AN2662

Sensorless Drive for Single and Two-Phase Brushless DC Motor Application Note

Introduction

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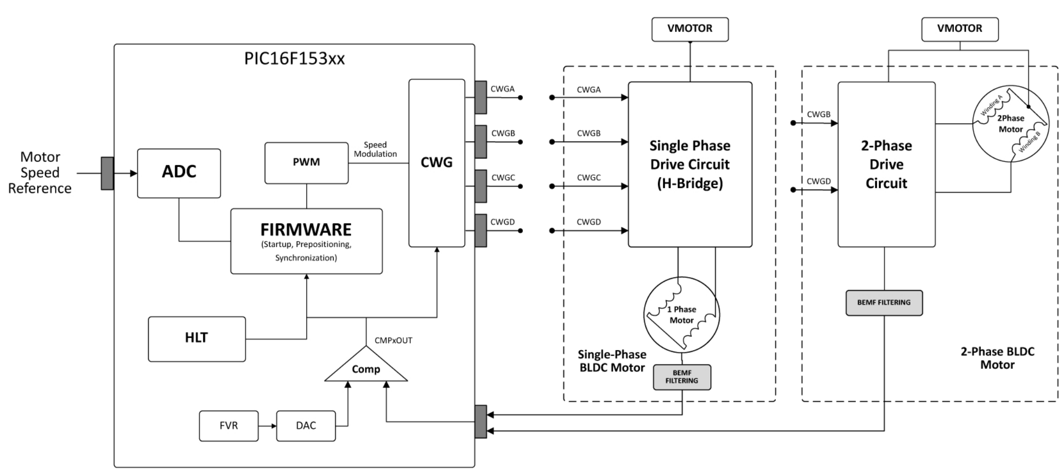
Single and two-phase Brushless DC (BLDC) motors are widely used in different small cooling fan and ventilating applications because of their low-cost, low-complexity and little to no required maintenance. Generally, a BLDC motor drive uses one or more Hall sensors to keep the motor synchronized and running. The implementation results in a higher overall cost due to the added sensor and wiring used. Additional components also reduce the system mean time between failures (MTBF). An alternative, sensorless solution is presented here which counters the aforementioned drawbacks.

This application note describes how to implement a sensorless control for single and two-phase BLDC motors using the 8-bit PIC® microcontroller. The implementation is based on the low-cost PIC16F153XX family of microcontrollers and hardware BEMF filtering in a cooling fan application. The application is tested on a 80 mm x 80 mm 12V DC fan with 3600 rated RPM. The fan is configured and modified to run as a single or two-phase BLDC motor and has a speed modulation range from 60-100%. The built-in comparator, DAC, FVR and CWG are used to implement a sensorless control. The firmware is used to provide a successful motor start-up, synchronization, and to determine when to perform the correct commutation. Figure 1 illustrates the block diagram of sensorless control of a two-phase BLDC motor.

Figure 1. Block Diagram (showing single and two-phase motor control scenarios)



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9. APPENDIX A: Circuit Schematics

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1. Sensorless Control

For a sensored control of a BLDC motor, Hall effect sensors are used to determine the position of the rotor and to provide the proper motor commutation interval. Instead of using a Hall effect sensor, the sensorless control uses the Back Electromotive Force (BEMF) that is generated by the moving rotor magnets over the stator coils. Detecting the motor position through BEMF gives the following known challenges:

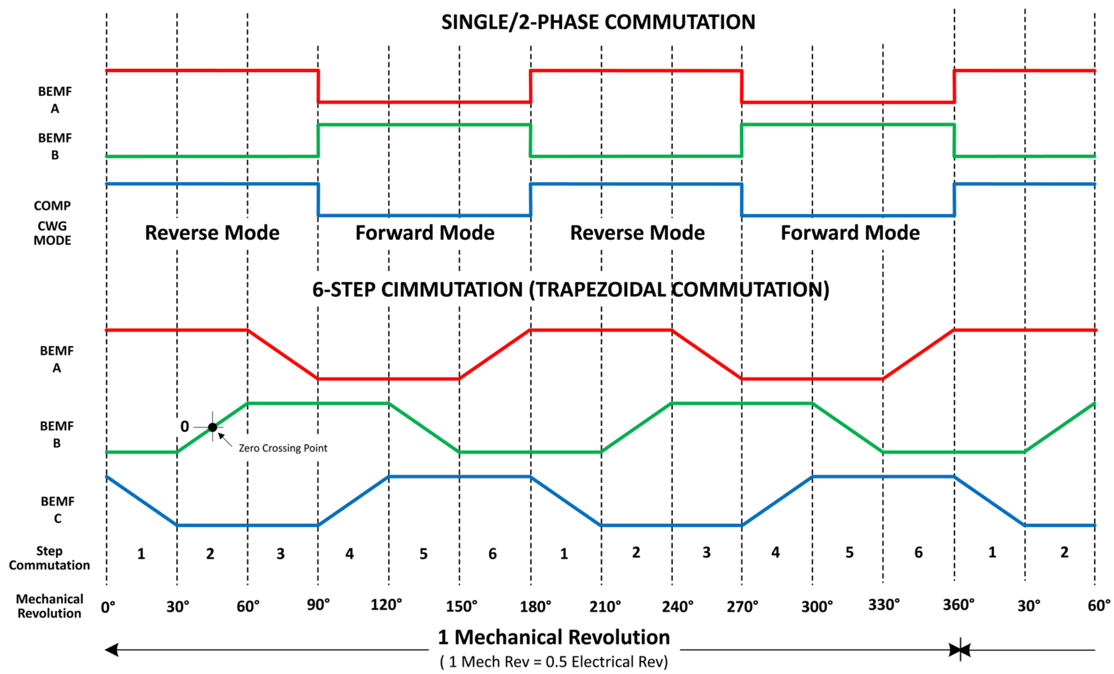
- A minimum motor speed is required to generate sufficient back EMF to be sensed
- Abrupt changes to the motor load can cause the BEMF drive loop to go out of lock
- The BEMF voltage can be measured only when the motor speed is within a limited range of the ideal commutation rate for the applied voltage
- Commutation at rates faster than the ideal rate will result in a discontinuous motor response
- Proper motor start-up and synchronization is required to successfully run the motor

