

Digital Sinusoidal PWM Generation using a Low-cost Micro-controller Based Single-Phase Inverter

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Abstract

This paper presents the implementation of two Digital Sinusoidal PWMs (DSPWMs) using a low-cost 8-bit micro-controller. Each DSPWM is implemented using two different PWM hardware modes on the micro-controller. The benefits and limitations of each DSPWM are investigated in relation to the switching frequency and micro-controller performance from experimental verification using a 2kVA single-phase inverter. The standard left aligned PWM module found on low-cost micro-controllers is shown to provide performance benefits similar to a DSPWM requiring a higher-cost micro-controller for its implementation. The main benefit being the reduction in micro-controller resources, allowing more time for features such as protection, monitoring, interfacing, variable switching frequency and grid synchronisation.

Keywords – Pulse Width Modulation, Inverter, Micro-controller.

1. Introduction

Micro-controllers and Digital Signal Processors (DSPs) are increasingly being used in applications previously assigned to the analogue domain. As their functionality continues to increase by integrating more peripherals into the one package, they are becoming a viable option to replacing an analogue design. One application previously controlled using analogue techniques are single-phase inverters, but there is a shift towards the digital domain for their implementation, due to the benefits a micro-controller or DSP can offer [1], [2] as shown in Table 1.

Table 1: Comparison of analogue and digital control [3].

	Advantages	Disadvantages
Analogue Control	- High bandwidth - High resolution - Ease of design	- Component aging - Temperature drift - Hardwired design
Digital Control	- Programmable solution - Insensitive to environment - Shows precise behaviour - Advanced algorithms - Capable of additional functions	- Creates numerical problems - Difficult to design

2. Single-phase Full-bridge Inverters

A single-phase inverter is a device that converts DC to AC for powering equipment requiring a sinusoidal voltage source to operate. One of the most simple and cost effective configurations for generating a pure sine wave from a DC source is the full-bridge configuration [4], [5], [6] as shown in Figure 1; where level triggered switches such as MOSFETs or IGBTs are often used.

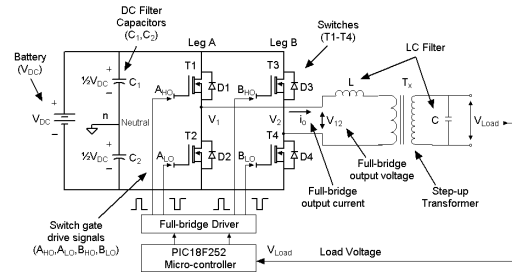


Figure 1. Single-phase full-bridge sine wave inverter.

This type of inverter operates by varying the pulse width at the switch gates, which varies the average voltage seen at the mid-point (V_1 , V_2) of each leg. The output voltage is taken across the midpoints of each leg and is calculated as (1):

$$V_{12} = V_1 - V_2 \quad (1)$$

There are two methods by which this sinusoidal PWM can be generated; the first is by using analog techniques, where a common method used is to compare a sinusoidal reference with a triangular carrier [7]. The second method is using digital techniques where a micro-controller, DSP or FPGA can generate the PWM, with a micro-controller being the method of PWM generation discussed in this paper.

3. Digital PWM Implementation

The standard method for generating a PWM using a micro-controller is by using one of the built-in PWM modules. Depending on the type of micro-controller used the PWM can be left, centre or right aligned [8] as shown in Figure 2. Many low-cost micro-controllers only produce a left aligned PWM, and therefore are limited as to the types of DSPWMs they can generate.

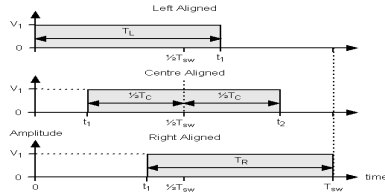


Figure 2. Alignment of three digital PWMs.

For this inverter application, the Microchip 8-bit PIC18F252 micro-controller was selected due to its low-cost, high instruction frequency (10MIPs), hardware multiplier, interrupt priority and ease of programming and support. These features made it suitable for the implementation of the required DSPWMs with a maximum PWM resolution of (2) [9]:

$$\text{PWMResolution(max)} = \frac{\log(F_{\text{osc}}/F_{\text{pwm}})}{\log(2)} \text{ bits} \quad (2)$$

The PIC18F252 has two options available for generating a PWM using the Capture, Compare, PWM (CCP) module. The most common and easily implemented is PWM mode, which only allows a left aligned PWM to be generated as shown in Figure 3.

