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AP08019

XC866

Sensorless Brushless DC Motor Control
Using Infineon 8-bit XC866 Microcontroller

Microcontrollers

Never stop thinking

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1 Introduction

A BLDC motor is a synchronous motor and as a consequence, the rotor position has to be known in order to generate the appropriate field. Brushless DC (BLDC) motors are popular because of their durability, linear control characteristics, efficiency and torque to volume ratio. The major disadvantage of BLDC motors is that proper operation requires knowledge of the rotor position. Generally, rotor position sensors (usually Hall-Effect devices) are used to determine the rotor position. These sensors are a disadvantage because they:

1. Increase the system design cost
2. Are a source of failure
3. Require extra wires and circuitry
4. Are sensitive to EMI

Figure 1 shows a typical structure of a three phase BLDC motor drive using hall sensors. An inverter is used to drive the motor, and a microcontroller can be used to control the inverter.

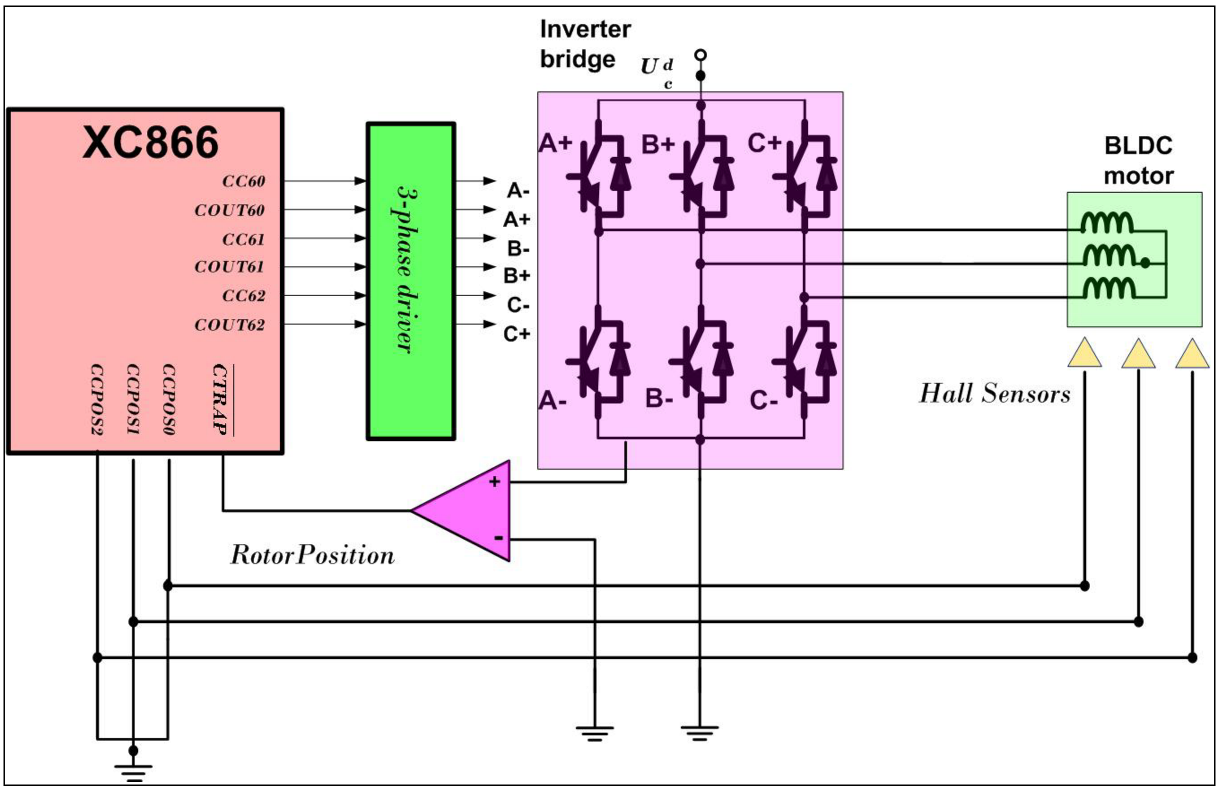


Figure 1. BLDC motor driver

2 Structure and Operation of BLDC Motors

The two major components of BLDC motors are the stator and the rotor. The stator is made of 3-phase blocked windings. The rotor is made of a permanent magnet. Figure 2 shows the structure of a 2 pole BLDC motor.

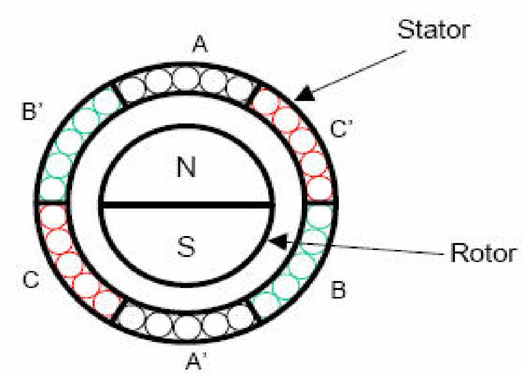


Figure 2: Structure of a 3 Phase BLDC Motor

If current is applied properly to the stator coils, constant torque (neglecting current harmonics, fringing, and finite commutation times) can be applied to the rotor. Figure 3 shows how the Lorentz force (B x I) causes the rotor to move, and how the commutation must occur to ensure constant torque.

As shown in Figure 3, the commutation instant depends on the rotor position. This is why rotor position sensors are used to control BLDC motors. To remove the rotor position sensors, the rotor position must be detected or calculated using some other method. Figure 4 shows the back-emf measured at the open circuited motor terminals (with respect to the neutral) as the rotor spins.

As shown in Figure 4, the back-emf is trapezoidal in shape and it can be seen that at any given time only two of the 3 phases conduct current. The inverter switching pattern can be derived easily from the back-emf. This switching pattern is organized into 6 commutation states. These states must occur at a certain order for the motor to rotate properly. Figure 5 shows the commutation states and the proper sequence at which these states must occur. The arrow passing thru the motor windings represent the overall direction of the current and also the magnetic field created by the current. The resultant magnetic field (red arrow) is followed by the magnetic field of the rotor (green arrow). Thus, in the given sequence, the rotor is rotating counterclockwise.

