Microcontroller for Variable Speed BLDC Fan Control System

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Introduction

Portable, feature rich, high-performance and compact in size are typical trends of most electronic products. The amount of heat generated by such electronic products, such as notebook computers, is a growing problem. Use of cooling fan remains the most common and efficient way of preventing electronics equipment from overheating.

Microcontroller (MCU) based, intelligent, variable-speed control, brushless DC (BLDC) fans are needed in order to fulfill the rapidly changing electronics products specification. Variable speed control, low acoustic noise, reliability, long lifetime, low power consumption, protection features, easy to maintain/upgrade and communication interface capability are the characteristics of flash MCU based BLDC.

This article describes variable speed control algorithms of BLDC fan, which include methods for acoustic noise reduction, power consumption consideration, lock detection and automatic restart, thermal shunt down and communication interface.

Different between DC Fan and BLDC fan

The physical appearance of conventional and BLDC fans are basically the same. Both of these fans operate on the same principle to convert the electrical energy to the mechanical motion. The fan is rotated when a dc voltage is applied to its terminals. The speed of the fan depends on the applied voltage across the terminals.

The significant difference between the conventional and BLDC fans is in their internal construction. Both fan systems require the commutation that allows the direction of current flowing through the fan windings to reverse every 180^o of rotation.

In the conventional DC fan system, the stator of the permanent magnet is composed of two or more permanent magnet pole pieces and the rotor is composed of windings that are connected to a mechanical brush (commutator). The opposite polarities of the energized winding and the stator magnet attract the rotor and the rotor will rotate until it is aligned with the stator. Just as the rotor reaches alignment, the brushes move across the commutator contacts and energize the next winding. As a result the fan rotor is rotated continuously.

The BLDC fan however is a rotating electric machine in which the stator is a classic two-phase stator and the rotor has surface-mounted permanent magnets. In this respect, the BLDC fan is equivalent to a reverse-conventional DC fan; the current polarity is altered by the electrical commutator instead of mechanical brushes.

Due to the polarity reversal performed by transistors / FETs switching in synchronization with the rotor position, a Hall Effect sensor is used to sense the actual rotor position. A typical construction of the BLDC fan is shown in figure 1.

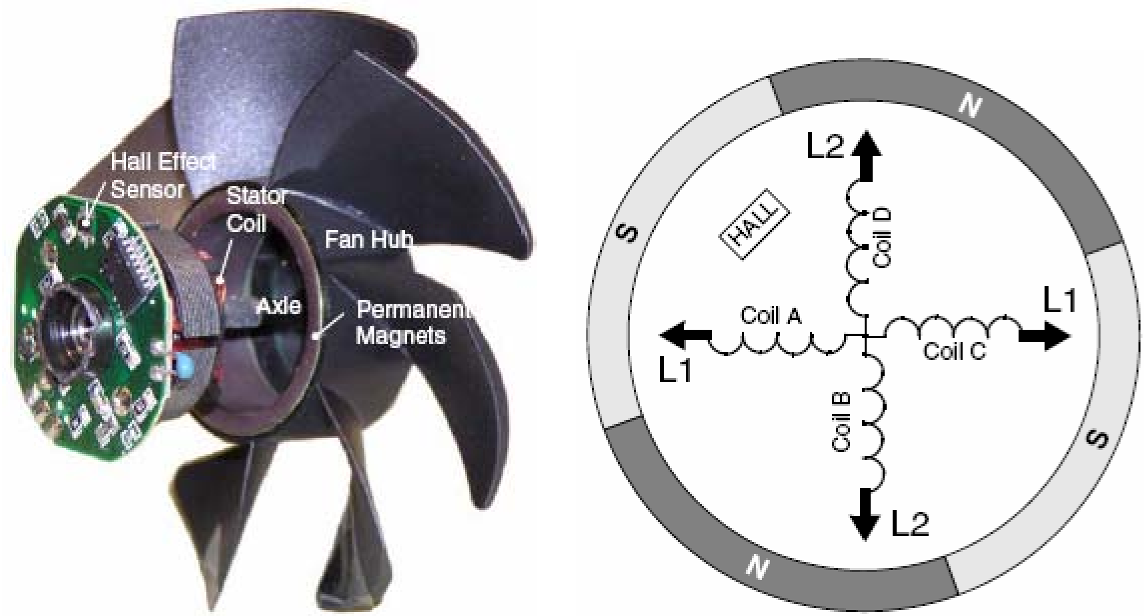

Figure 1. Construction of a BLDC Fan

Need for an Intelligent BLDC fan

The conventional DC fan has a higher inertia due to the bulky rotor coils, while the BLDC fan has a lighter rotor due to its permanent magnets. The BLDC fan has a higher efficiency as more energy can be transferred to the load because of the lighter rotor. The BLDC fan uses the electrical commutation and does not have some of the problems experienced by the conventional DC fan, such as mechanical wear of commutator brushes, sparking and electromagnetic interference (EMI) induced by its rotation.

An intelligent variable speed control BLDC fan system is becoming widely used because it is can be easily reconfigured to meet the fast changing requirements of modern electronic products, and includes enhanced features such as lock detection, automatic restart, and automatic thermal shunt down.

Speed Control in BLDC Fan

There are Fixed and Variable speed control BLDC fan.

1. **Fixed Speed Control in BLDC fan**

Hall-effect sensor with External or Built-in Driver is used in fixed speed control fan;

a) Three-pin Hall sensor with external driver

In this method, the single output latching Hall-effect sensor with external transistors / FETs is used. The sensor is commonly used in the BLDC fan because it senses both positive and negative magnetic fields of the BLDC fan for electrical commutation. The sensor includes an on-chip Hall voltage generator for magnetic sensing, a comparator that amplifies the Hall voltage and a Schmitt trigger to provide switching hysteresis for noise rejection, and open-collector output. A typically configuration is shown in figure 2.

