Control Circuit based Microcontroller Implementing a New Sinusoidal Pulse with Modulation Technique for Solar Inverter

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Abstract: This paper presents a new technique to generate a digital Sinusoidal Pulse Width Modulation (SPWM) control using PIC16F876 microcontroller. This technique is mainly used to control the DC/AC inverter output voltage in many applications such as photovoltaic pumping system and motor drive. It reduces significantly low harmonic components as well as distortion factor. The principle of this method is to transform the sampled dc-biased sine wave signal to a repeating pulses train. The widths of these pulses vary sinusoidally and thus as a digital SPWM. The different amplitude modulations index started from 0.5 until 1.3 (over modulation) with 1 kHz switching frequency was implemented and tested. The literature review of the existing digital SPWM techniques is presented firstly. Subsequently the proposed SPWM approach is briefly detailed. Finally, experimental results are presented to demonstrate the validity of this SPWM method and the good functionality of the realized control unit.

1 INTRODUCTION

Pulse width modulation PWM is widely used in power electronics to digitize the power so that a sequence of alternating voltage pulses can be generated by the on and off of the inverter power switches (Lucien, 2008), (Selvabharathi, Kamatchi, Sathish, 2018.). Inverter is defined as a converter that is used to change a DC input voltage to an AC output voltage of desired magnitude and frequency (Gavaskar, Maheswari, Adi, 2017), (Tarchanidis, Lygouras, Botsaris, 2013). The output voltage of an ideal inverter is the sinusoidal waveform which could be fixed or variable at a fixed or variable frequency. For the inverter, the harmonics spectrum exist at all odd number of harmonics. The low-pass filter design at the output of the inverter also can be quite difficult (Gavaskar, Maheswari, Adi, 2017).

Sinusoidal PWM SPWM is as the alternative due to the fewer harmonics introduced and it is widely used method for major AC appliances. The analogue method compares triangle wave which is used as carrier with the sinusoidal wave as the reference signal, whose frequency is the desired output frequency. The fundamental component is useful for any alternating current application. The digital SPWM version is inspired from analogue SPWM (Lucien, 2008).

With Field Programmable Gate Array FPG device (Selvabharathi, Kamatchi, Sathish, 2018), Digital Signal Processor DSP (Gavaskar, Maheswari, Adi, 2017), both the sine wave and triangle wave are generated by a special intern controller. An internal comparator is used to compare these signals. The crossover points are used to determine the switching instants such that if the sine wave is greater than triangle wave then the output is high otherwise output is low, thus a SPWM is created. These devices have very high performance and density, more flexible but present high cost.

With microcontrollers, there are three most methods used to generate the SPWM. The first one uses generally a counter (Abdel, Thomas, Ramadan, 2017). These counters have the task to create the sine wave using a look up table of a pre-calculated sine values. The triangle wave also is created with another counter along with a control bit showing the slope (positive – up, negative-down).

These two tasks are executed by the interrupt service routine and are running in parallel with the

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main program routine. The computation time consumed by the interrupt service routine is negligible. The second task consists of an endless loop that has the task to continuously compare the current triangle and sine values. The comparison result will be responsible to create the SPWM trigger signals.

The second technique uses the simple software modulation (multiplication) on microcontroller (Tarchanidis, Lygouras, Botsaris, 2013). A sine wave (with unity magnitude and low frequency) is multiplied with the impulse train (with high frequency and unity magnitude) in order to create a train of SPWM pulses. Theses SPWM triggers can be generated in such a manner that starting position of pulse should be same as that of impulse and duty cycle of the pulse must be equal to the product of unit impulse and value of sine wave at that instant.

The third approach (Bilal, 2018) uses the output compare modules in the DSPIC33FJ microcontroller.

This microcontroller contains two output compare modules. Both these Outputs are used to generate SPWM using two look up tables; sine look up table and triangular look up table. Each module use two sixteen bit timers that is Timer 2 and Timer 3. OCM register compares the set value of sine wave with triangular values in each period time of the triangular and write the comparison results to OCxR and OCxRS registers of the output compare modules.

When both values become equal to each other, state of output pin changes. It happens only once in one period of PWM.

The simplicity without increasing resources, programmability, the medium rapidity and the low cost make the microcontroller device the most favourable choice for prototyping digital control circuit for our solar pumping inverter (Pattnaik, Dash, Mukherjee, 2009), (Salam, 2001).

