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A Study on the Control Problem of Driving DC Motor with Very-low speed in Automatic Door System for Home

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Abstract

The direct driven automatic door, which absence of the gear box is developed for high efficiency and noise reduction. In this paper, low speed control problem of direct driven automatic door is introduced and analyzed about PWM (Pulse Width Modulation) control. Based on Fourier series of PWM waveform and electric motor modeling, it was found that linearity is related to duty ratio and PWM frequency. That is, harmonic components of PWM influence the dynamics of motor such as RPM and linearity. The harmonic components analysis of PWM control is verified by simulation studies and experiments. In experiments, the resolution of PWM control is reduced at low speed range and linearity is also decreased by low frequency PWM signal.

Keywords*: Automatic Door; Auto-door; Motor; PWM; Very-low speed*

1. Introduction

The automatic door is widely used due to its conveniences as well as reduction of heating and cooling load. Therefore, it is installed not only for outdoor use such as department stores, shopping centers, and office buildings but also for domestic use, which increase its demand in recent years.

The automatic door consist of four parts: 1) mechanical parts, 2) a control unit that transmits control signals to actuator system by algorithm and logic, 3) a remote control unit that transmits control signals to a control unit detected by sensors, an access keypad or a card reader and, 4) an actuator system operated by controller. A default operation is that the actuator starts by a control unit and stops by a proximity sensor. Also, the electric motor of automatic door is required to low speed control as the door closed or opened due to impact-resistant. To fulfill this requirement, a geared motor generally installed on the automatic door. However, the friction effect and backlash of gear make energy loss and noise. Moreover, the gear reducers not only reduce the rotor speed, but they also increase the resistive force of the system significantly. In the automatic door, a worm gear as well as spur gears is used to amplify the torque generated by an electric motor. The worm gear is self-locked when rotated from the load side, which implies a large resistive force of the system. In case of an emergency such as fire and earthquake, the automatic door doesn't work by temporary shutdowns. It turns out to be a total disaster. Therefore, an alternative approach should be sought to obtain the desired design; the automatic door should be coupled direct driven with motor. For the rejection of the gear box at automatic door, low speed controller should be designed by both hardware and software components. Lee [1] proposed VVPWM (Voltage-Varying Pulse Width Modulation) method that controls the motor at low speed without gear box. It is possible to open the automatic door by external force while temporary shutdowns. Also, Lee [2] investigated correlation between PWM

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digital bits and angular speed of motor, so that required bit can be set for operation speed range. In many applications, however, researches of the electric motor performance have been focused on high-speed control [3], precise control [4], torque ripple reduction [5][6], and high efficiency control [7-8].

In this paper, low speed control of automatic door is introduced. We have been developed a direct driven automatic door that aims escaping without any difficulties in an emergency. The PWM control of electric motor is investigated that provides nonlinearity and low resolution at low speed. Also, notice that the dynamic characteristics are varied by PWM frequency and it is related on current ripple and harmonic analysis. The harmonic frequency should be considered in controlling the direct driven automatic door at low speed.

2. Analysis of PWM Control

PWM voltage control is generally used to control electric motor compared to analog voltage control due to power efficiency. The PWM control which power device is switched at a high frequency generates averaging current through inductor. That is to say, the dynamic characteristic of PWM control is different with analog control. In this chapter, current ripple and harmonic frequencies are analyzed based on electric motor model and PWM signal model.

2.1. Analysis of Current Ripple by PWM Control

Figure 1 show an equivalent circuit for analyzing DC motor with PWM controller, where V_S and V_B are the supply voltage and back-EMF respectively, R is the resistance of winding, L is the inductance of winding.

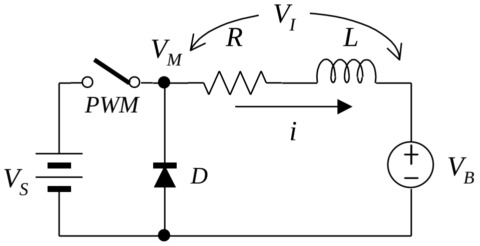


Figure 1. The Equivalent Circuit of Electric Motor

The back-EMF is assumed to be zero for simplicity and, V_M is switched voltage that determined by PWM controller and switching device as shown in Figure 2. The winding voltage, V_I is generated by V_M minus V_B. The current which flows into the inductor, L and resistor R makes ripple.