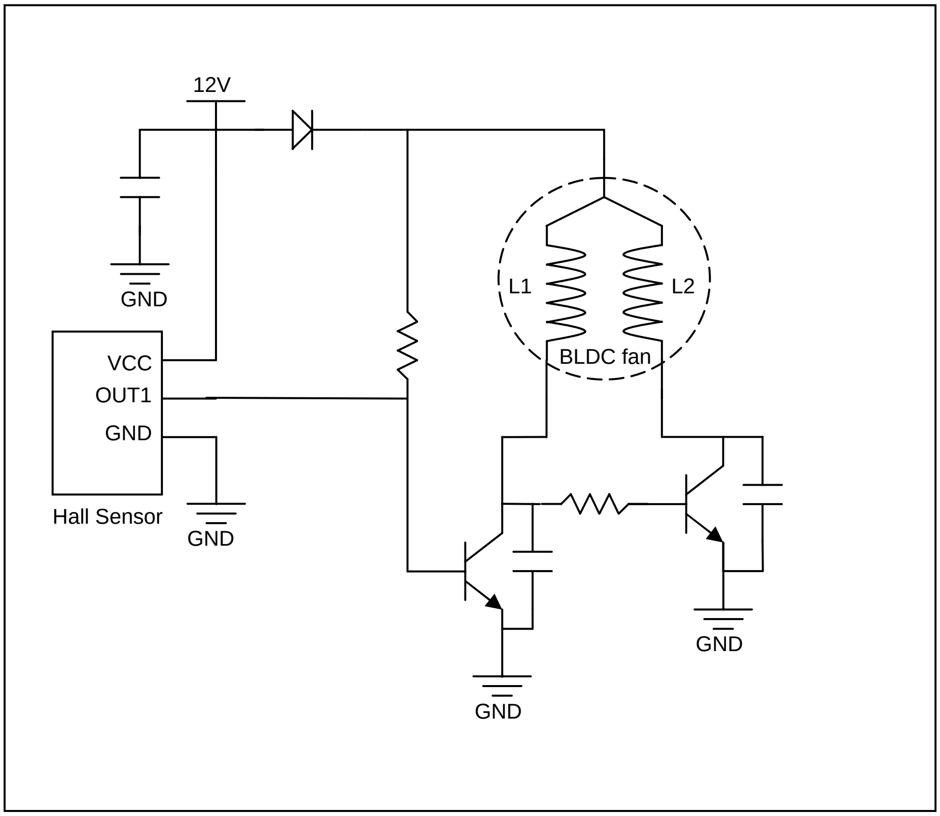

Figure 2. Three-pin Hall sensor with external driver

The sensor detects the polarity of the magnetic field generated by the permanent magnets on the rotor and provides information about the position of the rotor. This information is using to trigger the external transistors / FETs ON / OFF. As the transistors are operated the BLDC fan will rotate continuously and the speed depends on the supplied voltage.

b) Hall sensor with built-in drivers

This type of the implementation is the enhancement version of the three-pin Hall sensor with external drive. The Hall sensor not only includes on-chip Hall amplify circuitry as three-pin Hall sensor, but also two complementary outputs for two-phase BLDC fan's coil driving and some additional features such as auto lock shutdown and auto restart. The typical configuration is shown in figure 3.

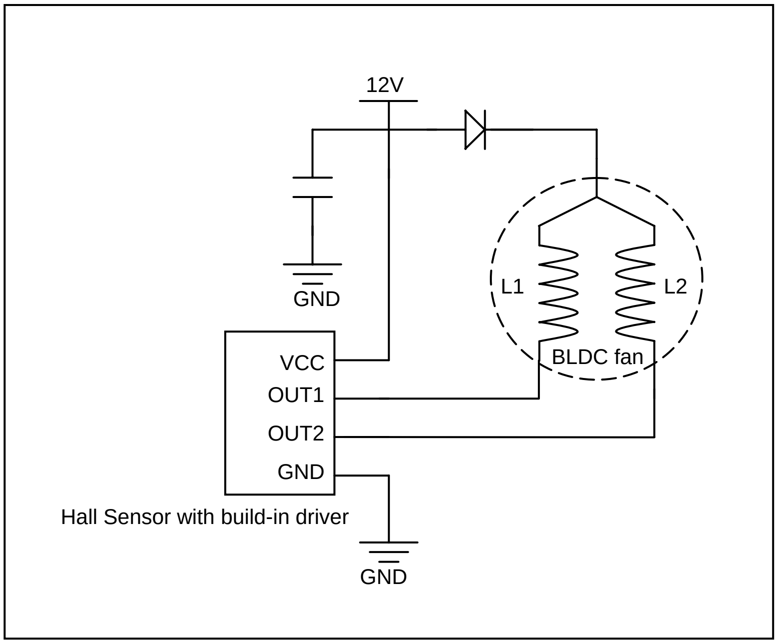

Figure 3. Hall sensor with build-in driver

Many BLDC fan manufacturer use this type of implementation. The advantage of this implementation is more PCB board space is available for additional external components and the fan will be more reliable due to built-in basic protection features included on chip. The disadvantage of this type of implementation is its drive capability. Due to the limited package spacing, the output drive capability will be limited to use of the smaller or lower rating BLDC fans. Typically the maximum output current should be limited to 20mA.

2. Variable Speed Control in BLDC fan

There are External and Internal approaches for variable speed control in BLDC fan;

The external approach is connecting one external transistor / FET in series of the BLDC fan (high side / low side) to control the supply voltage across the fan by (c) linear regulator, (d) DC-DC regulator or (e) pulse-width modulation (PWM) driving method. The speed of the BLDC fan is direct proportion to the supply voltage.

The internal approach is using the build-in internal transistors / FETs inside the BLDC fan. Change the speed by (f) ASIC solution or (g) MCU solution

The following shows some of the typical implementation in variable speed control BLDC fan solutions:

c) Linear Regulation driving method in external approach

The speed of the DC or BLDC fan can be changed by the applied voltage across the fan. The DC voltage across the fan is adjusted by using a traditional linear regulator. Figure 4a and 4b shows the low-side and high-side configurations. The major problem in this method is the heat dissipation of the passive component and the narrower controllable speed range.

When the fan is operating in the zero or full speed, the passive component is either fully off in zero speed or fully on in full speed. So under this condition, all the power is transferred to the BLDC fan. And it implies no power dissipation in the passive component. But when the BLDC fan is not in zero or full speed, part of the power will be dissipated in the passive component. So the efficiency in this method is questionable.

Since there is no speed monitoring, there is no way to know the condition of the fan. To ensure the fan can be started, it needs to choose the startup voltage around 60% of the maximum voltage. So the controllable speed range is around remaining potion 40% (i.e. 60% - 100% of the maximum speed).

