PWM Rotation of Brushless DC Motor EC-32 by PIC16F88 and Rotation in terms of Combinational Logic Circuit

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Abstract

The brushed direct current (DC) motor rotates by applying DC voltage. The brushless DC (BLDC) motor also known as electronically commutated motors (ECMs, EC motors) is categorized into synchronous motors. The method of pulse width modulation (PWM) rotation of the brushless DC motor seems to be not straightforward. From this viewpoint, this paper reports on the PWM rotation of brushless DC moto EC-32 by using the microcontroller PIC16F88 with 18 pins. Its circuit and PICBASIC PRO program list are shown. Furthermore, the report shows the method of rotating the brushless DC motor EC-32 in the relation with the combinational logic circuit. Here, the truth table for the brushless DC motor EC-32 is introduced and corresponding combinational logic circuit is illustrated.

Keyword：Brushless DC motor, PWM, combinational logic circuit, PICBASIC PRO program

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1. Introduction

Brushless DC (BLDC) motor has not the commutator and is called the AC synchronous motor. The BLDC motors are advantageous to the brushed DC motors in long life, smooth high speed control. The BLDC motors are used in positioning, motion control, actuation, etc. e.g. hybrid electric vehicle (HEV), ship propulsion system, computer hard disk drive (HDD), etc. [1] The position of the rotor in the BLDC motor is measured by the Hall effect sensor. In spite of the advantages of the BLDC motor, for the rotation of the BLDC motor, the control circuit is required [2]. Although we can purchase the speed control board, it is better to understand on its circuit and the rotation principle of the BLDC motor clearly. As far as I am concerned, it might be rare to find out a simple circuit, in books and from the internet web sites, to rotate the BLDC motor by low-cost PIC16F88.

This paper, at first, by using the microcontroller PIC16F88, shows the pulse width modulation (PWM) rotation circuit of the BLDC motor EC-32 for CW/CCW direction and the PICBASIC PRO program. Secondly, the combinational logic circuit for rotating the BLDC motor EC-32 is shown. This circuit is realized based on the truth table for rotating the BLDC motor EC-32 by referring to [3] on "An introduction to brushless DC motors" by Maxon Co. Ltd.

The purpose of this paper is to present easy interpretation on the method to rotate the BLDC motor to the high school and university students. This report stresses upon the following points.

(1) This report shows the PWM rotation of the BLDC motor by using low-cost PIC16F88. Here, the PICBASIC PRO program is shown.

(2) The rotation of the BLDC motor facilitates the study of the combinational logic circuit as an application example.

In comparison with the PWM rotation circuit in [4], the PWM rotation circuit by the microcontroller PIC16F88, proposed in this report, is advantageous in the point that it does not require the PWM circuit besides PIC16F88. In [5], by using PIC18F452 with 40 pins, the PWM rotation program by C language is shown. In comparison with [5], the proposed PWM rotation method is feasible for the purpose of education in the following points.

(1) Since PIC16F88 has less pins than those of PIC18F452, the PWM rotation circuit in [5] is more complex than the current circuit.

(2) The PICBASIC PRO program, proposed in this paper, might be easy to understand, in comparison with the C language for students of high school and university.

Also, in [6], the assembler program and circuit for the PWM speed control of the BLDC motor are shown by using PIC16F877 with 40 pins. The assembler program might be difficult to interpret in general compared with the C and PICBASIC PRO programs.

2. Circuit and PICBASIC PRO program for PWM rotation of BLDC motor

This section shows the circuit and PICBASIC PRO program for the PWM rotation of the BLDC motor EC-32.

Figure 1 illustrates the PWM rotation control circuit for the BLDC motor by the microcontroller PIC16F88.

