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Design brushless DC motor control by using proportional-integral strategy for a smart storage cabinet system

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ABSTRACT

As well know, the use of high technology is more and more encouraged in many countries to decrease the costs, time, and human resources. This paper presents a speed control of brushless DC motor (BLDC), which was applied for the smart storage cabinets. BLDC motor is proposed due to its low costs, high torque, and high performance. The proportional-integral (PI) controller is constructed for the speed control of the movement of cabinet systems. First, the mathematical model and transfer function of the BLDC motor is rewritten to show the structure of the BLDC motor. Second, the proposed PI controller is designed based on the tuning Ziegler-Nichols method and the PI controller is also expressed by the discretized form for BLDC motor. Third, the working principle of BLDC motor is clearly represented and analyzed. Forth, the detail configuration of the experimental system is presented. The STM32 microcontroller unit (MCU) was used to execute. Finally, the experimental test was implemented to validate the power of the proposed controller in practical cases. The experimental results at no-load and load were shown that the power of proportional integral derivative (PID) controller is good at tracking the desired speed signals.

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1. INTRODUCTION

As we all know, the storage of documents, books play an extremely important role in our life. Instead of storing data in the traditional way, which takes a lot of space and labor, and does not meet the user's quick search requirements, today many parts of the world have been equipped with smart storage systems. The application of high technology to document storage not only save space, time and human resources but also improves efficiency and reduces operates costs.

The smart storage system is designed by placing shelves (storage cabinets) next to each other to save space maximize storage space. Therefore, each cabinet in the storage system must be able to move to create circulation space for users by opening the cabinet to be used. To do that, the cabinets all have their own drive features by equipping each cabinet with a motor that uses motion support, having a motor will make the movement of the cabinet easy to open and close, which do not need to use human power.

The electric motor is an electric equipment, which can be used to transfer the electric energy to the mechanical energy. The energy consumption of an electric device should be carefully considered. Therefore, the brushless motor is a potential device to obtain the desired goal of saving energy equipment. The motor without the brush consists of some advantages such as low maintenance cost, less heat, light, high performance. The brushless motor is also known as the synchronous motor, the advantages of brushless motor in the industry field was discussed in the [1]. Brushless motors are classed into two forms, that are the permanent magnet synchronous motor (PMSM) and brushless DC motor (BLDC) motor. These devices have similar construction, both machines have a permanent magnet on the rotor shaft and the phases currents are switched continuously to generate the torque. Their structure can be found in [2]. It would have been confused to distinguish their differences due to its structure. Normally, it is identified by the shape of back electromotive force (B-EMF) waveform. The BLDC motor has trapezoidal waveform, and the rectangular currents are required to generate the torque; while the other requires sinusoidal shape, and the sinusoidal currents are asked to produce the torque [3], [4]. The comparison between BLDC and PMSM motors was discussed in the [5], [6]. The outstanding characteristics of BLDC are as follows: reliability, durability, low noise, self-start, high efficiency, high torque. Especially, easy control method and low cost, so that is a reasonable choice for our proposed storage cabinet system. In the Figure 1 shows the smart storage cabinets equipped the BLDC motor. To save the space, the cabinets can be stacked side by side as in the first part of Figure 1. Otherwise, the cabinets can be expended by using the BLDC motor to give the entrance space as in the second part of the Figure 1.