The new method we proposed in this work consists on storing the different pulse widths (i.e. duty cycles) of the desired SPWM signal in a look up table. These duty cycles are obtained beforehand from discrete values of a continuously dc-biased sinusoidal function.

These results are stored in memory as a pulse width table covering the entire period of the output signal of the inverter.

This method offers several advantages in terms of resolution and gain of the generated SPWM signal, which remain constant regardless of the PWM output frequency even at high frequency. The main feature of this approach is the simplicity of the hardware; only a very simple microcontroller with its associated PWM output modules is required without using a test of comparison. This results in a simple, low cost and reliable control for a solar pumping system. The full detail of this approach is given in the following section.

2 PROPOSED DIGITAL SPWM TECHNIQUE

2.1 Theory

The pulse widths (i.e. duty cycles) are constructed from discrete values of a sinusoidal function (Ismail, Taib, Isa, Daut, Mohd Saad, Fauzy, 2007). To generate the repeating SPWM pulse train in complete frequency F_{ref} cycle of the sine reference wave cycle, we first need a table whose values represent the magnitude of this sine wave using the following formula (Gavaskar, Maheswari, Adi, 2017):

$$S_i = A\sin\left(\frac{i \times 2\pi}{n}\right) \text{ For i = 0…n-1} \quad (1)$$

Since the PWM registers of the 16F876 accept only positive values (PIC16F87X microcontrollers, 2001), (Ismail, Taib, Mohd Saad, Isa, Daut, 2006), we can transform modulated sine wave in a dc-biased sine wave to avoid the negative values. With this transformation, the dc-biased sine wave samples S_{dc} can be written as:

$$S_{dci} = A\sin(\frac{i \times 2\pi}{n}) + B \text{ For i = 0…n-1} \quad (2)$$

Where i is the sample number, and n is the number of samples per complete F_{ref} sine wave cycle. This number is the equivalent parameter of the frequency modulation index in the analogue SPWM control (Ismail, Taib, Daut, Mohd Saad, Fauzy, 2007). It depends on the desired switching frequency F_s of the SPWM patterns and the F_{ref} sine wave cycle as:

$$n = \frac{F_s}{F_{ref}} \quad (3)$$

A is the amplitude of the considered sine wave, this parameter depends with the desired amplitude modulation index m_a like in analogue SPWM control (Ismail, Taib, Mohd Saad, Isa, Daut, 2006.) and with

PR2 register's value (PIC16F87X microcontrollers, 2001):

$$A = m_a \times \frac{PR2}{2} \quad (4)$$

PR2: period register of the PIC16F876.

B: the dc-biased value it depends with the value that will be specified in PR2 register, this value is the half of PR2 value that is expressed as follows:

$$B = \frac{PR2}{2} \quad (5)$$

A table of n values (sample points) of a complete F_{ref} sine wave cycle with an angle resolution ($2*\pi/n$) is obtained using equation (2). These samples values represent the pulse width values or exactly the duty cycles that can be sent periodically based Timer 2 interrupt mechanism to the PWM modules to generate the desired SPWM switching signal. The period T_s of the SPWM signal is set by writing to the PR2 register (PIC16F87X microcontrollers, 2001) using:

$$Ts = (PR2 + 1) \times 4 \times T_{osc} \times Tp \quad (6)$$

Where T_{osc} is the timer oscillator and T_p is the timer prescaler value.

The duty cycles d_{wi} are specified by writing S_{dci} values to the CCPRxL registers (x=1, 2) using only eight MSBs (PIC16F87X microcontrollers, 2001):

$$d_w = (CCPRxL) \times T_{osc} \times Tp \quad (7)$$

Based on equation (7), the PWM module transforms the S_{dci} values to a duty cycles values d_{wi}.

When the CCP modules are used in the PWM module (PIC16F87X microcontrollers, 2001), the timer 2 register is used as the PWM time base. It works by incrementing a counter at a user set frequency F_s, and when the value of this counter equals the period programmed in PR2 register, an interrupt is generated at each T_s period.

