Application Note, V 1.0, May 2004

# AP16057

# 16 Bit CMOS Microcontroller Product XC164CS

## Space Vector Modulation

Microcontrollers

Never stop thinking.

**16 Bit CMOS Microcontroller**

| **Revision History:** | 2004-05 | **V 1.0** |
|---|---|---|
| Previous Version: | - | |

| Page | Subjects (major changes since last revision) |
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# 1 Introduction

In the automotive area multiphase motors are replacing more and more brushes motors. For instance, Permanent Magnetic Synchronous Motors (PMSM) are used in fans, hydraulic pumps or for assistance of steering systems. Permanent synchronous motors, optimized for trapezoidal voltage shapes, are called Brushless DC motors. Applications like Electrical Power Steering with a higher demand on constant torque use a sinusoidal shaped voltage system. For these applications the space vector modulation is one of the favoured methods. Figure 1 shows the portioning of different electrical motor types.

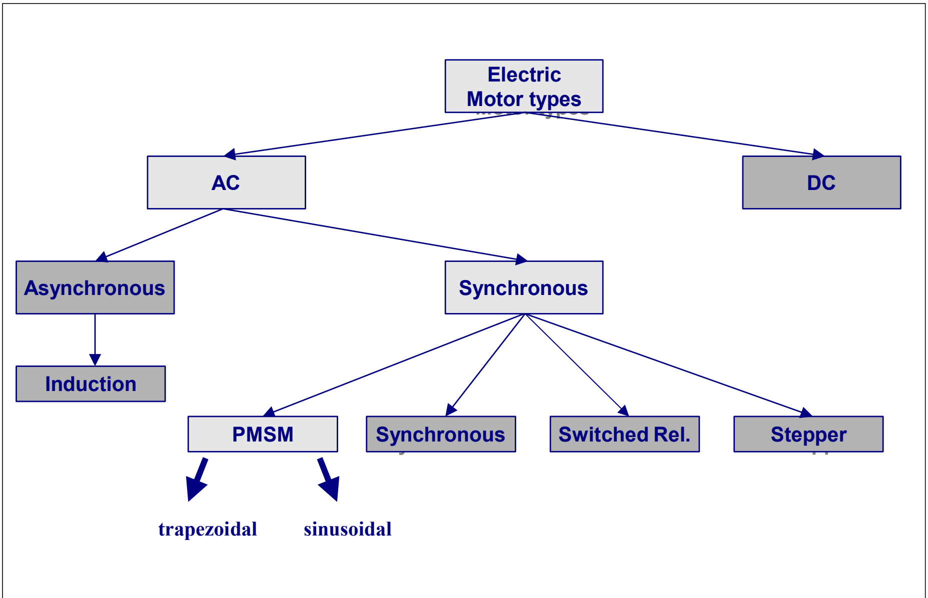



**Figure 1 Overview about different motor types**

## 1.1 Functional principle of a Permanent Magnetic Synchronous Motor

A brushless PMSM consist of a wound stator and a permanent magnetic rotor. It needs hall sensors, encoder or resolver to sense the rotor position. The sensing devices provide logic signals for electronically switching the stator windings in the proper sequence to maintain rotation of the permanent magnet.

The operation of a brushless PMSM is based on the conversion of electrical energy to mechanical energy. The generation of a rotation magnetic field is realized by applying sinusoidal voltages to the 3 stator phases. A resulting sinusoidal current flows in the coils and generates the rotating stator flux. The rotation of the rotor shaft is then created by attraction of the permanent rotor flux with the stator flux.

Usually the speed and position of an electrical motor can be defined in two ways. The mechanical position is related to the rotation of the rotor shaft. The electrical position of the rotor is related to the rotation of the rotor magnetic field. In figure 2 the rotor needs to move 360 mechanical degrees to obtain an identical magnetic configuration as when it started. In case of two pole pairs the rotor would need only to move 180 mechanical degrees to achieve the same magnetic configuration.

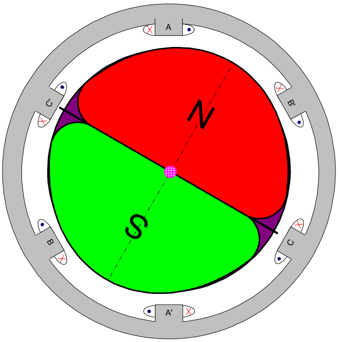



**Figure 2 Simplified cross section of PMSM with one pole pair**

## 1.2 System description of a multiphase motor application

A PMSM motor is a synchronous machine. The rotor position must be known at certain angles in order to align the applied voltage and is usually determined by Hall sensors or Incremental encoders. Commutation of a PMSM motor is performed electronically. A rectangular-shaped or sinusoidal three-phase voltage system is used to generate a rotational field. Based on these criteria, closed-loop control is essential. For low dynamic requirements, a speed/position control loop is used. For applications with higher performance needs, in addition a current control loop might be implemented.

Several loads (sensors, microcontroller, etc.) have to be supplied with constant CMOS/TTL-level voltages by the vehicle electrical system (12V).

Sensors deliver status information with the current values of several key parameters. The most vital parameters are position, speed, current and temperature. The outputs of sensors are either analogue or digital. Signal conditioning and interfaces are necessary to obtain stable and utilizable information in the closed-loop control system. A sinusoidal shape is favoured for a stable and constant torque. The torque of the motor is proportional to the applied current, which means that a PWM of the phase voltage is required to influence the torque. Typically, the PWM is generated by the control logic.

Driver stages and a level shifter are inserted between the control functionality and the phase stage. They transfer logic signals to the required Vgs (gate source voltage of MOSFET). The Vgs level is shifted for floating sources of the MOSFET Figure 3 shows the complete block diagram of such application.

Supervision and protection are important tasks within a system. Critical parameters need to be monitored and failure response scenarios implemented. Failsafe behaviour is essential, particularly with safety-relevant applications such as EPS (electrical power steering) and X-by-wire. In the event of a major electric failure, the fault has to be detected and the application immediately placed in a defined state.

MOSFETs are today's state-of-the-art solution for the inverter power stages used in low-voltage applications in the automotive industry. They are the physical switches from the DC rail voltage to the required phase voltages.

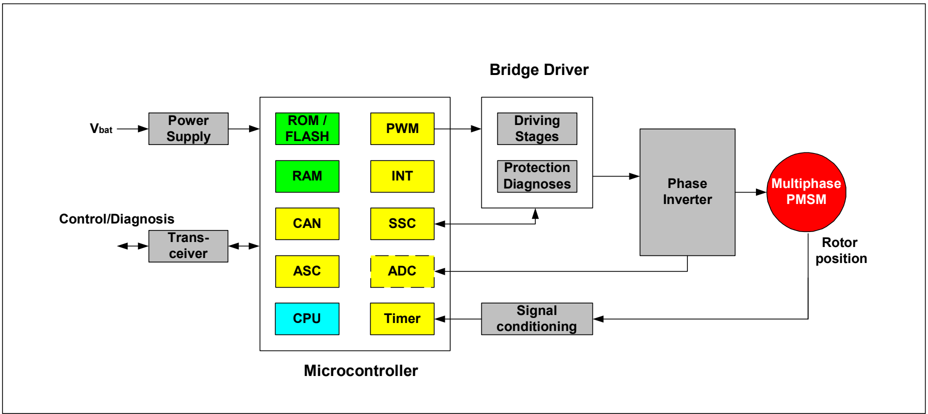



**Figure 3 Block schematic for control of PMSM application**

## 1.3 Advantages of Space Vector Modulation

Space Vector Modulation is a more sophisticated PWM method which provides advantages to the application.