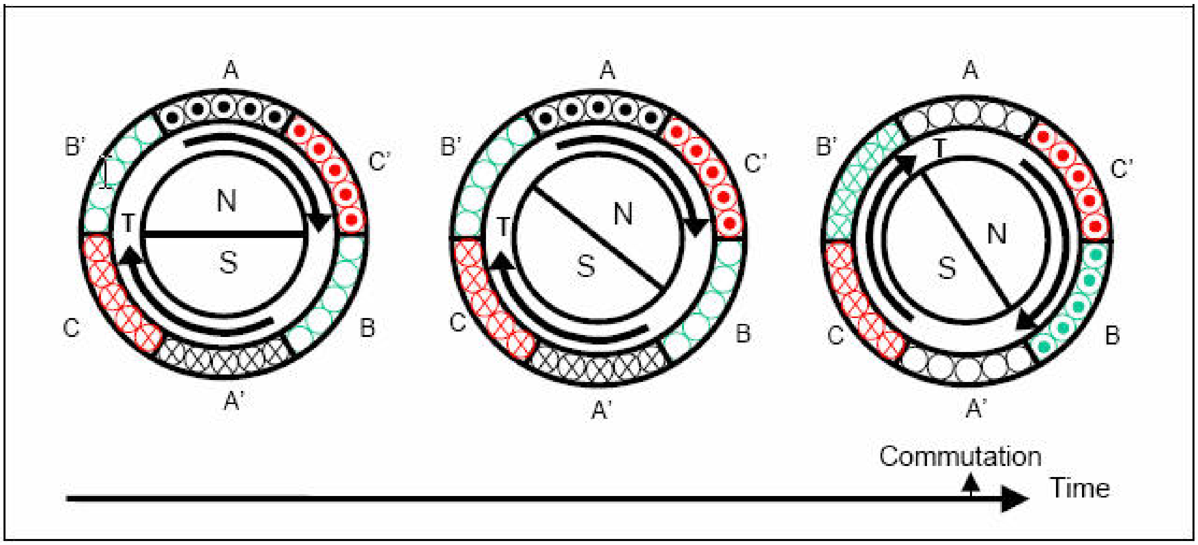


Figure 3. Operation of a BLDC motor

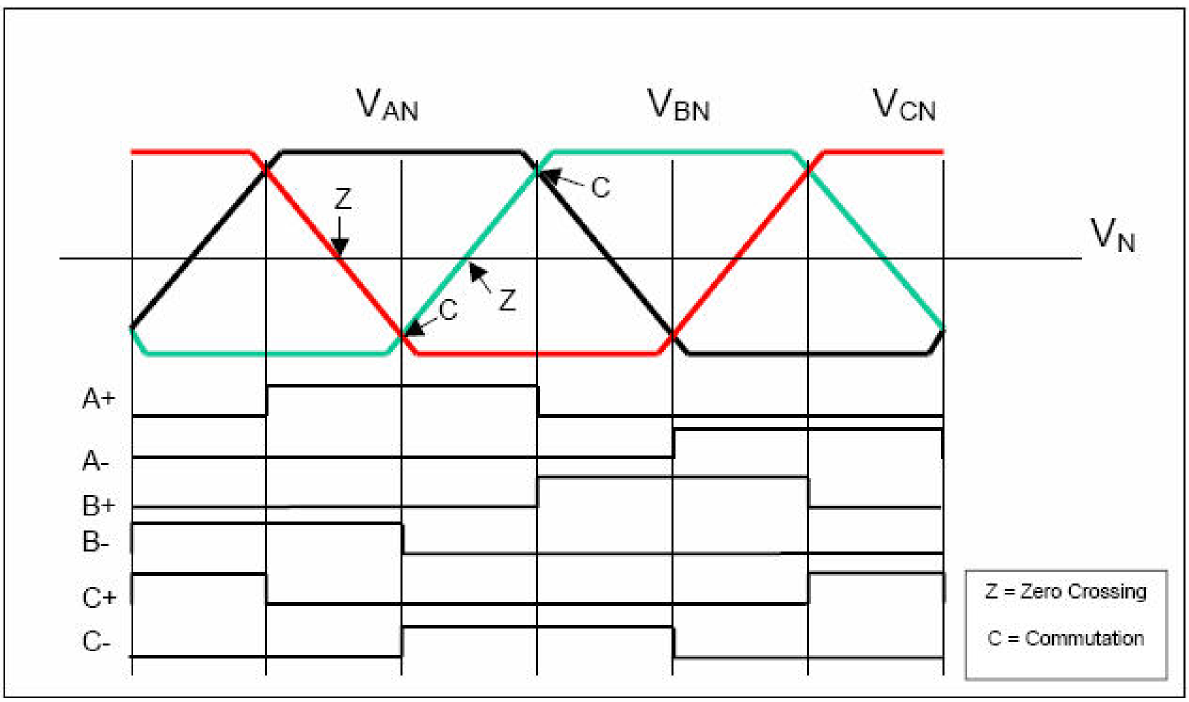


Figure 4. back-emf and Inverter Signals

The voltage applied to the motor is usually controlled by chopping the low or high side inverter transistors at a constant frequency with a variable duty cycle.

