Application Note, V1.0, July 2006

AP16097

# XC164

# Different PWM Waveforms Generation for 3-Phase AC Induction Motor with XC164CS

Microcontrollers

Never stop thinking

**Edition 2006-08-04**

**Published by**

**Infineon Technologies AG**

**81726 München, Germany**



**LEGAL DISCLAIMER**

THE INFORMATION GIVEN IN THIS APPLICATION NOTE IS GIVEN AS A HINT FOR THE IMPLEMENTATION OF THE INFINEON TECHNOLOGIES COMPONENT ONLY AND SHALL NOT BE REGARDED AS ANY DESCRIPTION OR WARRANTY OF A CERTAIN FUNCTIONALITY, CONDITION OR QUALITY OF THE INFINEON TECHNOLOGIES COMPONENT. THE RECIPIENT OF THIS APPLICATION NOTE MUST VERIFY ANY FUNCTION DESCRIBED HEREIN IN THE REAL APPLICATION. INFINEON TECHNOLOGIES HEREBY DISCLAIMS ANY AND ALL WARRANTIES AND LIABILITIES OF ANY KIND (INCLUDING WITHOUT LIMITATION WARRANTIES OF NON-INFRINGEMENT OF INTELLECTUAL PROPERTY RIGHTS OF ANY THIRD PARTY) WITH RESPECT TO ANY AND ALL INFORMATION GIVEN IN THIS APPLICATION NOTE.

**Information**

For further information on technology, delivery terms and conditions and prices please contact your nearest Infineon Technologies Office (**www.infineon.com**).

**Warnings**

Due to technical requirements components may contain dangerous substances. For information on the types in question please contact your nearest Infineon Technologies Office.

Infineon Technologies Components may only be used in life-support devices or systems with the express written approval of Infineon Technologies, if a failure of such components can reasonably be expected to cause the failure of that life-support device or system, or to affect the safety or effectiveness of that device or system. Life support devices or systems are intended to be implanted in the human body, or to support and/or maintain and sustain and/or protect human life. If they fail, it is reasonable to assume that the health of the user or other persons may be endangered.

| | | |
|---|---|---|
| **AP99007** | | |
| **Revision History:** | 2006-07 | V1.0 |
| Previous Version: | none | |

| Page | Subjects (major changes since last revision) |
|---|---|
| | |
| | |
| | |
| | |
| | |
| | |
| | |

**We Listen to Your Comments**

Any information within this document that you feel is wrong, unclear or missing at all?
Your feedback will help us to continuously improve the quality of this document.
Please send your proposal (including a reference to this document) to:

**mcdocu.comments@infineon.com**

**Table of Contents** **Page**

# 1 Introduction

In this application note, the methods to generate different PWM waveforms for 3-phase AC induction motor using an Infineon 16-bit microcontroller XC164CS are introduced.

For better understanding, the basic operation and control principle of 3-phase AC induction motors is described in Section 2. The content of Section 3 is the respective explanation of the theory of four popular PWM schemes frequently utilized in AC induction motor control, SPWM (Sinusoidal PWM), THIPWM (Third-Harmonic Injection PWM), SAPWM (Saddle-wave PWM), SVPWM (Space Vector PWM). In Section 4, XC164CS DAvE configurations and codes programming for different PWM schemes realization are discussed in detail and illustrated with flow charts. At the end of this article some experimental results including simulator waveforms and figures measured by oscilloscope are shown to validate the algorithms and some conclusions are drawn.

Furthermore, two sets of source codes for SPWM and SVPWM with 10KHz carrier frequency and output frequency from 0 to 50Hz in 10 seconds respectively as well as an EXCEL file on calculation tables for all PWM modes are attached.

# 2 3-Phase AC Induction Motor Control Principle

## 2.1 Basic Operation Theory

The 3-phase stators and 3-phase rotors are considered as two fundamental parts of a 3-phase AC induction motor. When the 3-phase stators are energized by the 3-phase AC power source, current flow is generated in the stators. The magnetic field synthesized by 3-phase stator current is always rotating incessantly with the variation of the current. This rotating magnetic field cuts the rotor and the current generated in it interacts with the rotating magnetic field and thus produces the magnetic torque which makes the rotor rotate (Figure 1). The rotating speed of the rotor $n$ should be less than that of the rotating magnetic field $n_0$. Reverse rotating of the rotor will be realized by two of the 3-phase power source positions exchanged.

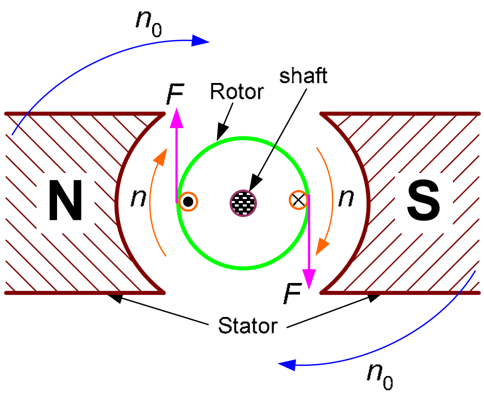



**Figure 1** Rotating start for AC induction motor

The rotating direction of the rotating magnetic field is consistent with the current phase and its speed is proportional to the power source frequency $f$ and inversely proportional to the magnetic polar pair number $P$. Calculated per minute, the speed of the rotating magnetic field $n_0$ can be represented by this equation:

$$n_0 = \frac{60f}{p} \qquad \text{(E-1)}$$

Where $f$ is the frequency of power source and $P$ is the magnetic polar pair number.

## 2.2 VVVF Control

From the equation (**E-1**) two primary methods for speed control of 3-phase AC induction motor can be concluded: one is to change the magnetic polar pair numbers but the inflexibility and low efficiency of this method has limited its popularity of application. Another method is to regulate the stator current frequency. Usually a principle of popular practical implementation called “VVVF” is adopted on speed regulation.

