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R8C/25

180 Degree Sinusoidal Motor Control

Introduction

The YMCRPR8C25 Motor Control Evaluation kit comes loaded new with software that does trapezoidal (six-step) modulation using the hall sensors on the motor. This application note describes a method that does sinusoidal interpolation between the hall sensor transitions, to allow lower torque ripple and reduce audible noise. This algorithm is provided in a HEW project for users to download and try on their board. The source code is open and suitable for adapting to different applications.

Target Device

R8C25

Contents

1. System Overview

The software and hardware of this system is designed to allow sinusoidal commutation of a Brushless DC (BLDC) motor without the traditional encoder or resolver feedback. By using simple, low-cost Hall sensors, we have enabled a way to do sinusoidal commutation by estimating the angle changes between Hall state transitions. This allows us the advantage of sinusoidal commutation, which includes lower audible noise, lower vibration and higher efficiency and sometimes allows a wider speed range. Tests confirmed quieter operation and wider speed range by using this approach with the standard YMCRPR8C25 kit board and motor, as compared to both the Hall Trapezoidal and BEMF trapezoidal options.

Figure 1 shows the system block diagram. This differs from a standard Hall Commutated approach in one major way: instead of driving the 3-Phase Pulse Width Modulator is a six-step mode, as determined by the Hall logic state, we implement an angle estimator that produces a higher resolution angle. This new angle is used in a sine lookup table to produce the three phases of sine values. These values are multiplied with the voltage command that comes out of the speed control loop, to produce three 120-degree PWM values that are sent to the power bridge and driven to the motor.

In Section 2, we discuss the differences between Trapezoidal versus Sinusoidal commutation in how the transistors are modulated, and in how it affects motor performance. In Section 3, we discuss the details of how the basic angle and speed is derived from the low resolution Hall sensors (Speed Measurement). Section 4 describes how the high resolution angle is derived from the low resolution Hall signals (Angle Estimator). Section 5 discusses the modulation of the PWM in sinusoidal (180-degree) mode (3-Phase Modulator and 3-Phase Transistor Bridge). Section 6 discussed the modified sine table with 3rd harmonic injection (Sine Table). Section 7 discusses the closed Speed Loop (Speed Ramp Control, Proportional Gain, Integral Gain and Limiter). Finally, Section 8 describes the System Performance including our test methods, results, and limitations of this algorithm.

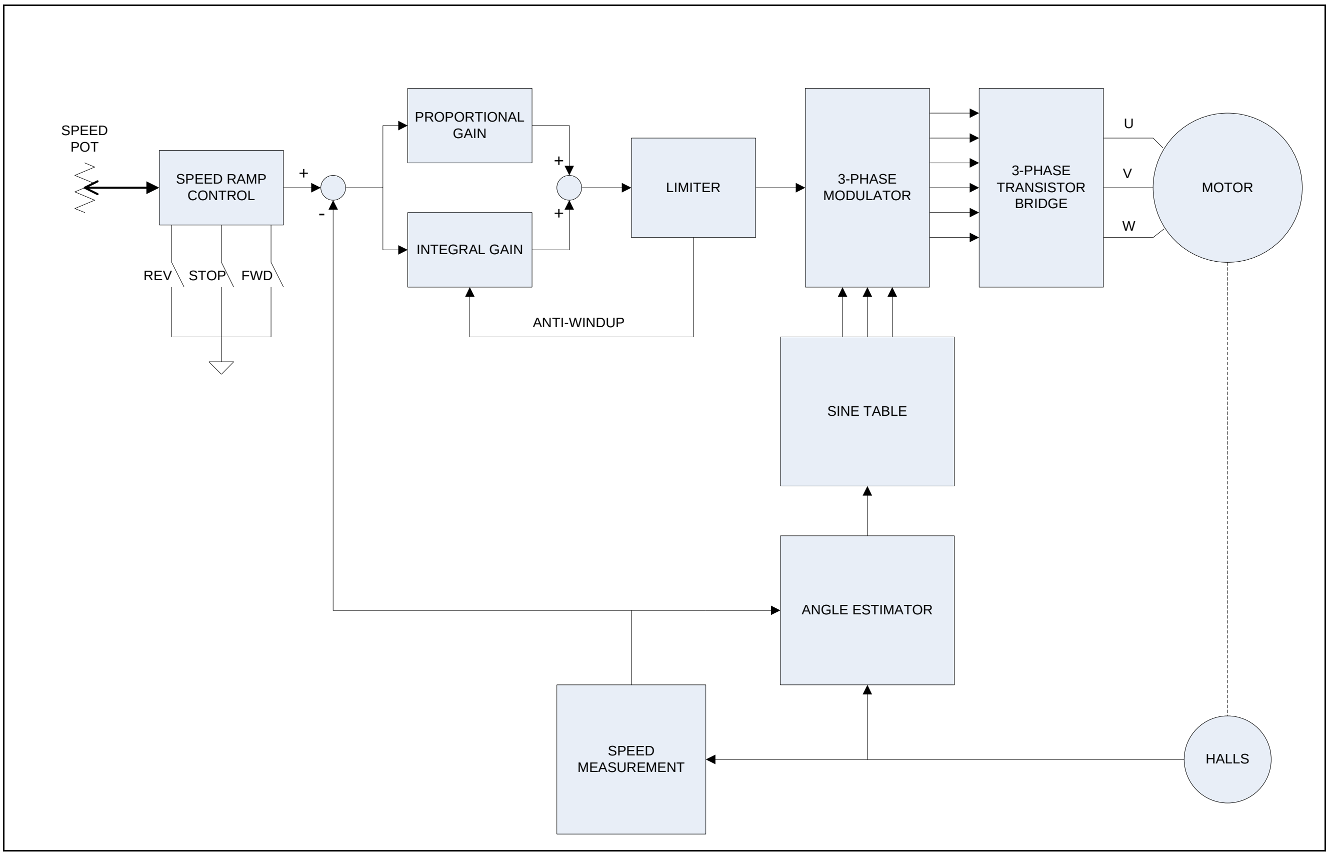

Figure 1. Functional Block Diagram of Sinusoidal BLDC Motor Control with Hall Sensors