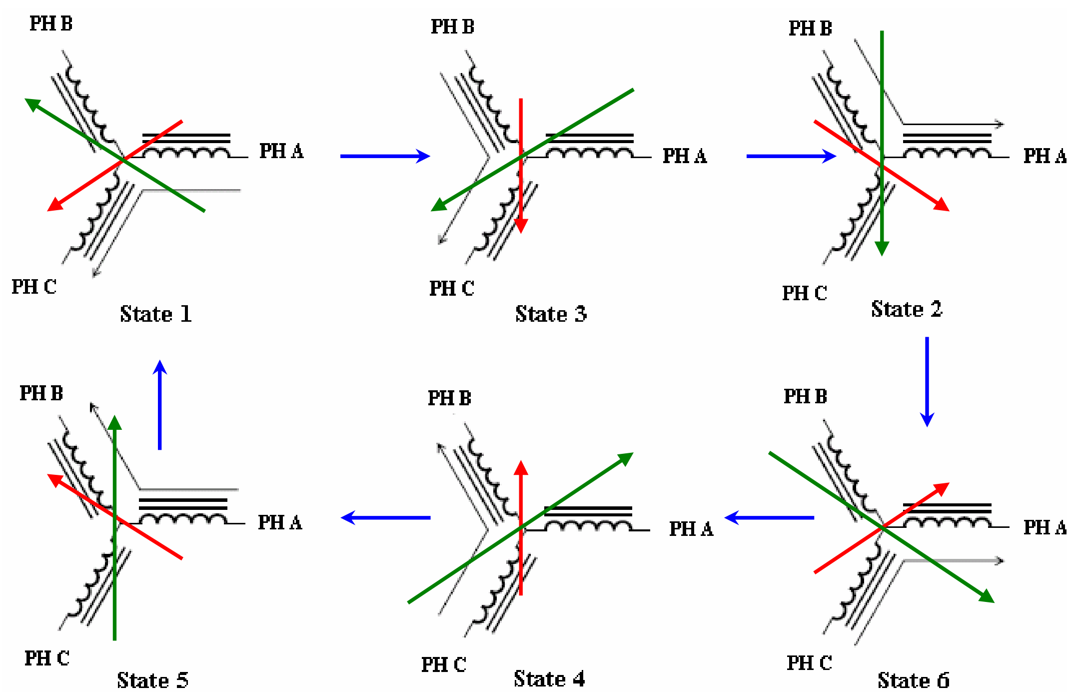


Figure 5. Commutation sequence

3 Rotor Position Calculation without Sensors

There are several methods that can be used to determine the rotor position. Since only two of the three motor phases are active at any given time, the phase that does not conduct is usually used to detect or measure the back-emf. The most common sensorless operating methods revolve around detecting the zero crossing of the back-emf with Op- Amps or other circuitry. From Figure 4, it can be seen that each zero crossing of the back-emf precedes a commutation event by thirty electrical degrees. This means that any type of zero crossing detection requires a “phase delay” to ensure proper commutation.

Many types of circuits can be developed to detect the zero crossing of the back-emf. There is even one method which uses the current in the free-wheeling diodes to detect the zero crossing. Unfortunately all of these methods require quite a bit of external circuitry and filtering. The method proposed in this application note uses only three voltage dividers (six resistors).

3.1 Measuring back-emf by Measuring the Motor Terminal Voltage

From Figure 4, it can be seen that while any two phases conduct, the back-emf of those phases are equal in amplitude and opposite in sign. From this information it can be derived that while any two phases are conducting, the neutral voltage is approximately one half the DC rail voltage. Furthermore, the relationship between a phase voltage and its back-emf is given by the following formula:

$$U_P = (R \times I) + \left(L \times {}^{dI}\!/\!_{dT}\right) + Ep \qquad [4.1]$$

where:

U_P stands for phase voltage
R stands for winding resistance
I stands for actual phase current
L stands for phase inductance
dI/dT stands for change of phase current over time
E_P stands for electromagnetic voltage caused by magnet

Since there is no current in the non-conducting phase, I = 0 and dI/dT = 0, thus $U_P = E_P$. This means that by measuring the terminal voltage on the open phase, the back-emf (and hence the zero crossing) can be easily determined.

The above conclusion is only valid while the two conducting phases are active. If one or both of the phases are being chopped, then the neutral voltage will vary and the simple relationship between terminal and phase voltage will not be valid. For this reason, any measurement of the terminal voltage must be synchronized with the PWM signal used for chopping. Figure 5 shows the terminal voltage of the 3 phases of a BLDC motor. With a properly scaled voltage divider, the terminal voltage can be measured directly by the A/D converter of a microcontroller. To connect the A/D converter of the microcontroller directly to the voltage divider, the microcontroller V_{SS} must be connected to the negative rail of the inverter.

Using a simple voltage divider has the advantage of being very inexpensive. The zero crossing occurs when the terminal voltage reaches one half of the DC rail voltage. Since the rail voltage can be measured on each phase periodically (whenever the high side transistor is conducting), this method is very robust with respect to component and temperature variation.

The disadvantage to using the A/D converter is that it is difficult to achieve a high speed range. This is because only one A/D sampling of back-emf is taken per PWM cycle. Therefore, the number of PWM cycles (or the number of back-emf samplings) per 60 electrical degrees is decreased when the motor speed increases. However, to obtain an accurate zero crossing measurement, probably a minimum of about 15 PWM periods per 60 electrical degrees of rotation are needed. This limits sensorless operation at high speed especially for motors with a large number of poles. The problem can be worse for applications that want to minimize switching losses by using a low PWM frequency, say less than 10kHz.

This method of voltage divider also sets a limit for high voltage application due to the maximum allowable internal resistance of the voltage source that feeds the A/D converter. For an accurate A/D conversion, the internal sample and hold circuit (which is made of capacitors) must be charged up. This requires a small current drain from the analog source. If the internal resistance of the analog source is too large, then the sample and hold circuit will not be charged up fast enough. This means that the values of the voltage divider are limited to typically less than 5 k Ohms. If a high voltage motor is attached to such a small voltage divider, the large current will require higher wattage resistors to be used. This increases the size and cost of the resistors and decreases the overall system efficiency. In addition, resistor and capacitor values of a voltage divider should be carefully chosen. During certain PWM whose duty cycle is too low, the phase voltage might not have enough time to stabilize if the RC time constant is comparatively long.

Figure 6 shows the basic structure of this sensorless drive. As shown in Figure 6, there is the resistor network for the measurement of back-emf. There is also one more voltage divider for the measurement of the dc rail voltage for the calibration of the zero crossing level. However, the additional divider for the dc rail voltage can be omitted in such a manner: if the low-side switches are used to chop, the dc rail voltage can be measured from the phase with the high-side switch turned on. Also, the CCU6 has a CTRAP functionality which will force the Capture/Compare Unit 6 (CCU6) outputs into a passive state and no active modulation is possible.