The 3-phase stators cutting the flux of the rotating magnetic field results in the back electromotive force generated and it can be calculated by the equation given below:

$$E_1 = 4.44 k_{r1} f_1 N_1 \Phi_M \qquad \text{(E-2)}$$

Where $k_{r1}$ is the winding structure related constant and $N_1$ is the number of turns of the stator winding per phase, $f_1$ is the stator current frequency, $\Phi_M$ is the main flux. Let a constant $K_{E1} = 4.44 k_{r1} N_1$, we have

$$E_1 = K_{E1} f_1 \Phi_M \tag{E-3}$$

Since the voltage drop on the stators impedance only occupies relatively very small portion of the whole stator voltage $U_1$ and can be ignored, therefore

$$U_1 \approx E_1 \tag{E-4}$$

Derived From (**E-3**) and (**E-4**), it holds

$$\Phi_M = K_\Phi \frac{U_1}{f_1} \tag{E-5}$$

Where $K_\Phi = \frac{1}{K_{E1}}$ is also a constant. From (**E-5**) it can be concluded that if the value of $U_1 / f_1$ can be controlled to be a constant, $\Phi_M$ remains unchanged. This control method to regulate frequency with voltage changed accordingly is usually called "VVVF", i.e. Variable Voltage Variable Frequency.

# 3 Different PWM Schemes for 3-Phase AC Induction Motor

## 3.1 General Theory of PWM (Pulse Width Modulation)

PWM (Pulse Width Modulation) technology was put forward based on an important conclusion in the sample control theory that when two groups of pulses with the same impulse area but different waveforms are input to an inertial link, the effectiveness of these two groups of impulses are the same. The main principle of PWM technique can be briefly described as: Through ON/OFF control on the semiconductor switching components, a series of pulses with the same amplitude and different width are generated on the output port to replace the sinusoidal wave or other waveforms required. The duty cycle of the output waveform needs to be modulated by a certain rule and as a result both the output voltage and output frequency of the inverter can be regulated.

The signals before PWM and after PWM are shown in Figure 2 and Figure 3 respectively. Compared with Figure 2, the frequency of the signal in Figure 3 is increased, the amplitude remains unchanged and therefore the average value of the signal is decreased. Therefore PWM just meets the requirement of VVVF described in section 2.2 and is adopted as the general method for AC induction motor control.

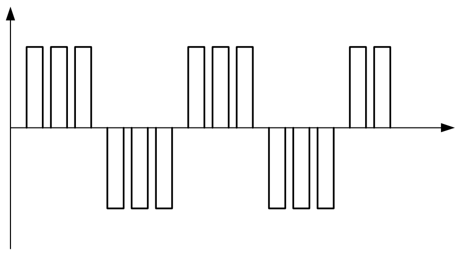


**Figure 2** Pulse before PWM

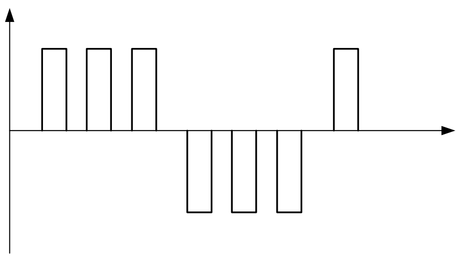


**Figure 3** Pulse after PWM

## 3.2 SPWM (Sinusoidal PWM)

### 3.2.1 Basic Principle

Among all PWM schemes, SPWM is one of the most popular and simple methods utilized in power inverter and motor control fields. Its main features can be summarized as sine-triangle wave comparison.

As shown in Figure 4, a sine wave (modulated wave, magenta) is compared with a triangle wave (carrier wave, green) and when the instantaneous value of the triangle wave is less than that of the sine wave, the PWM output signal (orange) is in high level (1). Otherwise it is turned into the low level (0). The level switching edge is produced at every moment the sine wave intersects the triangle wave. Thus the different crossing positions result in variable duty cycle of the output waveform.

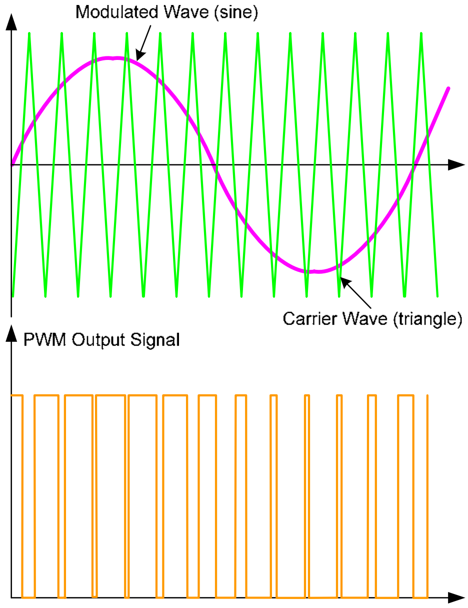



**Figure 4** SPWM Waveform Generation

### 3.2.2 Implementation Method

In terms of the basic principle of SPWM illustrated above, it's easy to implement using analog circuit (Figure 5). Sine and triangle waves are respectively generated by specially designed circuits and then fed to the properly selected comparator which can output the desired SPWM signal. But the control precision and reliability of this scheme are always not so satisfying due to the complicated circuit structure as well as the instability of the parameters of all analog devices.

With the development of the microcontroller, nowadays the software implementation for SPWM is absolutely mostly adopted to realize high precision control.

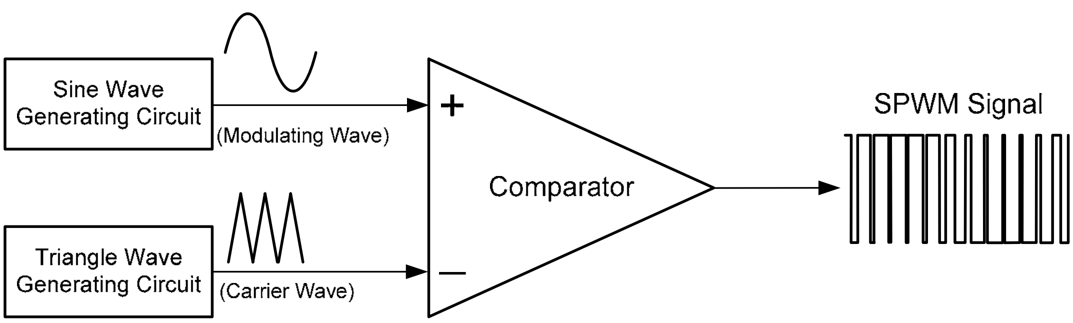



**Figure 5** Analog Scheme for SPWM Implementation

The method utilizing the natural intersection points of sine wave with triangle wave to realize PWM is called "Natural Sampled Method". It's able to demonstrate the true moments the pulse is started and ended and the SPWM waveform is much closer to sine wave. This method is not adopted in most control applications due to the random intersection points of sine and triangle wave which results in complicated calculation and difficult real-time implementation.