The main idea to generating the repetitive pulse train that varies sinusoidally is the use of the PWM module based its Timer 2 interrupt, so in each interrupt; the duty cycles d_{wi} values is read from the sampled sine value in look up table and then sent to CCPRxL registers. This approach is repeated for all the n values in the created look up table in order to generate SPWM patterns for complete T_{ref} period.

To generate the SPWM in the sine wave cycle (F_{ref}=50Hz), we noticed that only have to save a quarter value of the calculate values d_{wi} in a look up table array. This quarter allows creating the first SPWM quarter using a p pointer and a i counter.

The remained three SPWM quarters were deduced from this first SPWM1 quarter. Based only this created look up table, the complementary SPWM2 of the SPWM1 can be also deduced using the same p pointer with a similar manner.

2.2 Numerical Application

For this implementation, the values of used parameters are given in table 1 bellow.

Table 1: The values of used parameters.

F_s	F_{ref}	PR2	n	B
1 kHz	50 Hz	104	60	52

Using the equation (6), to obtain F_s equal to 1 kHz, we might use the timer prescaler with the value 16, and write 104 values to PR2 register. Based on equation (3), at this frequency, the number n of pulses per complete cycle of a reference frequency F_{ref} of 50 Hz is n= 60.

From equation (4), the constant A depends on the desired modulation index m_a and the PR2 value.

Knowing that CCPR1L and CCPR2L are an 8-bit registers, from equation (5), the constant B is equals to 52, and i=0…59. The exact number that need to be stored in look up table and thus be loaded into the pulse width register PWM must therefore equal to S_{dci} values obtained using equation(2) multiplied by the amplitude modulation index m_a.

The amplitude of the inverter output voltage is controlled by m_a. This is significant for using photovoltaic panels to supply this inverter, because the photovoltaic source produce a variable output voltage according to the variations of the climatic conditions. Thus producing constant amplitude output voltage. If m_a is greater than 1 (over modulation), the amplitude of the output voltage increase with m_a, but not linearly. In order to work in region, the m_a must be lower than 1 to keep a linear relationship between m_a and the output voltage amplitude in ordrer to control the solar inverter's output voltage.

Matlab Simulink software was used to generate 60 pulse widths train for i=0…59. And then we store only its 15 first values in look up table array. This trick allows optimizing the used of the microcontroller memory program.

3 SYSTEM DESIGN

The basic schematic diagram of the solar pumping inverter to be designed and realized in our laboratory is shown in the figure 1 below:

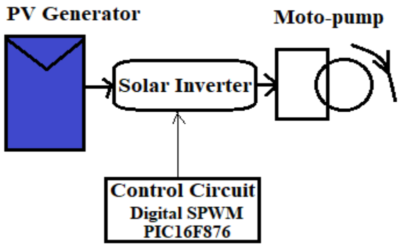

Figure 1: Control circuit of solar pumping inverter.

It consists of two parts: the power circuit and the control circuit. In this work, we focused on the control circuit. This last circuit is formed by many blocs; its heart is a PIC16F876 that generate two complementary SPWMs.

This section involves two parts: the Hardware and the Software. Indeed, the Software development involves the application of C language using CC5X compiler integrated with MPLAB Software based Bootloader technique (Beningo, 2015).

3.1 Hardware Design

The proposed technique deals with the use of a PIC16F876 microcontroller for the implementation.

The use of this microcontroller brings more reliable and resilient to change in software than analogue devices. The advantage of this new method is the use of a little calculation, and a discretized dc-biased sinusoidal signal look up table values is needed.

The schematic circuit for programming the microcontroller was drawn as shown in figure 2.

There are two integrated circuits in this schematic circuit. One is the PIC microcontroller, which does almost everything. The other is a MAX232 chip which converts TTL level (5V) signals to RS232 levels (12V) so that you can talk between a personal computer's serial port and a TTL level UART device. In order to ensure the microcontroller function, as supply of 5 volts has to be provided to V_{DD} pin of the PIC chip.