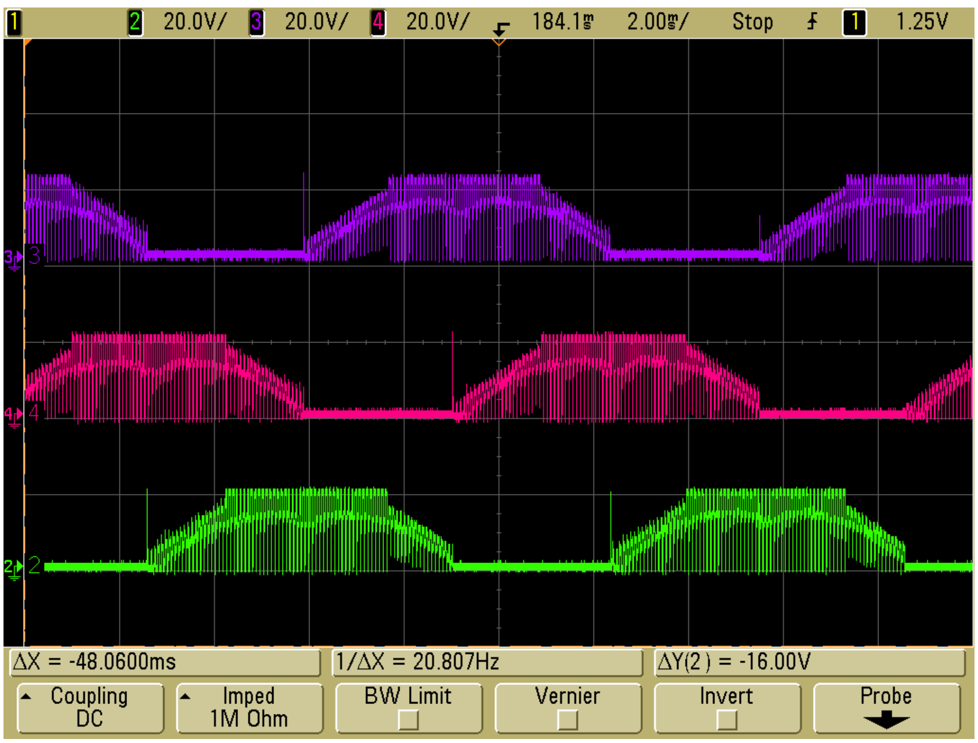


Figure 5. Phase Voltages

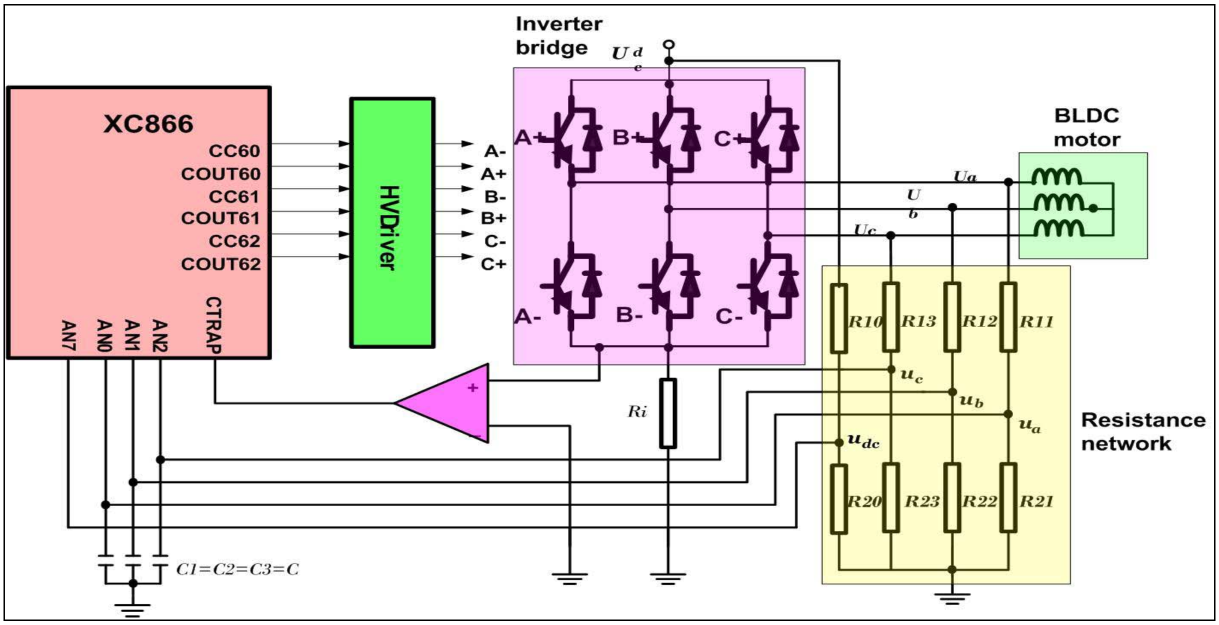


Figure 6. Sensorless BLDC motor driver

3.2 Sensorless Operation

Detecting the zero crossing of the back-emf is only part of the sensorless operation of a BLDC motor. Once the zero crossing is detected, the 30 degree delay must be implemented. The delay time depends heavily on the rotor speed. Acceleration and deceleration can also play an important role in determining the delay time.

Often it is sufficient to neglect the acceleration and deceleration, but the dependence of the delay time on motor speed cannot be overlooked. A look-up table can be used to determine the appropriate delay time, but the symmetry of 3 phase BLDC motors makes it easy to calculate the delay time. From Figure 4 it can be seen that each zero crossing is both preceded by and followed by a commutation. Ideally, the time from commutation to zero crossing is the same as the time from zero crossing to commutation (the time from zero crossing to commutation is the delay time). So, with no real calculation the delay time can be determined by simply measuring the amount of time between the previous commutation and the zero crossing.

This method of determining the delay time has some drawbacks. If for some reason the commutation occurs too early or too late, the next commutation will occur too late or too early (respectively). This type of oscillation can add stability if it decays, however, it can also add instability to the control scheme if it does not decay.

A better method to determine the delay time is to calculate one half the time between two consecutive zero crossings. This will provide the appropriate delay time and will be somewhat less sensitive to any miscalculations. In addition, some simple digital filter methods can be adopted to achieve more accurate prediction of next zero crossing instance.

4 Microcontroller Implementation of Sensorless BLDC Algorithm

Although the overall sensorless method described in the previous section is not very complicated, implementation of the method requires careful consideration of how to properly use the microcontroller peripherals. The powerful CCU6 module found in the Infineon XC866 microcontroller has several special BLDC motor control modes which can be very useful for both sensor and sensorless control.

