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Stepper Motor Control with dsPIC® DSCs

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INTRODUCTION

This application note describes how to drive a stepper motor with a dsPIC33F motor control family DSC.

The eight PWM channels (six pins from the PWM1 module and two pins from the PWM2 module) are used to control a stepper motor in all possible ways, whether it is bipolar or unipolar, using full step or microstepping, open or closed loop, without the need for external jumpers or complicated logic circuitry.

The dsPICDEM™ MCSM Development Board Kit (DV330022) was used in this application note. This kit includes the dsPICDEM MCSM Development Board, Stepper Motor, Power Supply, and Plug-in Module (PIM). The hardware topology is very simple, consisting of just the dsPIC® DSC, the drivers and two H-bridges. Each MOSFET in the dual H-bridge is controlled by one PWM signal. The powerful PWM module of the dsPIC DSC features independent or complementary control over each of the four PWM pairs, plus an additional override function on each pin, which gives even more control over the power MOSFETs.

The dsPIC DSC is used to achieve high-speed microstepping in closed loop current control. For this task, voltages higher than the motor rated voltage are needed to force the current quickly through the motor windings. These high voltages require a high PWM frequency with a synchronized ADC for fast and accurate current control. Fast timers and high processing power are also needed since one microstep can be as short as one PWM period.

The dsPICDEM MCSM Development Board was designed to work with drive voltages of up to 80V and therefore accommodate a wide range of stepper motors and driving algorithms. Since high voltages are used relative to the stepper motor rated voltage, a very fast reacting controller is needed. A PWM frequency of 40 kHz was chosen to have the smallest possible reaction time. For example, having a stepper motor with 2.3 ohm and 4 mH per phase driven at 80V, the current needs just 70 microseconds to reach the rated level of 1.4A. This is under three PWM periods with 100% duty cycle. At 24V, 10 PWM periods (250 microseconds) are needed to reach 1.4A.

FIGURE 1: dsPICDEM™ MCSM DEVELOPMENT BOARD BLOCK DIAGRAM
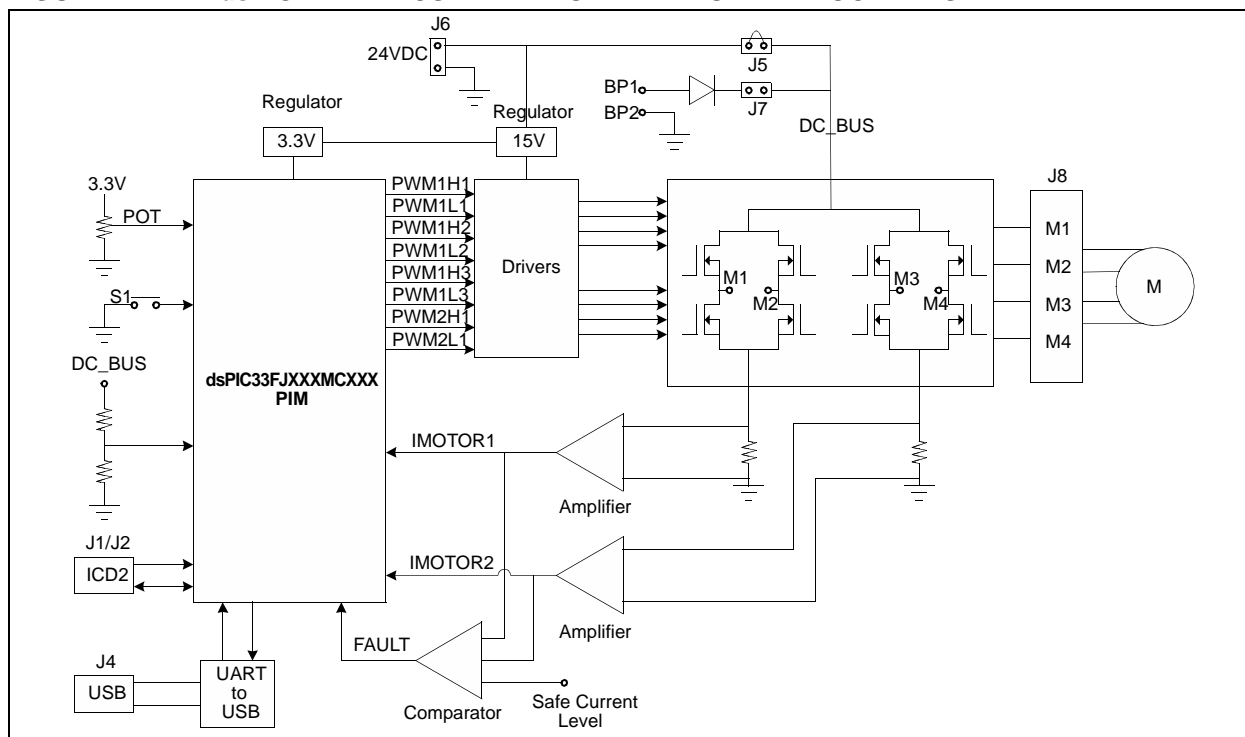
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OVERVIEW OF CONTROL TOPOLOGIES

This application note discusses several operating modes for stepper motor control. The following is a summary of the control methodology used in this application note, which can be selected using simple defines in the code or in real time through DMCI:

• Open Loop – Fixed Voltage
• Open Loop – Fixed Current
• Closed Loop Current Control

Each of these methods can be operated with a different granularity of voltage steps fed to the motor windings. The different granularity options available in this application note are:

• Full Step Mode (1/1 Step)
• Half Step Mode (1/2 Step)
• Microstepping:
  - 1/4 Step
  - 1/8 Step
  - 1/16 Step
  - 1/32 Step
  - 1/64 Step

Different decay modes are also implemented in this application note, which can also be combined with any control method and with any number of steps (full, half or microstepping). The available decay modes are:

• Fixed Decay Mode, which is configurable to either slow or fast decay
• Alternating Decay, which combines both slow and fast decay

Decay modes are described in detail in upcoming sections of this application note.

FULL STEP, HALF STEP AND MICROSTEP

In applications where high positional accuracy and low vibrations and noise are needed, the ideal waveform for driving a stepper motor winding is a sine wave. A two-phase stepper motor is driven by two sine waves shifted 90 degrees apart driving each of the motor windings.

All stepping modes are derived from the sinusoidal mode by adjusting the granularity of the driving sine wave. A full step is the largest step and it consists of 90 degrees of one sine wave period. A half step represents half of that and so on. Microstepping is used to increase the rotor position resolution and to reduce vibration and noise in motor operation. With typical motors, a microstepping value of 1/32 is more than enough to achieve the best performance. Going over this point will not usually bring significant improvements to positional accuracy, although running noise may decrease. The motor inductance and drive voltage play a key role here. Lowering the motor inductance value or increasing the drive voltage will give a better resolution to smaller microsteps.

A microstep table consisting of desired current or voltage levels is generated starting from a cosine, as shown in Figure 2. The x-axis is divided into evenly spaced intervals based on the desired microstep size. This application note uses a resolution of 1/64 microsteps, thus resulting in a number of 256 points per period. However, in the software implementation, one cosine period is divided into 1024 points. This allows the microstep resolution to be easily increased up to 1/256 if needed. The values of the cosine at each of these time intervals is stored in a look-up table that will later be used to reconstruct the original cosine at any desired resolution. The properties of the cosine function allows us to store only the first quadrant of the function in the look-up table (256 values, one-fourth of a period), while the other three quadrants are reconstructed from this first one.

FIGURE 2:   MICROSTEP GENERATION
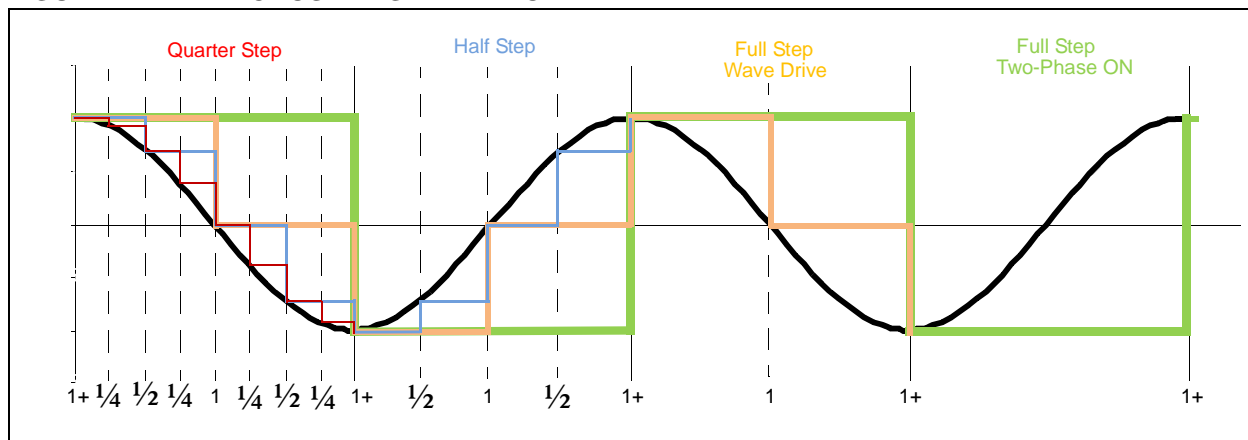
The values represented in the microstep table represent different things depending on the operating control mode. If the control mode is open loop voltage control, then this table represents desired voltages to be applied to each winding. If the operating mode is closed loop current control, the values in the microstep table represent current references. In both cases, the table is scaled with the maximum allowed voltage or current, as appropriate.

Figure 3 shows the voltage and current waveforms for full step generation in closed loop current control. The squared line represents the voltage command. The larger signal represents the current for the commanded voltage.

In Figure 4 microstepping is shown. Notice how the reference voltage has greater granularity than in Figure 3. This is because a 1/4 microstepping is used.

FIGURE 3:   FULL STEP MODE PHASE VOLTAGE AND PHASE CURRENT
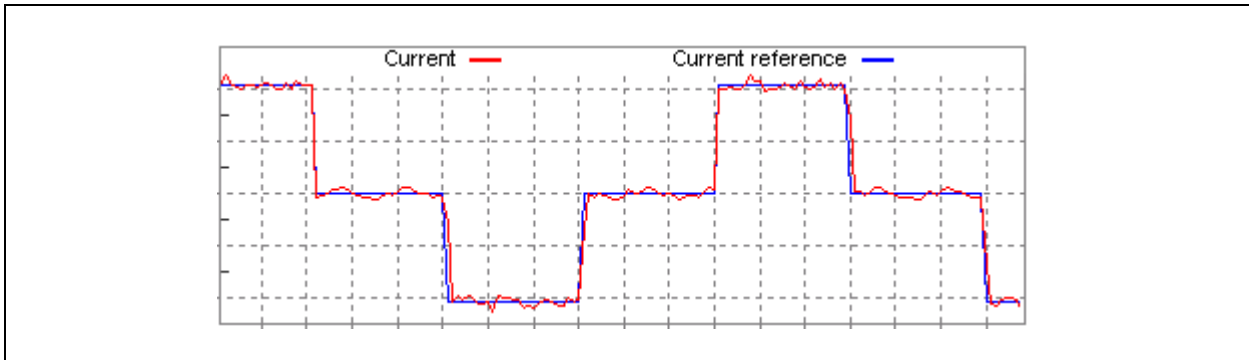
FIGURE 4:   MICROSTEPPING WITH 1/4 STEP SIZE
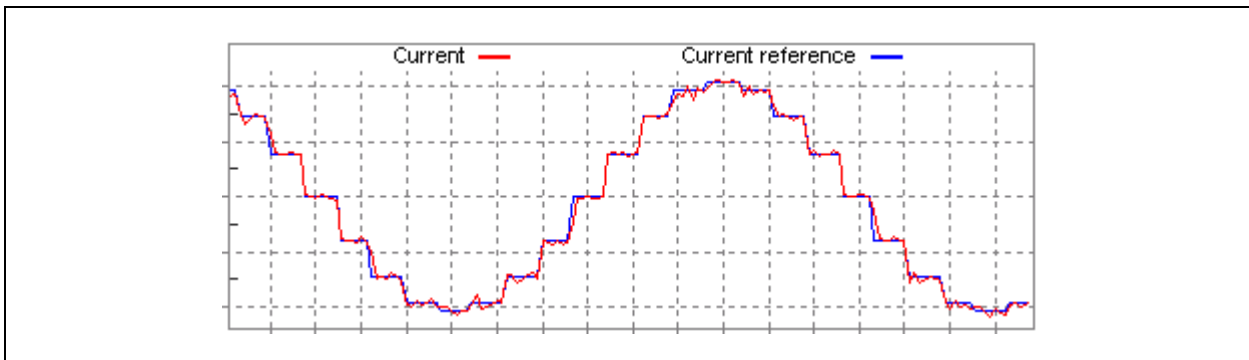
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Users can change microstep granularity by changing the value of the `stepSize` variable. The value of this variable can range from 0 to 6, which represents the granularity detailed in Table 1.

TABLE 1:   STEP MODES

`stepSize` value	Step Mode	Total of Steps Per Cycle
0	Full Step	4
1	Half Step	8
2	1/4 Step	16
3	1/8 Step	32
4	1/16 Step	64
5	1/32 Step	128
6	1/64 Step	256

Note that when the value of `stepSize` increases, the number of microsteps also increases.