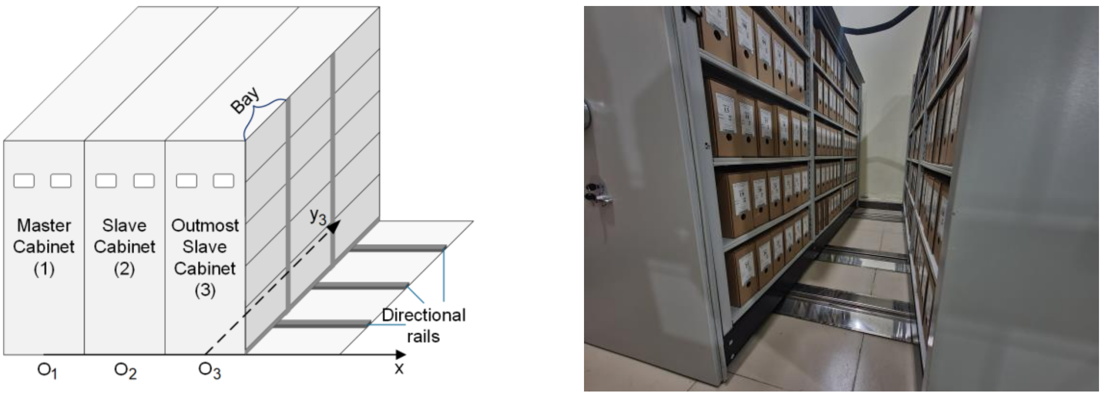

Figure 1. The smart storage cabinets equipped the BLDC motor

The first BLDC motor was invented in 1962, the brush and commutator components were not required. However, it still has similar electrical properties to a conventional DC motor. So, such of that. BLDC can be utilized in many applications like medical, industrial, drive system, electric vehicle, fans, and pumps [7]–[10]. Moreover, the optimum magnetic energy in the BLDC system for bicycle application was proposed in [11]. The discussions of BLDC motor can be found in [12]–[14]. The mathematical model of BLDC was presented in [15], [16]. But it was just verified by simulation. Herein, the simple mathematical model of BLDC is slightly rewritten. To operate the BLDC motor, the stator currents need to be produced sequentially based on the position of the Hall sensors [17], [18]. When the position of these sensors is determined, an inverter is equipped to provide the power for the coils, so the movement for the motor is generated by the current torque. The design of a BLDC driver was presented in [19]. Due to the development of semiconductor devices, the advantages of pulse width modulation (PWM) method were proposed for controlling BLDC motor. The detail concepts of conventional and digital PWM approaches were discussed in the [20]. The combination of unipolar and bipolar PWM can be found in [21], and the hybrid PWM was analyzed in [22].

To achieve the desired goal, a controller for the speed of BLDC is required. In this paper, the proportional-integral (PI) controller is proposed to obtain the goal. The comparative analysis of controllers for BLDC motor was discussed in [23]. However, the conducted results were obtained via the simulation only. The advanced controllers for BLDC were presented in [24], [25]. The disadvantages of these advanced methods are complicated and hard to apply for microcontroller unit (MCU) environment. The Zeigler-Nichol method was used to get the proportional integral derivative (PID) parameters. The PID tuning method by using Zeigler-Nichol method can be found in [26]. In the MCU environment requires the PID be discretized. The concept of PID discretized was presented in [27]. The prime contributions of this manuscript are: i) the mathematical model of BLDC motor was slightly rewritten; ii) the PI control method was proposed for the BLDC motor by using the Zeigler-Nichol method to obtain the PID parameters; and iii) the proposed system was analyzed and evaluated via the practical system. This research was done by using the STM32F030F4P6 MCU supported by STM32 CubeMX and Keil version 5 software.

The organization of this paper is as follows: first, the introduction of related concepts of proposed system is discussed. Second, the proposed controller is designed based on the tuning Ziegler-Nichols method for the BLDC motor and the PI controller is also expressed by the discretized time domain. Third, the working principle of BLDC motor was clearly represented and analyzed. Forth, the detail structure of the hardware system is presented. Finally, the experimental test was implemented to demonstrate the power of the proposed method in practical cases.

2. MATHEMATICAL MODELING

2.1. Mathematical modeling of BLDC motor

Mathematical models of objects are mathematical relationships for the purpose of describing that actual object, but in the form of mathematical expressions to facilitate the process of analysis, design survey. For the engine, the mathematical description plays an important role because all theoretical investigations and maths are based on the mathematical model. Therefore, the mathematical model is the key to open all problems in the process of calculating and designing the motor [28].

