
Stepper Motor Control with dsPIC[®] DSCs

*Author: Sorin Manea and Srisairam Gaarlapati
Microchip Technology Inc.*

INTRODUCTION

This application note describes how to drive a stepper motor using a Microchip Digital Signal Controller (dsPIC[®] DSC).

The eight PWM channels 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 application firmware is developed for demonstration using the dsPICDEM[™] MCSM Development Board (DM330022-1), which includes the dsPIC33CK64MP105 External Op Amp Motor Control PIM (Part# MA330050-1), along with a stepper motor (Leadshine Part Number 42HS03), which is supplied separately from Microchip as Part Number AC300024. The 24-volt power supply for the board is also supplied separately by Microchip as Part Number AC002013. As shown in [Figure 1](#), the hardware consists of 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 more flexibility in controlling the power MOSFETs.

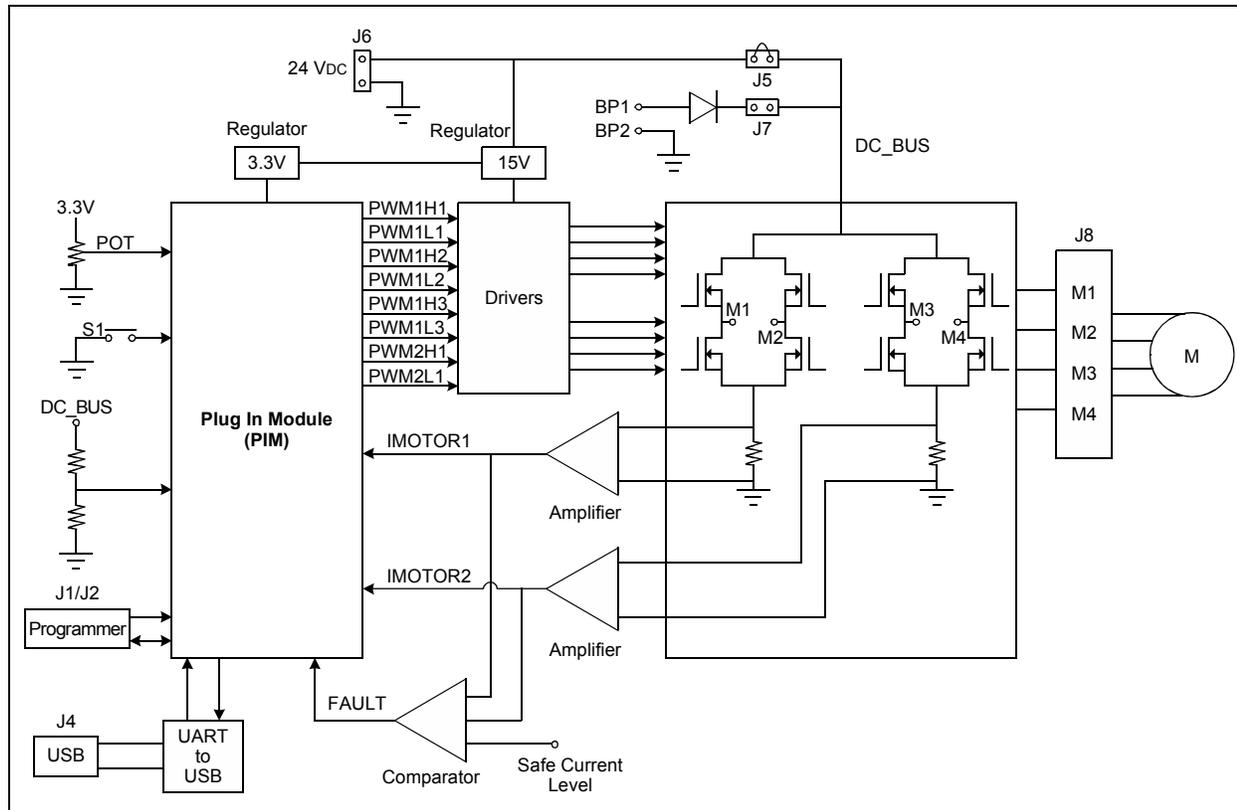
To learn more details about the hardware tool used, refer to the “dsPICDEM[™] MCSM Development Board User’s Guide” (DS70000610).

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 measurement, and control of currents. The characteristic features of the dsPIC[®] DSC fast timers and high processing power are necessary 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, requires 70 μ s to reach the current magnitude of 1.4A at 100% duty cycle, whereas at 24V, 250 μ s are needed to reach the current magnitude of 1.4A.

AN1307

FIGURE 1: dsPICDEM™ MCSM DEVELOPMENT BOARD BLOCK DIAGRAM



OVERVIEW OF CONTROL TOPOLOGIES

This application note discusses the following control methods for stepper motor control:

- 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 step-size options available 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 implemented and the available Decay modes are:

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

These Decay modes can be combined with any control method and with any Step modes (full, half or microstepping).

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

FULL STEP, HALF STEP AND MICROSTEP

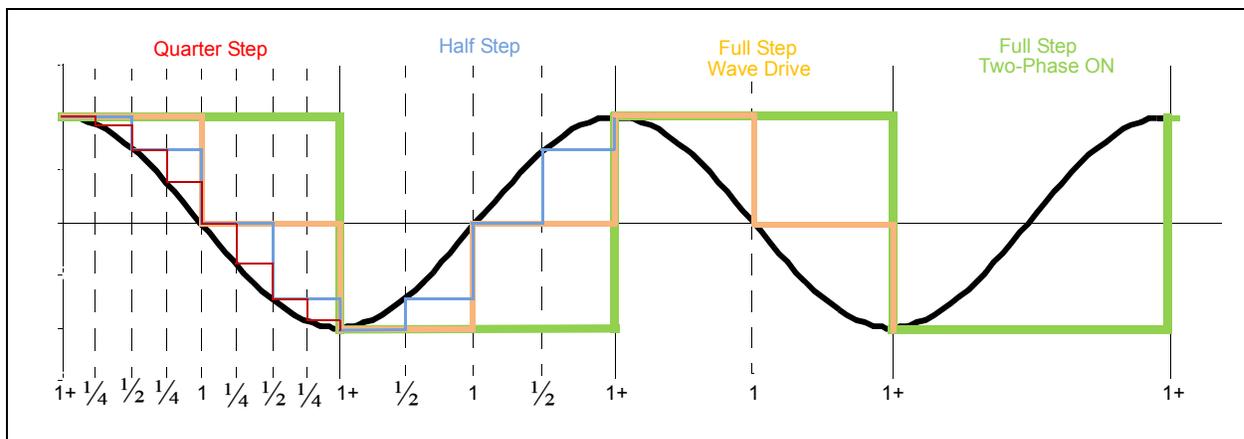
In applications where high positional accuracy and low vibrations and noise are needed, the ideal waveform for driving a stepper motor winding is a sine wave. A two-phase stepper motor is driven by two sine waves, shifted 90 degrees apart, driving each of the motor windings.

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. Since motor inductance cannot be reduced, 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. Considering an application with a resolution of 1/64 microsteps, there will be 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

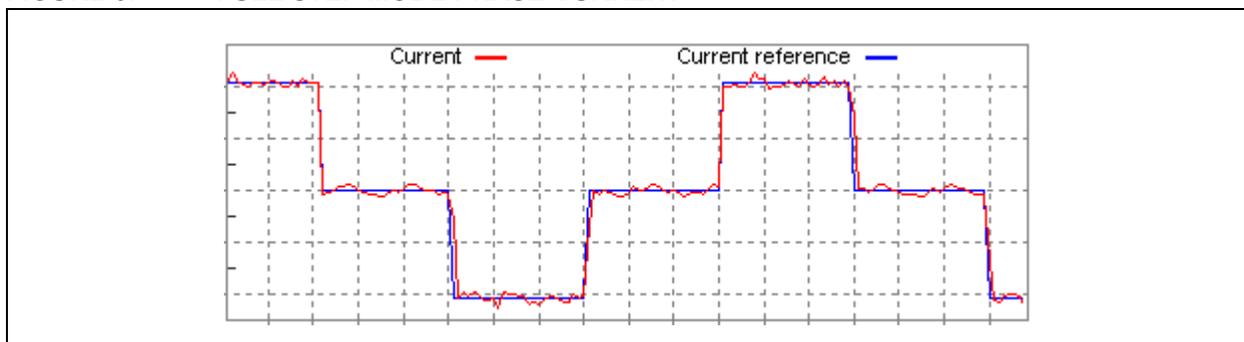


The values represented in the microstep table represent different things depending on the operating control mode. If the control mode is Open-Loop Voltage/Open-Loop Current Control, then this table represents the desired voltages to be applied to each winding. If the operating mode is Closed-Loop Current 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.

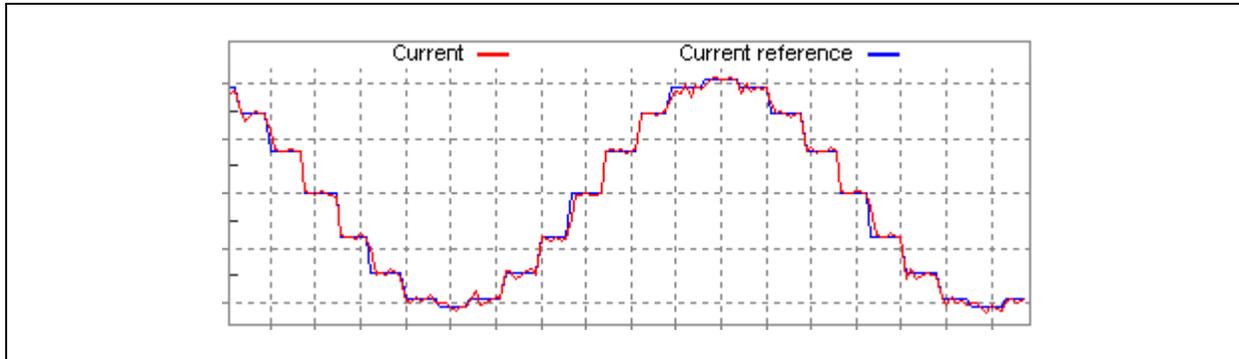
[Figure 3](#) shows the current waveforms for full step generation in closed-loop current control.

FIGURE 3: FULL STEP MODE PHASE CURRENT



AN1307

FIGURE 4: MICROSTEPPING WITH 1/4 STEP-SIZE



Users can change microstep granularity in software. [Table 1](#) summarizes steps per electrical cycle for various Step modes.

TABLE 1: STEP MODES

Step Mode	Steps per Electric Cycle
Full Step	4
Half Step	8
1/4 Step	16
1/8 Step	32
1/16 Step	64
1/32 Step	128
1/64 Step	256

Note that when the value of step-size increases, the number of microsteps also increases.

When operating in Full Step mode, two options are available to drive the motor:

- Full Step Wave Drive mode: In this mode, only one phase is on at any moment in time.
- Full Step Two-Phase On mode: In this mode, two phases are always on, but the polarity changes every two steps.

Note: [Figure 5](#) shows the current waveforms during Wave Drive mode and [Figure 6](#) shows the current waveforms during Two-Phase On mode.

