BLDC Contest Design Report

Team: Turning the Future

Project: Electric roller shutter drive

Date：2021. 07. 19

Content

1. Project Content

1.1 Background and Purpose of The Project

According to the International Energy Agency (IEA), the power consumption of motor takes up to 46% of global electricity consumption. In response to the demand for energy saving, the development trend of automated chemical factory and smart buildings, the global motor market is expected to grow at a rate of 6~7% per year. Various manufacturers are investing in the development of efficient and controllable BLDC motor and drive solutions for new applications (ex. smart building/factory), as well as replacing previous generation solutions (ex. pneumatic/diesel engine hand tools, agricultural tools...). Based on the overall market trend, and in view of Mean Well's recent transition from manufacturer to solution provider for smart building applications, the future entry into the BLDC drive market will significantly expand Mean Well's depth and breadth of power solutions.

BLDC motors are highly efficient, compact, and controllable (variable frequency). The efficiency of traditional AC single-phase induction motors is about 40-60%, and with an increase to over 70% with BLDC. However, BLDC needs to be worked with a suitable drive, the overall cost is also higher. Therefore, it is necessary to introduce a BLDC drive with good cost performance and high efficiency to be more competitive in the market.

In this project, a BLDC drive with WIFI communication, wide speed range operation, and low cost Hall-effect digital sensors is implemented in the electric roller shutter system. In addition, this project works with Field-oriented-control(FOC) to achieve appropriate current control, so that BLDC can use relatively small current drive under different mechanical loads, reducing the power loss of BLDC drive. The torque limiting function provides output torque adjustment. For applications that do not require instantaneous high torque output, the torque limiting size can be adjusted by software to obtain smoother acceleration effect and to avoid the stress generated by excessive torque output, which may cause load failure or damage.

1.2 Project Specifications

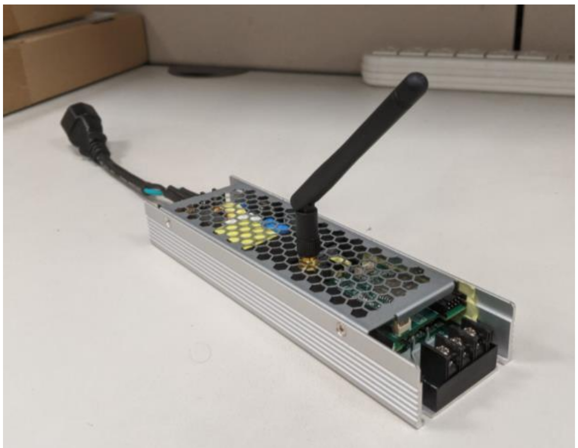


Figure 1 BLDC-300 with wireless module and external antenna

Figure 2 Curtain lifting control application

Table 1 Roller shutter project specifications

Drive efficiency	93%@300W(drive output)
Motor efficiency	80%@250W(motor output)
Rated current	1.2Arms
Acceleration/deceleration time	<1.5 sec (acceleration from static to rated 1200 RPM@no-load)
Maximum drive current	200% rated current for 5 sec
Speed control range	100~1200 RPM
Speed adjustment rate	<+/-1.5% (rated speed)
Software Setting Function	1. Output torque limiting (200% Io(rated) by default 2. S-curve slow start function
Drive function	1. Rotational speed control and torque limitation 2. Forward and reverse control 3. Simple acceleration and deceleration S-curve control 4. WIFI remote monitoring 5. Application: Hall display curtain lifting control (Fig. 2)

2. The Roller Shutter Application System Introduction

2.1 System Planning and Architecture Description

This project introduces the implementation of BLDC control method and the movement of the roller shutter system design by controlling motor parameters. Apart from that, with the combined use of WIFI module and APP, the BLDC drive is able to be controlled remotely, such as variable frequency and on/off control, as Figure 3 shown the system architecture.

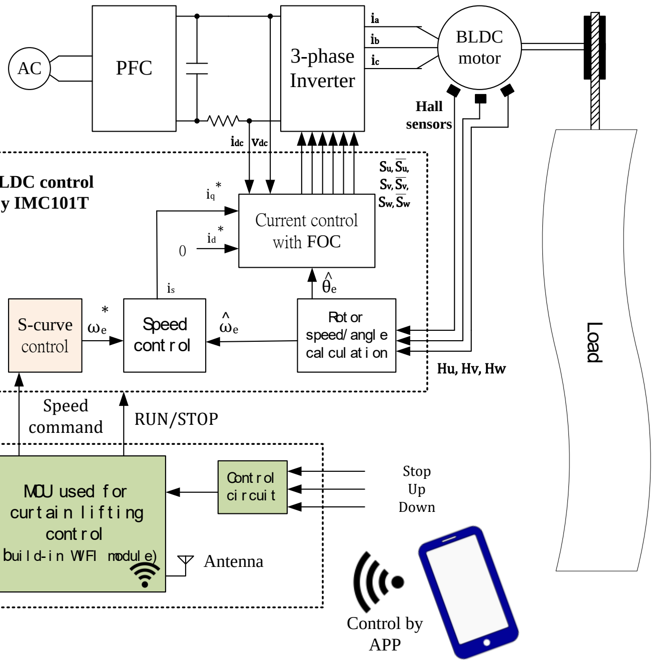


Figure 3: electric roller shutter control system diagram

2.2 Roller Shutter Mechanism Design

In order to quickly verify the proposed electric roller shutter control strategy, the finished product is purchased and assembled, as shown in Figure 4; Figure 5 shows the assembled module of BLDC and motor (BLDC-300), where the main components and their functions are shown in Table 2.

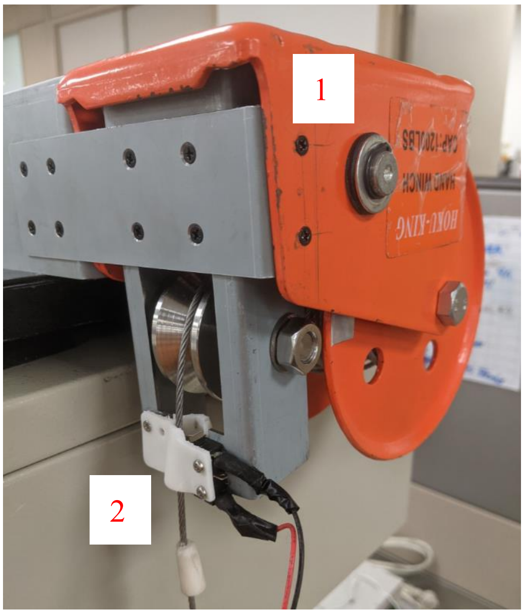


Fig. 4 Winch and micro switch

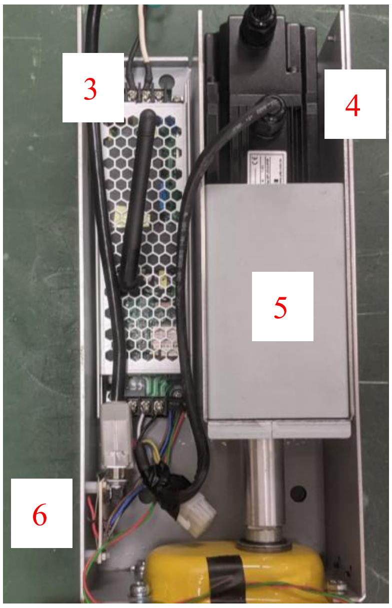


Fig. 5 BLDC and drive (BLDC-300) module

Table 2 BLDC roller shutter mechanism of the main components and the function description

project	name	Description
1	Winch	Winding and lowering the rope
2	Micro Switch	Limit the length of the wire coiling wire , when the wire rope is retracted and touches the micro switch, it can trigger the BLDC-300 to stop
3	BLDC-300	BLDC drive
4	YBL-6S-148	Power the motor and drives the rolling machine to run
5	MF60X-L1-3	Cooperate with the low-speed application of roller shutter. Reduction ratio: 3
6	Hall-effect sensor conversion interface	Electrical conversion interface between the H all-effect sensor position signal output by the motor and the B LDC-300

