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Application Note

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BLDC Motor Control with Hall Sensors Based on FRDM-KE02Z

by: Xianhu Gao

Contents

1 Introduction

The speed control circuits of DC motors are simple and easy to use, and hence are very popular in motor speed control systems. However, due to the brushes, DC motors suffer from a lower reliability. The brushless DC (BLDC) motor is also referred as an electronically commuted motor. There are no brushes on the rotor and the commutation is performed electronically at certain rotor positions.

Replacing a DC motor with a BLDC motor places higher demands on a control algorithm and a control circuit.

- First, the BLDC motor is usually a three-phase system; so, it has to be powered by a three-phase power supply.
- Second, the rotor position must be known at certain angles in order to align the applied voltage.

The most common way to control a BLDC motor is to use Hall sensors to determine the rotor position. The control system senses the rotor position and the proper voltage pattern is applied to the motor.

This application note describes the basic DC and BLDC motor theory and the implementation of the six-step commutation method on KE02 sub-family MCUs. KE02 is a 5 V MCU with enhanced FlexTimer(FTM), suitable for BLDC motor control.

1.1 FRDM-KE02Z board and transfer board

Kinetis E Series Freedom Development (FRDM-KE02Z) board forms the basis of the control system and has the following functions.

- Supplies PWM control signal to the BLDC board
- Processes Hall sensor signal and values of bus voltage and current

A transfer board is used to connect the FRDM-KE02Z board and the BLDC board.

1.2 BLDC drive board

The BLDC board is APMOTOR56F8000: Motor Control Demonstration System, powered by 9 V DC. On this board, you can implement the six-step Hall Sensor algorithm and sensorless algorithm. In this application note, Hall sensor is configured and used.

The detail information can be found at: APMOTOR56F8000: Motor Control Demonstration System

1.3 Software requirement

The software is based on CodeWarrior v10.3 (CW10.3) or higher versions.

The latest version of CodeWarrior is CW10.4, and can be found at: **freescale.com/CodeWarrior**

2 Basic theory of motor control

This figure shows the basic principle of nearly all kinds of motor rotations. The rotor and the stator in the motor generate the interactive force and the rotor spins as long as the force is in the same direction.

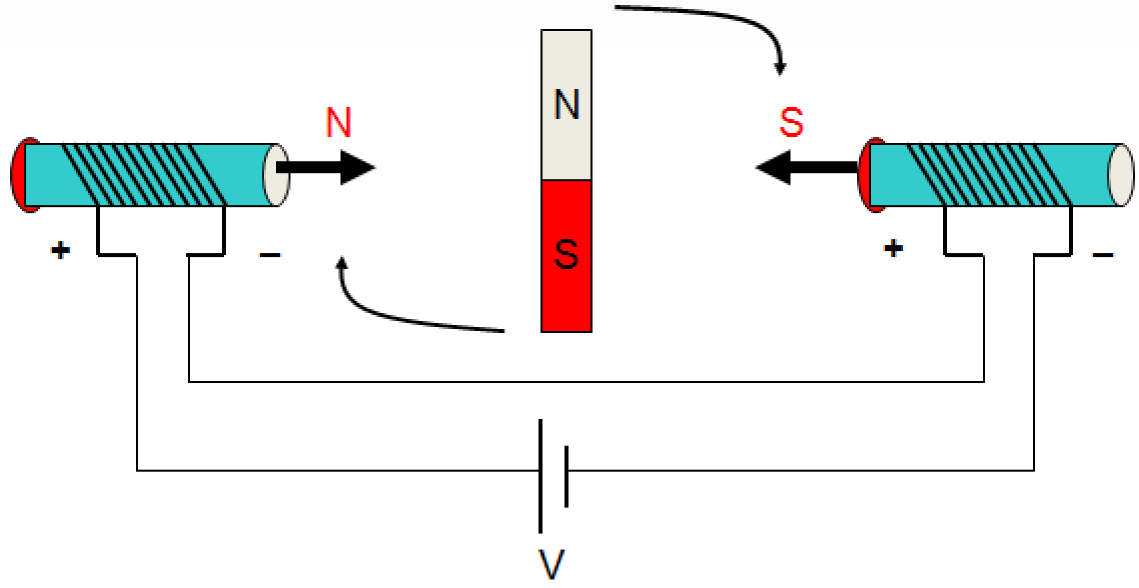


Figure 1. Motor control fundamentals

2.1 DC motor control

As seen from Figure 1, the rotor spins in the clockwise direction because the force is in the direction of the rotor spin. However, after rotating 180°, the direction of the force changes, preventing the rotor from spinning and trying to drag it back. At last, the rotor will not spin in the same direction but just sways.

One effective way of keeping the force in the same direction is to change the current direction in the coil at the same time when the force direction changes. See this figure. This process is called commutation.