One of the special modes of the CCU6 module is designed to control three phase BLDC motors. This mode is called “Multi-Channel Mode”. The multi-channel mode offers the possibility of modulating all six T12-related outputs. The bits in bit field MCMP are used to select the outputs that may become active. If the multi-channel mode is enabled (bit MCMEN = 1), only those outputs that have a 1 at the corresponding bit positions in bit field MCMP may become active. In such way, the multi-channel mode synchronizes all six PWM outputs and meanwhile keeps the flexibility of changing output pattern since they are totally controlled by software. This can fit various BLDC motor control applications whose Hall patterns and output patterns may differ.

In multi-channel mode, switching from one output state to another can be triggered by various events, such as

- Correct Hall event (useful in applications with Hall sensors)
- Timer 12 period match while counting up
- Timer 12 one match while counting down
- Timer 12 compare match of Channel 1
- Timer 13 period match

In this application, Timer 12 period match is utilized to trigger output pattern switching. However, Timer 12 compare match of Channel 1 can also be configured to deliver output states as long as Channel 1 works in compare mode.

Another good feature of multi-channel mode is that it is able to combine the modulation generated by Timer 13, which can be used to change motor speed. Figure 7 shows the outputs for Multi-Channel Mode. The polarity of each signal is completely programmable, and PWM (generated by the Compare Timer 13) can be automatically gated to either the low side or the high side, or even both high and low side transistors for chopping. In Figure 7, PWM generated by Timer 13 is gated with COUT6x (x = 0, 1, 2).

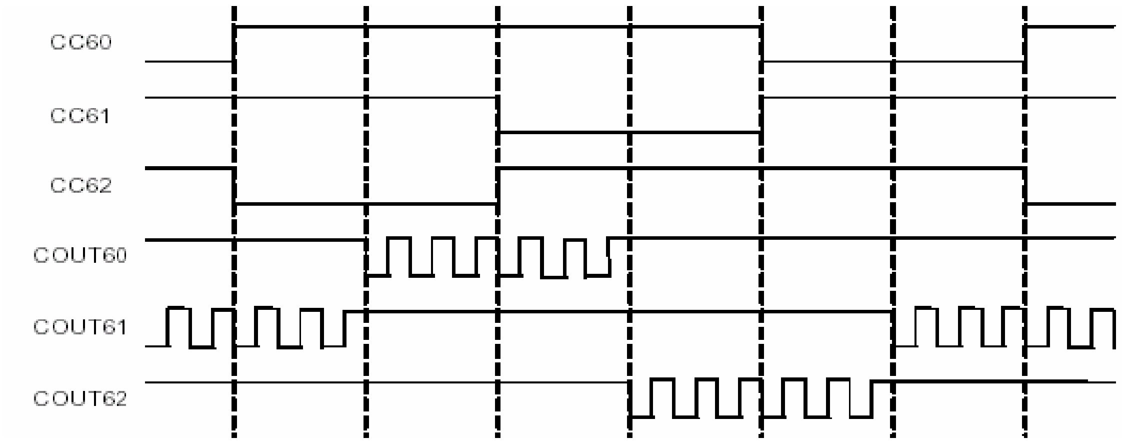


Figure 7. Output Pattern for Multi-Channel Mode (Rotate Left – Active Low)

4.1 Steady State Operation

The Multi-Channel Mode handles most of the tedious task of generating and applying the PWM signals to the appropriate output pins. There are many ways in which the higher level tasks associated with the sensorless algorithm can be partitioned and handled. However, three essential tasks must be done in the steady state:

1. Detect the Zero Crossing using the A/D Converter
2. Calculate one half the time between two successive back-emf zero crossings
3. Switch Output States after Delaying the period (from zero crossing to commutation moment) derived from step 2

Step 1 requires that the A/D converter samplings are synchronized with the compare timer 13 PWM. This can be achieved with the aid of external trigger feature of the A/D converter. Several events of CCU6 can be used to start the sampling and hold of A/D conversion, such as Timer 12/13 compare match and period match. Thus, upon every Timer 13 period match, the corresponding AD channel is triggered to measure back emf voltage and generates an interrupt service routine. In this ADC interrupt service routine, the captured voltage is compared with half the dc rail voltage. If the voltage value falls into the range of half the dc rail voltage considering some margin, Step 2 will be conducted.

However, the back-emf is affected by the switching of the inverter bridge circuit, causing the back-emf to spike up, as illustrated in Figure 8. This spike can be interpreted as a zero crossing if the back-emf value is within half of the DC rail voltage. To ignore this switching effect, a predefined period is compared with the value in timer 12 at the moment that the zero crossing is detected. If the timer 12 value, which indicates the commutation to zero crossing period (ΔCZ), is less than the predefined period, then the back-emf zero crossing is ignored.

On the other hand, if the timer 12 value is longer than the predefined period, the new commutation period will be calculated using the valid timer 12 value, and that is done in Step 2. The previous value of the zero crossing to commutation period (ΔZC) is averaged together with the value of Timer 12 (ΔCZ). If the motor startup is finished, then the averaged value will be loaded into timer 12 period register and will serve as the new commutation period.