Figure 6 shows the calculation of the load demand torque of the roller shutter reel, where the weight of the roller shutter is 10 kg, and with the shaft radius (0.02m), the required torque could be calculated

$$Tload = 10 * 9.8 * 0.02 = 1.96 \text{ (N-m)} \quad (1)$$

The reduction ratio of motor speed reducer and winder are 4.2 and 3 respectively, so the total reduction ratio m is 12.6. The combined deceleration ratio of the speed reduction mechanism and the torque T_{input} is required to convert the input shaft (motor output to the mechanism) under ideal conditions which is about 0.156Nm.

$$m = 4.2 * 3 = 12.6 \quad (2)$$

$$T_{input} = \frac{1.96}{12.6} = 0.156 \text{ (N-m)} \quad (3)$$

Roller shutter machine wire lifting speed requirements about 0.2m/s and the motor speed is estimated at about 1200RPM

$$N_{input} = \frac{0.2}{0.02*2\pi} * 60 * 4.2 * 3 = 1203 \text{ (RPM)} \quad (4)$$

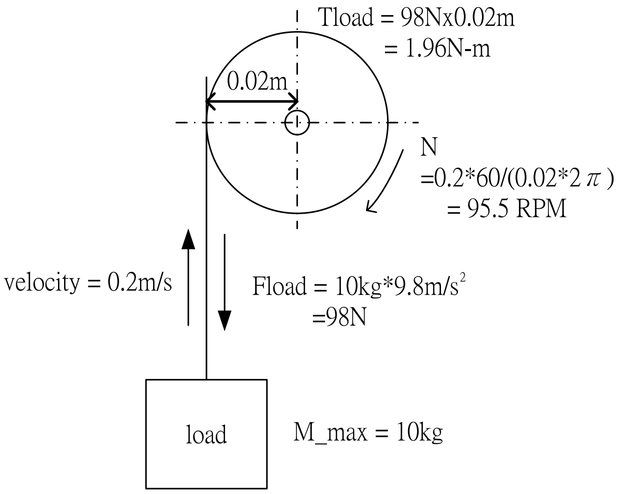


Figure 6 Calculation of the load of the roller shutter reel mechanism (without speed reduction mechanism)

3. Motor Drive Design

3.1 BLDC Motor Parameters

This section describes the basic parameters of the motor and the measurement results, as well as the measurement method of the three-phase Hall signal, which is used as a basis for the design of the BLDC drive.

3.1.1 Electrical Parameters of The Motor

The motor electrical parameters are based on the following information provided by motor supplier, and the BLDC control parameters are designed according to Table 3 below.

Table 3 BLDC parameters measurement table

Parameter	Numerical Value	Unit
Polarities Poles	8	-
Back electromotive force constant Ke	0.1815	Vrms(ψ)-s/rad
Equivalent d-axis inductance Ld	0.0106	H
Equivalent q-axis inductance Lq	0.0107	H
Torque constant Kt	0.5444	N-m/A
Phase resistance Rs	3.5	Ω

3.1.2 Hall-effect Sensor Signal Alignment and Wiring

In this project, the three-phase Hall-effect sensor signal indicates the angular position of the motor shaft, so that the FOC can control the current in the same phase as the back EMF. In this way the magnetic field of the rotor is orthogonal to the stator magnetic field and the electrical energy can be effectively converted into mechanical energy. Since most motor manufacturers do not provide the phase relationship between the Hall-effect sensor signal and back EMF, in practice it is necessary to measure the Hall signal phase in order to use with the motor drive.

It is based on the phase between the back EMF and the Hall-effect sensor signal defined by the control IC-IMC-101T. The actual motor three phase back EMF is required to be in the same phase with the Hall signal so it could be activated. Figure 8 shows the definition of Hall-effect sensors of IMC101T and the phase between UV line to line back EMF and Hall1 in positive phase sequence: Hall1 lags UV line back EMF by 150 degrees, and the control IC defines the input position signals Hall1~3 with a difference of 120 degrees each. With the active load to drive the motor to be tested (clockwise rotation), the actual motor HallU~W signal and the UV inverse potential are shown in Fig. 9. It can be seen that the Hall1 of IMC-101T should be connected to HallW in order to correspond to the phase relationship defined by the drive.

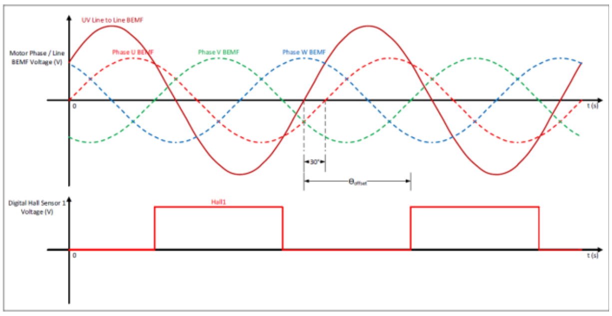


Figure 8 IMC101T Hall signal and BLDC three-phase voltage phase definition

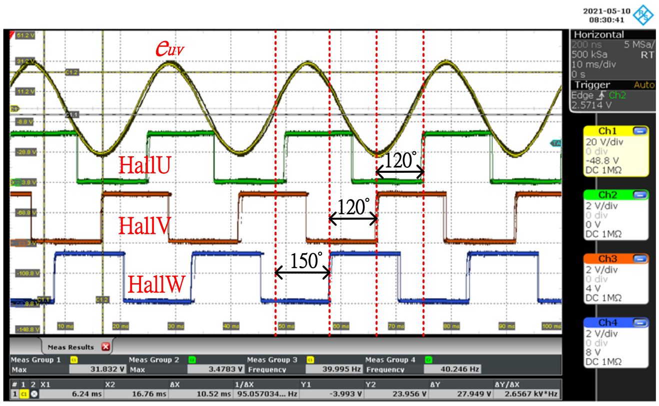
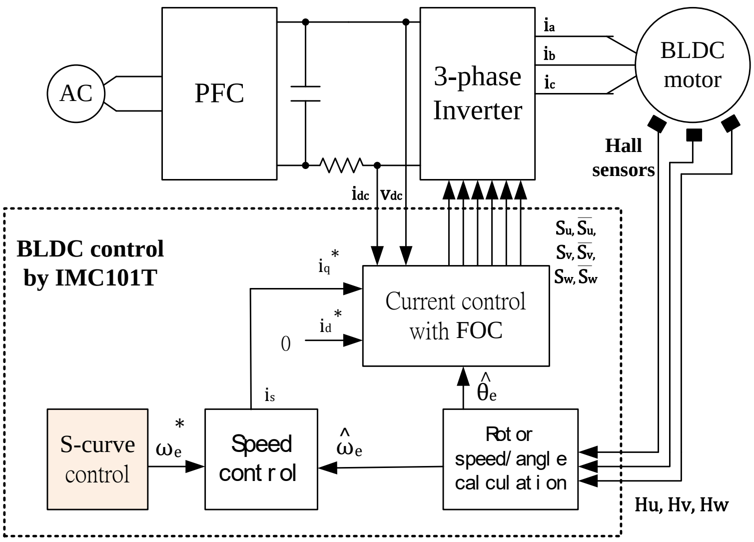


Figure 9 Relationship between measured UV back EMF and motor Hall signal

3.2 BLDC Controller Design

3.2.1 BLDC Drive System Architecture

Figure 10 shows the schematic diagram of the control architecture. The BLDC control core uses the IMC101T-T038 with built-in PMSM control algorithm and three Hall-effect sensor signals as the motor position feedback to achieve FOC, so that the motor can precisely output current at the correct phase and provide a smaller drive current. In terms of speed control, the S-curve acceleration curve is added to the speed command to improve the start-up stress of the original ramp acceleration/deceleration curve.