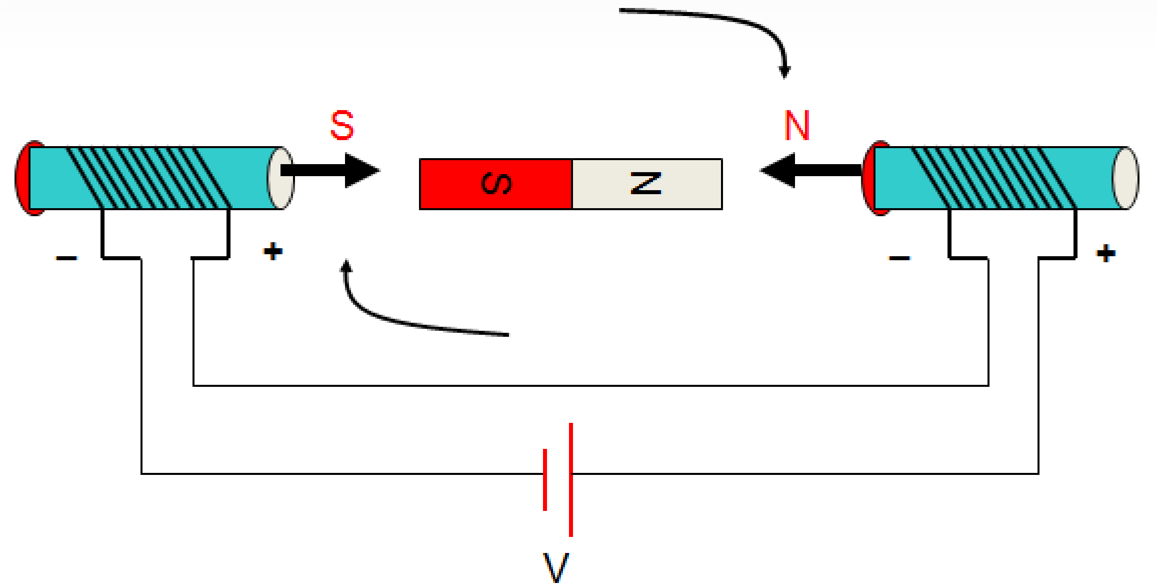
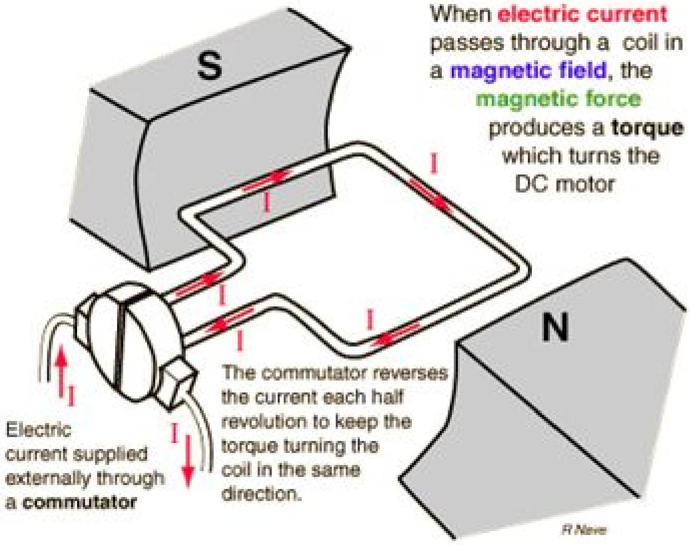


Figure 2. Motor commutation

In the DC motor, the brush commutator is used. See the following figure.



When **electric current** passes through a coil in a **magnetic field**, the **magnetic force** produces a **torque** which turns the DC motor

The commutator reverses the current each half revolution to keep the torque turning the coil in the same direction.

Electric current supplied externally through a **commutator**

Figure 3. Brushed DC motor

When the rotor spins to a certain position, the direction of the current in the coil will be changed by the brush, so the rotor will spin in the same direction forever. However, if the direction of the input current to the brush changes, so will the rotor spin direction.

The brush commutator has the following advantages.

- Ease of control
- Self-commutating
- Low rotor inertia, coreless rotors
- Lowest total system cost for basic motion
- High starting torque and can run with AC or DC

However it has some many disadvantages as follows.

- Higher maintenance cost due to brush wear
- Electrical noise due to mechanical commutation
- Maximal speed limited by commutator
- Heat is generated in armature which is difficult to remove because the armature is on the rotor.
- Friction losses associated with mechanical commutation
- Not usable in "intrinsically safe" environments

2.2 BLDC motor control

A BLDC motor can overcome the shortcomings of the DC motor. The basic structure of BLDC motor is different as compared to DC motor because it has no mechanical commutator (brush). In a BLDC motor, the coil is wound on the stator, the rotor has surface-mounted permanent magnets, and the brush commutator is replaced with the electronic commutator.

Figure 4 shows the structure of a three-phase BLDC motor. The external rotor (some motors are internal) has four pole pairs and consists of the permanent magnet. The stator consists of three-phase windings (A, B, and C). Figure 5 is an abstract schematic of the previous stator windings. It is easy and intuitive to analyze magnetic field of the stator using this schematic. The MCU and the control circuit is the commutator.