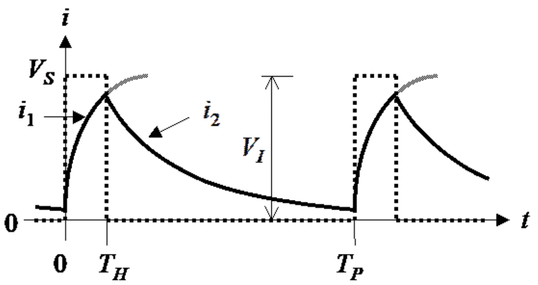


Figure 2. Simulation Result of the Ideal PWM Voltage and Current: the Dashed Lines Show the Switched Voltage and Continuous Line Show the Current

That switching device is on and that switching device is off are expressed equation (1) and (2) respectively [9].

$$i_1(t)=\left(\frac{V_1}{R}-i_2(T_P)\right)\cdot\left(1-e^{-t/\tau}\right)+i_2(T_P)\,,\qquad 0\le t\le T_H \tag{1}$$

$$i_2(t)=i_1(T_H)\cdot e^{-(t-T_H)/\tau}\,,\qquad T_H\le t\le T_P \tag{2}$$

Where time constant, τ is calculated as $\tau = L/R$.

1) Minimum current $i_2(T_P)$

Substitution of $t = T_H$ into equation (1) yields

$$i_1(T_H)=\left(\frac{V_1}{R}-i_2(T_P)\right)\cdot\left(1-e^{-T_H/\tau}\right)+i_2(T_P) \tag{3}$$

Substituting equation (3) into (2) yields

$$i_2(t)=\left\{\left(\frac{V_1}{R}-i_2(T_P)\right)\cdot\left(1-e^{-T_H/\tau}\right)+i_2(T_P)\right\}\cdot e^{-(t-T_H)/\tau}$$

$$=\left(\frac{V_1}{R}-i_2(T_P)\right)\cdot\left(e^{-(t-T_H)/\tau}-e^{-T_H/\tau}\right)+i_2(T_P)\cdot e^{-(t-T_H)/\tau} \tag{4}$$

Minimum current is obtained by

$$i_2(T_P)=\left(\frac{V_1}{R}-i_2(T_P)\right)\cdot\left(e^{-(T_P-T_H)/\tau}-e^{-T_H/\tau}\right)+i_2(T_P)\cdot e^{-(T_P-T_H)/\tau}$$

$$i_2(T_P)=\frac{V_1}{R}\cdot\frac{e^{-(T_P-T_H)/\tau}-e^{-T_H/\tau}}{1-e^{-T_P/\tau}} \tag{5}$$

2) Maximum current $i_1(T_H)$

Substitution of $t = T_P$ into equation (2) yields

$$i_2(t)=i_1(T_H)\cdot e^{-(T_P-T_H)/\tau} \tag{6}$$

Organizing (5) and (6), maximum current is obtained, *i.e.*,

$$i_1(T_H)=\frac{V_1}{R}\cdot\frac{1-e^{-T_H/\tau}}{1-e^{-T_P/\tau}} \tag{7}$$

3) Current ripple

Notice that equation (5) and (7) are not considered as back-EMF. When the back-EMF is increased by angular speed of motor, and inductor voltage, V_I is decreased. The winding voltage is represented [10] as

$$V_I = V_S - V_B \tag{8}$$

The back-EMF is related by only winding voltage in equation (5) and (7). Back-EMF can be obtained as

$$V_B = N\cdot K_B \tag{9}$$

where N is angular speed of motor and K_B is back-EMF constant. It is assumed that the RPM is proportional to voltage which is

$$N = V_M\cdot K_N \tag{10}$$

where K_N denotes speed constant that RPM per voltage. Substituting equation (9) and (10) into equation (8) yields

$$V_I = V_S - V_M\cdot K_B\cdot K_N \tag{11}$$

In practice, PWM voltage applied to the motor, V_M that RMS value of a pulse wave [9] is obtained as

$$V_M = \sqrt{\frac{1}{T_P}\left(\int_0^{T_H} V_S^2\,dt+\int_{T_H}^{T_P} 0\,dt\right)}$$

$$= V_S \cdot \sqrt{\frac{T_H}{T_P}} = V_S \cdot \sqrt{D} \tag{12}$$

where D is duty ratio (*i.e.*, T_H/T_P). Substituting equation (12) into (11) yields

$$V_I = V_S \cdot \left(1 - \sqrt{D} \cdot K_B \cdot K_N\right) \tag{13}$$

Assuming that the linear relationship RPM and voltage, peak to peak current can be calculated by

$$I_{r,pp} = i_1(T_H) - i_2(T_P)$$

$$= \frac{V_S}{R} \cdot \left(1 - \sqrt{D} \cdot K_B \cdot K_N\right) \cdot \frac{1 - e^{-(T_P - T_H)/\tau}}{1 - e^{-T_P/\tau}} \tag{14}$$