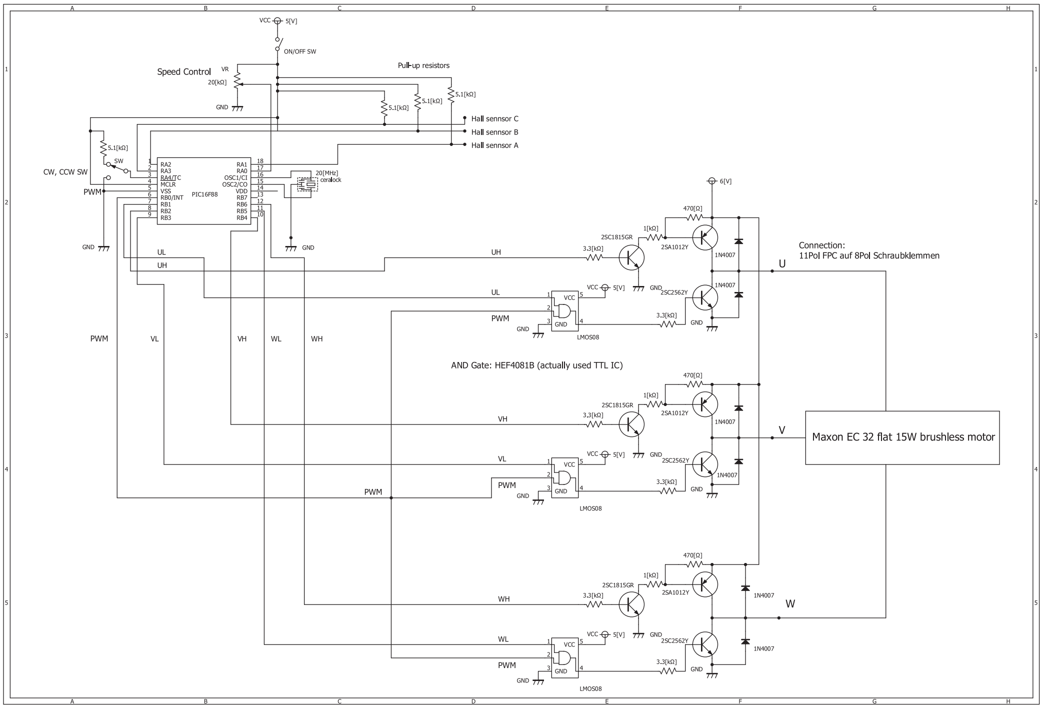

Fig. 1 PWM rotation circuit for the BLDC motor EC-32 by the microcontroller PIC16F88.

In Fig.1, the PWM signal, generated by PIC16F88, is applied to the terminals of three AND gates. The A/D converted value 255, taken into PIC16F88 through the RA0 terminal, gives 100 [%] duty cycle. Since 8 bit A/D conversion is used here, 5[V] in the variable resistance results in 100[%] duty cycle. Then the outputs from the AND gates are applied to the base terminals of the bipolar NPN transistors. The driving circuit by the NPN and PNP transistors are cited from [4]. It should be noted that, since the voltages from the three Hall sensors read by PIC16F88 are relatively small, it is difficult to detect if it is high or low. To avoid this unknown logic state trouble, we use pull-up resistors [4] as shown in Fig. 1. By the pull-up resistances, the voltages from the Hall sensors are transformed to 0 [V] or 5 [V], which are adequate voltages. The voltages are taken into PIC 16f88 for obtaining the rotor position.

The pin array of the BLDC motor EC-32 is as follows [7].

Pin 1 Hall 3.5…24 V DC (5 [V] is used here.)

Pin 2 Hall sensor 3 Motor winding 2 (Hall sensor A [7])
Pin 3 Hall sensor 1 (Hall sensor B [7])
Pin 4 Hall sensor 2 (Hall sensor C [7])
Pin 5 GND
Pin 6 Motor winding 3 (phase W [7])
Pin 7 Motor winding 2 (phase V [7])
Pin 8 Motor winding 1 (phase U [7])

The voltages from the Hall sensors 1, 2 and 3 show the rotor position of the BLDC motor. Based on the rotor position, the directions of the electric currents are assigned [3] between the three phases U_1, U_2, U_3 with the star connections. To generate electric currents between the three phases, the voltages from PIC16f88 are applied to the terminals of U_L, U_H, V_L, V_H, W_L and W_H. This relationship for 120-degree trapezoidal wave commutation using Hall sensors is summarized in Table 1. In 6 steps shown in Table 1, the BLDC motor rotates once for the CCW direction. The flow of the electric current in the reverse direction in each step result in the rotation for the CW direction.

In this paper, the PWM signal is output from the terminal RB0 for the purpose of speed control of the BLDC motor. By referring to the datasheet of PIC16F87/88 [8], some PWM setting commands are used as follows in the PICBASIC PRO program.

1. T2CON =%00000100 ' TIMER2 CONTROL REGISTER(Timer2 is on, Prescaler is 1: TMR2=1)
2. CCP1CON =%00001100 ' CAPTURE/COMPARE/PWM CONTROL REGISTER 1 (PWM mode)
3. PR2=255 ' PWM setting
4. CCPR1L=x ' PWM output x=0-255, which is given by the 8 bit A/D conversion of the voltage in the variable resistance at the terminal RA0.

PWM Period = [(PR2) + 1] • 4 • TOSC • (TMR2 Prescale Value) [s], PR2=255, TMR2=1,

TOSC=$\frac{1}{20\times10^6[Hz]}$ (20 [MHz] ceramic resonator is used in Fig. 1.)

It is interesting that the PWM signal, based on the AD conversion of the voltage in the variable resistance, is output during the other operations in PIC16F88 for rotating the BLDC motor.