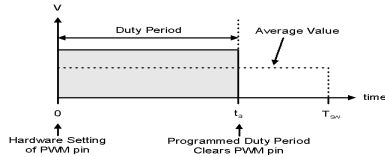


Figure 3. Left aligned PWM.

The CCP module on the PIC18F252 operating in PWM mode is shown in Figure 4. There are two identical CCP modules available (CCP1, CCP2) and they both share the same Timer 2 module. Timer 2 provides the time base for the PWM switching and duty periods, which are programmed by writing to the PR2 and CCPR1L/CCPR2L registers respectively. The programmed PWM is then output continuously until it is updated, allowing for an increase in switching frequency without any additional load on the micro-controller. As the PWM duty period is double buffered (CCPRxL, CCPRxH) it can be updated in the previous switching period, which allows a 0-100% duty period to be achieved. This enables a higher inverter overload to be achieved while maintaining load voltage regulation [10].

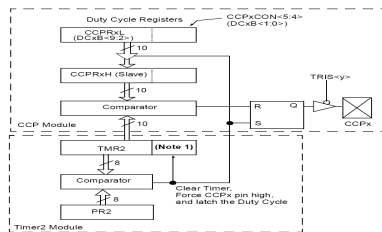


Figure 4. PIC18F252 CCP module in PWM mode.

The other option for generating a PWM using the PIC18F252 is the Compare mode, which allows for a centre aligned PWM to be generated as shown in Figure 5.

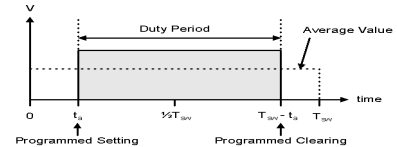


Figure 5. Centre aligned PWM.

The CCP module on the PIC18F252 operating in Compare mode is shown in Figure 6. In Compare mode, one of two timers (TMR1, TMR3) can be selected as the time base for PWM generation. To generate a centre aligned PWM using the Compare mode, Timer 1 (used as the common time base) is constantly compared with Compare registers CCPR1/CCPR2, and the CCP1/CCP2 pins set high on the first compare match and cleared on the second compare match; where the compare registers are updated at $t = 0$ and $t = 1/2 T_{\text{sw}}$. The main drawback to this method of PWM generation is that both the compare match to set the PWM pin and to clear it must be done during the switching period. Therefore, at 10kHz only a 2.80-97.20% duty period can be achieved, which means that a lower inverter overload (while maintaining load voltage regulation) occurs compared to RS Unipolar. The PWM also needs to be updated every switching period, which means that it cannot be repeated, as is the case for the PWM mode of operation, which increases the load on the micro-controller as the switching frequency is increased.

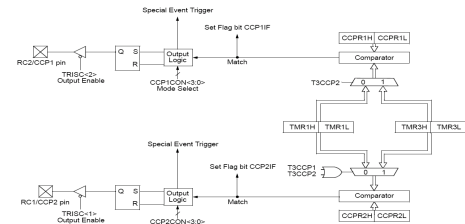


Figure 6. PIC18F252 CCP module in Compare mode.

A comparison between each of the two different modes of operation to generate a DSPWM using the CCP module on the PIC18F252 is shown in Table 2.

Table 2. CCP PWM and Compare mode comparison.

	CCP module mode of operation	
	PWM mode	Compare mode
PWM alignment	Left	Variable
Duty period register	Yes	No
Period register	Yes	No
Compare register	No	Yes
PWM duty period update	Previous period	Current period
PWM repeat without updating	Yes	No
Duty period limited	No	Yes

4. Digital Sinusoidal PWMs

A DSPWM is generated using a micro-controller by varying the PWM duty period according to a sinusoidal reference, which is often stored in a lookup table. By applying this PWM to each leg of the full-bridge (A_{HO} , B_{HO}), the average voltage seen at the full-bridge output (V_{12}) is sinusoidal (after filtering using an LC filter).

A DSPWM that can be easily implemented on a low-cost micro-controller using a left aligned PWM module is Regular Sampled (RS) Unipolar [11] shown in Figure 7 over one load period (T_L). RS Unipolar was implemented on the PIC18F252 using the CCP module in PWM mode.