- Higher performance to control mid / high dynamic motors
- Higher efficiency (86 %), sinusoidal weighted PWM (75%)
- Improved torque management
- Better start up performance, low speed with constant torque
- Constant torque, less torque ripple
- Improved dynamical reaction

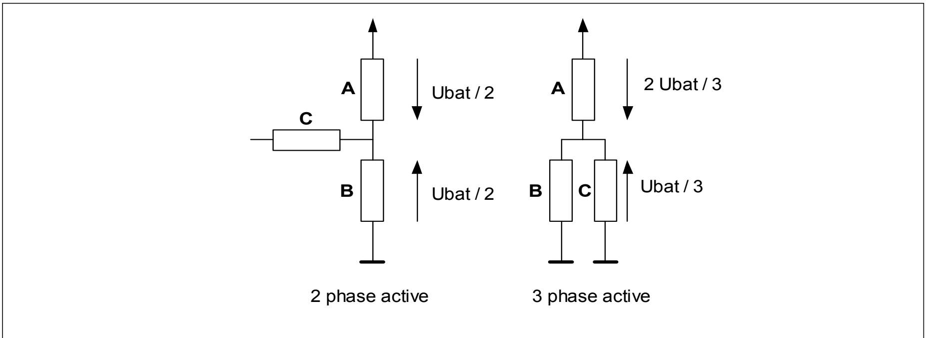
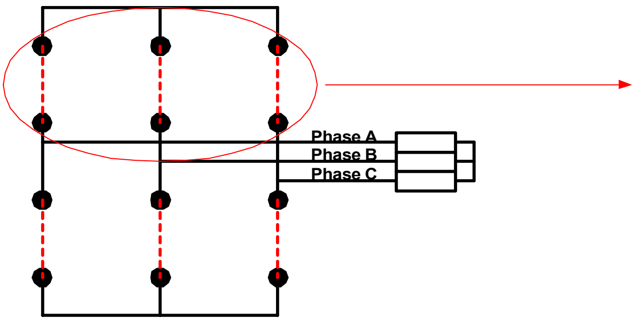



**Figure 4 Phase voltage (Block commutation and Space Vector Modulation)**

# 2 Space Vector Modulation

## 2.1 Introduction

One common way to represent the phase voltages A, B, C is the space vector model. The 3 phases of the motor can be applied with positive or negative voltage. Therefore 8 different states are possible. Each state represents a vector. In order to generate a rotating field the inverter has to be switched in six of the eight states. This mode of operation is called six-step mode. The remaining two states are called zero vectors (111, 000). In this case all phases are connected to GND or Vcc. The zero vectors, located in the middle of the hexagon, see figure 6, can be used to influence the amplitude of the vector. The angle between any two vectors is 60°.




**B6 Bridge:**
8 different switches are possible
for high side switches

| | | | |
|---|---|---|---|
| 0 | 0 | 0 | Vector zero |
| 0 | 0 | 1 | Phase C pos. |
| 0 | 1 | 0 | Phase B pos. |
| 0 | 1 | 1 | Phase A neg. |
| 1 | 0 | 0 | Phase A pos. |
| 1 | 0 | 1 | Phase B neg. |
| 1 | 1 | 0 | Phase C neg. |
| 1 | 1 | 1 | Vector zero |

The corresponding low side
switches build the complement

**Figure 5 B6 power bridge**

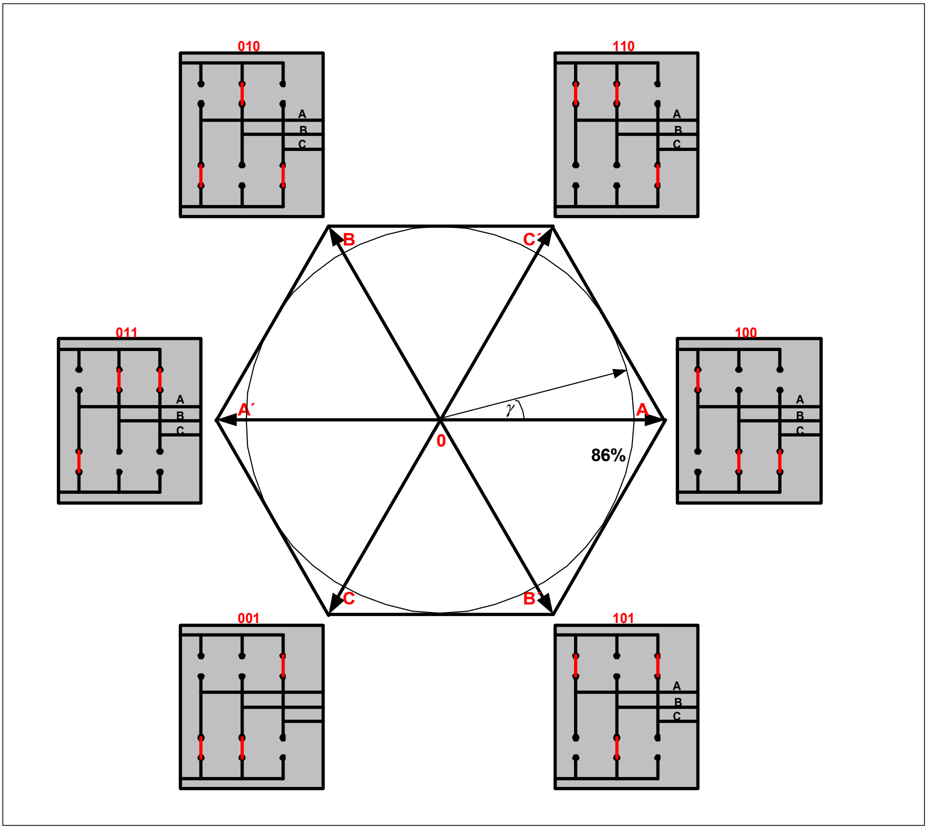



**Figure 6 Space Vector Model**

Operating in six-step mode uses the full capabilities of the inverter. Unfortunately six step mode creates high magnitude low order harmonics which can not be filtered by the motor inductance.

Basically the space vector modulation uses the six step mode, but smoothes out the steps through some sophisticated averaging techniques.

The first step in this re-definition is to transform the inverter voltages of six step mode into a space vector.

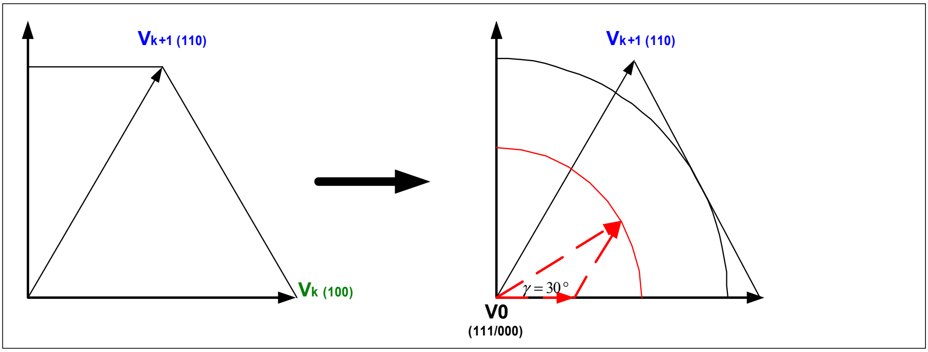



**Figure 7 Six step mode into space vector mode**

The goal of space vector modulation is to generate the appropriate PWM signals so that any vector can be produced. So given a space vector of angle y and modulation index of the vector, the approximation can be constructed by applying vector Vk and Vk+1 for percentage of times tk and tk+1respectively. For each position inside of the sector the times can be calculated and than applied to the appropriate inverter states. The higher the resolution inside of a sector the better is the stability of the torque.

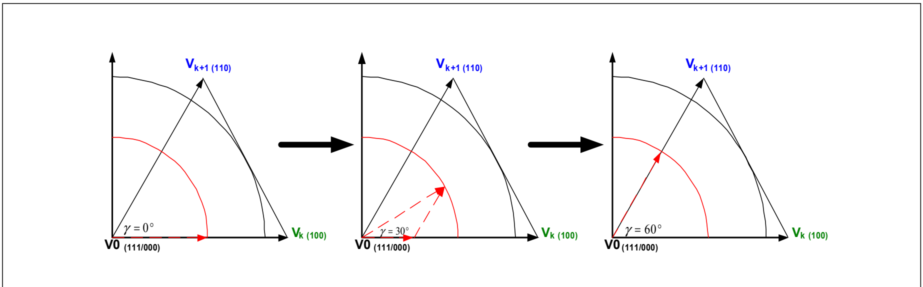



**Figure 8 Space vector modulation (example 0°, 30 °, 60° )**

## 2.2 Visualization of a rotation 0° - 360 °

In Space Vector Modulation three phases are energized in each state of the 3 half-bridges (B6 bridge). The following explanation will show the turning of a one pole-pair brushless DC motor as a function of the state of the appropriate switches shown in Figures 9-20. In fact, driving a one pole-pair motor means that the rotation speed of the electrical field has the same speed of the desired mechanical rotation speed ($\Omega = \omega / p$, where $\Omega$ is the mechanical rotation speed, $\omega$ the rotation frequency of the electrical field and p is the number of pole pairs).