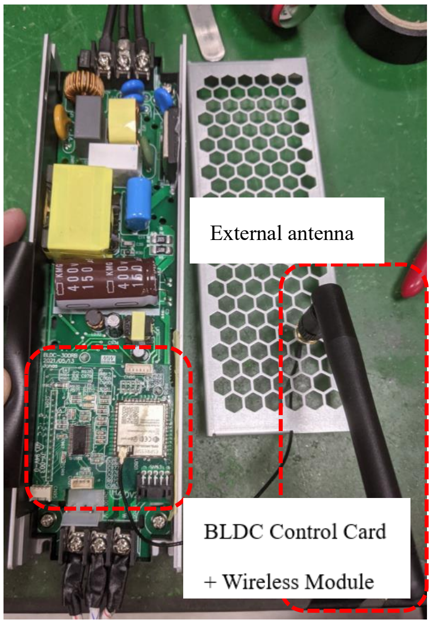
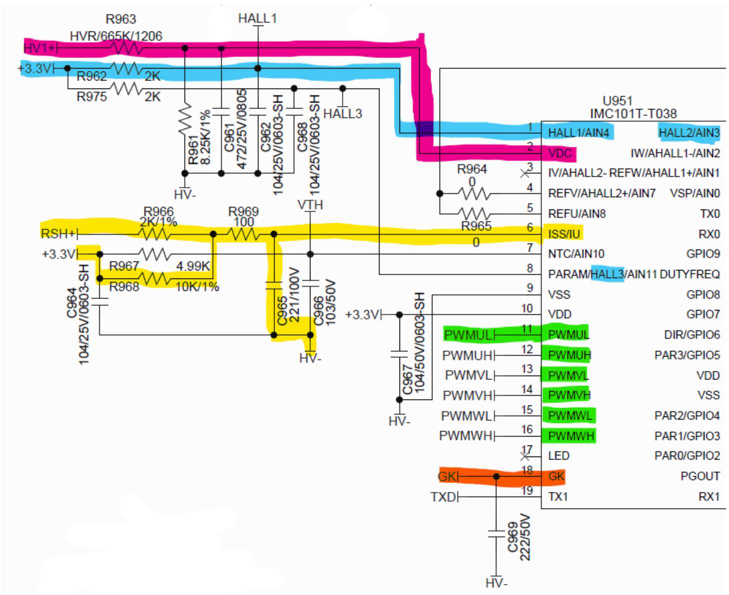
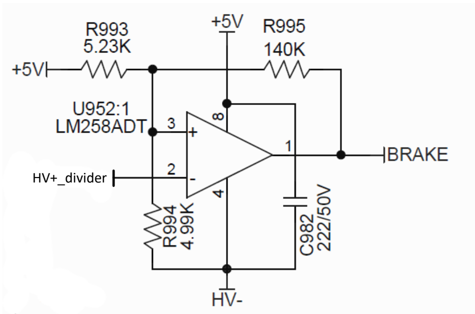


Figure 10 Control structure diagram and entity diagram

3.2.2 IMC-101T Peripheral Circuit Design

The following describes how the IMC-101T control peripheral circuit is designed.

Circuit	Description
 Fig. 11 IMC-101T controller feedback and protection cirucit	HV+ feedback: Pin2 $= \frac{8.25k}{665k+665k+8.25k} \times \mathrm{HV} +$ $= 0.006165\mathrm{HV} + (\mathrm{V})$ RSH+ feedback: Pin6 $= R_{shunt} \frac{10k}{10k+2k} \times i_{\mathrm{HV}}$ $= 83m \times i_{\mathrm{HV}} (\mathrm{V})$ PWM control circuit: PWMUL~PWMWH PWM output Hall sensor feedback: pull-up resistance 2kΩ, connected to the

	motor Hall sensor line (open-collector) [redacted]：To receive protection signal from gate-driver , to determine whether to turn off the PWM immediately.
 Figure 12. feedback control resistor	Design VDC detection circuit using LM258ADT OP+(H) =5 $\times \frac{4.99k}{(5.23k//140K)+4.99k} = 2.49V$ OP+(L) =5 $\times \frac{(4.99k//140K)}{(4.99k//140K)+5.23k} = 2.4V$ $HV_{BRAKE}(H) = \frac{2.49}{0.006165}$ =403V $HV_{BRAKE}(H) = \frac{2.4}{0.006165}$ =389V HV_{BRAKE}： high voltage side to trigger regenerative resistor ON/OFF

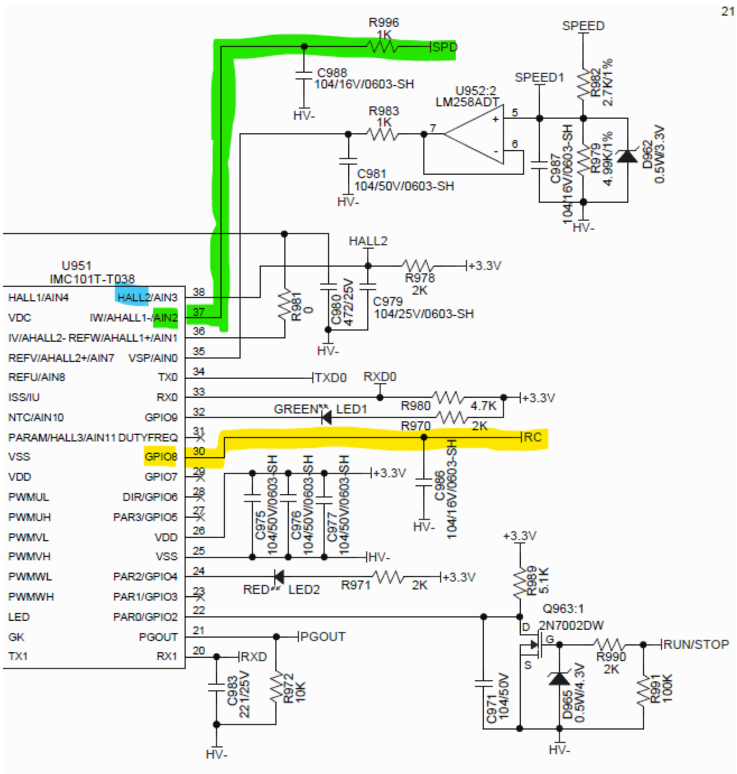


Figure 13 IMC peripheral control circuit

SPD： BLDC rotating speed control pins, receive signals from MCU wireless control modules and send control signal

RC： BLDC start/stop control pins, receive signals from MCU wireless control modules for remoting the BLDC motor.