BLDC motor consists of three stator phases windings in start-connection, the back-EMF has trapezoidal shape and, on the rotor, axis is mounted a permanent magnet. To perform the modeling of the BLDC motor, there are four basic assumptions considered as: i) the stator circuit is star-connection; ii) stator resistance, self and mutual inductance off three phases are equal and constant; iii) hysteresis and eddy current losses are ignored; and iv) all MOSFETS are ideal. Figure 2 shows the equivalent circuit of BLDC motor [15], [16].

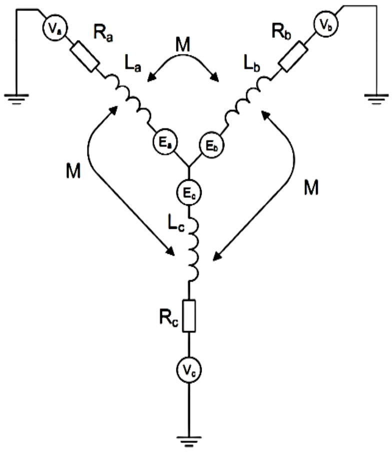

Figure 2. The equivalent circuit of BLDC motor

The voltage equations of the BLDC motor are as follows [16]:

$$V_a = R_a . i_a + L_a . \frac{di_a}{dt} + M_{ab} \frac{di_b}{dt} + M_{ac} \frac{di_c}{dt} + e_a \tag{1}$$

$$V_b = R_b i_b + L_b . \frac{di_b}{dt} + M_{ba} \frac{di_a}{dt} + M_{bc} \frac{di_c}{dt} + e_b \tag{2}$$

$$V_c = R_c i_c + L_c . \frac{di_c}{dt} + M_{ca} \frac{di_a}{dt} + M_{cb} \frac{di_b}{dt} + e_c \tag{3}$$

where $V_{a,b,c}$: the stator phase voltages, $i_{a,bc}$: the stator phase currents, and $e_{a,b,c}$: motor back-EMFs. From (1)-(3), the following matrix can be given as (4).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

Since on the assumptions, self and mutual inductance of three phases are equal and constant. Therefore:

$$L_a = L_b = L_c = L \tag{5}$$

and mutual inductances given as (6).

$$M_{ab} = M_{ac} = M_{ba} = M_{bc} = M_{ca} = M_{cb} = M \tag{6}$$

The requirement of (7) is fulfilled. Taking Laplace transform for (4) leads to (8).

$$R_a = R_b = R_c = R \tag{7}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = s.\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix}.\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{8}$$

For three phases balanced system can be given as (9).

$$i_a + i_b + i_c = 0 \tag{9}$$

Therefore, in (7) can be rewritten as (10).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = s.\begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}.\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{10}$$

Electromagnetic torque can be expressed as (11). Electromagnetic torque depends upon back EMF and rotor current and can be expressed as (12).

$$T_{em} = J.\frac{d\omega_m}{dt} + B.\omega_m + T_l \tag{11}$$

$$T_{em} = \frac{1}{\omega_m.(e_a.i_a + e_b.i_b + e_c.i_c)} \tag{12}$$

Where ω_m: angular frequency of motor shaft (rad/s), J: inertia of motor load system ($Kg.m^2$), T_L: load torque (Nm), and B: friction coefficient ($Nm.s$).