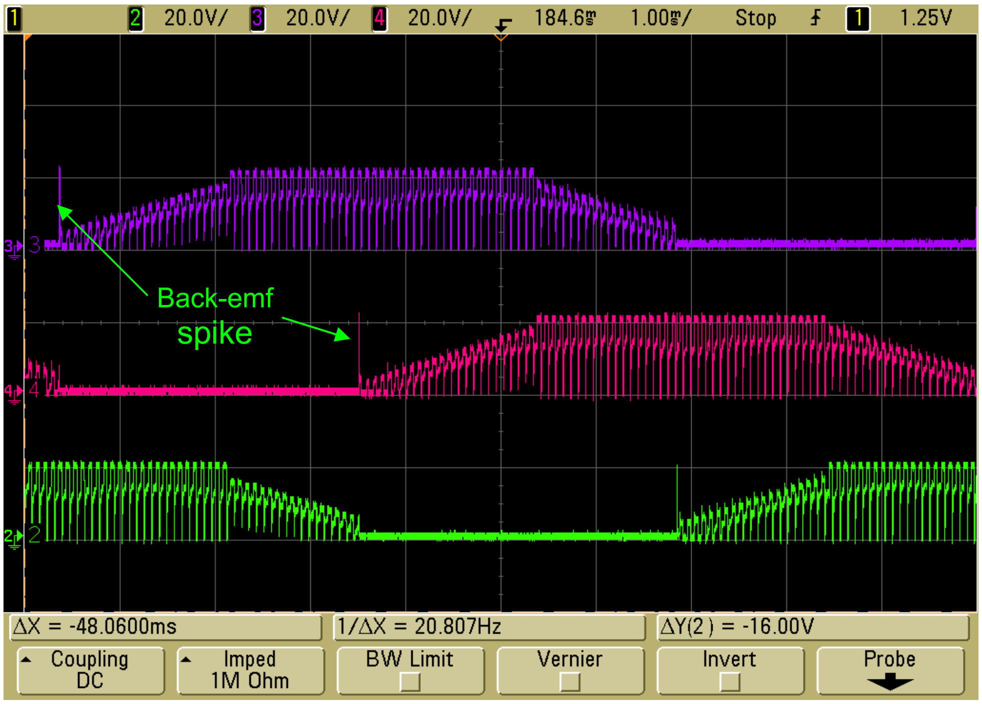
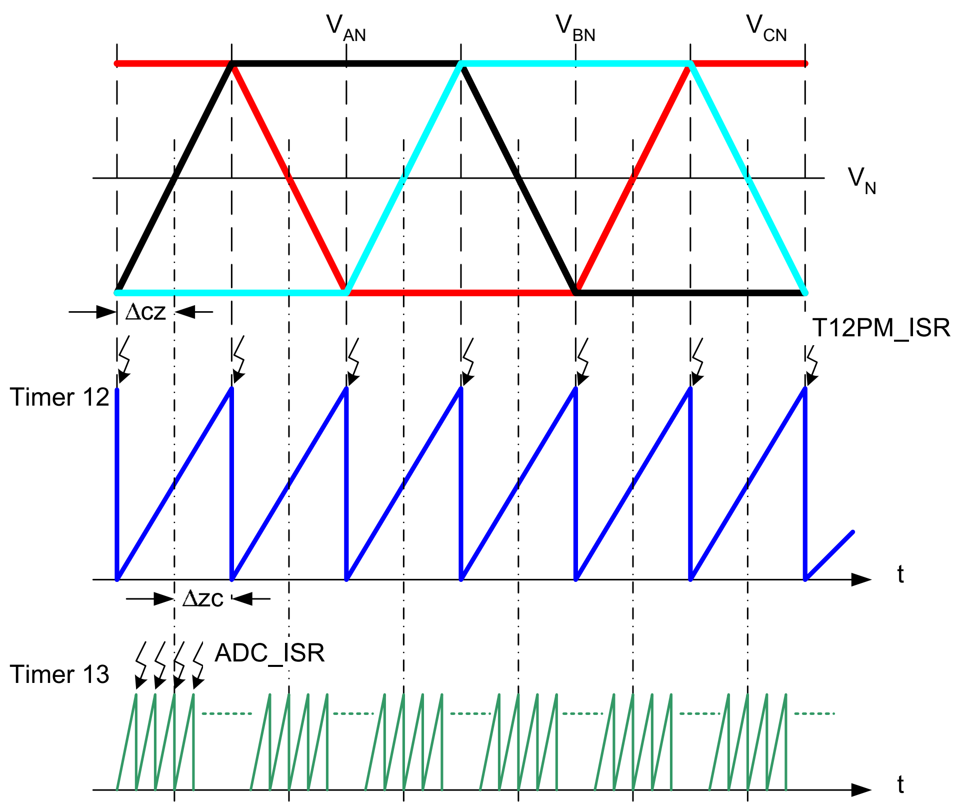


Figure 8. Switching Effect on back-emf

Once the updated value (from zero crossing to commutation point) is loaded into Timer 12 period register, Timer 12 starts counting until it reaches the period value, and generates a corresponding Timer 12 period match interrupt. In this interrupt service routine, Step 3 can be performed. With the aid of multi-channel mode, software overhead can be greatly reduced.

Figure 9 shows the basic timing and structure of the implementation of the sensorless algorithm. To further elaborate on the ADC and Timer 12 ISR, the flowcharts of the two interrupts are shown in Figures 10 and 11 respectively.



T12PM_ISR: Timer 12 period match interrupt service routine, in which commutation is conducted.
ADC_ISR: ADC interrupt service routine, which is triggered by Timer 13 period match. In this ISR, if correct zero-crossing is detected, Timer 12 period will be modified accordingly, to predict next commutation point.
Δcz: period from commutation to zero-crossing.
Δzc: period from zero-crossing to commutation.

