

AP16084

16 Bit CMOS Microcontroller Product

Field Oriented Control of a PMSM
using a Single DC Link Shunt

Microcontrollers



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1 Introduction

A Brushless Permanent Magnet Synchronous Motor (PMSM) has a wound stator and a permanent magnet rotor assembly. This configuration offers some advantages :

- High efficiency
- Reduction of the motor size (high torque per volume)
- Low moment of inertia (rotor inertia)
- In comparison with DC motors, the elimination of brushes reduces noise, electromagnetic emission generation and the maintenance of brushes.

A brushless motor is not self-commutating, therefore is more complicated to control this motor. The currents and voltages applied to the motor windings must be controlled independently and correctly as a function of rotor position in order to produce useful torque.

There are two different ways to control this motor:

- Brushless DC mode with a rectangular (trapezoidal) current impressed into the PMSM with constant amplitude during 60° .
- Field oriented control with sinusoidal currents, which provides an optimum of torque production (no torque ripple).

This Application Note describes a field-oriented control that is implemented on an Infineon XC167CI Microcontroller based system . It begins with an introduction of the most important technical bases, then are described the used hardware in this project and the implementation of the software components (especially the implementation of the space vector modulation, the transformations into the different co-ordinate systems and the current measurements in the DC-link).

2 Technical Bases

2.1 Mathematical Models for a PMSM

2.1.1 Per Unit Quantities

Per unit quantities are actual physical quantities (e.g. voltage, current, speed etc.) which are related to a reference quantity. Therefore, they have the dimension 1 and give the relative value of the physical quantity compared to the reference quantity. [1]

Example:

The nominal current of the PMSM is 10A. In order to get per unit current quantities we choose the peak current at rated operation as the reference quantity: $I_{ref} = \sqrt{2} * I_{nominalRMS} = 14.1A$. We get the p. u. quantity by $i(t) = I(t) / I_{ref}$. If, for example, the actual current were $I(t) = 7.07A$, we could write $i(t) = 0.5$ as p.u. quantity.

Physical quantity	Symbol	Reference quantity	p. u. symbol
Angular-position	?	$\theta_{ref} = 1rad$?
Angular speed	O	$O_{ref} = O_{nominal} (svnch)$?
Time	t	$t_{ref} = O_{ref}$	t
Voltage	V	$V_{ref} = \sqrt{2} * V_{nominalRMS}$	v
Current	I	$I_{ref} = \sqrt{2} * I_{nominalRMS}$	i
Flux linkage	?	$\lambda_{ref} = V_{ref} * t_{ref}$?
Resistance	R	$R_{ref} = V_{ref} / I_{ref}$	r
Inductance	L	$L_{ref} = 1 / O_{ref} * U_{ref} / I_{ref}$	l

Table 1 Set of reference quantities of the most important physical quantities used

Note: All physical quantities used in this document are per unit quantities (unless otherwise noted).

2.1.2 Basic Electrical Equations

Voltage equation of a coil:

$$v(\mathbf{t}) = r \cdot i(\mathbf{t}) + \frac{d\Psi}{dt} \quad (1)$$

This equation in a three-phases winding system, using the powerful space vector definition:

$$\underline{v}_S = r_S \cdot \underline{i}_S + \frac{d\Psi_S}{dt} \quad (2)$$

The stator flux linkage for a general AC machine with a permanent magnet system is given by the equation:

$$\underline{\Psi}_S = l_S \cdot \underline{i}_S + \underline{\Psi}_M \quad (3)$$

In which Ψ_M is meaning the flux linkage space vector evoked by the permanent magnet system. [2]

Note: Underscored variables are space vectors.

Torque production in a PMSM

Starting from the fact that the force F produced at a certain point in winding system is given by the vectorial product of the local vector quantities (no p. u. quantities)

$$\Delta \vec{F} = I \cdot \Delta \vec{s} \times \vec{B} \quad (4)$$

(With current in the winding I , the regarded length of winding piece Δs and the local flux density B). We can integrate the force around the air gap and substituting the local quantities by the proportional representing space vector quantities. Then we obtain

$$t = \left| \underline{i}_S \right| \cdot \left| \underline{\Psi}_S \right| \cdot \sin(\angle \underline{i}_S, \underline{\Psi}_S) \quad (5)$$

That means the torque t produced at a certain moment is proportional to the area defined by the space vectors of stator current and stator flux linkage. (Figure 1) [2]

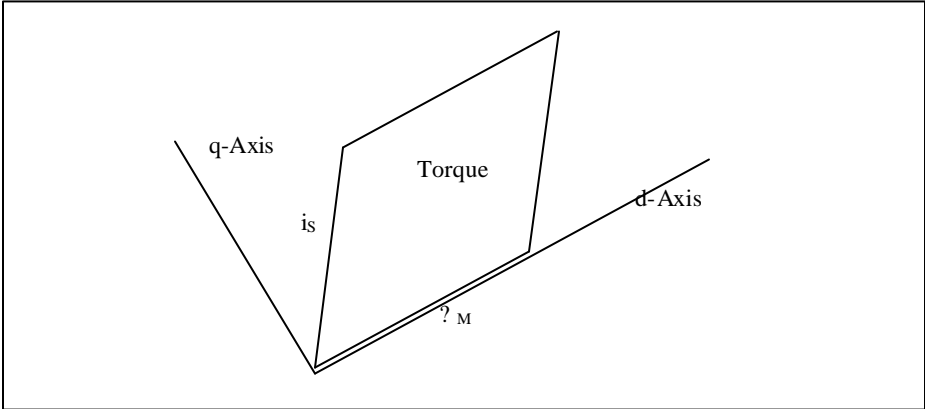


Figure 1 Torque Production in an AC Motor Visualized by Space Vectors

Note: *If the space vectors of stator current and stator flux linkage are parallel, the machine produces no torque. If the space vectors are orthogonal, the torque has a maximum.*

2.2 Construction of a PMSM

The Permanent Magnet Synchronous Motor is an important drive in servo, positioning and robotic applications. However, it gets increasing importance in the field of low cost drives as pumps, fans etc.

Compared to DC and induction motors, the PMSM has many advantages, especially high efficiency, high torque per volume and low moment of inertia.

The stator is laminated and has frequently slots like a classical AC stator. However, the stator may be skewed for reducing torque due slotting. Small PMSMs can be fitted with an air-gap winding system, hence no slots are used and the full winding space is filled with copper. This yields an extreme low stator inductance and hence high current per time. This is advantageous with respect to fast change of internal torque but needs high switching frequency for avoid current ripple.

Different rotor constructions are possible. The most usual is to glue the magnets onto the rotor surface. However, for flux concentration, buried magnets can be used.

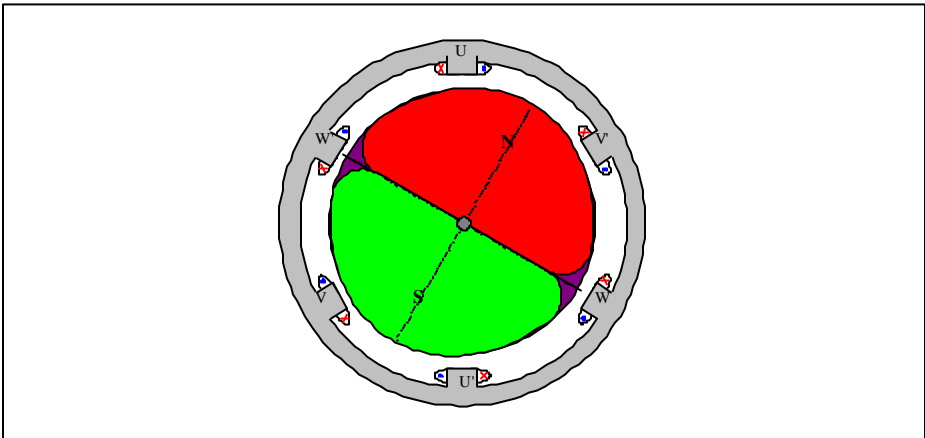


Figure 2 Principle Drawing of a PMSM

2.3 Field Oriented Control

The permanent magnets evoke a magnetic field in rotor, which links the stator winding system well. The main task of PMSM control is to impress the stator current space vector in an appropriate direction relative to the flux space vector. According to Figure 1 and equation 5, it is clear that the optimum torque production is achieved if the stator current space vector is placed $\pm 90^\circ$ relative to the permanent magnet flux space vector.

The control scheme like this in Figure 3 provides this functionality.

The currents i_U and i_V are measured with two current sensors. The Clarke transformation is applied to them to determine the stator current projection in the two co-ordinate α, β non-rotating frame. The Park transformation is then applied in order to obtain this projection in the d, q -rotating frame.

The speed controller calculates a reference torque, which is proportional to the quadrature-axis stator current component i_{Sqref} . The direct-axis stator current component i_{Sdref} is set to zero if there is no field weakening is used (refer to formula (5)).

The d, q projections of the stator phase currents are then compared to their reference values i_{Sqref} and i_{Sdref} and corrected by mean of PI current controllers. The outputs of the current controllers are passed through the inverse Park transform and a new stator voltage vector is impressed to the motor using the Space Vector Modulation technique.

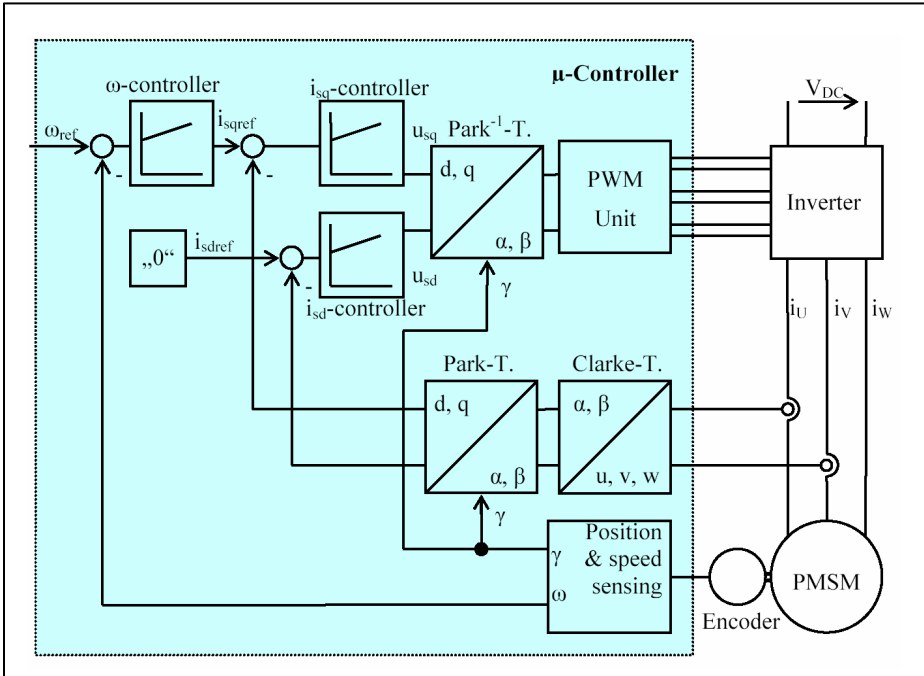


Figure 3 FOC of a PMSM

Note: For field-oriented control with sinusoidal currents, we need a quasi-continuous three phase's current information and a rotor position (speed) information.