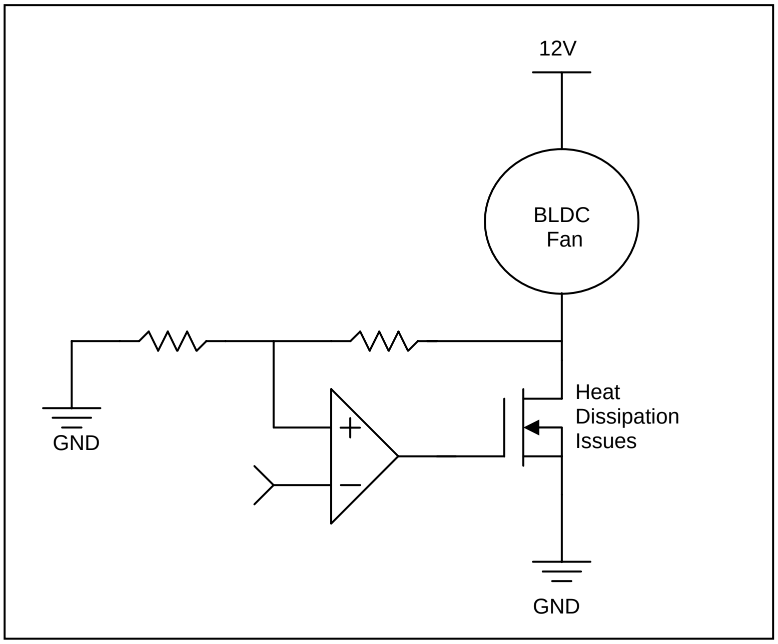

Figure 4a. Linear Regulation, low side

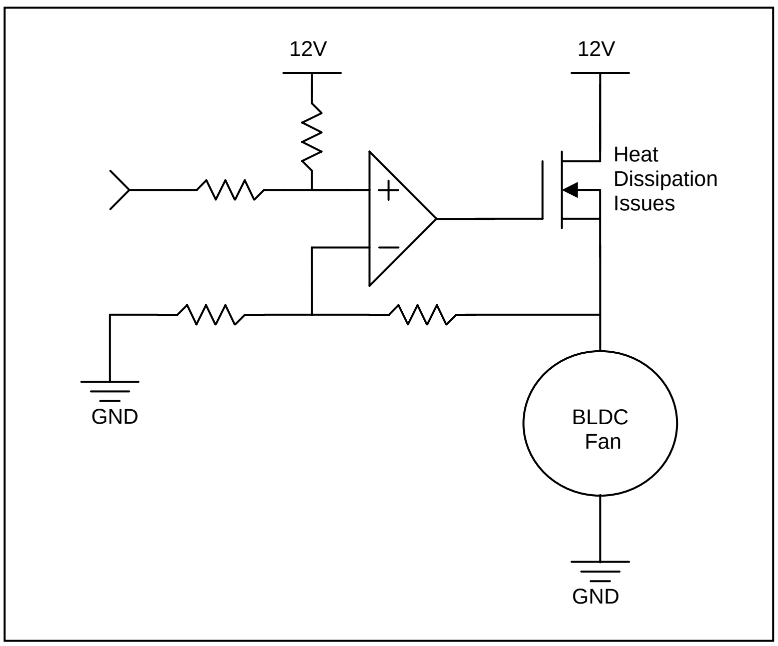

Figure 4b. Linear Regulation, high side

Some improvement can be obtained by adding a tachometer with external microcontroller to monitor the fan condition. In this case, efficiency and lower startup voltage will be achieved, but the system cost will also increase significantly.

d) DC-DC Regulation driving method in external approach

Due to the drawback in the linear regulation method, some designers use DC-DC regulation instead. The main idea of this drive method is to use the switching mode power supply to change the supply voltage of the fan. In this method the head dissipation effect is eliminated but the efficiency is also needed to be considered. Since it is impossible to reach 100% efficiency in DC-DC switching power supply, the overall efficiency of the fan will be reduced to around 5 – 25% loss in DC-DC switching mode regulation. But compare with the linear regulation, the overall efficiency is higher and it depends on the regulated voltage. Comparing to linear regulation method lower the regulated supply voltage will lower the power loss. The disadvantage in this method is the higher system cost, high frequency noise and circuit complexity. The typical configurations are as shown in figure 5a and 5b.