To overcome these disadvantages, another new method called “Regular Sampled Method” was put forward. It is widely used in engineering applications nowadays. It is based on the principle that a certain moment is selected in every cycle of the triangle carrier wave to find the corresponding value of the sine wave voltage which is introduced to sample on triangle wave and the sample result determines the ON/OFF moments of the power devices, ignoring whether the sine wave and triangle wave intersects in this moment or not. A more practical method named “Average Symmetric Regular Sampled Method” (illustrated in Figure 6) is applied in most control cases. In Figure 6, the sampled moment is given on the trough point of the triangle wave, then centered by the corresponding value of sine wave voltage, a horizontal line is drawn to intersect the triangle wave on both sides so the leading and trailing edges of PWM waveform are decided upon that. The leading edge is a little wider which just compensates the narrow trailing edge and therefore as an average consideration the effectiveness of this method is almost equivalent to that of the natural sampled method.

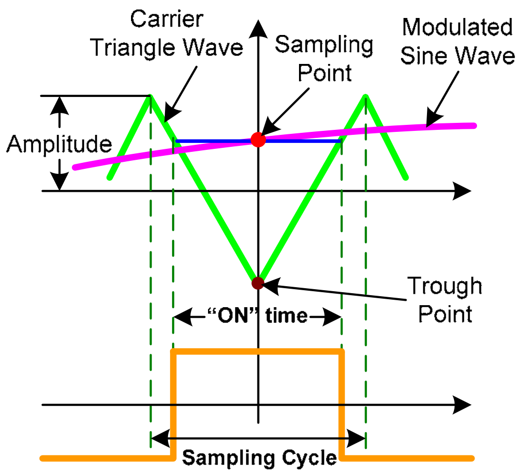



**Figure 6** Symmetric Regular Sampled Method

### 3.2.3 Modulation Index

When the amplitude of the modulated sine wave is larger than that of the carrier triangle wave, over modulation occurs. Once the sine wave reaches the peak of the triangle, the PWM pulses will obtain the maximum width so the modulation will enter the state of saturation (Figure 7). Therefore the item “Modulation index” (represented by $m$) defined by the ratio of the amplitude of the modulated wave to that of the carrier wave is introduced to describe the modulation state. When $0<m<1$, the linear relationship between the input and PWM output voltage is maintained. If the value of modulation index exceeds 1, this linear mode cannot be kept any more and the special control strategy for over modulation is required.

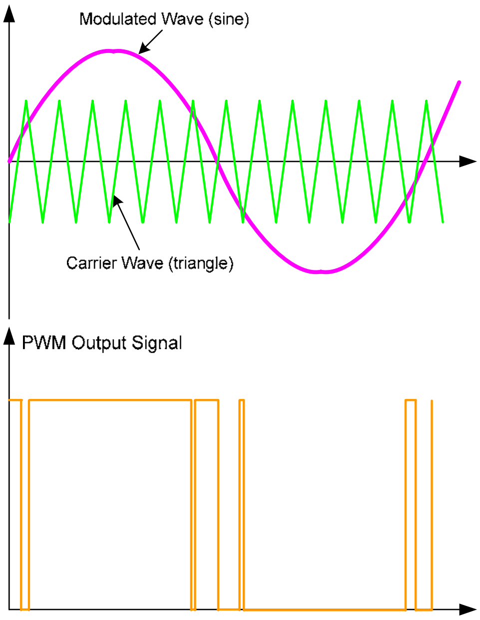



**Figure 7** SPWM Saturation

### 3.2.4 3-Phase SPWM

For 3-phase AC induction motor control system, the SPWM signals to trigger the six power switches in the voltage source inverter is generated by comparison of the 3-phase sine waves with the same triangle wave (Figure 8).

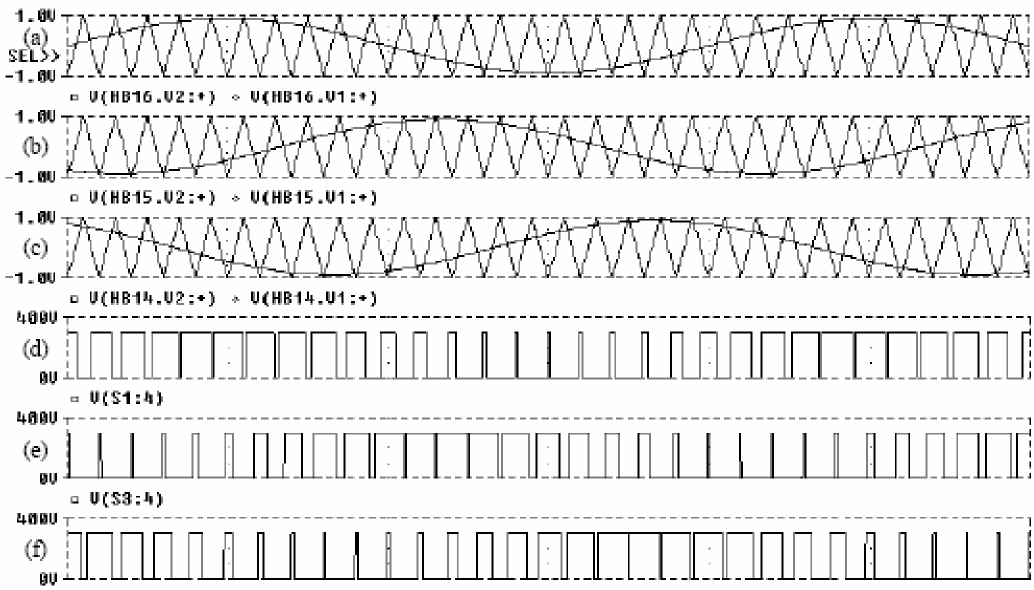



**Figure 8** 3-phase SPWM Waveforms (Pspice Simulation)

## 3.3 SPWM (Sinusoidal PWM)

If certain portion of the third harmonics wave is injected into the sine wave, the resulted modulated wave will appear as saddle-like shape (Figure 9) and the amplitude will obviously decrease. With keeping $m$<1, the amplitude of the fundamental wave can exceed that of the triangle wave and thus utilization ratio of the DC-bus voltage increases.