The information about the phase currents can be obtained by two current sensors e.g. by phase shunts or current transducers, so-called LEM's.

The information about the rotor position can be obtained by position sensors (e.g. incremental encoder, absolute encoder, resolver etc.) or indirect (with mathematical methods).

2.4 Phases Current Acquisition via DC Link Shunt Measurement

It is possible to economize one current sensor when the current measurement is not performed in the phases but in the dc-link. To effect this phase current acquisition through the dc link current is necessary to know the actual switching pattern.

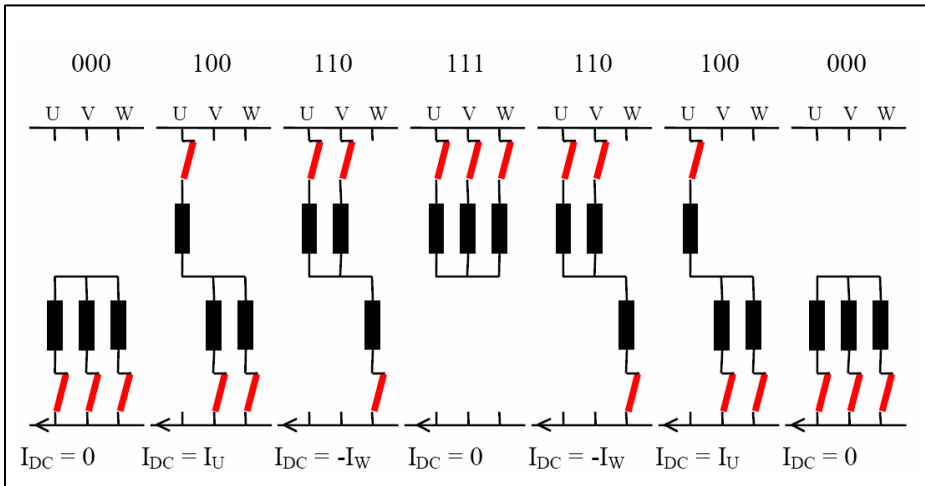


Figure 4 Power inverter Switching Pattern (the switches in are drawn in red and the active coils of motor in black)

Figure 4 shows the switching patterns during one PWM cycle (e.g. in sector 1). There are four active states (2x [100] and 2x [110]) and three inactive states (2x [000] and [111]) in inverter.

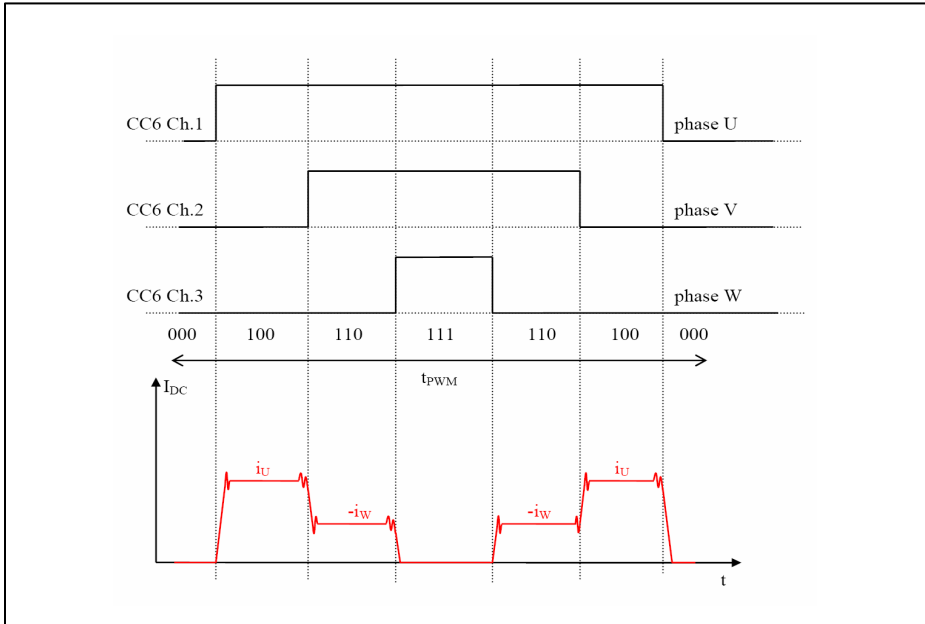


Figure 5 Current in DC link and the corresponding values in phases during one PWM period in the sector 1

According to the sector, the current in the shunt can be determined as follow (e.g. sector 1): in the first part, state [000] no current flows in the shunt because the 3 phases of the stator are in this case in short circuit. In the second part, state [001], the current i_U flows in the shunt and i_a can then be measured. For the same reasons the current in the phase W can be measured in the 3rd part, state [011], but the current measured corresponds to a negative current. In the 4th part, state [111] no current flows in the shunt because the stator is in this state in short circuit. The reverse sequence is then applied to the inverter bridges, then the current $-i_W$ can be measured in the 5th part, state [011], and the current i_U can be measured in the 6th part, state [001]. We finally apply the state [000] where no current can be measured. Finally, the shunt current can be described as follow: $[0, i_U, -i_W, -i_W, i_U, 0]$.

In this way during one PWM period two times, two different phase currents can be measured through a dc-link current measurement. The third phase current can be calculate by the equation $i_U + i_V + i_W = 0$.

In order to get a maximum time between the current conversions with the ADC, the measurement will be started on the edge of the phase with the middle "on time" (edge of phase V in sector 1 (Figure 5)

The main drawback of the presented method is that the length of the state where the current is measured must have a minimum value, which depends on the delay needed to get a stable current on the line (for filtering the noises), the sample time of the ADC, and the dead time between the gate signal of the high side Mosfet and the low side Mosfet. (Figure 6)

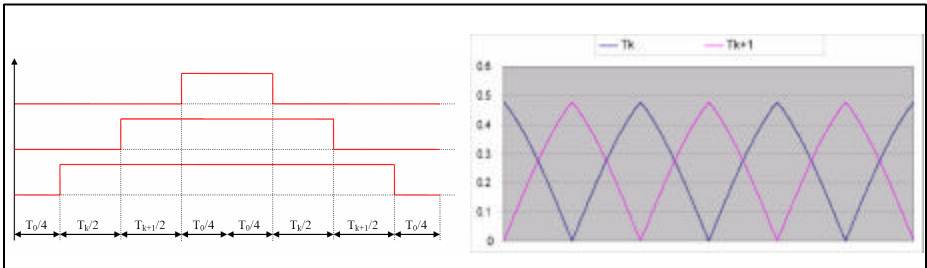


Figure 6 Relative State Length for Current Measurement as a Function of the Rotor Position [3]

States	1.	2.	3.	4.	5.	6.	7.
1. Sector	0	i_U	$-i_W$	0	$-i_W$	i_U	0
2. Sector	0	i_V	$-i_W$	0	$-i_W$	i_V	0
3. Sector	0	i_V	$-i_U$	0	$-i_U$	i_V	0
4. Sector	0	i_W	$-i_U$	0	$-i_U$	i_W	0
5. Sector	0	i_W	$-i_V$	0	$-i_V$	i_W	0
6. Sector	0	i_U	$-i_V$	0	$-i_V$	i_U	0

Table 2 Phase currents which can be measured (in theory) by the dc-link current in all 7 states and all 6 sectors during a full electrical revolution of the rotor

2.5 Sensorless Model¹

The basic idea of sensorless control (more exactly speed and position sensorless control) is to replace position information by measuring electrical quantities and modeling the PMSM to obtain the desired rotor angular position as an output quantity of a mathematical motor model.

¹ The sensorless model is not implemented in this project, in this way is necessary a rotor position detection. But this document will presented the mathematical bases for an implementation of this model.

The main effect which is used for evaluation is the EMF (induced voltage) when the rotor rotates at a certain speed.

The stator voltage equation

$$\underline{v}_s = r_s \cdot \underline{i}_s + \frac{d\Psi_s}{dt} \quad (6)$$

can be transformed in following equation:

$$\underline{\Psi}_s = \int (\underline{v}_s - r_s \cdot \underline{i}_s) dt \quad (7)$$

From a certain frequency, a PT1 operation has the same characteristic function for the transfer behaviour like an Integrative operation, but not the drifting problem of this. (Figure 1)

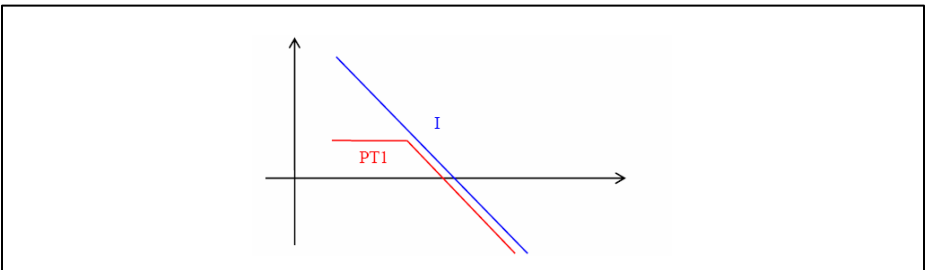


Figure 7 Characteristic Functions of PT1 and I Operation

$$\underline{\Psi}_s = PT1(\underline{v}_s - r_s \cdot \underline{i}_s) \quad (8)$$

The stator flux linkage equation

$$\underline{\Psi}_s = l_s \cdot \underline{i}_s + \underline{\Psi}_M \quad (9)$$

can be transformed in a equation for the permanent magnet flux space vector:

$$\underline{\Psi}_M = \underline{\Psi}_s - l_s \cdot \underline{i}_s \quad (10)$$

The (electrical) angular rotor position is given by the equation:

$$\underline{g}_{mech} = \arg(\underline{\Psi}_M) \quad (11)$$

The problem of this model is that at low speed (below 10-20% of nominal speed) no EMF occurs in the PMSM. This means that is possible that at low speed the back EMF model is not working.