### 2.2.1 Motor : 1 Pole pair, 3 Phases Next position : 0°

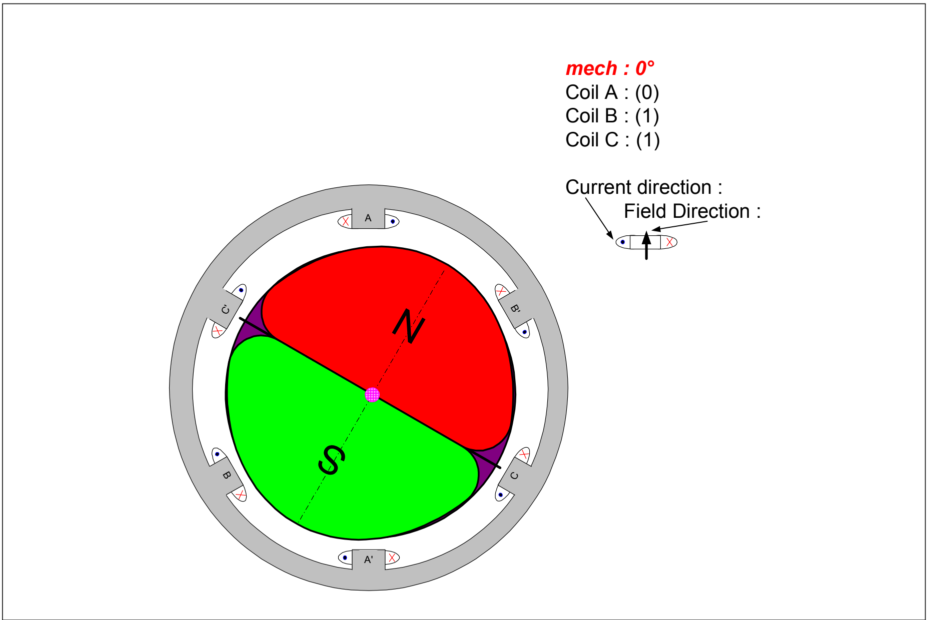



**Figure 9 Rotor position 0° next valid pattern will be '011'**

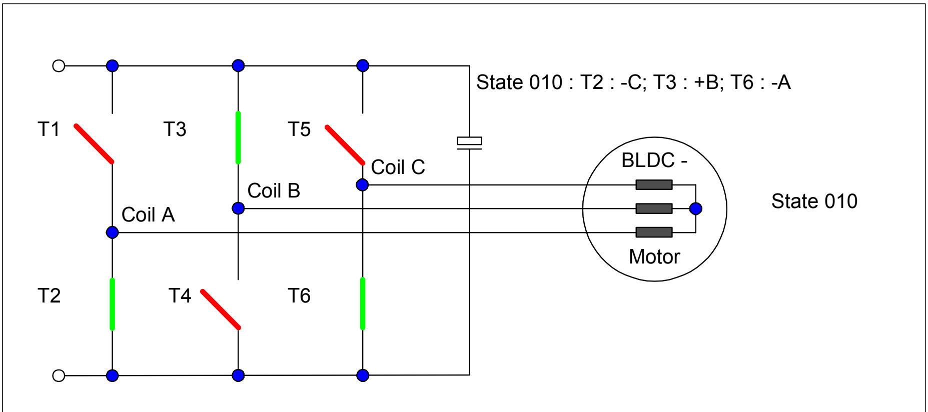



**Figure 10 B6 bridge 0° actual pattern is '010'**

## 2.2.2 Motor : 1 Pole pair, 3 Phases Next position : 60°

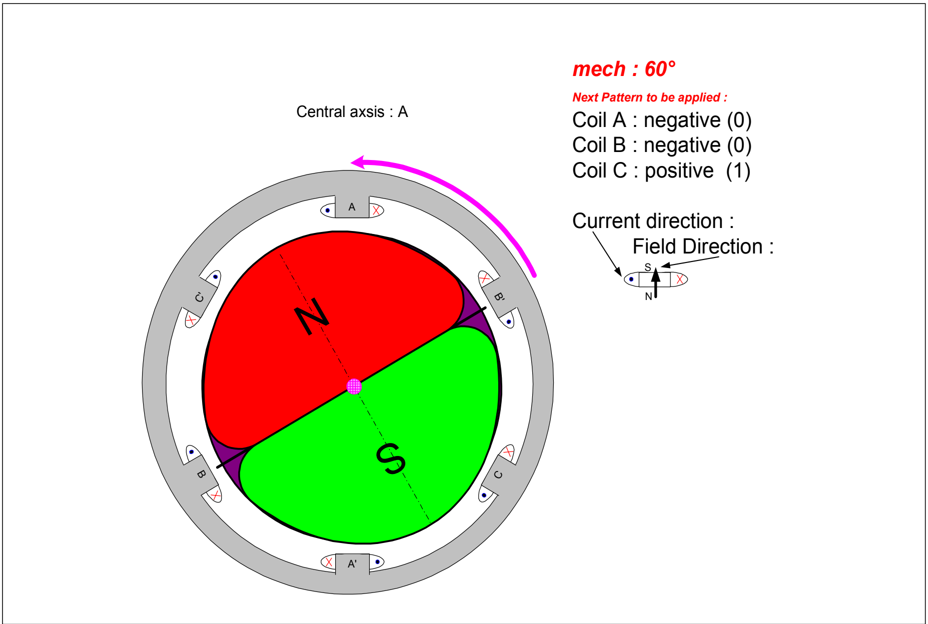



**Figure 11 Rotor position 60° next valid pattern will be '001'**

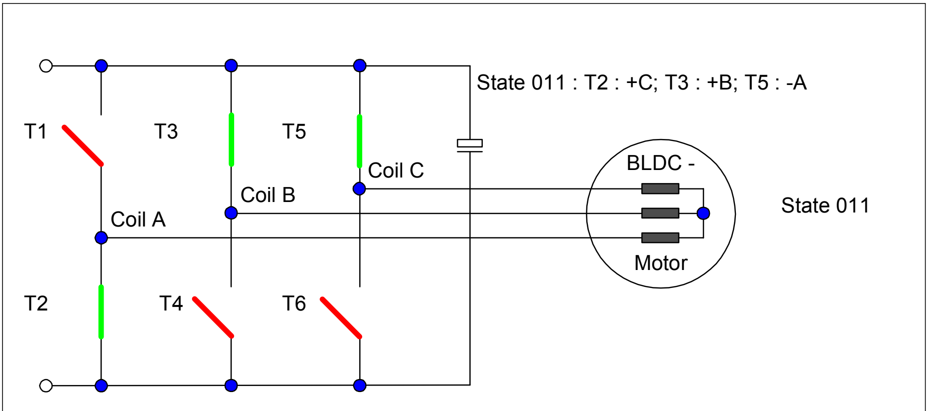



**Figure 12 B6 bridge 60° actual pattern is '011'**

### 2.2.3 Motor : 1 Pole pair, 3 Phases Next position : 120°

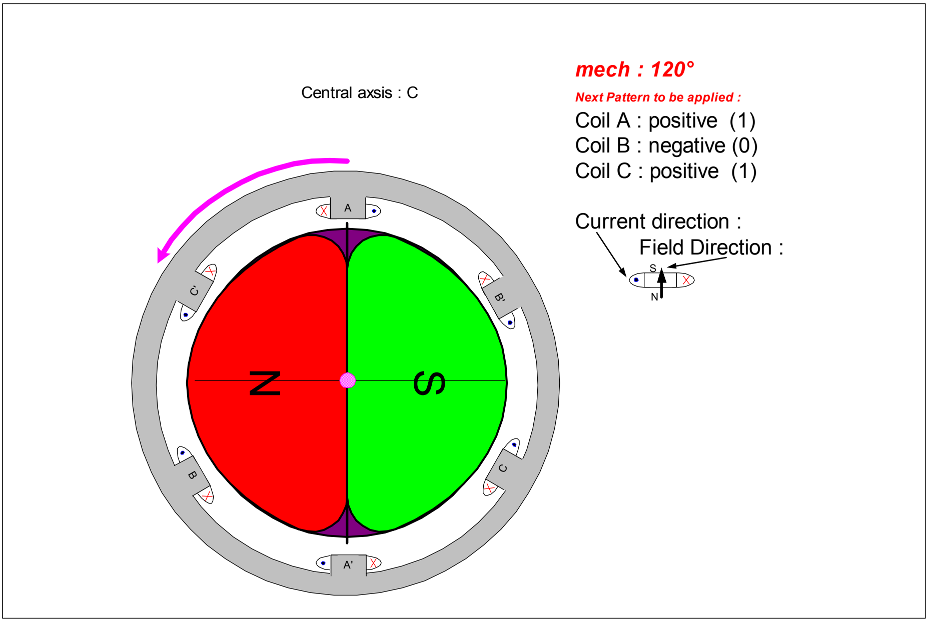



**Figure 13 Rotor position 120° next valid pattern will be '101'**

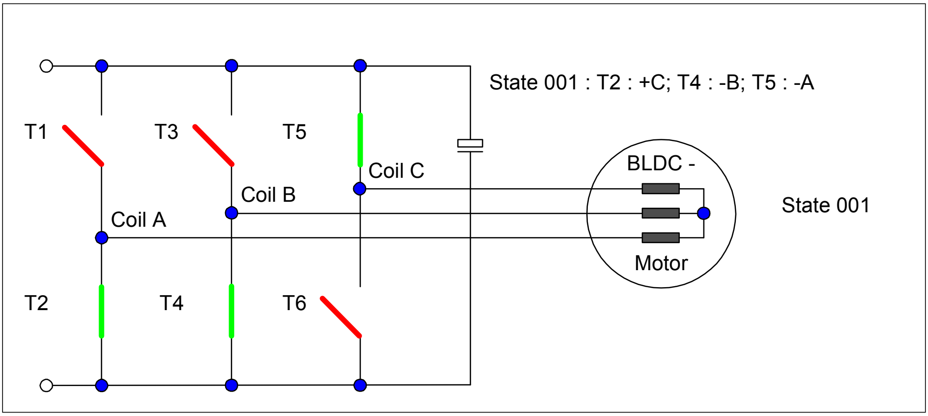



**Figure 14 B6 bridge 120° actual pattern is '001'**

### 2.2.4 Motor : 1 Pole pair, 3 Phases Next position : 180°

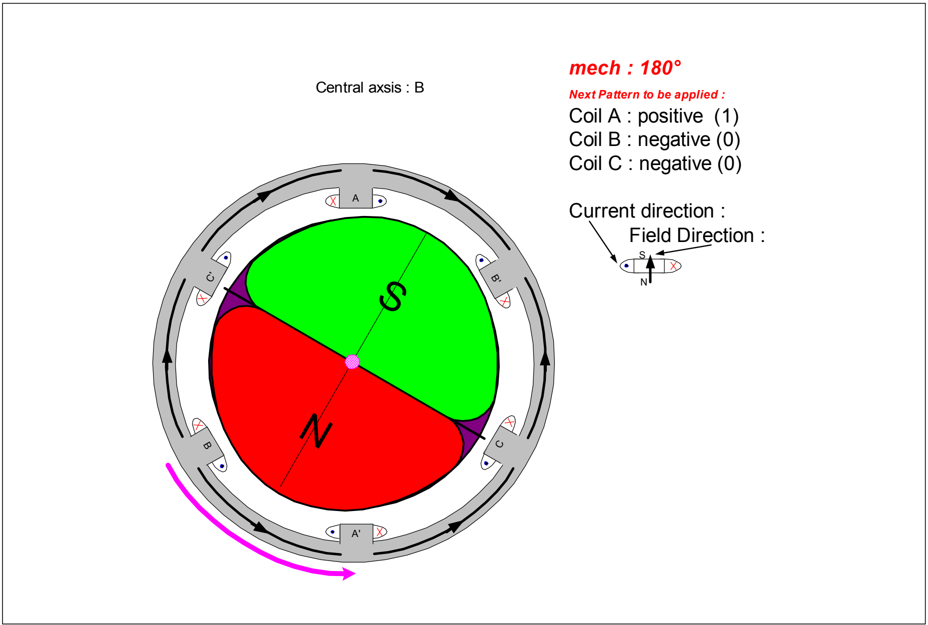



**Figure 15 Rotor position 180° next valid pattern will be '100'**

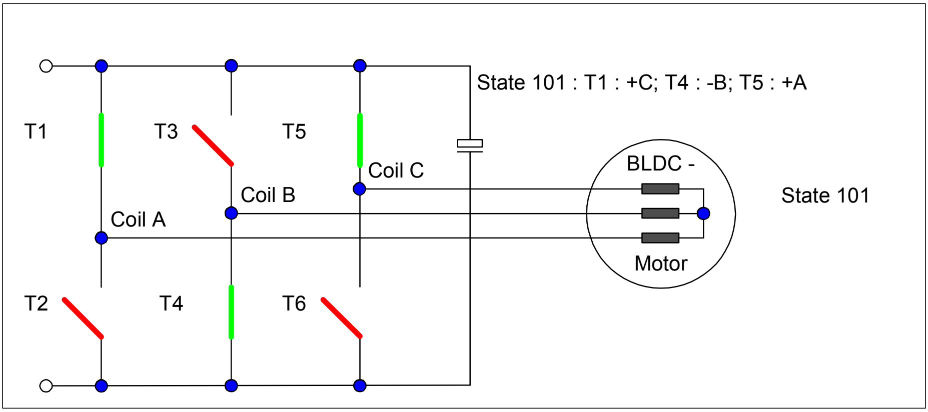



**Figure 16 B6 bridge 180° actual pattern is '101'**

### 2.2.5 Motor : 1 Pole pair, 3 Phases Next position : 240°

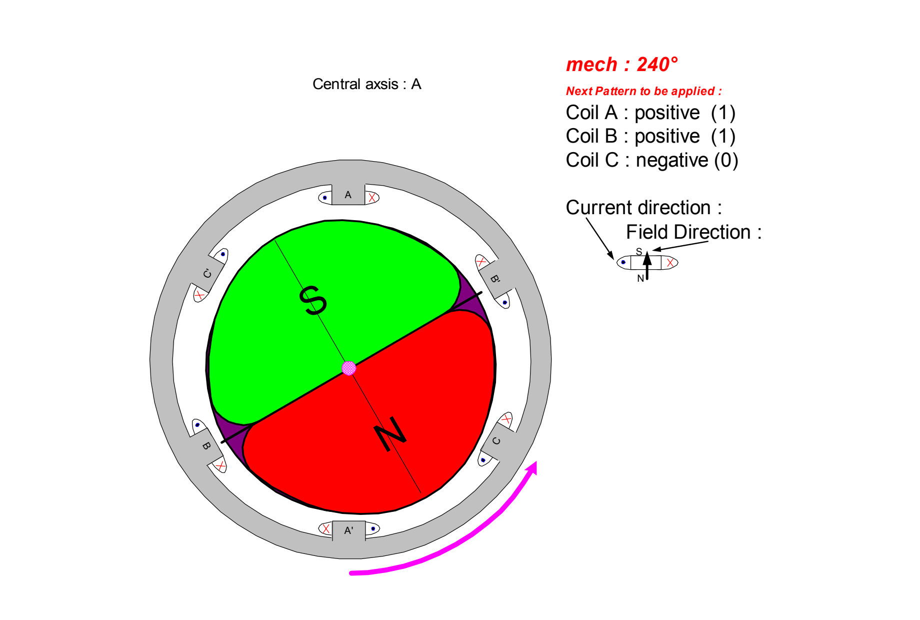