Sensorless control is best fitted on an application that requires the overall design to be low-cost, continuous low-speed operation is not required, and a rapid change in motor load are not expected. The implementation of sensorless control in this application note targets these application requirements.

2. Motor Back Electromagnetic Force (BEMF)

The implementation of sensorless drive is primarily based on the monitoring of the Back Electromagnetic Force (BEMF) to determine rotor position and using it to synchronize motor commutation. The BEMF is the voltage generated in the stator winding by a permanent magnet motor when the rotor of the motor is turning. Figure 2-1 shows the ideal BEMF voltages for single and two-phase and its comparison with the three-phase BLDC motor. A comparison with three-phase motor BEMF is shown below to briefly demonstrate the difference in implementation.

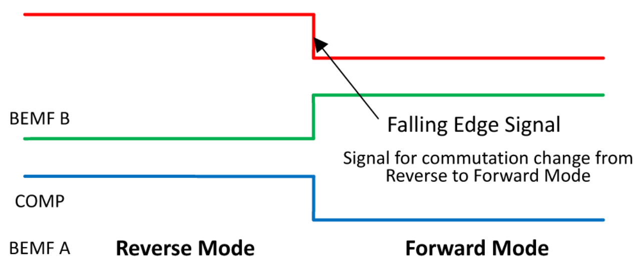
Figure 2-1. Single/2-Phase and 3-Phase BEMF Waveform



In the most common three-phase sensorless control, the motor commutation point is measured on the zero crossing of the BEMF signal. The six-step commutation sequence energizes two phases at any time, instantly leading to one phase winding being connected to the positive supply voltage, while one is connected to the negative supply voltage, and the remaining phase is floating (idle). The back EMF in the floating phase will result in a zero crossing when it crosses the average of the positive and negative supply voltage during the motor commutation sequence. This zero crossing provides a position datum from which the commutation can be correctly scheduled. On the other hand, a single-phase BLDC motor does not have an idle stator winding. Both windings of single phase are alternately energized to produce a rotating motion. Meaning current are flowing on the winding all the time but in an alternate direction. This caused the BEMF signal to behave more like that of a square wave rather than the trapezoidal BEMF wave produced by a three-phase BLDC Motor. The same square wave pattern applies on a 2-phase BLDC motor, its difference on the single-phase is that in the 2-phase the current is flowing on one winding while the other winding is turned off/idle at every commutation.

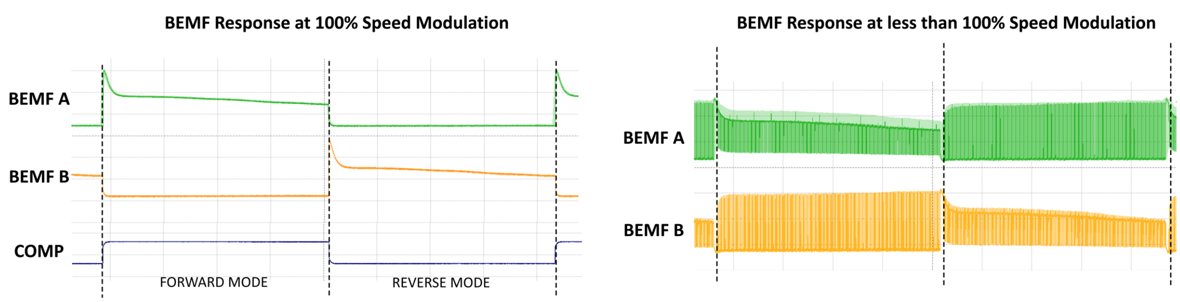
Due to the square wave BEMF pattern, the motor commutation sequence on the single or two-phase BLDC motor can be implemented the instant the BEMF changes its state or a rising/falling edge of the BEMF signal is detected instead of measuring the exact zero crossing. The detection of a rising/falling edge is done by the comparator. It is used to signal the CWG to change its drive mode from forward-to-reverse or vice versa. More information on the CWG implementation can be found in section Motor Commutation.

Figure 2-2.