Figure 9. Timing Diagram of Sensorless BLDC motor driver

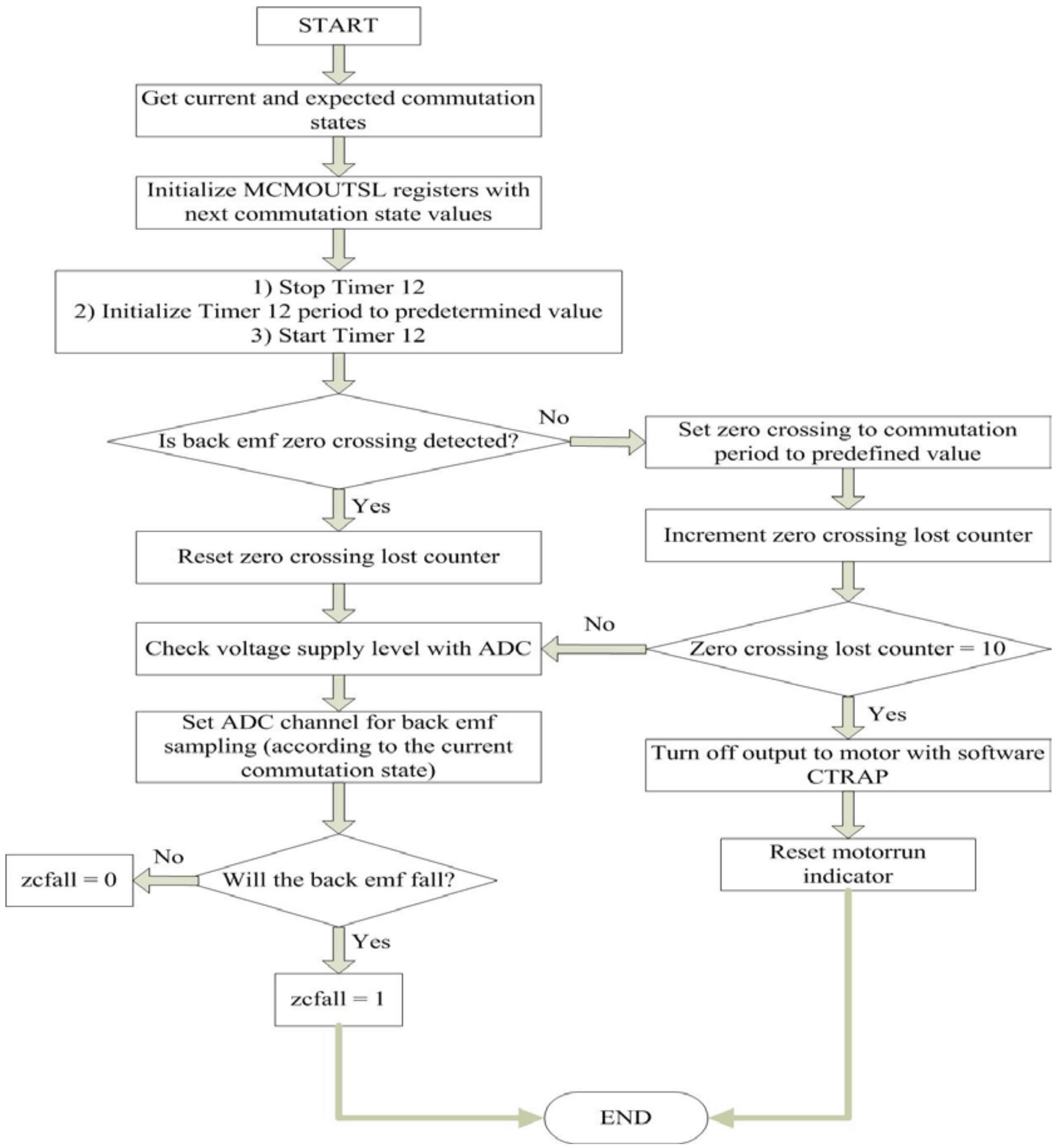


Figure 10. Flowchart of Timer 12 Interrupt Service Routine

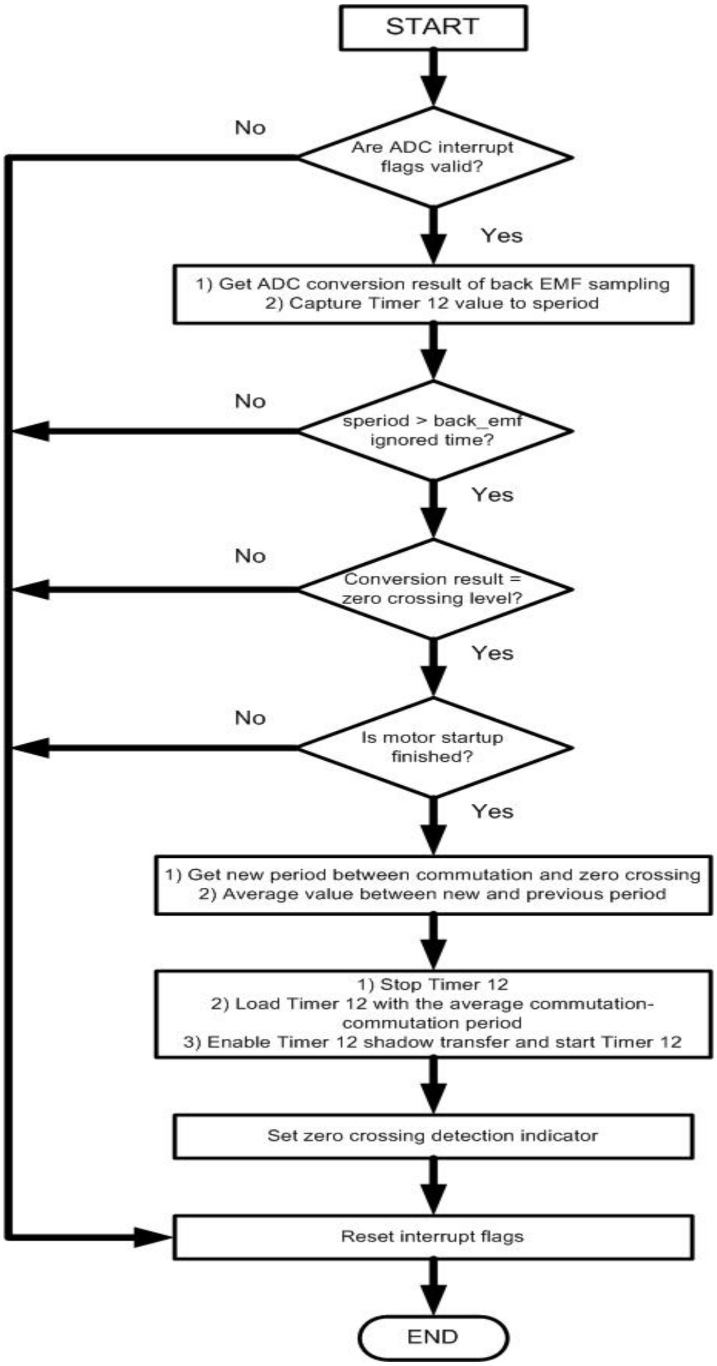


Figure 11. Flowchart of ADC Interrupt Service Routine

As in Figure 10, when the motor startup has finished, the current and expected commutation state is retrieved from the CCU6 MCMOUTS registers. These registers store the commutation pattern for the CCU6 output channels. Table 1 shows the commutation states and the corresponding CCU6 output patterns.