FIGURE 5: CURRENT – FULL STEP WAVE DRIVE MODE

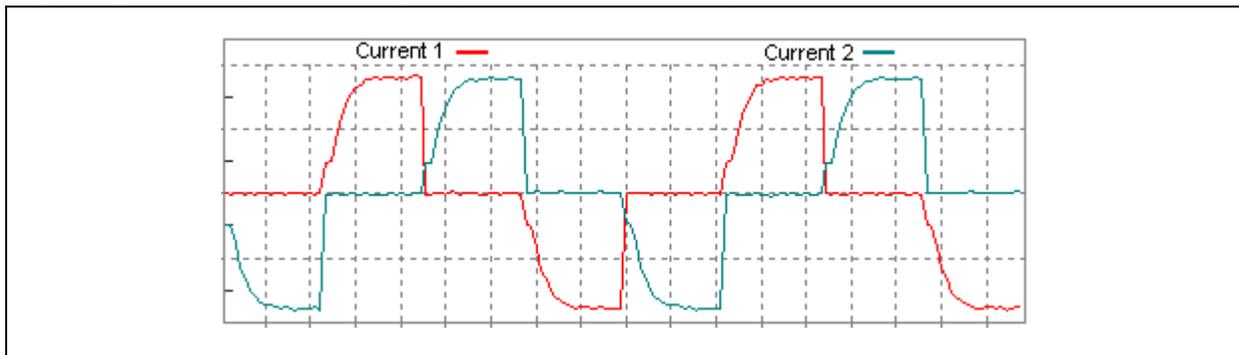
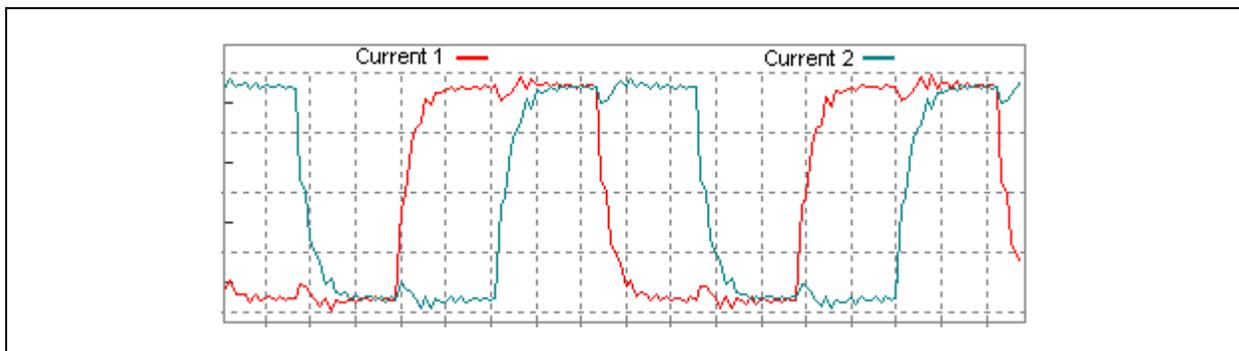


FIGURE 6: CURRENT – FULL STEP TWO-PHASE ON MODE



OPEN-LOOP CONTROL METHODS

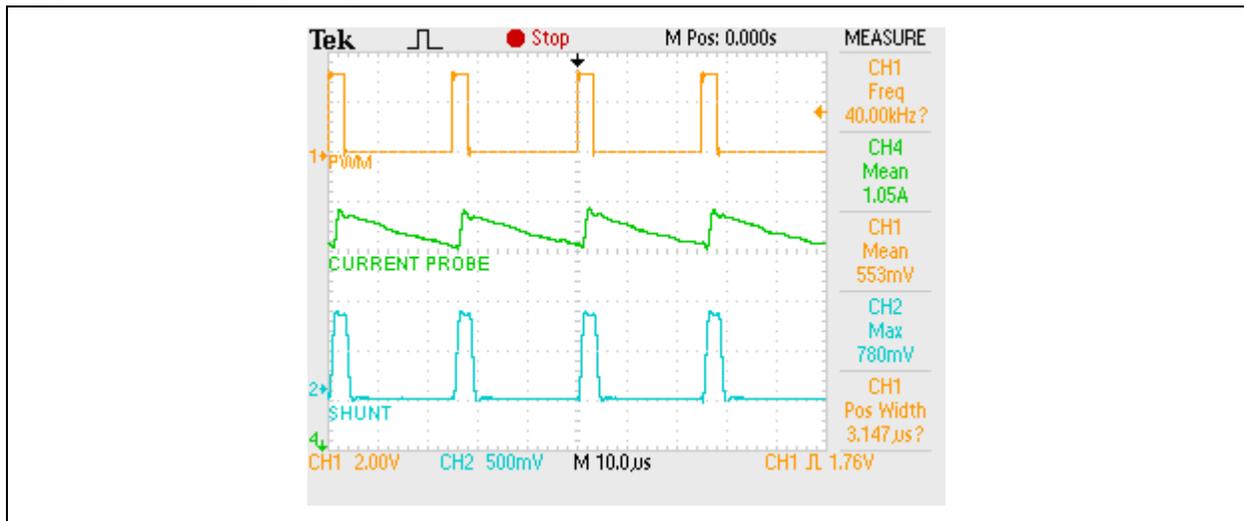
There are two open-loop control methods discussed in this application note. One is fixed voltage control, which is an open-loop control and does not adjust PWM duty cycles according to feedback. The second control method is fixed current control. In this method, the duty cycle is corrected every four 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.

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 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](#).

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.

FIGURE 7: MOTOR CURRENT AND PWM



AN1307

The fixed voltage control is implemented by generating the desired voltage levels with the appropriate PWM duty cycles. 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 magnitude of current varies in proportion to the voltage; however, since there is no current control, the resulting current waveform is distorted.

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 higher speeds, the current may not rise fast enough through the motor coil to reach the rated

current, which reduces the generated torque. The speed at which this starts to occur depends on the motor inductance and applied voltage.

As the motor speeds up, the step time gets smaller and the current amplitude reduces until the rotor eventually stalls. To overcome this problem, the 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

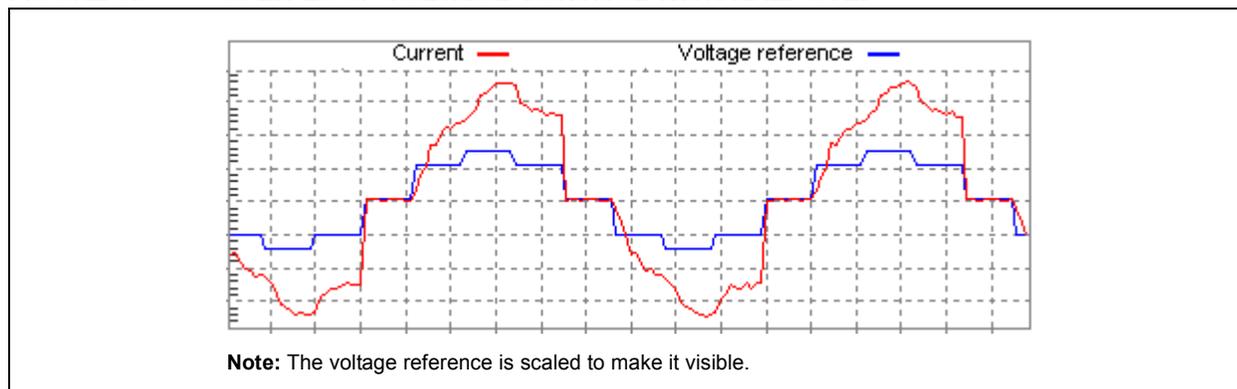


FIGURE 9: FIXED VOLTAGE CONTROL AT 120 RPM WITH ALTERNATE DECAY

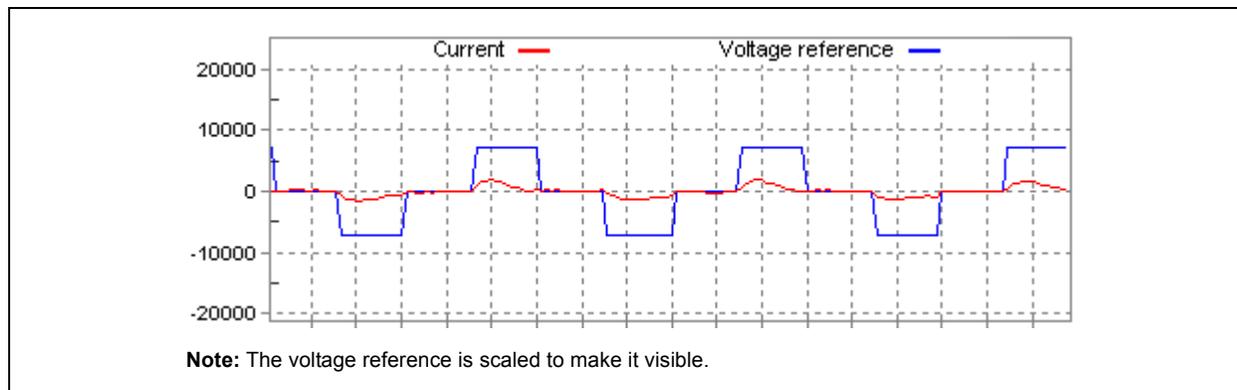
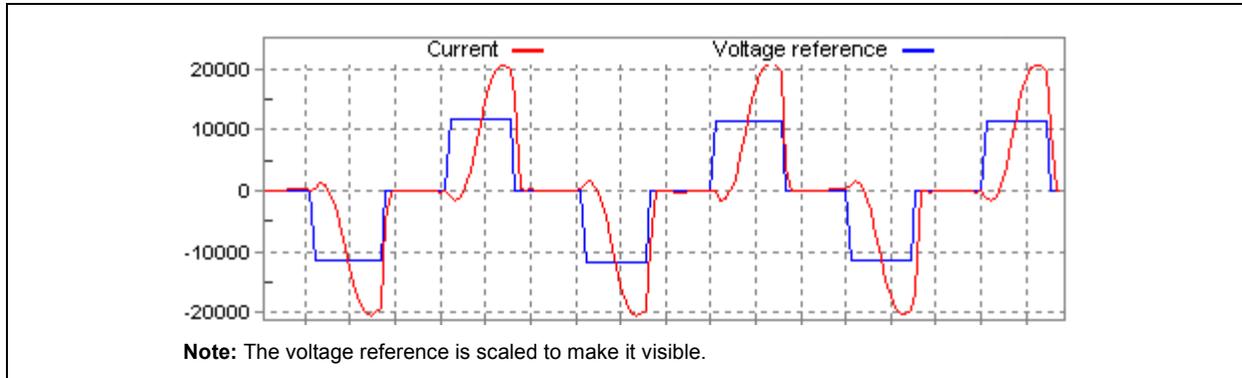


Figure 10, on the other hand, shows how the current amplitude is controlled to a higher value by applying a higher voltage. Only the current amplitude is controlled in this mode, not the shape or phase.

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



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 (Fixed Voltage Control) 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.

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 referred to as Decay modes in this document.