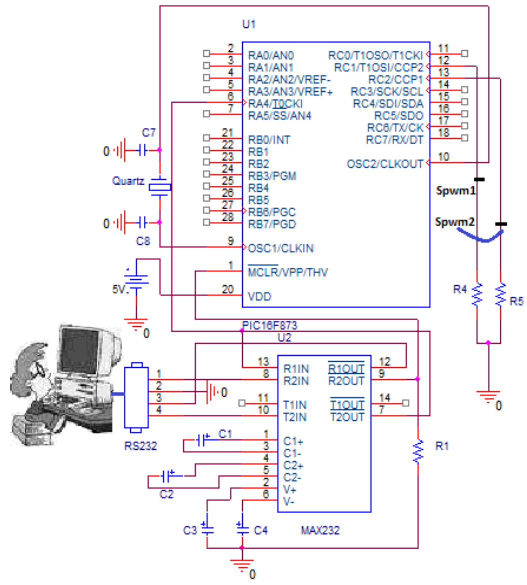

Figure 2: Schematic circuit for PIC programming using Bootloader technique.

Therefore, High Speed crystal (HS) of 4 MHz is chosen. The PWM pins were used to generate two complementary 5 volts level SPWM patterns.

3.2 Software Design

The flowchart (figure 3) of the SWPM patterns generation is composed into two parts: main function and interrupt service routine (ISR) function.

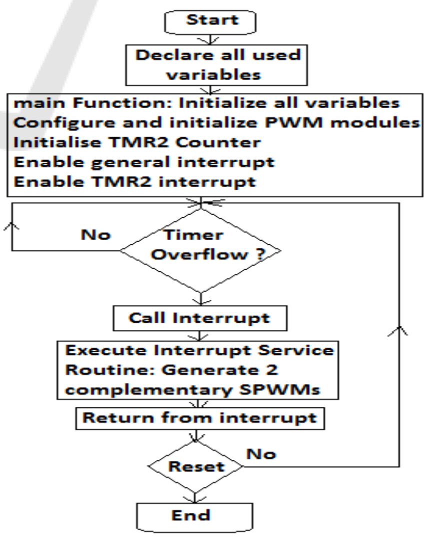

Figure 3: SPWMs patterns flowchart generation.

On reset, all hardware setting from the microcontroller configuration is loaded into the device and main function is executed firstly.

The figure 4 shows an infinite loop is entered, when Timer 2 reaches the PR2 value (TMR2 overflow), the interrupt service routine (ISR) is executed.

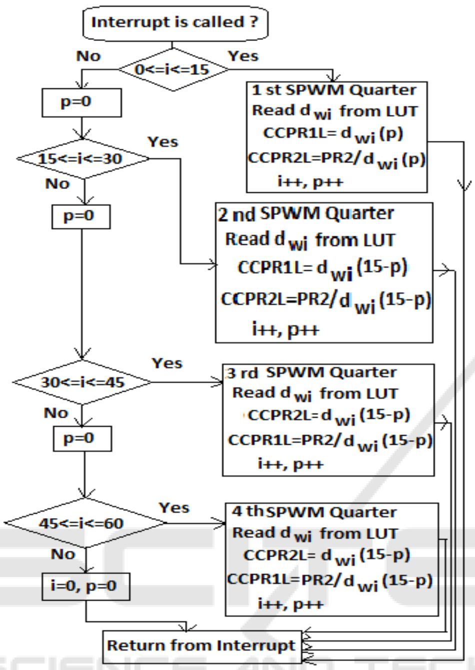

Figure 4: Interrupt Service Routine flowchart.

In this routine, the duty cycles values in look up table are read and sent to CCPR1L and CCPR2L registers every time when the TMR2 overflow. This figure describes all the operations taking place in this interrupt based p pointer and i counter.

This p pointer is incremented, to point the next duty cycle value in the table, and the i counter is also incremented in order to indicate the corresponding SPWM quarter. In each T_s, a new values are read and sent to CCPR1L and CCPR2L registers. In this interrupt mechanism, we have four tests to determine the corresponding SPWM quarter.

The duty cycles values are read from the table and then sent to the CCPRxL registers (x=1, 2) to generate two complementary SPWM signals. The loop can be terminated by resetting the reset switch of the hardware bar. These SPWM signals will be used to turn on and off the inverter's power transistors in order to create a sine wave output voltage with reference frequency F_{ref}.

4 EXPERIMENT RESULTS

The experimental setup is tested for different amplitude modulation index m_a for F_{ref} =50Hz and F_s=1kHz. The selected results have been chosen to illustrate some of main futures of microcontroller SPWM control, which have been presented in this paper. The control circuit is expected to output two pulses with varying duty cycles that are 180° out of phase with 1kHz switching frequency that depicted in figure 5 to figure 8 below.