2.2. Analysis about Harmonic Components of PWM

In order to analyze harmonic frequencies in PWM waveform, it can be represented by Fourier series as follows.

$$v_1(t) = \begin{cases} V_I, & 0 \le t \le T_H \\ 0, & T_H \le t \le T_P \end{cases} \tag{15}$$

The coefficient a_n is

$$a_n = \frac{2}{T_P} \int_0^{T_P} f(t) \cdot \cos \omega_0 t \, dt$$

$$= \frac{2V_I}{n\omega_0 T_P} \sin n\omega_0 T_H \tag{16}$$

$$a_n = \frac{1}{n} \cdot \frac{V_I}{\pi} \sin 2n\pi D \tag{17}$$

where $\omega_0 = 2\pi/T_P$. Similarly, the coefficient b_n is

$$b_n = \frac{2}{T_P} \int_0^{T_P} f(t) \cdot \sin n\omega_0 t \, dt$$

$$= \frac{1}{n} \cdot \frac{V_I}{\pi} \left(1 - \cos 2n\pi D\right) \tag{18}$$

For harmonic voltage, the equation follows as

$$V_n = \sqrt{a_n^2 + b_n^2} = \frac{V_I}{n\pi} \sqrt{\sin^2 2n\pi D + \left(1 - \cos 2n\pi D\right)^2}$$

$$= \frac{\sqrt{2} \cdot V_I}{n\pi} \sqrt{1 - \cos 2n\pi D} \tag{19}$$

Impedance of motor which expressed in complex form is represented by

$$Z_n = R + j\omega_0 nL \tag{20}$$

$$I_n = \frac{\sqrt{2} \cdot V_I}{n\pi} \frac{\sqrt{1 - \cos 2n\pi D}}{\sqrt{\left(2\pi nL/T_P\right)^2 + R^2}} \tag{21}$$

RMS of harmonic current can be calculated by dividing $\sqrt{2}$ due to cosine function, *i.e.*,

$$I_{n,rms} = \frac{V_I}{n\pi} \frac{\sqrt{1 - \cos 2n\pi D}}{\sqrt{\left(2\pi nL/T_P\right)^2 + R^2}} \tag{22}$$

Substituting equation (13) into (22) yields

$$I_{n,rms} = \frac{V_S}{n\pi} \cdot \left(1 - \sqrt{D} \cdot K_B \cdot K_N\right) \cdot \frac{\sqrt{1 - \cos 2n\pi D}}{\sqrt{\left(2\pi nL / T_P\right)^2 + R^2}} \tag{23}$$

As a result, harmonic current generated by PWM signal can be obtained by

$$I_{rms} = \sum_{n=1}^{\infty} \left\{ \frac{V_S}{n\pi} \cdot \left(1 - \sqrt{D} \cdot K_B \cdot K_N\right) \cdot \frac{\sqrt{1 - \cos 2n\pi D}}{\sqrt{\left(2\pi nL / T_P\right)^2 + R^2}} \right\} \tag{24}$$

3. Simulations and Experiments

Figure 3 shows the simulation results of peak to peak current based on the equation (14), and Figure 4 shows the simulation results of RMS current based on the equation (24). The simulation is assumed that the electric motor is linear system, and simulation parameters are actual motor system listed in Figure 5 [11].