When operating in Full Step mode (`stepSize = 0`), two options are available to drive the motor controlled by using the variable `fullStepMode`:

- FULLSTEP_WAVE_DRIVE: With this mode, only one phase is ON at any moment in time. This mode is enabled when the variable `fullStepMode` is FULLSTEP_WAVE_DRIVE
- FULLSTEP_TWO_PHASE_ON: With this mode, two phases are always ON, but the polarity changes every two steps. This mode is enabled when the variable `fullStepMode` is FULLSTEP_TWO_PHASE_ON

FIGURE 5:   WAVE DRIVE MODE CURRENTS
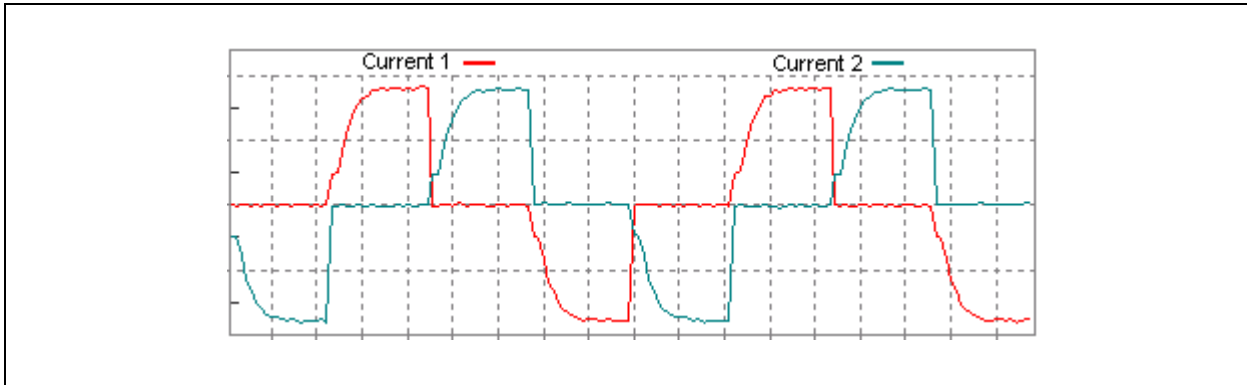
FIGURE 6:   TWO-PHASE ON MODE CURRENTS
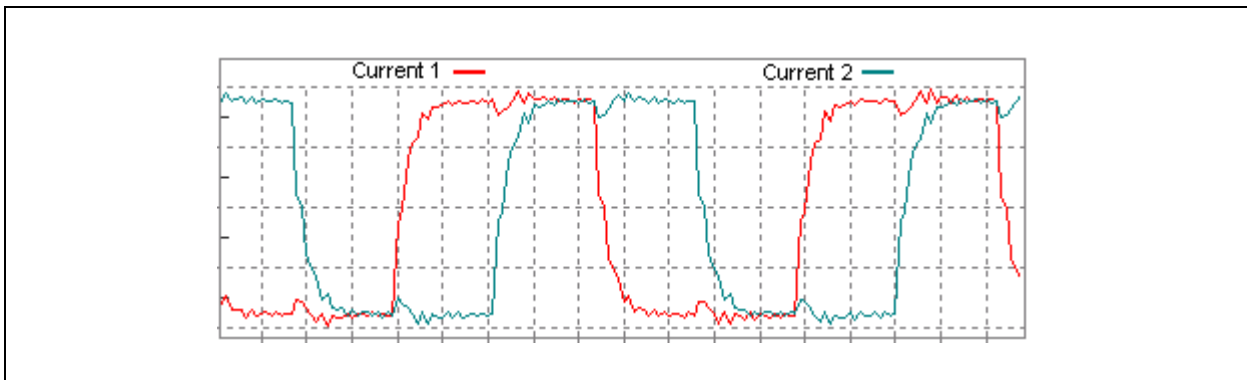
OPEN LOOP CONTROL METHODS

There are two open loop control methods implemented in this application note. One is fixed voltage control, which is an open loop control and does not adjust PWM duty cycles according to feedback. The second control method is fixed current control. In this method, the duty cycle is corrected every four full steps (one sine wave period) in order to reach a desired current amplitude set point. Both methods are described in the following two sections.

Fixed Voltage Control

In classic voltage control, the rated motor voltage is applied to the windings. When a higher power supply is used, such as 24V, the motor rated voltage is achieved with the use of a chopper, which is implemented with the Pulse Width Modulation (PWM) module.

Stepper motors are designed to run reliably at the rated current, as instructed by the manufacturer. The rated motor voltage is based on that current and the winding resistance. However, the voltage across the motor can be higher than that, as long as the current is kept at all times at the rated value or lower. As shown in Figure 1, the motor is connected to two H-bridges powered at 24V and driven by PWM signals. By carefully choosing the PWM duty cycle, the appropriate average voltage for driving the motor at the rated current is generated, as shown in Figure 7.

FIGURE 7: **MOTOR CURRENT AND PWM**
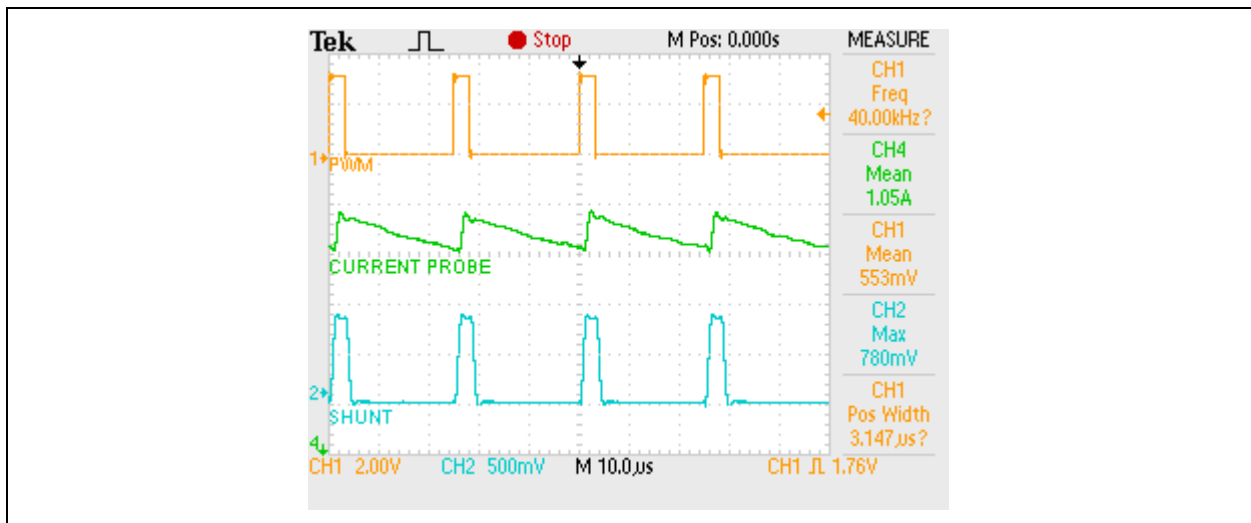
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This application note implements fixed voltage control by generating the desired voltage levels with the appropriate PWM duty cycles. Microstepping operation applies to open loop voltage control as well. If a particular application requires very low noise operation, open loop voltage control with microstepping would be the best choice.

Figure 8 shows the practical results of open loop voltage control. As shown by the red line in the graph, the current increases depending on the voltage magnitude; however, since there is no current control, the shape is not perfect. As shown in the figure, there are 8 steps per revolution in Half Step mode.

The flag, `uGF.controlMode`, is used for control method selection. If this flag has the value of `FIXED_VOLTAGE`, the control method selected is fixed voltage.
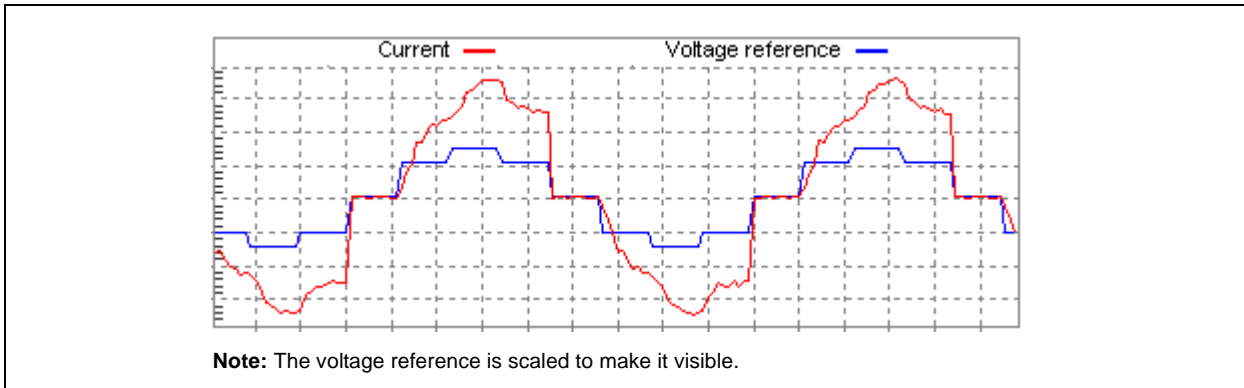
Fixed Current Control

When using fixed voltage control, the motor is driven with the rated voltage, which allows the current to rise from zero to the rated current value in a fixed amount of time. At a certain motor speed, which depends on the motor inductance and the drive voltage, the current will not rise fast enough through the motor coil to reach the rated motor current and torque will be lost. This presents a problem when higher speeds are required by the system.

As the motor speeds up, the step time is getting smaller and the current amplitude is falling more and more, until the rotor eventually stalls. To overcome this problem, the easiest solution is to increase the drive voltage as the motor speeds up in order to have a maximum current amplitude equal to the rated motor current and extend the maximum torque versus speed range.

Figure 9 shows the voltage and current for fixed voltage control. The voltage level is low and the measured current is rising slowly until the voltage drops. The desired level is far away and the motor torque is low.

FIGURE 8: **OPEN LOOP VOLTAGE CONTROL WITH HALF STEP**

Note: The voltage reference is scaled to make it visible.

FIGURE 9: **FIXED VOLTAGE CONTROL AT 120 RPM WITH ALTERNATE DECAY**

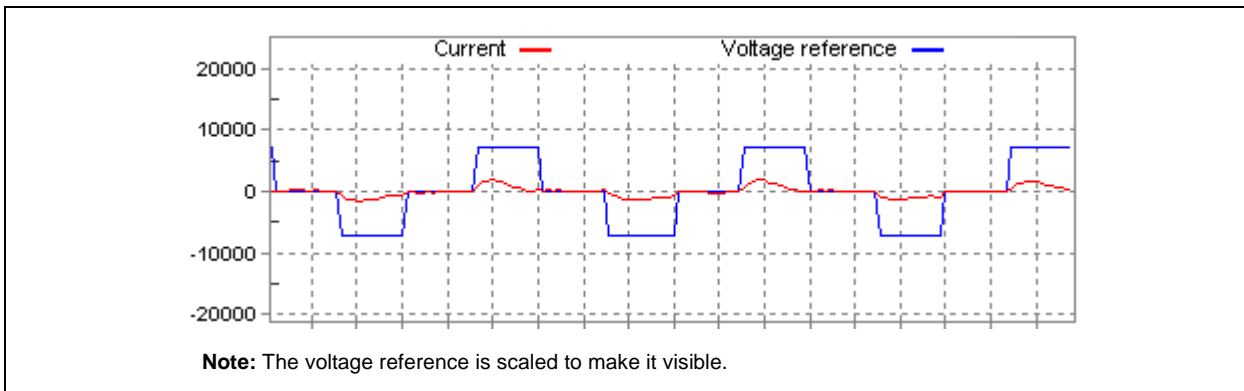**Note:** The voltage reference is scaled to make it visible.

Figure 10, on the other hand, shows how the current amplitude is controlled to a higher value by applying a higher voltage. Only the current amplitude is controlled in this mode, not the shape or phase.

FIGURE 10: **FIXED CURRENT CONTROL AT 120 RPM WITH ALTERNATE DECAY**

Note: The voltage reference is scaled to make it visible.
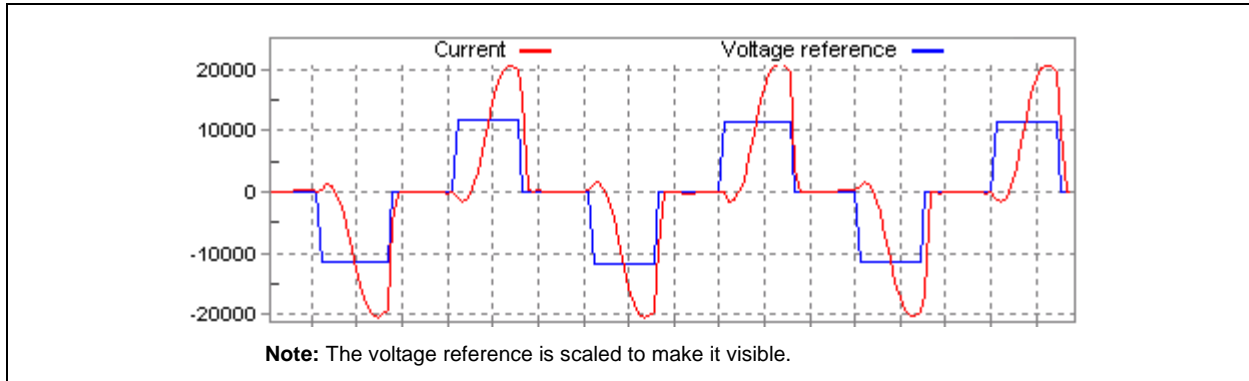
A simple control loop is used for controlling the current amplitude. The maximum amplitude of the current in both motor windings is sampled during one complete sine wave. If the maximum current amplitude is lower than the desired value, the drive voltage is increased gradually by adjusting the PWM duty cycle until the desired current amplitude is reached. If the current is too high the duty cycle is decreased, but not less than the initial value corresponding to the rated motor voltage.