2.2. Transfer function of BLDC motor

BLDC motor is controlled by three-phases converter, assume that phase A and phase B is in the conduction mode. The equations of current phase A and B can be expressed (13) [16].

$$i_a = -i_b = i$$

$$\frac{di_a}{dt} = -\frac{di_b}{dt} = \frac{di}{dt} \tag{13}$$

Then, the line-to-line can be expressed as (14).

$$v_{AB} = 2.R.i + 2.(L-M).\frac{di}{dt} + (e_a - e_b) \tag{14}$$

Whenever both phase A and phase B is conduction mode, their values are equal, but their signs are opposite. So, (14) is can be expressed as (15).

$$v_{AB} = 2.R.i + 2.(L-M).\frac{di}{dt} + 2.e \tag{15}$$

Generally, when BLDC motor is in operation mode, there are two phases of three phases in conduction mode. So, the general equation is:

$$V_d = r_a.i + L_a.\frac{di}{dt} + K_e.\omega \tag{16}$$

where V_d: DC Voltage; r_a: winding wire resistance, $r = 2.R$; L_a: wingding equivalent line inductance, $L_a = 2.(L-M)$; and K_e: coefficient of line back-EMF, $K_e = 2.p.\psi_m$.

Motor equation is given as (17). The no load conduction, the armature current is given by (18).

$$T_e - T_l = J.\frac{d\omega}{dt} + B.\omega$$

$$T_e = K_T.i \tag{17}$$

$$i = \frac{J}{K_T}.\frac{d\omega}{dt} + \frac{B.\omega}{K_T} \tag{18}$$

Combine (16) and (17), can be expressed as (19).

$$V_d = r_a.\left(\frac{J}{K_T}.\frac{d\omega}{dt} + \frac{B.\omega}{K_T}\right) + L_a.\frac{d}{dt}\left(\frac{J}{K_T}.\frac{d\omega}{dt} + \frac{B.\omega}{K_T}\right) + K_e.\omega \tag{19}$$

Therefore:

$$V_d = \frac{L_a.J}{K_T}.\frac{d^2\omega}{dt} + \frac{r_a.J+L_a.B}{K_T}.\frac{d\omega}{dt} + \frac{r_a.B+K_e.K_T}{K_T}.\omega \tag{20}$$

the transfer function of BLDC motor is the relation between DC voltage and angular velocity. Using Laplace transformation, for (20) leads to (21).

$$G(s) = \frac{\omega(s)}{V_d(s)} = \frac{K_T}{L_a.J.s^2+(r_a.J+L_a.B).s+(r_a.B+K_e.K_T)} \tag{21}$$

3. PROPOSED CONTROL SYSTEM

3.1. Proposed controller

The PID control strategy is the most conventional and simple algorithm in drive systems. In most cases, the closed loop is used to correct error(s) between the reference signal and the measured signal. The PID controller equation can be shown:

$$u(t) = K_P\left[e(t) + \frac{1}{T_I}\int_0^t e(\tau)d\tau + T_D\frac{de(t)}{dt}\right] = K_P\,e(t) + K_I\int_0^t e(\tau)d\tau + K_D\frac{de(t)}{dt} \tag{22}$$

where K_P: proportional gain, T_I: integral time or reset time, T_D: derivative time or rate time, and K_P, K_I, K_D: the PID parameters gain.

Figure 3 shows a closed loop control of BLDC motor, x(t) is a setpoint speed, e(t) is the incorrect value between the setpoint speed and the measured speed, y(t) is the actual speed. In the [26], Zeigler Nichols method was presented to compute the PID parameter gains. By using the Ziegler Nichols method, the PID parameters are obtained and shown in Table 1.

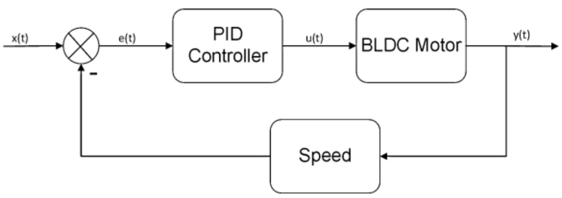

Figure 3. The closed loop control of BLDC motor

Table 1. The PID parameters

Parameter	Value	K_P, K_I, K_D
K_p	0.008	0.008
T_I	0.3	0.027
T_D	0	0

In this paper, STM32F030F4P6 is selected to process signals and PID controller. Since, on a Microcontroller device requires that PID controller be discretized. Accordingly, when the time step T_0 is sufficiently small, the integral term of the PID control law at time can be approximated by (23).