3 Components

3.1 General remarks

This application was implemented using following main components :

- Infineon XC167CI SK Board
- Infineon 3 phase low voltage inverter
- Brushless motor fan
- Incremental encoder

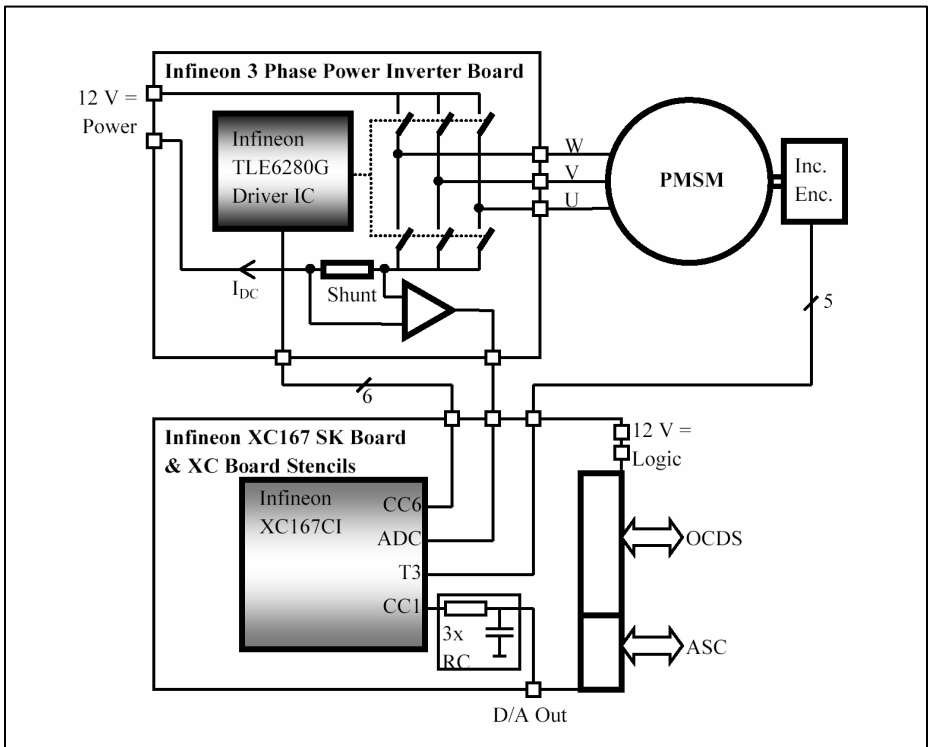


Figure 8 Main Hardware Components

3.2 PMSM

The motor which was used in this Application Note is a low voltage permanent magnet synchronous brushless motor with a heavy external rotor and with a radial fan as load.

Motor Characteristics

- Motor nominal voltage 24V
- Motor nominal current 14A
- Nominal speed 1800rpm
- Pole pairs 2
- Stator line to line resistance 0,21 Ω

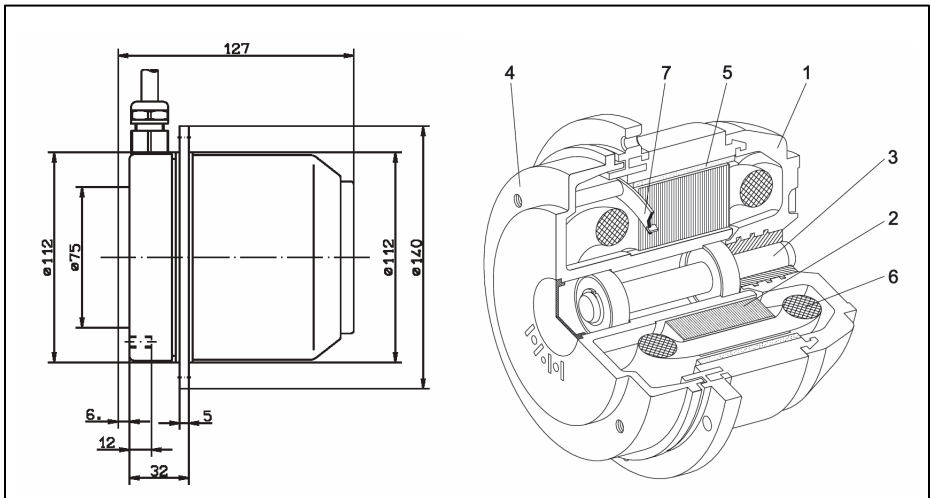


Figure 9 Dimensions and Design of the PMSM [6]

Functional Principle

The bell shaped external rotor motor (1) rotates around the fixed internal stator (2). The rotor is connected to a shaft (3), which rotates in bearing in a bearing tube. The motor is mounted on either end of the fixed shaft (4). The permanent magnets (5) in the rotor head generates a magnetic field, which react with the magnetic field generated in the current carrying stator winding (6) and thus creating torque. (Figure 9)

3.3 Inverter

In this project was used a low voltage 3-phase inverter with a maximal power of 1.2 kW or a maximal current of 50A² and at a voltage of 12 -24V DC. The 3-phase bridge driver on board is a Infineon TLE6280G and as power switches are used six Infineon OptiMos MOSFET.

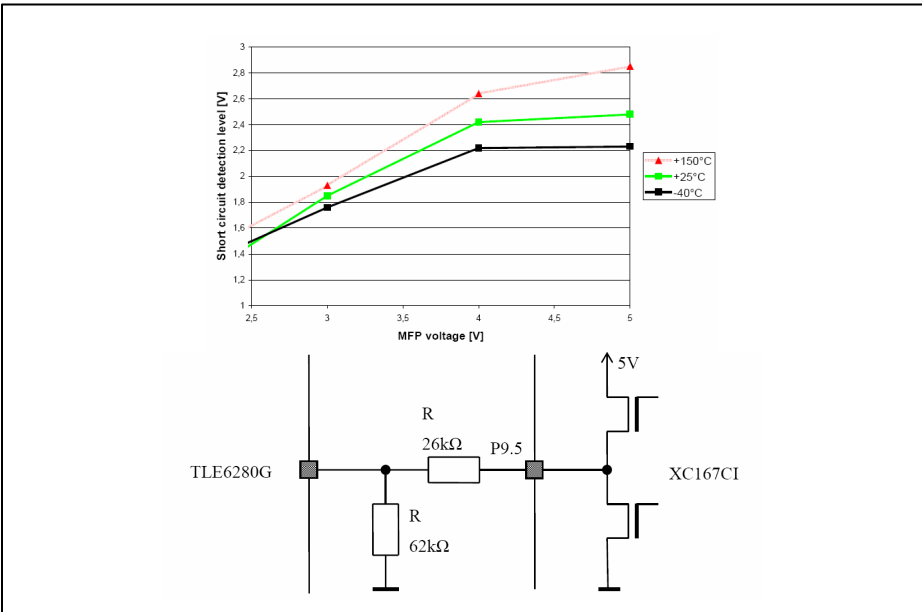


Figure 10 Short circuit detection level and the circuit for the MFP (Multi functional pin) of TLE6280GP (3.4V at active state)

The TLE6280GP driver IC provides a short circuit protection for the external Mosfets, by monitoring the Drain-Source voltage of the external Mosfets. The short circuit detection level is dependent upon the voltage of the MFP pin.

The MFP pin has multiple tasks: Reset the device (at 0 - 1.1V), adjust the short circuit detection level of the external Mosfet and define the gate voltage limitation for current limitation in case of short circuit (2.5 - 4V), deactivate the shoot-through protection (>4.5V). (Figure 10)

The dead time generated by the TLE6280GP can be varied from 100ns to 4μs by connecting an external resistor from the DT pin to GND. The dead time has to be long

² Possibly a heat-sink is necessary .

enough to avoid a short between battery and GND, while the dead time should be as short as possible to reduce extra power dissipation in the external Mosfets.

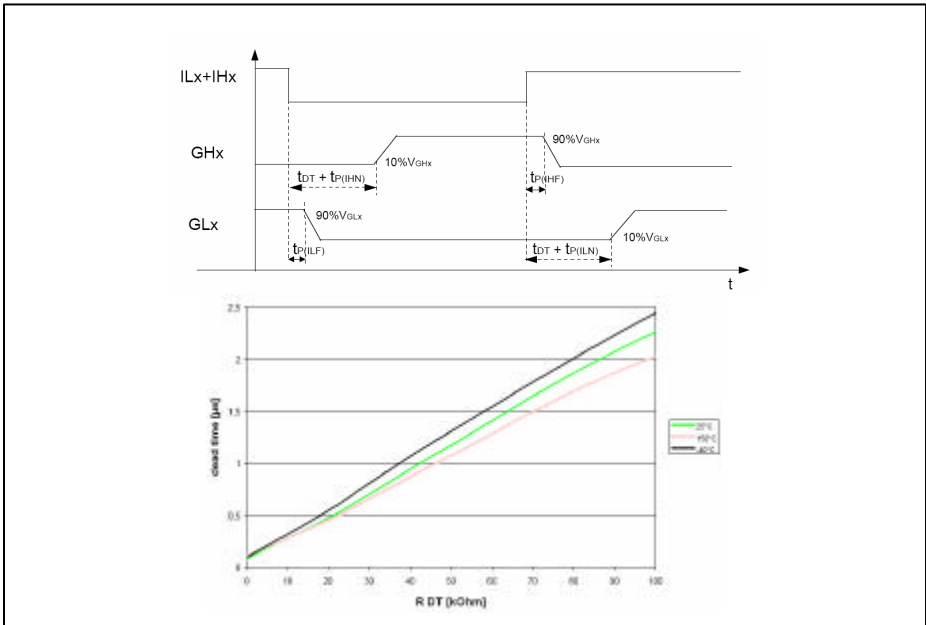


Figure 11 Internal dead time generation with resistor R22 between DT Pin and GND on Inverter Board

In this application a dead time of 600ns was chosen ($R_{22} = 27k\Omega$).

3.4 XC167CI-Board

The XC167CI is a members of Infineon's family of 16-bit microcontrollers based on the high-performance C166S V2 core in a sub- 0.25μ technology. The C166S V2 core more than doubles the performance of the well established C166 core while still providing code compatibility.

The XC16 board is an euro-sized (160 x 100mm) Board equipped with all necessary hardware such as non-volatile memory, SRAM memory, crystal oscillator (for clock generation), power supply and drivers for the interfaces.

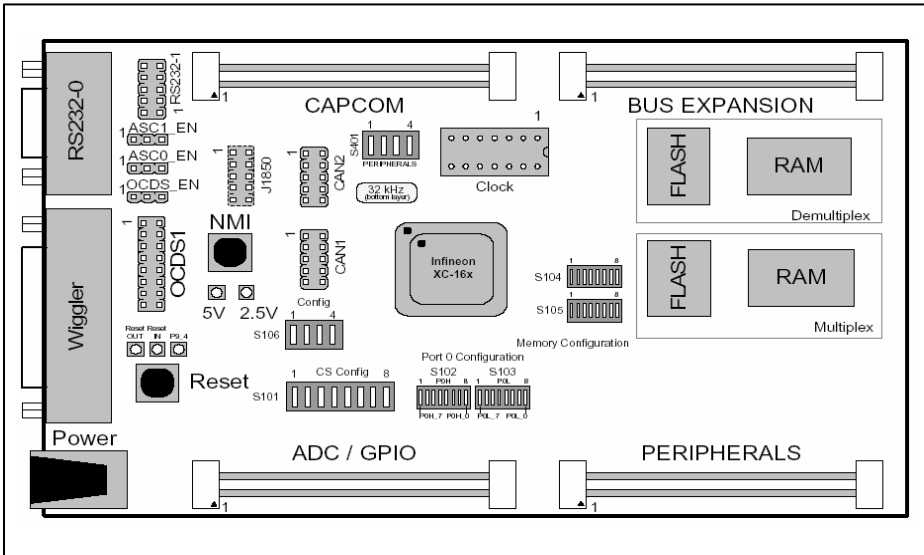


Figure 12 The Infineon Technologies XC167CI Starter Kit Board

Simple wires effected the connection between the XC167CI board and the power inverter board. For a better and easier connection was used the XC board stencils.

3.5 Sensors

3.5.1 Incremental Encoder

In this application example was used an incremental encoder to detect the angular position of the rotor. The code-wheel of this encoder has 500 windows thus became 500 counting cycles on channel A and on channel B. (see Figure 13)

Note: The channel A is connected to T3IN at P3.6, the channel B to T3EUD at P3.4 and channel I to the fast external interrupt input at P2.15.