As long as the drive voltage is higher than the motor rated voltage, this method provides an extended speed range over the classic open loop approach. Another advantage to using this algorithm is that there is no need to retune for different motors. As long as the starting voltage produces a lower current than desired, the algorithm will increase this voltage until the desired current level amplitude is reached.

This control method is selected by assigning `FIXED_CURRENT` to the `uGF.controlMode` flag.

DECAY MODES

When a motor winding is turned OFF by the PWM, such as in a chopping circuit, the current through that winding starts to decay until it reaches zero or until the winding is energized again. The rate at which the current decays depends on the configuration of the H-bridge at that specific moment. The different current decay methods are called decay modes.

There are two decay modes discussed in this application note:

• Fast Decay: This mode is active when the voltage across the de-energized winding is reversed, which produces a fast current drop, hence the name Fast Decay mode

• Slow Decay: This mode is active when the motor winding is shorted. Current drop is much slower, since there is no voltage applied to the winding

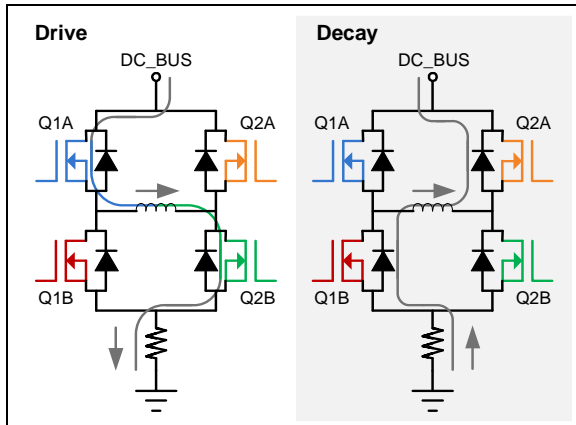These two modes are used in this application note in two different ways:

• Fixed Decay: Users can select this option where only one of the six decay modes is used by the controller at all times. It is recommended to use one of the slow decay modes in this configuration

• Alternating Decay: The controller uses two selected decay modes and switches between them at the appropriate time
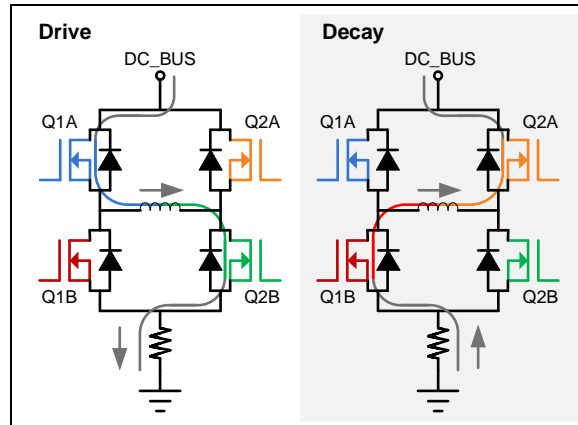
Fast Decay

In Fast Decay mode, when the current is flowing through a motor's winding and all MOSFETs are switched off, the voltage on that winding will be equal to the negative of the supply voltage plus the drop voltage on two freewheeling diodes, as shown in Figure 11. The decay rate can be adjusted slightly by shorting one or two diodes in the circuit with their corresponding MOSFETs. However, the reverse voltage applied to the coil will not change significantly since the voltage drop across a diode (1V) is much smaller than the supply voltage (24V). Still, the advantage of using this method is that the decaying current is flowing through the MOSFET body diodes only briefly, until the MOSFET turns ON. The MOSFET has a lower ON-resistance and thus, the dissipated power will be much lower, which presents an advantage to the overall system power dissipation.

Another advantage of Fast Decay mode is the simplicity of the current feedback circuit, since motor current can be read from the simple shunt resistor at all times. When the winding is driven, the current is positive. While the current is dropping during Fast Decay mode, the current will be negative since the voltage is reversed across the winding. Therefore, current is available on the shunt resistor at all times.
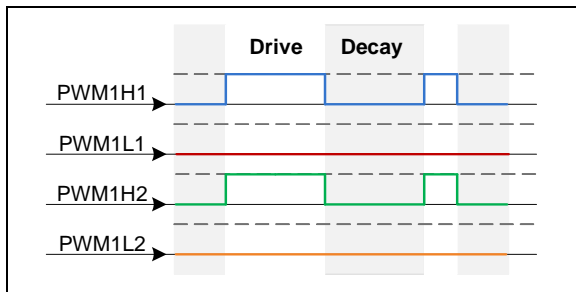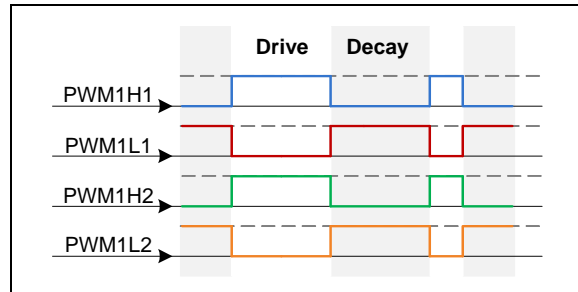
FIGURE 11: FAST DECAY CURRENT FLOW

FIGURE 12: FAST DECAY PWM TIMING DIAGRAM

TABLE 2: FAST DECAY DRIVE SIGNALS

Mosfet	Driving Signal	Value
Q1A	PWM1H1	PWM
Q1B	PWM1L1	0
Q2B	PWM1H2	PWM
Q2A	PWM1L2	0

With a slight variation on the drive signals, we have something called Reverse Decay mode. Reverse Decay mode behaves like Fast Decay mode until the current reaches zero, at which point it forces the current in the opposite direction. For short decay times though, until the current reaches zero, this is not an issue. If reverse decay is continued after the current has dropped to zero, then negative current will be generated when a positive current is desired, and vice versa. Reverse decay generates the lowest possible dissipated power in the fast decay configuration.

FIGURE 13: FAST DECAY (REVERSE) CURRENT FLOW

FIGURE 14: FAST DECAY (REVERSE) PWM TIMING DIAGRAM

TABLE 3: FAST DECAY (REVERSE) DRIVE SIGNALS

Mosfet	Driving Signal	Value
Q1A	PWM1H1	PWM
Q1B	PWM1L1	PWM
Q2B	PWM1H2	PWM
Q2A	PWM1L2	PWM

Fast decay and reverse decay modes can be set in software by changing the initialization value of variable alternateDecay to each of the following defined values shown in Table 4.

Fast decay is not recommended as a base decay since the current may drop faster during Fast Decay than it is actually rising when the supply voltage is applied to the winding.

TABLE 4: FAST DECAY MODES

| Variable Name	Initialization Value	Active Components During Decay
baseDecay alternateDecay	D_FAST	Low Side Diode + Opposite High Side Diode
	D_REVERSE	Low Side MOSFET + Opposite High Side MOSFET

Slow Decay

Slow decay is entered by shorting the motor winding when it is not driven by the supply voltage. This is achieved by keeping one of the drive MOSFETs opened at all times (see the Q1A or Q2B MOSFETs in Figure 15). The current recirculates through the motor winding, drive MOSFET and the opposite MOSFET or its body diode. If two MOSFETs are ON (lower ones or upper ones) the diodes are shorted allowing less power dissipation and less current drop during slow decay.

FIGURE 15: SLOW DECAY LOW SIDE MOSFET CURRENT FLOW
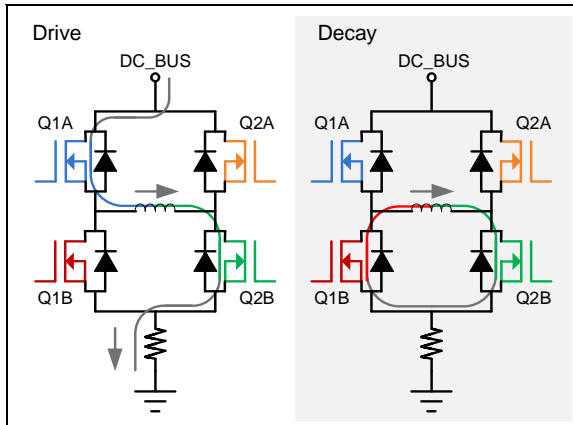
FIGURE 16: SLOW DECAY LOW SIDE MOSFET PWM TIMING DIAGRAM
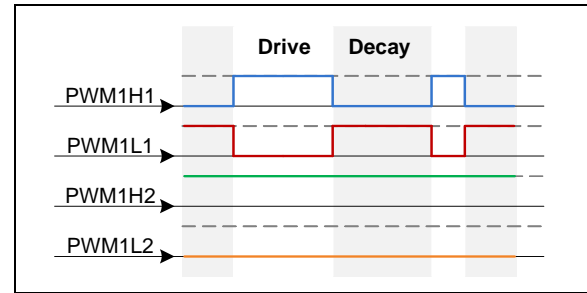
TABLE 5: SLOW DECAY LOW SIDE MOSFET DRIVE SIGNALS

Mosfet	Driving Signal	Value
Q1A	PWM1H1	PWM
Q1B	PWM1L1	PWM
Q2B	PWM1H2	1
Q2A	PWM1L2	0

Depending on which MOSFET remains ON during decay, there are several slow decay modes that can be selected in the software. The recommended slow decay mode when using a bootstrap is the Low Side MOSFET Recirculation mode. Using this mode helps the bootstrap capacitors used to drive the upper MOSFETs to fully recharge. If the bootstrap capacitors discharge, the upper MOSFETs cannot be turned ON. Appendix B lists all slow decay modes including the current flow path, timing diagrams and drive signals. Table 6 summarizes all slow decay modes.

TABLE 6: SLOW DECAY MODES

| Variable Name	Initialization Value	Active Components During Decay
baseDecay alternateDecay	D_SLOW_L_DIODE	Low Side Diode + Opposite Low Side MOSFET
	D_SLOW_H_DIODE	High Side MOSFET + Opposite High Side Diode
	D_SLOW_L_MOSFET	Low Side MOSFET + Opposite Low Side MOSFET
	D_SLOW_H_MOSFET	High Side MOSFET + Opposite High Side MOSFET

Current measurement is not possible in slow decay modes with the shunt resistor circuit used for current sensing. This is because in slow decay modes, current is not flowing through the shunt resistor since it recirculates through the motor and MOSFETs or diodes.

Figure 17 shows how the current measurement signal changes when the decay mode changes from slow (low MOSFET recirculation) to fast. This transition from slow to fast happens during the high level of the upper signal. The peaks of the bottom signal represent the shunt resistor current and the peaks match with the ON time of the PWM. The shunt resistor current is positive when the winding is driven, which is during the ON phase of the PWM (Q1A and Q2B switches are ON) and negative in Fast Decay mode. The signal in the middle of the plot represents the actual motor current using a current probe. It can be observed that during slow decay (when the top signal is low) the current is zero when the winding is not driven.

FIGURE 17:   CURRENT SIGNALS FOR FAST AND SLOW DECAY MODES
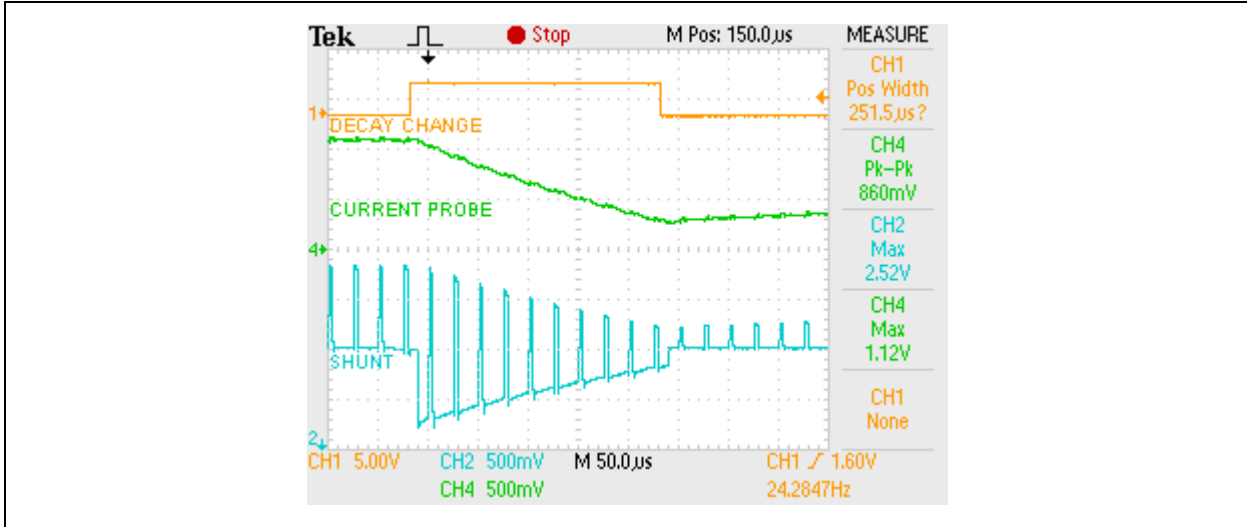
COMBINING DECAY MODES

In this application note, there are two ways that the decay modes can be used. The first one is Fixed Decay mode, where the user selects a decay mode (fast, slow, etc.) and that same decay mode will be used all of the time. The second option is alternate decay, where two decay modes are combined while driving the stepper motor. Table 7 shows which flag and which values should be used for any of the two decay operation modes.