Ideally, the back EMF signal is a clean square wave signal. In actuality, the back EMF signal has noises coming from the effect of motor speed modulation as well as the coupled signal of the other driven windings. This speed modulation causes the BEMF signal to introduce some noises. Therefore, when speed modulation is applied (speed modulation less than 100%), noticeable noises can be seen on the measured BEMF. Figure 2-3 shows the BEMF response at a speed lower than the rated RPM. Due to this PWM noise, detecting the exact BEMF signal could be difficult and the key in successfully implementing a sensorless algorithm is to detect the BEMF signal accurately. Thus, BEMF filtering should be added for a successful sensorless mode implementation.

Figure 2-3. BEMF Waveform Comparison at <100% and >100% Speed Modulation



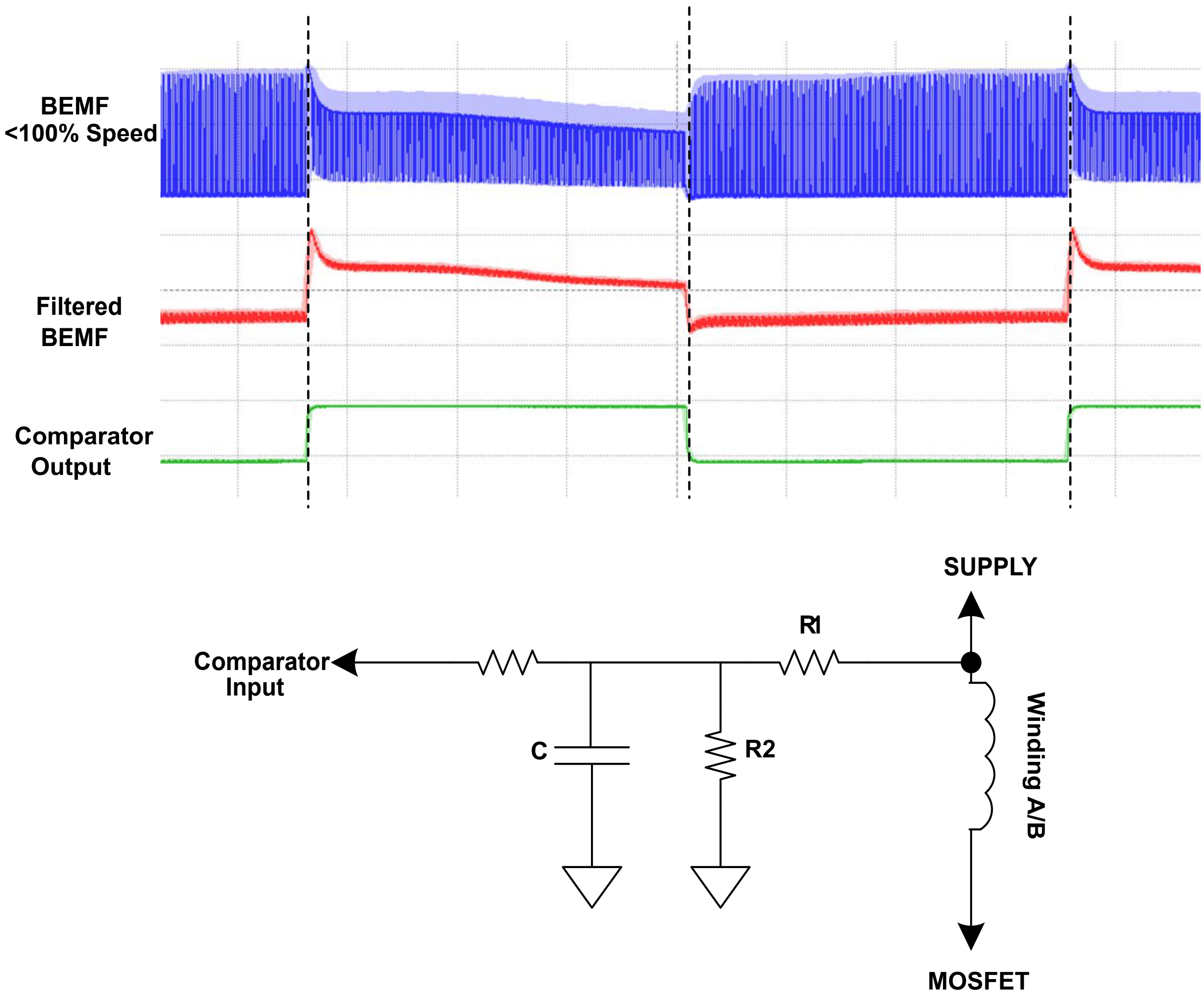
Related Links

[5. Motor Commutation]

3. BEMF Filtering

To reiterate, the back EMF signal is not a clean signal. The effect of PWM or speed modulation causes a ringing effect that adds up as a noise on the BEMF signal. This is needed to be filtered out to detect the proper motor commutation point and successfully run the motor at its allowable speed range. There are different methods of filtering out BEMF signal noise. The most common technique is adding a hardware filtering. The implementation of hardware BEMF filtering uses a RC low-pass filter in combination with a voltage divider. Figure 3-1 shows the schematic of the hardware BEMF filtering.