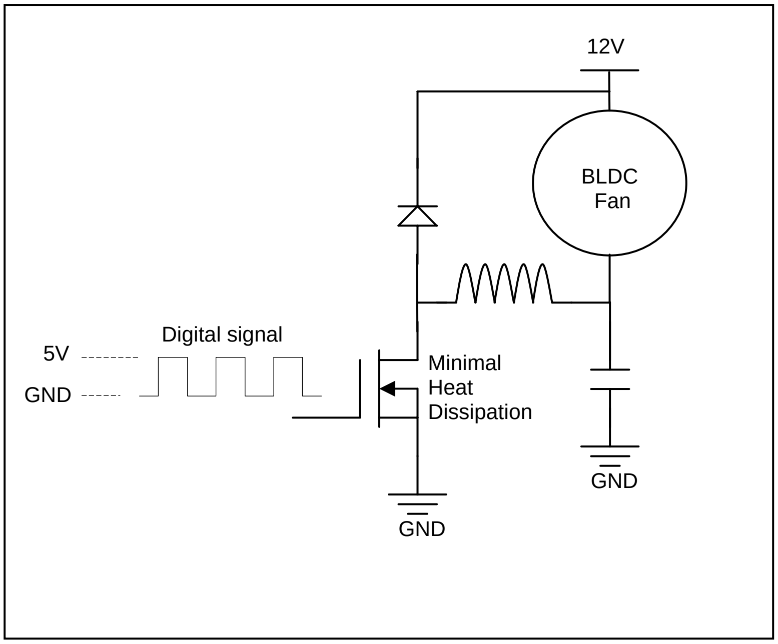

Figure 5a. DC-DC Regulation, low side

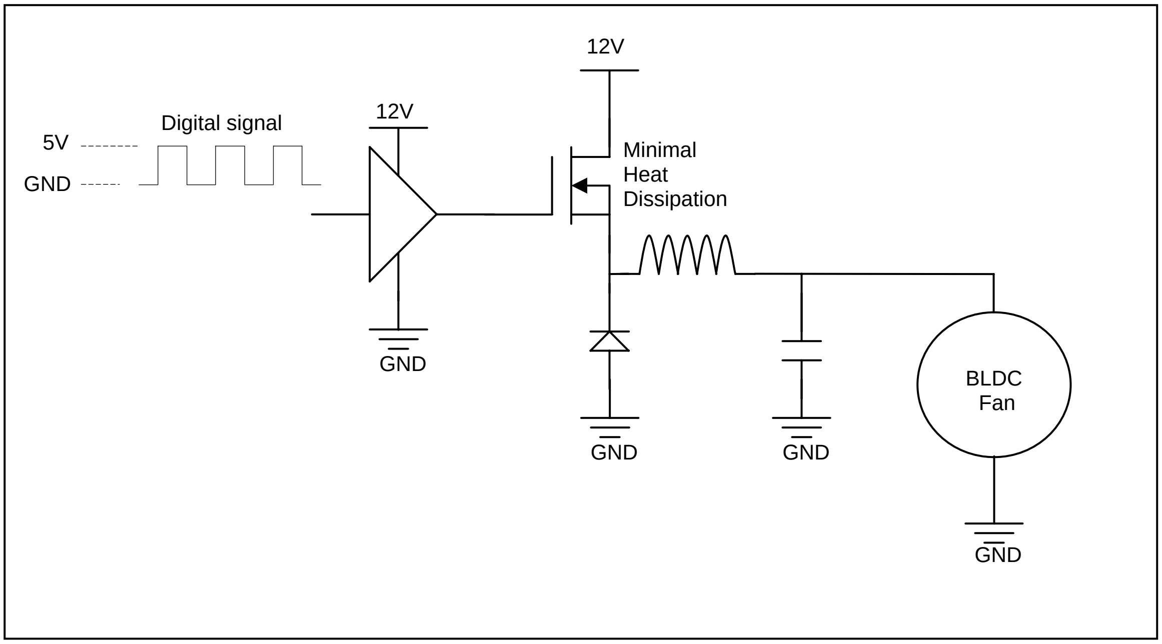

Figure 5b. DC-DC Regulation, high side

e) PWM drive method in external approach

The PWM driving methods was introduced to overcome the efficiency problem in the linear and DC-DC regulations. The speed of the BLDC fan is controlled by the duty cycle of fixed PWM signal that applied to the external switching device (transistor / FET). The speed of the fan is direct proportional with duty cycle of the PWM. Increase the percentage in duty cycle of the PWM signal will increase the speed of the fan. But one important consideration in this method is the choice of PWM frequency. Higher PWM frequency will cause the malfunction of the internal commutation circuit inside the fan. Lower PWM frequency will cause the fan oscillate. So the popular value of PWM frequency is the major consideration in this method. Typically the PWM frequency is around 30 - 150Hz to avoid the mentioned problems. Due to the PWM frequency is falling into the audible range of human ear, the acoustic noise will be occurred when the fan is running. As a result, some additional component needs to add to eliminate this effect. The typical configurations are shown in figure 6a and 6b.

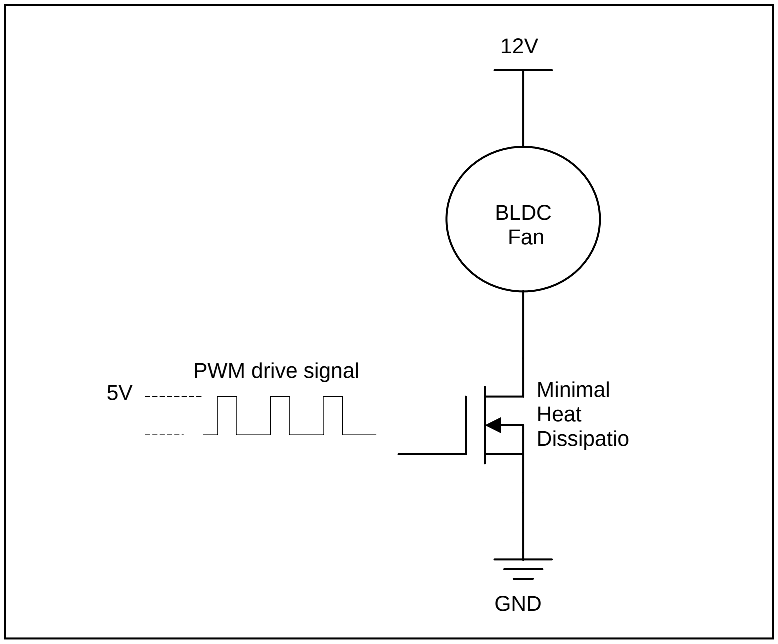

Figure 6a. PWM Drive, low side

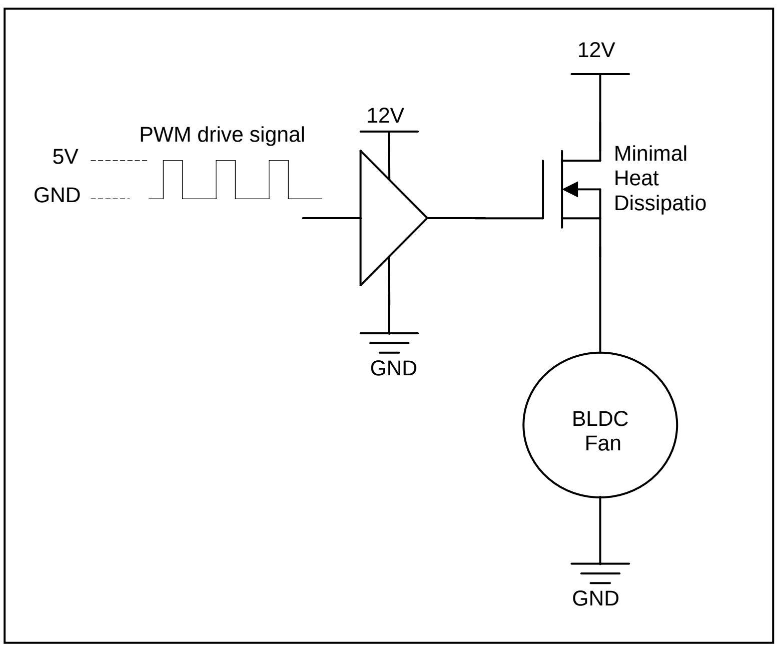

Figure 6b. PWM Drive, high side

The advantage of this method is no heat dissipation and low efficient problem as in the linear regulation and also no cost and complexity issues as in the DC-DC regulation. But when considering the system cost and the fan's performance, most of the external approach cannot be improved easier. Therefore some manufacturer starts to use the internal approach to reduce the system cost and improving the performance and even adding some advanced protection and features inside the BLDC fan for customer needs.

f) ASIC Solution

In ASIC solution, all features, speed control method and hardware configuration pin had been defined and fixed. The advantage of this method is easier to implement but the disadvantage is lack of flexibility. The ASIC semiconductor manufacturer to design the ASIC controller to fit for some particular fan control application with some pre-defined speed control algorithm and some feature for protection and other purposes.

When ASIC solution was introduced, most of the ASIC controller is to control the energizing off time to adjust the speed of BLDC fan. Typical configuration of this type of fan speed control solution is shown in figure 7a.