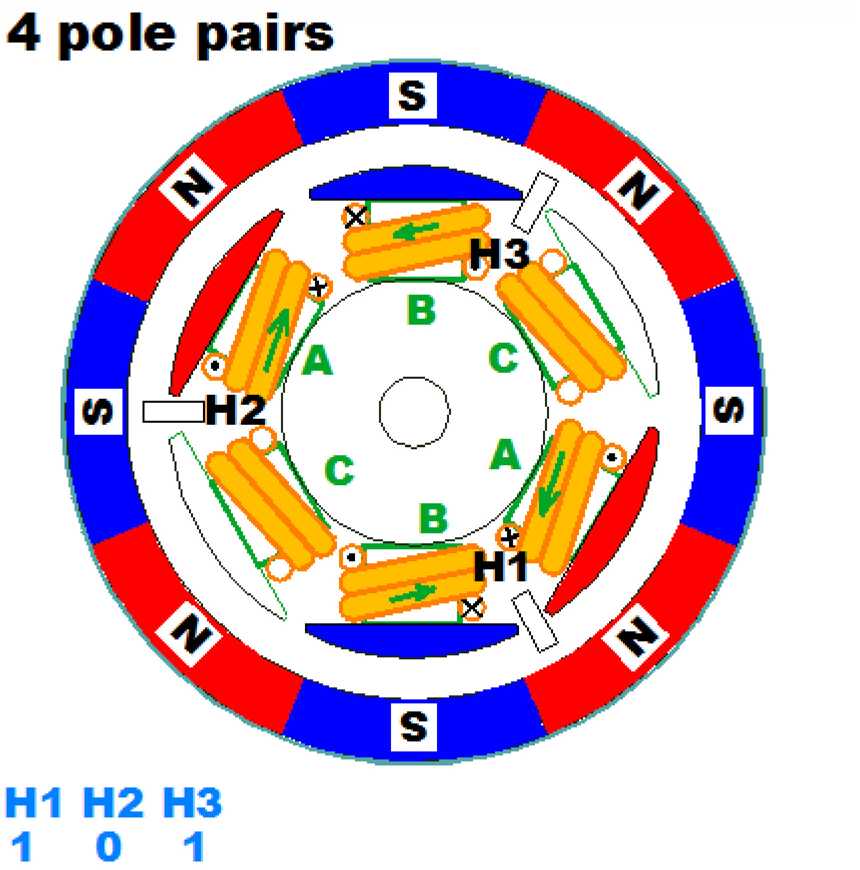


Figure 4. BLDC motor structure

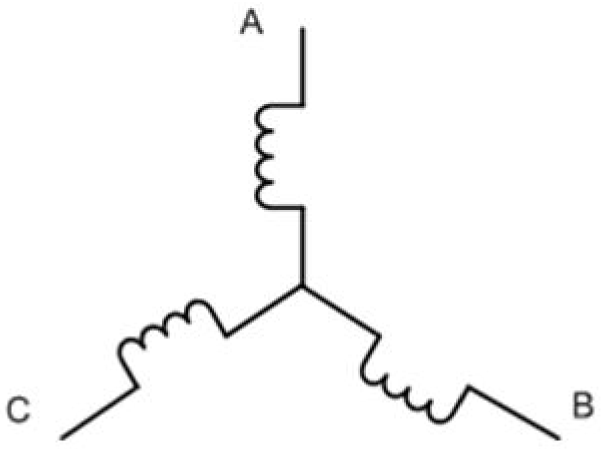


Figure 5. Stator winding connection of a three-phase BLDC motor

The stator windings can generate the magnetic field when powered, which will attract or repel the permanent magnet (rotor), as a result of which the rotor spins. See the following figure.

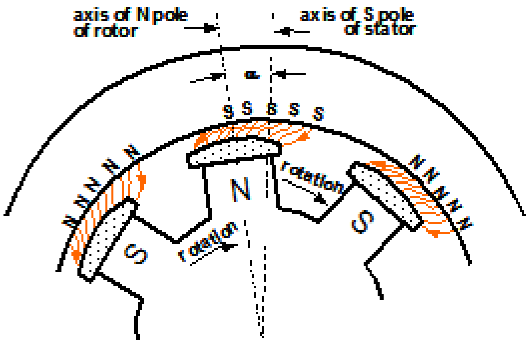


Figure 6. Internal magnetic force

The following figure shows how to generate the magnetic field in the stator. Here, the positive current is defined as the current flowing into a specific phase, or coming out of a specific phase.

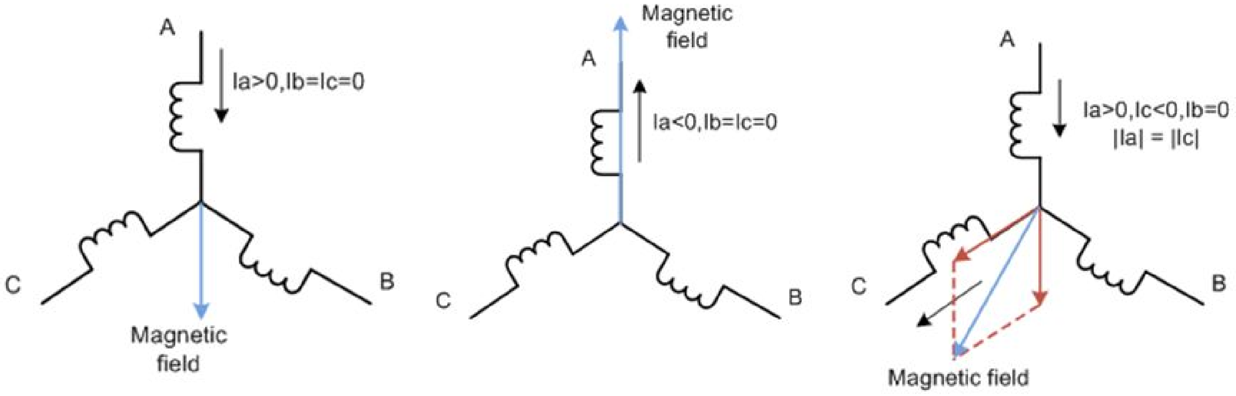


Figure 7. Magnetic field generation

Similar to the DC motor, if the MCU and control circuit in a BLDC motor do not change the direction of the magnetic field generated by the stator windings in time, the rotor won't spin. In BLDC motor, a rotating magnetic field should be generated by the windings. Therefore, there must be a way to conform the position of commutation and change the direction.

For this purpose, the Hall sensor method is discussed in this application note.

3 Basic theory of six-step commutation method

If the rotor wants to spin stable clockwise or counterclockwise, an associated rotating magnetic field must be generated from the stator windings, which will attract or repel the permanent magnetic (rotor).

3.1 Rotating magnetic field

As shown in Figure 7, each phase of the stator coil can generate the magnetic field in two directions and so, the current and the rotating magnetic fields in the three-phase coils can be easily controlled. Six patterns of magnetic fields (see the following figure) generated are the basis of six-step commutation, which is explained in the following section.