By changing the resistance in the variable resistor, the speed of the BLDC motor rotates smoothly. To the pin RA1 the voltage from the Hall sensor A is applied. To the pin RA2 the voltage from the Hall sensor B is applied. Similarly, to the pin RA3 the voltage from the Hall sensor C is applied. In the program, by using the “SELECT CASE” command for the equation concerned with the logic values from the Hall sensors, the directions of the electric currents are classified for the three phases.

Based on Table 1, the PICBASIC PRO program driving the BLDC EC-32 are listed in Fig. 2. It should be noted that in the program there are following correspondences in comparison with related references.

Hall0 (in the program): HS1 (Maxon motor reference [3], Hall sensor A [7])

Hall1 (in the program): HS2 (Maxon motor reference [3]), Hall sensor B [7])

Hall2 (in the program): HS3 (Maxon motor reference [3]), Hall sensor C [7])

On the three phases:

U (in the program): phase 1 (Maxon motor reference [3])

V (in the program): phase 2 (Maxon motor reference [3])

W (in the program): phase 3 (Maxon motor reference [3])

Table 1 Relationship of logic values from Hall sensors A, B and C with direction of electric current through logic values at U_L, U_H, V_L, V_H, W_L and W_H. [3] (see page 18)

Input			Output						Direction of electric current (Rotation for CCW direction)
Hall sensor A	Hall sensor B	Hall sensor C	U_L	U_H	V_L	V_H	W_L	W_H	
1	0	1	0	1	1	0	0	0	U → V
1	0	0	0	1	0	0	1	0	U → W
1	1	0	0	0	0	1	1	0	V → W
0	1	0	1	0	0	1	0	0	V → U
0	1	1	1	0	0	0	0	1	W → U
0	0	1	0	0	1	0	0	1	W → V

```
'****************************************************************
'*   Name      : bush.pbp                                        *
'*   Author    : Seiichi Nakamori                                *
'*   Notice    : Copyright (c) 2015                              *
'*             : All Rights Reserved                             *
'*   Date      : 2015/06/22                                      *
'*   Version : 1.0                                               *
'*   Notes     : 20 MHz Ceralock                                 *
'*             : RBO PWM output, configuration setting           *
'****************************************************************
' program name: bush.pbp
TRISB = %00000000
TRISA.1=1
```

```
TRISA.2=1
TRISA.3=1
TRISA.4=1
'-------------Main Code------------
'------------Variables-------------
 x VAR BYTE ' Byte for potentiometer input
 T2CON =%00000100                ' PWM setting
 CCP1CON =%00001100              ' PWM setting
 PR2=255                          ' PWM setting
 hall0 var byte
 hall1 var byte
 hall2 var byte
 hallval var byte
'----------Initialization----------
ANSEL = %00000001 ' Leaves AN0 in analog mode, but
' changes other analog bits to digital.
' See table below.
' Analog Bit Analog or Digital PIC16F88 Pin
' ------------ ------------------ --------------
' AN0 Analog RA0
' AN1 Digital RA1
' AN2 Digital RA2
' AN3 Digital RA3
' AN4 Digital RA4
' AN5 Digital RB6
' AN6 Digital RB7
' PIC16F88 datasheet. For Microchip PIC datasheets, see:
' http://www.microchip.
' The ANSEL Register is Register 12-1: ANSEL Register,
' look around page 113 in the 16F88 datasheet.

start:
ADCIN 0, x ' Read analog voltage on AN0 and
' convert to 8-bit digital value
' and store as x.
pauseus 100
```

```
CCPR1L=x                    ' PWM output x=0-255