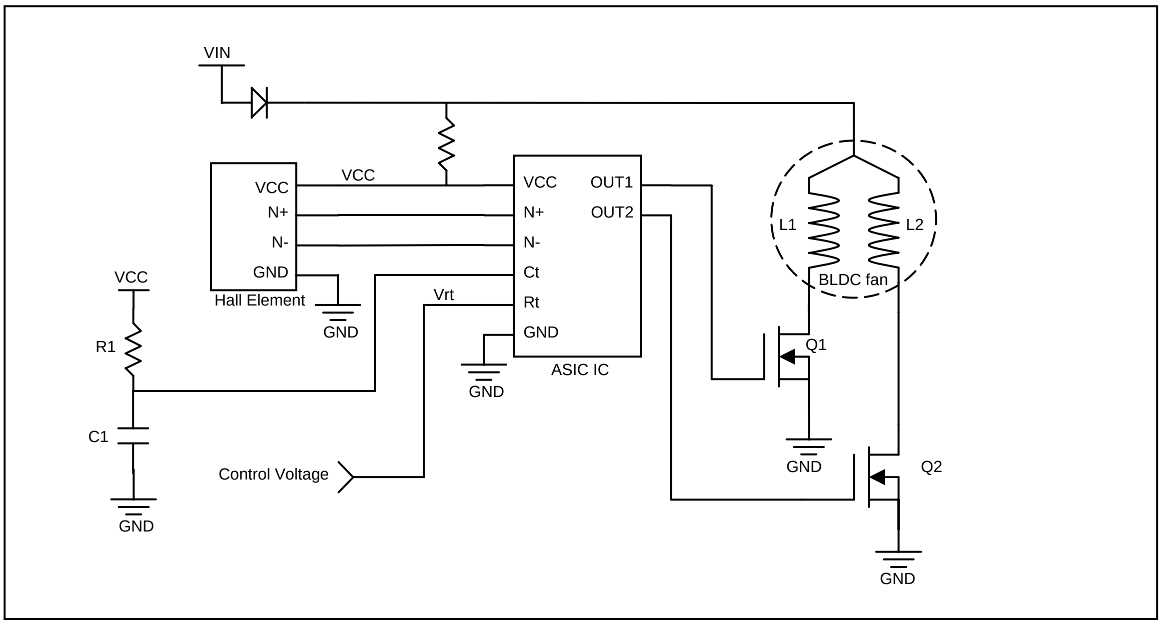

Figure 7a. Energizing off time speed control in ASIC IC

In this configuration, the rotation speed is determined by setting the charging time of Ct voltage according to the time constant of R1 and C1. Compare it with the external voltage command Vrt to determine the energizing off time of the fan windings. There is linear relationship between the voltage command Vrt and the actual speed of the BLDC fan. Higher the Vrt will higher speed of the fan. The advantage in this type of variable speed control method is easier to implement, and low cost but the disadvantage is the relative higher tolerance in rotation speed. Typically the accuracy of the rotation speed is around +/- 10%. In addition, most of the ASIC controller has build-in Hall sensor circuitry that can be acceptable by both Hall element and Hall sensor.

Nowadays, some manufacturer starts to develop more advance ASIC controller for BLDC fan. This type of the ASIC controller uses the closed-loop speed control with high speed PWM technique to improve the efficiency and reliability. More and more additional features will also be added into those chips which including some basic protection, interfacing communication, different input command interface for speed control and even the automatic on-chip thermal shunt features. A typical configuration of this type of fan speed control solution is shown in figure 7b.

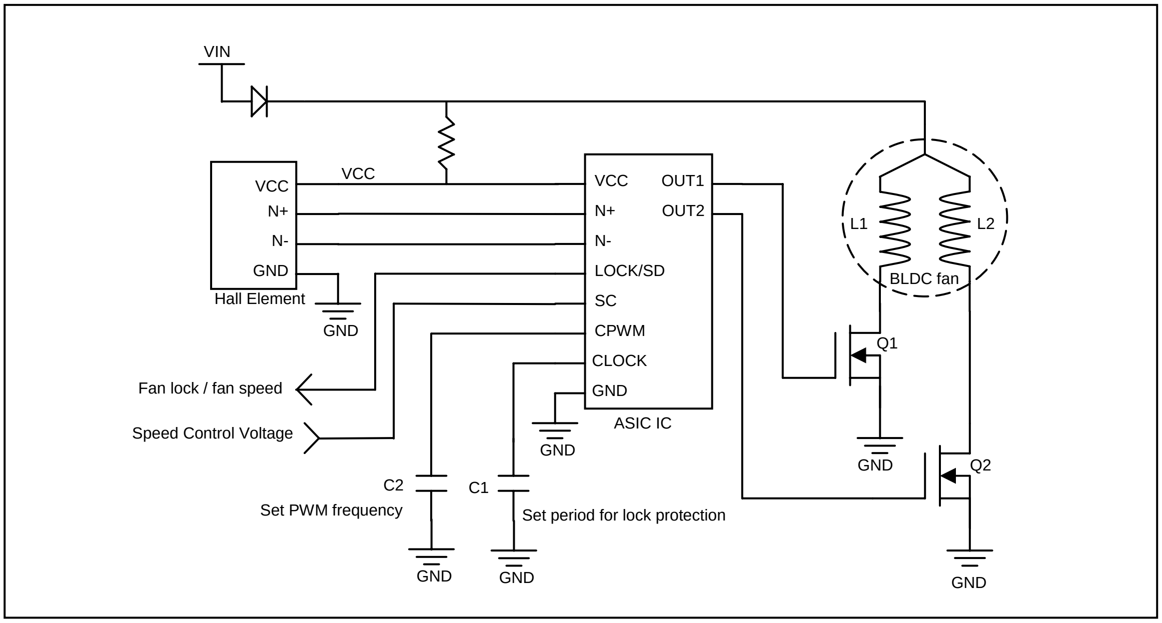

Figure 7b. PWM speed control in ASIC IC

In figure 7b, the rotor position of the BLDC fan is detected by the differential signal from the external Hall element or open collector output signal from Hall sensor. All of the driving output needs to be synchronized with the rotor position. The speed of the BLDC fan will be controlled either by the external voltage from the speed control "SC" pin or by the external PWM signal from the "CPWM" pin.

Using the "SC" pin to control the fan speed, increasing the voltage in "SC" pin will higher fan speed by higher percentage of the duty cycle of the PWM drive to the complementary output pins "OUT1" and "OUT2". When using the "CPWM" pin to control the fan speed, the fan speed is direct proportional with the duty cycle of the PWM input signal. The PWM frequency can be set by the external capacitor connected to this pin. Typical PWM frequency is set to around 25 kHz.

There is also the LOCK/SD pin to indicate the fan status. In normal operation, this pin will output the signal with double frequency of the rotation speed of the fan. If the fan is locked this pin will be in logic high by the internal pull-up resistor. Then the OUT1 and OUT2 will go to the auto-start driving mode to protect the external drive devices and the motor windings. Under this situation, the fan will drive a short period and then waiting for a longer period before trying again. The period is depended on the value of the capacitor that connected to the "CLOCK" pin.

ASIC controller for BLDC comes with different features, some with communication interface (e.g. I2C, ISI or SM bus) and some with on-chip thermal shut down feature.

The advantage of the ASIC solution is easier to implement. All the features are pre-defined. The designer in BLDC fan manufacturer only needed to change the external component to fit for her product requirement. The major disadvantage of the ASIC solution is lack of flexibility.

Since different end customer may need different performance and features of the BLDC fan, the pre-defined ASIC IC may not be satisfied their requirements. The ASIC IC cannot be provided the space for the customer requirement. For example, ASCI controller only provides the linear relationship speed control with the external voltage. If need to change the relationship between the speed and voltage, the ASIC controller cannot do it. Problem such as this can be easily overcome with the use of microcontroller (MCU). With MCU it just only need to change the lookup table, then the relationship between speed control and the external command (voltage) will be change accordingly even the relationship is non-linear. This is why many BLDC fan start to use the MCU instead of the ASIC. Furthermore, MCU can provide the easier way to change any timing related parameter by firmware. In ASIC controller, changing any timing related parameter require changing external component.

g) MCU Solution

Recently, the cost of microcontrollers has decreased, causing many BLDC fan manufacturers to start using microcontrollers in their products.