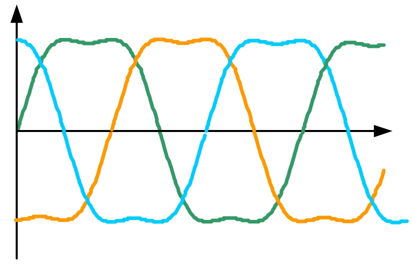


**Figure 9** 3-phase THIPWM Modulated Wave

## 3.4 SAPWM (Saddle PWM)

SAPWM is one type of the optimized PWM methods and its modulated wave (Figure 10) can be exactly described by the mathematic equation (**E-6**):

$$y(t)=\begin{cases}\sqrt{3}\sin\omega_1 t, & 0<\omega_1 t<\dfrac{\pi}{3}\\ \sin(\omega_1 t+\dfrac{\pi}{3}), & \dfrac{\pi}{3}<\omega_1 t<\dfrac{\pi}{2}\end{cases} \quad (\text{E-6})$$

It can be concluded from the research results that the maximum output voltage of the inverter adopting SAPWM can reach the value of the input voltage of the electric net which is 15% higher than that of the inverter using SPWM. Furthermore, the SAPWM inverter has been improved in restraining harmonic current, reducing torque fluctuation and enhancing output torque.

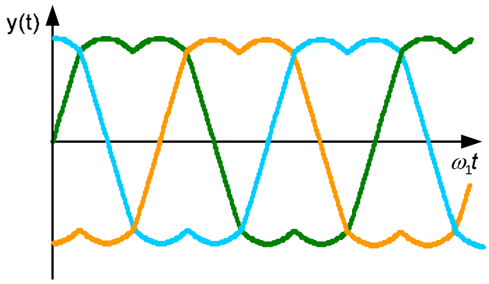



**Figure 10** 3-phase SAPWM Modulated Wave

## 3.5 SVPWM (Space Vector PWM)

Based on the 3-phase integrated generation effectiveness and for the purpose of approaching the ideal rounded track with constant amplitude of the rotating field formed by the gap flux, SVPWM waveform is realized by the combination of different switching modes of the inverter. In a 3-phase inverter, if “1” is defined as the positive half of the DC-bus voltage and “0” as the negative half (both are referred to the neutral point), there are totally 8 switch states for the six power switches (Figure 11). Therefore 8 voltage vectors (active vectors $\vec{U}_1 \sim \vec{U}_6$ and zero vectors $\vec{U}_0$, $\vec{U}_7$) can be correspondingly defined to form the vector space which is divided into 6 sectors (Figure 12).

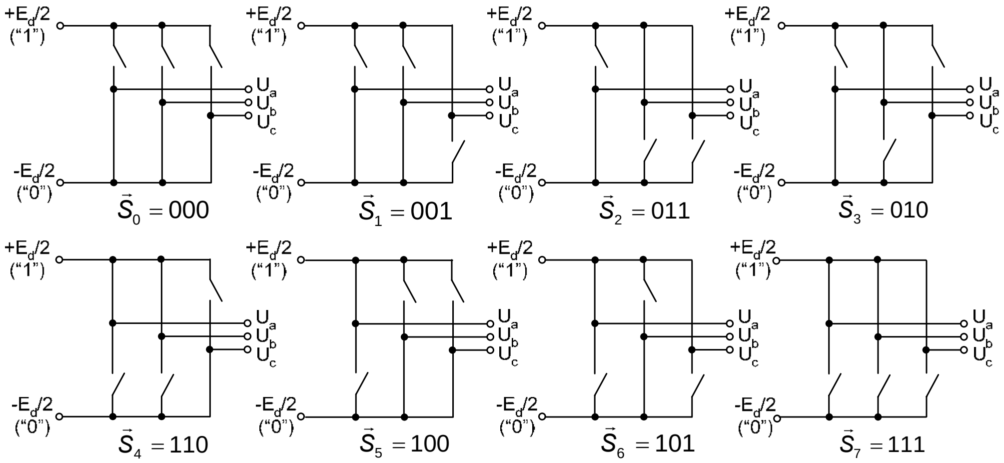



**Figure 11** Eight Switch States

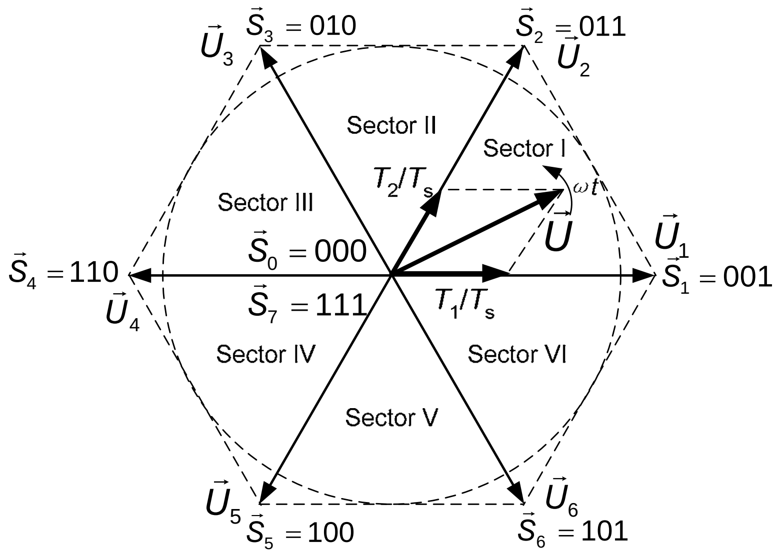



**Figure 12** Voltage Vector Space

The voltage vector $\vec{U}$ is generally decomposed into two nearest adjacent voltage vectors with zero vectors $\vec{U}_0$ and/or $\vec{U}_7$ as supplement. Thus the vectors in the six sectors $\vec{U}_I$ ~ $\vec{U}_{VI}$ are relatively calculated (assume that the zero vector operation time is halved by $\vec{U}_0$ and $\vec{U}_7$) as the equations **(E-7)**:

$$\begin{cases} \vec{U}_I = \frac{T_1}{T_s}\vec{U}_1 + \frac{T_2}{T_s}\vec{U}_2 + \frac{T_s - T_1 - T_2}{2T_s}(\vec{U}_0 + \vec{U}_7) \\ \vec{U}_{II} = \frac{T_2}{T_s}\vec{U}_2 + \frac{T_3}{T_s}\vec{U}_3 + \frac{T_s - T_2 - T_3}{2T_s}(\vec{U}_0 + \vec{U}_7) \\ \vec{U}_{III} = \frac{T_3}{T_s}\vec{U}_3 + \frac{T_4}{T_s}\vec{U}_4 + \frac{T_s - T_3 - T_4}{2T_s}(\vec{U}_0 + \vec{U}_7) \\ \vec{U}_{IV} = \frac{T_4}{T_s}\vec{U}_4 + \frac{T_5}{T_s}\vec{U}_5 + \frac{T_s - T_4 - T_5}{2T_s}(\vec{U}_0 + \vec{U}_7) \\ \vec{U}_V = \frac{T_5}{T_s}\vec{U}_5 + \frac{T_6}{T_s}\vec{U}_6 + \frac{T_s - T_5 - T_6}{2T_s}(\vec{U}_0 + \vec{U}_7) \\ \vec{U}_{VI} = \frac{T_6}{T_s}\vec{U}_6 + \frac{T_1}{T_s}\vec{U}_1 + \frac{T_s - T_6 - T_1}{2T_s}(\vec{U}_0 + \vec{U}_7) \end{cases} \quad (\text{E-7})$$