Fast Decay

In fast decay, 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 free-wheeling 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 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, 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

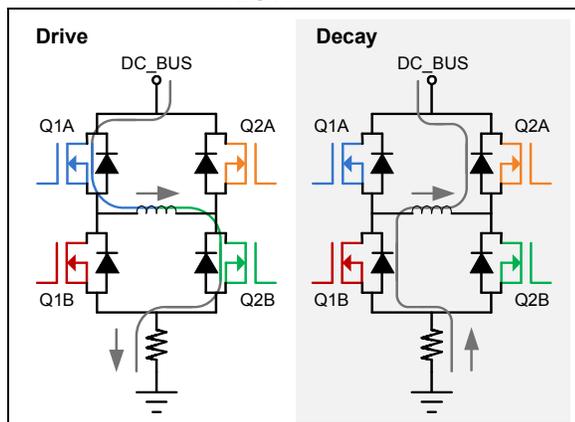


FIGURE 13: FAST DECAY (REVERSE) CURRENT FLOW

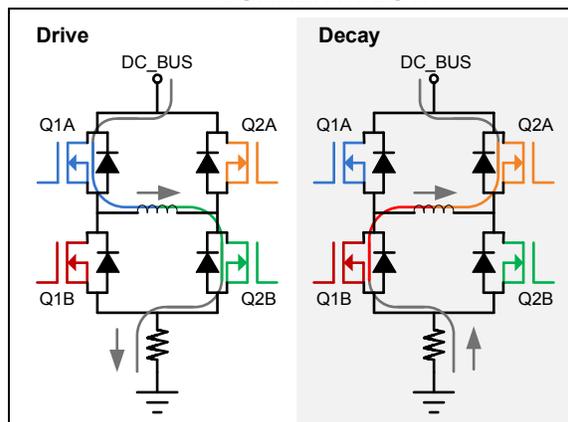


FIGURE 12: FAST DECAY PWM TIMING DIAGRAM

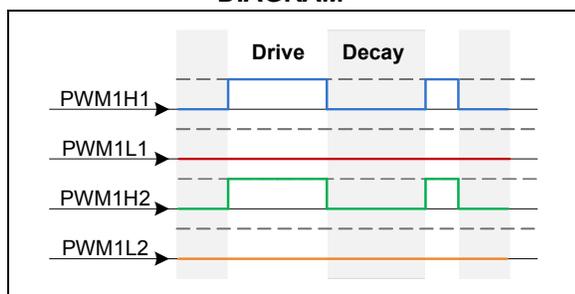


FIGURE 14: FAST DECAY (REVERSE) PWM TIMING DIAGRAM

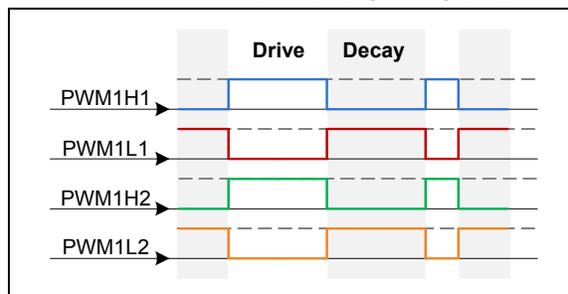


TABLE 2: FAST DECAY DRIVE SIGNALS

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 another variant of this Decay mode which is referred to as Reverse Decay mode. Reverse decay behaves like fast decay 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.

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 (refer to [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

Name	Active Components During Decay
Fast Decay Mode	Low-Side Diode + Opposite High-Side Diode
Reverse Decay Mode	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 open at all times (see the Q1A or Q2B MOSFETs in [Figure 15](#)). The current recirculates through the motor winding, driving the 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

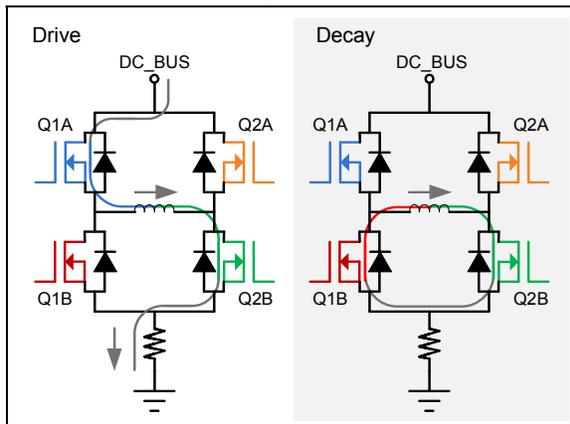


FIGURE 16: SLOW DECAY LOW-SIDE MOSFET PWM TIMING DIAGRAM

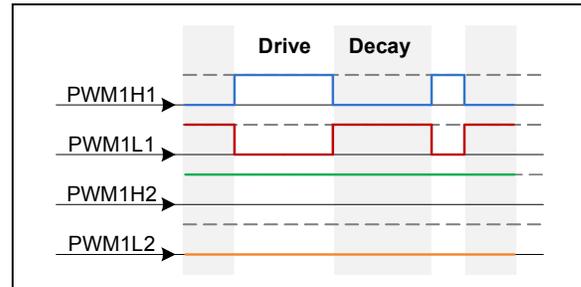


TABLE 5: SLOW DECAY LOW-SIDE MOSFET DRIVE SIGNALS

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 used. When a bootstrap topology is used for driving high-side MOSFETs, the Slow Decay mode, called the Low-Side MOSFET Recirculation mode, is recommended as it helps the bootstrap capacitors to charge. If the bootstrap capacitors discharge, the upper MOSFETs cannot be turned on. [Appendix B: “Decay Modes”](#) 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

Name	Active Components During Decay
Low-Side Diode Recirculation Mode	Low-Side Diode + Opposite Low-Side MOSFET
High-Side Diode Recirculation Mode	High-Side MOSFET + Opposite High-Side Diode
Low-Side MOSFET Recirculation Mode	Low-Side MOSFET + Opposite Low-Side MOSFET
High-Side MOSFET Recirculation Mode	High-Side MOSFET + Opposite High-Side MOSFET

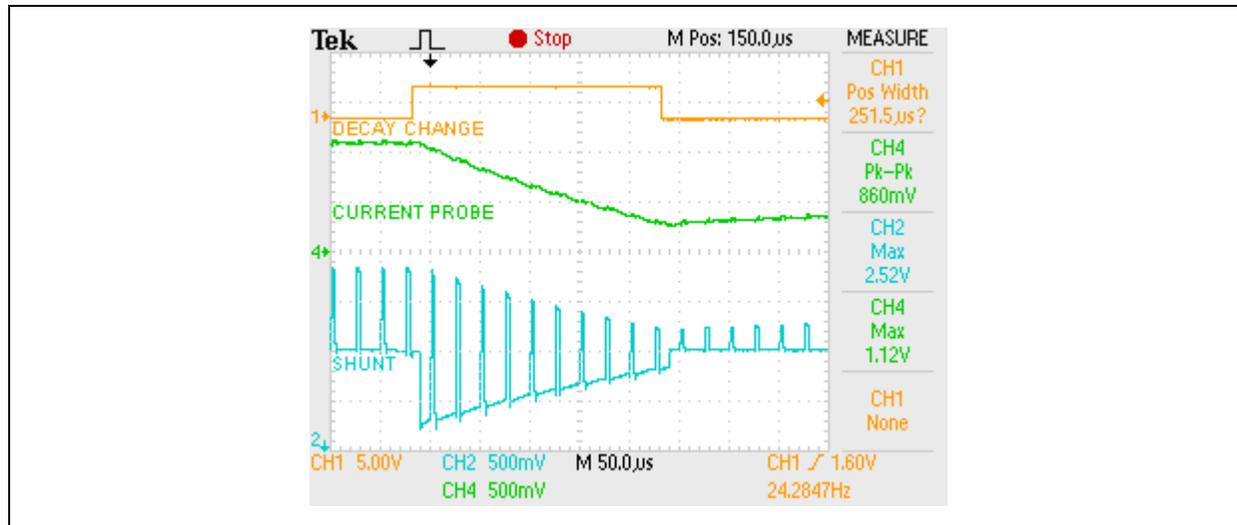
AN1307

Due to the shunt resistor circuit used for current sensing, current measurement is not possible in Slow Decay modes. This is because in Slow Decay modes, current does not flow 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. 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, in which either fast or slow decay is used, and this can be selected by the user in application code. The second option is Alternate Decay mode, where two Decay modes are combined while driving the stepper motor. Table 7 shows 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 mode 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 provides quieter motor operation and is good at relative

low speeds. As the motor speed increases and the desired current declines at a faster rate, the winding current can no longer follow this curve using slow decay. Although operation in fast decay 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 modes, 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.

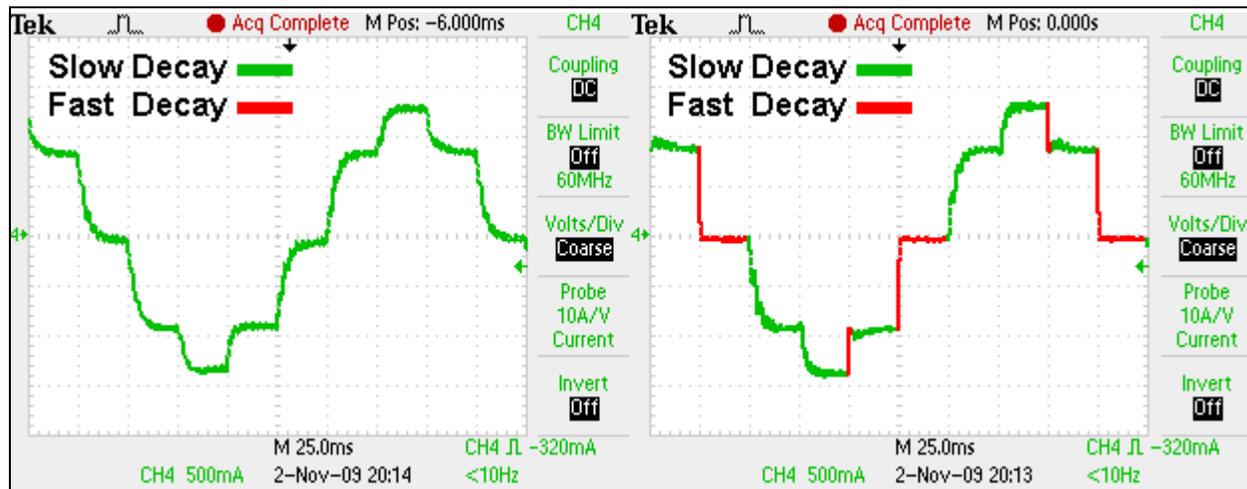
For each step, a different current drop is required, so a smaller or larger ratio of fast to slow decay is needed based on the step amplitude change. If fast decay is not used long enough, the current decreases too slowly and does not follow the desired shape. If it is used for too long, the current 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

Decay Modes	Description
Fixed Decay Mode	Only one Decay mode is used: Base Decay.
Alternate Decay Mode	Alternates between two Decay modes: Base Decay and Alternate Decay.

FIGURE 18: COMPARISON BETWEEN FIXED AND ALTERNATE DECAY



AN1307

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 the 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.

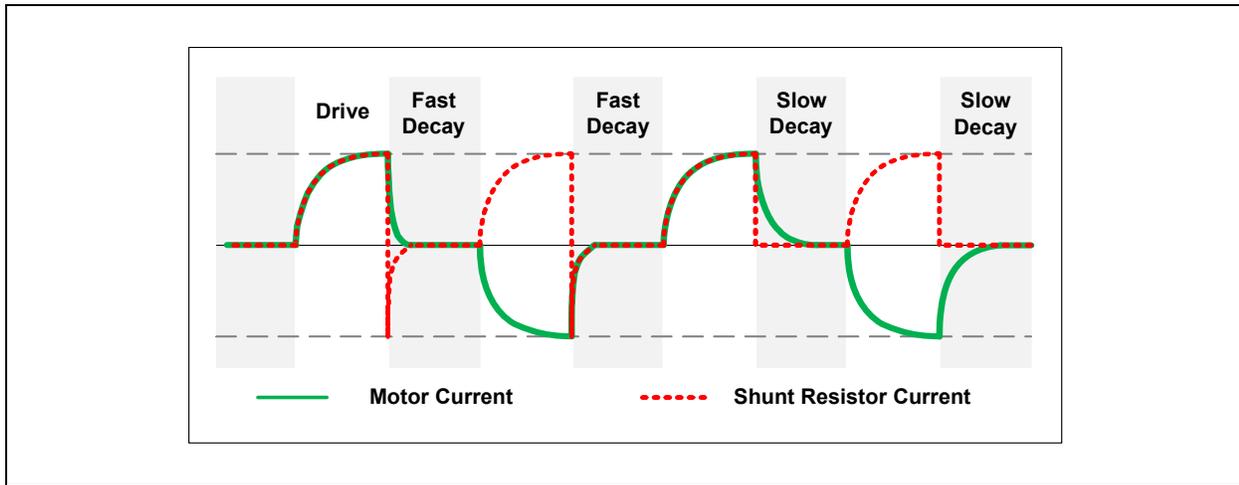
When the motor winding is energized, the shunt current will always be positive, regardless of the current direction in the motor winding. Whenever the winding is in

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 the 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 increases. 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 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