' PAUSE 500 ' Pause 1/2 second
 'hall0=PORTA.1: Hall a
 'hall1=PORTA.2: Hall b
 'hall2=PORTA.3: Hall c
 'goto start
 hall0=0
 hall1=0
 hall2=0
 if PORTA.1=1 then hall0=1     ' Hall a: PORTA.1=1 then hall0=1
 if PORTA.2=1 then hall1=1     ' Hall b: PORTA.2=1 then hall1=1
 if PORTA.3=1 then hall2=1     ' Hall c: PORTA.3=1 then hall2=1
 if PORTA.1=0 then hall0=0     ' Hall a: PORTA.1=0 then hall0=0
 if PORTA.2=0 then hall1=0     ' Hall b: PORTA.2=0 then hall1=0
 if PORTA.3=0 then hall2=0     ' Hall c: PORTA.3=0 then hall2=0
 hallval=hall0*4+hall1*2+hall2     ' Hall signal: abc ---> decimal

 if PORTA.4=1 then gosub forw    ' rotation forward if PORTA.4=1
 IF PORTA.4=0 then gosub rever ' rotation reverse if PORTA.4=0
 goto start

 forw:           ' rotation for forward (CCW) direction
 SELECT CASE hallval
 case 5        ' %101     ' U -> V
 PORTB.1=0     'UL
 PORTB.2=1     'UH
 PORTB.3=1     'VL
 PORTB.4=0     'VH
 PORTB.5=0     'WL
 PORTB.6=0     'WH
 case 4        '%100     ' U -> W
 PORTB.1=0     'UL
 PORTB.2=1     'UH
 PORTB.3=0     'VL
 PORTB.4=0     'VH
```

```
PORTB.5=1     'WL
PORTB.6=0     'WH
case 6        '%110     ' V -> W
PORTB.1=0     'UL
PORTB.2=0     'UH
PORTB.3=0     'VL
PORTB.4=1     'VH
PORTB.5=1     'WL
PORTB.6=0     'WH
case 2        '%010     ' V -> U
PORTB.1=1     'UL
PORTB.2=0     'UH
PORTB.3=0     'VL
PORTB.4=1     'VH
PORTB.5=0     'WL
PORTB.6=0     'WH
case 3        '%011     ' W -> U
PORTB.1=1     'UL
PORTB.2=0     'UH
PORTB.3=0     'VL
PORTB.4=0     'VH
PORTB.5=0     'WL
PORTB.6=1     'WH
case 1        '%001      ' W -> V
PORTB.1=0     'UL
PORTB.2=0     'UH
PORTB.3=1     'VL
PORTB.4=0     'VH
PORTB.5=0     'WL
PORTB.6=1     'WH
case else
PORTB.1=0     'UL
PORTB.2=0     'UH
PORTB.3=0     'VL
PORTB.4=0     'VH
PORTB.5=0     'WL
```

```
PORTB.6=0    'WH
end select
return

rever:          ' rotation for reverse (CW) direction
SELECT CASE hallval
case 5          '%101    ' V --> U
PORTB.1=1    'UL
PORTB.2=0    'UH
PORTB.3=0    'VL
PORTB.4=1    'VH
PORTB.5=0    'WL
PORTB.6=0    'WH
case 4          '%100     ' W -> U
PORTB.1=1    'UL
PORTB.2=0    'UH
PORTB.3=0    'VL
PORTB.4=0    'VH
PORTB.5=0    'WL
PORTB.6=1    'WH
case 6          '%110     ' W -> V
PORTB.1=0    'UL
PORTB.2=0    'UH
PORTB.3=1    'VL
PORTB.4=0    'VH
PORTB.5=0    'WL
PORTB.6=1    'WH
case 2          '%010     ' U -> V
PORTB.1=0    'UL
PORTB.2=1    'UH
PORTB.3=1    'VL
PORTB.4=0    'VH
PORTB.5=0    'WL
PORTB.6=0    'WH
case 3          '%011      ' U -> W
PORTB.1=0    'UL
```

```
PORTB.2=1    'UH
PORTB.3=0    'VL
PORTB.4=0    'VH
PORTB.5=1    'WL
PORTB.6=0    'WH
case 1    '%001    ' V -> W
PORTB.1=0    'UL
PORTB.2=0    'UH
PORTB.3=0    'VL
PORTB.4=1    'VH
PORTB.5=1    'WL
PORTB.6=0    'WH
case else
PORTB.1=0    'UL
PORTB.2=0    'UH
PORTB.3=0    'VL
PORTB.4=0    'VH
PORTB.5=0    'WL
PORTB.6=0    'WH
end select
return
end
```

Fig.2 PICBASIC PRO program by PIC16F88 for PWM rotation of BLDC EC-32.

The experimental waveforms regarding program in Fig.2 are shown in section 4.
In section 3, let us also consider the rotation by the combinational logic circuit.

3. Rotation of BLDC motor EC-32 by combination logic circuit

By referring to [4] and “maxon EC motor An introduction to brushless DC motors” [3], the BLDC motor EC-32 rotates in terms of the combinational logic circuit.
At first, the truth table is shown in Table 2.