**Figure 17 Rotor position 240° next valid pattern will be '110'**

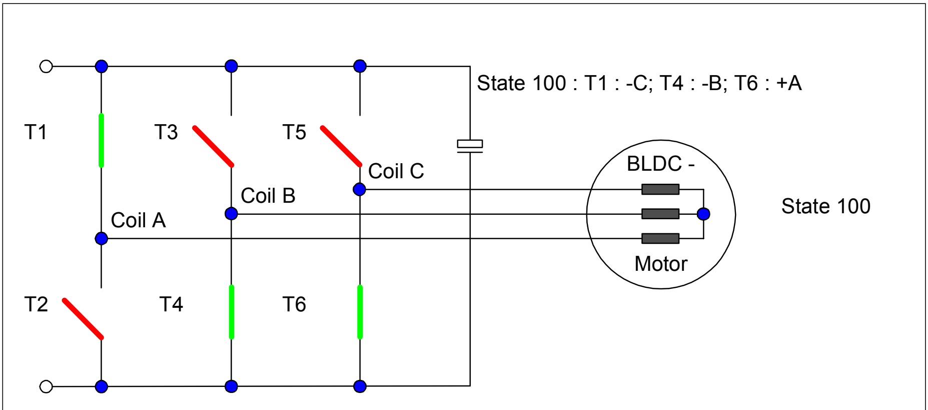



**Figure 18 B6 bridge 240° actual pattern is '100'**

### 2.2.6 Motor : 1 Pole pair, 3 Phases Next position : 300°

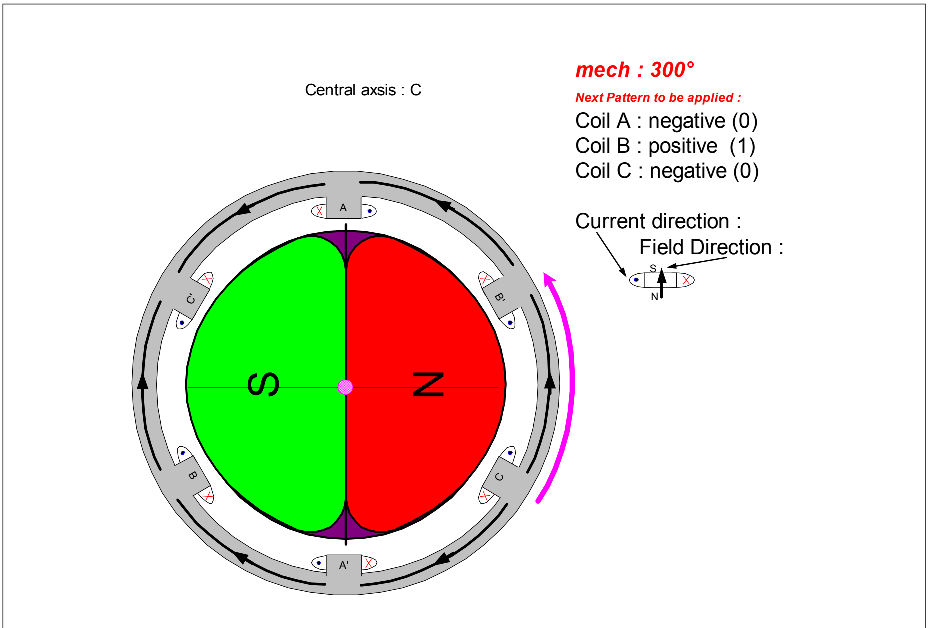



**Figure 19 Rotor position 300° next valid pattern will be '010'**

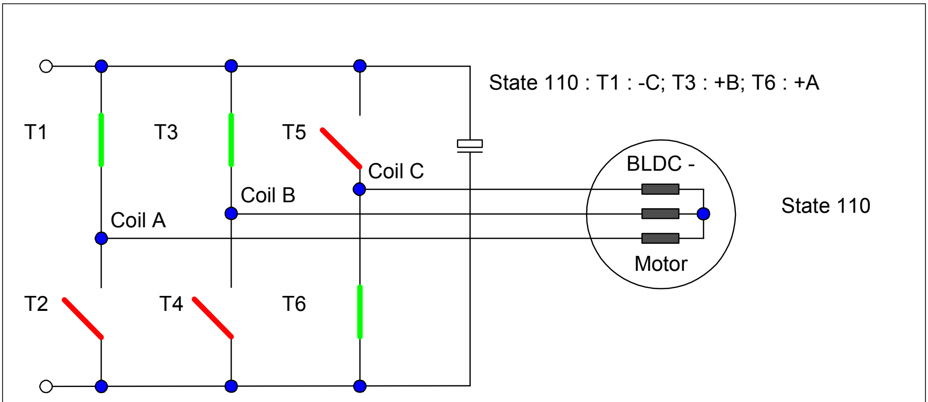



**Figure 20 B6 bridge 300° actual pattern is '110'**

## 2.3 Generation of output pattern

The space vector modulation is based on the fact that the space vector turns through the six sectors. This vector represents the weighted average voltage combination of 2 adjacent active space vectors during one PWM period.

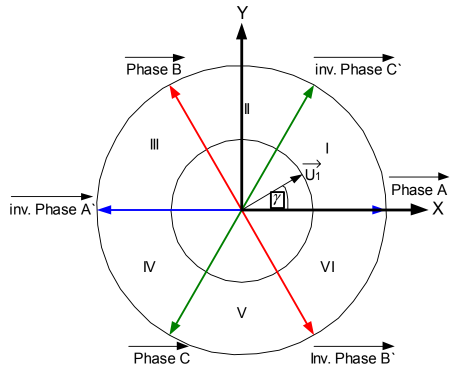



**Figure 21 Sectors of space vector**

For a better understanding the following explanations focus on sector one.

### 2.3.1 Calculation of PWM pattern

In order to create a smooth rotating field each point in the inner circle of the hexagon has been reached. This technique is called space vector modulation. The field orientation is given by the rotating angle γ and the amplitude U by the length of the vector. Each position inside the