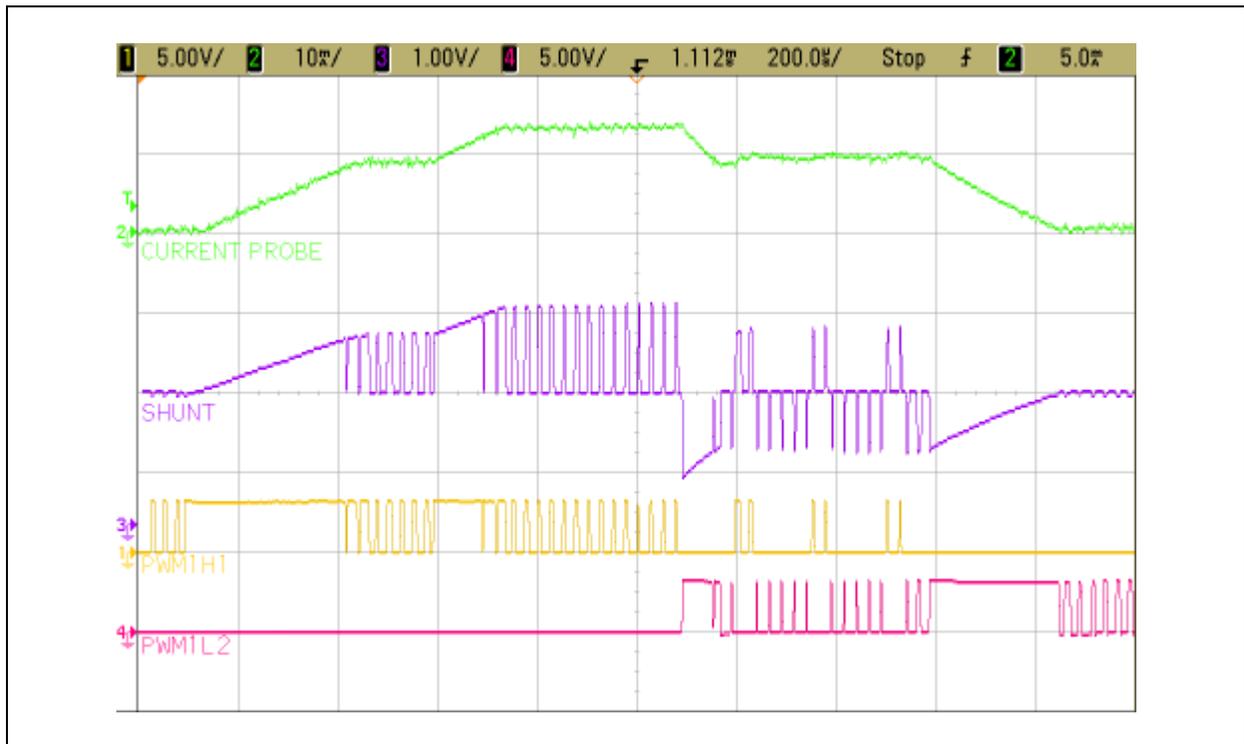
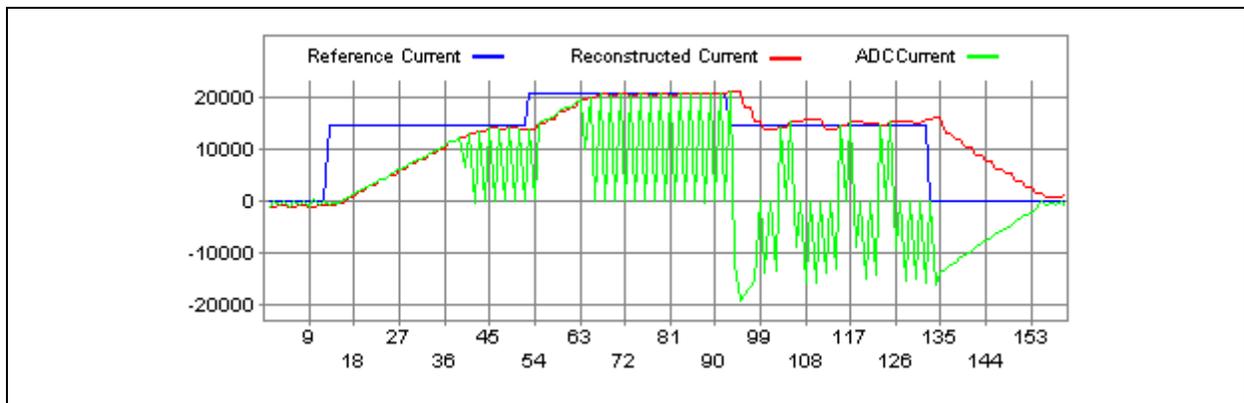


FIGURE 21: RECONSTRUCTION OF WINDING CURRENT FROM ADC READINGS



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.

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 μ s. 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

In order to compensate the motor transfer function pole and achieve a zero steady-state error, a classic PI controller is chosen. See [Equation 1](#) and [Equation 2](#).

EQUATION 1: MOTOR WINDING EQUATION

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

Legend:

- 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

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

Legend:

- s = Laplace Variable
- K = Continuous Controller Gain

By applying Tustin discretization to [Equation 3](#), the formula shown in [Equation 4](#) is obtained:

EQUATION 4: DISCRETE PI CONTROLLER

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

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

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

$$T = 25 \mu\text{s}$$

$$G = K/R$$

Legend:

- 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](#). As step response rise time of the first order system is approximately three times the time constant, by choosing the response time controller, gains can be calculated. Controller gains can be calculated using [Equation 6](#). 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

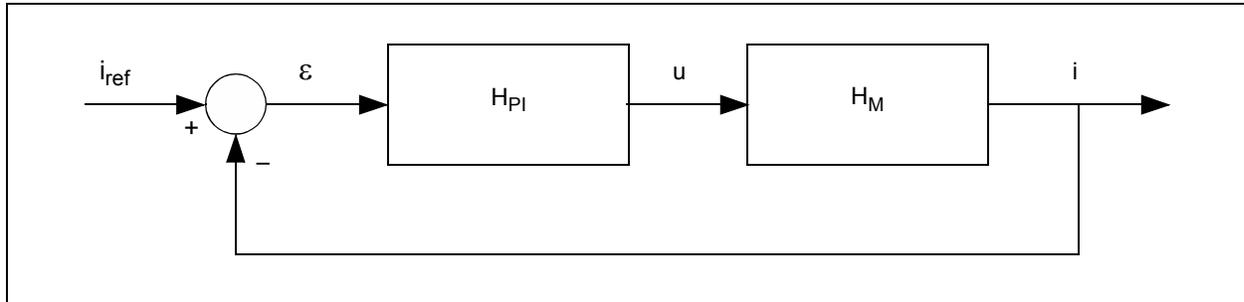
$$3 \frac{R}{K \cdot V} = 70 \mu\text{s}$$

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

Legend:

- G_0 = Scaled Discrete Gain

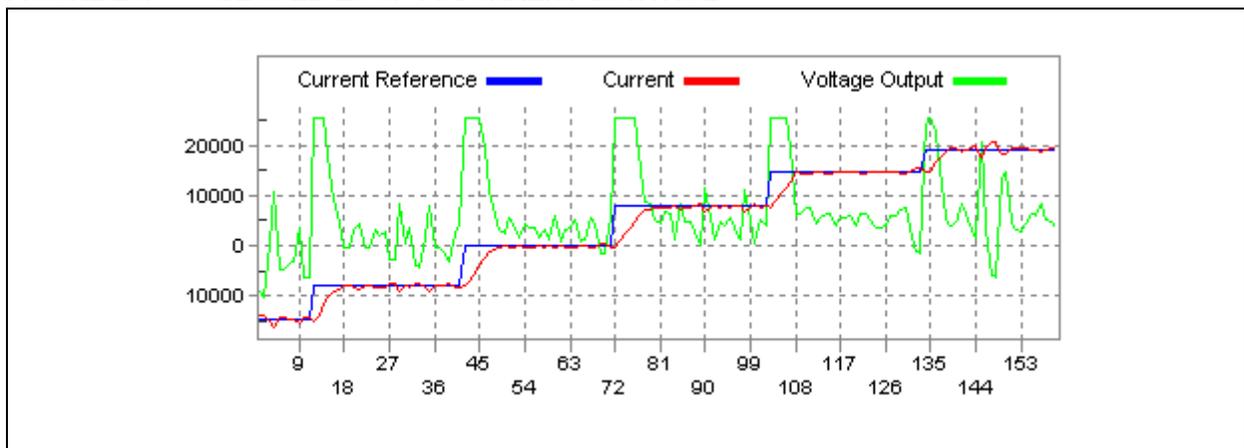
FIGURE 22: CLOSED-LOOP CONTROLLER BLOCK DIAGRAM



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. 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 six 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 the DC bus would be needed to achieve the set rise time.

FIGURE 23: CLOSED-LOOP PI CURRENT CONTROL



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

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

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

Legend:

acc = Integral Accumulator
 u = Output Voltage
 ε = Current Error
 p_1, p_2 = Discrete Controller Parameters
 acc_k, ε_k = Values from Previous Cycle
 $acc_{k+1}, \varepsilon_{k+1}$ = Values from Present Cycle

EQUATION 8: ANTI-WINDUP PI CONTROLLER

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

Legend:

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. Keep anti-windup sufficiently high to prevent motor Stall at higher speeds.

