Designers can choose from a wide range of microcontrollers to provide digital control for variable speed drives. Microcontrollers based on Freescale's HCS08 core are particularly well suited for low end motor control applications.

Devices based on this high-performance HCS08 core support 1.8–5V applications and come packed with valuable features, such as up to 60 KB flash memory, up to 2 KB RAM, a flexible internal clock generator that eliminates the need for external components, low voltage detection, an analogue-to-digital converter (ADC), timer (TIM) module, serial communication modules and many more. This article deals with the implementation of various pulse width modulation techniques using a TIM module and how the chosen PWM modulation technique impacts motor control application features.

The PWM modulation techniques can be distinguished according to various parameters, such as edge/centre aligned PWM, unipolar/bipolar PWM, complementary/independent PWM, the number of PWM channels, etc.

The timer/PWM module (TPM module) comes from the well known TIM module for the HC08 family. The basic structure of the TPM module can be seen in Figure 1. The main features are:

- Up to six channels per module
  - Each channel may be input capture, output compare, or buffered edge-aligned PWM
  - Rising-edge, falling-edge, or any-edge input capture trigger
  - Set, clear, or toggle output compare action
  - Selectable polarity on PWM outputs
- Each TPM may be configured for buffered, center-aligned pulse-width modulation (CPWM) on all channels
- Clock source to the prescaler for each TPM is independently selectable as bus clock, fixed system clock, or an external pin
  - Prescale taps for divide by 1, 2, 4, 8, 16, 32, 64, or 128
  - External clock inputs
- 16-bit free-running or up/down (CPWM) count operation
- 16-bit modulus register to control counter range
- Timer system enabled
- One interrupt per channel plus a terminal count interrupt for each TPM module

The advanced features of center-aligned PWM modulation extends the field of applications to motor control in small appliances.

Another thing to be considered in PWM generation is the current or back-EMF voltage sensing. A low-cost motor control application usually uses a shunt resistor for current sensing. In this case, the current has to be sensed in the middle of the PWM pulse. This requires the synchronization of the TPM and ADC modules. Since no member of the HCS08 family is equipped with TPM to ADC synchronization, how to synchronize both modules has to be considered at PWM generation. The situation is similar with sensorless brushless DC (BLDC) motor control applications, where Back-EMF voltage has to be sampled in the middle of a PWM pulse. Other PWM generation connected motor control application features will be discussed in detail further on.
**Edge/Center-aligned PWM Modulation**

This parameter defines how the pulses channels from different TPM channels are synchronized. With edge-aligned PWM modulation all the pulses start at the beginning of the PWM period. With center aligned PWM modulation, all the pulses are centered on the middle of the pulse. The advantage of center-aligned PWM can be seen in three-phase sinusoidal PWM modulation. If the duty cycles in all the phases are different, the transistor switching is spread over the entire PWM period. Since each transistor switching generates electromagnetic noise, a lower overall noise level can be achieved. If all pulses are synchronized in the middle of the pulse, they can be used for TPM to ADC synchronization. The polarity of the output signal can be set in order to have the TPM Overflow interrupt in the middle of the pulse. This interrupt can be used to start the ADC conversion. The edge/center-aligned mode can be set by the CPWMS bit in the TPMxSC register.

**Unipolar/Bipolar and Independent/Complementary PWM Modulation**

The unipolar/bipolar PWM defines how the voltage is applied to the motor. If the motor sees either the DC bus or zero voltage during one PWM cycle, we refer to this modulation technique as unipolar. If the motor sees both polarities of the DC bus voltage during one PWM cycle, the technique is called bipolar. Unipolar PWM is also called “soft switching,” while bipolar PWM is called “hard switching.” A second differentiator is the way of switching opposing semiconductor switches. If they are switched independently, we call this independent switching. If they are switched in a complementary manner, we call this complementary switching. Both PWM features can be combined with each other, so we get four possible combinations: unipolar independent, unipolar complementary, bipolar independent and bipolar complementary PWM modulation. The right choice in the modulation technique has a significant impact on the drive features. The features of each modulation technique are illustrated in a DC motor connected into an H-bridge, which consist of four transistors, Q1-Q4, with anti-parallel diodes (see Figure 2). The same topology can be considered for a six step control of a BLDC motor, since at any time only two phases are powered.
Independent Bipolar PWM Modulation