Fixed Decay

As mentioned earlier, in Fixed Decay mode there is only one decay mode used during motor operation. The recommended decay mode is slow decay in the low MOSFET recirculation configuration.

Alternate Decay

With all of the available decay modes, the question arises of which one to use and when. Slow Decay mode provides quieter motor operation and is good at relative low speeds. As the motor speed increases and the desired current falls on a steep decline, the winding current can no longer follow this curve using Slow Decay mode. Although operation in Fast Decay mode is noisier, it allows greater control of the current descent rate.

The two plots in Figure 18 show the difference between Fixed Decay mode, using slow decay, and Alternate Decay mode, using fast and slow decay. In Alternate Decay mode (right plot), fast decay is only used when the current is decreasing and only for a limited time until the current reaches the desired level.

The advantage of using the alternate decay mode can be seen at high speeds, where slow decay cannot provide a fast current drop rate as demanded by the switching pattern. Also, the BEMF of the motor prevents the current from decreasing fast enough. Fast decay can be used to bring the current down faster to the desired level. Where fast decay is too aggressive or needs to be used for a very short time, slow decay with diode recirculation can be used for a longer period as it forces the current to decay faster than in the MOSFET recirculation mode.

For each step, a different current drop is required, so a smaller or larger ratio of fast to slow decay is needed based on the step amplitude change. If fast decay is not used long enough, the current decreases too slow and does not follow the desired shape. If it is used for too long, the current drops too much and will have to rise back up. This is why the number of fast decay (or alternate decay) periods must be proportional to the current amplitude drop. Since the motor back-EMF induces current in the windings, it is recommended to keep the winding in fast decay whenever the desired current level is zero. This is an efficient and fast method of controlling the current to zero.

TABLE 7: DECAY MODE COMBINATIONS

Flag	Value	Description
uGF.decayMode	FIXED_DECAY	Only one decay mode is used: baseDecay.
	ALTERNATE_DECAY	Alternates between two decay modes: baseDecay and alternateDecay.

FIGURE 18: COMPARISON BETWEEN FIXED AND ALTERNATE DECAY
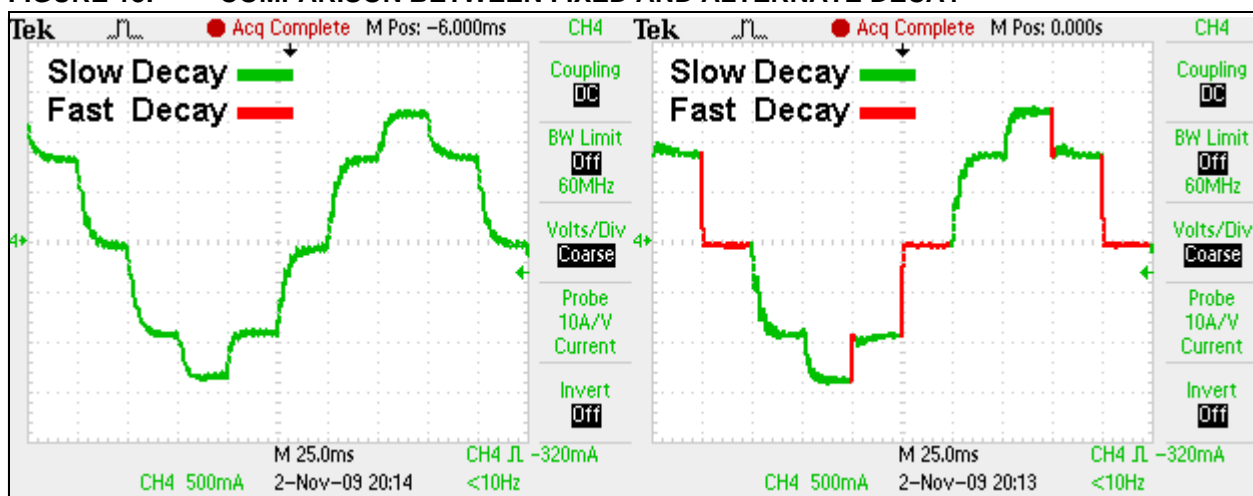
CURRENT MEASUREMENT

Current measurement in the full-bridge configuration brings up some challenges. First of all, the measuring shunt resistor is located between the ground and the low side MOSFETs, which means that no current will be visible unless there is a path opened between DC_BUS and ground. The path can either be one high-side MOSFET plus the opposite low-side MOSFET, or the body diodes of the same MOSFETs when they are turned OFF.

When the motor winding is energized, the shunt current will always be positive, regardless of the current direction in the motor winding. Whenever the winding is in fast decay, the shunt current will be negative. In all slow decay modes there is no current flowing through the shunt resistor.

Figure 19 shows a typical shunt resistor waveform during motor operation in full step wave drive with fast and slow decay. For simplicity we will assume first that there is no PWM driving the motor and that only DC voltages are applied to the winding.

The challenge is to reconstruct the real motor current based on the available measured data from the shunt resistor. As DC voltage is replaced by PWM, the step pattern shown in Figure 19 is reproduced on a much smaller scale, a number of times inside each of those steps, as shown in Figure 20.
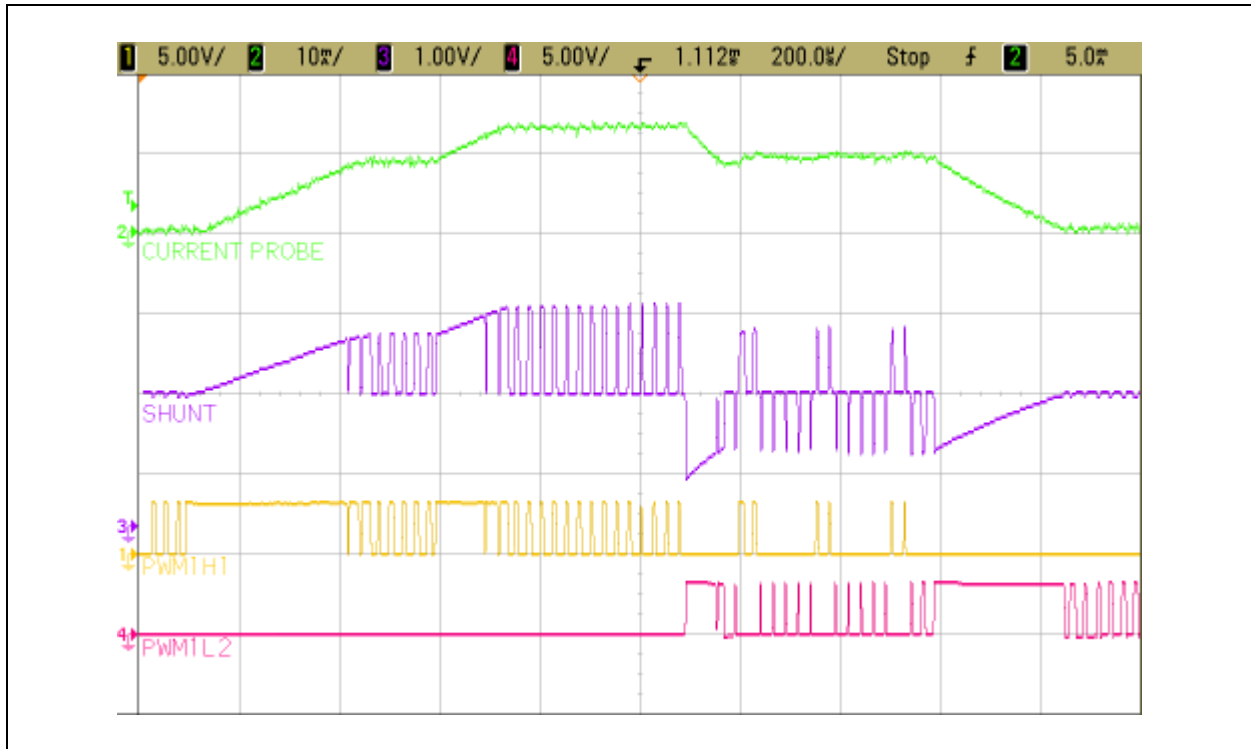
**FIGURE 19:   WINDING CURRENT VERSUS SHUNT CURRENT IN DC MODE**
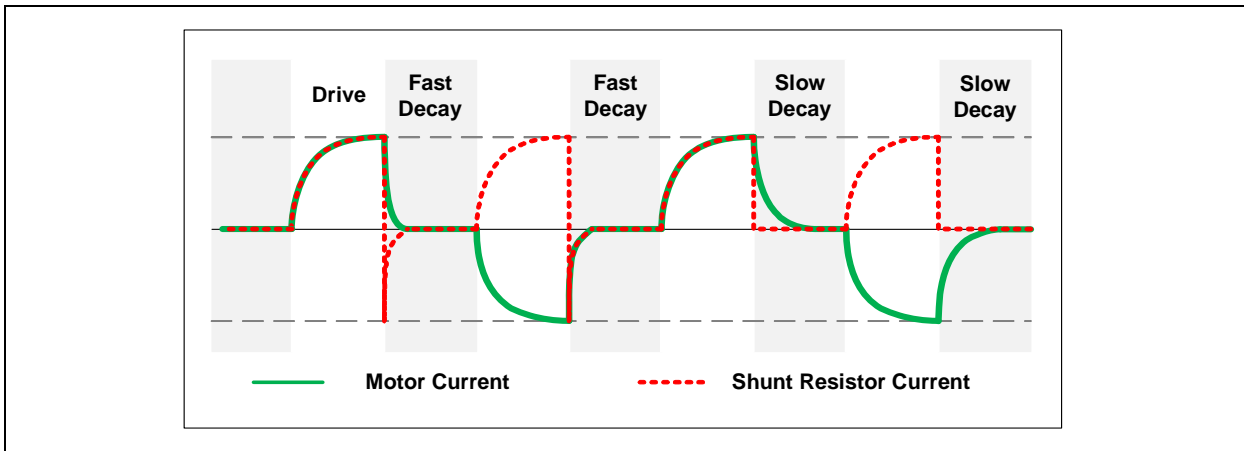
In the Closed Loop Control mode, the PI controller switches from slow to fast decay often and at small time intervals, as shown in Figure 20 and Figure 21. In this scenario, PWM1H1 and PWM1H2 are driving the winding current in the positive direction. PWM1L1 and PWM1L2 are driving the winding current in the negative direction, but as long as the winding current is positive, this is identical to fast decay. The PWM1H1 and PWM1L2 signals are controlling the high MOSFETs of the H-bridge. Since the slow decay with low MOSFET recirculation mode is used, the PWM1L1 and PWM1H2 signals are complementary to PWM1H1 and PWM1L2, respectively.

Whenever PWM1H1 is high, the entire supply DC voltage is applied to the winding and its current is increasing. The shunt resistor only sees this current when the PWM signal is high. When PWM1L2 is high, the same DC voltage is applied to the winding, but in reverse polarity. This puts the winding in Fast Decay mode and forces the shunt resistor current to negative values, but equal in amplitude with the real winding current. When both of these PWMs are low, their complementary PWM pins driving the H bridge low MOSFETs are high; therefore, the winding is in the Slow Decay MOSFET Recirculation mode and no current flows through the shunt resistor.

FIGURE 20:   SHUNT CURRENT IN CLOSED LOOP CURRENT CONTROL

FIGURE 21:   RECONSTRUCTION OF WINDING CURRENT FROM ADC READINGS

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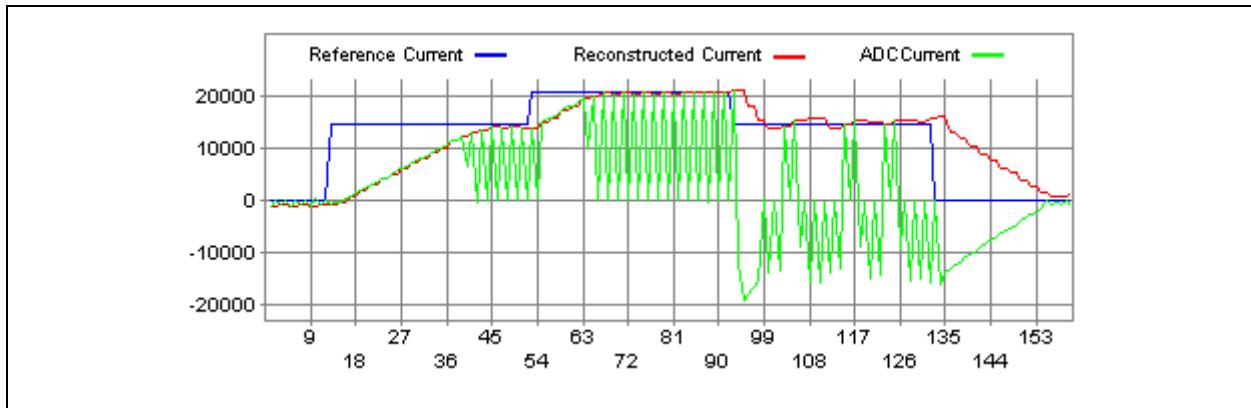
The ADC reads the shunt current twice every PWM cycle, once on the active pulse (PWMxHx is high) and once on the inactive pulse (PWMxLx is high). By properly connecting all of the high amplitude peaks, the real winding current is reconstructed in software. By monitoring in which direction the winding is driven, the reconstructed current variable is only updated at the right time. The current value is updated on the active pulse if the driving direction is positive, and on the inactive pulse when the driving direction is negative. The flag, setDir1HW, holds the driving direction for winding 1.