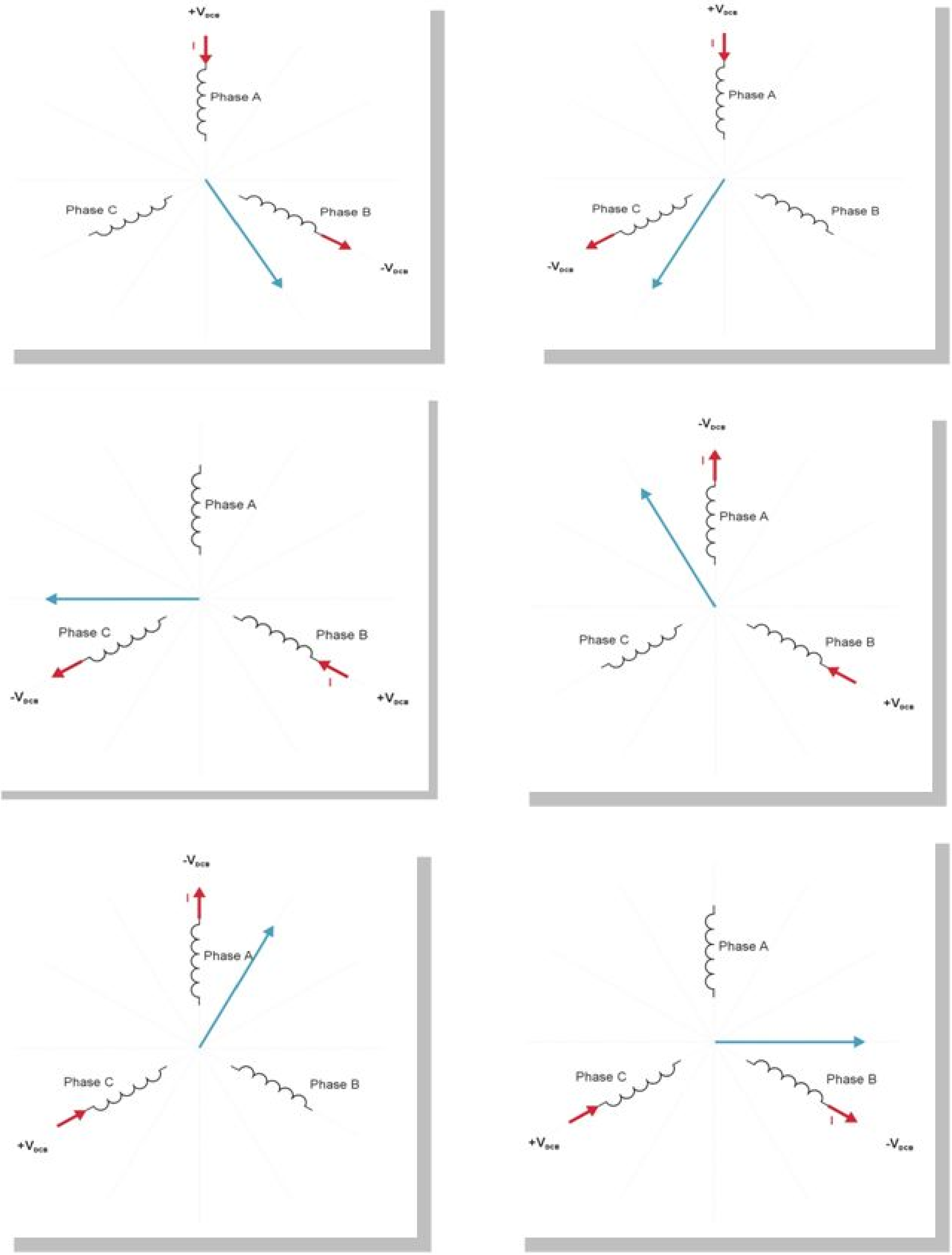


Figure 8. Rotating magnetic field

3.2 Six-step commutation

The Hall effect sensor is a sensing switch that outputs a logic level based on the magnetic field detected. The Hall effect sensors (Ha, Hb, and Hc) are inserted into the stator.

For example, when the Ha sensor is under the N pole of the permanent magnet, it will output signal 1, otherwise 0. See the following figure.

Combining the outputs of all the three sensors will theoretically give 8 status from 000 to 111. However, in most cases, because of the hardware constraint, signal 000 and 111 don't exist. So, the other 6 status can divide the one electrical 360° of position into six areas, and the exact point where the status changes from one to another is the position that the commutator changes the direction of the stator's magnetic field.

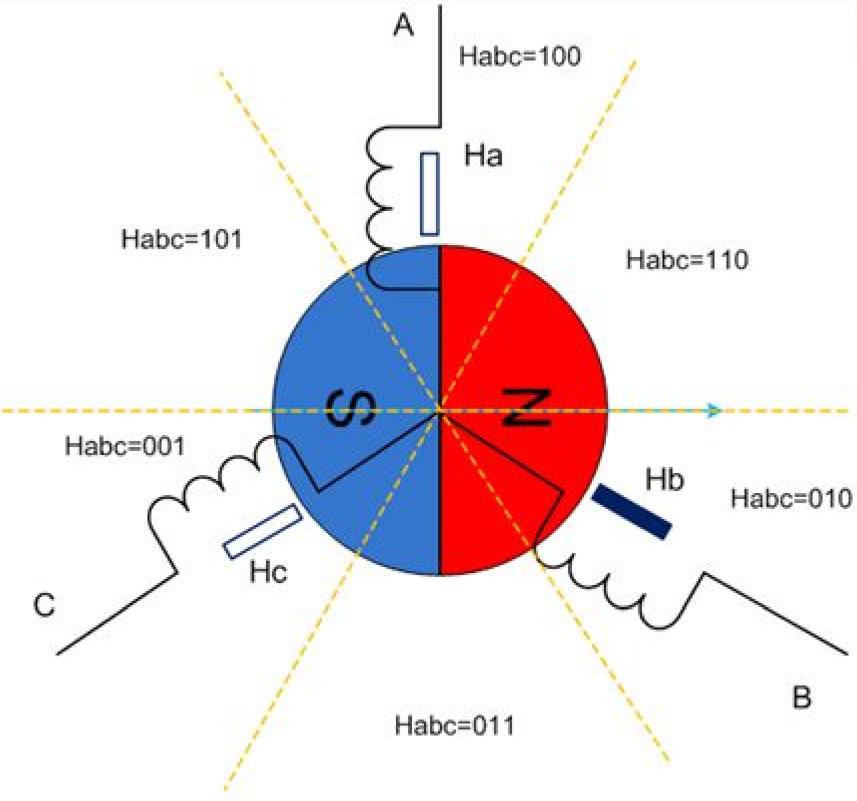


Figure 9. Hall sensor output

Figure 10 depicts an example of commutation where the Hall sensor status is shown to be 010. Now, for the rotor to spin clockwise, the clockwise rotating magnetic field must be generated in its nearest area, that is, where the Hall sensor status is 011. This direction of magnetic field can be generated by turning on the coil AC, which means that the current flows into A, and runs out of C. When the rotor runs to the area of 011, the Hall sensor status changes to 011 and at the same time, the commutator changes from AC to BC, to keep the rotor running after the rotating magnet.