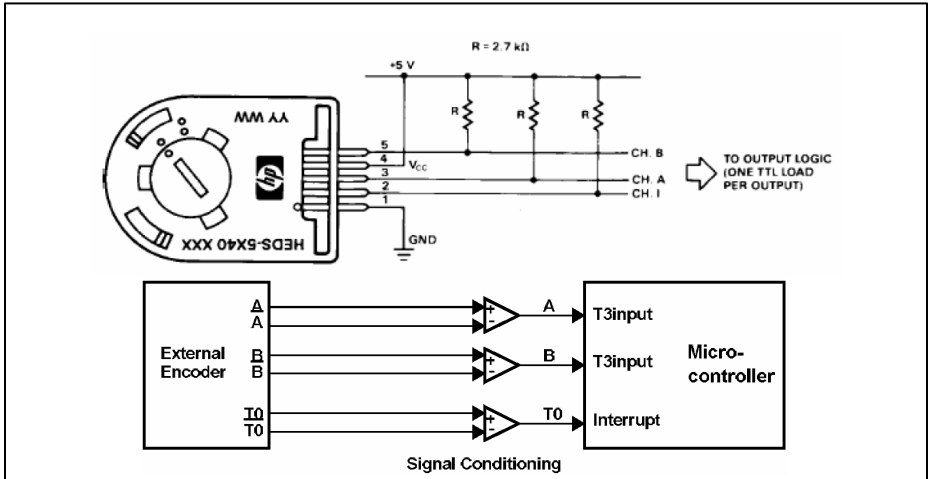


Figure 13 The Incremental Encoder - how to connect it to a microcontroller³

When any transition (rising and falling edge) of the encoder signals with a 90° phase shift are evaluated a maximum resolution of 2000 is possible. (see Figure 14)

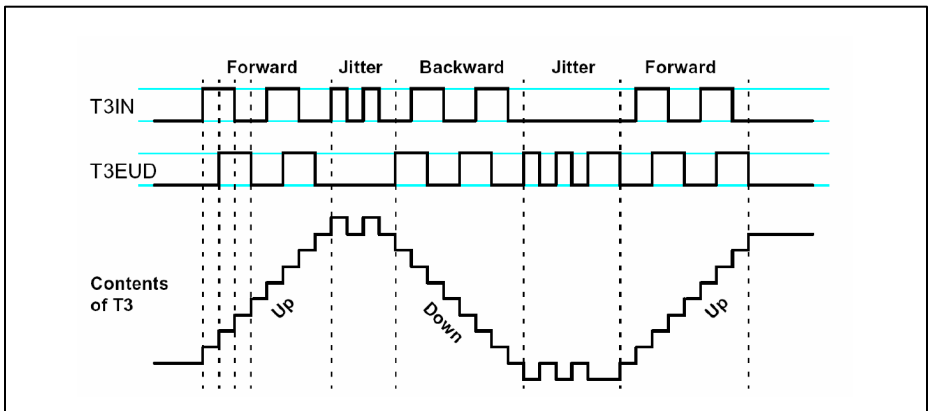


Figure 14 Evaluation of Incremental Encoder Signals with Timer 3 in Counter Incremental Mode

The third encoder output CH I indicates the mechanical zero position. This output is connected to an external interrupt and trigger a reset of timer T3 via PEC transfer. In this way, the absolute rotor position is known.

³ The signal conditioning is effected by the encoder

Note: After a reset the absolute position of the rotor is unknown. Therefore the top zero must be found. This position can be found with a manually turn of the rotor or automatically with a startup procedure (A rotating constant current is to impress in the stator windings)⁴.

3.5.2 Shunt-Current Sensor

A circuit like this in Figure 15 can effect an amplification and noise reduction of the current signal from the dc link shunt.

It is important that the operational amplifier have a high slew rate (e.g. 15V/ μ s) because the switching periods are in some cases very short.

The Shunt (R_{40} on inverter schematic) must have good power dissipation ($P=R \cdot I^2$) and high resistance to become a good signal from it. Two parallel 0.1O resistors with a power dissipation of 3W was used in this application example.

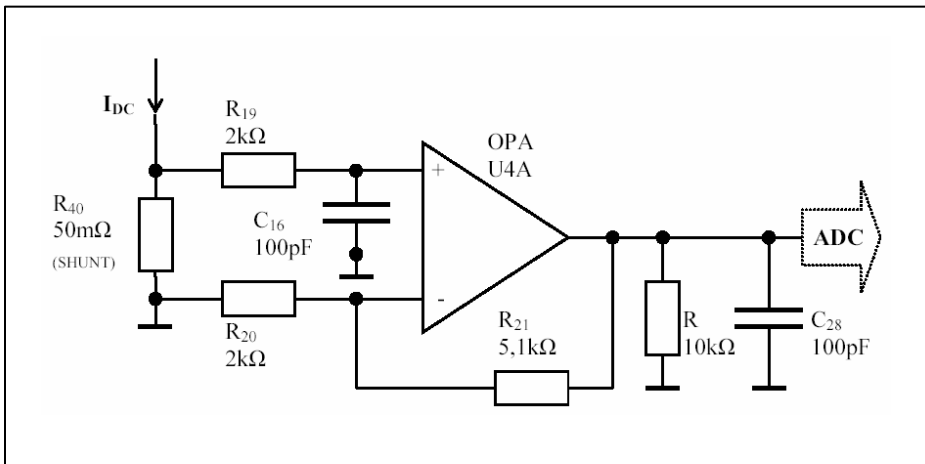


Figure 15 Schematic for DC-Link Shunt Current Measurement

⁴ Not implemented in this application.

4 Implementations

4.1 Software Flow Charts

The main control tasks are effected by the *Pmsm_Foc()* C-function. (Figure 16)

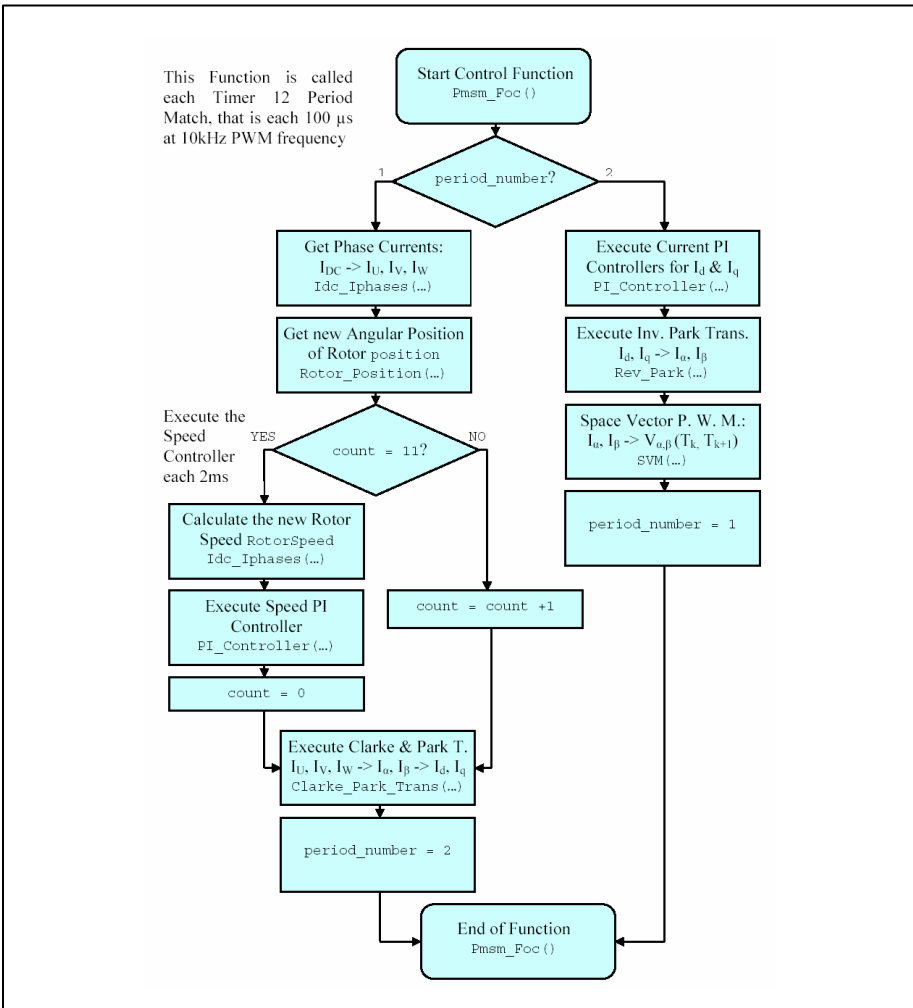


Figure 16 Flow Chart for the control Function *void Pmsm_foc()*

This function is called upon each period match of the 6 Timer 12 i.e. each 100µs at a PWM frequency of 10 kHz. (Figure 17)

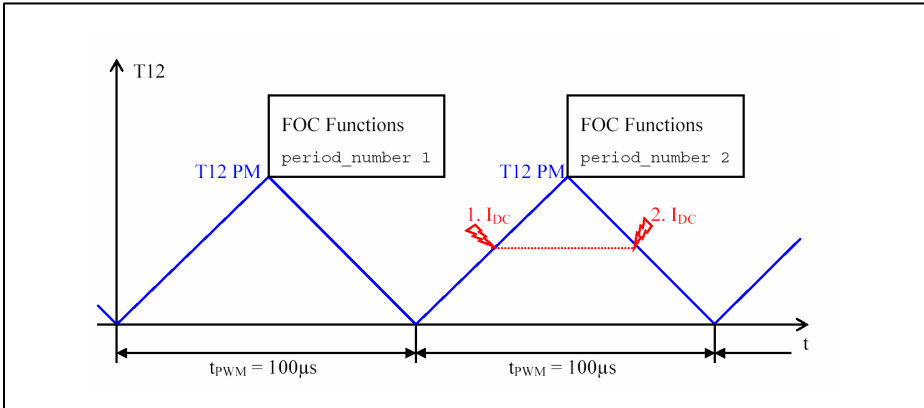


Figure 17 Call of Control Function upon T12 Period Match

The initialization of the different units has been done with the DAve tool. The specific code for the SVM, frame transformations, current measurement were written in C and the code for the PI controller as assembly function.

For the SVPWM was used the 6 Unit in center aligned mode in order to drive a three phase line to line sinusoidal voltage at the output of the power stage.

4.2 Fixed Point Number Representation

The p. u. quantities move the values of the physical quantities in a relatively narrow band. If are used the reference quantities of table 1 all quantities are limited between -1 and +1. It has been shown that the greatest precision is obtained in 1Q15 fixed-point format.⁵

1Q15 numbers can be represented by following formula:

$$X = -k_0 \cdot 2^0 + k_1 \cdot 2^{-1} + k_2 \cdot 2^{-2} + \dots + k_n \cdot 2^{-n} + \dots + k_{15} \cdot 2^{-15}, \text{ with } k_i = \{0;1\}.$$

For instance, the number 0.6543 can be represented in 1Q15 as follow:

$$0.101001111000000_2 = 53C0_{16} = 2^{-1} + 2^{-3} + 2^{-6} + 2^{-8} + 2^{-9} \text{ (approx. 0.6543)}.$$

⁵ Note that the dynamic range of this format is small.