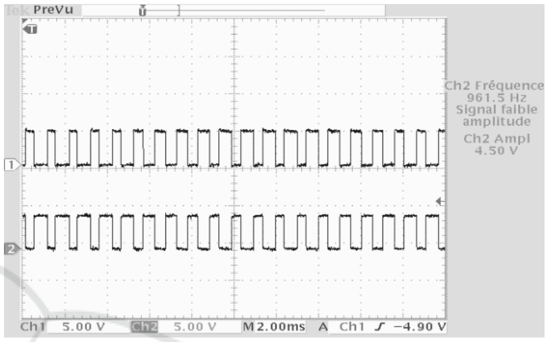

Figure 5: Complementary SPWMs for m_a = 0.5.

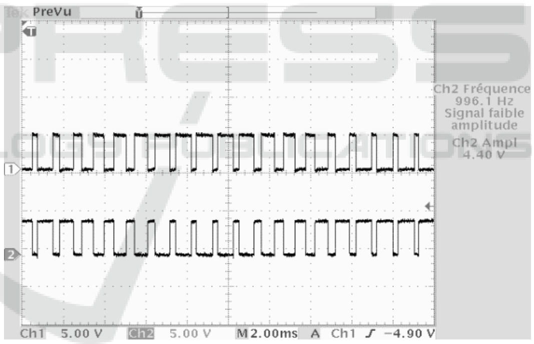

Figure 6: Complementary SPWMs for m_a = 0.7.

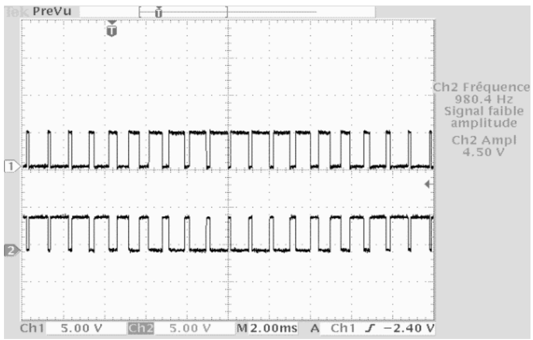

Figure 7: Complementary SPWMs for m_a = 0.8.

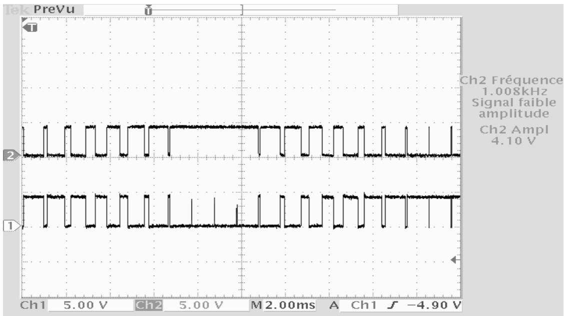

Figure 8: Complementary SPWMs for m_a =1.3 (over modulation).

These figures show the switching signal for difference amplitude modulation index m_a (m_a=0.5; 0.7; 0.8 and m_a=1.3).

These results illustrate the amplitude modulation index effect in the size of the pulses width. When the m_a is lower, the size of pulse is reduced and vice versa. This allows implementing a very simple adaptive voltage control for an inverter.

The results are very close to the expected values, which certify that the SPWM control circuit is functioning appropriately. For the reasons of safety and to ensure better switching mechanism in the power circuit, an opto-coupler and driver must be inserted between the microcontroller output and the power switches of the solar inverter.

5 CONCLUSION

The main task in this work was to develop a new SPWM technique for the inverter control circuit for a solar pumping system using look up table technique. This proposed approach remains very simple and allows eliminating the use of more electronic components, thus a low price and minimum occupation in the PCB board concept.

The investigated controller approach is able to produce two complementary SPWMs with desired switching frequency and amplitude modulation index. The efficiency of this method is that the output pulse width can be easily varied by changing PWM register's value based m_a index and thus a simple adaptive control system can be implemented.

Also, this technique may be extended for a three-phase solar inverter for pumping system.

The obtained experimental results were presented and they were found to agree well with other established work. In addition, we are working on the practical realization of a new and compact solar Boost pumping inverter.

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