At small duty cycles, the winding current does not have enough time to energize the shunt resistor, filter capacitors and amplification circuits, and therefore, it is not read properly by the ADC. The minimum PWM pulse width that still allows reliable ADC readings is approximately 1.75 µs. At 40 khz PWM frequency, this results in a duty cycle of 7%. All duty cycles below this value are set to 7%. Current levels that normally require lower duty cycles in open loop are still achieved by the PI controller by properly controlling the decay mode.

CLOSED LOOP PI CURRENT CONTROL

Two Proportional Integral (PI) controllers are used to control the current, one for each of the two motor windings. For the best possible results, a theoretical approach is used that allows easy tuning for any motor configuration. As long as the motor parameters are known, such as resistance, inductance and rated current, setting up the system to run with different motors poses no real challenge in terms of tuning.

PI controller

Stepper motors have two windings, so two PI controllers are needed, one for each winding.

EQUATION 1:   MOTOR WINDING EQUATION

$$V \cdot u = R \cdot i + L \frac{di}{dt}$$

L = Motor resistance
R = Motor inductance
V = DC voltage
i = Instantaneous motor current
u = PWM duty cycle percentage

EQUATION 2:   MOTOR TRANSFER FUNCTION

$$\frac{i(s)}{u(s)} = H_M(s) = \frac{V}{L \cdot s + R} = \frac{V/R}{L/R \cdot s + 1}$$

EQUATION 3:   CONTINUOUS PI CONTROLLER

$$H_{PI}(s) = K \cdot \frac{L/R \cdot s + 1}{s}$$

s = Laplace variable
K = Continuous controller gain

In order to compensate the motor transfer function pole and achieve a zero steady state error, a classic PI controller is chosen. By applying Tustin discretization to Equation 3, the formula shown in Equation 4 is obtained:

EQUATION 4:   DISCRETE PI CONTROLLER

$$\frac{u(z)}{\varepsilon(z)} = H_{PI}(z) = G \cdot \frac{p_1 \cdot z - p_2}{z - 1}$$

$$p_1 = L + R \cdot T/2$$

$$p_2 = L - R \cdot T/2$$

T = 25 µs

$G = K/R$

ε = Current error
u = Voltage output
z = z-transform variable
p_1, p_2 = Discrete controller parameters
T = Controller sample time
G = Controller discrete gain

The closed loop transfer function of the entire system is shown in Equation 5. The step response rise time of this system, being a first order system, is approximately three times the time constant. By choosing the desired response time, the value for the continuous controller gain can be calculated. Following Equation 6, the value for the discrete controller gain is found. For the discrete gain, a multiplication factor of 4 is used in order to get more resolution from fixed point calculations by avoiding underflows.

EQUATION 5:   CLOSED LOOP TRANSFER FUNCTION

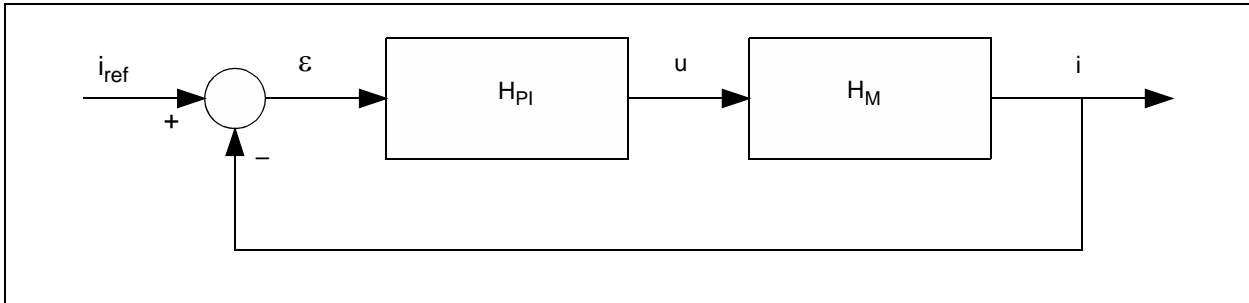$$H_0 = \frac{H_M \cdot H_{PI}}{1 + H_M \cdot H_{PI}} = \frac{1}{\frac{R}{K \cdot V} \cdot s + 1}$$

EQUATION 6: **DISCRETE GAIN USED IN THE FIXED POINT IMPLEMENTATION**

$$3\frac{R}{K \cdot V} = 70 \mu s$$

$$G_0 = 4 \cdot K/R$$

G_0 = Scaled discrete gain

FIGURE 22: **CLOSED LOOP CONTROLLER BLOCK DIAGRAM**

In this application, a value of 70 µs was chosen as the desired rise time. The step response of the closed loop system is shown in Figure 23. Since the gain has a high value, the controller is very aggressive. The maximum voltage is limited to the available DC voltage of 24V. We can only measure the correct rise time as set by the PI parameters during the last pulse, where the voltage output is not limited. We can count 6 periods, which at 12.5 µs for one period equals 75 µs, which is very close to the desired time. In all other cases, when the output is limited, the rise time will be longer because higher voltages than DC_BUS would be needed to achieve the set rise time.

FIGURE 23: **CLOSED LOOP PI CURRENT CONTROL**

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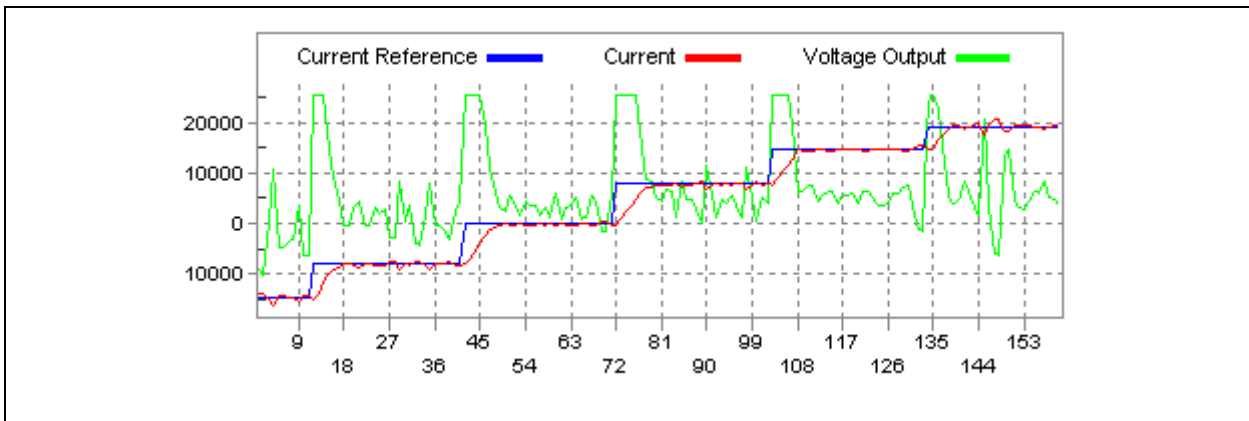
Anti-Windup

Limiting the controller output leads to a problem called accumulator wind-up. The output is saturated but the PI integrator accumulator keeps counting and grows until it eventually saturates. When the error is returning from the saturation area, the accumulator value is much higher than normal for that specific error value and, as a result, the system response slows. To prevent this effect, the accumulator also has to be compensated. To do this, another gain is added in Equation 8, which is called the anti-windup gain. The difference between the actual (saturated) output and the accumulator is multiplied with this gain and then subtracted in the next accumulator calculation cycle.

EQUATION 7: DISCRETE PI CONTROLLER IMPLEMENTATION

$$acc_{k+1} = G_0 \cdot p_1 \cdot \varepsilon_{k+1} - G_0 \cdot p_2 \cdot \varepsilon_k + acc_k$$

$$u_{k+1} = -24V \le acc_{k+1} \le 24V$$

acc = Integral accumulator
u = Output voltage
ε = Current error
p_1, p_2 = Discrete controller parameters
acc_k, ε_k = Values from previous cycle
acc_{k+1}, ε_{k+1} = Values from present cycle

EQUATION 8: ANTI-WINDUP PI CONTROLLER

$$acc_{k+1} = G_0 \cdot P_1 \cdot \varepsilon_{k+1} - G_0 \cdot P_2 \cdot \varepsilon_k + acc_k - G_w(acc_k - u_k)$$
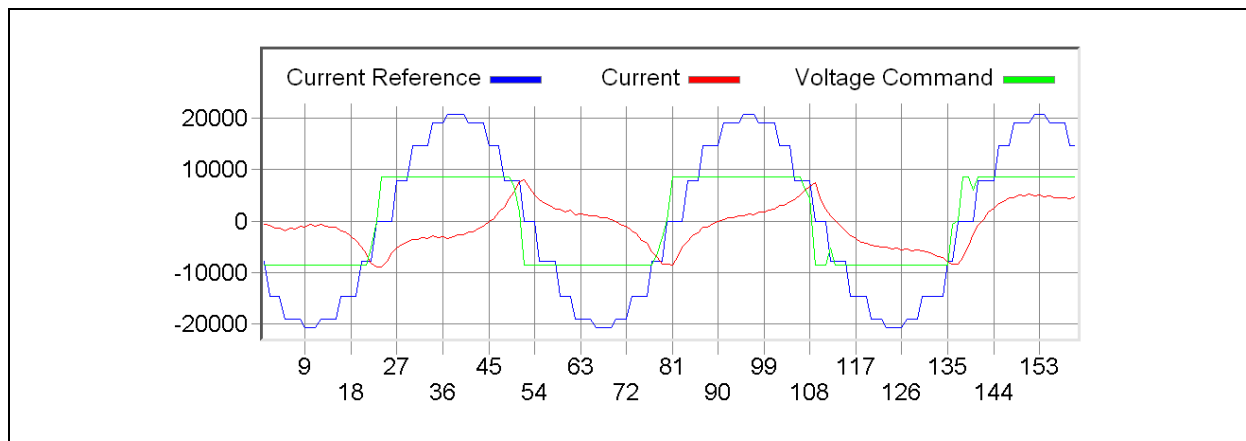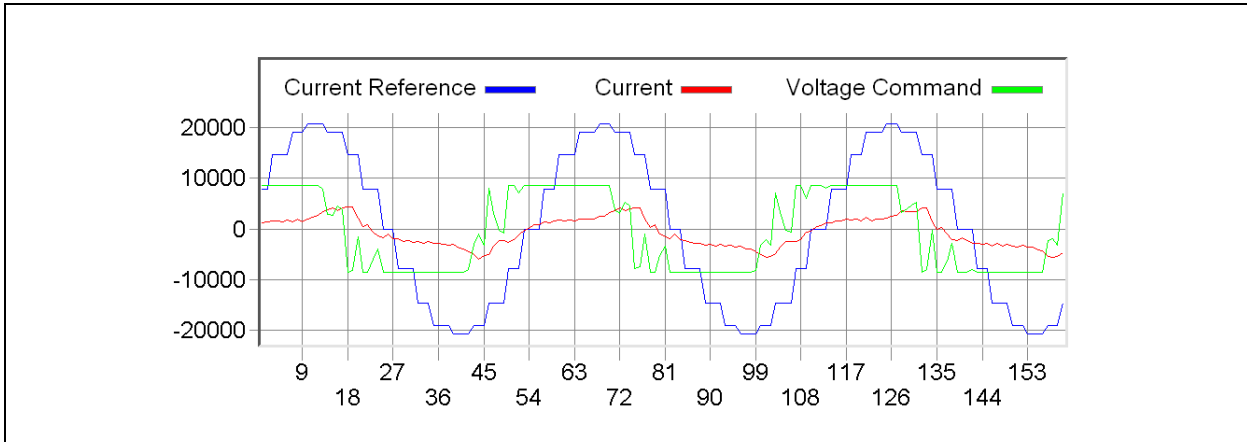
G_w = Anti-windup gain

Phase Advance

By changing the value of the anti-windup gain, different controller behaviors are achieved. For low speeds, it is good to have a small gain so that the current tracks the reference as precise as possible. At higher speeds, when the DC_BUS voltage is not strong enough to bring the current to the reference value and the fast decay rate is not sufficient to bring the current down in the allocated time frame for one step, the anti-windup gain helps to change the phase of the current, thereby allowing transition to higher speeds, which otherwise could not be reached. Keeping the anti-windup gain low will result in the motor eventually stalling as the speed increases.

Figure 24 and Figure 25 are taken with one-fourth microstep resolution at a motor speed of 840 RPM. With a low anti-windup gain, Figure 24 shows that the output voltage and the desired current are in phase. However, because of the high speed at which the motor is running, the winding current is not able to follow the reference. At some point, the current will be rising too late and brake the rotor instead of accelerating it, since the stator poles will be energized too late, after the rotor has passed them.

**FIGURE 24: 1/4 STEP AT 840 RPM WITH A LOW ANTI-WINDUP GAIN**

FIGURE 25: 1/4 STEP AT 840 RPM WITH A HIGH ANTI-WINDUP GAIN

In Figure 25, The high anti-windup gain forces the controller output voltage to exit saturation sooner and therefore changes the phase of the winding current relative to the desired current. With this phase advance, the current has enough time to rise into the winding before the rotor pole reaches the energized stator pole.