Per Unit Model for Currents

The nominal current of motor is $I_{\text{nominalRMS}} = 14\text{A}$ so that the peak current is $I_{\text{nominalRMS}} \cdot \sqrt{2} = \text{ca. } 20\text{A}$. This peak current was chosen as reference value I_{ref} for the calculation of the p. u. quantity, which is calculated by $i(t) = I(t) / I_{\text{ref}}$.

The full per unit transformation for the phase currents are given by the equation:

$$i(t)_{pu} = \frac{I(t)}{14\text{A} \cdot \sqrt{2}} \quad (12)$$

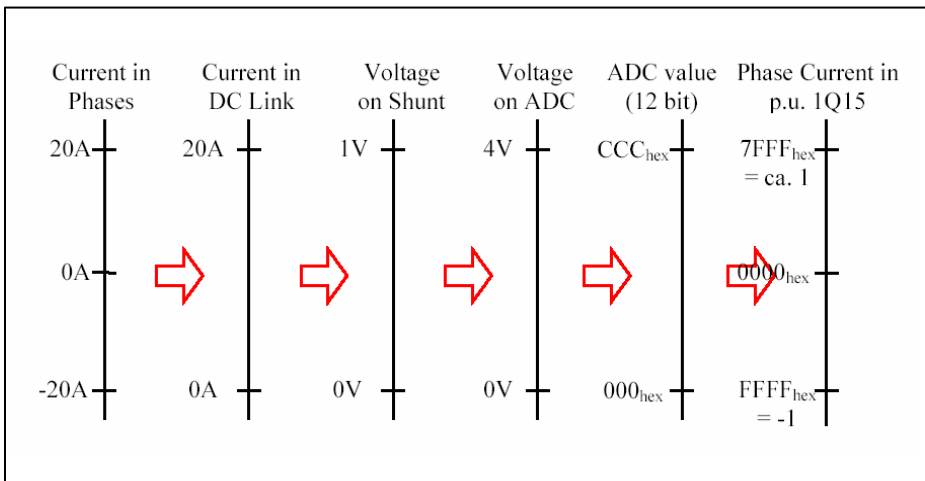


Figure 18 Scaling for Phase Currents

Per Unit Model for Speed

The per unit transformation for angular speed is given by the equation⁶:

$$w_{pu} = \frac{w}{w_{ref}} = \frac{w}{2p \cdot f_{\text{nom,el}}} = \frac{w}{2p \cdot \frac{3600\text{rpm}}{60\text{s}}} \quad (13)$$

The speed can be calculated with an angular position changing over time:

$$w = \frac{\Delta g}{\Delta t} \quad (14)$$

⁶ The electrical angular speed is meaning. In the case of a pole pair number p of 2 is the electrical angular speed $f_{\text{nom,el}} = f_{\text{nom}} \cdot p = 1800 \cdot 2 = 3600$ electrical rpm

At 1800 rpm (3600 electrical rpm = nominal speed of PMSM) the encoder gives 250 pulses in $t=4.2\text{ms}$. 252 equals to FC_{hex} as hex number. When FC_{hex} is shifted for 7 bit in left direction the outcome is $7E00_{\text{hex}}$.

In 1Q15 format $7D00_{\text{hex}}$ equals to $2^{-1}+2^{-2}+2^{-3}+2^{-4}+2^{-5}=0.97 = \text{circa } 1$. Hence no other per unit scaling is to do.

Angle Representation

The angular position of rotor is given by the counter value of timer 3, on which are connected the incremental encoder outputs. The encoder gives 2000 counting steps for one full mechanical rotation, which are 1000 steps for one electrical rotation. This angular information is then transformed in two orthogonal components in 1Q15 format, using a sinus-cosine look-up table. (Figure 19)

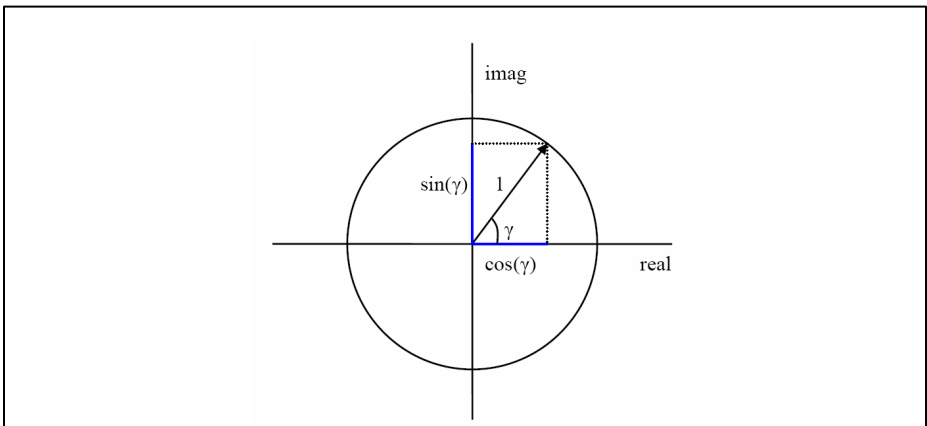


Figure 19 Rotor Angle Representation as complex components⁷

4.3 Frame Conversions

In Field Oriented Control, motor currents are manipulated in the d-q reference frame of the rotor. Therefore measured motor currents must be transformed from the three-phase static reference frame of the stator windings to the two axis rotating dq reference frame, in order to processing by the PI controllers.

Although the reference frame transformations can be performed in a single step, they are best described in two single steps.

⁷ The ADC of the XC167CI has a resolution of 10 bit, but in enhanced mode the converted value is saved in the ADC_DAT2 register as an 12 bit value.

The Clarke Transformation

The motor currents are first translated from the 120-degree physical frame of the motor stator windings to a fixed orthogonal reference frame.

$$\begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} = \begin{bmatrix} i_U \\ \frac{1}{\sqrt{3}}(i_V - i_W) \end{bmatrix} \text{ with } i_U + i_V + i_W = 0 \quad (15)$$

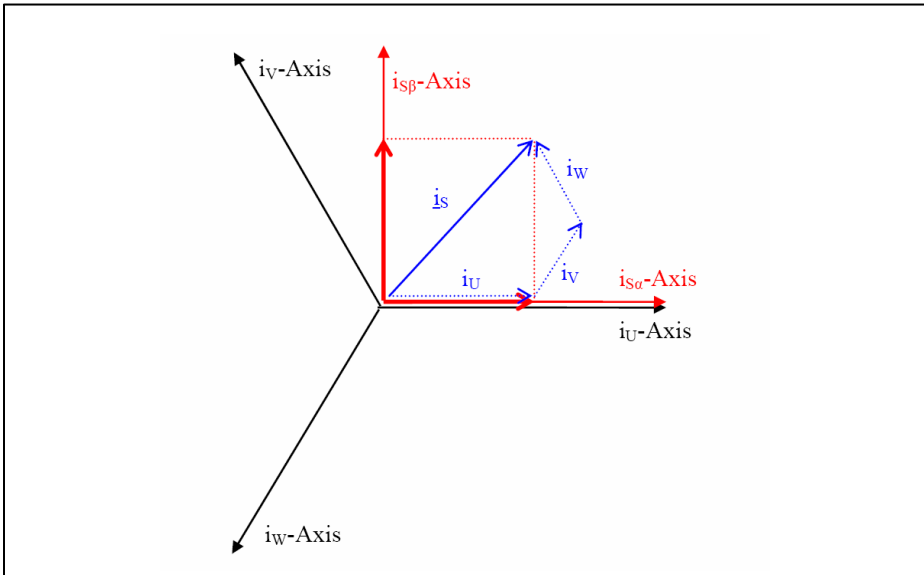


Figure 20 Transformation from the 3 phases reference frame of the stator to the orthogonal a,β-frame

The Park Transformation

They are then translated from the fixed frame of the stator to the rotating frame of the rotor.

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos g & \sin g \\ -\sin g & \cos g \end{bmatrix} \cdot \begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} \quad (16)$$

The full operation in one-step:

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos g & \sin g \\ -\sin g & \cos g \end{bmatrix} \cdot \begin{bmatrix} i_U \\ \frac{1}{\sqrt{3}}(i_V - i_W) \end{bmatrix} \quad (17)$$

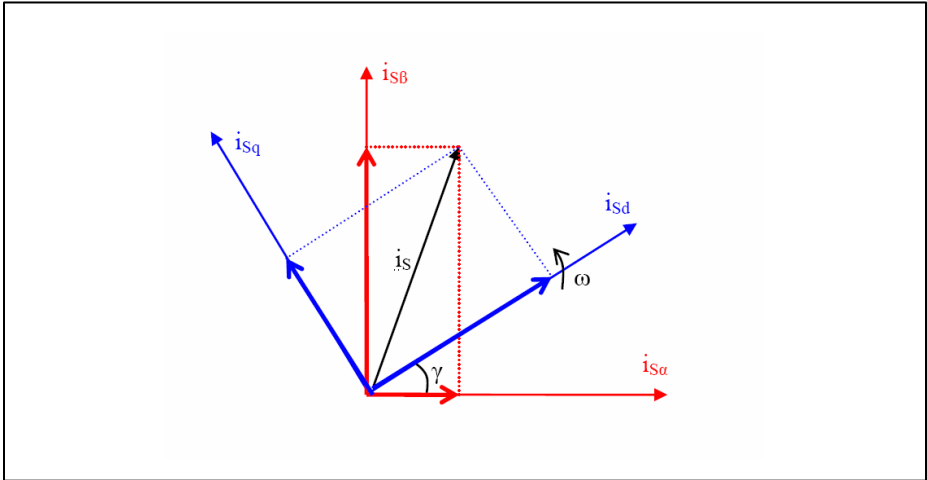


Figure 21 Transformation from the static a,β-frame to the rotating d,q-frame.

The Inverse Park Transformation

This process is reversed to transform voltage signals from the P-I controllers from the d-q frame of reference to the static stator frame:

$$\begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} = \begin{bmatrix} \cos g & -\sin g \\ \sin g & \cos g \end{bmatrix} \cdot \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (18)$$

These signals are then converted from an orthogonal frame to the 120 degree physical frame of the U,V and W motor windings.