There are many speed control algorithms that can be adopted in the MCU solution. The typical variable speed control methods are i) phase on/off time delay and ii) PWM control.

Selecting the type of control method depends on the requirements of the BLDC fan. Freescale Semiconductor has developed a series of MCUs that can be fitted for fan control applications. This MCU series includes the M9RS08KA2, M9S08QG8 and M9S08QD4 MCU. All of these 8-bit MCUs have a built-in Internal Clock Source (ICS), which is used as the clock source for the MCU operation. An external clock source can be eliminated by using the ICS module, therefore the system cost of the fan will decrease and there are more pins available in the same package. These MCUs not only have common MCU features, such as Analog-to-Digital Converter (ADC), Analog Comparator (ACMP), Module Timer, External Interrupts and Timer/Pulse-Width Modulator, but also some serial communication interfaces such as Serial Communication Interface (SCI) and Serial Peripheral Interface (SPI) are included. On the other hand, a on-chip temperature sensor that can be used for the ADC calibration and for on-chip thermal shut down protection in fan application is also provided.

The flexibility of the MCU allows many features to be easily implemented with changes of the firmware. Thus, in this paper we limit our discussion to the configuration of two types of closed-loop speed control, their advantages and disadvantages and design / implementation consideration issues.

i. Phase on/off delay time control method in internal approach

The phase on/off delay time method in internal approach is to adjust the off time at phase switching. The rotation speed can be adjusted by the length of the off time. The off time is inversely proportional to the energy provided to the fan. That is, the longer the off time, the less energy is supplied to the stator coils, which results in a lower speed of the fan. But one condition should be satisfied is that it needs to be synchronized to the feedback signal from the Hall sensor (*i.e*. the commutation). The basic principle of this method is similar to the PWM method. Both methods change the ratio of the on/off time to change the energy that is applied to the winding coil. But the accuracy, current ripple, noise level may vary between these two methods.

The configuration of the phase on/off delay time method is shown in figure 8a below. The basic operation is that the MCU will drive the transistors to start the BLDC fan and the Hall sensor will change the logic level according to the BLDC fan position. Based on the signal from the Hall sensor the MCU drives the fan accordingly (commutation). The speed depends on the input signal from the external voltage of the thermal sensor. The MCU will change the off-time period based on the input from thermal sensor.

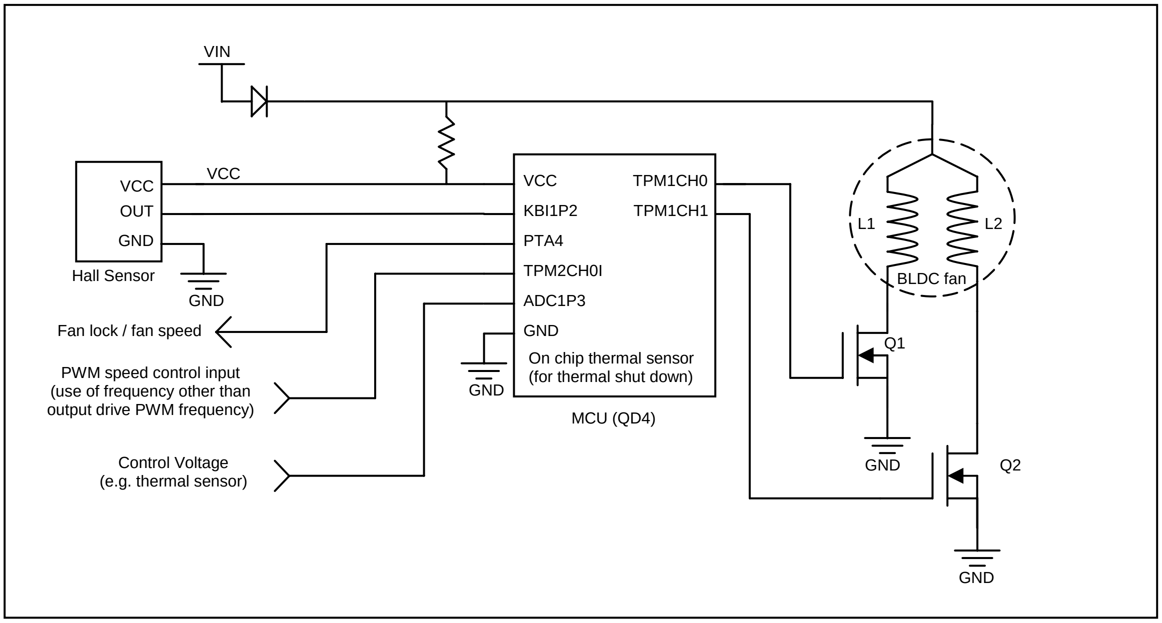

Figure 8a. Phase on/off delay time or PWM speed control in MCU

Figure 8b shows the relationship between the commutation and speed control in the BLDC fan. L1 needs to synchronize with the falling edge of the Hall signal, while L2 needs to synchronize with the rising edge of the Hall signal to ensure correct commutation. The full speed of the BLDC fan, the off-time period equals zero. For lower speeds, the off-time period will increase and the on-time period will decrease.