$$\frac{1}{T_I}\int_0^t e(\tau)d\tau \approx \frac{T_0}{T_I}\sum_{i=0}^{k} e(i-1) \tag{23}$$

Also, the derivative can be approximated in control law using finite differences:

$$T_D\frac{de(t)}{dt} = \frac{T_D}{T_0}[e(k) - e(k-1)] \tag{24}$$

from (22)-(24), the equation of the discretized PID controller can be derived as [27]:

$$u(k) = K_P\left[e(k) + \frac{T_0}{T_I}\sum_{i=0}^{k} e(i-1) + \frac{T_D}{T_0}[e(k) - e(k-1)]\right] \tag{25}$$

3.2. Driving principle of BLDC motor

The basic concept of the BLDC motor is to control the switch of phase A B C, which should be determined by the position rotor the rotation mode. Three output Hall signals provide information to the commutation block giving the control signals to switch the on and off status of the corresponding semiconductor valve. The Figure 4 shows the BLDC motor drive system.

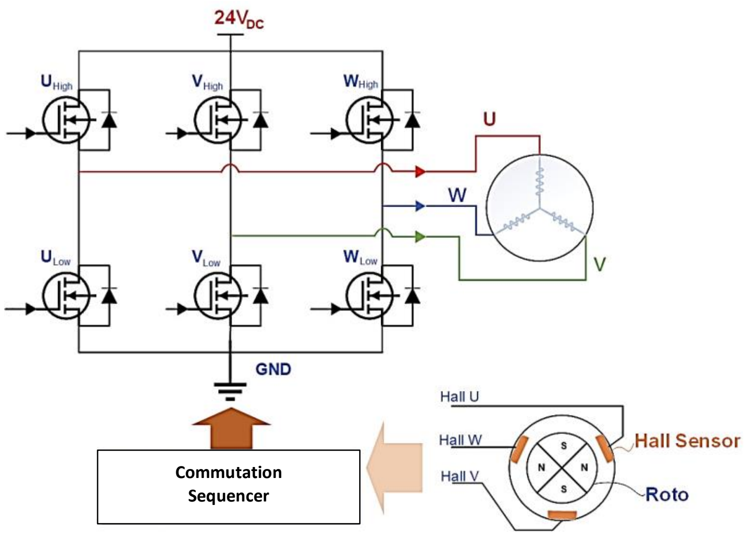

Figure 4. The BLDC motor drive system

The motor is in the forward/reverse mode based on the Hall sensors, which mounted on the rotor of motor. The Hall sensor signals are scanned and send the digital signals to commutation sequencer block. The switching MOSFET valve is controlled by this block. Normally, BLDC motor has three Hall sensors, and the sensors are arranged inside the motor every 120 degrees. Sectors are determined based on the position of Hall sensors. From the sector, A voltage vector is applied to the BLDC motor. For example, in the counterclockwise rotation, when rotor position is in sector 6, the voltage vector 1 is selected to the inverter converter; for next status of the rotor, the voltage sector 2 has to select to the inverter converter. Table 2 will show the decoder sequences of the BLDC motor in the counterclockwise rotation [29]. The true table for switching signal was presented in Figure 2.

Table 2. True table for switching signal

Sector	HU	HV	HW	H_U	L_U	H_V	L_V	H_W	L_W
1	1	0	0	1	0	0	0	0	1
2	1	1	0	0	0	1	0	0	1
3	0	1	0	0	1	1	0	0	0
4	0	1	1	0	1	0	0	1	0
5	0	0	1	0	0	0	1	1	0
6	1	0	1	1	0	0	1	0	0