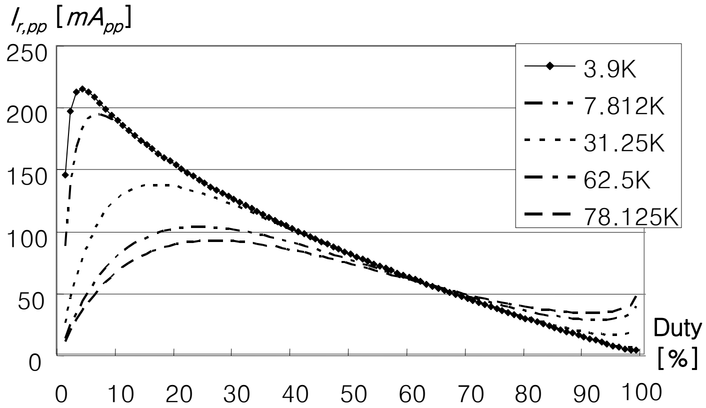


Figure 3. Simulation Results of Peak to Peak Current in Motor A

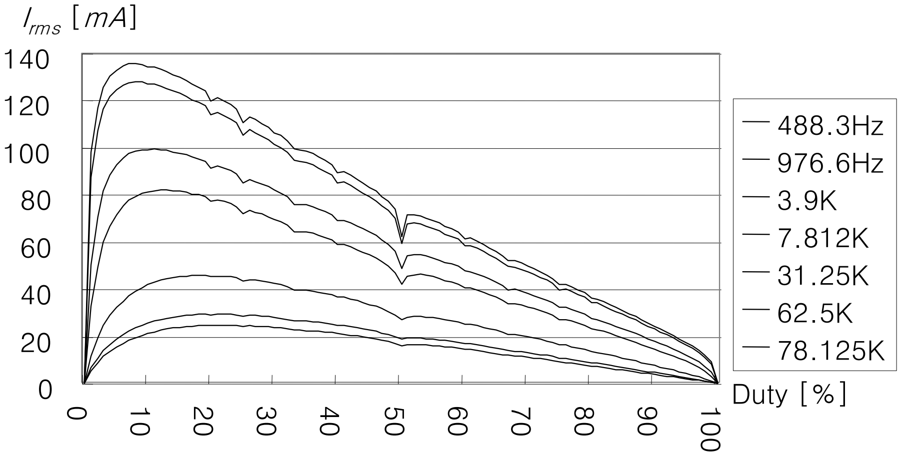


Figure 4. Simulation Results of Harmonic Current in Motor A

Motor A : Made in Swiss
Nominal voltage : 36 V
Terminal resistance : 130 Ω
Terminal inductance : 380 μH
Angular speed constant : $K_N = 175.7\ RPM/V$
Back-EMF constant : $K_B = 5.68\ \mu V/RPM$

Figure 5. Specifications of an Electric Motor a used in Experiments

Both the simulation results show different PWM frequency; the higher the frequency, the lower peak to peak current and RMS current. Notice that the harmonic current of the motor is increased by high frequency, which means that *RL* circuit attenuates below the cutoff frequency. Also, notice from Figure 3 and Figure 4 that the harmonic current is increased when the PWM duty ratio is reduced. This was because when the angular speed is reduced (*i.e.*, PWM duty is reduced), back-EMF (*i.e.*, DC component) is also reduced by equation (24).

An experiment was carried out for verification of simulation result as shown in Figure 6. In the experiments, PWM output (OC0A) was 8-bit resolution in microprocessor [12]. The angular speed was measured by an incremental encoder with timer/counter in microprocessor. The sampling rate of angular speed was 1 *Hz*.

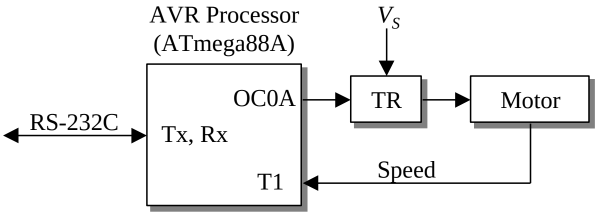


Figure 6. Experiential Setup for Verification of Effectiveness of Harmonic Components

The experimental results coincide with simulation results, which imply that the harmonic components definitely related with linearity of motor dynamics.