4.4 Space Vector Modulation

The continuous space vector modulation is based on the fact that the space vector turns through the 6 sectors, and represents the weighted average voltage combination

of the 2 adjacent active space vectors and the null vectors during one PWM period. (Figure 22)

$$\underline{V_{ab}} = V_a + jV_b \quad (19)$$

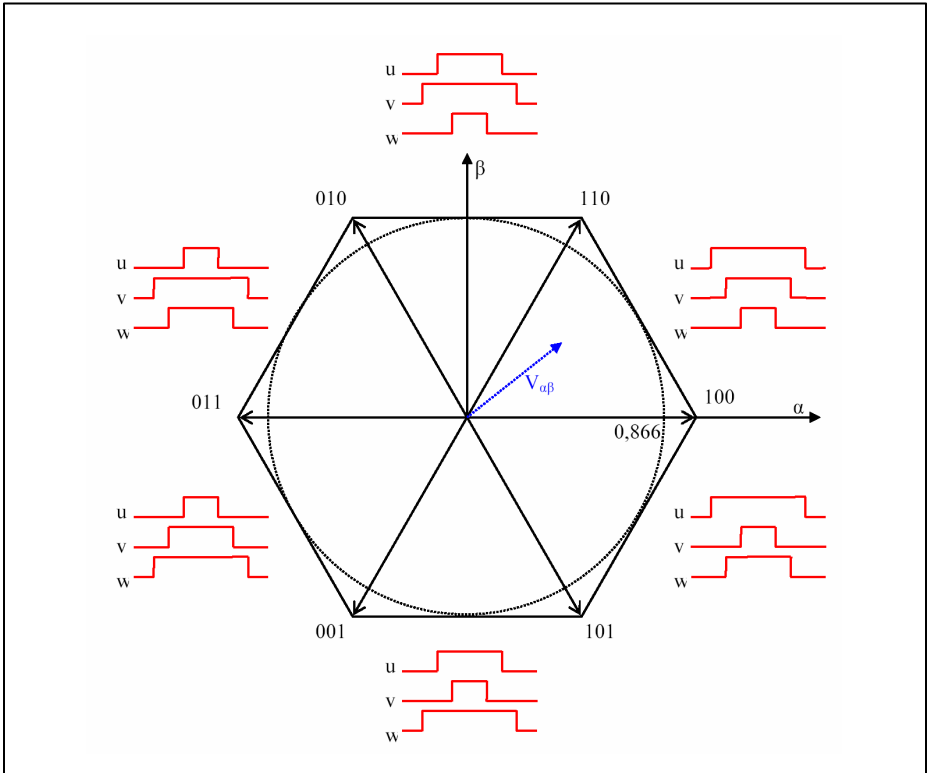


Figure 22 Space Vector in α,β -frame and PWM output pattern in all 6 sectors

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]. (Figure 4 and Figure 23)

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. T_k , and T_{k+1} represent the time of the respecting state.

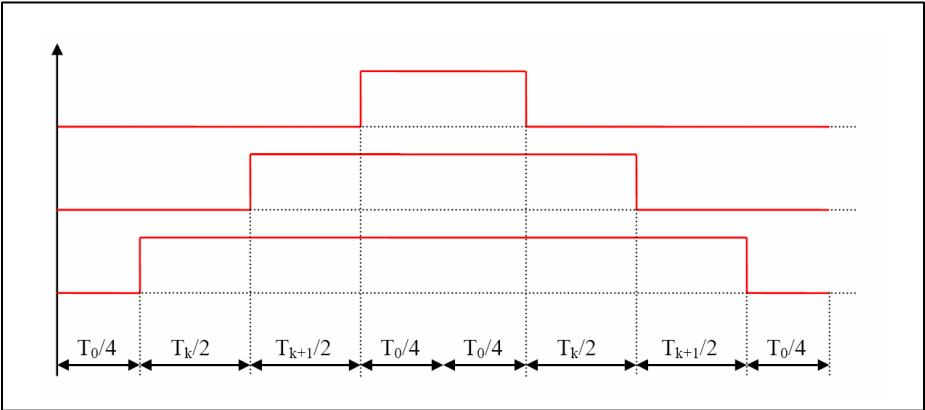


Figure 23 Timing for Space Vector Modulation

The output space vector voltage average can be computed by the integral

$$\underline{V}_{ab} = \frac{1}{T_{PWM}} \cdot \left[\int_0^{T_0} V_0 \cdot dt + 2 \cdot \int_0^{T_k} V_k \cdot dt + 2 \cdot \int_0^{T_{k+1}} V_{k+1} \cdot dt + \int_0^{T_0} V_7 \cdot dt \right] \quad (20)$$

with the equations

$$T_{PWM} = T_0 + T_k + T_{k+1} \quad (21)$$

and

$$V_0 = V_7 = 0 \quad (22)$$

the resulting equation for the voltage space vector is:

$$\underline{V}_{ab} = \frac{[V_k \cdot T_k + V_{k+1} \cdot T_{k+1}]}{T_{PWM}} \quad (23)$$

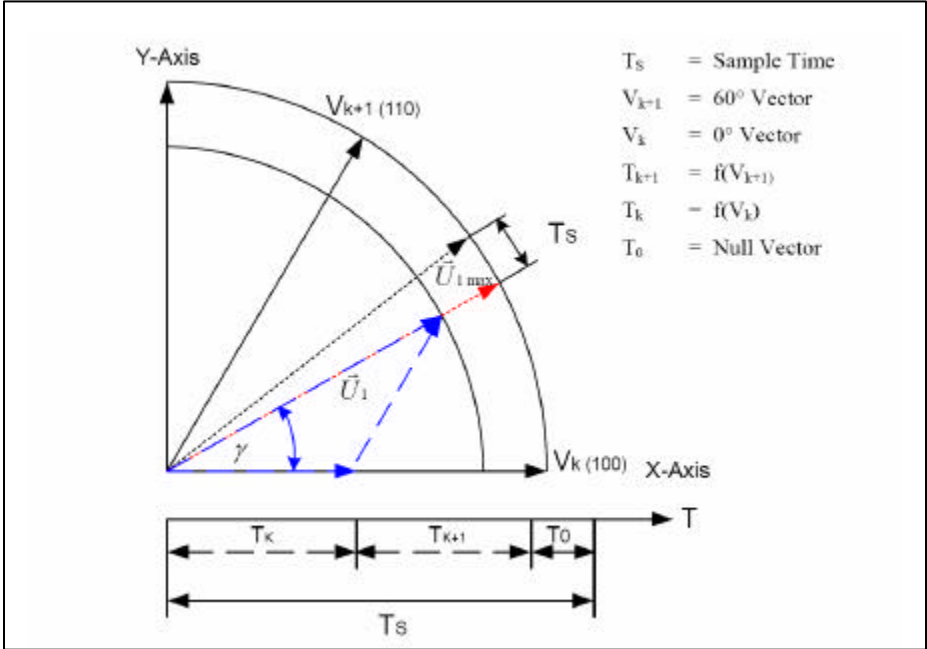


Figure 24 Vector Product for Space Vector Modulation in Sector 1

The timing values T_k and T_{k+1} for the space vector can be calculated by the equation:

$$\begin{bmatrix} T_k \\ T_{k+1} \end{bmatrix} = T_{PWM} \cdot \frac{\sqrt{3}}{2 \cdot U_{DC}} \cdot \begin{bmatrix} \sin(k \cdot \frac{p}{3}) & -\cos(k \cdot \frac{p}{3}) \\ -\sin((k-1) \cdot \frac{p}{3}) & \cos((k-1) \cdot \frac{p}{3}) \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \end{bmatrix} \quad (24)$$

Where k as to be determined from the argument of the reference space vector such that

$$\frac{(k-1) \cdot p}{3} \leq \arg(V_a, V_b) \leq \frac{k \cdot p}{3} \quad (25)$$

For an example Space Vector \underline{V}_s with an amplitude $|V_s|=0.5$ and an angle $\arg(V_s)=30^\circ$ at a PWM frequency 20kHz the switching times are shown in Figure 25.

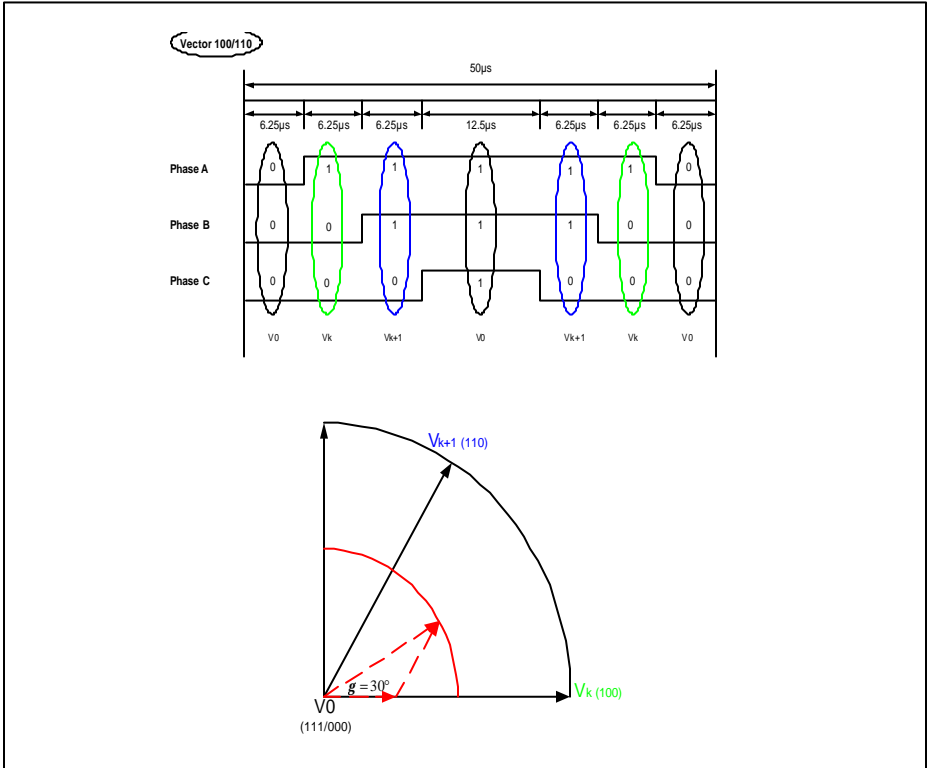


Figure 25 Example of a SVPWM

4.5 PI Controller⁸

The Field Oriented Control of a PMSM needs three PI Controller. One for each current in rotating frame (i_d and i_q) and one for the angular speed. (Figure 3)

The structure of a PI controller is shown in Figure 26.

⁸ in this application was implemented the digital PI Controller as an assembler routine

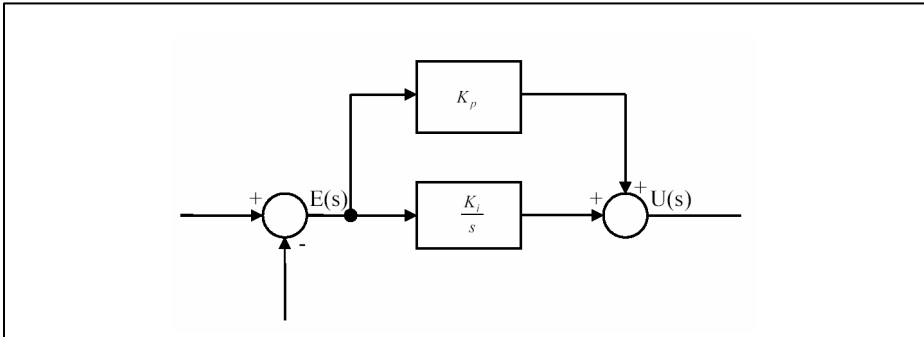


Figure 26 Structure of a PI Controller

The Laplace equation of a PI Controller is given by:

$$U(s) = \left[K_p + \frac{K_i}{s} \right] \cdot E(s) \quad (26)$$

For a discrete implementation as a digital PI Controller is valid following equation:

$$U(k+1) = K_p \cdot e(k) + K_i \cdot e(k) + \sum_{n=0}^{k-1} e(n) \quad (27)$$

4.6 Current Measurement in the DC Link

The cheapest way to measure the currents in a PMSM is to measure the DC-link current, because only one shunt is used. But this method has its drawbacks, as for example the current can not be measured in defined machine states .