Figure 3-1. Hardware BEMF Filtering



The component values in this circuit depend on the desired low-pass filter corner frequency. The low-pass filter should be designed to filter out as much high-frequency noise as possible without introducing notable delay to the BEMF signal. The following observations should assist the choice of components:

- At low frequencies, the circuit behaves as a normal voltage divider.

$$V_{OUT} = \left(\frac{R_2}{R_1 + R_2}\right)V_{IN}$$

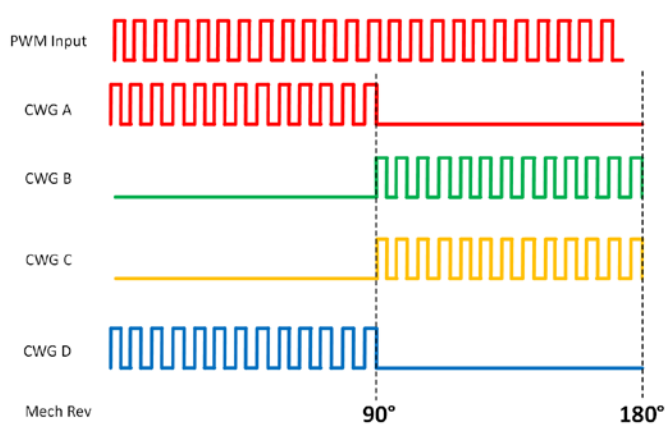
- For high frequencies, the capacitor C behaves as a short to ground, filtering away these frequencies.
- The corner frequency of the filter is given by the equation:

$$\omega_0 = \left(\frac{R_1 + R_2}{R_1 \times R_2 \times C}\right)$$

- R1+R2 should be large (10-100 kΩ) to avoid large currents through the filter.

Another method of filtering BEMF signal noise is by implementing a low and high side transistor modulation. This method reduces the ringing effect by modulating both high and low side transistor driver at the same time on an H-Bridge circuit instead of just using low side modulation during a change in desired speed. This method can be implemented by using the CWG Steering mode. In Steering mode, the CWG input signal can be replicated on any of the CWG output. More information about CWG and motor commutation sequence can be found on the “Motor Commutation” chapter. Figure 3-2 shows the implementation of low and high side modulation on driving a single-phase BLDC motor using CWG.

Figure 3-2. CWG Steering Mode



OUTPUT	STEERING	STATIC DATA	90°
CWGA/Q1	1	0	Modulated
CWGB/Q2	0	0	OFF
CWGC/Q3	0	0	OFF
CWGD/Q4	1	0	Modulated

OUTPUT	STEERING	STATIC DATA	180°
CWGA/Q1	0	0	OFF
CWGB/Q2	1	0	Modulated
CWGC/Q3	1	0	Modulated
CWGD/Q4	0	0	OFF

Given a filtered BEMF signal, it is easier to detect rising/falling or changing of state of the BEMF more accurately. When this event is detected, the filtered signal is then fed to the comparator to provide the proper commutation sequence to the CWG peripheral.

This peripheral allows the user to specify combinations of signals as inputs to a logic function, and to use the logic output to control other peripherals and I/O pins.

4. Motor Prepositioning and Start-up

Since back EMF magnitude is directly proportional to the motor speed, detecting the back EMF at low speed can be extremely difficult. Thus, the sensorless commutation scheme does not work during motor start-up where the speed is at its lowest. To solve BEMF issues at low speed start-up, a motor start-up, prepositioning and open-loop operation procedure are used on this application to start and accelerate the motor until the back EMF is sufficient to provide information of the rotor position.

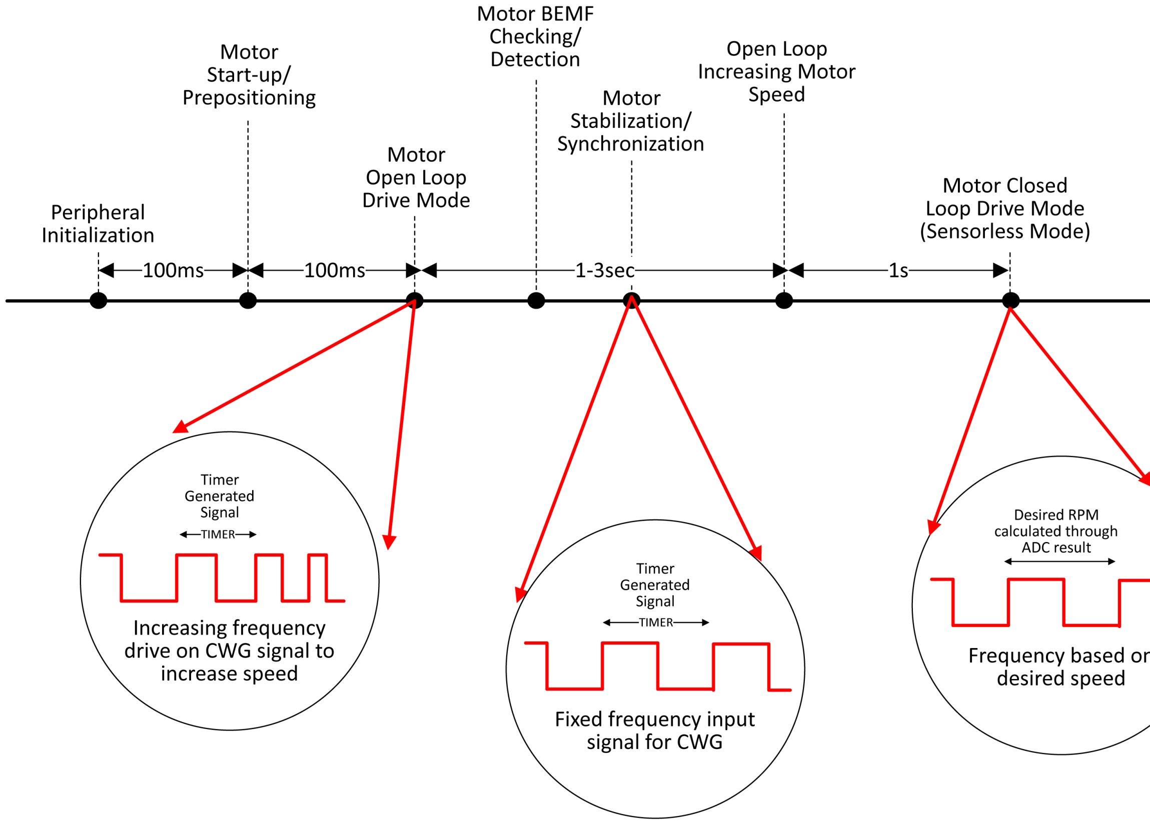
The sequence for motor start-up and prepositioning up to implementation of Sensorless mode is illustrated in Figure 4-1.