Table 2 Truth table for BLDC motor EC-32 (120-degree trapezoidal wave commutation using Hall sensors)

Input			Output					
Hall sensor A	Hall Sensor B	Hall Sensor C	U_L	U_H	V_L	V_H	W_L	W_H
1	0	1	0	1	1	0	0	0
1	0	0	0	1	0	0	1	0
1	1	0	0	0	0	1	1	0
0	1	0	1	0	0	1	0	0
0	1	1	1	0	0	0	0	1
0	0	1	0	0	1	0	0	1

Logic equation:

$$U_L = \bar{A} \cdot B \cdot \bar{C} + \bar{A} \cdot B \cdot C = \bar{A} \cdot B$$
$$U_H = A \cdot \bar{B} \cdot C + A \cdot \bar{B} \cdot \bar{C} = A \cdot \bar{B}$$
$$V_L = A \cdot \bar{B} \cdot C + \bar{A} \cdot \bar{B} \cdot C = \bar{B} \cdot C$$
$$V_H = A \cdot B \cdot \bar{C} + \bar{A} \cdot B \cdot \bar{C} = B \cdot \bar{C}$$
$$W_L = A \cdot \bar{B} \cdot \bar{C} + A \cdot B \cdot \bar{C} = A \cdot \bar{C}$$
$$W_H = \bar{A} \cdot B \cdot C + \bar{A} \cdot \bar{B} \cdot C = \bar{A} \cdot C$$

Based on the logic equation, the driving circuit of the BLDC EC-32 for CCW direction is illustrated in Fig. 3.

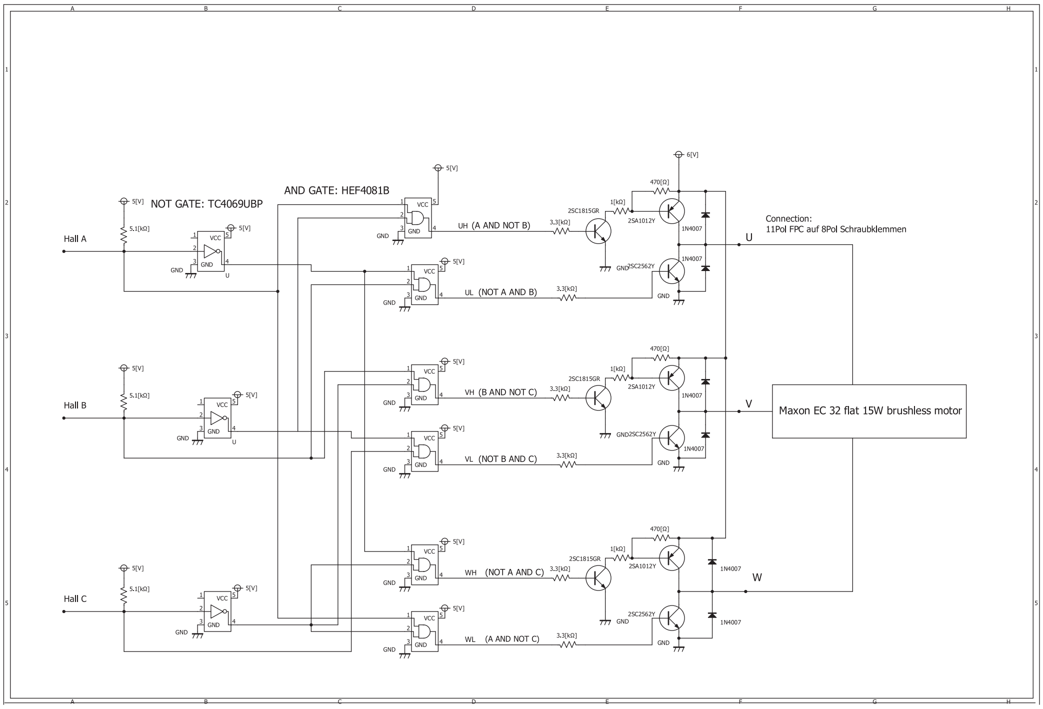

Fig. 3 Driving circuit of BLDC motor EC-32 for CCW direction by combinational logic circuit.

Furthermore, the truth table for rotating the BLDC moto EC-32 for CW/CCW direction is shown in Table 3.

Table 3 Truth table for rotating BLDC motor EC-32 for CW/CCW direction

Input				Output					
CW	Hall sensor A	Hall Sensor B	Hall sensor C	U_L	U_H	V_L	V_H	W_L	W_H
1	1	0	1	0	1	1	0	0	0
1	1	0	0	0	1	0	0	1	0
1	1	1	0	0	0	0	1	1	0
1	0	1	0	1	0	0	1	0	0
1	0	1	1	1	0	0	0	0	1
1	0	0	1	0	0	1	0	0	1
0	1	0	1	1	0	0	1	0	0
0	1	0	0	1	0	0	0	0	1
0	1	1	0	0	0	1	0	0	1
0	0	1	0	0	1	1	0	0	0
0	0	1	1	0	1	0	0	1	0
0	0	0	1	0	0	0	1	1	0

・CW=1: rotating the BLDC motor for CW diredtion

・CW=0: rotating the BLDC motor for CCW direction

Logic equation :

