Minimum THD PAM control method is proposed. In case of this control method, the THD is reduced compared with the PAM control method. It is achieved by waveform analysis of the motor voltage aimed at reduction of the THD.

V. MTHDPAM CONTROL METHOD[6][7]

The MTHDPAM control method controls pulse amplitude similarly the PAM control method, depending on the motor speed. Therefore it is beforehand calculating the switching pattern to minimize THD by adding a redundant pulse. Moreover, it is changing the number of pulses per half cycle by varying the number of θ , and it is changing the pulse width and position by varying the value of θ as shown in Fig. 9 (however, this figure is one example of it, and it is 9 pulses per half cycle).

Furthermore, Fourier coefficient of output voltage v is become as follows.

$$B_n = \frac{4E}{n\pi} \sin\left(\frac{n\pi}{2}\right) \sin\left(\frac{n\pi}{3}\right) (1 - 2\cos n\theta_1 + 2\cos n\theta_2 - 2\cos n\theta_3 + 2\cos n\theta_4) \quad (21)$$

TABLE I
THD OF MTHDPAM CONTROL

Number of pulses	1	3	5	7	9	11	13	15	17
Number of θ	0	1	2	3	4	5	6	7	8
$\theta_1(^{\circ})$	-	1.2	1.5	1.5	1.6	1.6	1.7	1.6	1.7
$\theta_2(^{\circ})$	-	-	2.7	3.1	3.0	3.3	3.2	3.4	3.2
$\theta_3(^{\circ})$	-	-	-	4.3	4.8	4.7	5.0	4.8	5.1
$\theta_4(^{\circ})$	-	-	-	-	5.9	6.5	6.3	6.7	6.4
$\theta_5(^{\circ})$	-	-	-	-	-	7.6	8.2	7.9	8.5
$\theta_6(^{\circ})$	-	-	-	-	-	-	9.2	9.9	9.6
$\theta_7(^{\circ})$	-	-	-	-	-	-	-	10.8	11.7
$\theta_8(^{\circ})$	-	-	-	-	-	-	-	-	12.5
THD (%)	30.5	28.6	26.5	24.4	22.3	20.3	18.3	16.5	14.7

TABLE II
SPECIFICATIONS OF MOTOR

Armature winding resistance	R_a (Ω)	0.21
Equivalent iron loss resistance	R_c (Ω)	2000
Number of pole pairs	P_n	10
Flux linkage	Ψ_a (Wb)	0.75
d -axis self-inductance	L_d (mH)	1.4
q -axis self-inductance	L_q (mH)	2.5
Inertia	J ($\text{kg} \cdot \text{m}^2$)	0.090
Viscous friction coefficient	B ($\text{kg} \cdot \text{m}^2/\text{s}$)	0.001

From equation (21) the comparison of harmonics of voltage waveforms with MTHDPAM and PAM control methods is shown as Fig. 10. From Fig. 10, it is obvious that the MTHDPAM control method is effectiveness about reduction of harmonics than the PAM control method. In addition, table I indicates THD of the MTHDPAM control method, when changing the number of θ per half cycle. It is indicates that the MTHDPAM control method can reduce harmonics than the PAM control method, depending on increasing number of θ per half cycle. However, increasing of θ number is caused to increase inverter switching loss. Therefore, it is necessary that considering the inverter switching loss and motor iron loss for decide the optimum number of pulses.

VI. SIMULATION OF EFFICIENCY MEASUREMENT[8][9]

Fig. 11 indicates PWM and Quasi-PAM control methods simulation model. In this case PWM pulse is generated by battery voltage V_{batt} and inverter switching. Inverter switching pattern is calculated by carrier signal and modulation signal $V_{uref}, V_{vref}, V_{wref}$. Modulation signal is converted from V_{dref} and V_{qref} , using phase transformation and co-ordinate transformation. By contrast, Fig. 12 indicates PAM and MTHDPAM control methods simulation model. In this case PAM pulse is generated by chopper output voltage V_{chop} and inverter switching. V_{chop} is controlled to command value

Fig. 13. Motor efficiency simulation result

Fig. 14. Motor iron loss simulation result

Fig. 15. Motor copper loss simulation result

circuit as shown in Fig. 3 and 4 may be cannot consider the increasing iron loss by harmonics. For this reason, in case of dq -axis equivalent circuit can consider the increasing iron loss by harmonics, the difference from the MTHDPAM control method and the PAM control method will be become more remarkable.

VII. CONCLUSION

For reduction of the PM motor iron loss, the MTHDPAM (Minimum Total Harmonic Distortion Pulse Amplitude Modulation) control method is proposed as a new pulse pattern generation for PM motor drive system. This control method is beforehand calculating the switching pattern to minimize THD by adding a redundant pulse. This is attributed to increase of the motor iron loss depending on harmonic voltage. The simulation results are shown and the effectiveness of the proposed method is confirmed.

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