In this sequence, the motor is initially prepositioned, followed by open loop starting and energizing the stator windings according to the predetermined commutation sequence. This prepositioning of the rotor is done by gradually increasing the applied voltage over the winding and waiting a given period of time until the rotor has settled in a known position. The motor is then started in an open loop fashion, with inter-commutation time based on a predetermined set of frequency values. The inter-commutation time contains a set of increasing frequency value implemented through the use of Timer1. Over the course of Motor Open-Loop Drive mode, the Timer1 frequency values gradually increase, resulting in increased motor speed. As the speed increases the firmware also starts to detect and check the motor BEMF response.

In the case where the motor fails to synchronize and rotate after these procedures, a stall detection will be triggered, allowing the firmware to re-execute the procedure with a different inter-commutation time. This procedure continues until the motor successfully rotates. When it is successfully rotating, the inter-communication time values will become the default value and used every time power is applied.

Aside from the Timer1 value, the applied voltage also varies together with the Timer1 frequency at a certain ratio. This start-up procedure is known as variable-voltage variable-frequency control. Furthermore, the ratio of supply voltage and commutation frequency should be designed properly according to the motor and the load parameters so that the rotor can be forced to follow a proper motor acceleration. In addition, these parameters need to be determined on every user’s given application or system. Once the starting sequence is completed and the motor is running stable and synchronized at a certain speed enough for the back EMF to be detected, the control is then passed over to the sensorless commutation controller.

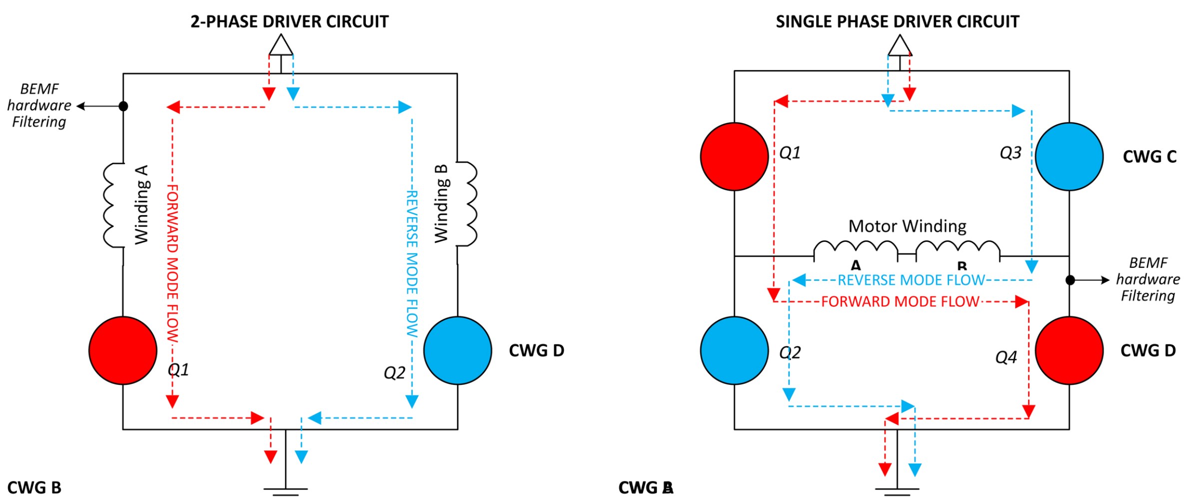
Figure 4-1. Motor Prepositioning and Start-up Sequence



5. Motor Commutation

The sensorless commutation is implemented through the use of the comparator, Complimentary Waveform Generator (CWG) and several timer interrupts. The comparator, together with the FVR and DAC as its reference, is used to detect the rising/falling edge of the filtered BEMF signal. The reference is set such that the BEMF magnitude can trigger and sustain a stable motor rotation. Once a change in state on the filtered BEMF signal is detected, the comparator will trigger a timer interrupt that signals the CWG to toggle its mode from Forward to Reverse. For single phase BLDC, the CWG Forward and Reverse modes or CWG Steering mode can be used to drive the H-Bridge MOSFETs alternately, while in the 2-phase the two MOSFETs are driven ON and OFF. MOSFET switches are used to alternately energize the two motor windings, allowing current to flow. Figure 5-1 shows the CWG Drive mode on the MOSFET switch driver of the two-phase BLDC motor. To learn more about CWG and how to implement its different drive modes, refer to TB3118, *Complementary Waveform Generator Technical Brief* (DS90003118): (http://ww1.microchip.com/downloads/en/AppNotes/90003118A.pdf).