triangle can be reached by a combination of vector Vk, vector Vk+1 and the zero vectors. Any space vector can be realized with a time multiplex of the three vectors during the sample time Ts. Figure 22 explain the calculation of Tk, TK+1 and T0.

**Tk: Timeframe to apply the vector Vk**

**Tk+1: Timeframe to apply the vector Vk+1**

**T0: Timeframe to apply the zero vectors**

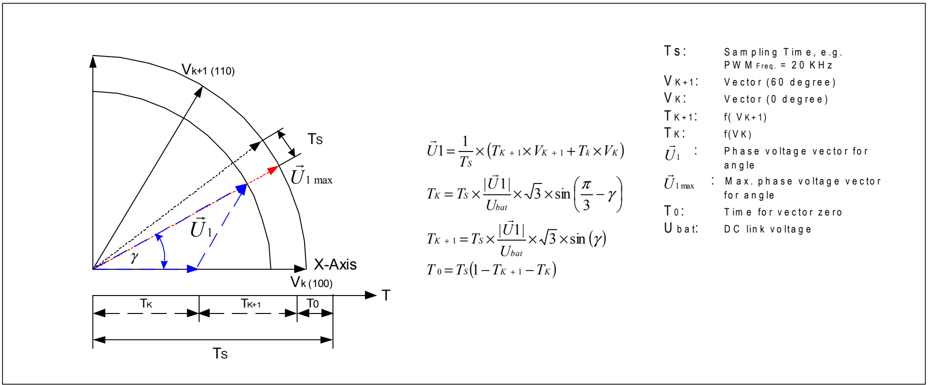



**Figure 22 Voltage vector for space vector modulation**

Typically the rotating angle γ is provided by an encoder or resolver. Dependent of the requirement of the application the sampling time Ts can be adapted. Each PWM sequence will be updated after the sampling time Ts. That means the next values for Tk, Tk+1 and T0 have calculated during one PWM sequence. In order to reduce computing load of the CPU parts (α,β) of the calculation can be put in look up tables.

A PMSM needs a closed loop speed/position feedback. This can be realised by an encoder device. With this information and a PI controller the vector length can be calculated. Furthermore with the angle position the corresponding values (α,β) are provided to compute the values Tk, Tk+1.