3.2.4 IMC-101T Parameter Design

The IMC-101T uses sinusoidal current drive and FOC control. The position feedback used the three-phase digital Hall sensors signal feedback (6 step signals) for BLDC rotor angle estimation at full speed.

The IMC-101T is mainly used with the original software MCEWizard to design drive parameters. It provides a built-in script language, which is mainly used for developers to design simple programs for control functions. Figure 14 shows the motor parameters for the YELI-YBL-6S-148 motor. Figure 15 shows the parameters of the motor regulator, by the adjustment of 58-Current Regulator Bandwidth, 64-Speed Regulator Proportional Gain, 65-Speed Regulator Integral Gain, current waveform of the motor could be adjusted to a close shape of sinewave.

Motor 1 Motor Parameters		
1 - Motor Model Name	YBL-6S-148	
2 - Motor Rated Amps	1.2	Arms
3 - Motor Poles	8	
4 - Motor Stator Resistance	3.49	Ohms/phase
5 - Motor Lq Inductance	10.7	mH
6 - Motor Ld Inductance	10.6	mH
7 - Motor Back EMF Constant (Ke)	19	V(ln-rms)/krpm
8 - Motor Max RPM	800	RPM
9 - Minimum Running Speed	10	RPM
10 - Speed Ramp Rate	5000	RPM/sec

Figure 14 Motor parameters

Motor 1 Regulators		
58 - Current Regulator Bandwidth	1200	rad/sec
59 - Enable DC Bus Compensation	Enable	
60 - Flux Estimator Time Constant	12	msec
61 - Speed Feedback Filter Time Constant	1	msec
64 - Speed Regulator Proportional Gain	100	
65 - Speed Regulator Integral Gain	10	

Figure 15 Controller parameters

Figure 16 shows the angle correction parameter of the Hall-effect sensor, which affects the accuracy of the motor return position. The parameter is set to 60 degrees based on the phase difference between the back EMF line voltage UV and Hall1 and then minus 90 degrees.

When using the Hall-effect sensor, the speed is calculated by the differential method (take the change time of Hall signal), which is more likely to amplify the signal error and cause distortion of the current waveform. The speed filtering parameter HallSpdFiltBW is set to 1000, and the bandwidth is 36.7Hz according to the following formula (7).

$$BW = \frac{1}{2\pi \cdot T_{decay}} = \frac{Fast\_Control\_Rate}{F_{PWM} \cdot Ln(1 - \frac{HallSpdFiltBW}{2^{16}})} = 36.7Hz \qquad (11)$$

Fast_Control_Rate is Control and cut frequency ratio; F_{PWM} is BLDC drive Switching frequency; T_{decay} is Filter time constant.

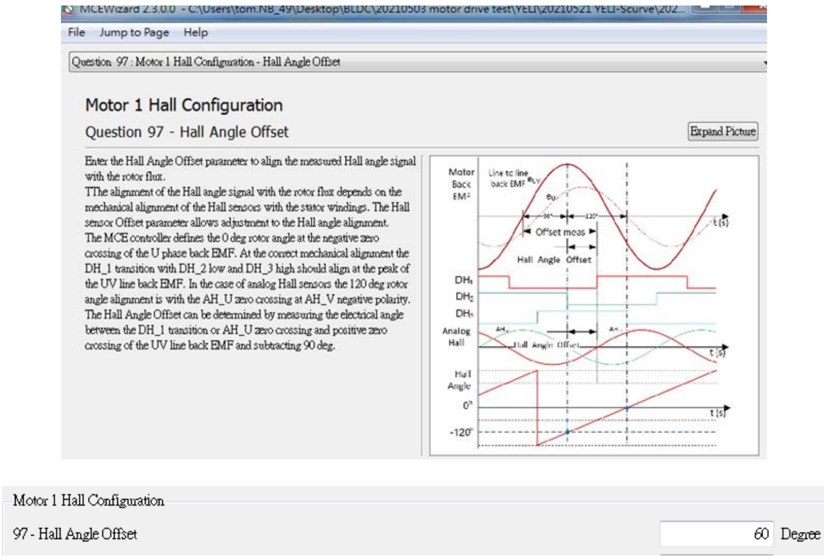


Figure 16 Motor Hall-effect sensor angle correction definition

3.2.5 S-curve Control

The main function of S-curve slow start is to achieve smooth start and stop action which could improve the start/stop mechanical stress, resulting the noise and shaking problems during shutter operation. The principle of S-curve is to add a “accelerated soft start” to the motor start and stop operation. S-curve can be used with the script-function in IMC-101T, calculated by equations.

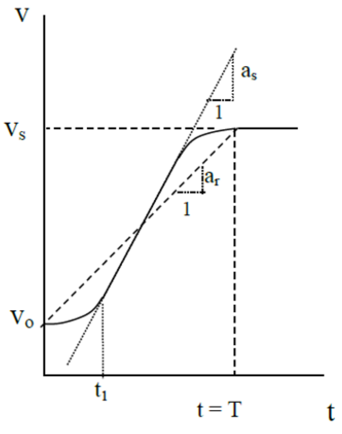


Figure 17 S-curve acceleration curve

$$ScurveLvL1 = \alpha * ScurveLvL1 + (1 - \alpha) * TargetSpeed \quad (12)$$

$$ScurveSpeed = \beta * ScurveSpeed + (1 - \beta) * ScurveLvL1 \quad (13)$$

A smooth input speed curve can be obtained from ScurveSpeed. By adjusting α and β, the accelerated soft start could be adjusted: the higher the value, the slower the acceleration. The actual S-curve acceleration and deceleration of the motor is shown below:

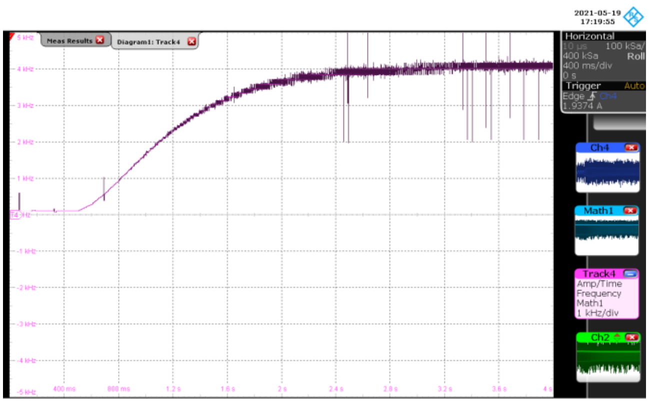


Figure 18 Accelerated S-curve

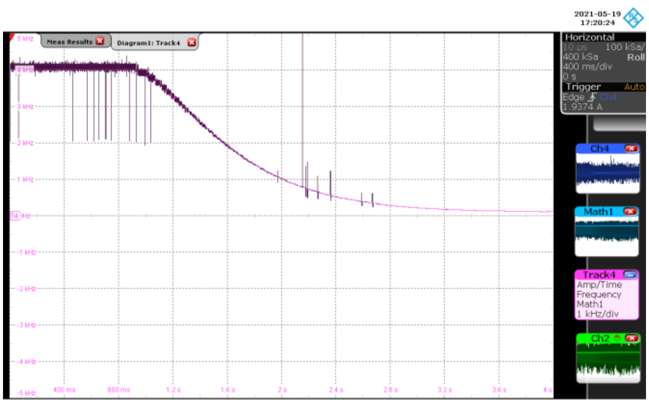


Figure 19 Deceleration S-curve

3.2.6 Script Program Flowchart

Script mainly focuses on the external functions of BLDC (e.g. Speed Command Detection/Remote...) and protection functions, and the program flow chart is as follows:

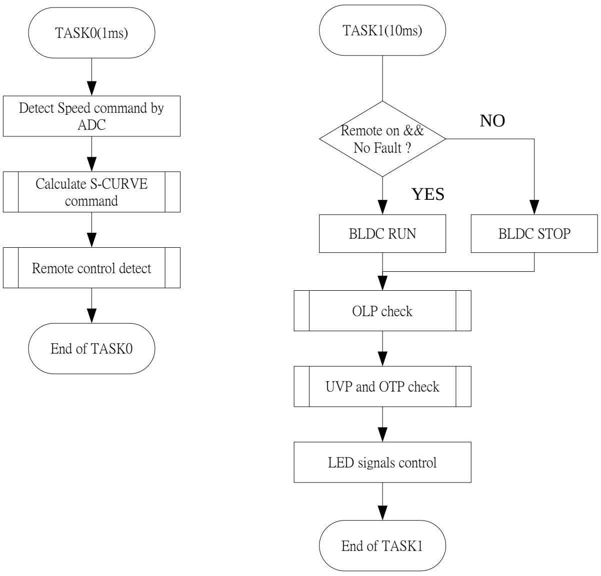


Figure 20: Flowchart of IMC-101T peripheral function program

3.3 Wireless Function Design

Wireless function is mainly achieved by WIFI protocol for the control of the roller shutter lift and stop. A user with accessible Internet could remotely control the BLDC roller shutter, through the mobile device APP.

3.3.1 Wireless Module System Architecture

The wireless function is achieved by ESP-WROOM-32U wireless module from Espressif Systems, which is mainly designed by WIFI function with IEEE 802.11 b/g/n protocol, supporting up to 150Mbps data transmission and 20dB antenna output power.

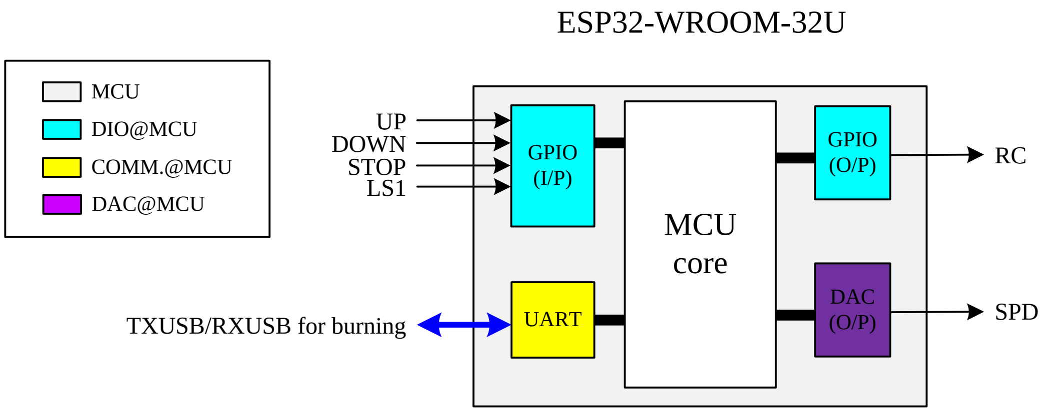


Figure 21 ESP32-WROOM-32U Architecture

In addition to WIFI packet sending and receiving, the wireless module could be further developed through Arduino IDE for peripheral GPIO and DAC functions, for the control of external hardware signal (Roll-up/down and stopping, micro switch LS1 receiving), output speed setting (SPD) as well as remote control function (RC) for IMC-101T module.

Wireless function is mostly used for roll-up/down and stop control. During application two shutters could be controlled synchronously by APP, where the APP is designed from IoT platform provided by Blynk. The architecture is as follows:

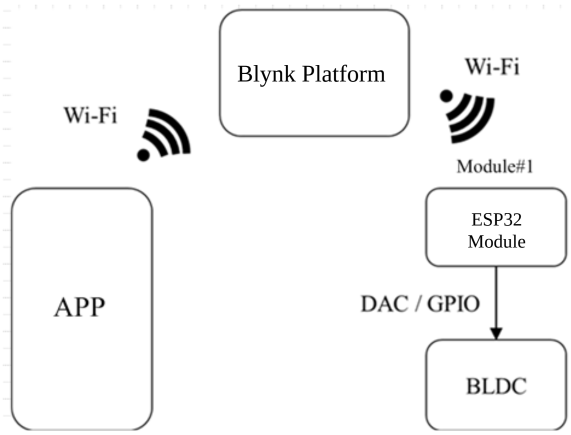


Figure 22 BLDC wireless control architecture

The key functions are described as follows.

1. APP: responsible for transmitting the mobile device APP screen button information to Blynk cloud platform.
2. Blynk platform: responsible for handling the control connection between APP and ESP32 wireless module.
3. ESP32 module: responsible for decoding APP button information and sending control signal to BLDC after decoding.
4. BLDC: Motor drive

3.3.2 Wireless Module Control Function

When the auxiliary power supply +3.3V is established, delay 500ms until the MCU function initialization is completed, then mark the INI_STAT flag RESET to indicate that the initialization is complete.

Before the motor starts for the first time, RC and SPD are not established. When the external start-up control signal EnableInput (source: UP/DOWN by hardware or WiFi) receives a low signal and lasts for more than 20ms, enter the roller shutter system start-up procedure. When EnableInput is detected, the system enable flag SysEnable SET means the roller shutter is ready to run.

After SysEnable is enabled, the RC SET is delayed 20ms, and the SPD speed command starts 10ms earlier than the RC. When DisableInput (source: STOP/LS1 by hardware) is received for more than 20ms, or WiFi receives a stop command, the SysEnable flag RESET indicates that the system is stopped, while RESET RC signal, waiting for the next start.

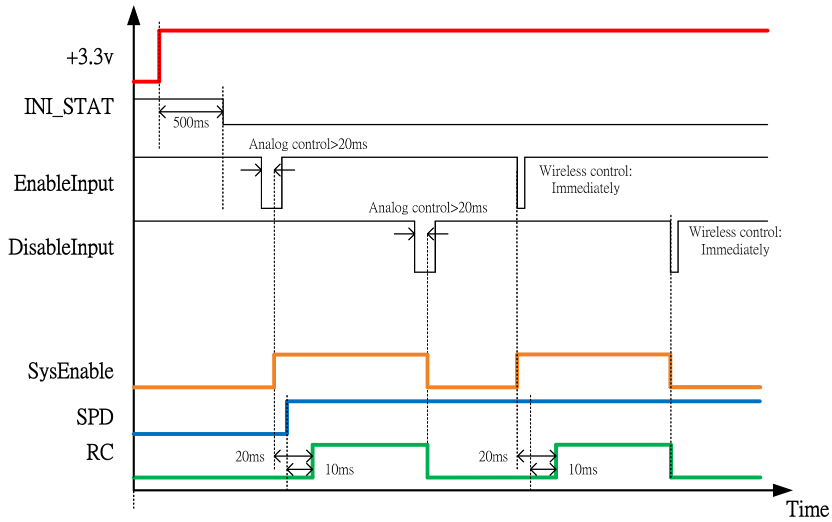


Figure 25 Wireless module start-up and control timing

The priority of control priority is mainly when three control actions happen at the same time: 1.stop; 2.upward roll; 3.downward roll.