Figure 5-1. CWG Drive Mode



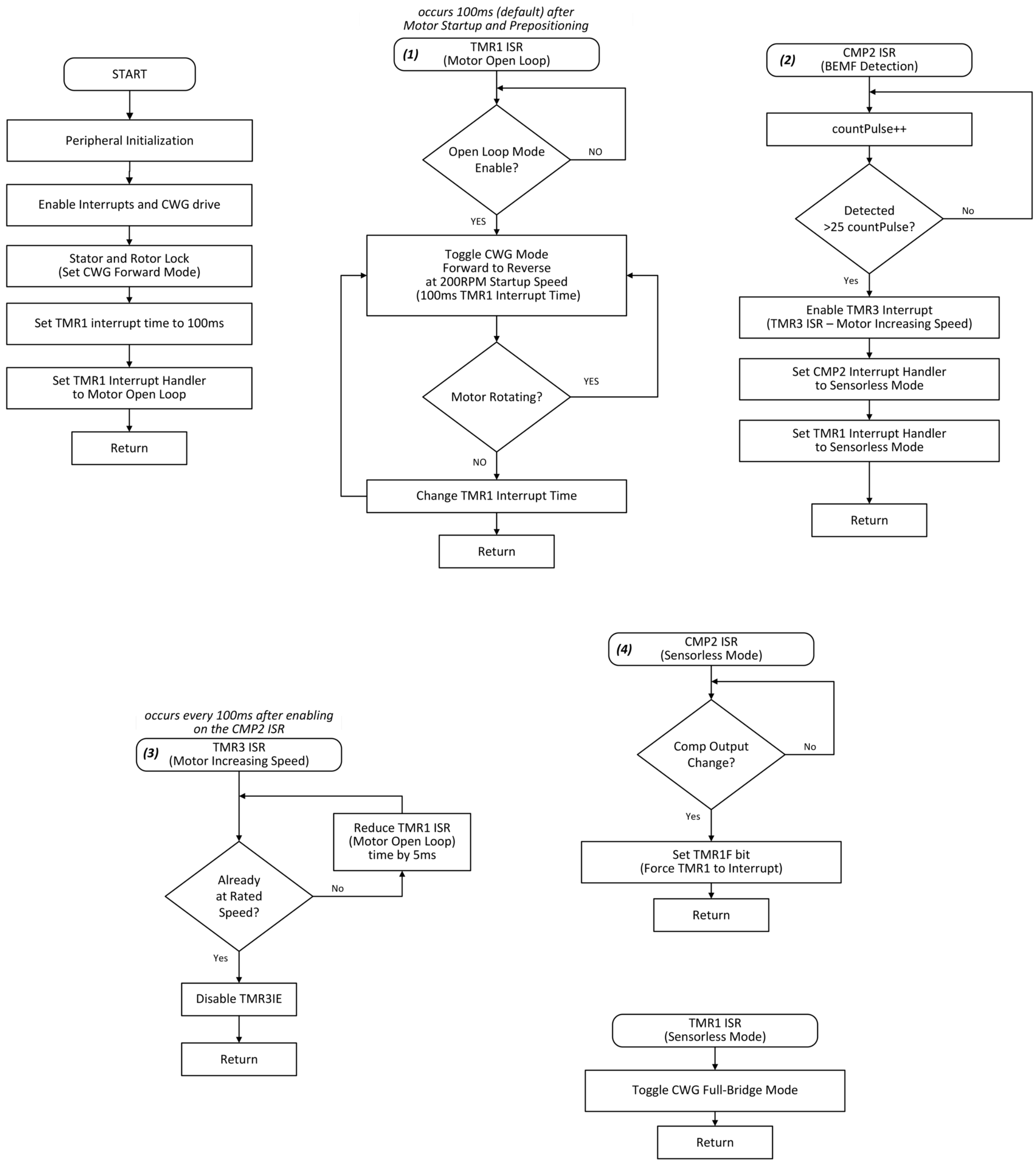
	OUT	FORWARD MODE	REVERSE MODE
Q1	CWGB	Modulated	
Q2	CWGD		Modulated

	OUT	FORWARD MODE	REVERSE MODE
Q1	CWGA	ON	OFF
Q2	CWGB	OFF	MODULATED
Q3	CWGC	OFF	ON
Q4	CWGD	MODULATED	OFF

6. System Firmware

To illustrate the exact code flowchart for the sensorless drive, Figure 6-1 shows the main code and the Interrupt Service Routine (ISR) used on the design. All peripherals used in the firmware are configured and initialized using the MPLAB® Code Configurator (MCC). "*Appendix B: MPLAB Code Configurator (MCC) Peripheral Initialization*" provides the procedures on how the peripherals are initialized using MCC. For the complete source code, refer to "*Appendix C: Source Code Listing*".