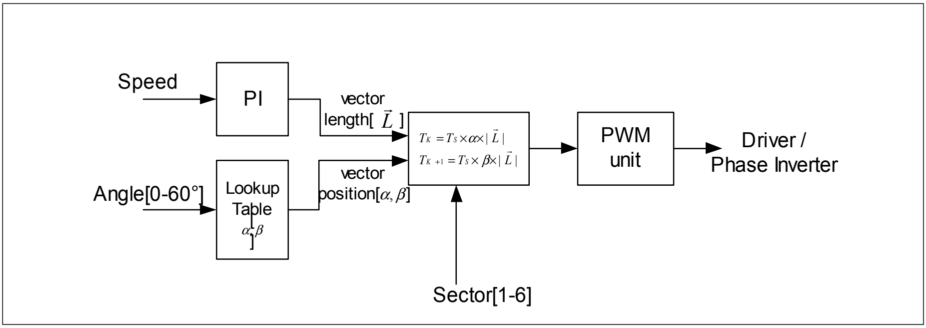



**Figure 23 Implementation of SVM with lookup table**

Figure 24 illustrates a proposal how a look up table may be organized.

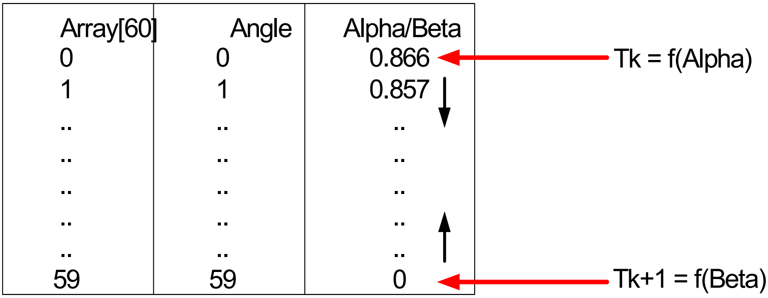



**Figure 24 Proposal for a look up table**

### 2.3.2 Generation of PWM pattern

In order to obtain an optimum harmonic performance and the minimum switching frequency for each of the power devices, the state sequence is arranged such that the transition from one state to the next is performed by switching only one inverter leg. This condition is met when the sequence begins with the null-state [000] and the inverter switches are toggled until the next null-state [111] is reached. To complete the cycle, the sequence is reversed, ending with the null state [000], see figure 25.

The sequence is $T_0/2$, $T_k$, $T_{k+1}$, $T_0$, $T_{k+1}$, $T_k$, $T_0/2$ for the odd sectors and $T_0/2$, $T_{k+1}$, $T_k$, $T_0$, $T_k$, $T_{k+1}$, $T_0/2$ for the even sectors. Where $T_k$, and $T_{k+1}$ represent the time of the respecting states.

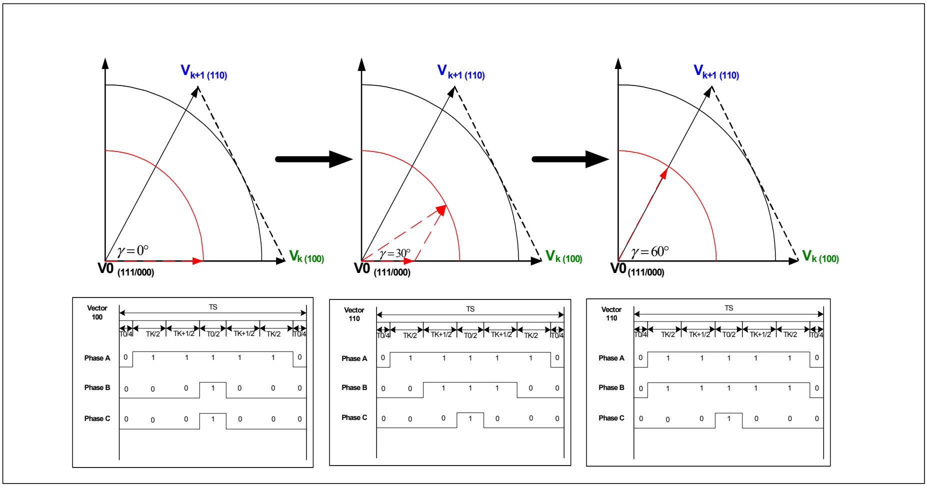



**Figure 25 Timing conditions for angle γ = 0°,30,60**

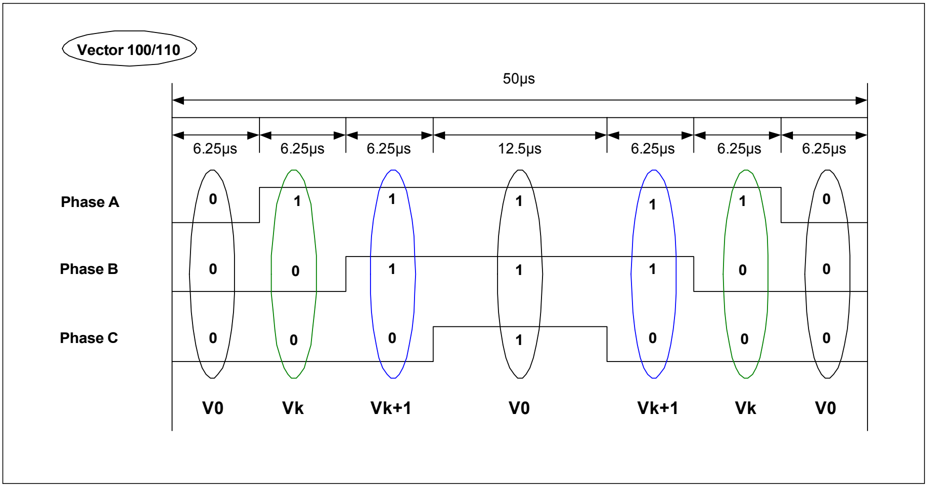



**Figure 26 Example for PWM generation (angle γ = 30°, vector length = 50 %, freq. = 20 kHz)**

| Degree(°) | TS(μs) | TK(μs) | TK+1(μs) | T0(μs) | PWM(%) | Alpha | Beta |
|---|---|---|---|---|---|---|---|
| 0 | 50 | 43.30 | 0 | 6.69 | 100 | 0.866 | 0 |
| 10 | 50 | 38.30 | 8.68 | 3.02 | 100 | 0.766 | 0.174 |
| 20 | 50 | 32.14 | 17.10 | 0.76 | 100 | 0.643 | 0.342 |
| 30 | 50 | 25.00 | 25.00 | 0 | 100 | 0.5 | 0.5 |
| 40 | 50 | 17.10 | 32.14 | 0.76 | 100 | 0.342 | 0.643 |
| 50 | 50 | 8.68 | 38.30 | 3.02 | 100 | 0.174 | 0.766 |
| 60 | 50 | 0 | 43.30 | 6.69 | 100 | 0 | 0.866 |

| Degree(°) | TS(μs) | TK(μs) | TK+1(μs) | T0(μs) | PWM(%) | Alpha | Beta |
|---|---|---|---|---|---|---|---|
| 0 | 50 | 21.65 | 0 | 28.35 | 50 | 0.866 | 0 |
| 10 | 50 | 19.15 | 4.34 | 26.5 | 50 | 0.766 | 0.174 |
| 20 | 50 | 16.07 | 8.55 | 25.38 | 50 | 0.643 | 0.342 |
| 30 | 50 | 12.5 | 12.5 | 25.0 | 50 | 0.5 | 0.5 |
| 40 | 50 | 8.55 | 16.07 | 25.38 | 50 | 0.342 | 0.643 |
| 50 | 50 | 4.34 | 19.15 | 26.5 | 50 | 0.174 | 0.766 |
| 60 | 50 | 0 | 21.65 | 28.35 | 50 | 0 | 0.866 |

**Figure 27 Relationship between angle ,Tk , Tk+1, $\alpha$ and $\beta$**

## 2.4 Sensors

The PMSM motor is a synchronous motor and so the rotor position has to be known exactly in order to generate the appropriate field.

### 2.4.1 Incremental Encoder output signal

Sensors are essential as a means of recognizing the positioning of a synchronous motor. The signals of an incremental encoder generated after appropriate signal conditioning are shown in figure 28. The pulse trains of Enc A and Enc B are 90 ° shifted to differentiate between the turn directions. Pulse trains from an encoder can vary from a few pulses per revolution to over 5000 pulses per revolution. The signal TOP Zero is used as start trigger for each revolution. Typically a timer unit (GPT12) processes these signals and provides the precise rotor position to the CPU. The rotor speed can be calculated by the CPU.