Thus, the power sequence is AC -> BC -> BA -> CA -> CB -> AB -> AC.

Here is the summary of the commutation process.

- In one complete rotation of 360 electrical degrees, the excitation of the stator windings will be changed six times, and each change is called a commutation.
- The angle between S-N pole (rotor) and magnet field (stator windings) is 60-120°, commutation happens at 60°.
- The commutation position is when the status of the Hall sensor changes.
- At every moment, only two phases have current, while the third one is powered off.

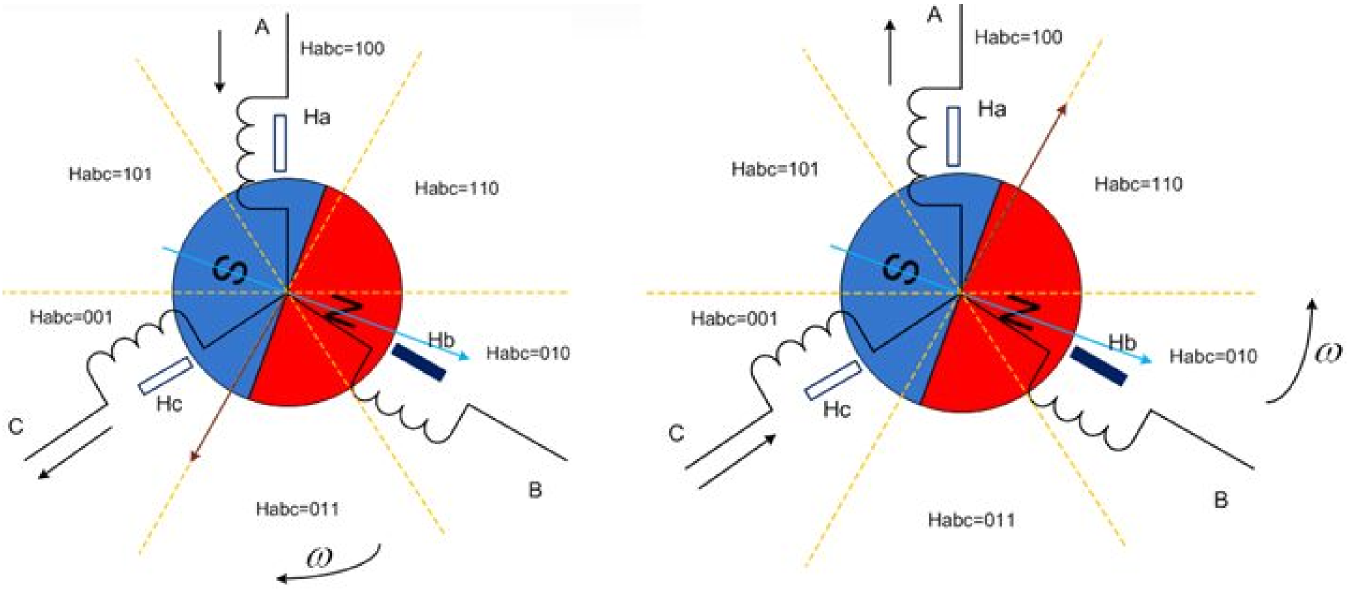


Figure 10. Commutation

3.3 Commutation table

As discussed in Six-step commutation, the six commutation positions are fixed in a 360 electrical degrees. So, a special table can be built to describe the relationship between the sensor status and stator winding excitation, which is called commutation table. With this commutation table, the MCU can easily control the commutation.

Table 1. Commutation table

Hall sensors			Phase		
a	b	c	A	B	C
0	1	1	NC	+	–
0	0	1	–	+	NC
1	0	1	–	NC	+
1	0	0	NC	–	+
1	1	0	+	–	NC
0	1	0	+	NC	–

Following is the terminology used in the commutation table.

- Hall sensors header column provides the Hall sensor status captured from the motor.
- Phase header column determines how the stator windings are excited.
- ‘+’ means the current flows into that terminal.
- ‘-’ means the current flows out of that terminal.
- ‘NC’ means no voltage is applied on that terminal.

Applying this table to Figure 10, it is easy to control the motor spin clockwise and counterclockwise.

- If the Hall sensor status is changed to 100, check Table 1 and then let phase CB turn on; the rotation is clockwise.
- Reversing this, if the Hall sensor status is 011, check Table 1 and then let phase BC turn on; the rotation is counterclockwise.

4 How to control BLDC motor with FRDM-KE02Z

It is almost impossible to control BLDC motor directly with KE02Z MCU since driving motor needs high voltage and large current. Actually, the MCU mainly offers the control signal and detects the Hall sensor information. So, the motor drive board APMOTOR56F800e is used.

4.1 Basic motor control topology

The following figure shows a basic three-phase motor control topology where a three-phase inverter is used to control the voltage applied on motor phases. The PWM control signal comes from the MCU, and in this motor drive board, voltage level ‘1’ turns on the transistor, ‘0’ turns off the transistor. As indicated in this figure, PWM0A and PWM0B are combined and complementary, PWM1B is on, and the others are off, which means that phase AB is excited.