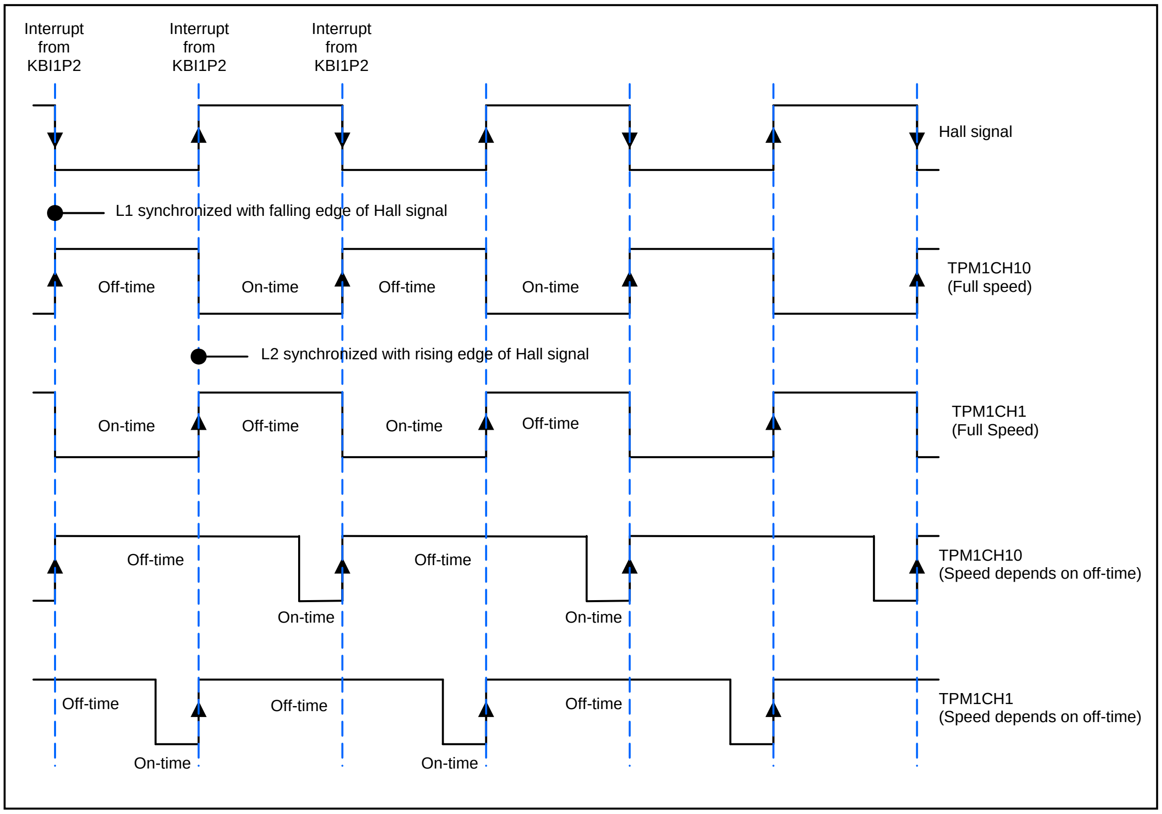

Figure 8b. Timing diagram for on/off delay time speed control in MCU

The speed of the fan is dependent on the temperature of the thermal sensor connected to the ADC pin of the MCU. The speed control algorithm adjusts the off-time period in both Q1 and Q2 transistors / FETs according to the thermal sensor reading. Since BLDC fan and thermal sensor characteristics vary amongst different manufacturers, the thermal speed profile needs to be tailored for different designs. A look-up table for temperature-speed mapping provides an easy way to achieve this. Figure 8c shows the actual temperature and speed relationship. Using MCU, the temperature-speed look-up table can be easily changed to fit for different BLDC fan requirement. This is a major advantage of the MCU solution.

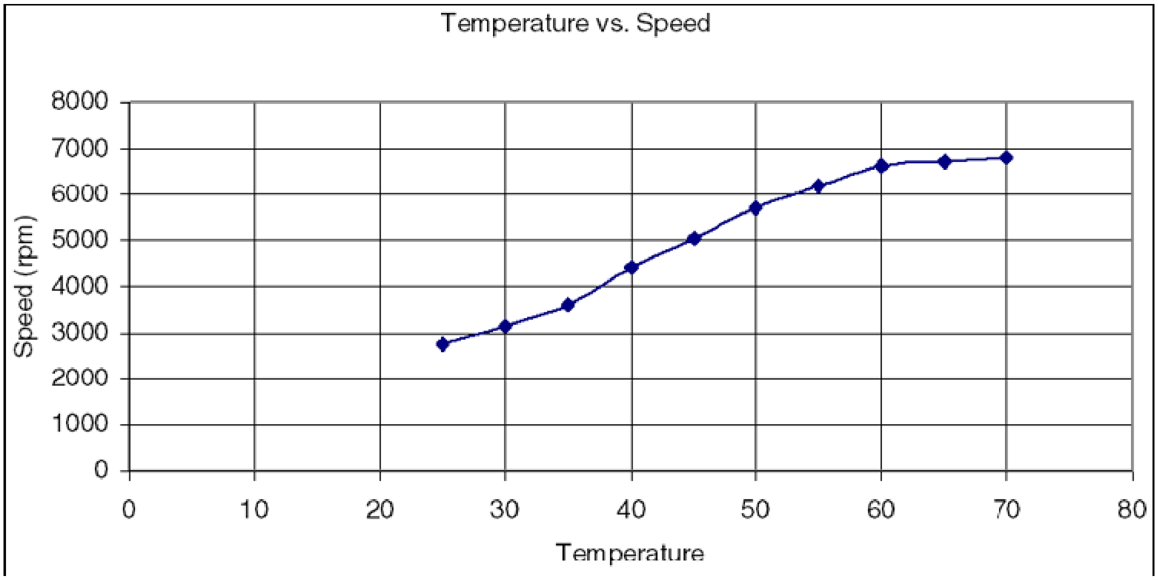

Figure 8c. Temperature-speed profile

Since this speed control method is relatively simple, the requirement of the MCU is also lower. Many low-end MCUs can be use for this application, such as the MC9RS08KA2 MCU. The advantages of this method are that it's easy to implement, easy to change the speed profile, and easy to add additional features.

Another advantage of the MCU solution is that some fan manufacturers design their products for different end customers. The hardware is the same but the speed profile may be based on the requirements of the end-customer. The manufacturer can use different firmware for different customers. Some fans also need to have different serial numbers for identification purposes, particularly in multi-fan systems.

Although the implementation of this speed control method is relatively simple, there are some disadvantages in this method such as the lower accuracy and higher acoustic noise level. Therefore it may not fit for some high-end system requirement. The accuracy of this type of the speed control method is around +/- 10% which is depended on the maximum speed of BLDC, maximum bus speed of the MCU and number of bit in the timer. For example, if we need to drive higher speed of BLDC fan with lower speed of the MCU with lower resolution timer, then lower accuracy of the speed will be occurred. If using the MC9RS08KA2, the maximum bus speed is 10MHz that is generated by ICS and 8-bit timer resolution. It can improve the accuracy of the speed.

ii. PWM control method in internal approach

Due to some drawbacks of the phase on/off delay time control method, the PWM control method can provide higher accuracy and lower acoustic noise level. The hardware configuration/connection of this control method is same as phase on/off delay time control method shown in Figure 8a but the drive control mechanism is different. The speed is controlled by changing the duty cycle of the PWM, instead of changing the off-time period.

In this method, the speed is controlled by the duty cycle of the PWM that drives two winding coils in the BLDC fan independently. The two winding coils are turned on alternately but the voltage of the coil is controlled by the duty cycle of the PWM drive signal. The PWM frequency is a major design consideration. The PWM frequency can be chosen to be between 18 kHz to 60 kHz typically.