2. Trapezoidal versus Sinusoidal Commutation

During trapezoidal commutation (also called six-step and 120-degree commutation), the motor voltages or currents are turned on and off to a constant voltage or current value. The mechanism for controlling the voltage or current is either a fixed PWM duty (for voltage control) or a closed-loop PWM current loop (for current control). In either case, the motor sees more or less square driving signals. During one of the steps, one phase is driven positive, one is driven negative, and the third is not driven. As the motor rotates, the phases are switched positive for two steps, then off for one step, then negative for two steps, then off again. When one phase is at a positive step, another is at a negative, and the third is undriven. These step changes must be aligned with particular motor angles in order to produce torque. The basic method of driving only two phases at a time, and driving each phase either positive or negative for two steps is why it is called 120-degree modulation. The amplitude of the DC step voltage (PWM value) is usually adjusted to control the motor speed, and the current level of these steps will be in proportion to the motor torque. The resultant waveform, as simulated in the Figure 2., is that of periodic, bi-polar square wave, with two steps positive, one undriven, two steps negative, then another undriven, for a total of six steps. The dotted lines show the motor Back-EMF during the undriven phase. We show the hall sensor waveform also, to show the relationship between the halls and the motor driving states.

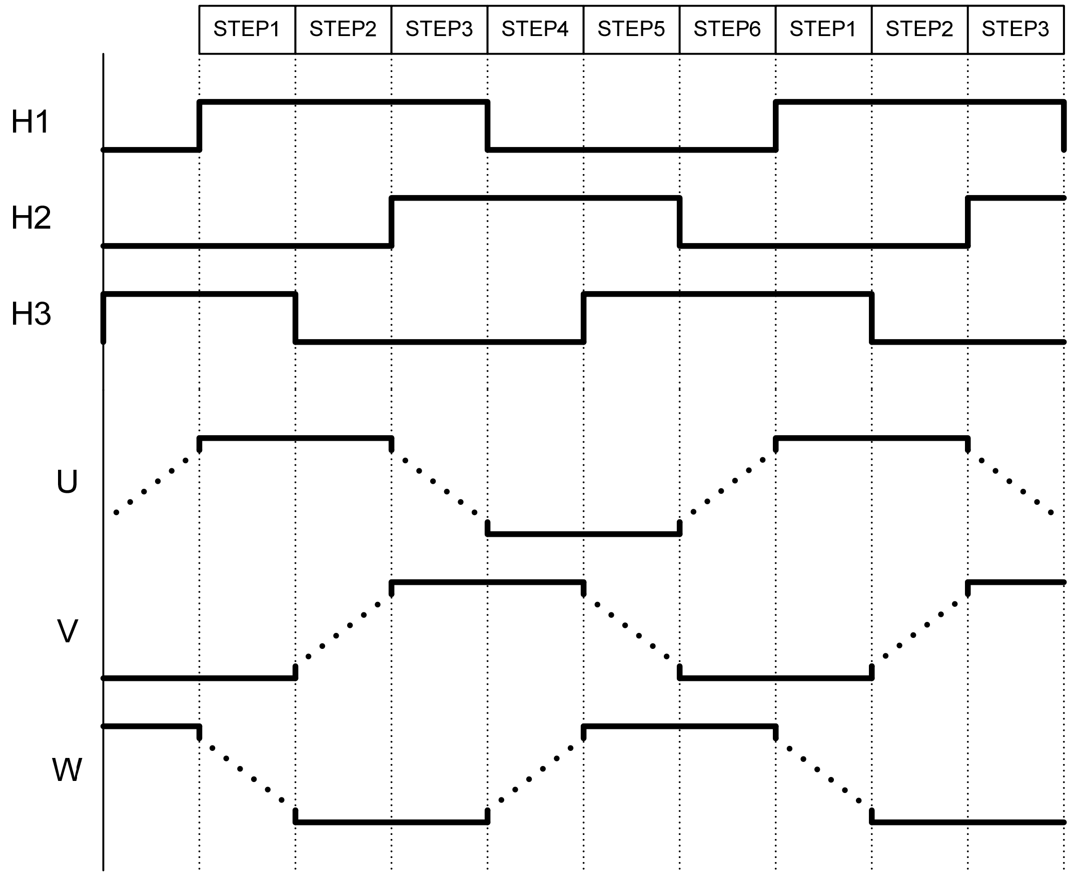

Figure 2. Six-step commutation relating hall sensors signals (upper three) to motor phase signals (lower three).

This six-step algorithm does a good job in driving the current in the motor in the desired direction and producing a net torque. Unfortunately, this torque can be distortion as a result of the trapezoidal wave shape impressed on the motor Back-EMF. This distortion exhibits itself as torque ripple and as audible noise from the motor body or load. It would be optimal to have a waveform sent to the motor that matches the waveform created by the back-emf. As many brushless motors have sinusoidal BEMF (called Permanent Magnet Synchronous Motors PMSM), it is possible to match these motors with a sinusoidal driving voltage. The Emerson motor included in the YMCRPR8C25 kit has a very sinusoidal Back-EMF and it has Hall sensors, so it is ideal for applying and testing this algorithm.

3. Using the Hall sensors to derive the motor angle and speed

The hall sensor signals provide the six steps of motor angle, as determined by the logical state expressed in the combination of the three bits. Of course, it is normal to have these three hall signals be spaced by 120-degrees, which means that two states (111 and 000) will not normally occur and do not have any meaning for commutation (some hall sensors are set up at 60-degrees, and in that case the 111 and 000 states are valid, but two others are not). Because there are six possible states in 360-degrees of electrical rotation, we can say that each state defines an angle within 60-degrees. We could also say that at Step 1, we are at 30 degrees, plus or minus 30 degrees.

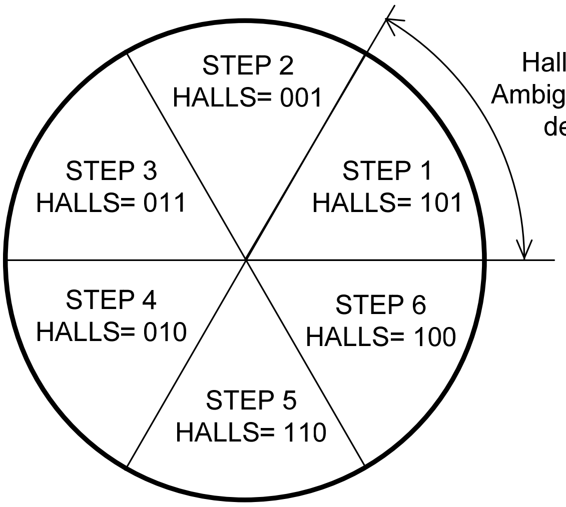

Figure 3. 3-Phase Hall Sensors provide angular resolution of 60-degrees.