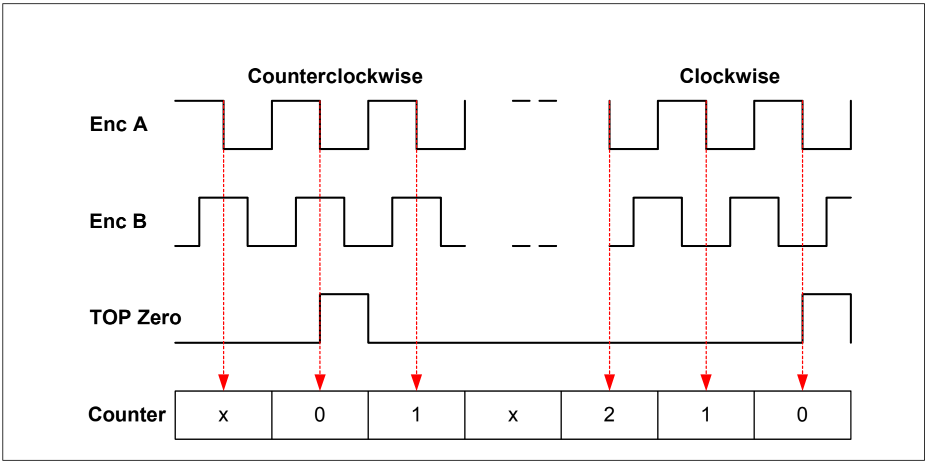



**Figure 28 Signals provided by an Incremental Encoder**

## 2.5 Required peripherals

The PWM unit (CAPCOM6), see figure 29, meets all the criteria for digital signal generation and event capturing, e.g. pulse-width modulation, pulse-width measurement. It supports generation and control of timing sequences on up to three 16-bit capture/compare channels plus one additional 16-bit compare timer. The multi-channel control unit generates output patterns which can be modulated by both timers. The modulation sources can be selected and combined for signal modulation. A dead time control unit allows specified delay times to be implemented for each high-side and low-side switch to avoid short circuits.

The CAPCOM6 provides two output signals per 16-bit channel, which may have inverted polarity pulse transitions. Timer T12 can be used to control the commutation speed. Timer 13 can be used to modulate the capture/compare outputs to influence the speed/torque of the motor. For space vector modulation a dead time generation is mandatory. It can be realized with the dead time control unit. For more detailed information about the CAPCOM6E unit please refer to the XC164CS peripheral manual.

## Space Vector Modulation

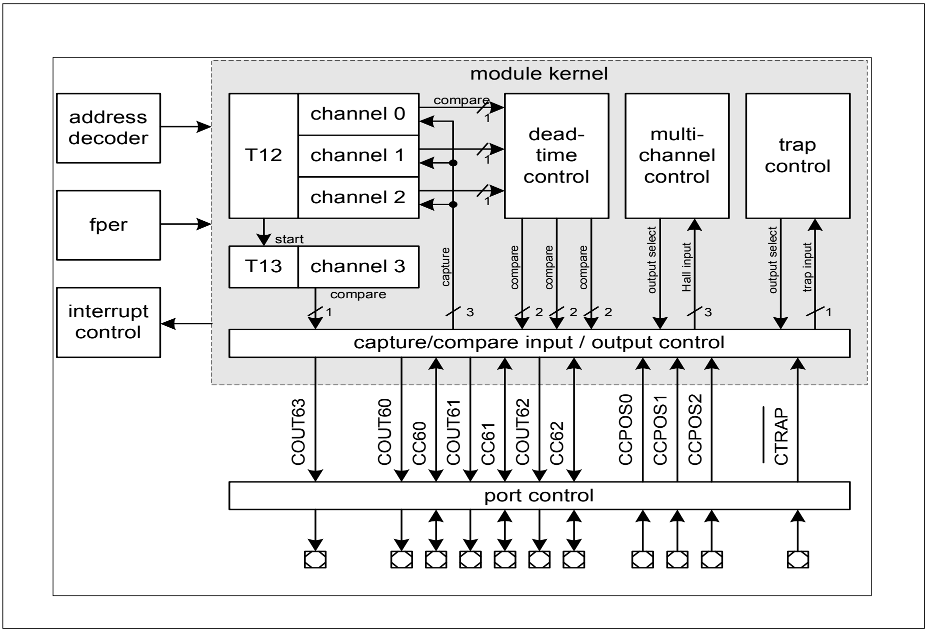



**Figure 29 CAPCOM6E unit**

The CAPCOM6E unit includes the enhanced multi-channel mode. It offers a possibility to modulate all six T12 related output signals within one instruction. The bits in bit field MCMP are used to select the CAPCOM6 outputs that may become active. The transfer of the new output values to the bit field MCMP can be triggered by T12, T13 or correct hall events. This structure allows writing new time pattern to the outputs at a defined moment and synchronized to a PWM period.

# 3 Implementation

## 3.1 Functional description

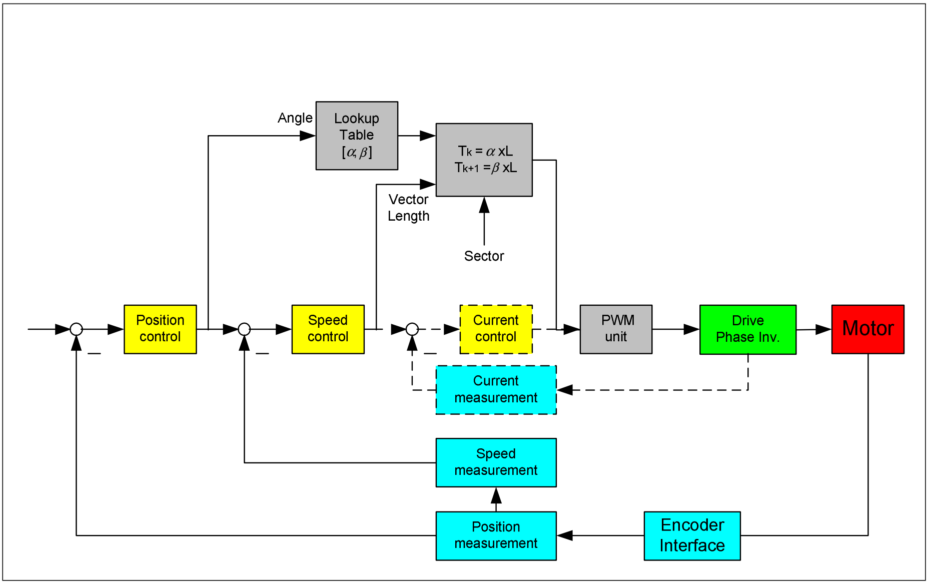



**Figure 30 Cascaded control for a multiphase motor drive application with space vector modulation**

### 3.1.1 General description

The application is divided into several sub functions. First, all relevant peripherals are configured. Next, the ramp up phase is started to turn the motor until the top zero point of the encoder is reached. Then the encoder offset is added to reach the next 60 degree section. Now the motor starts turning in a regular way. Interrupt driven the capture registers of the CAPCOM6 are updated. The PI controller for speed or torque control may be activated based on a sum of Timer T12 events. Figure 30 presents a block diagram for cascaded control for a multiphase motor drive application with space vector modulation.

### 3.1.2 Management of Space Vector Modulation

The space vector modulation of the PMSM motor is based on the following events:

- Acquire actual rotor angle position
- Take coefficients from look up table
- Calculation of vector components
- Allocate coefficients to corresponding compare registers

## 3.2 Implementation of the Software

The software is divided into several routines.

- Initialization of Ports, CAPCOM6, GPT1, Interrupt Controller
- Initialization of PI controller (closed loop speed control)
- Interrupt for external event (top zero detection)
- Interrupt routine GPT1:
  - Change of count direction
  - Timer over/underflow
- Interrupt routine CAPCOM 6 (Timer T12 period match,):
  - Management of space vector modulation
  - Six step State machine
- Process PI Controller

### 3.2.1 Initialization

A number of small routines perform all the necessary initializations before the motor has started turning:

**CPU initialization:** Initialization of CPU specific registers

**Peripherals initialization:**

Port initialization: P1L.0 – P1L5 (CCx,COUTx) output, Control Port for Bridge Driver

GPT1 (Timer) initialization:

Timer T3 in timer incremental mode, counts on any transition, interrupt on timer over- / underflow and on change direction

Interrupt controller initialization:

CAPCOM6 initialization: Disable multi-channel mode, passive output level is low, set timer T12 (PWM 20 kHz), set compare register CCx to start value, centre aligned mode, active dead time generation, enable ext. trap function for emergency cases, interrupt on T12 period match

**PI – Controller initialization:**

Proportional gain, sampling period time and the integral time constant

Figure 31 gives an overview about the program flow of the main routine.