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

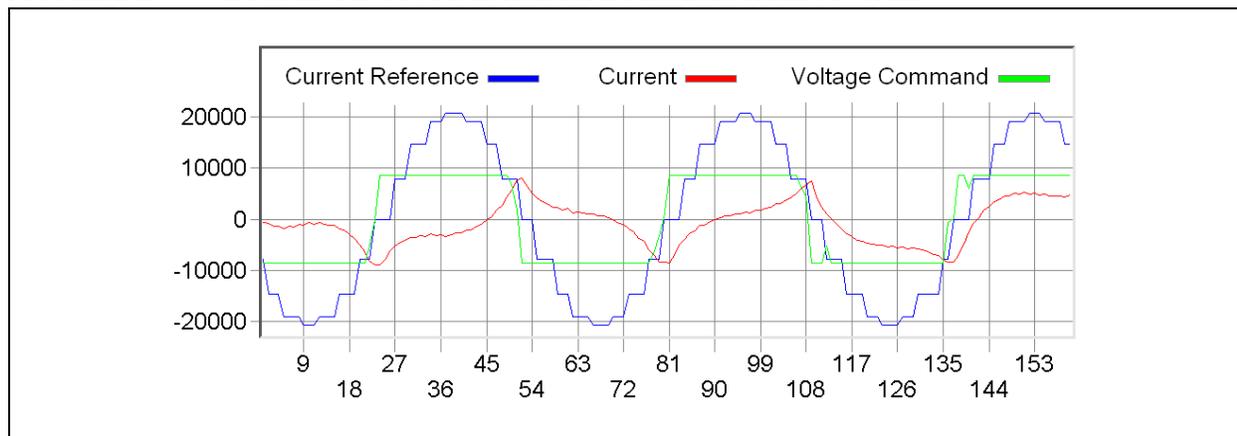
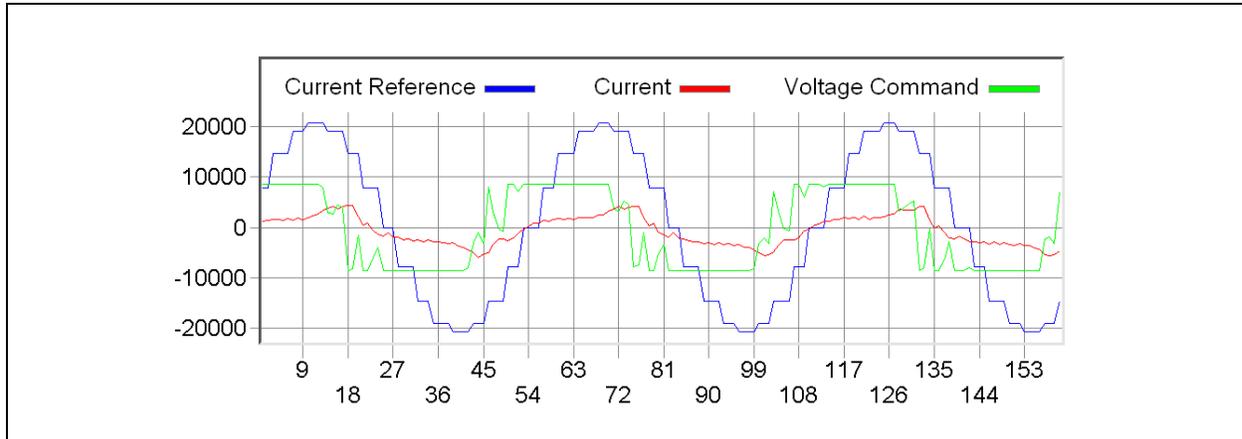
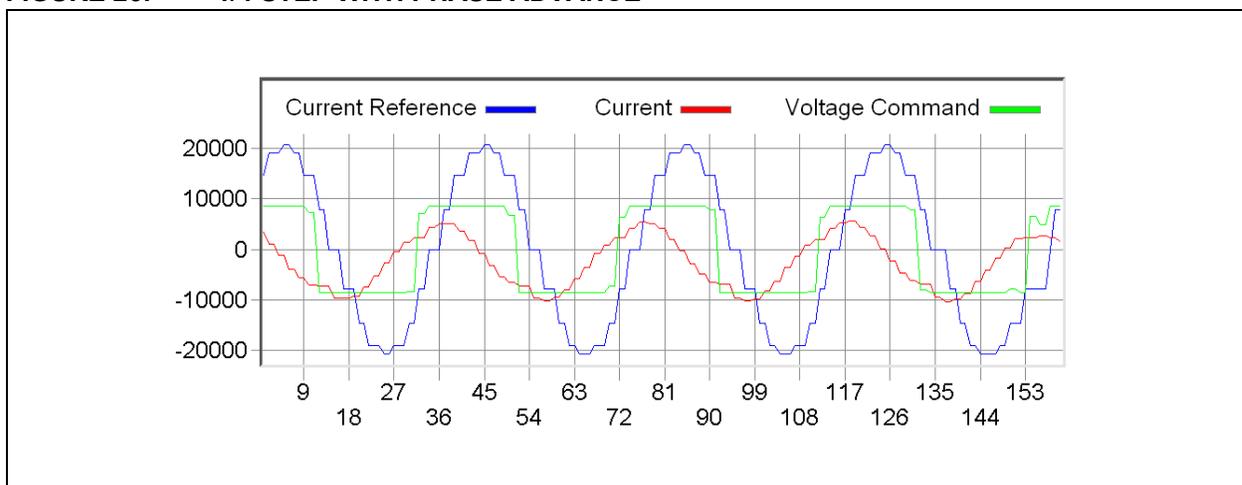


FIGURE 25: 1/4 STEP AT 840 RPM WITH A HIGH ANTI-WINDUP GAIN

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

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 than the maximum allowed deceleration rate.

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

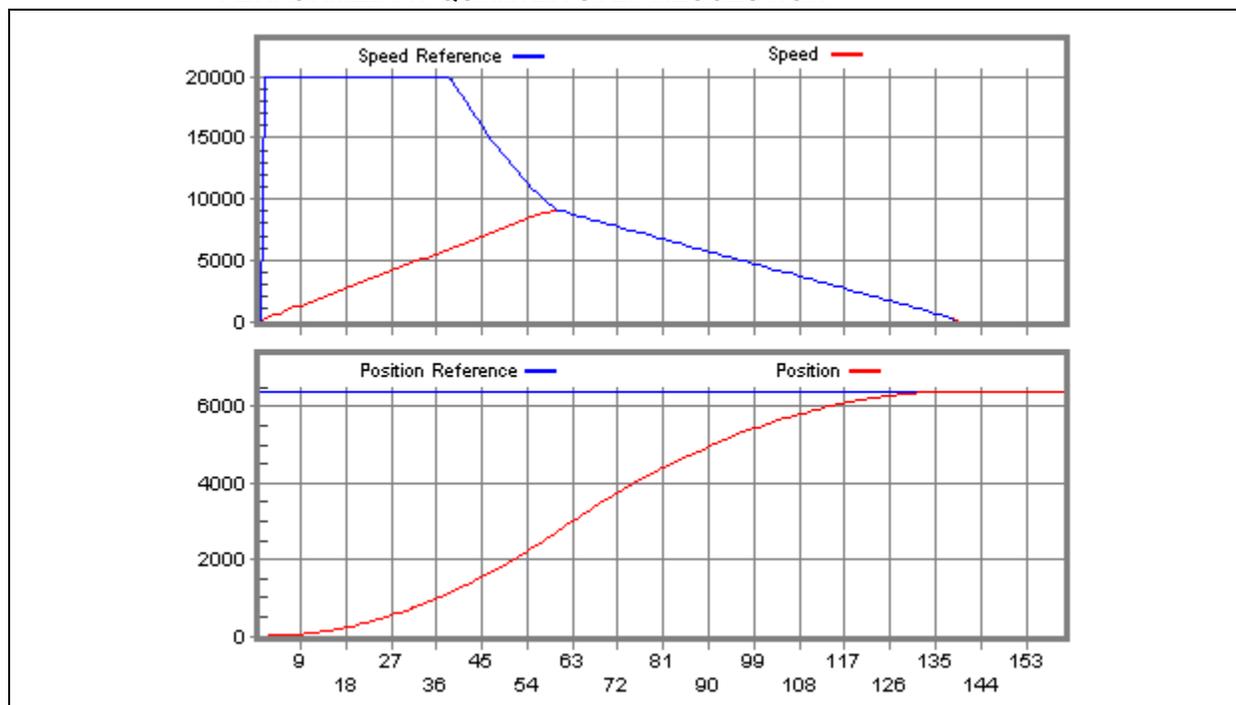
This application note presented three methods to control a stepper motor: Fixed Voltage mode, Fixed Current mode and PI Closed-Loop Control mode.

A method of generating up to 1024 points per cycle was also discussed 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 requirements.

For software implementation, code is available for download from the Microchip website at: www.microchip.com/mcsm.

To learn more details about the hardware tool used, refer to the “dsPICDEM™ MCSM Development Board User’s Guide” (DS70000610).

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

$$speed_{Ref} = pos_{Gain} \cdot pos_{Err} = \frac{pos_{Fixed_gain} \cdot decelerationRate}{|speed_{Out}|} \cdot pos_{Err}$$