For detailed SVPWM calculation and more related information, please refer to another application note (AP0803601, Title: “Space Vector Modulation and Over-Modulation with an 8-bit Microcontroller”, www.infineon.com/microcontroller->Application Notes -8-bit Microcontrollers).

# 4 XC164CS Implementation of Different PWM Generation

## 4.1 CAPCOM6 Unit Introduction

### 4.1.1 Overview

The CAPCOM6 unit of XC164CS provides 2 independent timers T12 and T13 for PWM signals generation, especially for AC induction motor control. Its block diagram is shown in Figure 13.

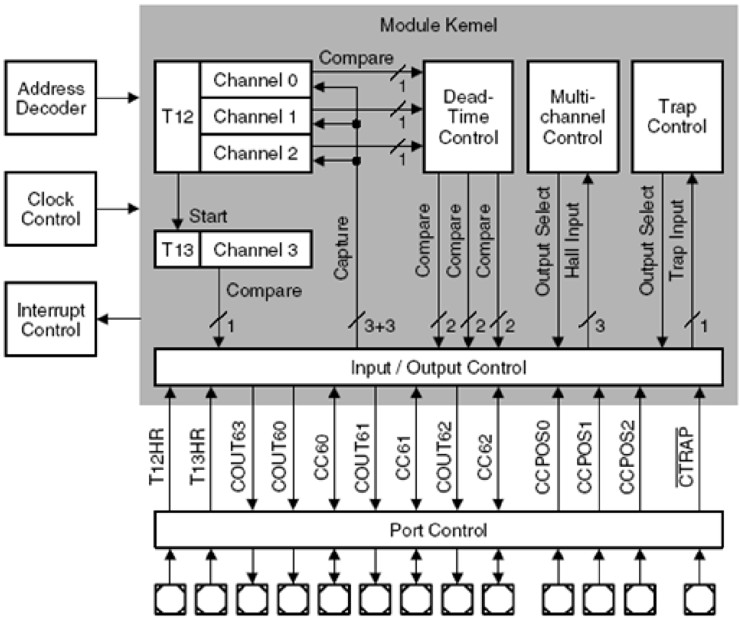



**Figure 13** CAPCOM6 Block Diagram

There are 3 capture/compare channels for Timer12 (16-bit) and each channel can be used either as capture or compare channel. Generation of a 3-phase Center- or edge-aligned PWM signals with dead-time control for each channel to avoid short-circuits in the power stage is supported (6 outputs, individual signals for lowside and highside switches) by T12. Timer13 (10-bit) has one independent compare channel with one output. It can be synchronized to T12 and supports single-shot mode. Fast emergency stop without CPU load via external signal CTRAP and related software interrupt process are both supported by CAPCOM6 unit to ensure the reliable protection under unexpected faults.

### 4.1.2 T12 Center-Aligned Mode

T12 block is the main unit to generate the 3-phase PWM. A 16-bit counter is connected to 3 channel registers via comparators, which generate a signal when the counter contents match one of the channel register contents. Besides the 3-phase PWM generation, the T12 block offers options for individual compare and capture functions as well as dead-time control.

T12 can operate in Edge-Aligned mode or Center-Aligned mode. In this article the Center-Aligned mode is adopted in PWM implementation and its operation principle is illustrated in Figure 14.

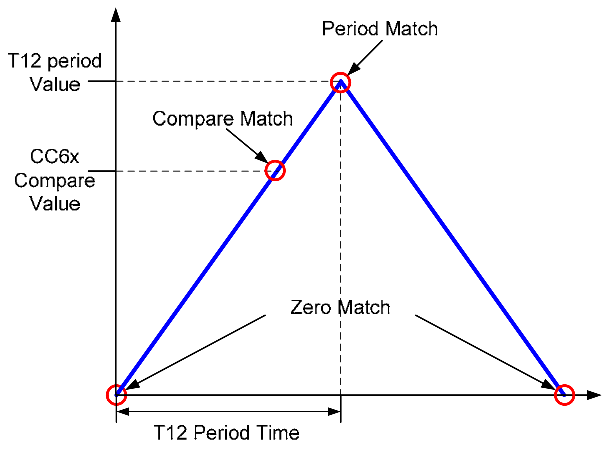



**Figure 14** T12 Center-Aligned Mode

### 4.1.3 PWM Signals Generation

As shown in Figure 15, each channel of T12 is connected to the T12 counter register via its individual equal-to comparator, which generates a match signal (CC6x_O) when the contents of the counter (CC6_T12) matches those of the associated compare register (CC6xR).

Each channel consists of the comparator and a double register structure - the actual compare register CC6xR feeds the comparator and an associated shadow register CC6xSR is preloaded by software and transferred into the compare register when T12 shadow transfer (T12_ST) becomes active.

CC6xST is a State Bit which holds the compare operation status of each channel. Bit CC6xPS/COUT6xPS selects the state of each channel, considered as the passive state during which the passive level (defined in register PSLR) is driven by the output pin: "0" represents that the compare output drives passive level while CC6xST is 0 and "1" defines that the compare output drives passive level while CC6xST is 1.