Figure 6-1. Main Code Flow



The motor start-up will begin after initializing the ADC, Comparator, PWM, DAC, FVR and CWG. The motor start-up and prepositioning are responsible for initializing and locking the rotor and stator at a known position and, enabling the comparator for detection of BEMF followed by setting the TMR1 Interrupt handler from default Interrupt Service Routine (ISR) to Motor Open-Loop mode routine. The Motor Open-Loop mode routine is a TMR1 ISR that toggles CWG mode gradually from forward to reverse at a predefined set of interrupt time. The toggling is done to create an open-loop motor rotation(1). This predefined time changes from time to time until it is tuned and the rotor shows a continuous or stable rotating motion. During this period, the rotor is running at a slow pace but with continuous rotating motion, thus allowing the BEMF pulses to be detected by the comparator(2). Once the comparator detects enough BEMF pulses, it will gradually increase the motor speed up to the rated speed(3) as well as start transitioning the control into Sensorless mode. In Sensorless mode(4), the comparator output serves as the trigger on when the CWG will change from forward to reverse or vice versa.

Related Links

10. APPENDIX B: MPLAB Code Configurator (MCC) Peripheral Initialization
11. APPENDIX C: Source Code Listing

7. Conclusion

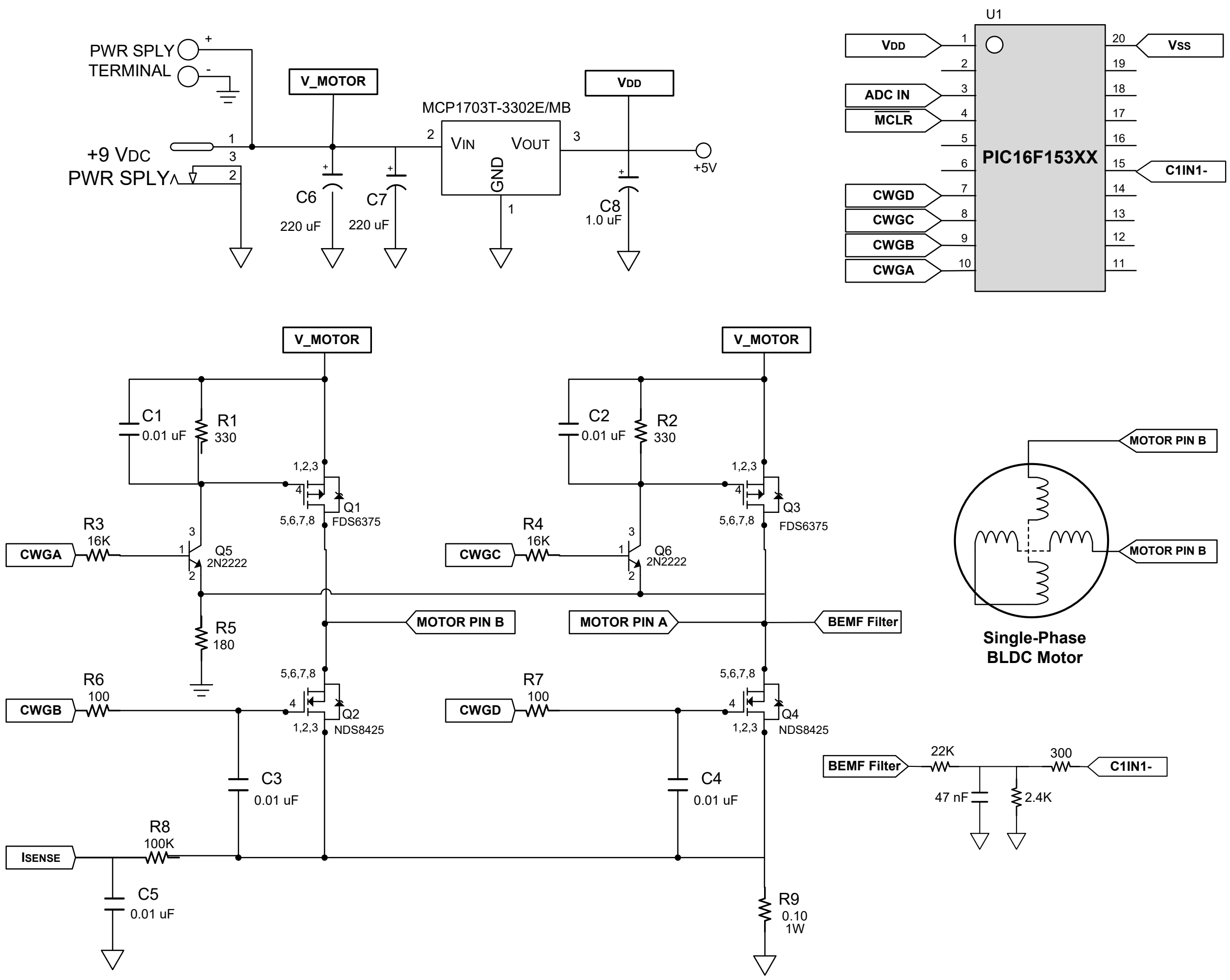
Single phase motor control applications tend to align with low-cost requirements. The traditional use of a Hall sensor for detecting rotor position adds to system cost and reduces MTBF. Thus, rotor position through sensorless detection can assist with system reliability and cost improvements. This application note implements a sensorless alternative and demonstrates how to easily drive a single or two-phase BLDC motor using a combination of Core Independent Peripherals (CIPs) from the PIC16F153XX microcontroller family and a simple low-pass hardware filter. Aside from the capability of successfully driving these low-cost motors, added peripherals on the PIC16F153XX family such as HLT and Temperature Indicator can also be used for added intelligence to the design. The Temperature Indicator (TempInd) can be used as an on-board temperature monitor while the HLT can be used to implement an intelligent motor stall detection.