The principle of independent bipolar PWM modulation can be seen in Figures 3 and 4. The PWM period can be divided into three phases. In the first phase, the transistors Q1 and Q4 are driven by the same signal. When Q1 and Q4 are switched on, the DC motor is connected to the positive DC bus voltage and the current through the DC motor rises. In the second phase, transistors Q1 and Q4 are switched off and current starts to fall. The current flows through freewheeling diodes of Q2 and Q3, and the DC motor is connected to the negative DC bus voltage. Now independent—the transistors in the phase (Q1, Q2 and Q3, Q4) are switched independently and bipolar—the DC motor sees both polarities of the DC bus voltage. If the DC motor current falls to zero before the end of the PWM period, there is a third phase. The current through the DC motor is zero and the DC motor is disconnected from the power supply. The detail of the one PWM period can be seen in Figure 5. The transistors Q2 and Q3 are switched off for the entire PWM period. To run the DC motor in the opposite direction, transistors Q2 and Q3 are driven by a control signal, and Q1 and Q4 are switched off.

This PWM modulation can be generated either as an edge-aligned or center-aligned PWM. There is no advantage in reducing the electromagnetic noise since both transistors are switched in the same time. Alignment can be chosen according to the current sensing method.

This modulation is easy to implement using the TPM module. Two channels are set to generate the same signal. If by chance the circumstances are right, a single timer channel can be used to generate the signal for two transistors (Q1+Q4 and Q2+Q3). On the other hand there are some drawbacks, as the transition from discontinuous to continuous current mode can dramatically change the drive’s behavior. With discontinuous current the DC motor exhibits low torque, while in continuous current the torque dramatically increases. The drive can work in two quadrant operation and cannot actively brake. From a current sensing point of view the duty cycle changes from 0 to 100 percent. This means that some minimal pulse width is necessary to measure the current.
Independent Unipolar PWM Modulation

Figures 6 and 7 show the differences between this modulation and the previous one. In the first phase, transistor Q1 is driven by a control signal, and transistor Q4 is switched on over the entire period. The DC motor is connected to the positive DC bus voltage and the current increases. The first phase of the PWM period is the same as in the independent bipolar PWM modulation. In the second phase, transistor Q1 is switched off while transistor Q4 is still switched on. The current still flows through the DC motor but it is closed through the freewheeling diode of Q2. During this second phase, the motor sees zero voltage. The DC motor current starts to fall, but, due to zero voltage on the motor the negative slope is very slow. This means that the current goes into continuous mode with a very narrow pulse, leading to a much better behavior in the drive. The DC motor exhibits high torque from a very small duty cycle, and so tuning the torque and speed controllers is much easier. The drive can work as a motor and not as a brake, in two quadrant operation only. Also, the current ripple is smaller, which means smaller losses in the semiconductor devices.

Implementation using a TPM module is also simple. The PWM signal is generated by two TPM channels, usually for the top transistors (Q1 and Q3). The bottom transistors can be driven either by other TPM channels or by GPIO pins, since they remain switched on for the entire PWM period. With regards to current sensing, the situation is the same as in the previous case. The duty cycle varies from 0 to 100 percent so some minimal pulse width is necessary for current measurement.
Complementary Bipolar PWM Modulation

Unlike the two previous modulations, all transistors are switched in a complementary manner. Details can be seen in Figures 9 and 10. The transistors Q1 and Q4 are driven by the same signal, Q2 and Q3 are switched off. In the first phase the DC motor is connected to the positive DC bus voltage and the DC motor current increases. In the second phase the transistors Q2 and Q3 conduct current, and Q1 and Q4 are switched off. The DC motor is connected to the negative DC bus voltage and the DC motor current falls through the freewheeling diodes of Q2 and Q3. If the current reaches zero, it can continue to flow in a negative direction. When the current is negative, the drive works as an active brake and works in a four quadrant operation. The current flows in continuous mode under any condition, so the drive has a stable behavior.

Complementary switching requires dead-time generation to avoid cross conduction. Since the TPM module is not equipped by hardware for dead-time generation, dead-time has to be generated by software.

Since the TPM module does not support complementary signals by hardware, setting the TPM module is more complex. The correct settings for all channels can be seen below:

PWM0: (duty_cycle + dead_time),
   negative polarity
   (TMPxCnSC:ELSnB =x, TMPxCnSC:ELSnA =1)
PWM1: (duty_cycle − dead_time),
   positive polarity
   (TMPxCnSC:ELSnB =1, TMPxCnSC:ELSnA =0)
PWM2: (duty_cycle − dead_time),
   positive polarity
   (TMPxCnSC:ELSnB =1, TMPxCnSC:ELSnA =0)
PWM3: (duty_cycle + dead_time),
   negative polarity
   (TMPxCnSC:ELSnB =x, TMPxCnSC:ELSnA =1)

The duty_cycle is changed from 0 to 100 percent. On the other hand, current measurement is much simpler. Since current flows through the transistors at any time, it can be measured in the first or second half of a PWM period depending on the actual duty cycle. The detail of a PWM period is shown in Figure 11.
Complementary Unipolar PWM Modulation

In this PWM modulation technique, all the transistors are also switched in a complementary manner. The PWM period of the complementary unipolar PWM modulation can be divided into three phases. The first phase can be seen in Figures 12 and 13. Both the bottom transistors are switched on, a zero voltage is applied to the DC motor and current flows through Q4 and the freewheeling diode of Q2.