3.3. Hardware system design

The experimental setup is shown in the Figure 5. The system is fed by 220 VAC source, then converted to 24 VDC, the DC voltage directly supplied to the motor drive including H-bridge inverter. The DC source also converts to 5 VDC providing power for the operation of control unit. The BLDC motor is controlled by 3 wires of the corresponding force circuit U, V, W. The motor load is connected directly to the moving mechanism of the cabinet shown in the Figure 6. The motor is embedded hall sensors, which is connected to the processor, which provides the position of the rotor. The processor circuit is equipped with a UART port to help communicate with a PC for convenience during communication. The PC has the function of displaying the speed of the motor, receiving the set value to control the movement of the system. In this paper, STM32F030F4P6 microcontroller can process the input and output signals quickly and continuously. The speed results shown on the screen by using serial plotter function of Arduino.

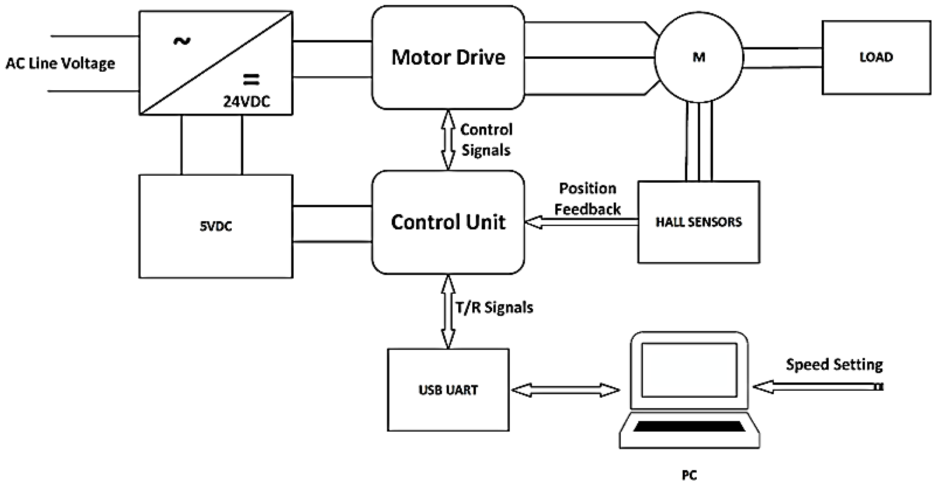

Figure 5. Hardware system

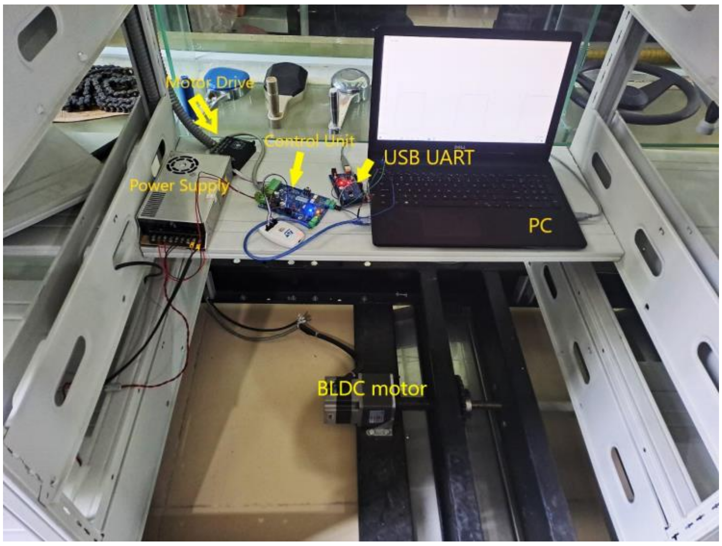

Figure 6. Proposed hardware system

4. RESULTS AND DISCUSSION

To show the correction and power of the proposed method, the experiment was tested and evaluated at tracking the measured speed with two cases: free-load and full-load. The experimental setup is as follows:

a laptop support by Windows 10, BLDC driver, driver circuit using STM32 MCU, UART device, power supply, and BLDC motor. To observe the experimental results, two case studies will be shown below.