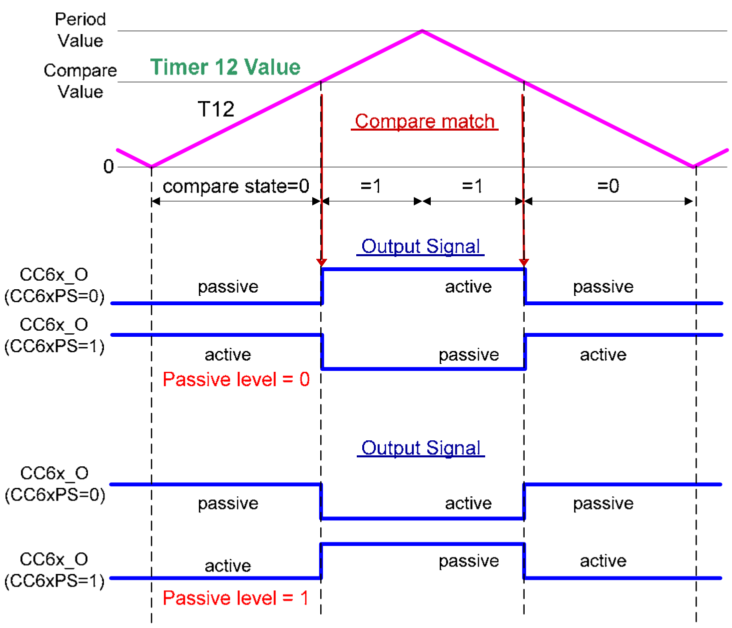



**Figure 15** PWM Signals Generated by T12

## 4.2 CAPCOM6 Initialization

The general initialization of CAPCOM6 for all the PWM schemes discussed in this article is summarized below (according to display order in DAvE):

***“Module Clock”***: Enable module.

***“Pin Control”***: Use pin CC60, CC61, CC62, COUT60, COUT61, COUT62 as output.

***“T12”***: fcpu/4 (Resolution: 0.100us); Center-Aligned mode; T12 period 100us (carried frequency 10KHz); Start T12 after initialization; Enable interrupt for T12 period match (generating interrupt per carrier cycle).

***“T13”***: No initialization is required for it, T13 isn’t used here.

***“Multi Ch.”***: Disable multi-channel mode.

***“Channels”***: Channel 0,1,2 should be individually configured as (x=0,1,2): Compare Mode 3 (Use pins CC6x/COUT6x as output); Enable T12 modulation for CC6x; The compare output CC6x drives passive level while CC6xST is “0”; The compare output COUT6x drives passive level while CC6xST is “1”; The passive level of CC6x and COUT6x output are all “1”; Enable dead time generation.

***“Trap/INT”***: The demo code is just focus on PWM algorithm implementation and verification, CTRAP function is not necessary to be configured. In “Interrupt Configuration” select “Enable T12 interrupts / node I2(IE)”.

***“Interrupts”***: CCU6 I2 INT -> Level 15, Group 0 (For convenience it’s set to the highest priority.)

***“Functions”***: In “Initialization Function” select “CCU6_vInit”.

## 4.3 Programming Consideration and Flow Charts

Here in all these PWM schemes 10KHz carrier frequency is adopted and thus T12PR value is $1F3_H$ ($499_D$) with resolution set to 0.1us. As a result $499_D$ is regarded as the PWM cycle value in the code programming and pulse width table calculation.

For SPWM/THIPWM/SAPWM, all the modulated waveforms can be described with mathematic equations so pulse width tables can be directly pre-calculated for look-up. Here the $2\pi$ modulated wave is divided into 3000 points and therefore the 3-phase look-up pointers have 1000 points difference with each other. In the T12 period match interrupt service program, the increment of the 3-phase look-up pointers $P_{\mathrm{inc}}$ are determined by:

$$P_{inc} = 3000 \times \frac{T_{carrier}}{T_{PWM\text{-}out}} = 3000 \times \frac{F_{PWM\text{-}out}}{F_{carrier}} = 3000 \times \frac{F_{PWM\text{-}out}}{10000} = \frac{10}{3} F_{PWM-out} \qquad \text{(E-8)}$$

The 3-phase look-up pointers are updated respectively with $P_{\mathrm{inc}}$ increment every T12 Period-Match Interrupt. Hence the pulse width can be obtained by using these pointers to look up the precalculated table. Please refer to the attached EXCEL file for more details about the look-up table generation. It’s easy to generate THIPWM or SAPWM waveforms directly using their look-up tables to replace SPWM table in the attached SPWM demo code files.

About detailed SVPWM algorithm programming, please refer to another two application notes (AP0801701, Title: “XC866 Constant V/f Control of Induction Motors Using Space Vector Modulation”; AP0803620, “Optimized Space Vector Modulation and Over-modulation with the XC866”. www.infineon.com/microcontroller->Application Notes -8-bit Microcontrollers)

Figure 16 shows the general flow chart of the T12 Period-Match Interrupt service subprogram in all these PWM schemes.

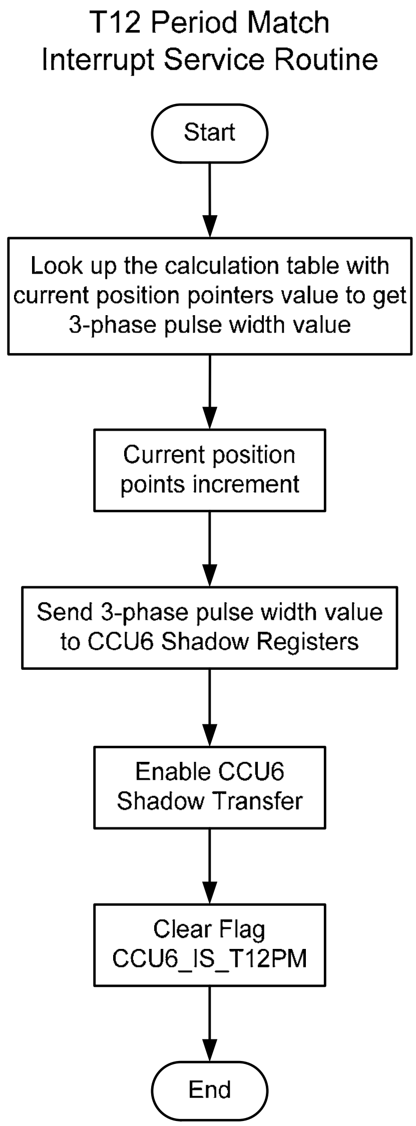
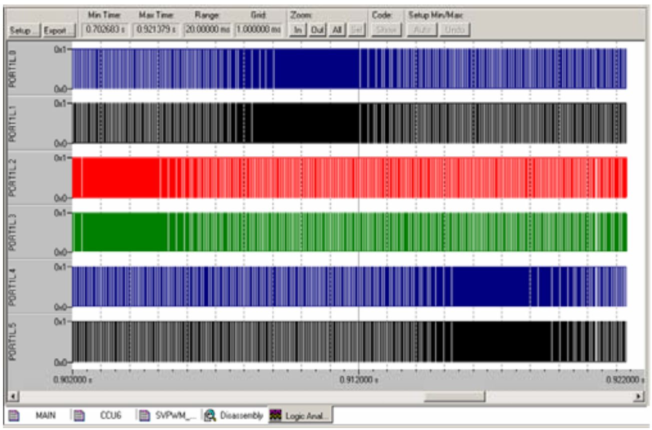