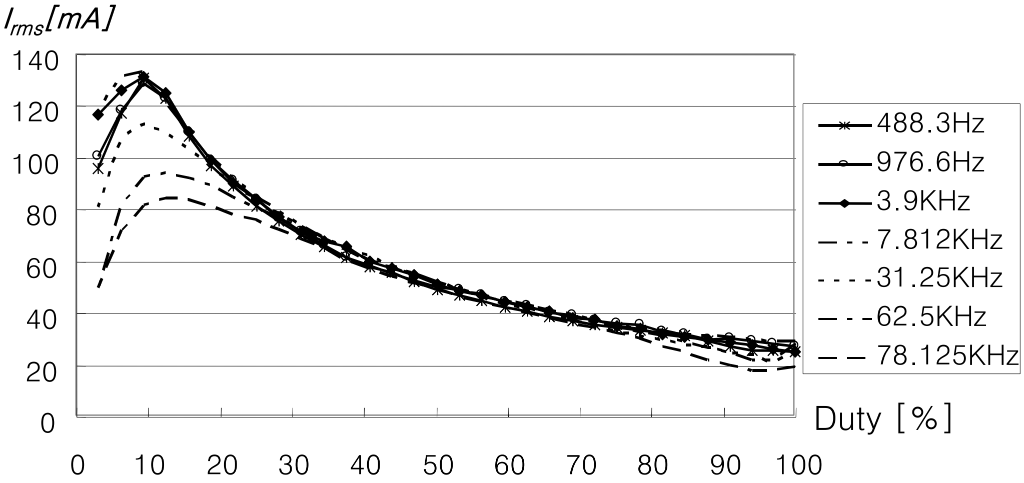
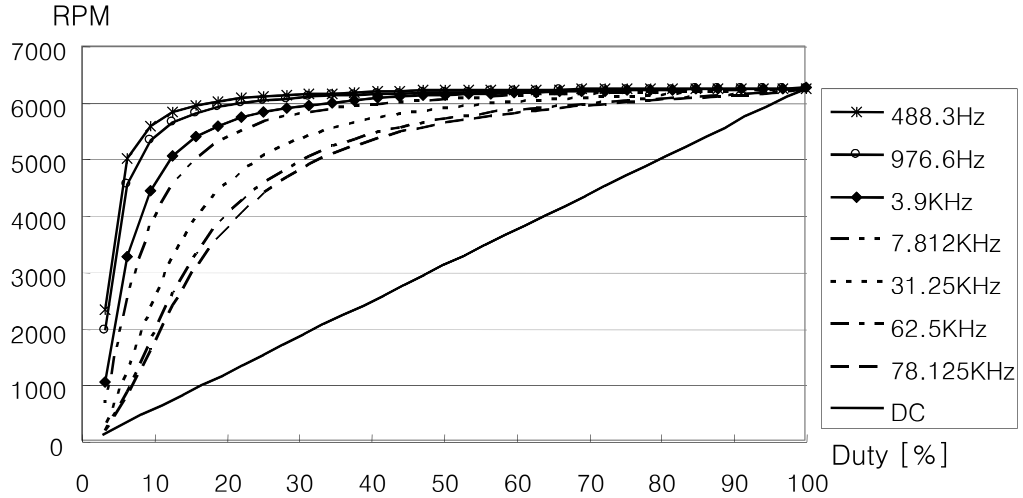
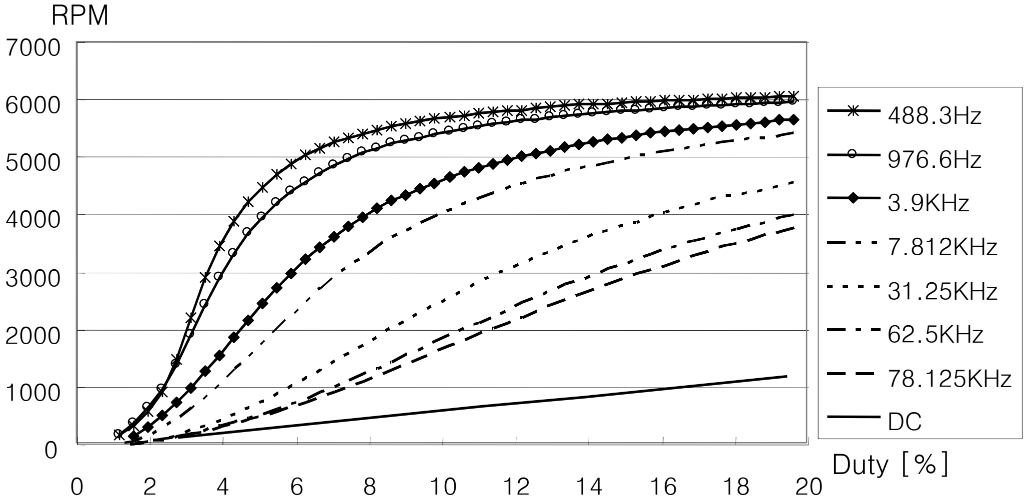


Figure 7. Experimental Results of AC Current in Motor A



(a) Overall View



(b) Low Speed Range

Figure 8. Experimental Results of RPM with Various PWM Frequencies in Motor A

The experimental results showed that duty ratio control provided nonliterary of an actuator performance. For this reason, the back-EMF was also nonlinear factor. The RPM of motor was measured according to the duty ratio, and then, various frequencies were tested as shown in Figure 8(a). In the zoomed-in graphs shown in Figure 8(b) which mainly focus on the low speed range, nonliterary of the low frequency PWM control is clearly shown.