There is other information encoded in the three hall bits which we can derive for purposes of motor control. We can measure the frequency of a single hall signal to determine motor speed. As long as the motor is rotating continuously, the frequency will be in proportion to the rotational speed. We might also detect a frequency on a single hall signal if the motor is oscillating and not rotating continuously, so this method can be fooled. We can also detect the order in which the hall sensors change state in order to detect the rotation direction; this technique can detect oscillation to help us reject false speed measurements. If we derive the speed information from each hall state change, we can get six speed updates for each electrical rotation.

The method we use to derive the motor speed from the halls is not to measure frequency directly, but to count the time between hall transitions. By measuring the time per step, we can get an updated speed measurement on each transition. We measure the time using a 16-bit hardware timer, and divide the count value into a constant, which provides a result that is a speed of whatever units we want to use, such as RPM or Radians-per-second. The value of the constant is determined by the frequency of the clock counting the time, the poles of the motor, and the unit we want to use. In our software, we sized the constant to work with the Emerson motor, with 10-poles, and with an output in Radians-per-second.

4. High Resolution Angle Estimation

Provided that the motor speed can be measured by hall sensor frequency, and that motor angle can be captured on a hall signal transition, then it should be possible to calculate the angle of the motor as it turns. We use an algorithm that captures the hall transitions and sets each to a specific angle, then uses the last measured speed to increment that angle to estimate how far it has changed between hall transitions. In this way, we should be able to get an angle value that increments or decrements smoothly, rather than at only 60-degree steps. We can use that angle to produce a sinusoidal waveform, much smoother than six-step trapezoidal, from the same discrete hall sensor data. This interpolation is valid as long as the motor speed is high enough for it to be measured, and consistent enough that it is within a reasonable accuracy before the next hall transition occurs.

To do the interpolation, each of the six hall states is divided up as equal parts of the 360-degree electrical rotation. Then, when a transition occurs, it triggers an edge-sensitive interrupt. During that interrupt, the state of the halls is read, and an angle value is loaded into the estimator. That angle that is loaded is read from a table that has the six hall states and their associated angle values.

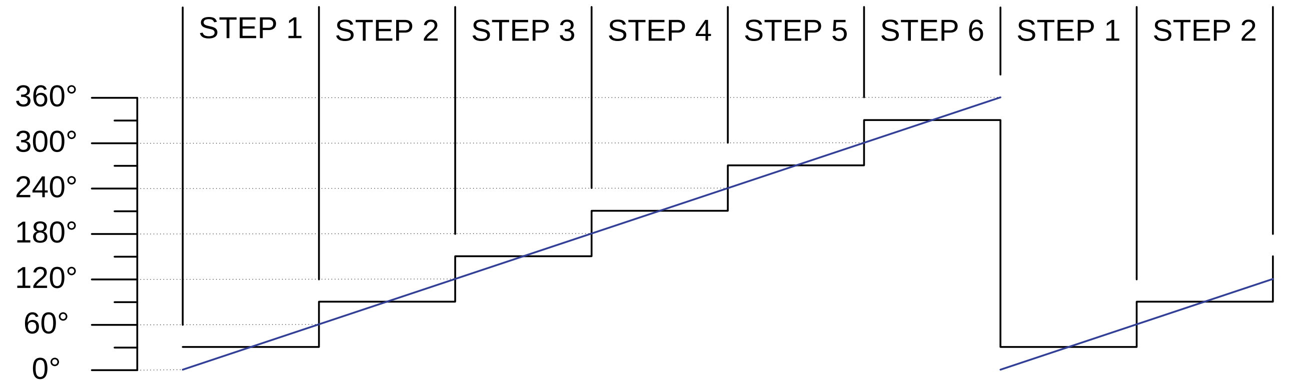

Figure 4. Hall Angle Data (stepped) and Interpolated Angle Data (linear)

During the time intervals between the hall edges, the angle value is incremented or decremented during the PWM interrupt by a value that is proportional to motor speed. This value is scaled so that, if the motor is turning at a constant speed, the angle register should be incremented to same angle that will occur on the next hall edge. The angle estimation is a first order linear approximation, which is updated on each hall edge, and it will be accurate so long as the changes in speed are not a large percentage between hall edges. The worst case for this is at lower speeds. At 500 RPM, for example, to get an error of 30-degrees per step (about the same as six-step commutation), the motor would have to accelerating or decelerating at about 40,000 RPM/sec, which is very fast acceleration.

5. Modulating the 3-Phase Sinusoidal Waveform

The timer used in the R8C for 3-phase complementary PWM is TimerRD, as shown in Figures 5 and 6. In Complementary PWM mode, it offers three high-side and three low-side PWM outputs, each with adjustable deadtime between the upper and lower pairs. The timer is 16-bit, allowing any value up to that point for a peak value. We use a PWM maximum (TRDGRA register value) of 667, which translates to 1334 clocks per PWM period. The timer counter register, TRD0 counts up to the value of TRDGRA, then turns around and counts down until another counter, TRD1, reaches zero, then it counts up again. The difference between the two counters is the Deadtime value which is preloaded before the timer is started. At the 20MHz crystal frequency, that count value gives us a 15kHz PWM frequency. TimerRD allows us to get an interrupt on the peak (maximum) of this count, or at the trough (the minimum). We use the trough interrupt, and in the routine we calculate the newest speed ramp setting, calculate the motor angle estimate, lookup the three phase sine values, and multiply them with the speed loop output value. Finally, these are scaled and offset to fit in the PWM compare buffer registers (TRDGRD0, TRDGRC1 and TRDGRD1), and the new values are loaded into the actual compare registers on the next counter trough.