**Figure 16** Flow Chart of T12 Period-Match Interrupt Service Routine

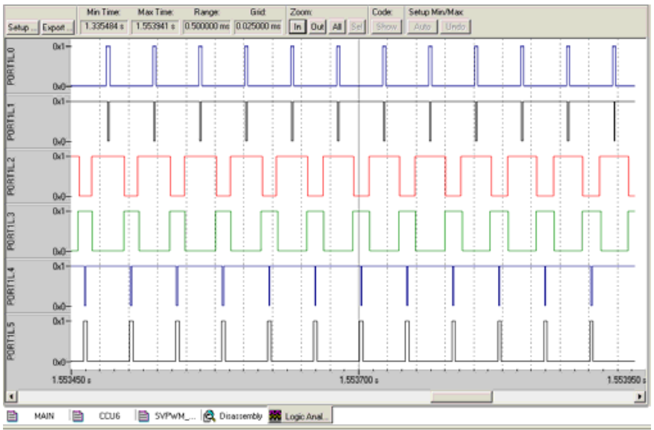
# 5 Experiment Results

## 5.1 Simulation Results

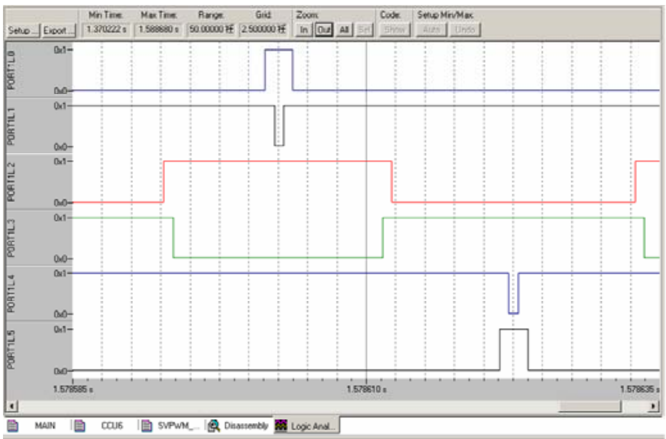
Figure 17 shows the simulated 3-phase SVPWM waveforms with dead-time control (P1L.0/CC60, P1L.1/COUT60, P1L.2/CC61, P1L.3/COUT61, P1L.4/CC62, P1L.5/COUT62) using KEIL uVision3 simulator.



(a) 3-phase SVPWM signals



(b) 3-phase SVPWM signals (Zoomed-in)



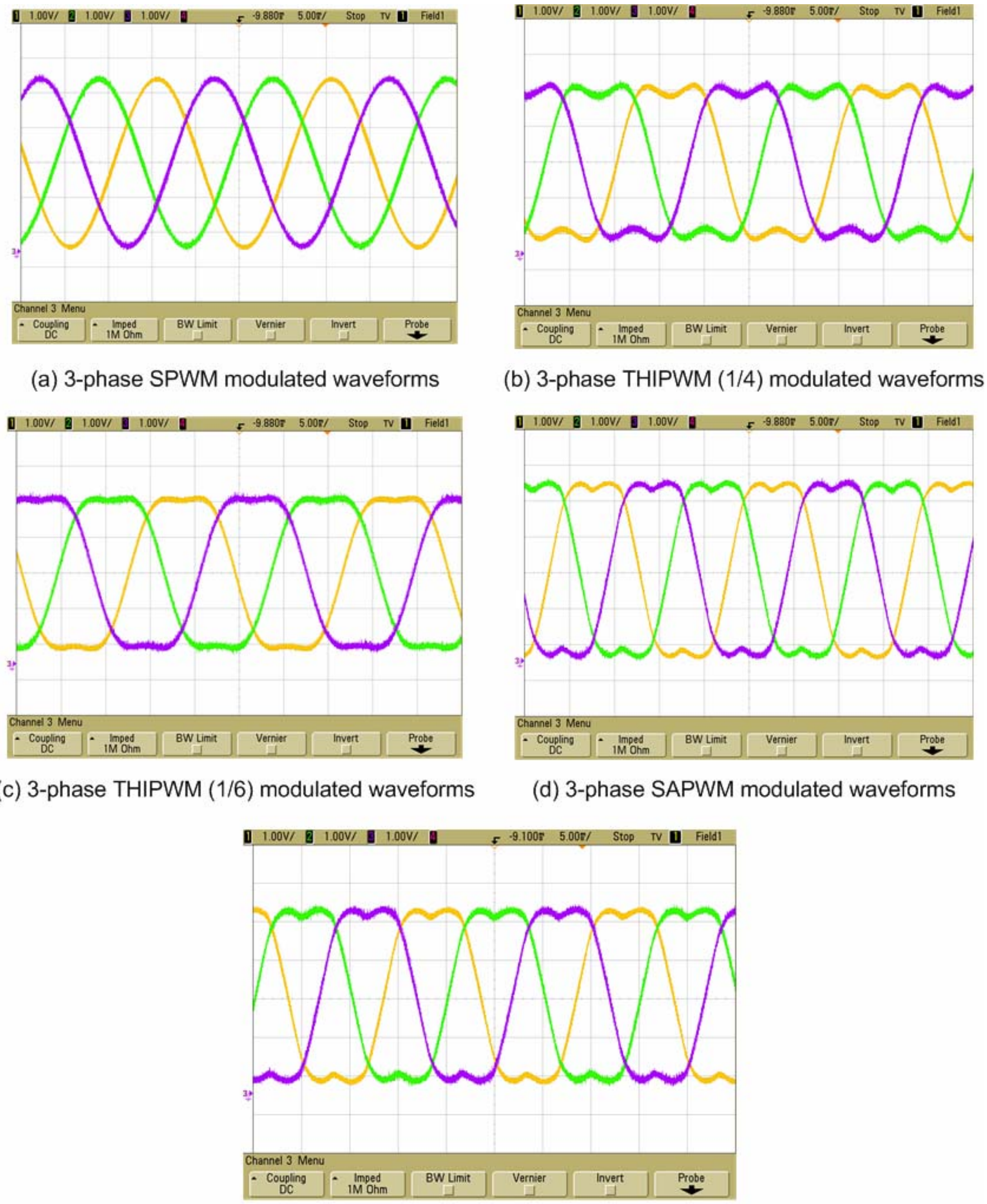
(c) dead-time control

**Figure 17** SVPWM Simulated Waveforms

## 5.2 Oscilloscope Measured Waveforms

The modulated waveforms of 3-phase SPWM, THIPWM (with 1/4 and 1/6 amplitude third harmonics injection respectively), SAPWM and SVPWM measured by oscilloscope are individually shown in Figure 18. All the signals are measured after being filtered respectively with three 3.3KΩ resistors and eight 1uF capacitors between CC6x/COUT6x and ground.