Further increasing the speed, the current amplitude keeps dropping until it eventually changes phase forced by the back-EMF. At this point, the current amplitude will begin to rise again and the phase advance and motor back-EMF work together to keep the motor running, as shown in Figure 26. The motor torque at 2400 RPM is strong enough to operate the motor under a light load. As a comparison, the maximum speed achieved in the open loop control modes with the same motor is around 200 RPM.

The current waveform reference plays an important role here. If it is closer to a sine wave, the current will follow it better and the motor will have better torque. At high speeds, it is best to use the smallest possible microsteps, in order to obtain the best motor torque. However, at high speeds, the microstep changing rate becomes faster than the output frequency of 40 kHz. The dsPIC DSC device might also run out of time to execute all of the step changes if they are very fast. For these reasons, a value of approximately 20 µs for one microstep is implemented as the lower limit for one microstep time, regardless of the microstepping resolution used. This means the top speed is higher for low resolution modes, such as full, half or quarter step, and lower for high resolution microstepping.

FIGURE 26: 1/4 STEP WITH PHASE ADVANCE

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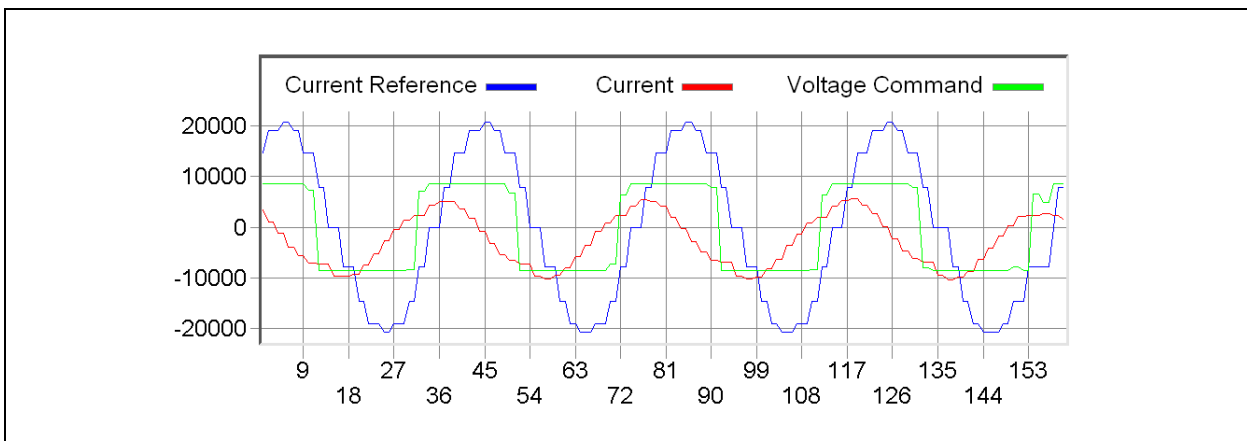
POSITION CONTROL

Open loop position control is the main reason why stepper motors are used. In combination with the closed loop current control, open loop position control is more accurate and reliable up to considerable speeds. To reach high speeds though, the motor has to be accelerated gradually to prevent the rotor from stalling. Stopping the motor must be done in the same way, so maximum acceleration and deceleration rates for the motor speed are used.

A classic Proportional (P) position controller with a variable gain and a maximum speed limit is implemented based on Equation 9. The fixed gain is chosen in such a way that the deceleration rate is slightly smaller that the maximum allowed value.

When the desired position is reached, the motor should stop immediately to avoid position oscillations. Since a fixed deceleration rate is imposed to the motor, the position controller must take it into account and begin the deceleration at the right time, before it is too late. A variable gain is used to ensure that the motor starts deceleration at the right point and a fast stop is obtained. Compared with a fixed gain solution, this controller output exits saturation later.

CONCLUSION

This application note presented three methods to control a stepper motor: Fixed Voltage mode, Fixed Current mode and PI Closed Loop Control mode.

A method of generating up to 1024 points per cycle was also implemented in this application note using microstepping. Different decay methods were also presented allowing the controller to operate the stepper in a variety of ways depending on system's requirements.

For software implementation, code is available for download from the Microchip website, which is posted on the same web page as this application note.

To learn more details about the hardware tool used, refer to the *"dsPICDEM MCSM Development Board User's Guide"* (DS70610).

FIGURE 27: **POSITION CONTROL WITH VARIABLE GAIN – EIGHT MOTOR ROTATIONS ARE PERFORMED AT QUARTER STEP RESOLUTION**
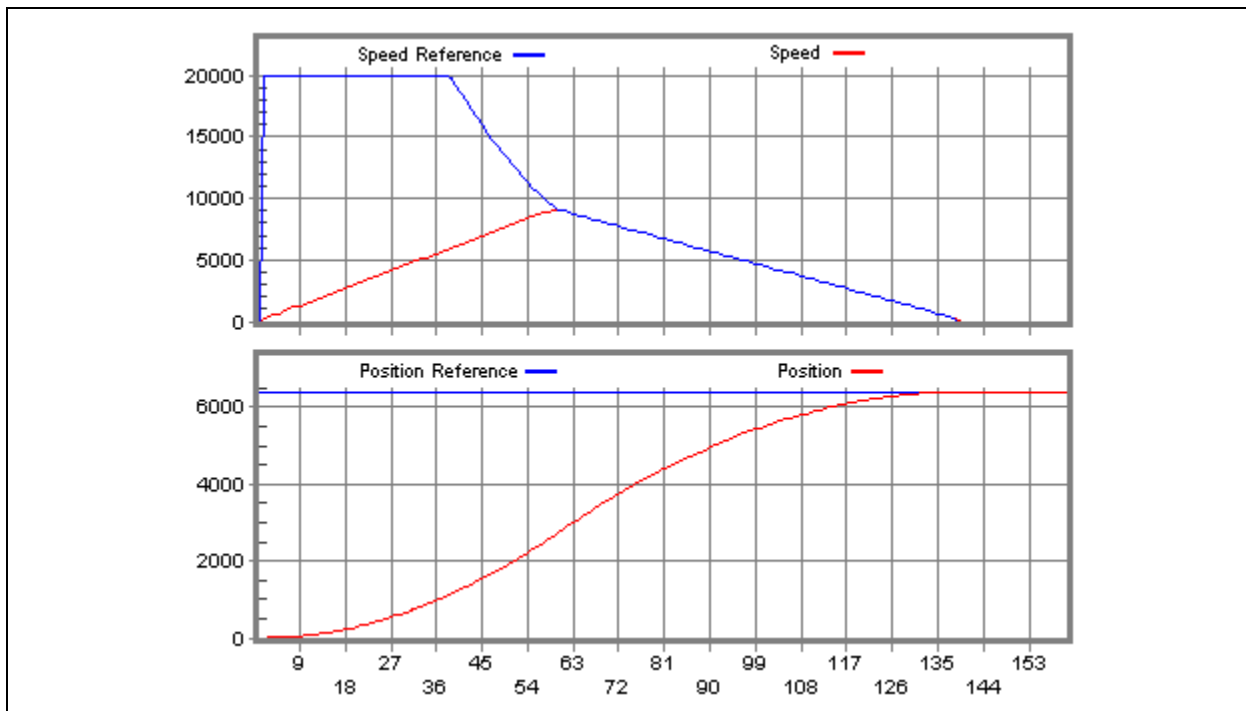
EQUATION 9: **PROPORTIONAL (P) POSITION CONTROLLER WITH VARIABLE GAIN AND MAXIMUM SPEED LIMIT**

$$speed_{Ref} = pos_{Gain} \cdot pos_{Err} = \frac{pos_{Fixed\_gain} \cdot decelerationRate}{|speedOut|} \cdot pos_{Err}$$