4.1. The experimental result of free load

The experimental test at free load is set up as follows: the BLDC motor was working at initial speed 900 (rpm). At the time 7 (s), the reference speed was increased to 1100 (rpm) and at the time 22 (s), the reference speed was changed to 1200 (rpm). The speed responds at free load will be displayed in the Figure 7. In the Figure 7, X and Y axis represented the time $(10^{-1} sec)$ and the speed (rpm); the red signal is the reference speed, the one is the actual speed. To obtain the graphic, when the motor system is not in the cabinets system, setting a reference signal (900 rpm) from the PC and measuring the speed of BLDC motor. When the motor system is in the steady-state, changing the reference signal at 1100 (rpm) and 1200 (rpm). From the Figure 7, it is seen that the error value is small, when changing the reference signal, the actual speed still follows it almost immediately. The result also shows that the response of the PID controller with free-load case was good.

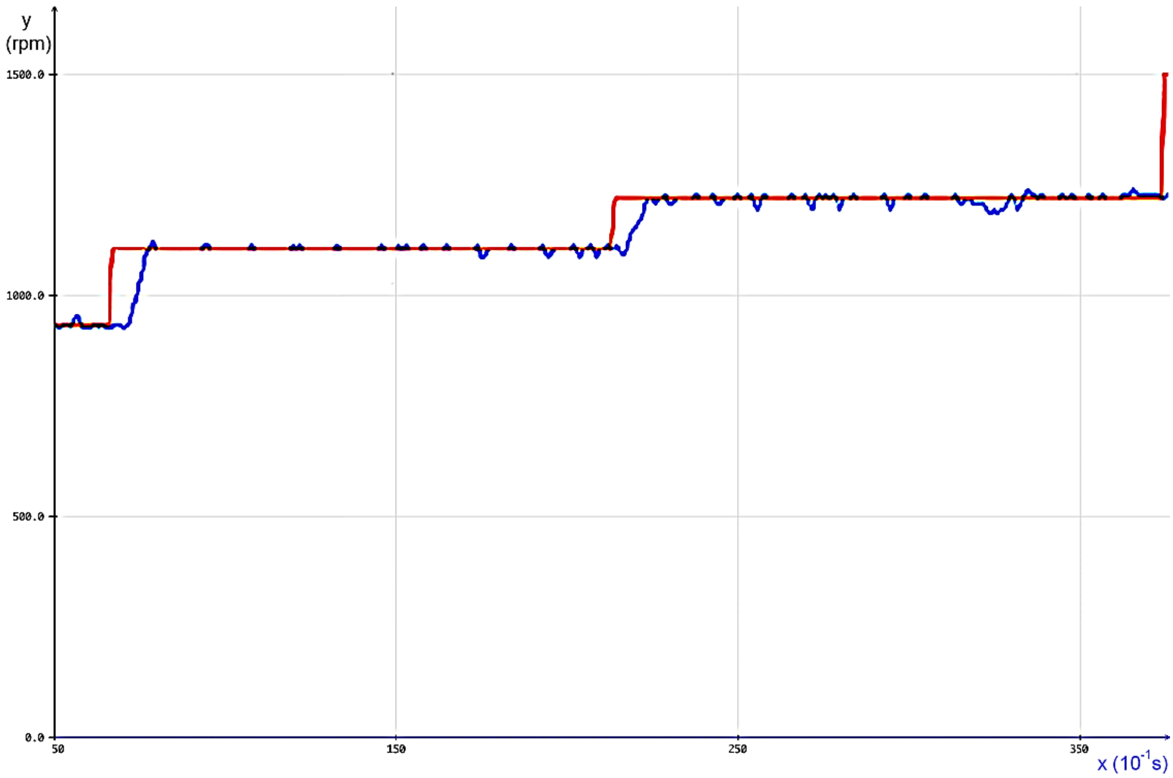

Figure 7. The speed of motor at no-load

4.2. The experimental result of full-load

The practical test at full-load was set up as follows: at the time 70 (s), the speed set was changed to 900 (rpm) and at the time 87 (s), the reference set was 0 (rpm). In the Figure 8, it will display the setpoint and actual speed at full-load. Figure 8 shown the measured speed and the setpoint speed in the proposed drive system. The experimental test was completed to get the goal, it is the cabinets system can