Creating a sinusoidal wave shape that is accurate to the motor rotational angle is now possible since we have a reasonably accurate angle. The value of the estimated angle is calculated in each PWM interrupt, so we use that value at that point to do a lookup to a sine table to get the three sine values for the three phases. Of the U, V and W phases, the U-phase angle is selected directly from the angle value as an index to the table. The V and W values are taken from the same table, but at index offsets that are equivalent to 120 and 240-degrees respectively.

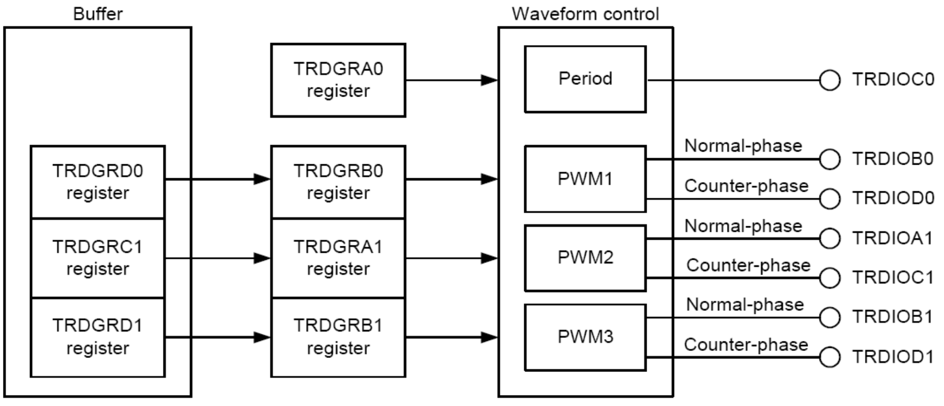

Figure 5. Register Diagram of TimerRD in Complementary PWM Mode

The sine values for U, V and W, as read from the sine table, are not usable directly into the Pulse Width Modulator values. First, they are multiplied by a value output from the speed control loop. It is this loop that determines if the motor is going too slow or too fast, and adjusts the voltage command value to be higher if the motor is too slow, or to be smaller if the speed is too fast. The value of this can range from zero to 4096. This value is somewhat arbitrary, but is chosen in this range to provide plenty of resolution for the proceeding calculations. The voltage command is multiplied into each of the three sine values, each now in proportion to the commanded voltage. Each product is then scaled down and offset before being fed into the PWM timer comparator buffer register values (TRDGRD0, TRDGRC1 and TRDGRD1).

For more information on how TimerRD is used in Complementary PWM mode, see the R8C25 Hardware Manual (REJ09B0244-0300), section 14.3.

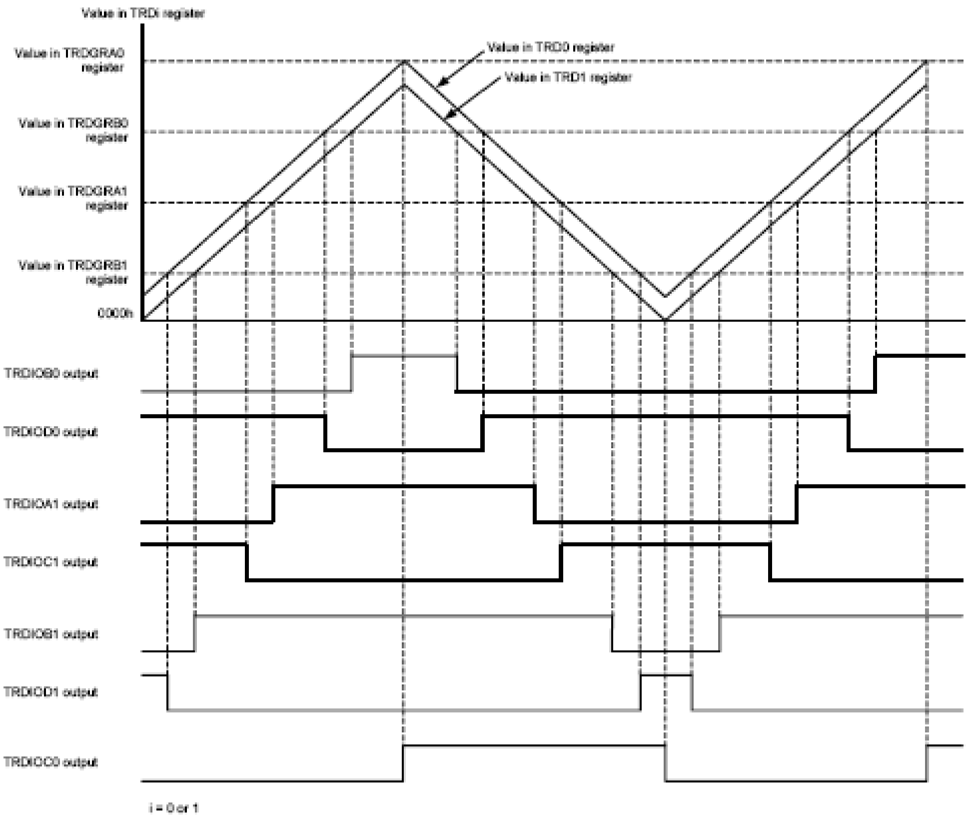

Figure 6. Output Diagram of Complementary PWM Operation

6. 3rd-Harmonic Injection

The sine wave generated in the table can be very pure, and this will translate into a PWM voltage equivalent which is also pure. The voltages of each phase will rise and fall in a sinusoidal waveform, and this is fine for driving the motor. However, one problem becomes apparent when we look at each waveform relative to the bus voltage. We find that when we want the motor to go at maximum speed, the sine waves peaks reach the bus voltage rails. When one phase is at a positive peak, the other two phases are at a negative value of only one-half the negative peak (with respect to the midpoint of the bus voltage, where the duty would be at 50%, the middle of the sine waves are centered here). The same is true for the negative peaks, the one phase is at the negative rail, but the other two phases are not at the plus rail. This means that at any moment, we cannot fully use the available bus voltage to allow the real maximum speed at the motor.

There are a few methods to deal with this. One method is the Space Vector modulation approach, which basically sets one phase at a time equal to a bus rail, and pivots the other two phases around it, until one of the other phases reaches the rail, then the pivot switches to that phase, and it works its way around to both rails on all three phases. This utilized the whole bus voltage, but requires the algorithm to detect which phase is stationary, and which phases are pivoting. Also, the Space Vector approach uses 100% modulation on the pivot phase, which means that some gate driver chips may experience a time without a voltage refresh, especially at lower speeds.