It is noteworthy that the DC voltage control was perfectly linear as shown in the Figure 8. On the other hand, the linearity was reduced, as frequency was decreased. More specifically, the angular speed was decreased linearly as 23.4 *RPM* per bit in the DC voltage control. However, the angular speed was decreased as 3 *RPM* per bit at high speed range and 730 *RPM* per bit at low speed range in 488.8*Hz* PWM control. For this reason, 13-bit 488.8*Hz* PWM control has the same resolution as 8-bit DC control at low speed. Table 1 shows a comparison between DC control and PWM control for minimum controllable RPM according to the variation of the resolution.

Table 1. A Comparison between DC Control and PWM Control for Minimum Controllable RPM According to the Variation of the Resolution

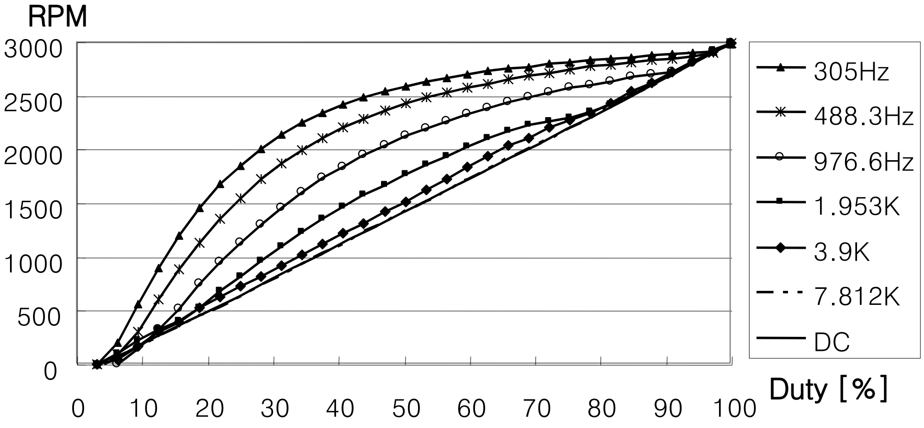
DC control		PWM Control	
bit	***RPM* per bit**	**78.125 *KHz***	**488.8 *Hz***
8-bit	23.43 RPM	11-bit	13-bit
10-bit	5.859 RPM	13-bit	15-bit
12-bit	1.465 RPM	15-bit	17-bit
16-bit	0.092 RPM	19-bit	21-bit

As shown in the Figure 9, another experiment which motor parameters were different with Figure 5 was carried out for repeatability. Figure 10 shows that DC voltage control was more linear than PWM control; this result is similar to Figure 8.

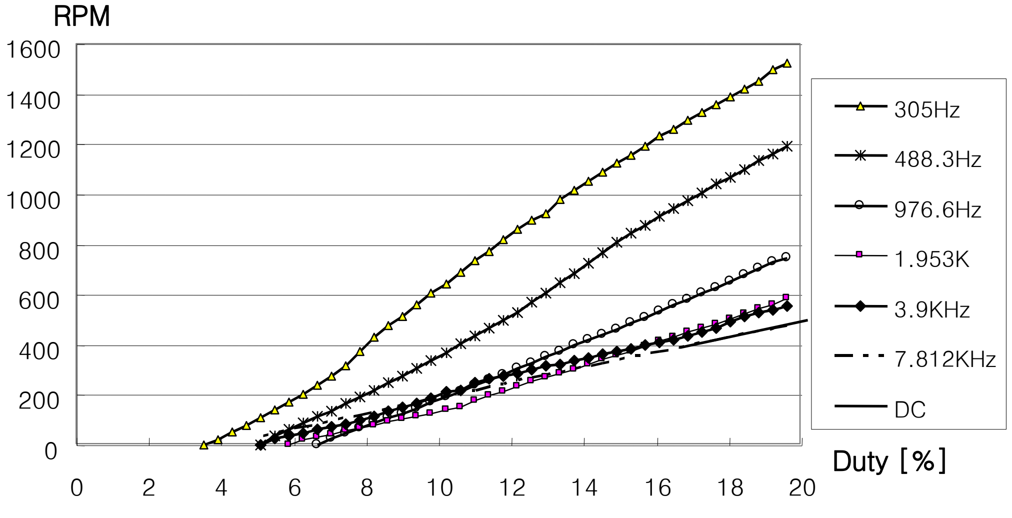
Notice that the linearity was increased when the PWM frequency was high due to the high time constant of motor windings. The effectiveness of the PWM frequency for linearity was verified by experimental results as shown in the Figure 10. Also, high resolution was required to control precisely at low speed with PWM control.