In order to be able to sample the current in the shunt at a predetermined instant, and to link it to one of the three motor phase currents, a synchronization between the actual sector, the output signals of the 6, and the ADC sampling instant has to be done. According to the sector, the current measurement will be triggered by one of the three CC6x channels on the rising and falling edges. The Infineon XC167CI microcontroller provides a feature to perform this measurement without software interrupts: In order to filter the noise from the IGBT commutation, and the dead time, the timer 13 from the 6 will be used to introduce a delay between the CCx edge and the ADC start sample. This timer 13 will be started automatically upon a timer 12 compare event and will be start the ADC conversion when the timer reaches the period match. (Figure 27)

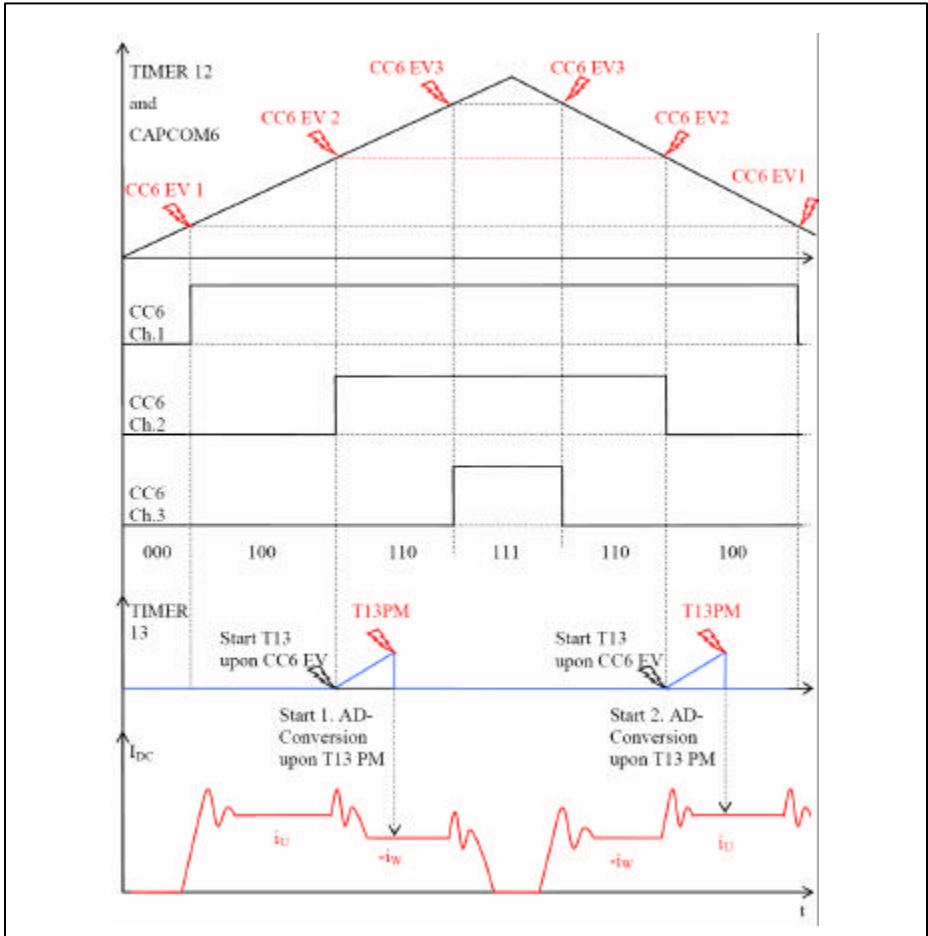


Figure 27 Synchronization of the ADC with the SVPWM by 6 Unit

Then the converted value from the ADC will be stored to the current variable by a PEC transfer. (Figure 28)

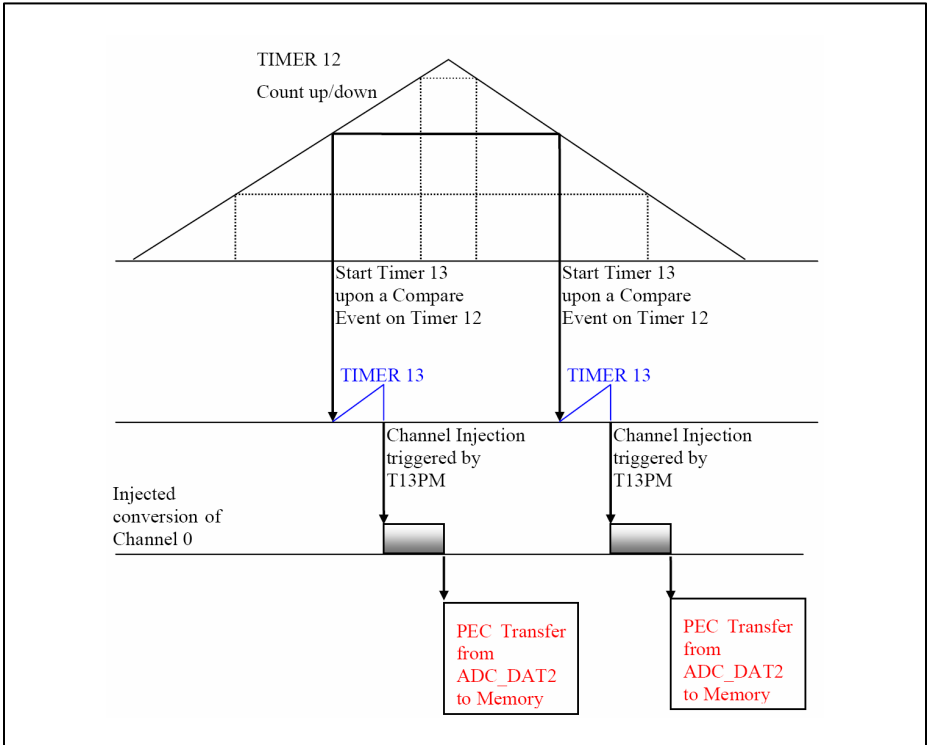


Figure 28 Triggering of ADC upon a 6 Event with the Channel Injection Mode and PEC-Transfer

The Peripheral Event Controller (PEC) provides 8 PEC service channels which move a single byte or word between any two locations. A PEC transfer can be triggered by an interrupt service request and is the fastest possible interrupt response. During a PEC transfer, the normal program execution of the CPU is halted and a special instruction is injected in the pipeline. No internal program status information needs to be saved. The PEC transfer is the fastest possible interrupt response. The PEC channels source and destination pointers specify the locations between which the data is to be moved. (Figure 29)

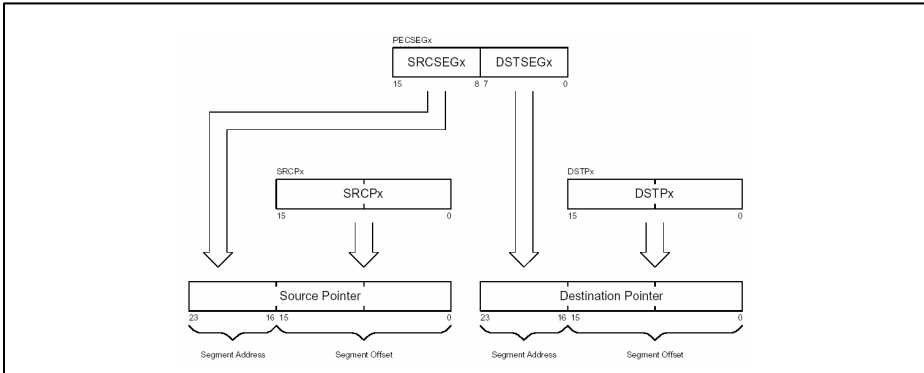


Figure 29 The PEC Pointer Address Handling

4.7 Analog Output (D/A Conversion)

A simple D/A converter were realized in this application. In thus way it is possible to check some quantity in microcontroller (e.g. the reconstituted phase currents, the angular position, the rotor speed etc.).

The D/A converter has been realized with PWM and a smoothing of the PWM output signal with a low-pass filter. (Figure 30)

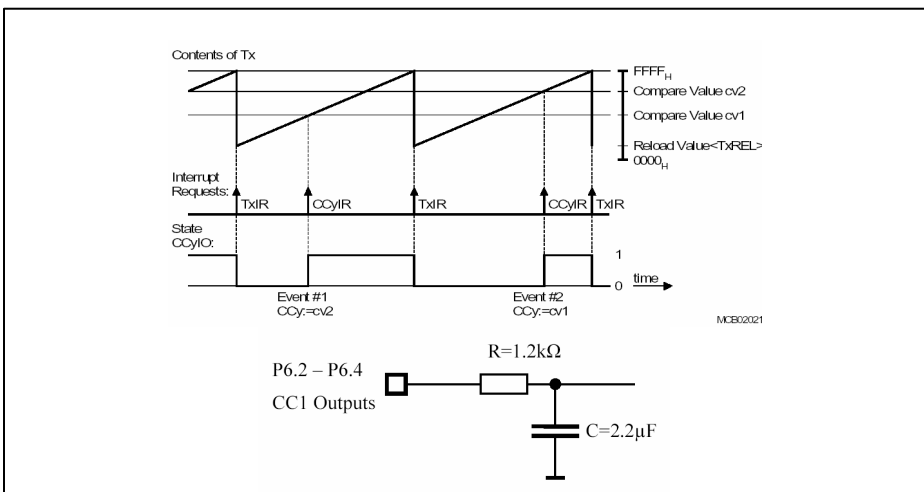


Figure 30 D/A Conversion with PWM and Low-Pass Filtering

5 Optimizations

5.1 Measurement Handling in sector edges („Black Zones“)

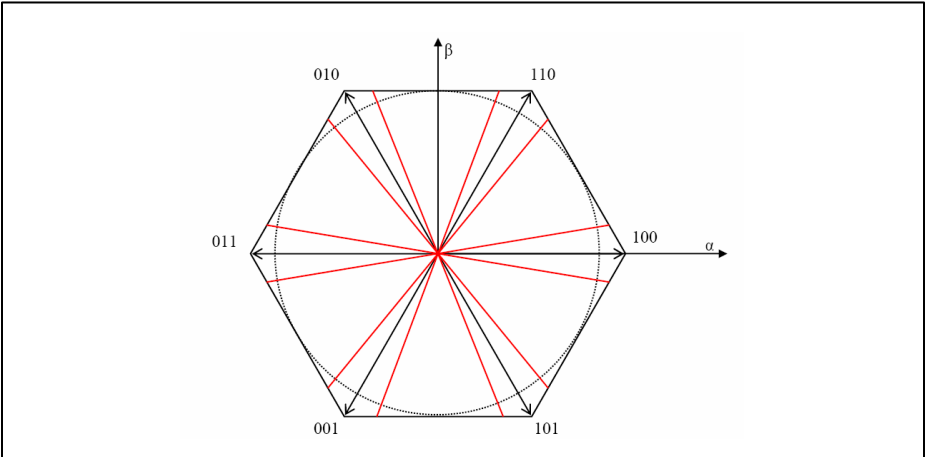


Figure 31 “Black Zones” during a full rotation where is not possible to measure 2 phase currents with a dc link measurement

Approximation Method

The idea of this method is to measure the currents in all sectors where is possible and to approximate mathematically the phase currents in the sectors where a measurement is not possible.