Another method which we use in this code is the method of third-harmonic injection. In this method, the only thing that differs from the standard sine lookup table is that the sine table has a third harmonic component added to the fundamental sine component. The amplitude of the third-harmonic component is one-sixth that of the fundamental. The resulting waveform looks somewhat flattened, as the peaks of the harmonic and the peaks of the fundamental are opposite in polarity, so the normally rounded peak of the sine is dipped down slightly. The motor phases have the modified sine wave on each, 120-degrees apart. Each phase has the same third harmonics which, after the 120 and 240-degree index offsets, are still exactly the same amplitude and phase. The resulting phase-to-phase voltage is a clean sine wave, because the third harmonic component is entirely canceled out. What is more important for us is that each phase is now centered within the bus rails better, so that we can now utilize 16% more of the bus voltage for motor control than we could without the added harmonic. The benefit is higher speed capability, which can be utilized without any penalty in processor demand. The only difference in using this over the pure sine version is in the data loaded into the table we read to determine the sinusoidal wave form, and in the scaling of the voltage command limiter. For the benefit of the user, we provide both tables in the code (in file sine.h), where the original sine table is commented out.

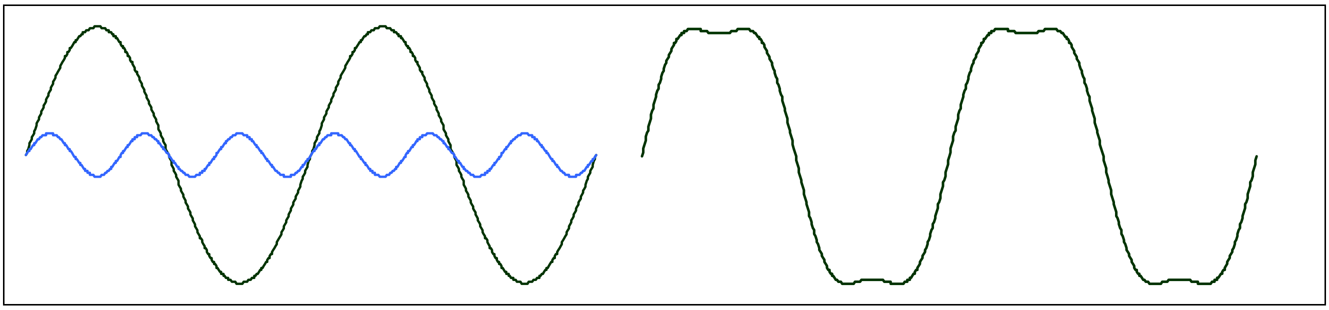

Figure 7. Sine waveform (left black) with Third-Harmonic (left blue) and the sum (right)

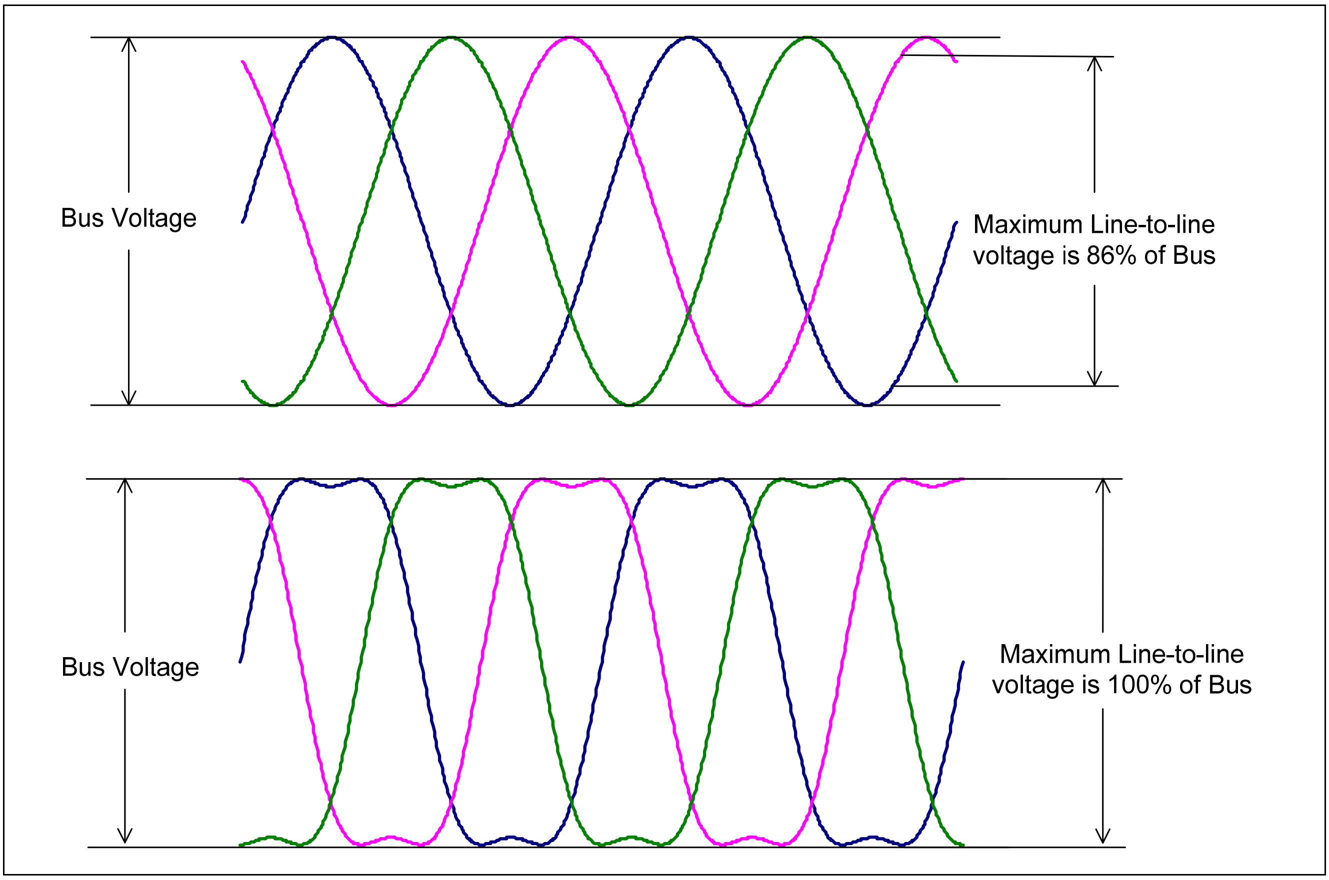

Figure 8. Comparison of the Effective Line-to-line Voltage Available Before and After Adding Third Harmonic Injection

7. Closing the Speed Loop

The data already collected from the Hall sensors includes the speed, as was used in the linear angle interpolation. This measurement is updated on every hall signal edge. We can measure the time between edges and use it to calculate the motor speed. This can be used to close a speed loop; we use a Proportional Integral (PI) loop.