8. Revision History

Doc Rev.	Date	Comments
A	09/2018	Initial document release.

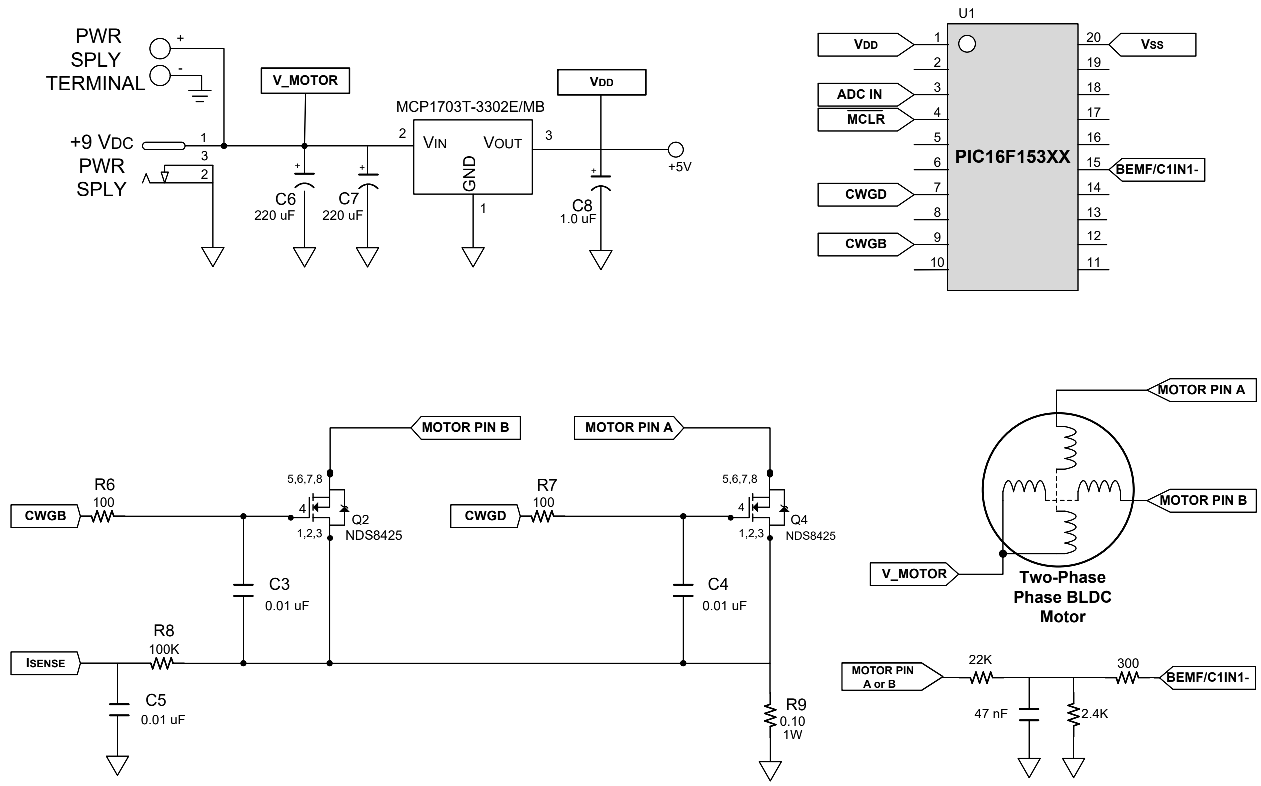
9. APPENDIX A: Circuit Schematics

Figure 9-1. Sensorless Single-Phase Brushless DC Motor Using PC16F153XX



APPENDIX A: Circuit Schematics

Figure 9-2. Sensorless Two-Phase Brushless DC Motor Using PIC16F153XX



10. APPENDIX B: MPLAB Code Configurator (MCC) Peripheral Initialization

In this application note, the MPLAB® Code Configurator (MCC) is utilized to easily configure the peripherals used in this motor control application. The MCC is a user-friendly plug-in tool for MPLAB® X IDE which generates drivers for controlling and driving peripherals of PIC microcontrollers, based on the settings and selections made in its Graphical User Interface (GUI). Refer to the MPLAB Code Configurator User's Guide (DS40001725) for further information on how to install and set up the MCC in MPLAB X IDE. The latest MCC file which contains the MCC setup and configuration for this application can be downloaded from the Microchip website (www.microchip.com). The user will find the MC3 file appended to the electronic version of this application note.

Note:
MCC Version 3.16 was used for writing this application note. The latest software version can be downloaded from the Microchip website (http:// www.microchip.com/mplab/mplab-codeconfigurator).

11. APPENDIX C: Source Code Listing

The latest software version can be downloaded from the Microchip website (www.microchip.com). The user will find the source code appended to the electronic version of this application note. The latest version is v1.0.

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