When the up/down scrolling action is switched, it will first RESET RC signal for 10ms, modify the SPD signal to run in the opposite direction, and then SET RC signal to make BLDC start

Upward scrolling limit signal LS1 is used to limit the upper limit of the curtain system, the curtain machine continues to scroll to touch the limit micro switch, the micro switch signal state from High to Low, triggering the wireless module will be closed RC output, at this time the curtain machine is prohibited to continue to scroll, to achieve the function of positioning the curtain.

Wireless module control flow chart is as follows.

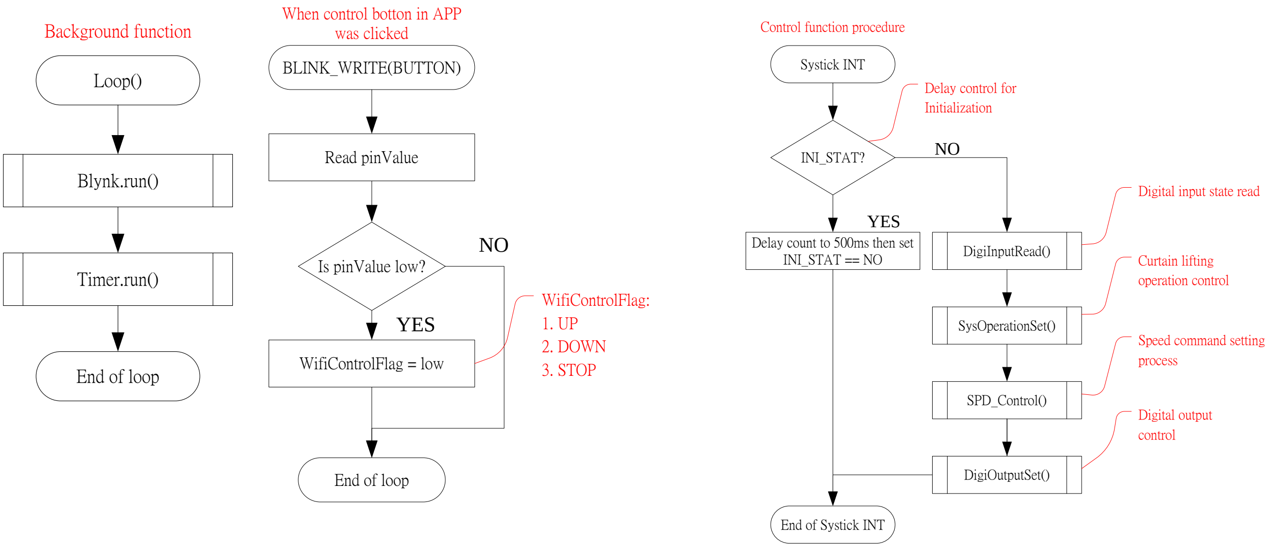


Figure 26 Wireless module control flow chart

3.3.3 APP Interface Planning

The APP interface is planned to provide up/down scrolling and stopping actions for users to send control messages, and the interface is as follows.

Fig. 27 APP control interface

4. System Performance Evaluation

4.1 Roller Shutter Machine Tests

The real application of the roller shutter machine is shown in the following figure and video, where the company's lobby curtain, with the weight of the curtain of about 2kg, can be smoothly lifted from the ground floor to the second floor and trigger the micro switch to complete the positioning of the roller shutter machine.

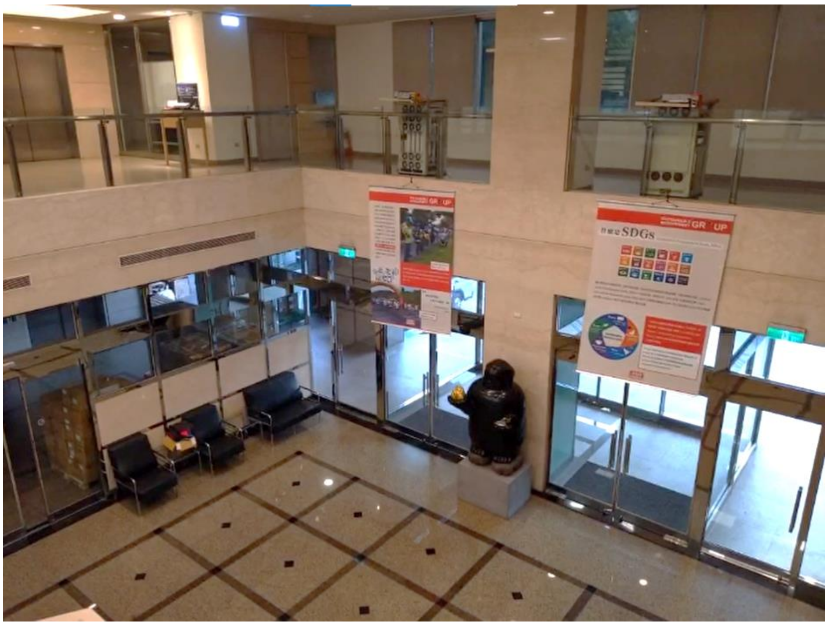


Figure 28 Actual fabric curtain with roller shutter machine

Table 4 Action movie and description of actual rolling machine

Video link	Description
Video 1	The actual curtain is hung synchronously from the ground on the first floor to the second floor.
Video 2	APP linkage BLDC roller shutter controller actual operation process.

4.2 Drive Test Waveform

The following description of the project proposes the stability and dynamic testing of the roller shutter application to evaluate its operational characteristics. In addition to efficiency measurements need to be tested on the power platform, the rest of the test are on the roller shutter platform test verification. Efficiency testing using the power platform as follows

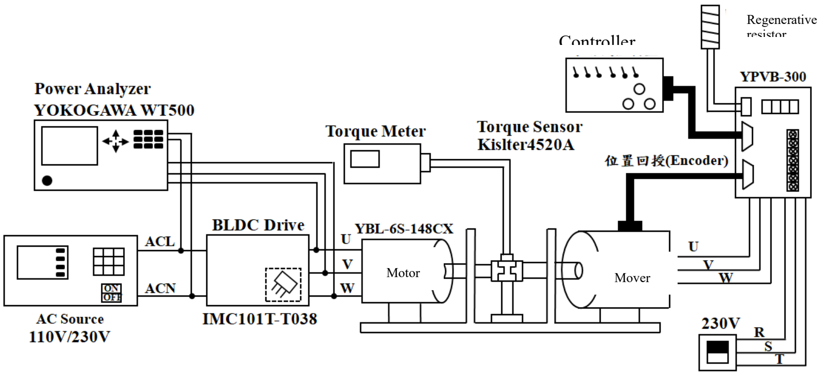
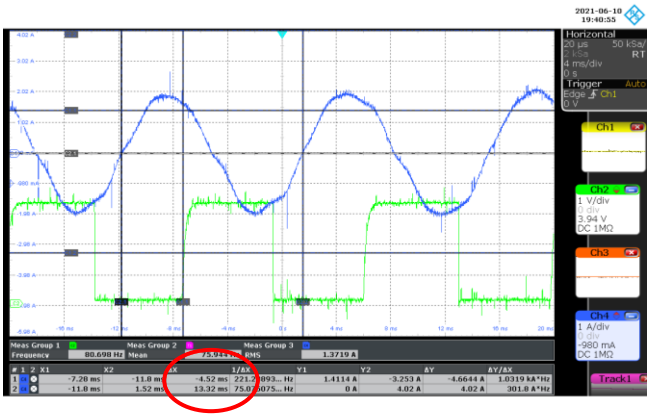