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

APPENDIX A: SOFTWARE FLOW CHARTS

FIGURE A-1: MAIN STATE MACHINE

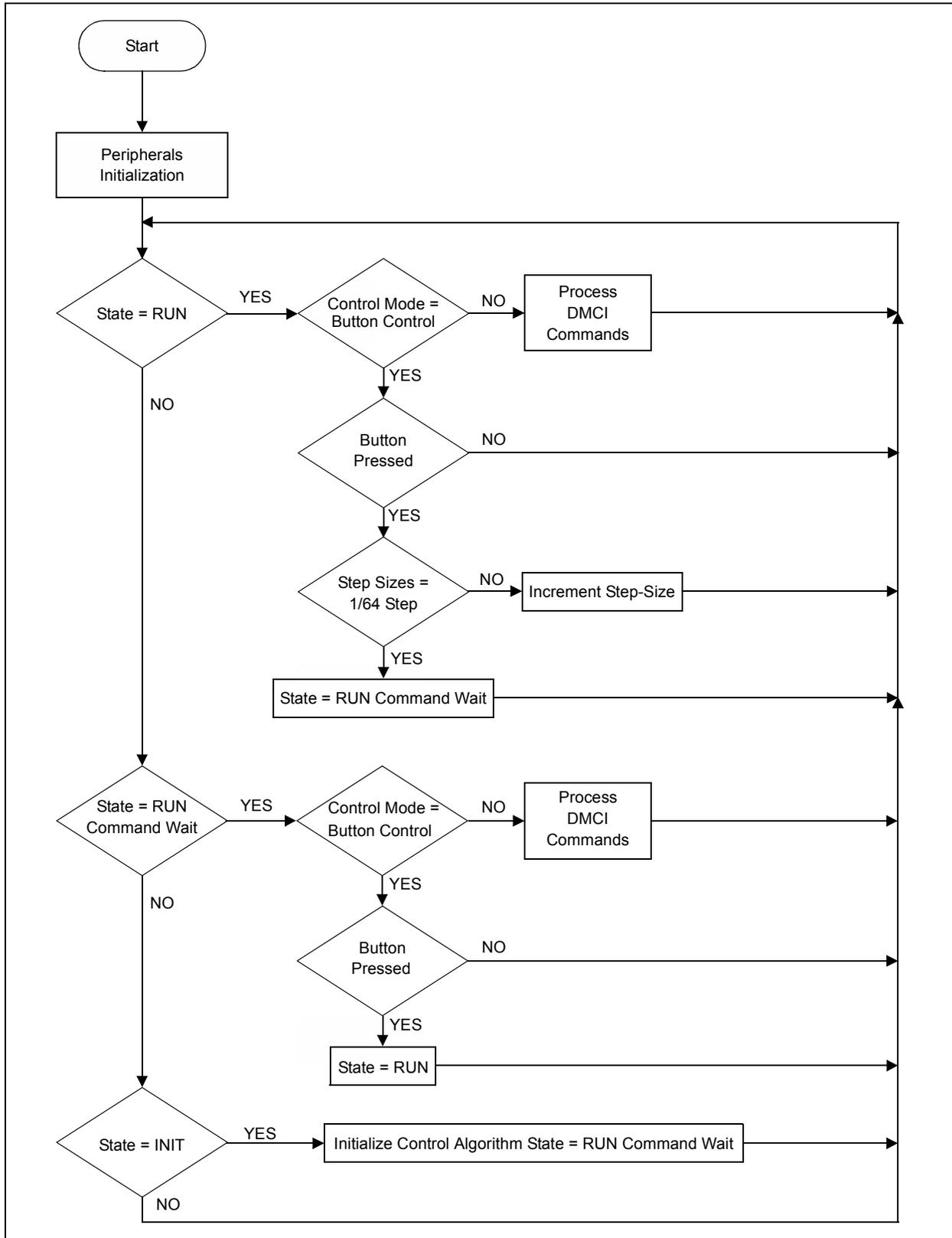


FIGURE A-2: ADC INTERRUPT

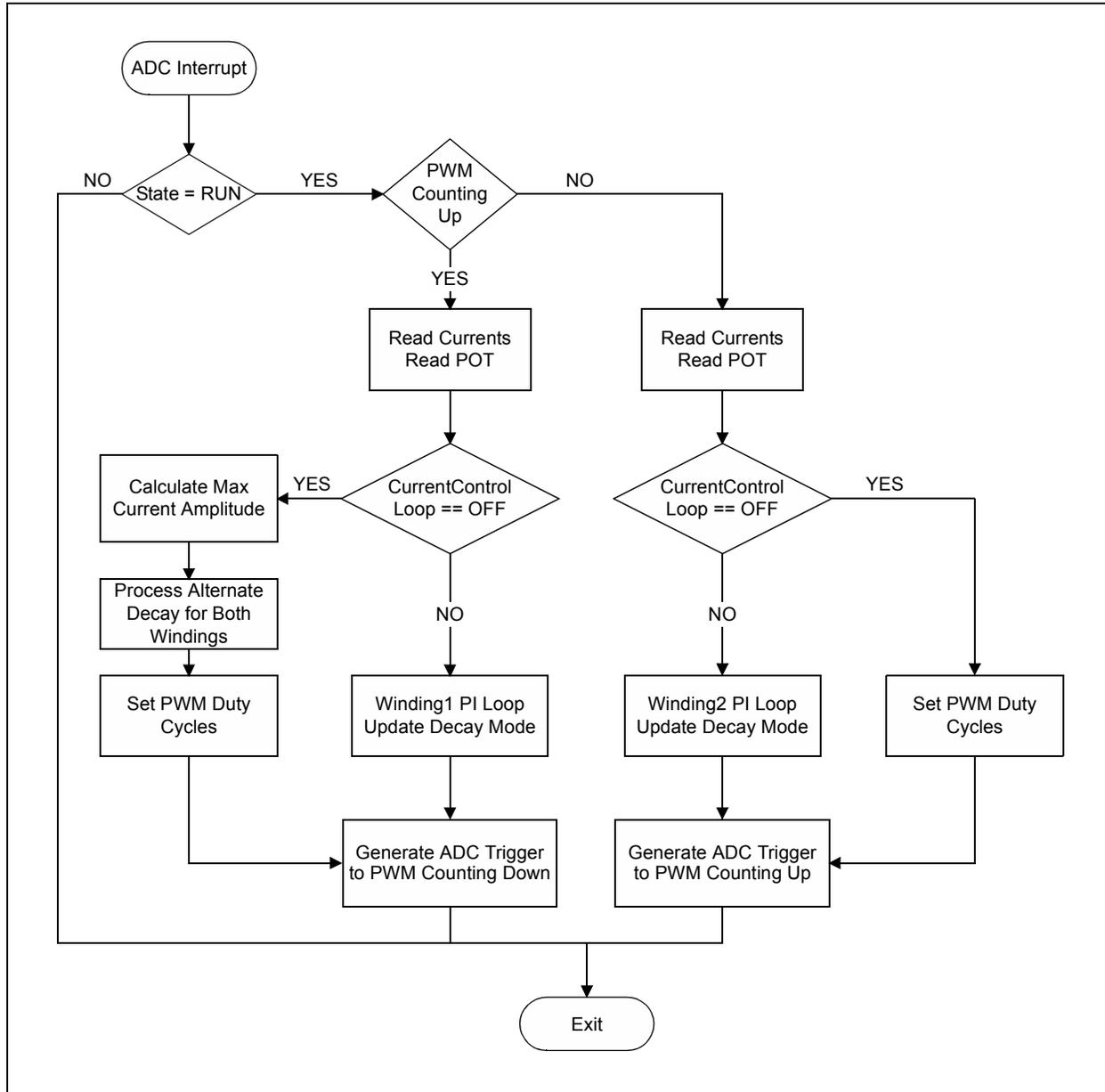
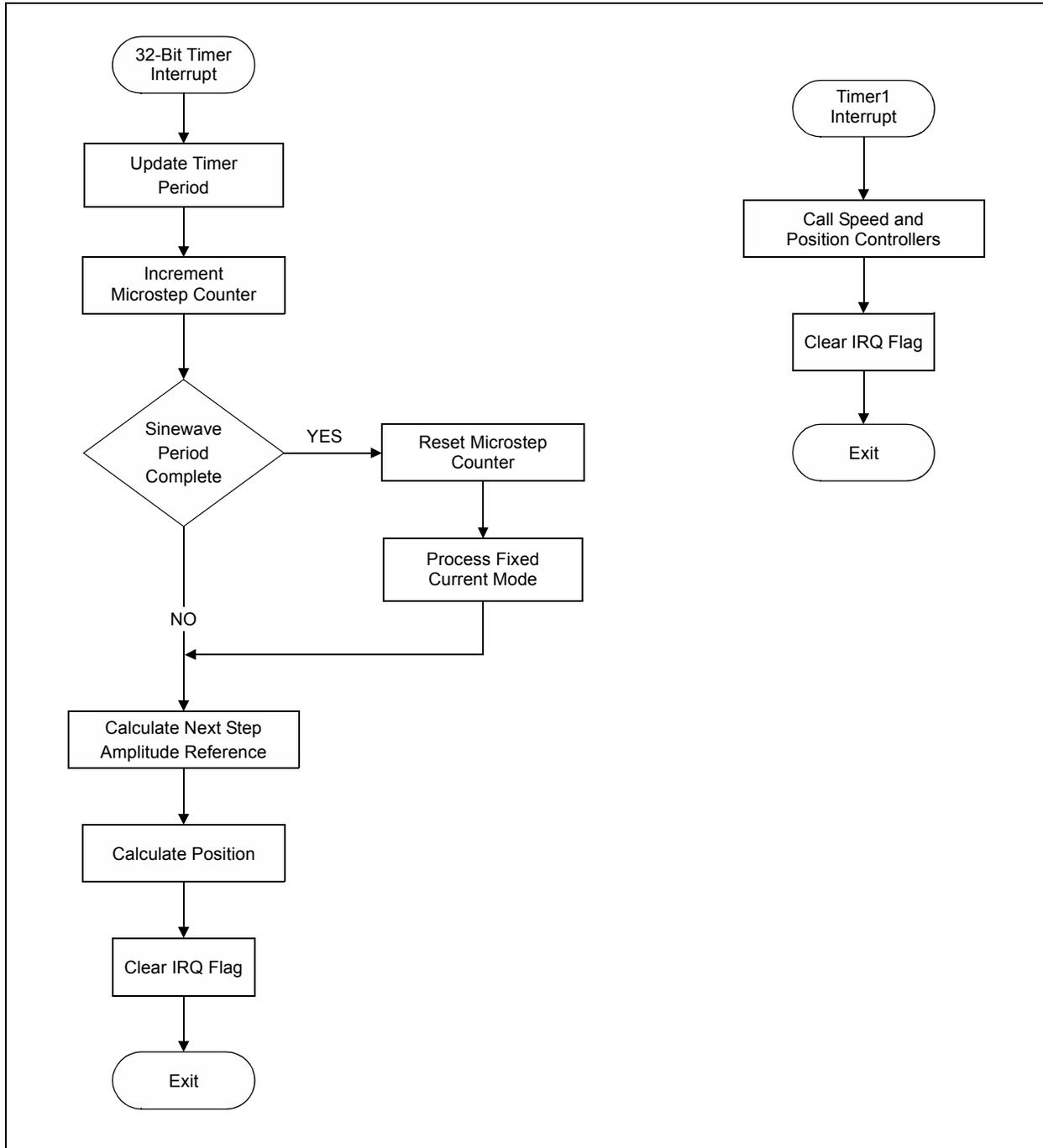