The PWM frequency range is chosen based on three factors; acoustic noise, efficiency, and controllable speed range. As mentioned in the external PWM control method, the acoustic noise will occur if the PWM frequency is falling into the audible range of the human ear. In this method, the PWM frequency is higher than 18 kHz, which is higher than the audible range of the human ear. This means that the fan can be operated in a quieter manner. On the other hand, use of higher PWM frequency to control the voltage of the winding coil means the higher efficiency can be obtained. Because the high speed PWM (18 kHz – 60 kHz) that is much higher that the 1 / commutation period. This means changing the duty cycle will change the averaging dc voltage that applied in the winding coil. Compare with the phase on/off time delay method the current ripple is reduced. Therefore it will improve the efficiency and acoustic noise level by current ripple reduction. Since the power loss is eliminated by the external component, more available power can be use. Therefore the controllable speed range can be improved from 40% - 100% in external approach to around 25% - 100% without any startup and stall issues.

The efficiency can be further improved with the use of the higher cost H-bridge switching driver maintaining the energy in the stator winding by recirculation of inductive current through during both of high-side switches are turned on.

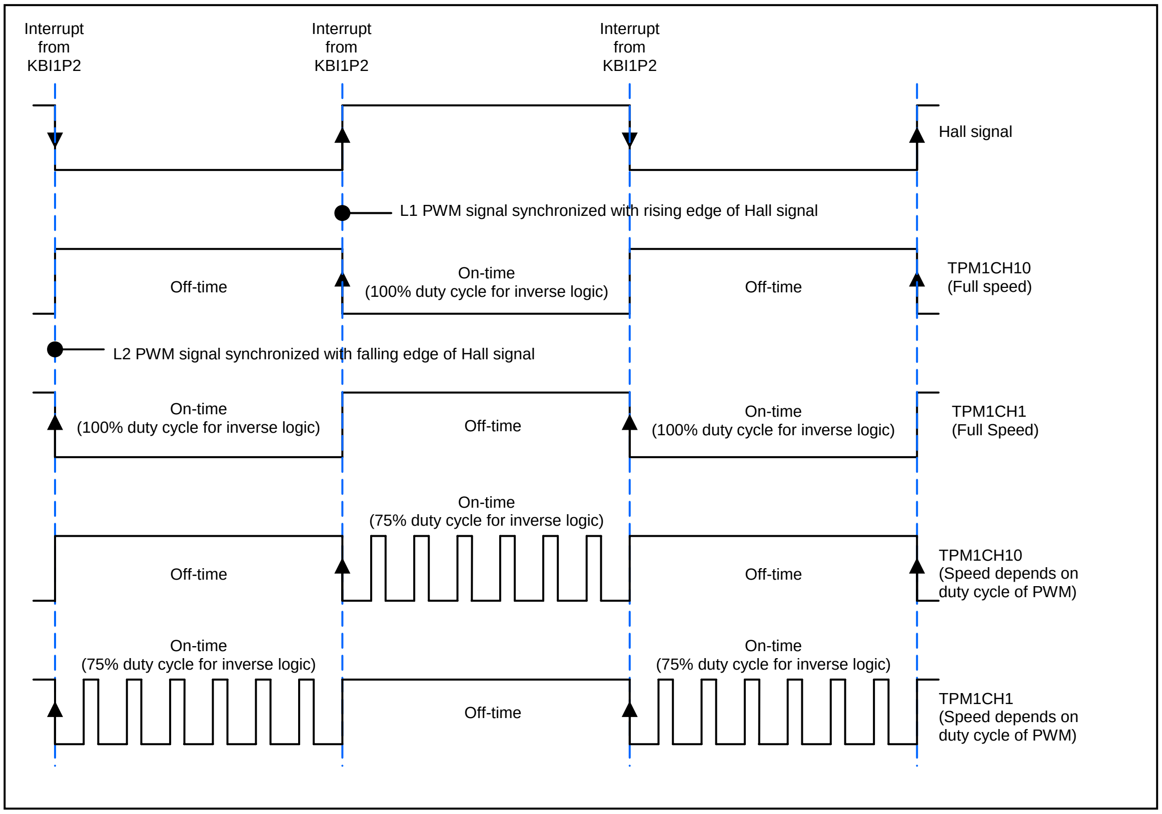

Figure 9a. Timing diagram for PWM speed control in MCU

Figure 9a shows the driving PWM waveform of two complementary outputs TPM1CH0 and TPM1CH1. Similar to the phase on/off delay time method, the speed of the fan is dependent on the temperature of the thermal sensor connected to the ADC pin of the MCU. But the speed in PWM method is changed by adjusting the duty cycle of the PWM during driving the corresponding winding coil by Q1 and Q2 transistors / FETs. In the ASIC solution, the PWM input control frequency is fixed (*e.g.* 25 kHz) because the ASIC IC will use it to drive the fan. Unlike the ASIC controller, the PWM input control signal in MCU solution can be used at any frequency. Lower PWM frequency (*e.g.* 5 kHz) can be used for PWM input control signal and the output PWM frequency can be maintained in higher PWM frequency (e.g.25 kHz) to drive the winding coil of the fan.

In the MCU solution, the input speed command (*i.e.* voltage from the thermal sensor) is sensed by ADC pin, it will compare with the temperature-speed lookup table first to get the corresponding pre-defined requirement speed for the temperature. And the duty cycle of the PWM will be change accordingly. And the actual speed will be monitored by the Hall signal and it will be used for the closed-loop speed control to change the duty cycle of the PWM. The closed-loop control can be either the simple pre-calculated PI / PID lookup table or real time calculation by the firmware of MCU. It depends on the application and performance of the MCU. For low-end application, the table lookup should be used.

A new MCU MC9S08QD4 from Freescale is very suitable for low-end to middle-end BLDC fan application. It not only provides 10-bit ADC pins for accurate thermal sensing, but it also provides two 16-bit timer / PWM modulator for PWM generation and speed sensing for BLDC fan control. Use of the PWM modulator can off load the MCU, so the MCU has enough bandwidth to execute different task if needed. Some common MCU features such as the build-in ICS provide 8MHz bus frequency, external interrupts and programmable slew rate I/O port are also included in this MCU.

Conclusion

There are many different implementation methods for fan control from as simple as using a Hall sensor plus two transistors to drive the fixed speed BLDC fan. Various implementation methods from fixed speed to variable speed control, from external approach to internal approach have been described.

The intelligent BLDC fan can provide sophisticated speed control algorithms, high efficiency, low acoustic noise, low power consumption, low standby power consumption, and intelligent system protection features for both electrical and mechanical protection and interface communications.

ASIC and MCU internal approaches are becoming more popular solution for the intelligent variable speed BLDC fan control. The MCU solution has the advantage of flexibility. Many manufacturers have started to use MCUs in their products, particularly for customized fans. Therefore a low cost, low pin count, high precision built-in oscillator (*e.g.* ICS), high resolution ADC and high resolution PWM modulator / generator MCU is suitable for future BLDC fan products. The Freescale MC9S08QD4 is an example of an MCU that meets these requirements. It is a low cost 8-bit, 8-pin count MCU and it also includes a +/-2% built-in oscillator, 10-bit ADC module, and two 16-bit timer / PWM modulators. All of these features are well suited for BLDC fan applications.