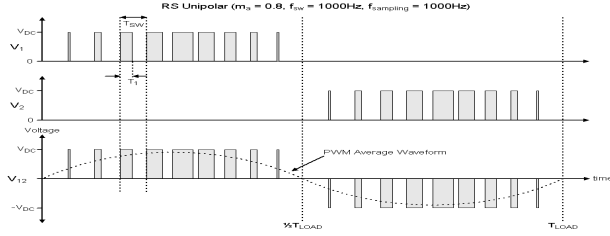


Figure 7. RS Unipolar DSPWM load period.

The full-bridge output average voltage for RS Unipolar can be calculated as (3):

$$V_{12,ave} = \frac{1}{T_{sw}} \int_0^{t_a} V_{dc} dt - \frac{1}{T_{sw}} \int_0^{t_b} V_{dc} dt \quad (3)$$

where t_a and t_b are the PWM clear times for Leg A and Leg B respectively (Figure 3) and calculated as [11]:

$$t_a = \begin{cases} m_a T_{sw} \sin(2\pi f_L k T_{sw}), & k = 0 \dots \frac{T_L}{2T_{sw}} - 1 \\ 0, & k = \frac{T_L}{2T_{sw}} \dots \frac{T_L}{T_{sw}} - 1 \end{cases} \quad (4)$$

$$t_b = \begin{cases} 0, & k = 0 \dots \frac{T_L}{2T_{sw}} - 1 \\ m_a T_{sw} \sin(2\pi f_L (k T_{sw} - \frac{T_L}{2})), & k = \frac{T_L}{2T_{sw}} \dots \frac{T_L}{T_{sw}} - 1 \end{cases} \quad (5)$$

A centre aligned DSPWM, which is more difficult to implement on a low-cost micro-controller due to its PWM centre alignment is single-phase SVM [11] proposed in [12], and shown in Figure 8 for one load period (T_L). SVM was implemented on the PIC18F252 using the CCP module in Compare mode.

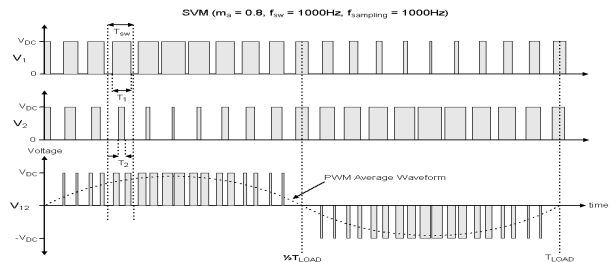


Figure 8. SVM DSPWM load period.

The full-bridge output average voltage for SVM can be calculated as (6):

$$V_{12,ave} = \frac{1}{T_{sw}} \int_{t_a}^{t_b} V_{dc} dt + \frac{1}{T_{sw}} \int_{T_{sw}-t_b}^{T_{sw}-t_a} V_{dc} dt \quad (6)$$

where t_a and t_b are the PWM set times for Leg A and Leg B respectively (Figure 5) and calculated as [11]:

$$t_a = \frac{-m_a T_{sw}}{4} \sin(2\pi f_L k T_{sw}) + \frac{T_{sw}}{4}, k = 0 \dots \frac{T_L}{T_{sw}} - 1 \quad (7)$$

$$t_b = \frac{m_a T_{sw}}{4} \sin(2\pi f_L k T_{sw}) + \frac{T_{sw}}{4}, k = 0 \dots \frac{T_L}{T_{sw}} - 1 \quad (8)$$

5. Experimental Results

Efficiency tests for RS Unipolar and SVM on the 2kVA inverter are shown in Figure 9. As RS Unipolar used the PWM mode, the switching frequency could be easily increased without any additional load on the micro-controller. SVM uses the Compare mode, so the switching frequency could not be increased due to it resulting in an increased load on the micro-controller.

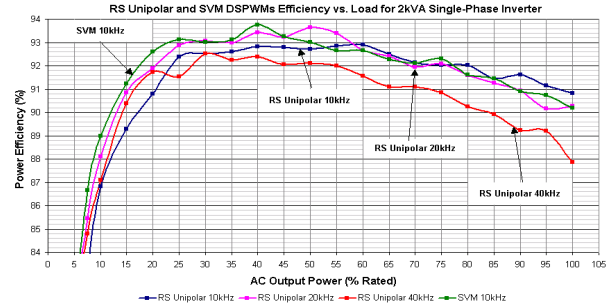


Figure 9: Efficiency plots for 2kVA inverter (experimental).