$U_L = CW\cdot\bar{A}\cdot B\cdot\bar{C} + CW\cdot\bar{A}\cdot B\cdot C + \overline{CW}\cdot A\cdot\bar{B}\cdot C + \overline{CW}\cdot A\cdot\bar{B}\cdot\bar{C}$

$= CW\cdot\bar{A}\cdot B + \overline{CW}\cdot A\cdot\bar{B}$

$U_H = CW\cdot A\cdot\bar{B}\cdot C + CW\cdot A\cdot\bar{B}\cdot\bar{C} + \overline{CW}\cdot\bar{A}\cdot B\cdot\bar{C} + \overline{CW}\cdot\bar{A}\cdot B\cdot C$

$= CW\cdot A\cdot\bar{B} + \overline{CW}\cdot\bar{A}\cdot B$

$V_L = CW\cdot A\cdot\bar{B}\cdot C + CW\cdot\bar{A}\cdot\bar{B}\cdot C + \overline{CW}\cdot A\cdot B\cdot\bar{C} + \overline{CW}\cdot\bar{A}\cdot B\cdot\bar{C}$

$= CW\cdot\bar{B}\cdot C + \overline{CW}\cdot B\cdot\bar{C}$

$V_H = CW\cdot A\cdot B\cdot\bar{C} + CW\cdot\bar{A}\cdot B\cdot\bar{C} + \overline{CW}\cdot A\cdot\bar{B}\cdot C + \overline{CW}\cdot A\cdot\bar{B}\cdot\bar{C}$

$= CW\cdot B\cdot\bar{C} + \overline{CW}\cdot\bar{B}\cdot C$

$W_L = CW\cdot A\cdot\bar{B}\cdot\bar{C} + CW\cdot A\cdot B\cdot\bar{C} + \overline{CW}\cdot\bar{A}\cdot B\cdot C + \overline{CW}\cdot\bar{A}\cdot\bar{B}\cdot C$

$= CW\cdot A\cdot\bar{C} + \overline{CW}\cdot\bar{A}\cdot C +$

$W_H = CW\cdot\bar{A}\cdot B\cdot C + CW\cdot\bar{A}\cdot\bar{B}\cdot C + \overline{CW}\cdot A\cdot\bar{B}\cdot\bar{C} + \overline{CW}\cdot A\cdot B\cdot\bar{C}$

$= CW\cdot\bar{A}\cdot C + \overline{CW}\cdot A\cdot\bar{C}$

Based on the logic equation, the driving circuit of the BLDC EC-32 for CW/CCW direction is illustrated in Fig. 4.

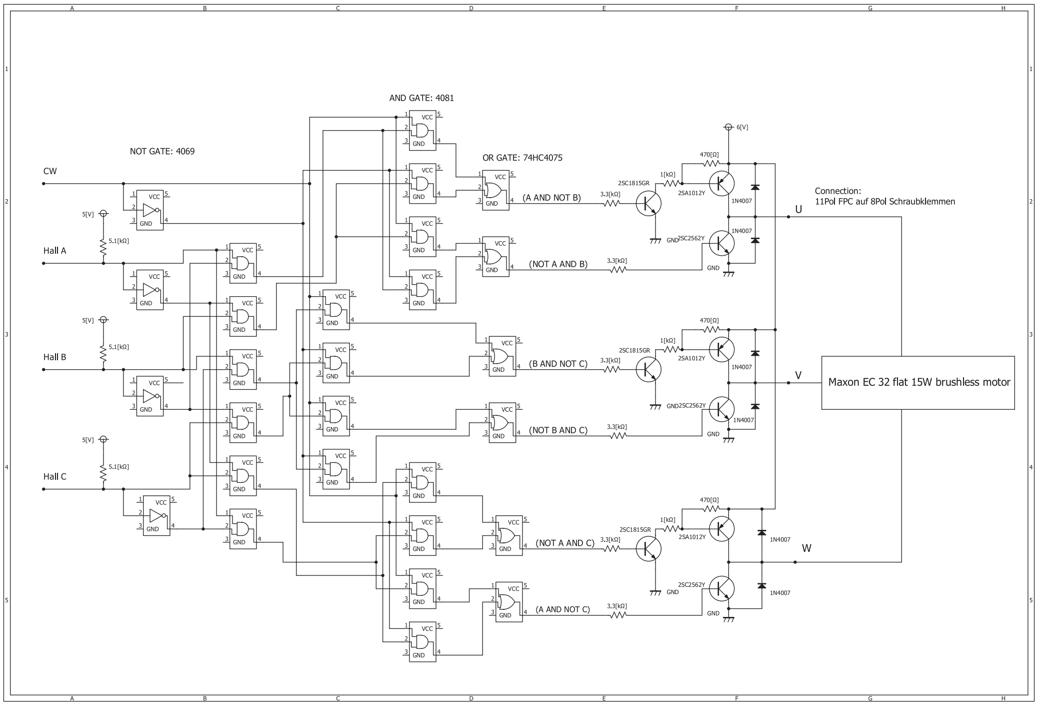

Fig. 4 Driving circuit of the BLDC motor EC-32 for CW/CCW direction

4. Waveforms for the driving circuit of BLDC motor EC-32

In this section, the waveforms are shown during rotating the BLDC motor EC-32 by PIC16F88. The waveforms for the CW direction are omitted here for page limitation.