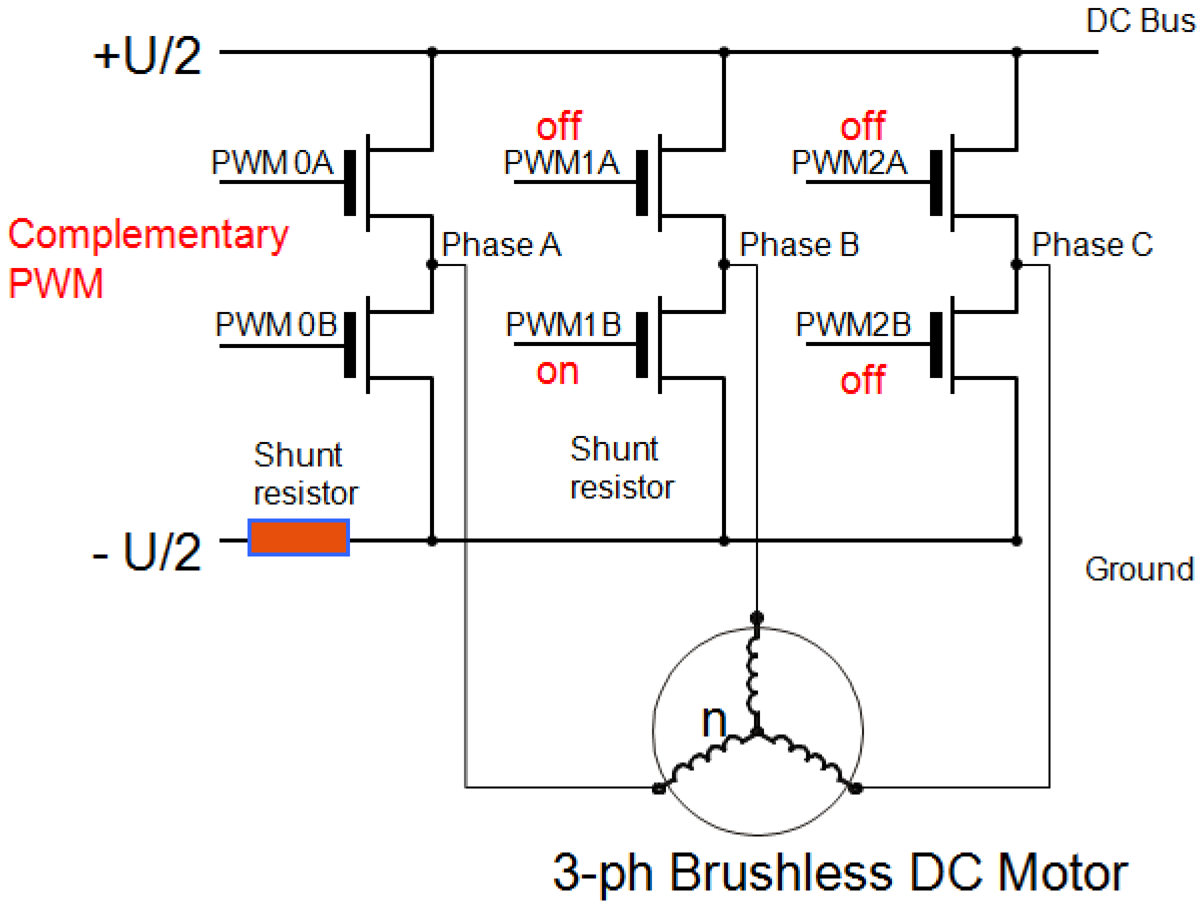


Figure 11. Motor control topology

It is easy to implement the six-step way commutation on this topology. The waveforms for PWM signals together with Hall sensor values during one 360 electrical degrees when driving BLDC are shown in the following figure. Besides, the duty cycle of the PWM changes the speed of the rotor. In this figure, the Hall sensor status is 011->001->101->100->110->010, and the excitation of the stator windings is like CB->AB->AC->BC- >BA->CA.