Figure 29 Dynamic test platform

4.2.1 Phase Current and Current Phase

Test conditions：	Input condition	Input voltage Vin : 230Vac	
	Output condition	Output speed： 1200 RPM; Output load： 11kg load	
Test method：	In accordance with the test conditions of the actual roller shutter machine, the conditions of the attached roll to trigger the shutdown microswitch of the roller shutter machine. And record the current and Hall-effect sensor phase under the pulling attachment of the roller shutter to confirm the current phase and the phase of the back EMF with the same phase.		
Test results	Test u phase line current Iu(line) ahead of Hall1 angle = 4.52/13.32 × 360° = 122° According to the measured counter-potential corresponding to Hall sensor, the line voltage waveform is about 150° ahead of Hall-effect sensor, and the three-phase line voltage is 30° ahead of phase voltage under Y winding, so we can know that the phase voltage is ahead of Hall-effect sensor = 150-30 = 120°, which confirms that the actual current waveform is in phase with the opposite potential and the phase is correct.		

Waveforms	
CH1:- CH2:Hall1	CH3: - CH4: Iu(line)



11kg@1200RPM

4.2.2 Efficiency

Test condition：	Input condition	Input voltage Vin : 230Vac	
	Output condition	(1)	Output speed： 4000 RPM Output load： 0.6 N-m
		(2)	Output speed： 800 RPM Output load： 0.6N-m
Test methods：	The efficiency test is evaluated by the power platform, and the Drive efficiency and motor efficiency are recorded respectively according to the test conditions and calculated as follows. $EFF._{(drive)} = \frac{P_{out(drive)}}{P_{in(drive)}}$; $EFF._{(motor)} = \frac{P_{out(motor)}}{P_{out(drive)}}$ $P_{out(motor)} = \frac{2\pi \cdot N \cdot T}{60}$; N: Output Machine Speed; T: Output mechanical torque		

測試結果	EFF.(drive) = 93.51%@4000 RPM; 74.62%@800 RPM EFF.(motor) = 83.77%@4000 RPM; 80.21%@800 RPM

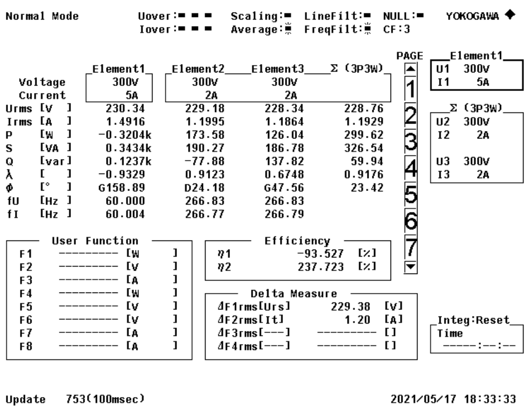
Waveforms and data

Input/output power @4000 RPM

$P_{out(\text{motor})} = (2\pi/60) * 4000 * 0.6 = 251\text{W}$

$P_{out(\text{drive})} = 299.62\text{W}$; $P_{\text{in(drive)}} = 320.4\text{W}$

Element1: Pin(Drive) ; Σ:Pout(Drive)

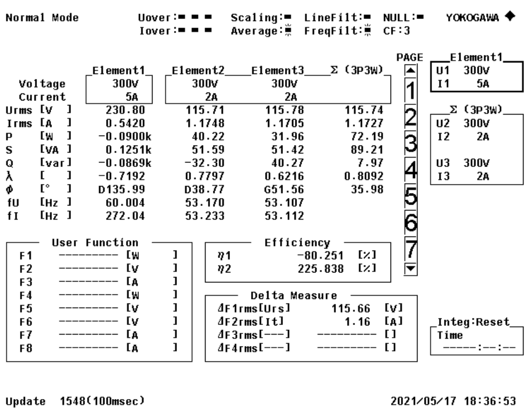


Pout(Motor): 1 V: 1 N-m

Input/output power @800 RPM

$P_{out(\text{motor})} = (2\pi/60) * 800 * 0.643 = 53.87\text{W}$

$P_{out(\text{drive})} = 72.19\text{W}$; $P_{\text{in(drive)}} = 90\text{W}$

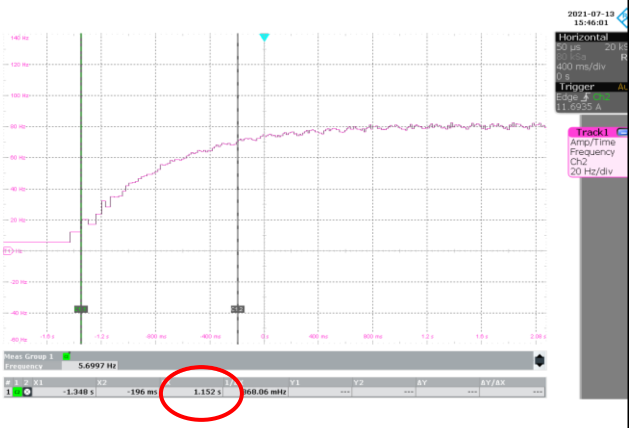
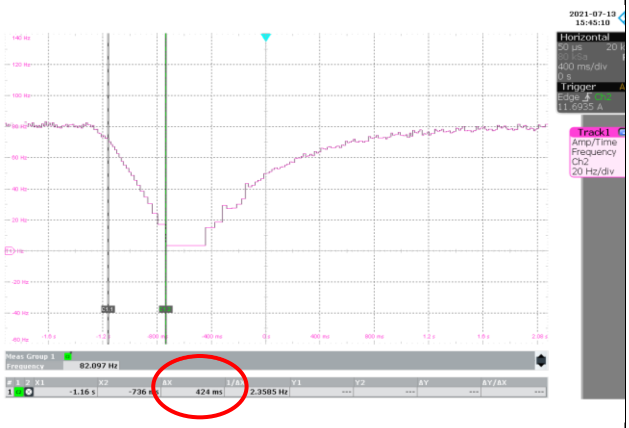


Pout(Motor) : 1 V: 1 N-m

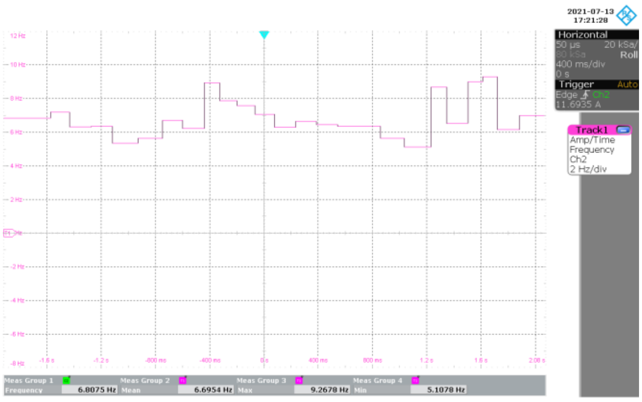
4.2.3 Acceleration/ Deceleration Time

<table>
<tr><td rowspan="2">Test conditions:</td><td>Input condition</td><td>Input voltage Vin : 230Vac</td></tr>
<tr><td>Output condition</td><td>Output speed: 1200 RPM
Output load : No load</td></tr>
<tr><td>Test methods:</td><td colspan="2">Acceleration time: the actual roller shutter in accordance with the test conditions, the conditions of the attached scroll to the speed setting, record the rising time (rising time) from the start of the roller shutter motor to reach the target speed, as the acceleration time of the roller shutter.