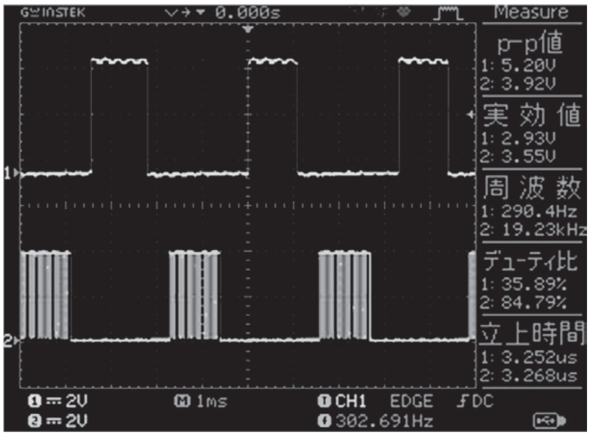

Fig. 4-1 Voltage waveform at U_H (upper) and U_L (lower).

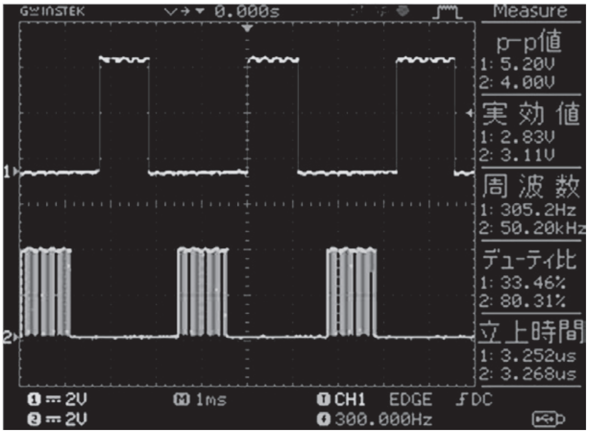

Fig. 4-2 Voltage waveform at V_H (upper) and V_L (lower).

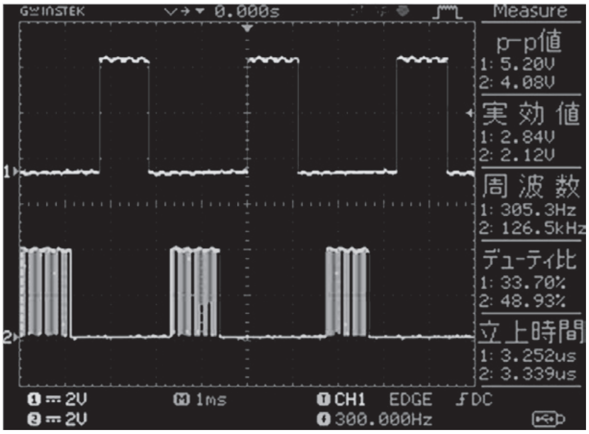

Fig. 4-3 Voltage waveform at W_H (upper) and W_L (lower).

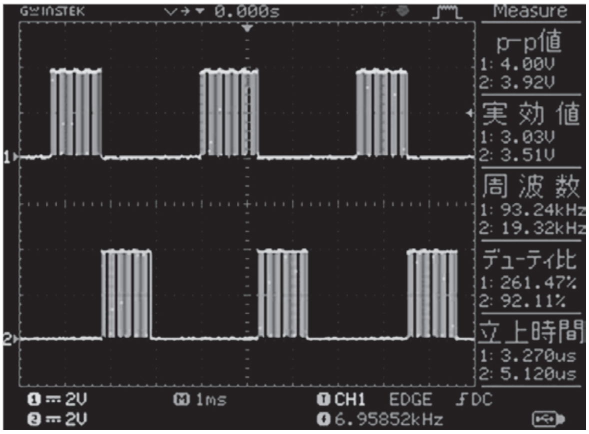

Fig. 4-4 Voltage waveform at U_L (upper) and V_L (lower).