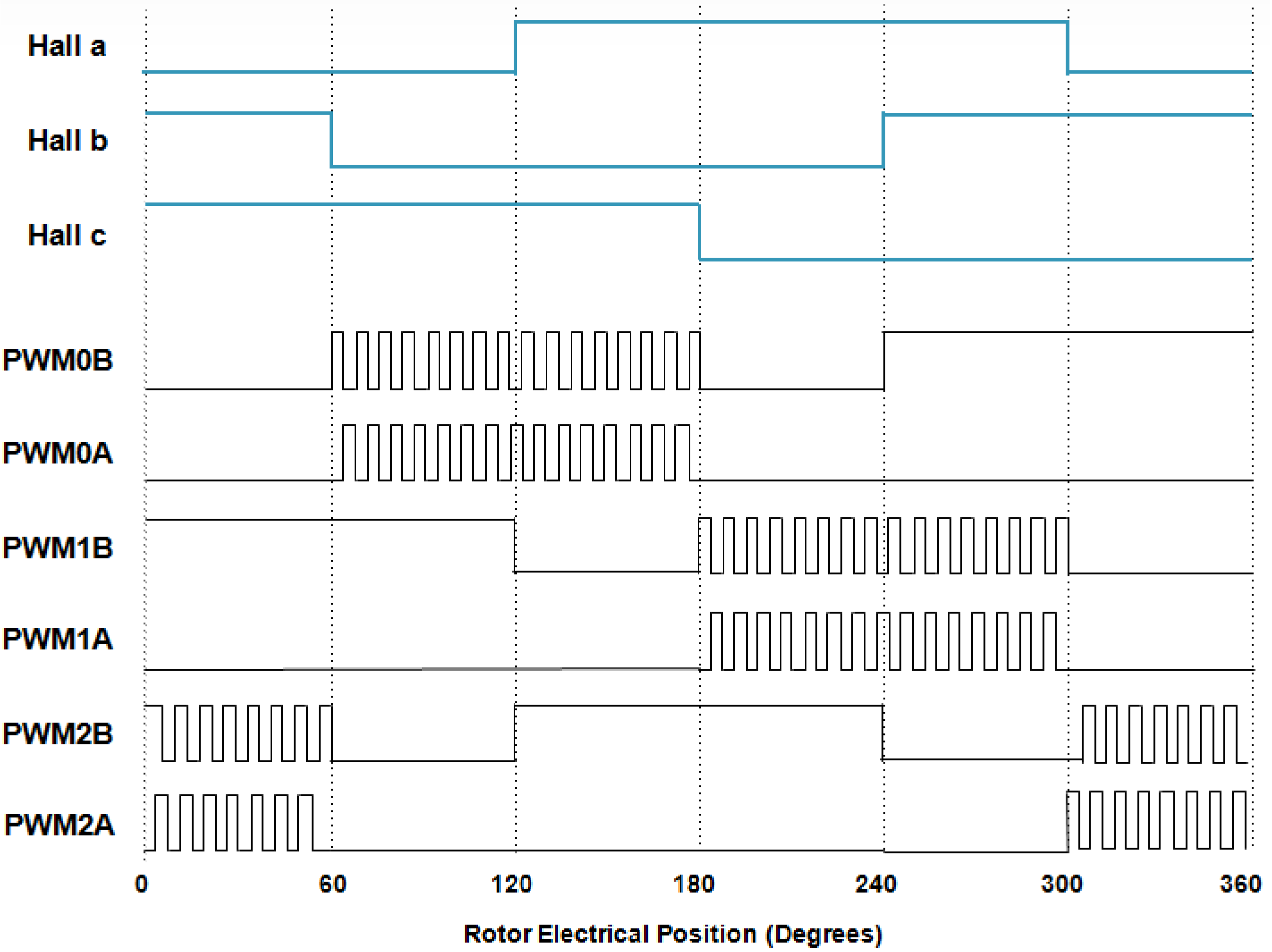


Figure 12. Six-step control and PWM wave

4.2 PWM control on KE02

The PWM control signals are generated by the FlexTimer module in KE02.

The FlexTimer module (FTM) is a 16-bit timer that supports input capture, output compare, and the generation of PWM signals to control electric motor and power management applications. Besides, the features such as hardware deadtime insertion, polarity, fault control, and output forcing and masking, greatly reduce loading on the execution software and each of these are usually controlled by a group of registers.

This application note uses the following features of the FTM module in KE02 MCU.

- The input capture feature is used to get the Hall sensor signal.
- PWM with deadtime insertion is used to control the speed of the rotor.
- Software output control and output mask feature is used for commutation.

For example, consider that the system needs a PWM with 70% duty cycle, the current runs into phase B and comes out from phase C (see the following figure). The FTM module can be configured as follows.

- PWM2 and PWM3 output complementary with deadtime insertion;
- Mask PWM0 and PWM1
- Software control PWM4 and PWM5

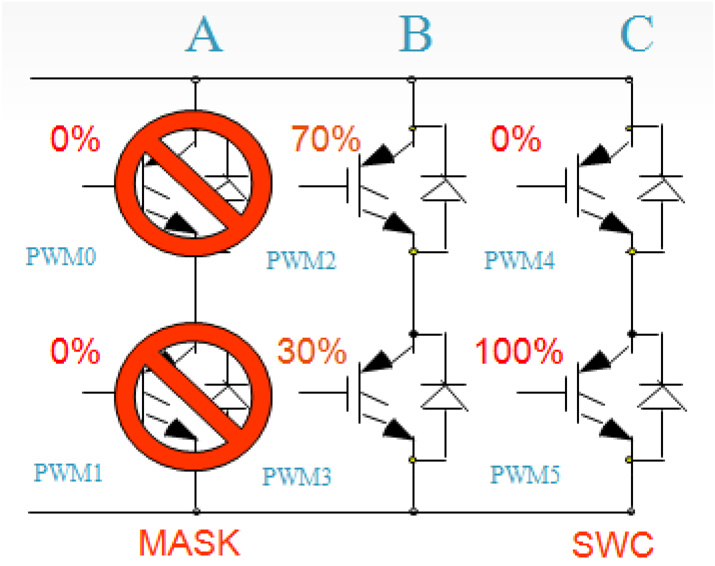


Figure 13. Commutation control using MASK and SWC feature

4.3 Closed loop control

The PWM control and six-step way commutation can drive the rotor spin in a BLDC motor. However, still certain issues need to be resolved like determining the PWM duty cycle, getting the desired speed, adjusting the speed smoothly, and protecting the system from overvoltage or overcurrent.

To solve the problems, the system needs to build a close loop in the software. See the following figure. The core is the speed PI controller, the input is the required speed and the actual speed, the output is the duty of PWM. However, in this application note, only proportion control is designed.