The second phase is shown in Figures 14 and 15. The transistors Q1 and Q4 conduct current, the DC motor is connected to the positive DC bus voltage and the current flows through the DC motor.

The third phase is similar to the first one, but both upper transistors Q1 and Q3 are switched on. On the motor, zero voltage is applied and the DC motor current is closed through Q1 and the freewheeling diode of Q3. Phase 3 is depicted in Figure 16.

This type of the PWM modulation offers the lowest current ripple since the motor is connected twice to the power supply. It allows using a lower switching frequency to get the same current ripple in comparison to the previous PWM modulation technique. The drive features are also equal to the previous type of PWM modulation.

The implementation of this modulation is again quite complex, since the complementary signals and the dead-time have to be generated by software. Configuration of the TPM channels is shown in the next paragraph:

**PWM0**: MODULO/2 +/- duty_cycle + dead time
**PWM1**: MODULO/2 +/- duty_cycle - dead time
**PWM2**: MODULO/2 -/+ duty_cycle + dead time
**PWM3**: MODULO/2 -/+ duty_cycle - dead time

The **duty_cycle** is changed from 0 to 50 percent. All the top channels are set to negative polarity (TMPxEN:ELSnB =x,TMPxEN:ELSnA =1) and all bottom channels are set to positive polarity (TMPxEN:ELSnB =1,TMPxEN:ELSnA =0). The notation of TPM channel configuration means that if the variable **duty_cycle** is added to channels PWM0 and 1, the **duty_cycle** is subtracted from PWM2 and PWM3, and vice versa.
Sinusoidal PWM Modulation

The sinusoidal PWM modulation requires six TPM channels when considering three phase motors. This modulation uses center-aligned PWM, due to the reduction of electromagnetic noise. All three phases work in a complementary manner and the duty cycle is modulated by a sinusoidal table every PWM period, shifted by 120 electrical degrees in every phase. The configuration of the TPM module is similar to the previous case. The duty cycle is changed from 0 to 100 percent. All the top channels are set to negative polarity (TMPxSC:ELSnB = x, TMPxSC:ELSnA = 1) and all bottom channels are set to positive polarity (TMPxSC:ELSnB = 1, TMPxSC:ELSnA = 0).

Based on the drive type (DC motor—one direction of rotation, DC motor—both directions of rotation, BLDC motor, AC induction motor, PM synchronous motor, etc.), the appropriate microcontroller has to be selected. Table 1 shows the number of necessary TPM channels dependent on the type of motor and the operational mode. Table 2 summarizes the available members of the HCS08 family, including the number TPM modules and channels.

The practical implementation of PWM modulation using a TPM module can be found in the application notes or designer reference manuals (e.g. complementary bipolar modulation for a BLDC motor in DRM086) on the Freescale web pages.

### Table 1: Number of TPM Channels for Different Types of Motors and Operational Modes

<table>
<thead>
<tr>
<th>Operational Mode</th>
<th>Modulation Technique</th>
<th>Number of TPM Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DC Motor</td>
</tr>
<tr>
<td>1Q</td>
<td>Single PWM</td>
<td>1</td>
</tr>
<tr>
<td>2Q</td>
<td>Independent bipolar</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Independent unipolar</td>
<td>2 + 2 GPIO</td>
</tr>
<tr>
<td>4Q</td>
<td>Complementary bipolar</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Complementary unipolar</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Sinewave modulation</td>
<td>—</td>
</tr>
</tbody>
</table>

### Table 2: HCS08 MCU Overview

<table>
<thead>
<tr>
<th>MCU</th>
<th>Number of TPM</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC9S08GQx</td>
<td>1</td>
<td>2 (1 8-pin)</td>
</tr>
<tr>
<td>MC9S08GBx</td>
<td>2</td>
<td>3/5</td>
</tr>
<tr>
<td>MC9S08GTx</td>
<td>2</td>
<td>2/2</td>
</tr>
<tr>
<td>MC9S08AWx</td>
<td>2</td>
<td>2/6</td>
</tr>
</tbody>
</table>

(**Figure 16: Complementary Unipolar PWM Modulation—Detail of PWM Period Phase 3**)

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