Figure 19 displays the zoomed-in PWM output waveforms (directly measured between CC6x/COUT6x and ground) and the dead-time for these PWM schemes. For SPWM, THIPWM (1/4), THIPWM (1/6), SAPWM, SVPWM, the dead-time is correspondingly set to 1us, 2us, 3us, 4us, 5us.



(a) 3-phase SPWM modulated waveforms

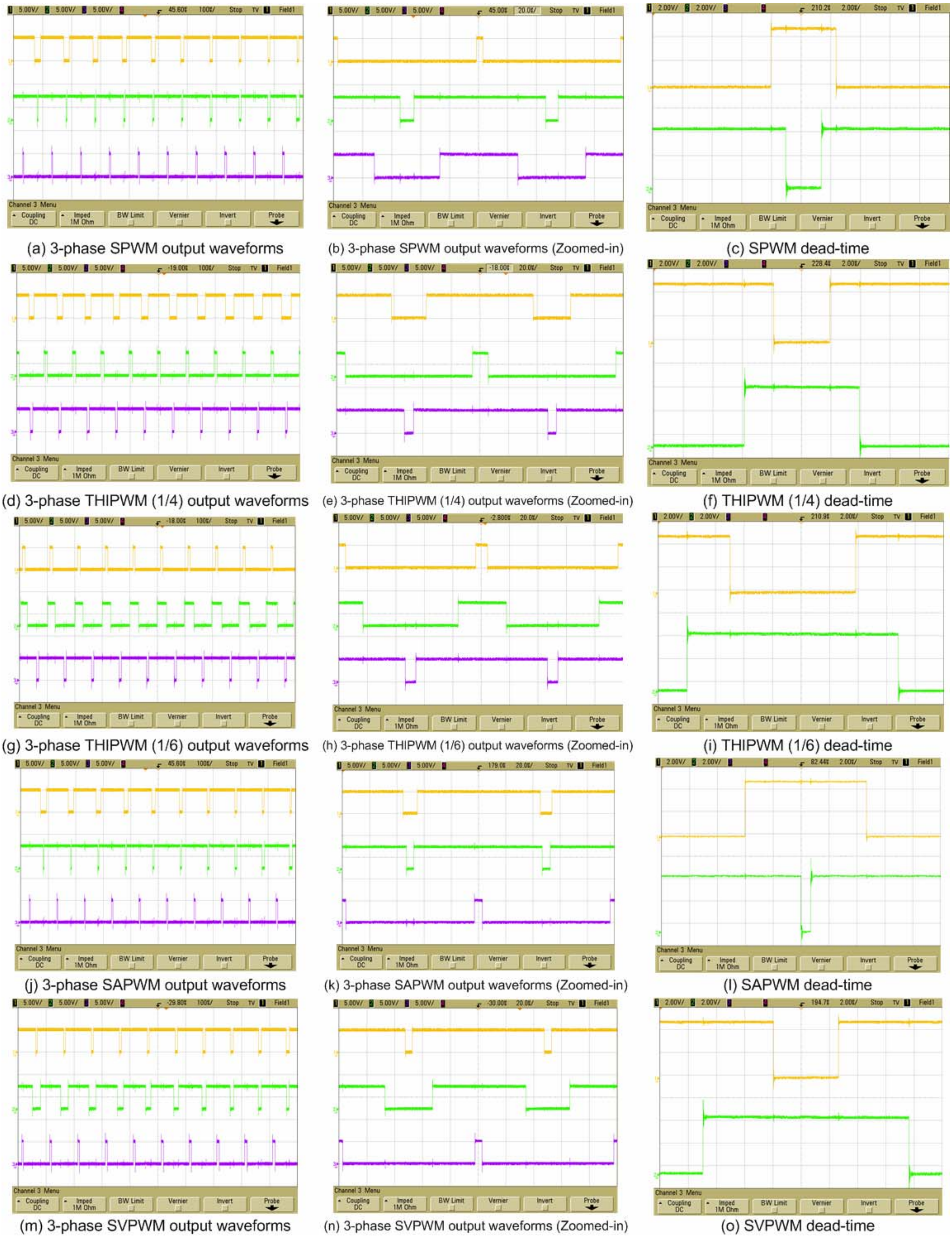
(b) 3-phase THIPWM (1/4) modulated waveforms

(c) 3-phase THIPWM (1/6) modulated waveforms

(d) 3-phase SAPWM modulated waveforms

(e) 3-phase SVPWM modulated waveforms

**Figure 18** Modulateds Waveforms for Different PWM Schemes



(a) 3-phase SPWM output waveforms
(b) 3-phase SPWM output waveforms (Zoomed-in)
(c) SPWM dead-time
(d) 3-phase THIPWM (1/4) output waveforms
(e) 3-phase THIPWM (1/4) output waveforms (Zoomed-in)
(f) THIPWM (1/4) dead-time
(g) 3-phase THIPWM (1/6) output waveforms
(h) 3-phase THIPWM (1/6) output waveforms (Zoomed-in)
(i) THIPWM (1/6) dead-time
(j) 3-phase SAPWM output waveforms
(k) 3-phase SAPWM output waveforms (Zoomed-in)
(l) SAPWM dead-time
(m) 3-phase SVPWM output waveforms
(n) 3-phase SVPWM output waveforms (Zoomed-in)
(o) SVPWM dead-time

**Figure 19** Output Signal for Different PWM Schemes

# 6 Conclusions

The implementation of different PWM schemes for 3-phase AC induction motor control via Infineon 16-bit MCU XC164CS is discussed in this article. The high-performance CAPCOM6 unit dedicated for motor control provides an easy and fast way to realize various types of 3-phase PWM signals generation.

http://www.infineon.com

Published by Infineon Technologies AG