FIGURE A-3: TIMER INTERRUPTS



APPENDIX B: DECAY MODES

FIGURE B-1: FAST DECAY

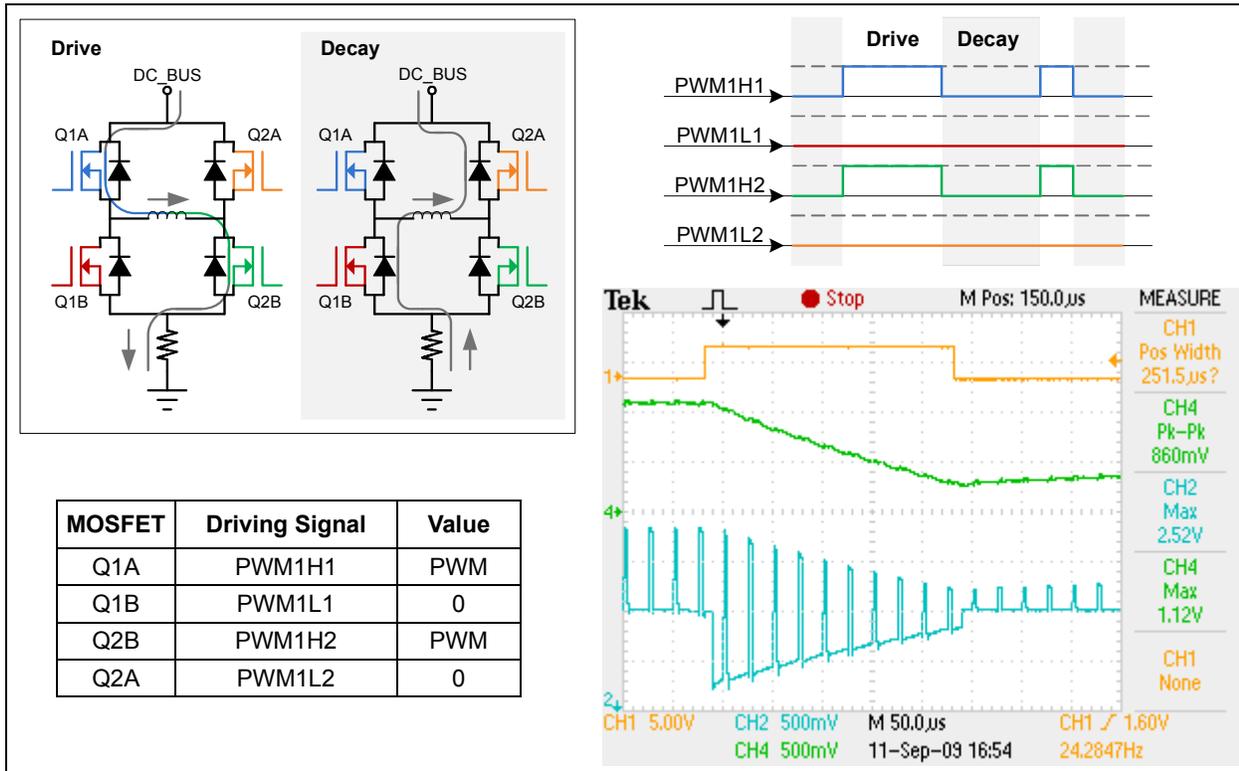


FIGURE B-2: SLOW DECAY LOW DIODE RECIRCULATION

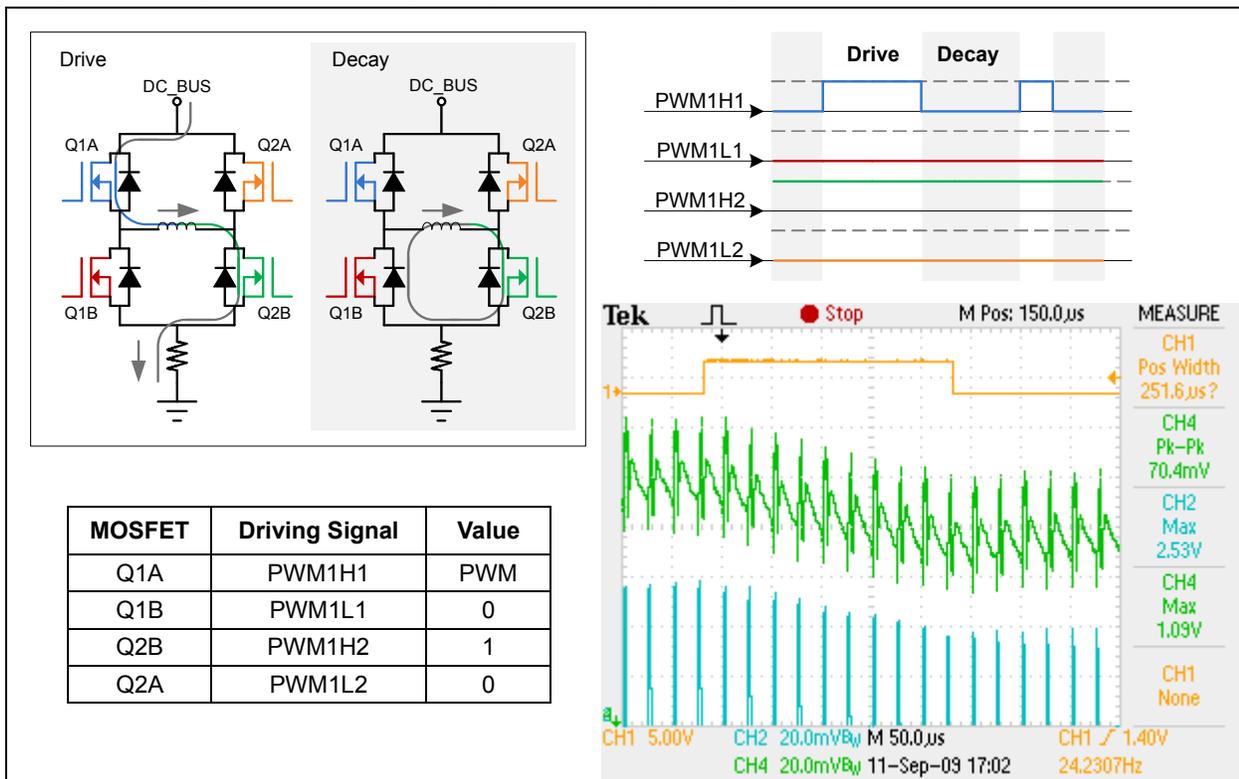


FIGURE B-3: SLOW DECAY HIGH DIODE RECIRCULATION

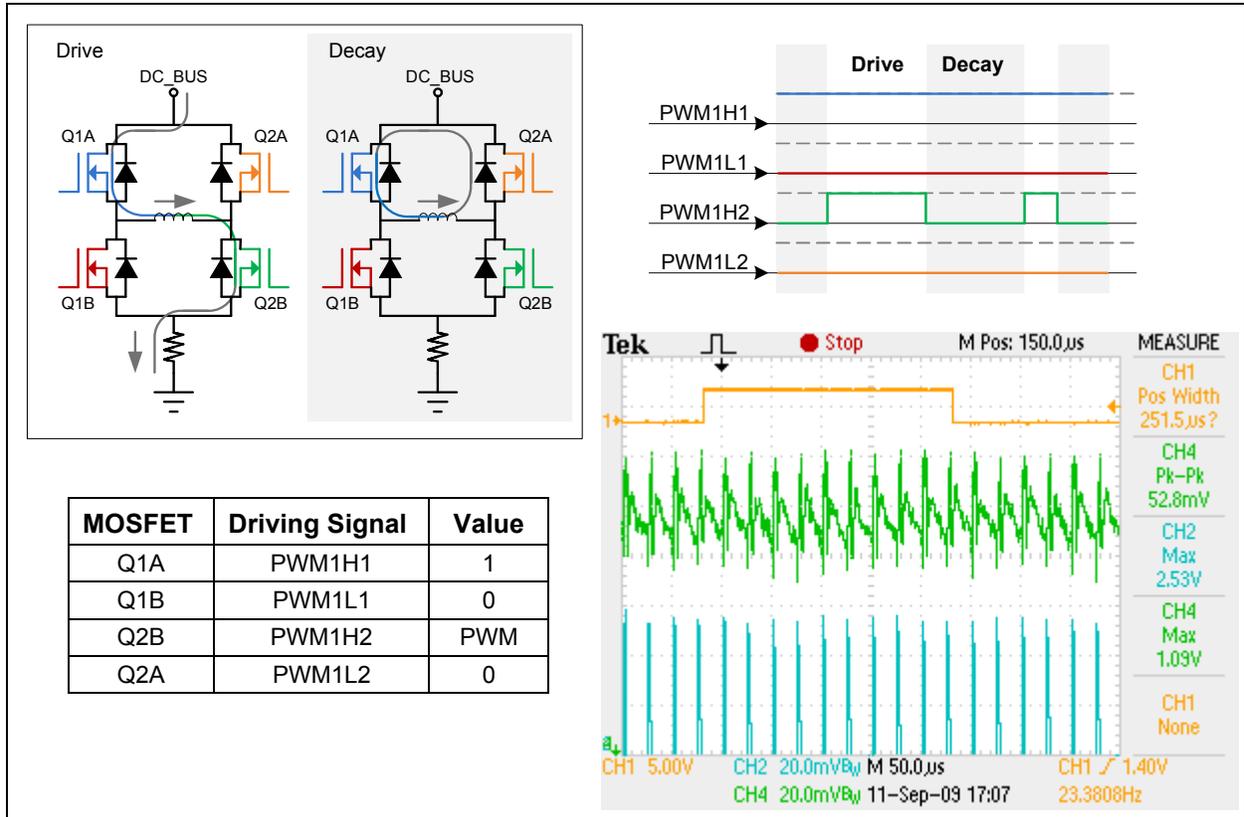
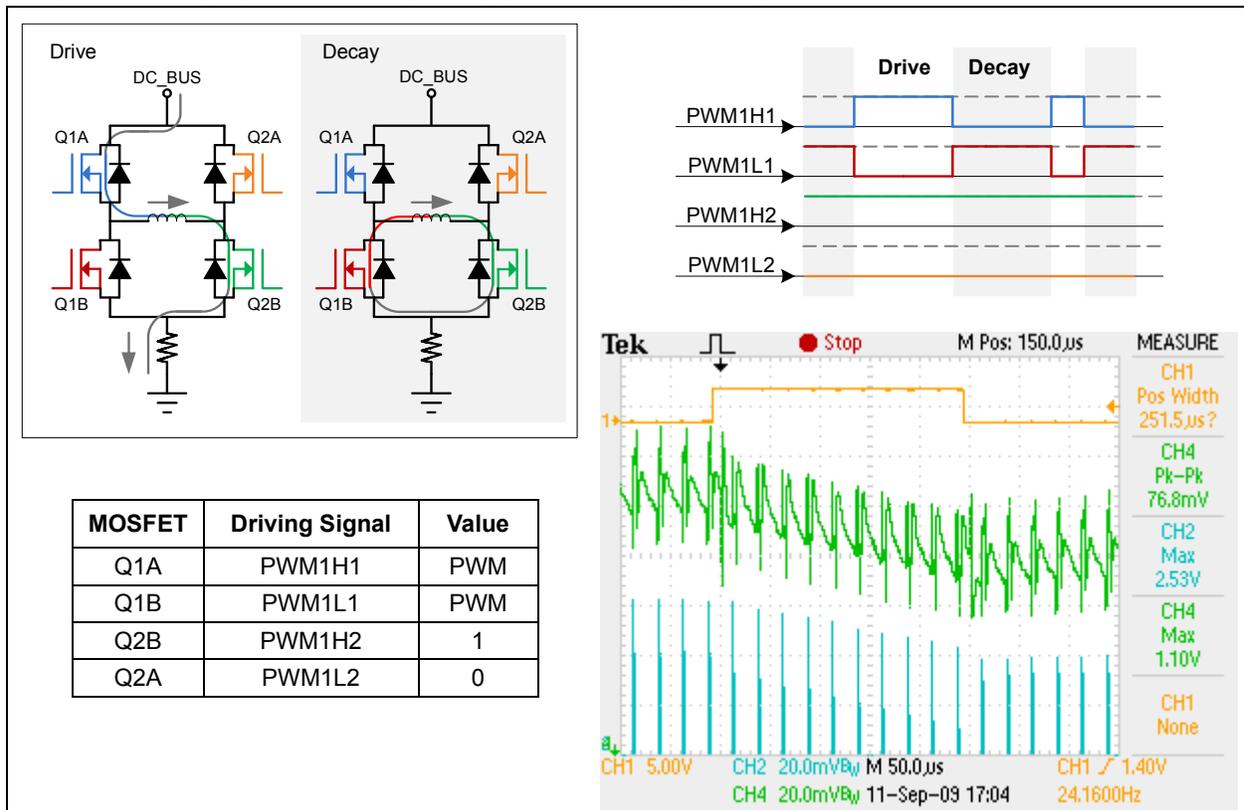


FIGURE B-4: SLOW DECAY LOW MOSFET RECIRCULATION



AN1307

FIGURE B-5: SLOW DECAY HIGH MOSFET RECIRCULATION

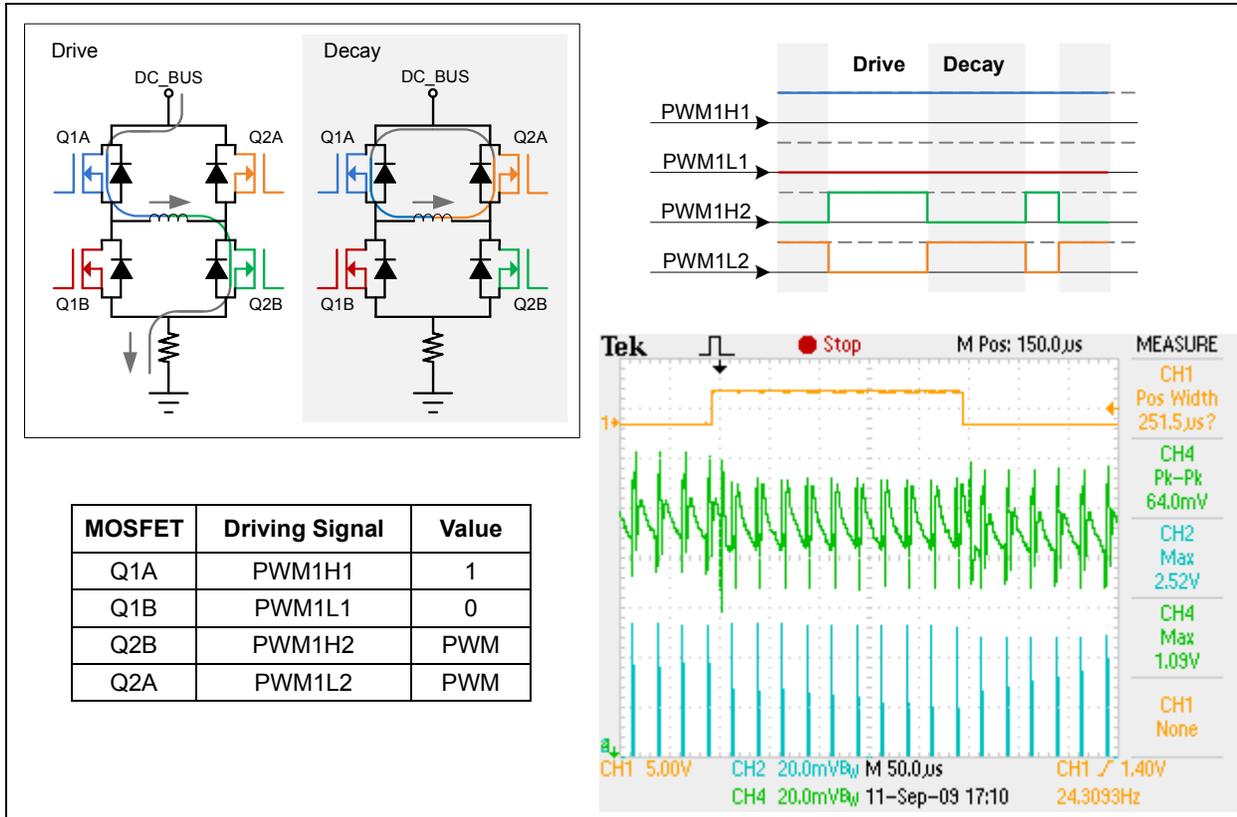
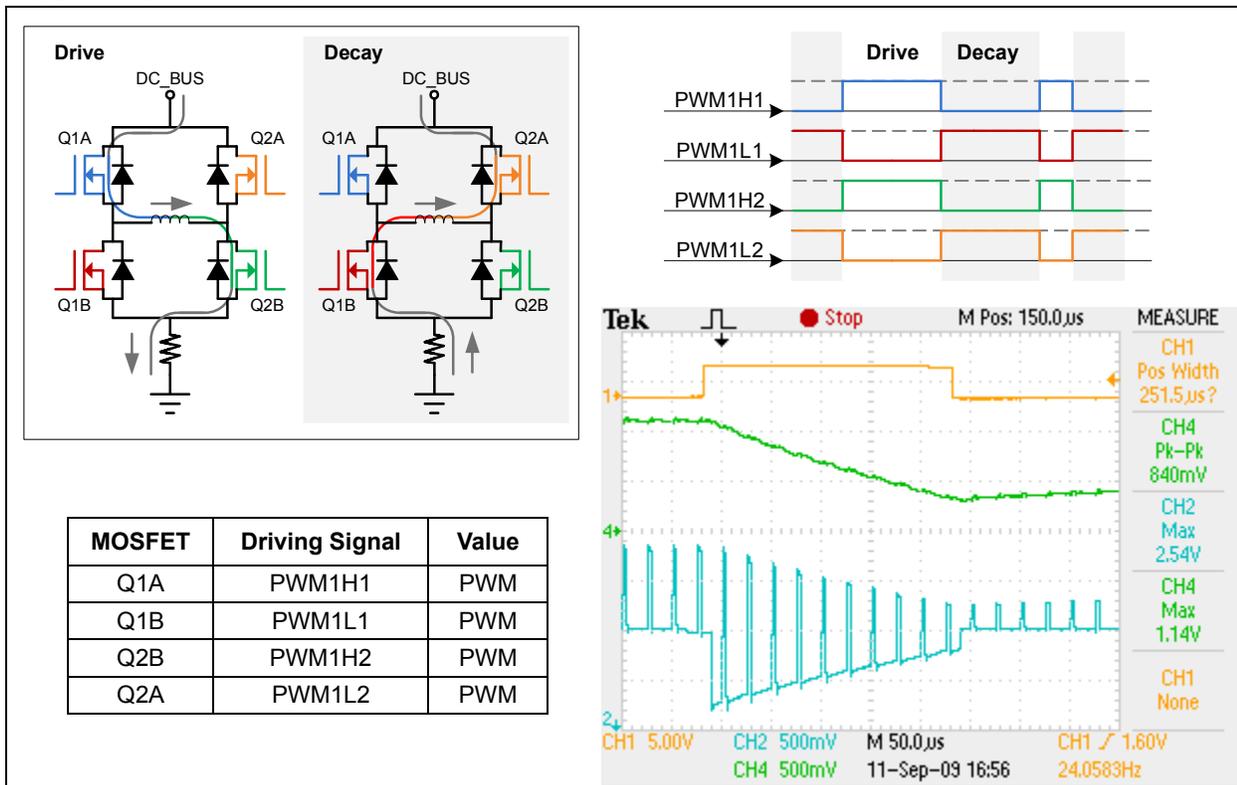