Commutation State	Next State	COUT62 C+	CC62 C-	COUT61 B+	CC61 B-	COUT60 A+	CC60 A-	Hex equivalent
1	3	0	1	0	0	1	0	0x12
2	6	0	0	1	0	0	1	0x09
3	2	0	1	1	0	0	0	0x18
4	5	1	0	0	1	0	0	0x24
5	1	0	0	0	1	1	0	0x06
6	4	1	0	0	0	0	1	0x21

Table 1 Commutation Table

The new commutation patterns are then loaded into the MCMOUTS registers. These commutation patterns are realized in the program by storing them in a table.

```
unsigned char HallPatt[] = { 000, 013, 026, 032, 045, 051, 064};

unsigned char revHallPatt[] = { 000, 015, 023, 031, 046, 054, 062};

unsigned char OutputPatt[] = {0x00, 0x12, 0x09, 0x18, 0x24, 0x06, 0x21};
```

Then the timer 12 is loaded with a predefined value. This value is the minimum time it takes for the next commutation to occur and is obtained by experimentally observing the motor right after its startup. Timer 12 will be loaded with the new commutation period once the zero crossing has been detected, and when this happens, the zero crossing detection indicator is set and the zero crossing lost counter is reset. This counter serves as an indicator of how many consecutive commutations have occurred without the detection of the back-emf zero crossing. If this counter has reached a certain value, the CTRAP will be activated and cause the motor to stop immediately. The timer 12 interrupt ends with an ADC conversion request for the ADC channel connected to the motor phase that is not energized. This will trigger the ADC to repeatedly sample the back-emf upon every Timer 13 period match event until the zero crossing is detected.

4.2 Starting the Motor in Sensorless BLDC Operation

Please refer to ***Application Note AP08018 - Start-up Control Algorithm for Sensorless and Variable Load BLDC Control Using Variable Inductance Sensing Method***, for detailed discussion of BLDC motor startup methods.

5 Evaluate Your Own BLDC Motor Control in Sensorless Mode

Consistent motor operation can be achieved with the BLDC motor in Sensorless mode. Several functions were added like the speed up/down and changing of direction of the BLDC motor. Also, due to the periodic calibration of the zero crossing level, the motor continues to operate even with a changing power supply. However, the motor cannot start properly with a voltage supply below 20V if the ramp up method is used for the startup. However, the motor is able to start with a supply below 20V with the use of the variable inductance sensing method.

This application note has presented some key features of Infineon's 8-bit XC866 microcontroller and how the CCU6 and ADC unique features are able to achieve high performance motor control. The BLDC motor sensorless control techniques presented in this application note can be implemented using the following hardware available from Infineon now:

1. Infineon XC866 Microcontroller Starterkit (Innovator Kit for XC800 Family)
2. Infineon Low Voltage Motor Driver Board (MDB LV45G v1.1)
3. BLDC motor (BL3056-18-028)
4. Power Supply - I/P: AC 100-240V 50/60 HZ 0.3 A, O/P: DC 24V 2.1A (Meanwell S-50-24)

Additionally, the folder **HOT4_BLDC_Sensorless_Operation** contains all the DAvE and Keil reference source files needed for the operation of the BLDC motor using Infineon's 8-bit XC866 microcontroller. The software provided was written in C for the Keil Compiler using DAvE and comes with step-by-step guides on setting up your own BLDC motor control in sensorless operation. All references codes and guides can be easily migrated to other Infineon microcontrollers in the XC800 family for immediate evaluation too. Figure 12 shows the phase voltages and current while operating in sensorless mode.

Additionally, Infineon's Autocode generator, DAvE configures all the peripherals of the XC866 microcontroller with ease, saving many hours of work. Although no speed or torque control loop was implemented in this application note, however a simple PI controller can be easily implemented and should provide robust regulation.

Kindly refer to the software attached with this application note for further evaluation on how Infineon's low-cost high performance 8-bit microcontrollers allows you to achieve your demanding design requirements. Please contact your local distributor should you wish to obtain your own motor control training kit complete with hardware and reference algorithm to perform an evaluation or allow our experts to contact you on how we may assist you in your designs needs.

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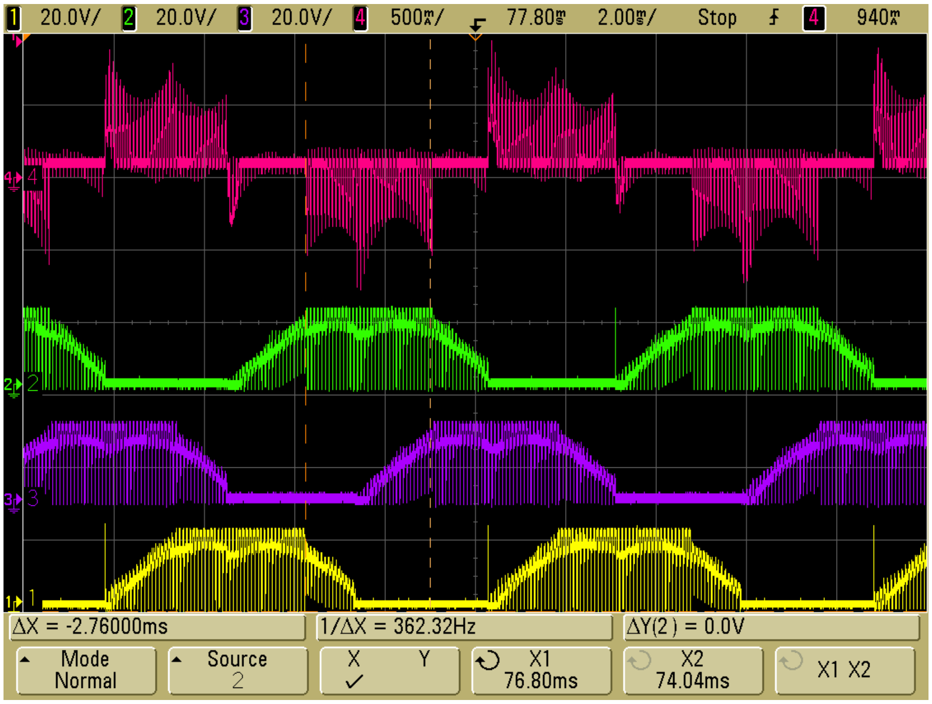

Figure 12. Phase voltages and current during sensorless operation

6 Other Relating References

You may wish to refer to the following application notes to learn more about Infineon's 8-bit XC866 microcontroller and Brushless DC motor control.

1. Application note **AP08026** – Brushless DC Motor Control with Hall Sensor
2. Application note **AP08018** - Start-up Control Algorithm for Sensorless and Variable Load BLDC Control Using Variable Inductance Sensing Method.

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