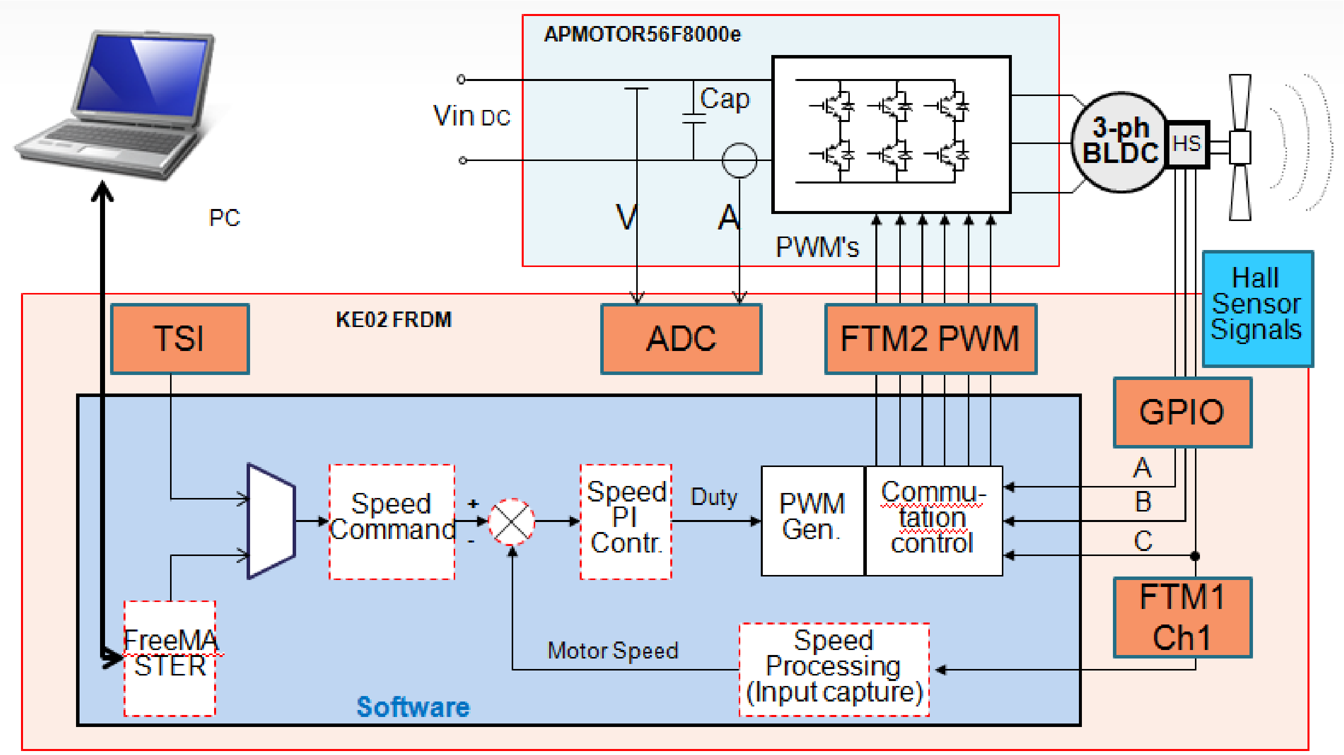


Figure 14. BLDC closed loop control diagram

The main function of primary components of the closed loop system is given as follows.

- FTM2 generates the PWM with deadtime insertion.
- FTM1 captures the Hall senor signals and calculates the actual speed.
- ADC samples the current and voltage of the BUS to protect the system.
- TSI (GPIO method) and FreeMASTER enter the required speed.

4.4 Others

4.4.1 NMI pin

On the board APMOTOR568000e, PWM4 connects to the PTB4 pin of FRDM-KE02Z board (this pin is also used as NMI pin). But, by default, PWM4 is pulled down to GND, which can cause NMI interrupt at the very beginning. See the following figure. So, the NMI pin must be disabled in the NMI ISR.

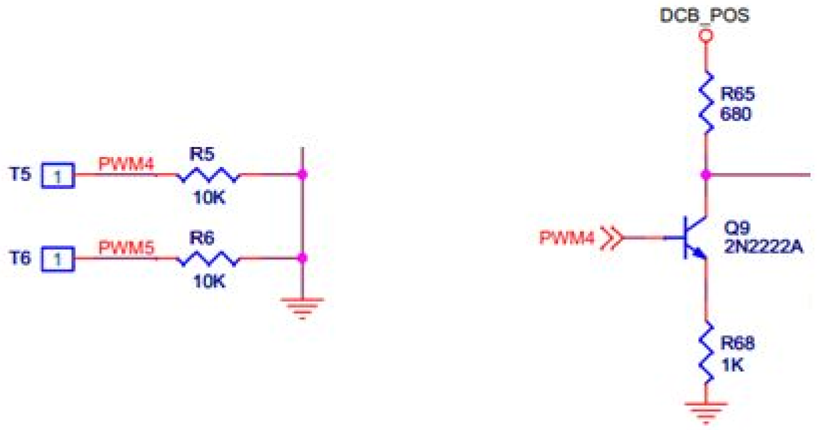


Figure 15. PWM4/NMI pin

4.4.2 R50 and R51

On FRDM-KE02Z board, PTA1 is by default, connected to the infrared port (R51 = 0 Ω, R50 DNP); the values of R50 and R51 must be interchanged (R50 = 0 Ω, R51 DNP) because PTA1 pin should be connected to one Hall Sensor on the motor board. See this figure.

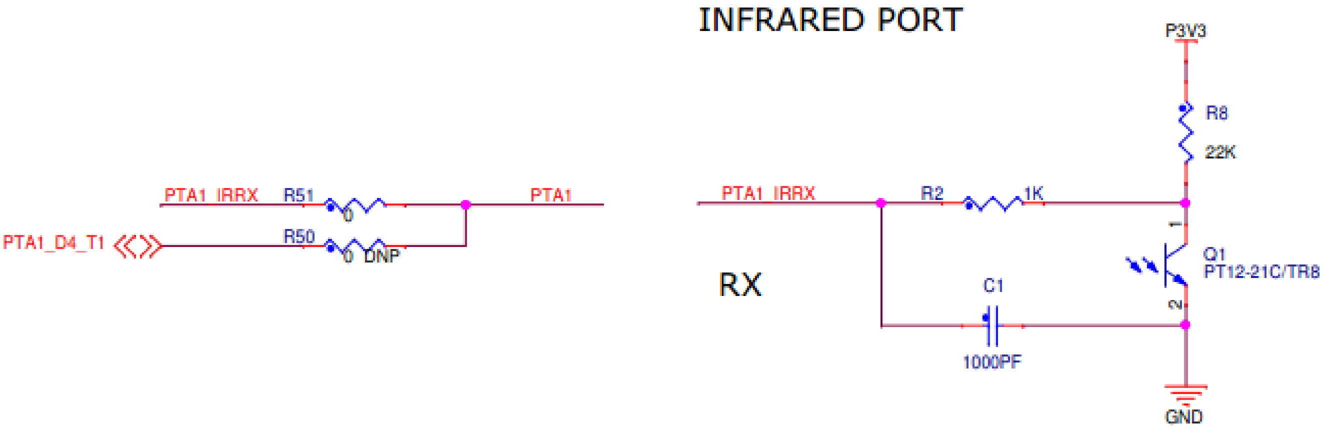


Figure 16. R50 and R51

5 Conclusion

This application note introduced the basic theory of BLDC motor control and the six-step way commutation. The document also discussed the PWM control through FRDM-KE02Z board. Through this application note and the attached demo code (AN4776SW.zip), the users can get a clear idea about the BLDC motor control method.

6 References

For further reference, the following documents are available at **freescale.com**.

1. AN4413: BLDC Motor Control with Hall Sensors Driven by DSC 8257 (AN4413)

2. AN4376: BLDC Motor Control with Hall Effect Sensors Using MQX on Kinetis (AN4376)
3. KE02Z64M20SF0RM: KE02 Sub-Family Reference Manual

7 Revision history

Revision number	Date	Substantial changes
0	07/2013	Initial release

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