$$speed_{Ref} \leq speed_{Max}$$

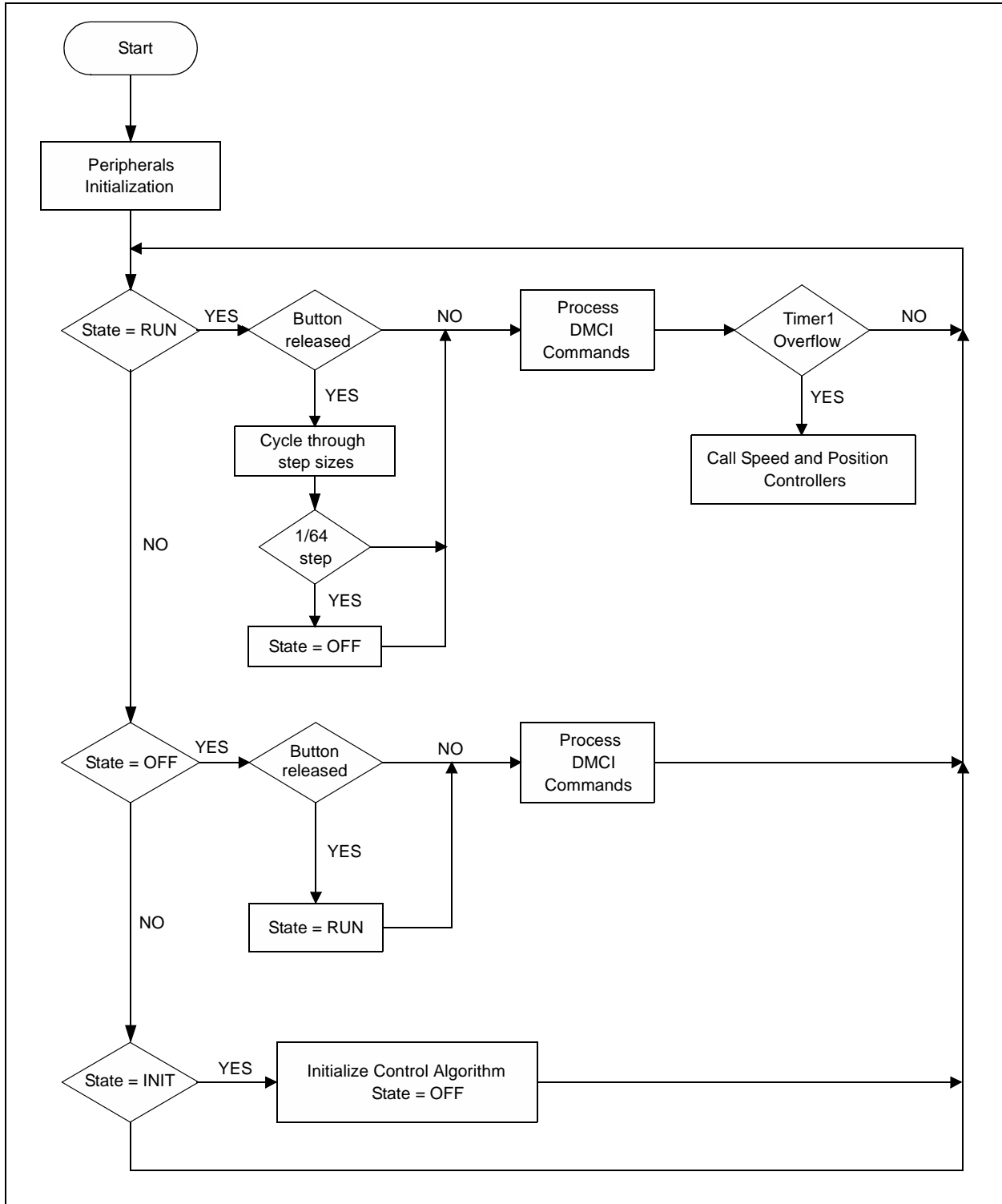## APPENDIX A: SOFTWARE FLOW CHARTS

FIGURE A-1:   MAIN STATE MACHINE
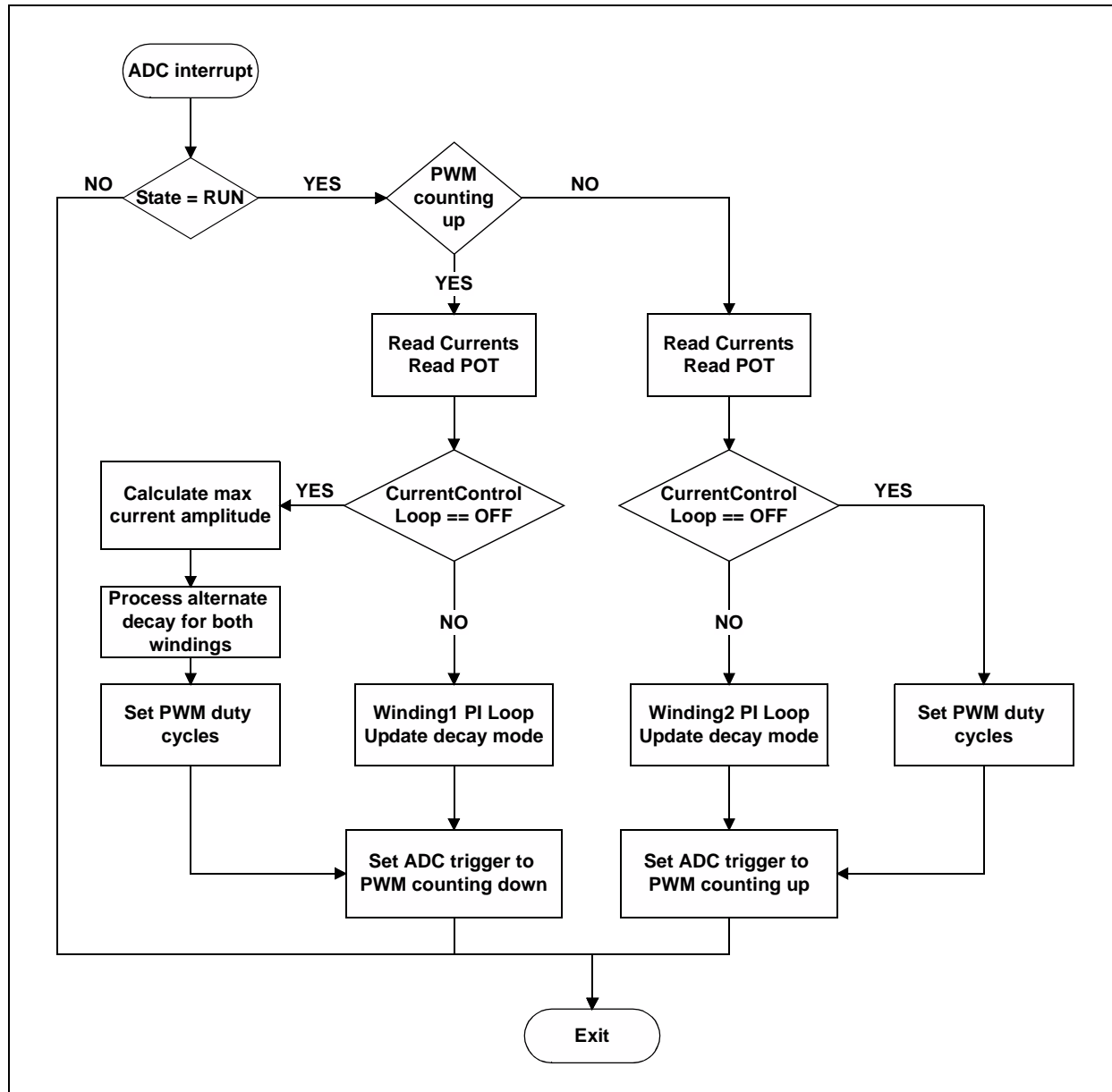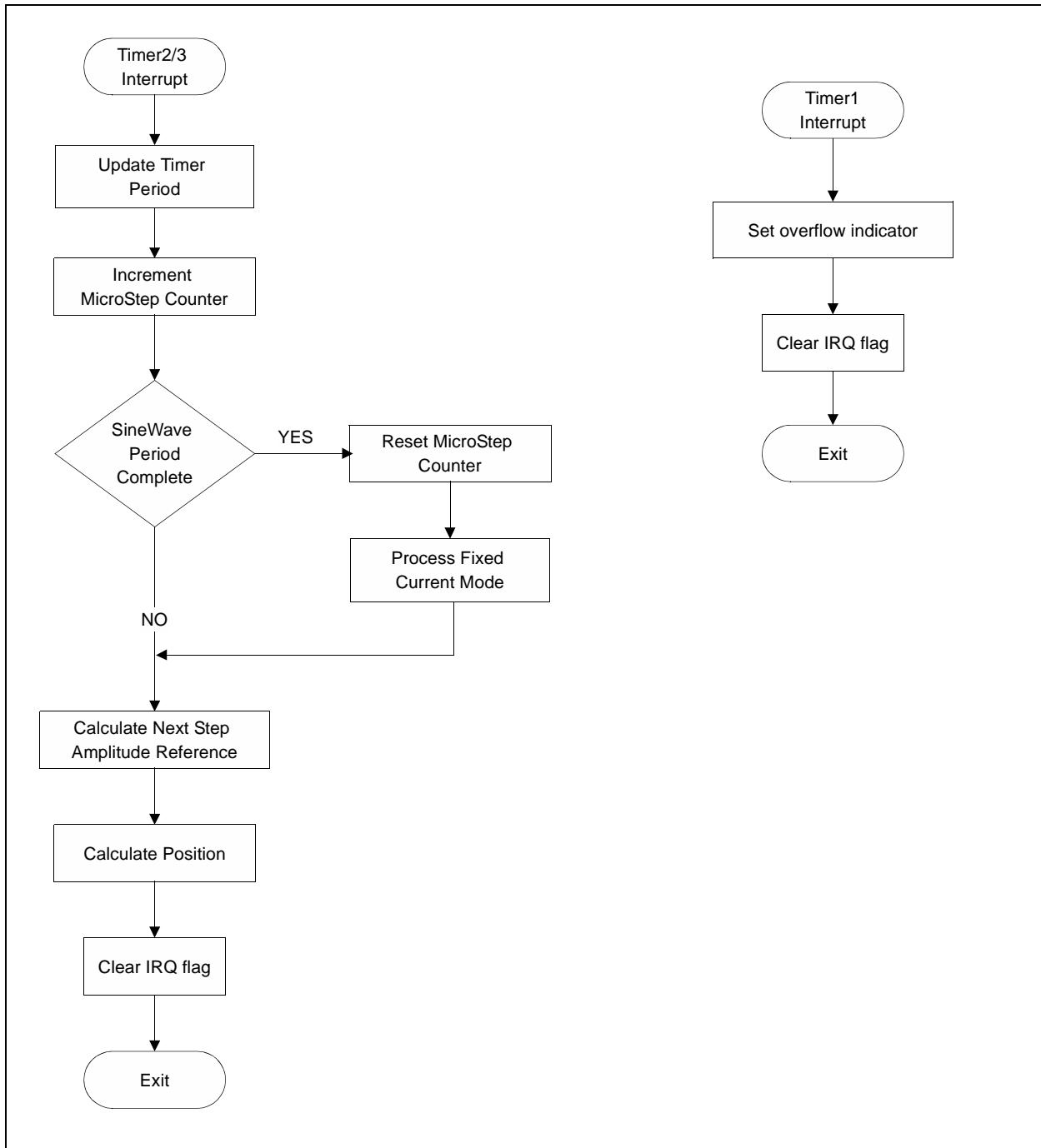
FIGURE A-2:   ADC INTERRUPT

FIGURE A-3: TIMER INTERRUPTS

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APPENDIX B: DECAY MODES

FIGURE B-1: FAST DECAY

Mosfet	Driving Signal	Value
Q1A	PWM1H1	PWM
Q1B	PWM1L1	0
Q2B	PWM1H2	PWM
Q2A	PWM1L2	0
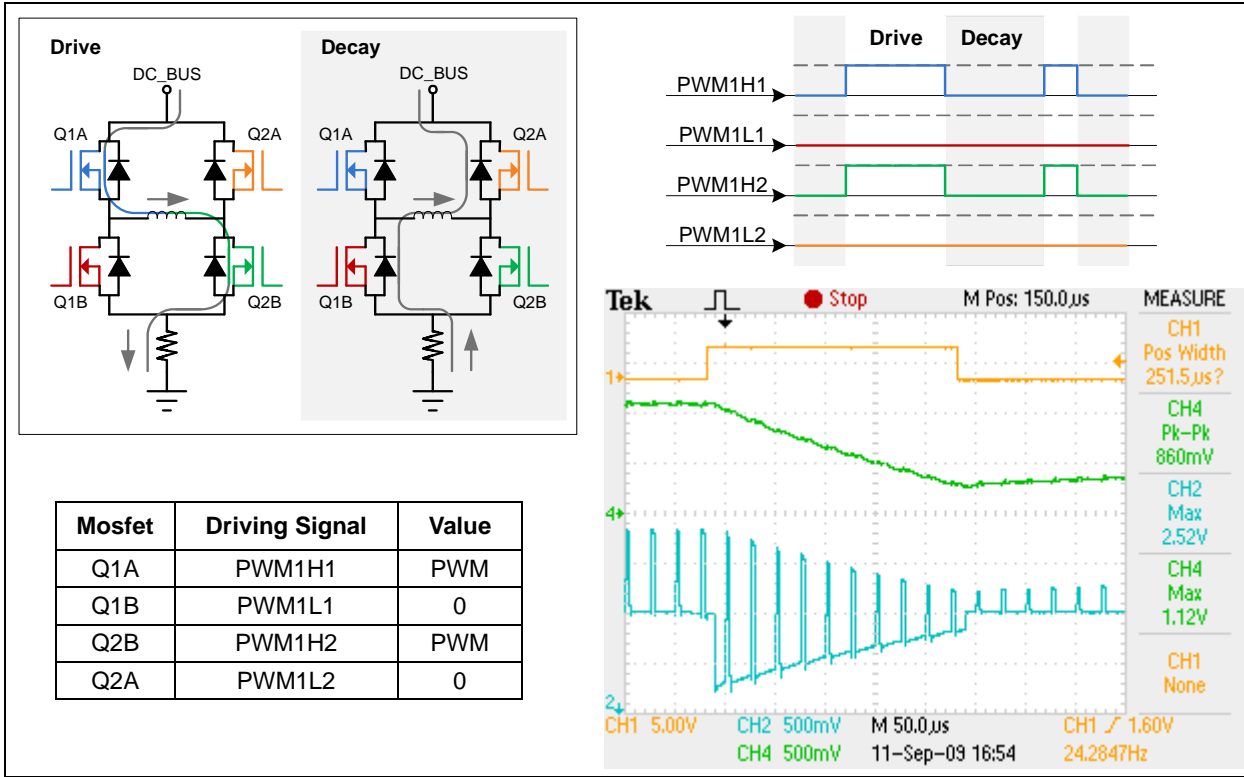
FIGURE B-2: SLOW DECAY LOW DIODE RECIRCULATION

Mosfet	Driving Signal	Value
Q1A	PWM1H1	PWM
Q1B	PWM1L1	0
Q2B	PWM1H2	1
Q2A	PWM1L2	0

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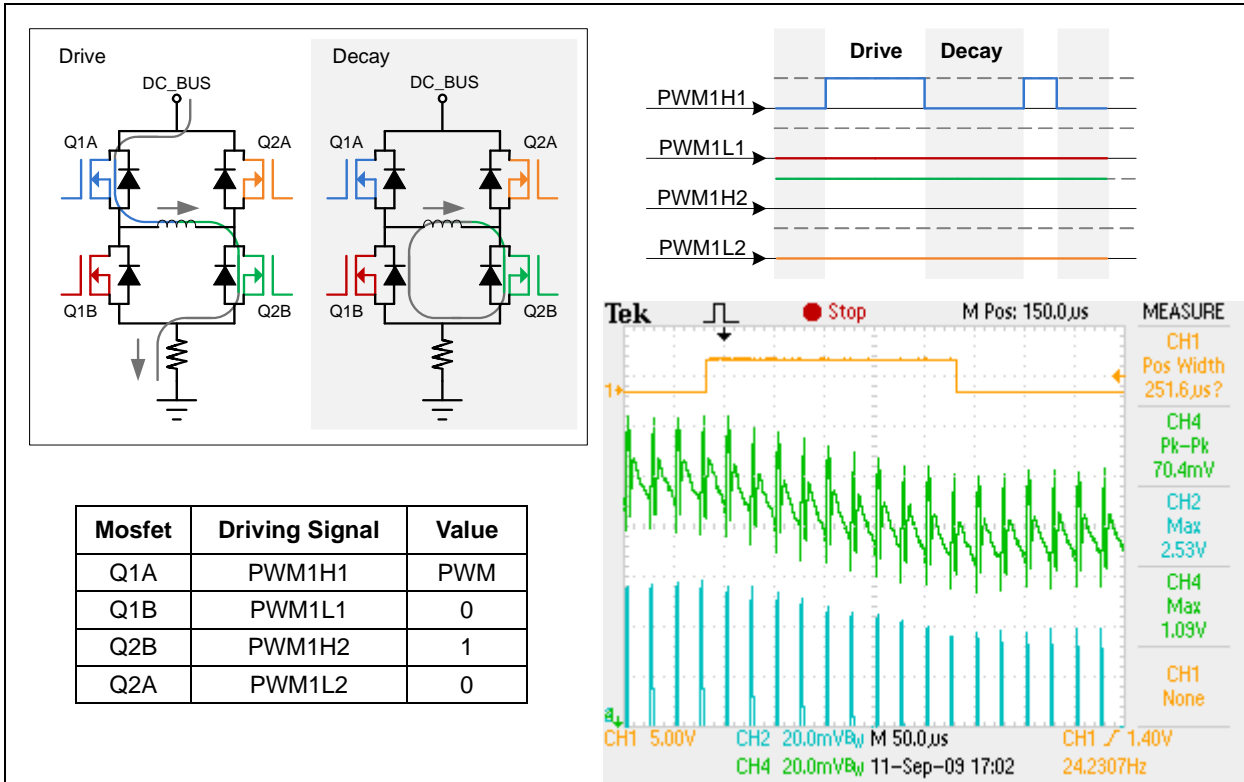
FIGURE B-3: SLOW DECAY HIGH DIODE RECIRCULATION