The speed control loop, derived from the hall edges, works on the kit motor through a speed range of about 10:1 (4000 RPM down to 400 RPM). Below 400 RPM, the update rate from the halls is not sufficient to provide accurate data, so it can go unstable. We set the minimum speed at 400 RPM to avoid the instability, and when accelerating or decelerating through that range, we do it quickly enough to prevent the build up of oscillations, and we set the measured speed at zero if it is below the cutoff point where the timer counting the speed underflows. For applications that need wide range speed control, it may be necessary to use a higher resolution feedback device, such as an encoder, resolver, or higher resolution pulse tachometer.

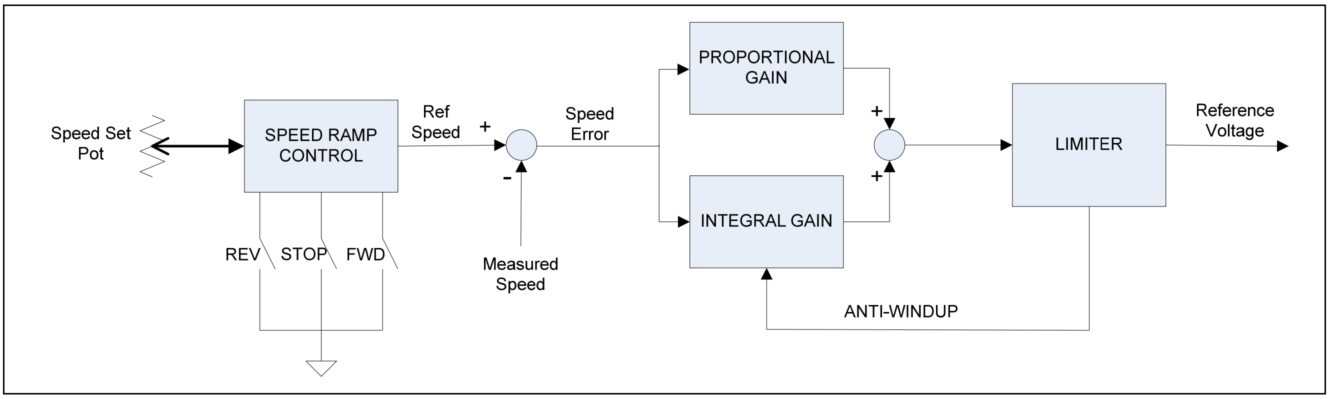

Figure 9. Block Diagram of PI Speed Control Loop

In the PI speed loop, the Reference Speed is derived from the Speed Set Pot, and is ramped up or down in response to the user operated direction switches. The Speed Ramp Control is necessary to control the rate at which the motor speed is changed. Next, we find the difference, by subtraction, between the motor speed we measure and the reference speed that we want the motor to go, the difference is the Speed Error. The Speed Error is used to calculate a new PWM value that is multiplied by our sine waveform at that given moment in time, and is sent to the motor phases as a 3-phase voltage. The calculations have a purely proportional component (the P part of PI) which is the error multiplied by a constant Kp, and an integral component (the I part), which is the error multiplied by the constant Ki, and which is integrated (accumulated) over time. These are added together to come up with the new PWM commanded value. For more information on PI and PID control loops, see the application notes links on the reference page. In the code, the Kp and Ki constants are found in the parameter_define.h file.

There is a Limiter in the PI loop software that checks to see if the sum of the Proportional Gain and Integral Gain stages exceeds the Reference Voltage maximum limit. If it does, the value of the integrator is reduced by the amount of the of the overage. This prevents a situation called Loop Windup, which is a problem where the integrator will continue to accumulate the error signal during heavy motor loads, even though the applied correction is at maximum. If the load is reduced, and the motor is able to move freely, the motor may "wind out" or overshoot the speed to a maximum level until the value in the integrator is reduced to a normal level. By using anti-windup to clip the integrator value, the motor will recover the speed in a well behaved manner, without a large overshoot, after a heavy load is removed.

8. System Performance

As was discussed in section 5, there is a certain limitation to our ability to calculate speed accurately as we go lower in speed. Since the speed information is necessary to calculate the interpolated angle and the associated sine functions, then it is necessary to be above this critical speed in order to get reliable sine estimation. If we operate the motor below this speed (such as during acceleration and deceleration), we switch to a fixed amplitude waveform, which is the same as trapezoidal six-step mode.

Another potential cause for error in the angle estimation is the hall sensors themselves. If the signal from each hall sensor is not perfectly symmetrical or has jitter with respect to another hall sensor, then this will appear as angular anomalies on the hall edges and the sine waveform we calculate from this will have discontinuities. For the speed calculations, we apply a low-pass filter to the calculated speed measurements to reduce the variation from one step to the next. For using this software for motor different than that provided with the kit, it may be necessary to scale the filter or allowable speed range to keep that motor operating smoothly.

As the speed of the system goes up to very high rates, the sine wave approximation will begin to suffer distortion. As the electrical frequency of the motor approaches the update frequency (the PWM frequency), we reach a point at which the sine wave becomes very distorted, and the advantage gained from having a sinusoidal wave shape has diminished. Also, since the sine value is held for the entire sampling period, there is a net phase lag caused by the sampling period, relative to the sine period. As speed continues to go up, the phase lag will become large enough to affect motor performance. The point at which this might be a concern is when the electrical frequency is about 1/20th the sampling frequency, above that rate, the phase lag and distortion become very significant, and loss of efficiency may result.