Motor B : Made in China
Nominal voltage : 24 *V*
Terminal resistance : 24 Ω
Terminal inductance : 875 μH
Angular speed constant : K_N = 125 *RPM*/*V*
Back-EMF constant : K_B = 5.16 *mV*/*RPM*

Figure 9. Specifications of an Electric Motor B used in Experiments



(a) Overall View



(b) Low Speed Range

Figure 10. Experimental Results of RPM with Various PWM Frequencies in Motor B

4. Conclusion

In this paper, a new approach that direct driven automatic door was analyzed. For the sake of low speed control in automatic door, the effectiveness of harmonic components of PWM control was verified by simulation studies and experimental results. The harmonic components of PWM were changed with various frequency and duty ratio; it was investigated based on Fourier series and modeling of the motor system.

The experimental results showed that the harmonic components related to dynamics of motor such as RPM and linearity. Analysis in this paper reveals that the linearity was reduced, as frequency and duty ratio was decreased. For this reason, the resolution of PWM control was reduced at low speed.

In the future work, the effect of harmonic components on the motor dynamics will be investigated.

Acknowledgments

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References

[1] H. C. Lee, “Apparatus and Method for Controlling Automatic Door using Brushless Direct Current Motor”, Korea Patent 10-1639695(KR101639695B1), **(2016)**.

[2] H. C. Lee, K. T. Lee and J. E. Lee, “Analysis of Driving Limitation at Very-low speed in DC-motor”, ICGHIT 2017 conference, Hangzhou China, **(2017)**, pp. 304-305.

[3] M. Lee, J. Lee, K. Kim, M. Choi and K. Kong, “Dynamic Characteristics of High Speed BLDC Motors and High Torque BLDC Motors”, Conference of the Korean Society of Mechanical Engineers, Korea, **(2015)**, pp. 3362-3367.

[4] T. S. Low, K. J. Tseng, T. H. Lee, K. W. Lim and K. S. Lock, “Strategy for the instantaneous torque control of permanent-magnet brushless DC drives”, IEE Proceedings B - Electric Power Applications, vol. 137, no. 6, **(1990)**, pp. 355-363.

[5] J. H. Kim, K. H. Cho and H. W. Kim, "Torque Ripple Reduction Algorithm of PM Synchronous Motor at High Speed Operation", Transactions of the Korean Institute of Power Electronics, Vol. 20, No.5, **(2015)**, pp.429-436.
[6] S. Funabiki and T. Himei, "Estimation of torque pulsation due to the behaviour of a converter and an inverter in a brushless DC-drive system", IEE Proceedings B - Electric Power Applications, Vol. 132, No. 4, **(1985)**, pp. 215-222.
[7] Jacob Tal, "Optimal commutation of Brushless Motors", Incremental Motion control systems and devices, **(1982)**, pp.49-53.
[8] M. Lee and K. Kong, "Fourier-series-based Phase Delay Compensation of Brushless DC Motor Systems", IEEE Transactions on Power Electronics, ieeexplore.ieee.org/ abstract/document/7855832, **(2017)**.
[9] S. Franco, "Electric Circuits Fundamentals", Oxford University Press, **(1994)**, pp. 335-353.
[10] T. Kenjo and S. Nagamori, "Permanent Magnet and Brushless DC Motors", Sogo Electronics Publishing Company, Tokyo, **(1984)**, pp. 4-9.
[11] Maxon Motor AG., Brushed DC Motors - RE Program (http://www.maxonmotor.com), **(2016)**.
[12] Atmel Corp., ATmega48A/88A/168A - Complete Datasheet (http://www.atmel.com), **(2016)**, pp. 135-142.

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