Timing measurements for RS Unipolar on the PIC18F252 for switching frequencies of 10kHz, 20kHz and 40kHz are shown in Figure 10 (a), (b) and (c) respectively. These switching frequencies were chosen, as they required minimal software changes. From Figure 10 it can be seen that the ISR and housekeeping times remained constant as the switching frequency was increased.

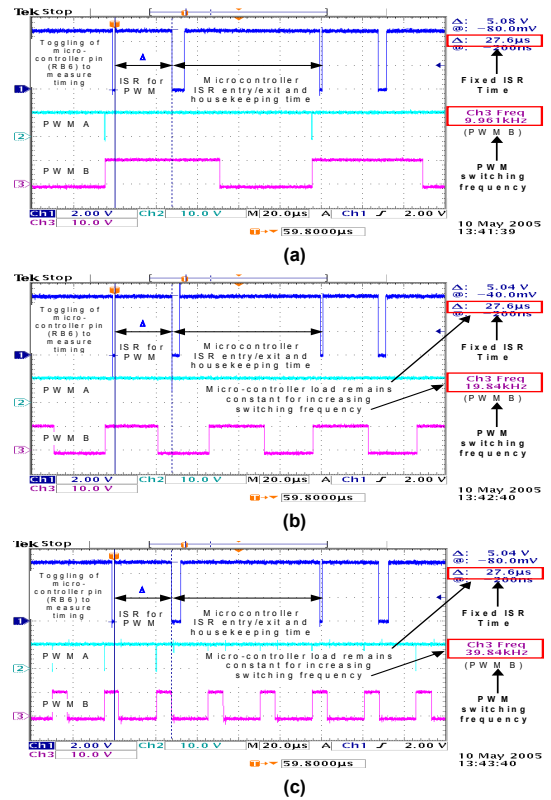


Figure 10. PIC18F252 micro-controller load vs. switching frequency for RS Unipolar (a) 10kHz (b) 20kHz (c) 40kHz.

Timing measurements for SVM on the PIC18F252 for a switching frequency of 10kHz is shown in Figure 11.

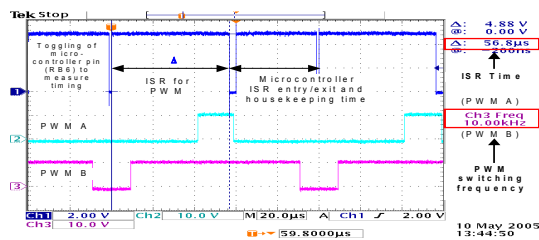


Figure 11. PIC18F252 micro-controller load vs. switching frequency for SVM at 10kHz.

From Figure 11 it can be seen that implementing SVM on the PIC18F252 micro-controller requires more ISR time (56.8 μ s) compared to RS Unipolar (27.6 μ s) due to using the compare mode for generating a centre aligned PWM and the required updating during each switching period.

6. Conclusion

This paper compared two different PWM generating hardware modes on the PIC18F252 micro-controller for generating two different DSPWMs. It showed that a standard left aligned PWM mode found on many low-cost micro-controllers has performance benefits compared to generating a PWM using the Compare mode, such as being able to achieve a 100% duty period and achieving increases in switching frequency without any additional load on the micro-controller resources.

SVM was shown to provide better efficiency results below 25% of rated load for the 2kVA inverter, with RS Unipolar having similar efficiency results above 25% and requiring close to half the micro-controller resources due to it using the PWM mode. This enables more features to be added to the design such as protection, monitoring and interfacing, which provides a more sophisticated inverter for lower cost. The PWM mode also allows for variable switching frequency and grid synchronisation, which is more difficult to implement using the Compare mode for SVM DSPWM generation on the PIC18F252. SVM would be the preferred DSPWM for a single-phase inverter, but requires dedicated centre aligned PWM hardware only available on higher cost micro-controllers and DSPs. Therefore, RS Unipolar is a better option for low-cost single-phase inverters without dedicated centre aligned PWM hardware. More results comparing RS Unipolar and SVM for the single-phase 2kVA inverter can be found in [10].

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