Rapid changes in speed can also cause estimation error. If the motor changes speed significantly during the interval between hall transitions, then the estimated angle will be incorrect. The next hall edge will correct the angle, but the difference between the estimated value and the next measured value will cause a discontinuity in the sinusoidal waveform. Attempting to predict this rapid change is not feasible in most systems. For our purposes, we say that this error in angle that is caused by changes in speed is always more likely to happen at lower speeds, where the difference is speed is a higher proportion of actual speed. We use a technique of switching out of angle interpolation mode and using six-step commutation when the speed is below a pre-determined value. It may be possible to still have some control of the speed loop, despite this, so it may continue to operate below this threshold, but eventually, even the speed estimation will go unstable at lower speeds. This is where higher resolution feedback systems are more appropriate for low speed operation, such as below 400 RPM.

Testing on the dynamometer shows that the speed control loop is very tight with this algorithm. The graph in Figure 10 shows the speed regulation (top line) versus a step change in torque load.

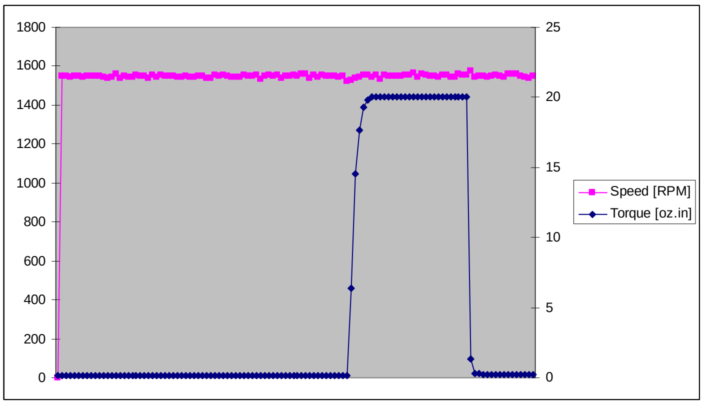

Figure 10. Speed Loop Performance on Dynamometer under step load change.

9. Hardware Implementation on the YMCRPR8C25 Motor Control Evaluation Kit

In setting up the YMCRPR8C25 board to run the 180 Degree Sinusoidal software, one should configure the board jumpers to the same configuration as the Trapezoidal 6-Step operating mode. Figures 11 and 12 are provide additional information the hardware on the board, and should be helpful in relating to your own motor control design and to the software referenced in this Application Note.

As is seen in Figure 11, the Hall sensors are first buffered, then connect to the MCU at the INT1-3 interrupt inputs. There, the edges of the hall signals triggers an interrupt routine (ex. int1_isr) that calls the hall_cal() function that calculates the speed, by first measuring the time since the last hall edge interrupt. The new speed value (spd_act) is filtered elsewhere for use in the speed loop and angle calculation functions. This same function also calibrates the rotor angle to the new hall edge.

The PWM signals, as generated in TimerRD, are connected to the on-board IGBT power module, U10. The signal names here are UP (for U phase, positive side), UN (U phase, negative side) and so on for each of the three phases. Note that the IR IGBT module we use has active low inputs, so the PWM values will drive low to turn a transistor on in the bridge. There is a software setting for changing this; PWM_ACTIVE_STATE in parameter_define.h can be set to 1 if different gate drivers are used that have active high inputs.

The same IGBT module has an input for directly disabling the transistor operation, in case of a fault. We show this input on the module as ITrip, and a similar signal is sent to the MCU to INT0 input. This input will disable the PWM output of the TimerRD PWM. We recommend that user have at least one or the other approach in their designs to detect and protect from overcurrents. See the YMCRPR8C25 Users Manual for full schematics and other information on how this is implemented.

The speed input potentiometer is input to an A/D input pin, labeled AN4. Other analog inputs are implemented on the board for monitoring Bus voltage, Bus current and IGBT Module temperature. For simplicity, these are not shown, nor are they implemented in this reference software. The Hall Trapezoidal and BEMF software that comes in the kit does use these and the schematic shows details on how they are implemented.

The user switches, SW1, SW2 and SW3, as seen in Figure 13, function as the Forward Start, Stop, and Reverse Start controls. This should work the same as in the other kit reference software. The LCD will show the direction status and the commanded speed (top), and the measured speed (bottom). This software, however, does not include the GUI interface that allows viewing the speed and current on the computer. Note, when running in one direction, if the other direction button is pressed, the motor will stop, but it is necessary to press the stop button before the motor can go again in either direction.