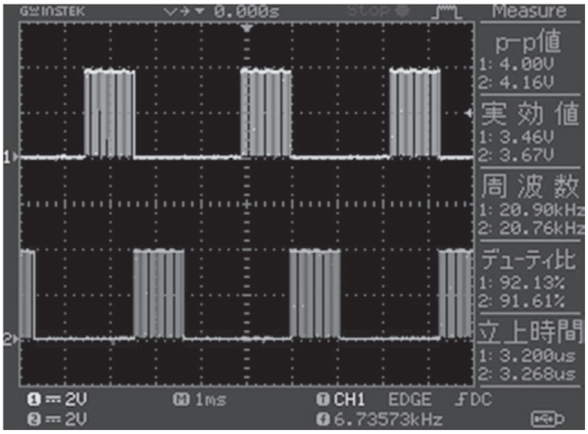

Fig. 4-5 Voltage waveform at V_L (upper) and W_L (lower).

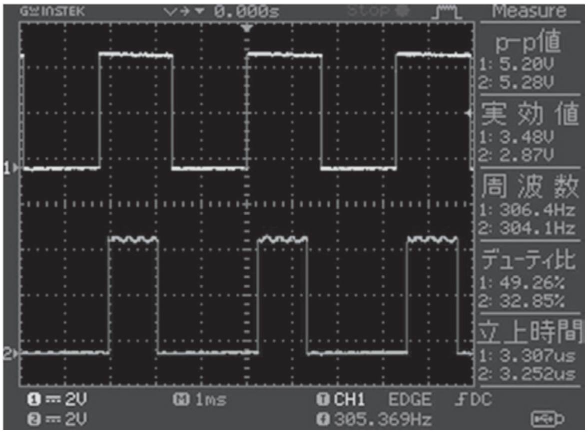

Fig. 4-6 Voltage waveform at Hall A (upper) and U_H (lower).

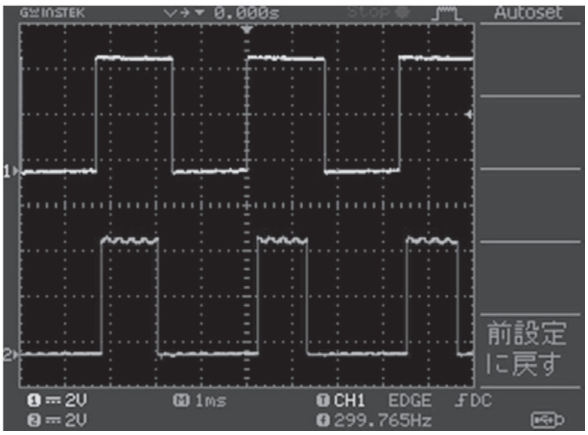

Fig. 4-7 Voltage waveform at Hall B (upper) and V_H (lower).

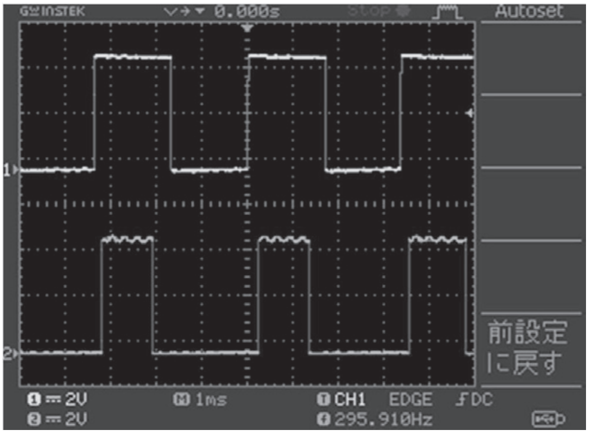

Fig. 4-8 Voltage waveform at Hall C (upper) and W_H (lower).

From Fig. 4-1, since we adopt 120-degree trapezoidal wave commutation using Hall sensors, we find that the collector current does not flow from the upper transistor to the lower transistor of the phase U simultaneously. This indicates that short current does not flow from the DC voltage source 5 [V] to the ground in the phase U. Same phenomenon apply for the phases V and W (see Fig. 4-2 and Fig. 4-3).

5. Conclusions

This report has explained on the method to rotate the BLDC motor EC-32. The first procedure uses the microcontroller PIC16F88 and the rotation speed of the BLDC motor is adjusted smoothly for the CW/CCW direction by the PWM signal applied to the AND gate terminals. In the second method, the combinational logic circuit rotates the BLDC motor in a constant speed.

From the viewpoint of technology education, the rotation technique described in this report might be available for the high school/university students to learn on the speed control of the BLDC motor. In addition to the speed control of the BLDC motor by PIC16F88, it is possible to change the direction of rotation. The combinational logic circuit rotates the BLDC motor in a constant speed. The technique might be useful for the students to learn on the combinational circuit, the truth table and the logic equation along with experiments.

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