FIGURE B-6: REVERSE DECAY



Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip's Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.
- Microchip is willing to work with the customer who is concerned about the integrity of their code.
- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as “unbreakable.”

Code protection is constantly evolving. We at Microchip are committed to continuously improving the code protection features of our products. Attempts to break Microchip's code protection feature may be a violation of the Digital Millennium Copyright Act. If such acts allow unauthorized access to your software or other copyrighted work, you may have a right to sue for relief under that Act.

Information contained in this publication regarding device applications and the like is provided only for your convenience and may be superseded by updates. It is your responsibility to ensure that your application meets with your specifications. MICROCHIP MAKES NO REPRESENTATIONS OR WARRANTIES OF ANY KIND WHETHER EXPRESS OR IMPLIED, WRITTEN OR ORAL, STATUTORY OR OTHERWISE, RELATED TO THE INFORMATION, INCLUDING BUT NOT LIMITED TO ITS CONDITION, QUALITY, PERFORMANCE, MERCHANTABILITY OR FITNESS FOR PURPOSE. Microchip disclaims all liability arising from this information and its use. Use of Microchip devices in life support and/or safety applications is entirely at the buyer's risk, and the buyer agrees to defend, indemnify and hold harmless Microchip from any and all damages, claims, suits, or expenses resulting from such use. No licenses are conveyed, implicitly or otherwise, under any Microchip intellectual property rights unless otherwise stated.

Trademarks

The Microchip name and logo, the Microchip logo, Adaptec, AnyRate, AVR, AVR logo, AVR Freaks, BesTime, BitCloud, chipKIT, chipKIT logo, CryptoMemory, CryptoRF, dsPIC, FlashFlex, flexPWR, HELDO, IGLOO, JukeBlox, KeeLoq, Klear, LANCheck, LinkMD, maXStylus, maXTouch, MediaLB, megaAVR, Microsemi, Microsemi logo, MOST, MOST logo, MPLAB, OptoLyzer, PackeTime, PIC, picoPower, PICSTART, PIC32 logo, PolarFire, Prochip Designer, QTouch, SAM-BA, SenGenuity, SpyNIC, SST, SST Logo, SuperFlash, Symmetricom, SyncServer, Tachyon, TempTracker, TimeSource, tinyAVR, UNI/O, Vectron, and XMEGA are registered trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.

APT, ClockWorks, The Embedded Control Solutions Company, EtherSynch, FlashTec, Hyper Speed Control, HyperLight Load, IntelliMOS, Libero, motorBench, mTouch, Powermite 3, Precision Edge, ProASIC, ProASIC Plus, ProASIC Plus logo, Quiet-Wire, SmartFusion, SyncWorld, Temux, TimeCesium, TimeHub, TimePictra, TimeProvider, Vite, WinPath, and ZL are registered trademarks of Microchip Technology Incorporated in the U.S.A.

Adjacent Key Suppression, AKS, Analog-for-the-Digital Age, Any Capacitor, AnyIn, AnyOut, BlueSky, BodyCom, CodeGuard, CryptoAuthentication, CryptoAutomotive, CryptoCompanion, CryptoController, dsPICDEM, dsPICDEM.net, Dynamic Average Matching, DAM, ECAN, EtherGREEN, In-Circuit Serial Programming, ICSP, INICnet, Inter-Chip Connectivity, JitterBlocker, KlearNet, KlearNet logo, memBrain, Mindi, MiWi, MPASM, MPF, MPLAB Certified logo, MPLIB, MPLINK, MultiTRAK, NetDetach, Omniscient Code Generation, PICDEM, PICDEM.net, PICKit, PICtail, PowerSmart, PureSilicon, QMatrix, REAL ICE, Ripple Blocker, SAM-ICE, Serial Quad I/O, SMART-I.S., SQI, SuperSwitcher, SuperSwitcher II, Total Endurance, TSHARC, USBCheck, VariSense, ViewSpan, WiperLock, Wireless DNA, and ZENA are trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.

SQTP is a service mark of Microchip Technology Incorporated in the U.S.A.

The Adaptec logo, Frequency on Demand, Silicon Storage Technology, and Symmcom are registered trademarks of Microchip Technology Inc. in other countries.

GestIC is a registered trademark of Microchip Technology Germany II GmbH & Co. KG, a subsidiary of Microchip Technology Inc., in other countries.

All other trademarks mentioned herein are property of their respective companies.

© 2009-2019, Microchip Technology Incorporated, All Rights Reserved.

ISBN: 978-1-5224-4625-5

For information regarding Microchip's Quality Management Systems, please visit www.microchip.com/quality.



MICROCHIP

Worldwide Sales and Service

AMERICAS

Corporate Office
2355 West Chandler Blvd.
Chandler, AZ 85224-6199
Tel: 480-792-7200
Fax: 480-792-7277
Technical Support:
<http://www.microchip.com/support>
Web Address:
www.microchip.com

Atlanta

Duluth, GA
Tel: 678-957-9614
Fax: 678-957-1455

Austin, TX

Tel: 512-257-3370

Boston

Westborough, MA
Tel: 774-760-0087
Fax: 774-760-0088

Chicago

Itasca, IL
Tel: 630-285-0071
Fax: 630-285-0075

Dallas

Addison, TX
Tel: 972-818-7423
Fax: 972-818-2924

Detroit

Novi, MI
Tel: 248-848-4000

Houston, TX

Tel: 281-894-5983

Indianapolis

Noblesville, IN
Tel: 317-773-8323
Fax: 317-773-5453
Tel: 317-536-2380

Los Angeles

Mission Viejo, CA
Tel: 949-462-9523
Fax: 949-462-9608
Tel: 951-273-7800

Raleigh, NC

Tel: 919-844-7510

New York, NY

Tel: 631-435-6000

San Jose, CA

Tel: 408-735-9110
Tel: 408-436-4270

Canada - Toronto

Tel: 905-695-1980
Fax: 905-695-2078

ASIA/PACIFIC

Australia - Sydney
Tel: 61-2-9868-6733

China - Beijing
Tel: 86-10-8569-7000

China - Chengdu
Tel: 86-28-8665-5511

China - Chongqing
Tel: 86-23-8980-9588

China - Dongguan
Tel: 86-769-8702-9880

China - Guangzhou
Tel: 86-20-8755-8029

China - Hangzhou
Tel: 86-571-8792-8115

China - Hong Kong SAR
Tel: 852-2943-5100

China - Nanjing
Tel: 86-25-8473-2460

China - Qingdao
Tel: 86-532-8502-7355

China - Shanghai
Tel: 86-21-3326-8000

China - Shenyang
Tel: 86-24-2334-2829

China - Shenzhen
Tel: 86-755-8864-2200

China - Suzhou
Tel: 86-186-6233-1526

China - Wuhan
Tel: 86-27-5980-5300

China - Xian
Tel: 86-29-8833-7252

China - Xiamen
Tel: 86-592-2388138

China - Zhuhai
Tel: 86-756-3210040

ASIA/PACIFIC

India - Bangalore
Tel: 91-80-3090-4444

India - New Delhi
Tel: 91-11-4160-8631

India - Pune
Tel: 91-20-4121-0141

Japan - Osaka
Tel: 81-6-6152-7160

Japan - Tokyo
Tel: 81-3-6880-3770

Korea - Daegu
Tel: 82-53-744-4301

Korea - Seoul
Tel: 82-2-554-7200

Malaysia - Kuala Lumpur
Tel: 60-3-7651-7906

Malaysia - Penang
Tel: 60-4-227-8870

Philippines - Manila
Tel: 63-2-634-9065

Singapore
Tel: 65-6334-8870

Taiwan - Hsin Chu
Tel: 886-3-577-8366

Taiwan - Kaohsiung
Tel: 886-7-213-7830

Taiwan - Taipei
Tel: 886-2-2508-8600

Thailand - Bangkok
Tel: 66-2-694-1351

Vietnam - Ho Chi Minh
Tel: 84-28-5448-2100

EUROPE

Austria - Wels
Tel: 43-7242-2244-39
Fax: 43-7242-2244-393

Denmark - Copenhagen
Tel: 45-4450-2828
Fax: 45-4485-2829

Finland - Espoo
Tel: 358-9-4520-820

France - Paris
Tel: 33-1-69-53-63-20
Fax: 33-1-69-30-90-79

Germany - Garching
Tel: 49-8931-9700

Germany - Haan
Tel: 49-2129-3766400

Germany - Heilbronn
Tel: 49-7131-72400

Germany - Karlsruhe
Tel: 49-721-625370

Germany - Munich
Tel: 49-89-627-144-0
Fax: 49-89-627-144-44

Germany - Rosenheim
Tel: 49-8031-354-560

Israel - Ra'anana
Tel: 972-9-744-7705

Italy - Milan
Tel: 39-0331-742611
Fax: 39-0331-466781

Italy - Padova
Tel: 39-049-7625286

Netherlands - Drunen
Tel: 31-416-690399
Fax: 31-416-690340

Norway - Trondheim
Tel: 47-7288-4388

Poland - Warsaw
Tel: 48-22-3325737

Romania - Bucharest
Tel: 40-21-407-87-50

Spain - Madrid
Tel: 34-91-708-08-90
Fax: 34-91-708-08-91

Sweden - Gothenberg
Tel: 46-31-704-60-40

Sweden - Stockholm
Tel: 46-8-5090-4654

UK - Wokingham
Tel: 44-118-921-5800
Fax: 44-118-921-5820