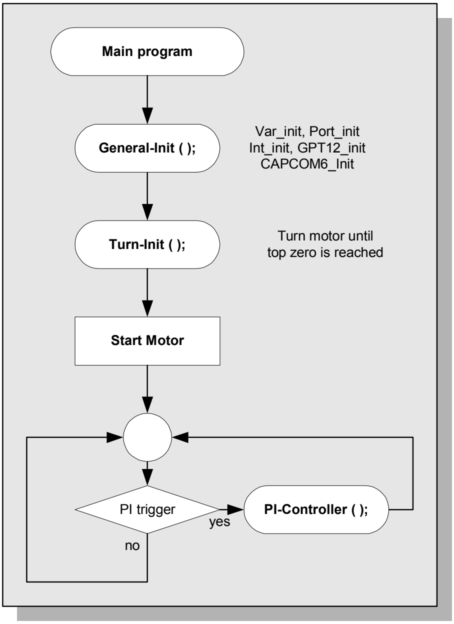
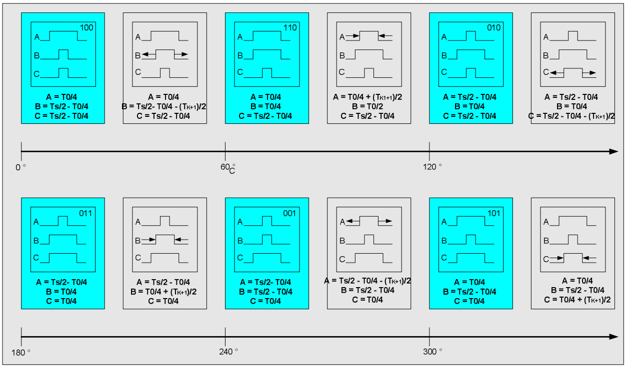


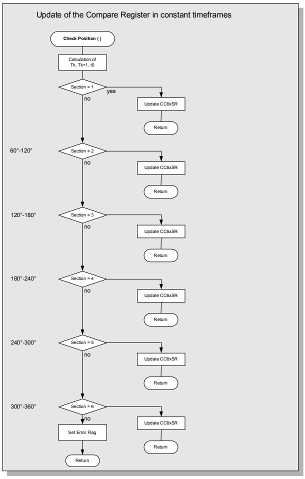

**Figure 31 Flow chart main routine**

## 3.2.2 Finite State Machine

The space vector modulation is based on the fact that the space vector turns through the 6 sectors, each 60 degrees wide, and represents the weighted average voltage combination of the 2 adjacent active space vectors. The length of the vector is controlled with the zero vector[000] and [111]. The state machine verifies the rotor position and updates the corresponding vector. Figure 32 gives an overview about the PWM pattern. Figure 33 illustrates the state machine.




## Figure 32 Overview about PWM generation for 360 °




## Figure 33 Finite State Machine

### 3.2.3 Interrupt routine

Each 50 µs a new Timer12 period match interrupt is generated. Based on the actual rotor position, Tk, Tk+1 are calculated. The function **check_position** calls the state machine and updates the Capture/Compare Registers of the CAPCOM6. If a one match of the Timer 12 is detected a shadow transfer writes the new pattern in the Capture/Compare Registers. After the shadow transfer, a time trigger is incremented. Ten times later, the PI controller compares the reference speed with the present speed and calculates the new vector magnitude.

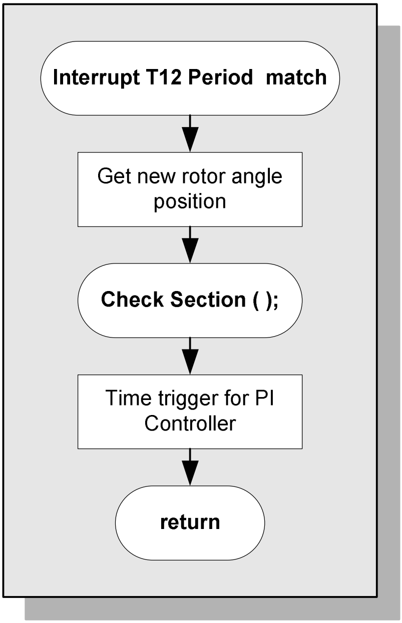



**Figure 34 Interrupt routine Timer T12 period match**

## 3.3 Performance Analysis

As shown in figure 35 the calculation of space vector modulation needs around 3.6 µs (CPU clock @ 40 MHz) to update the capture compare registers of the CAPCOM6 unit. Channel 1 to 3 represents the CC6x outputs. Channel 4 is used to measure the CPU load (7.2 %) in function **check_position.**

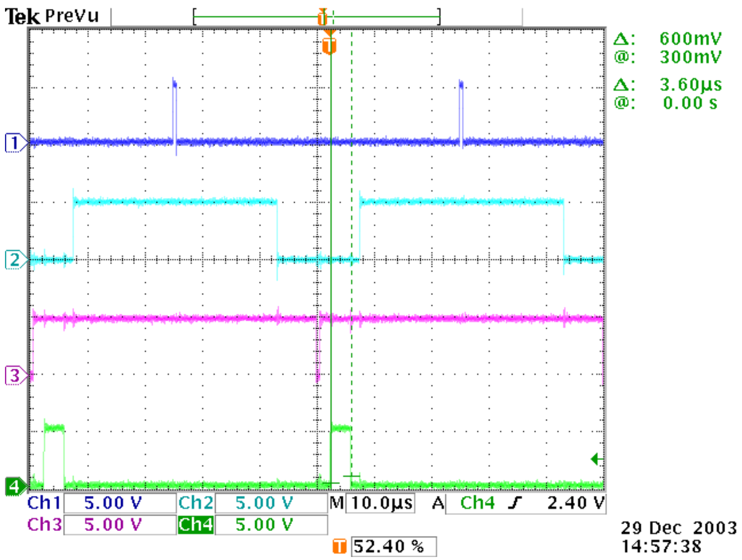



**Figure 35 CPU load for calculation of the space vectors**

# 4 Conclusion

There is an increasing demand in the automotive industry for applications using BLDC motors. In the past, many applications were addressed with DC motors. Automotive suppliers would like to use BLDC motors in order to achieve greater robustness and efficiency. Currently, the only limitation is the price gap between BLDC motors and DC motors. On the other hand, automotive suppliers are intensely price-driven and need smart solutions to meet the requirements of the market.

This application note aims to provide an understanding of the functionality of a BLDC motor, explains how such a motor is driven, describes all the necessary components and the necessity of knowing the positioning of a synchronous motor. Furthermore, the space vector modulation has been discussed and a method has been demonstrated to implement this type of modulation in a smart way in the XC164. Thanks to the high performance of the microcontroller and its powerful peripherals, this software approach consumes only limited CPU resources and allows the implementation of further algorithms like field oriented control.

The system approach discussed might be considered as a starting point for designing a complete system-specific closed-loop BLDC application

# 5 Glossary

| | |
|---|---|
| ADC: | Analogue Digital Converter |
| ABS: | Automatic Brake System |
| BACK-EMF : | Back electromagnetic force |
| B6 : | Bridge with 6 switches (e.g. MOSFET) for 3 phases |
| BLDC: | Brushless DC |
| CAN: | Controller Area Network |
| CAPCOM: | Capture Compare Unit, peripheral that measure events or provide PWM signal |
| CPU: | Central Processor Unit |
| EHPS: | Electro Hydraulic Power Steering |
| FOC: | Field Oriented Control |
| PI: | Proportional Integral |
| PWM: | Pulse width modulation |
| PMSM: | Permanent Magnetic Synchronous Motor |
| ROM: | Read only memory |
| RAM: | Read Access Memory |

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