move with stable speed (900 rpm). From the results, the red line is the setpoint value (900 rpm) and the blue line is the actual speed, observing the graphic, the overshoot is approximately 23% and the response time was in the short period. Comparing the results between the current research and the previous research in [16] shown that the quality of this PID controller is better than the controller in [16]. The best performance of the proposed control in [16] with simulation under no-load consists of an overshoot is about 200 (rpm), which was shown in Figure 6 of paper [16]. While the overshoot of the experimental study of this paper is about 207 (rpm). So, the proposed method in this paper can be stated that good with fully load system.

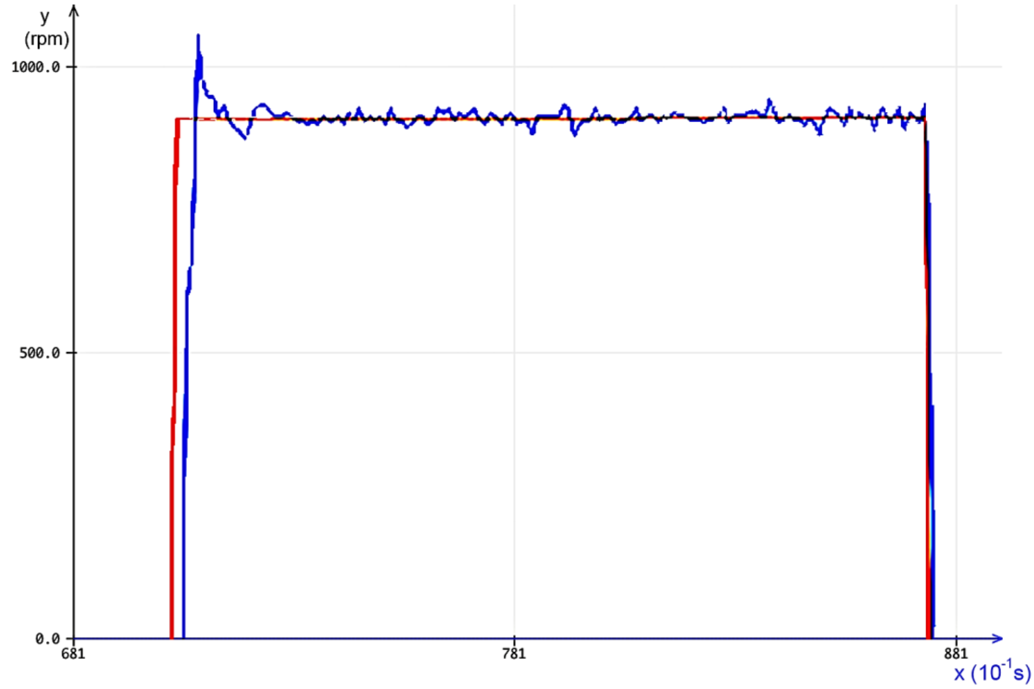

Figure 8. The speed of motor at load

5. CONCLUSION

This paper presented the design of smart storage cabinet system equipped the brushless DC motor, successfully. The mathematical modelling and transfer function of BLDC motor was represented and analyzed, clearly. The PID controller was proposed to control the rotational speed $\omega -$ signal, respectively. The tuning approach of PID parameter was demonstrated by using the Ziegler-Nichols method. The performance of the proposed controller was verified at observing the measured speed in the free-load and full-load state. From the experimental test, PI controller responses the speed requirement of the drive system, and the control strategy provides the best performance.

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