Mosfet	Driving Signal	Value
Q1A	PWM1H1	1
Q1B	PWM1L1	0
Q2B	PWM1H2	PWM
Q2A	PWM1L2	0
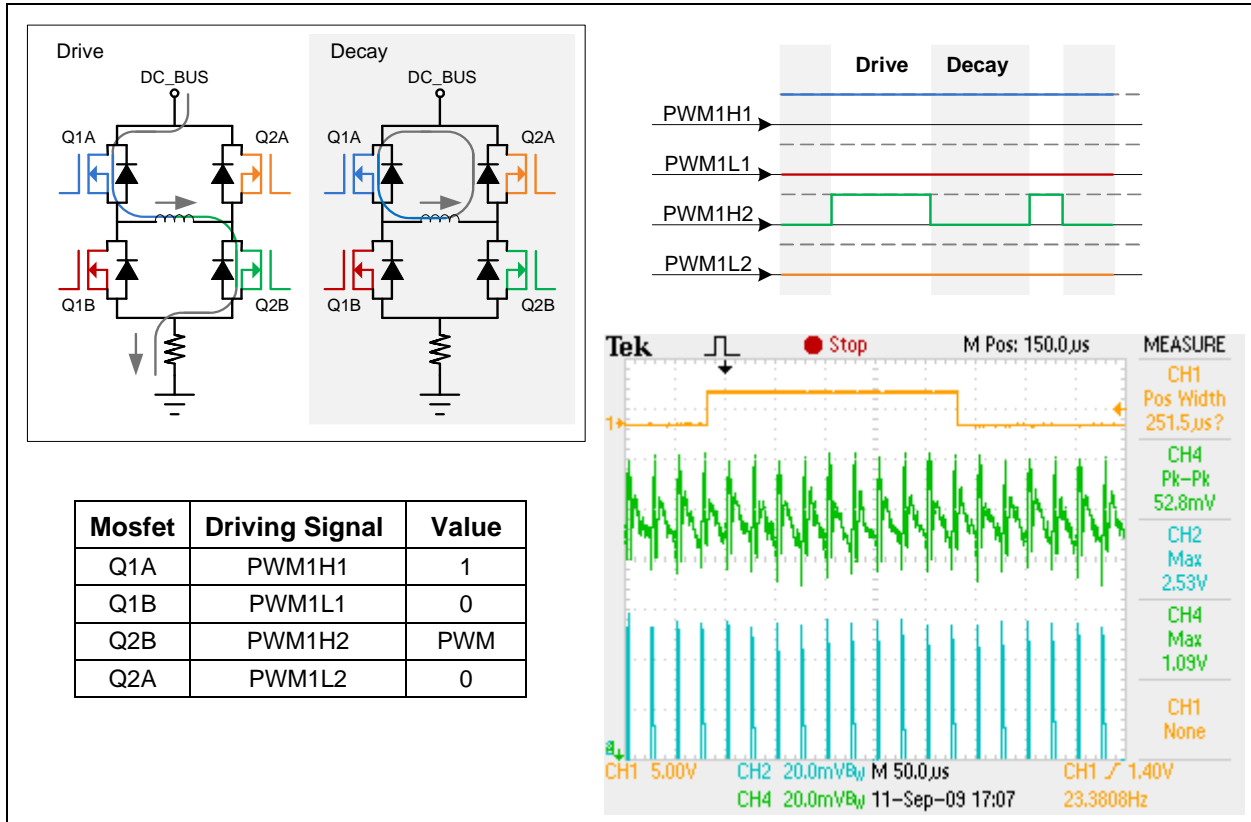
FIGURE B-4: SLOW DECAY LOW MOSFET RECIRCULATION

Mosfet	Driving Signal	Value
Q1A	PWM1H1	PWM
Q1B	PWM1L1	PWM
Q2B	PWM1H2	1
Q2A	PWM1L2	0
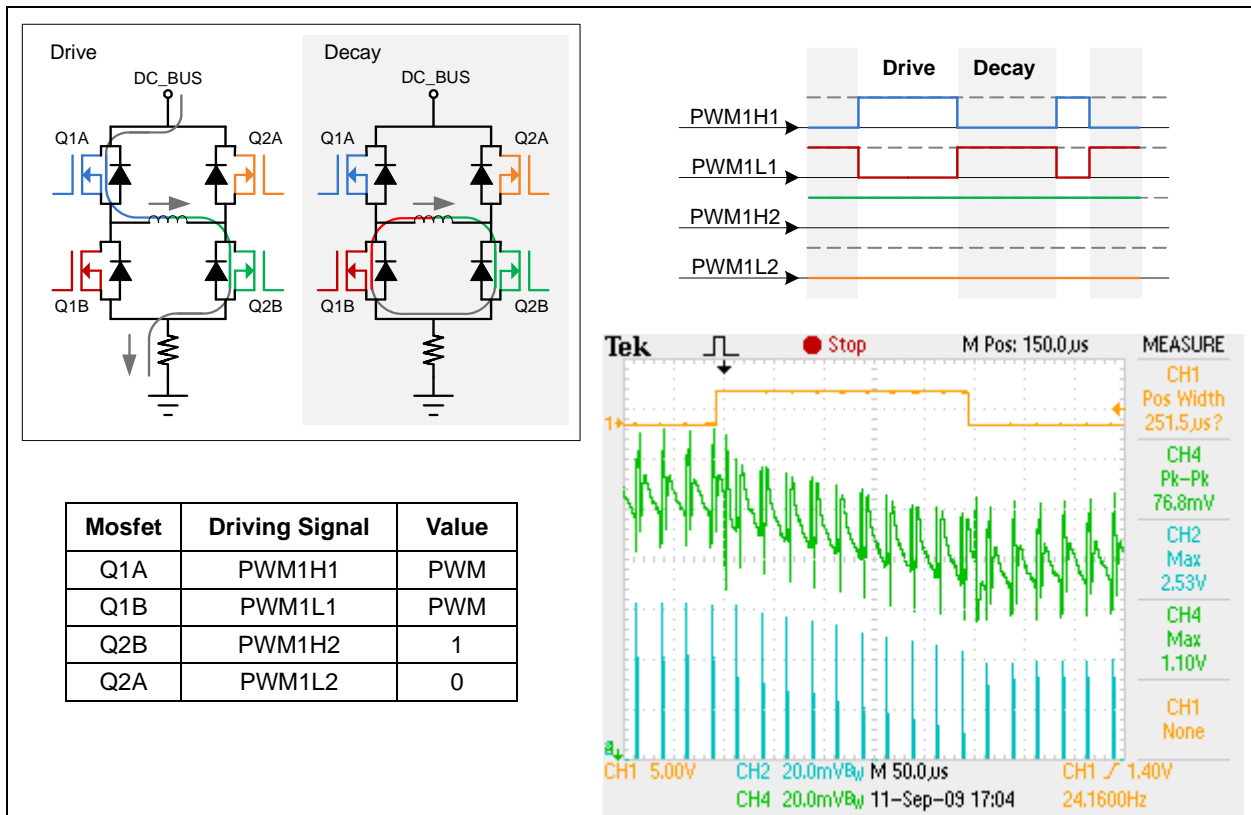
FIGURE B-5: **SLOW DECAY HIGH MOSFET RECIRCULATION**

Mosfet	Driving Signal	Value
Q1A	PWM1H1	1
Q1B	PWM1L1	0
Q2B	PWM1H2	PWM
Q2A	PWM1L2	PWM

FIGURE B-6: **REVERSE DECAY**

Mosfet	Driving Signal	Value
Q1A	PWM1H1	PWM
Q1B	PWM1L1	PWM
Q2B	PWM1H2	PWM
Q2A	PWM1L2	PWM
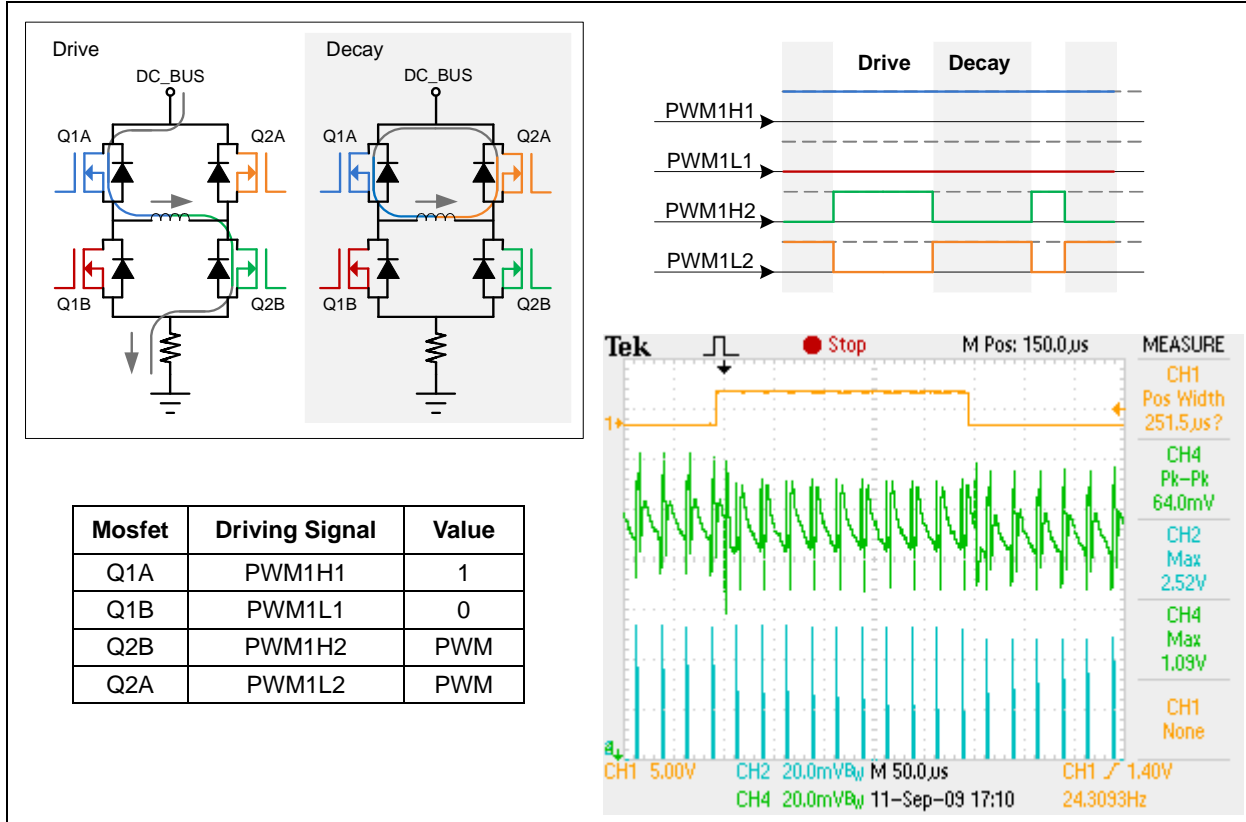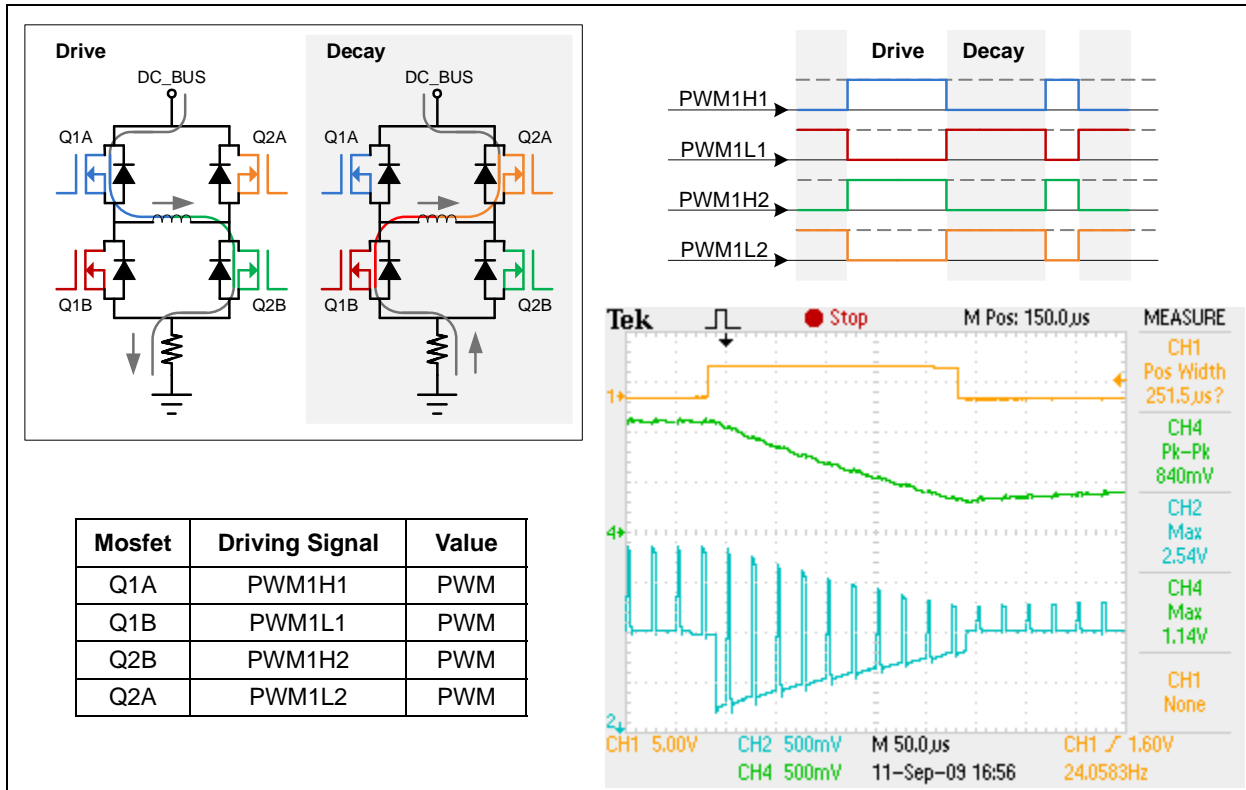
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