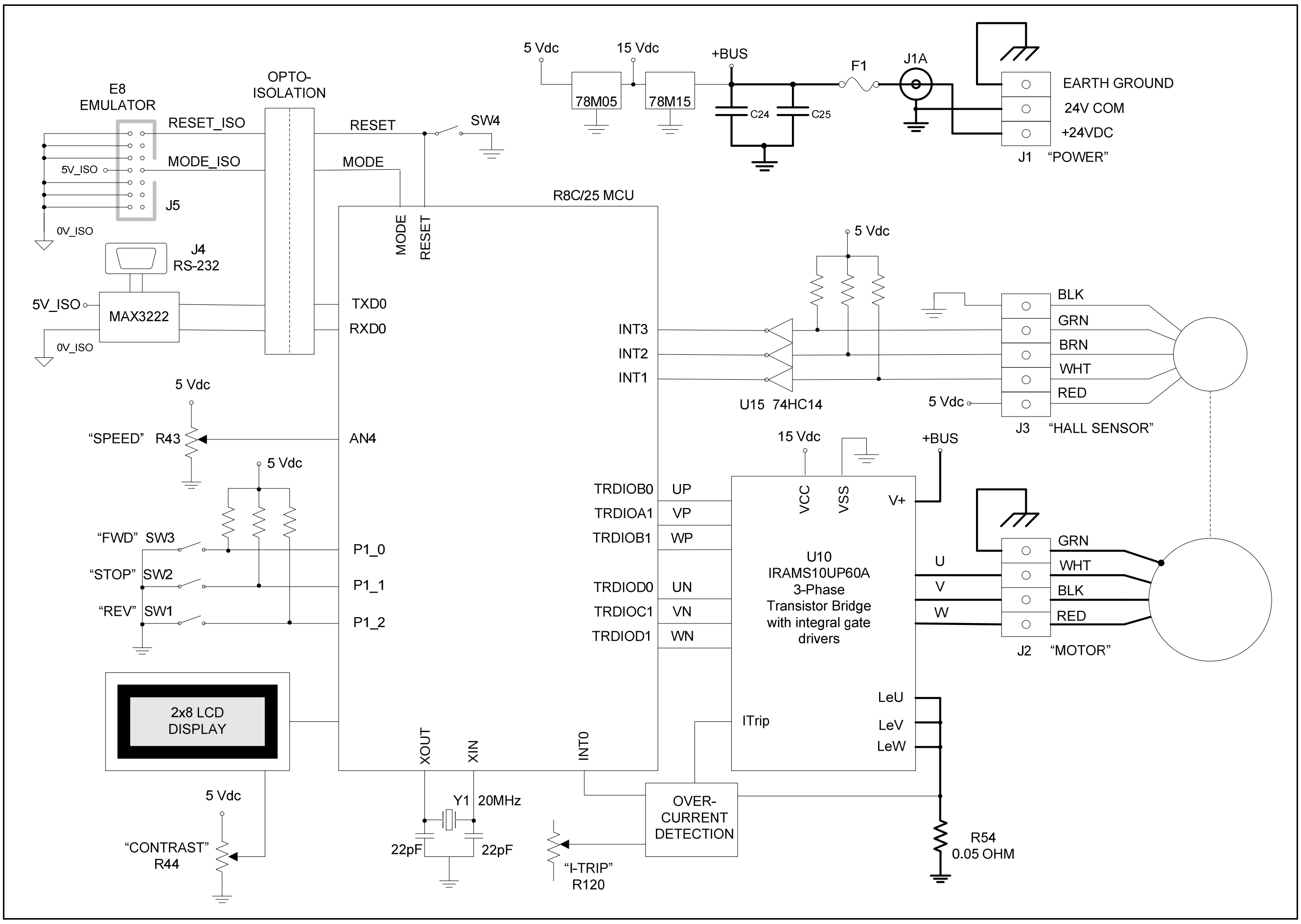

Figure 11. Electrical Block Diagram of YMCRPR8C25 Motor Control Board

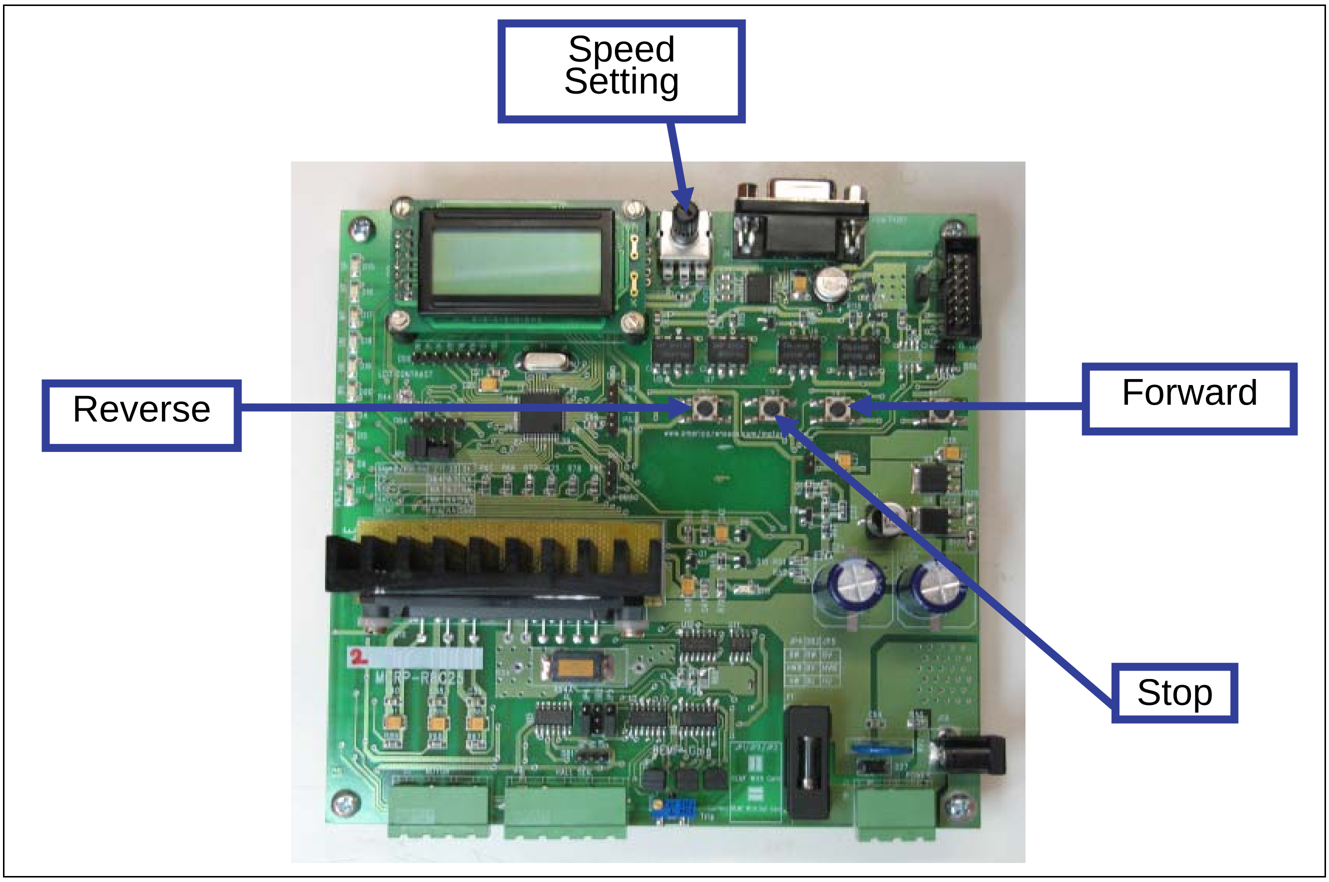

Figure 12. YMCRPR8C25 Board Top View and User Interface

Website and Support

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Revision Record

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1.00	Feb.12.09	—	First edition issued

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