Deceleration time: The condition of the attachment is rolled up to the speed setting, and pressed down after reaching the set speed, and recorded the deceleration time (falling time) of the motor from the rated speed to zero speed as the deceleration time of the roller shutter machine.</td></tr>
<tr><td>Test results</td><td colspan="2">Acceleration time: 1.152 sec
Deceleration time: 0.424 sec</td></tr>
</table>

<table>
<tr><td colspan="4">Waveforms</td></tr>
<tr><td>CH1:-
CH2:-</td><td>CH3: -
Track1: Freq.(Hall1)</td><td>CH1:-
CH2:-</td><td>CH3: -
Track1: Freq.(Hall1)</td></tr>
<tr><td colspan="2">
No load@0→1200RPM</td><td colspan="2">
No load@1200→0 RPM</td></tr>
</table>

4.2.4 Minimum Speed Control

Test conditions:	Input condition	Input voltage Vin : 230Vac	
	Output condition	Output speed: according to test results Output load: No load	
Test method:	The actual roller shutter in accordance with the test conditions, the conditions of the attached roll to trigger the shutdown micro switch, and reduce the speed setting, record the speed of stable operation as the minimum speed point. And record the rotation speed of the product peak to peak.		
Test results	Minimum Speed: 6.7*60/4 = 100.5 RPM@no load, Speed ripple(p-p) = (9.3-5.1)*60/4 = 63 RPM		
Waveforms			
CH1:- CH2:-	CH3: - Track1: Freq.(Hall1)		
 No load@100 RPM			

4.3 Control Card Circuit Diagram and Parts List

The BLDC-300R kit is mainly modified by the control card, adding wireless communication module and antenna, as well as micro switch and Hall-effect sensor conversion circuit, etc. The main component costs are listed in Table 5 below, and the wiring diagrams are shown in Figure 30 and 31.Table 5 BOM

Part#	Specification	Q't	Cost(NTD)	Note
1	MSD3 PWM(Motor) IMC101T-T038 SOP-38	1	23	BLDC control IC
2	OP LM258ADT	1	2	Regenerative resistor control
3	ESP-WROOM-32U	1	123	WIFI wireless module
4	OP TS321A SOT23-5	1	3	Speed control signal conversion circuit
5	2.4G antenna + IPEX to SMA conversion wiring	1	50	WIFI antenna
6	3P micro switch 5A/125V	1	12	Upper roll limit switch
Cost			**213**	

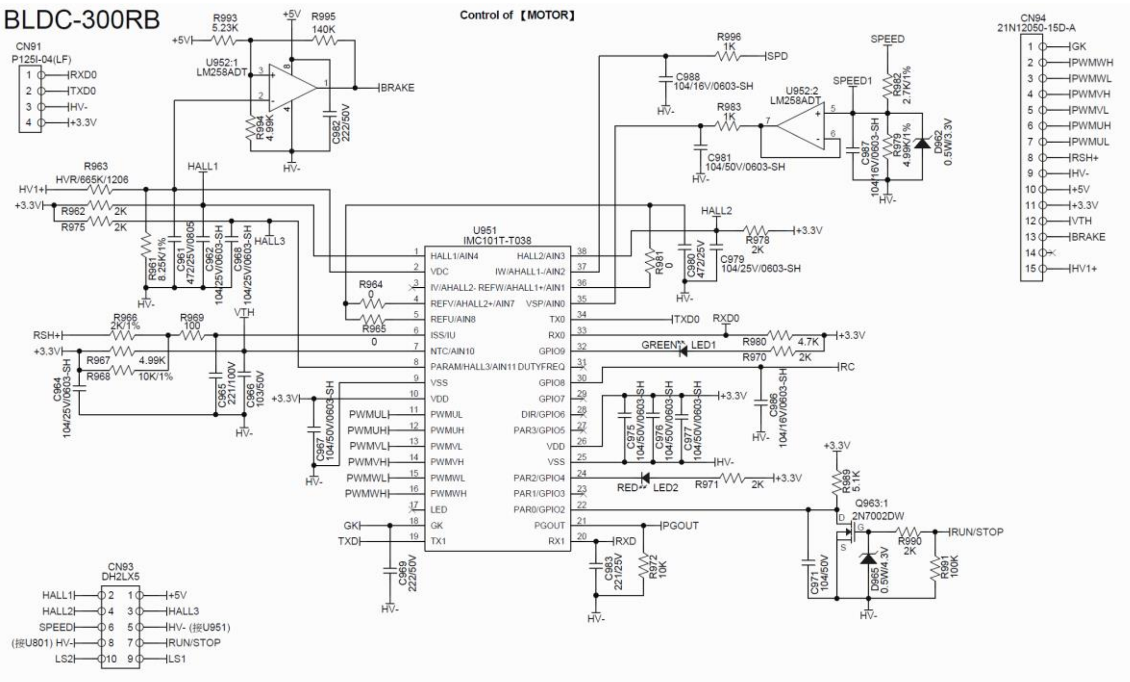


Fig. 30 Control card wiring diagram (IMC-101T circuit wiring)

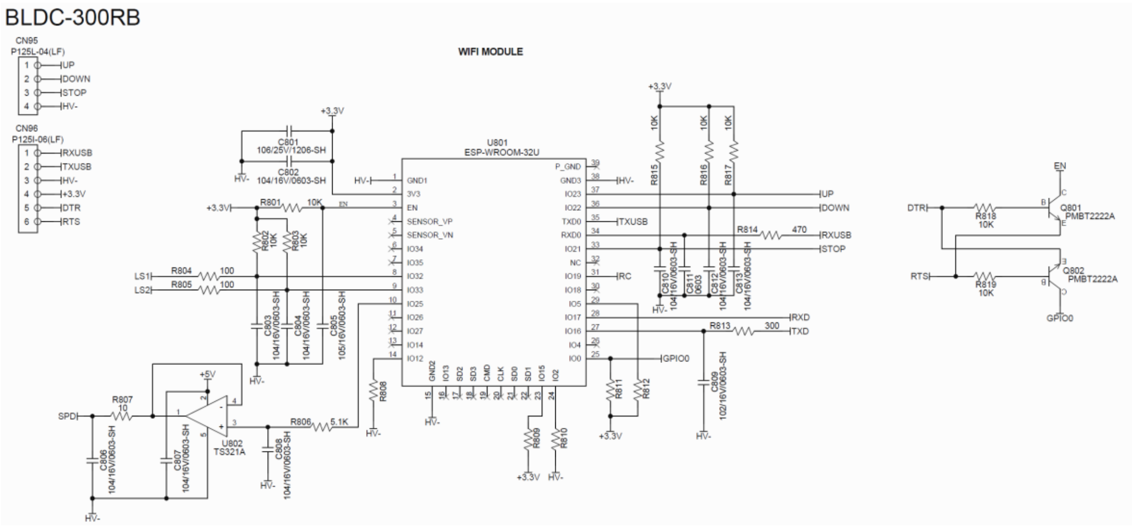


Figure 31 Control card wiring diagram (wireless module peripheral circuit)