For the sectors where is not possible to measure the current (Figure 31) the last valid measurement result of i_s ($i_{sdvalid}$ and $i_{sqvalid}$) is to correct with the dynamic factor Δi_d and Δi_q :

$$i_{sd} = i_{sdvalid} + \Delta i_d \quad \text{and} \quad i_{sq} = i_{sqvalid} + \Delta i_q \quad (28)$$

The factors Δi_d and Δi_q can be calculated by starting with the full stator voltage equation:

$$\underline{v}_s = r_s \cdot \underline{i}_s + L_s \cdot \dot{\underline{i}}_s + j\hat{\omega}_m \cdot \underline{\Psi}_M \quad (29)$$

It is possible to write

$$\underline{i}_s \approx \frac{1}{l_s} \left[v_{sref} - i_s(0) \cdot r_s - j \hat{\omega}_m \cdot \left| \hat{\Psi}_M \right| \cdot e^{j\theta_m} \right] \quad (30)$$

with $i_s(0)=0$ and in the rotating d,q frame this equation can be simplified. Therefore it is possible to calculate a difference for the d-co-ordinate:

$$\Delta i_d = \frac{\Delta t}{l_s} \cdot [u_{sd}] \quad (31)$$

and a difference for the q-co-ordinate:

$$\Delta i_q = \frac{\Delta t}{l_s} \cdot [u_{sq} - \hat{\omega}_m \cdot l] \quad (32)$$

Lengthen the Switching Pattern Time

It is possible to extend the state where the current has to be measured when the length of the state is smaller than the minimum value required for the current measurement. This method brings noises on the motor current but allows measuring it everywhere.

$$t_k, t_{k+1} \geq t_{dead} + t_{noise} + t_{conversion} \quad (33)$$

5.2 Faster Operations with the MAC Unit

The MAC unit provides single-instruction-cycle, non-pipelined, 32-bit additions, 32-bit subtractions, right and left shifts, 16-bit by 16-bit multiplication and multiplication with cumulative subtraction/addition. For further information about the MAC unit, refer to the XC16x User's Manual Volume 1 "System Units" or on <http://www.infineon.com>.

6 Measurement Results

6.1 Phases and DC-Link Currents

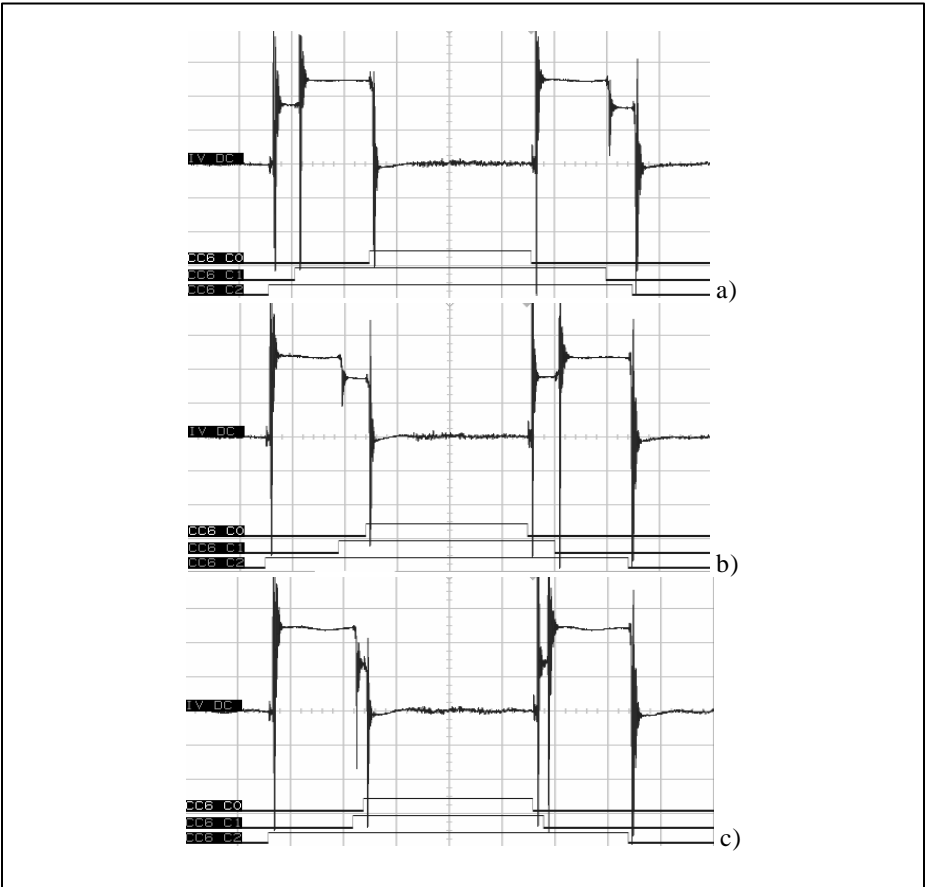


Figure 32 DC Link Current (on 50mO Shunt) and PWM states at 15° (a), 45°(b) and 55° (c). Duty cycle = 30%.

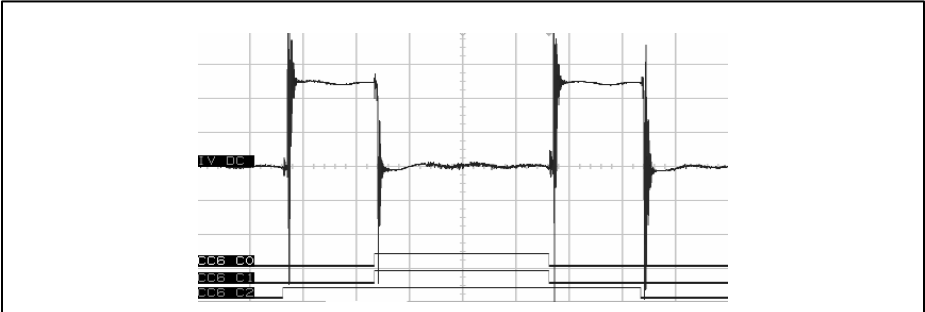


Figure 33 DC Link Current (on 50mΩ Shunt) at 60°. There is not possible to perform the measurement of 2 phase currents.

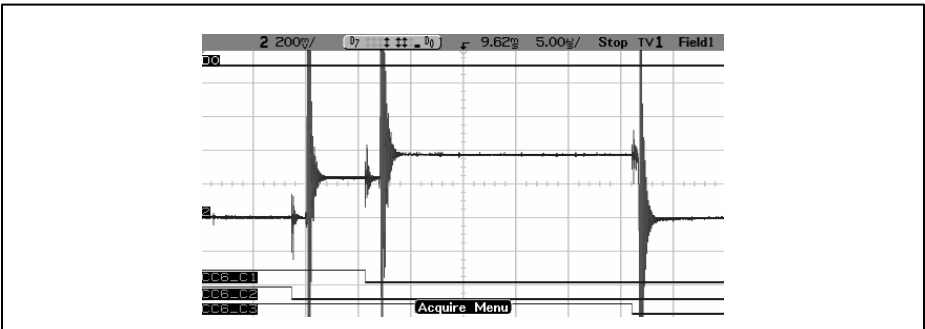


Figure 34 DC Link Current (Detail)

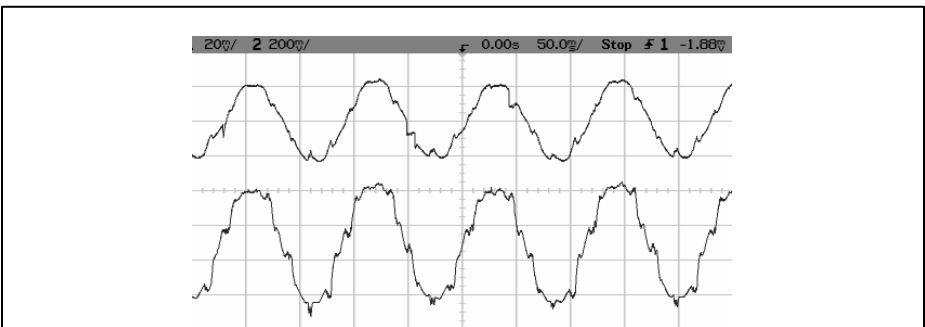


Figure 35 Current in Phase U reconstructed from DC Link Current (upper curve) and measured with Current Probe (lower curve with 2A/Div) with a load at 400 rpm

6.2 Dynamical Behavior

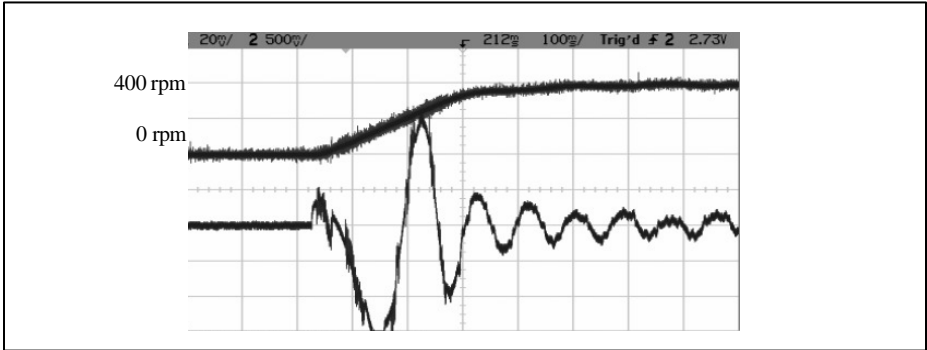


Figure 36 Speed step from 0 to 400 rpm

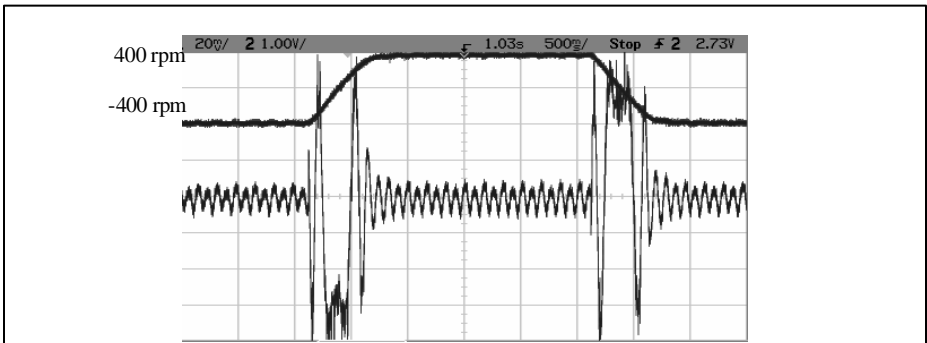


Figure 37 Speed step from -400 to 400 rpm (change the rotation direction)

Note: The measurements in Figure 35 - Figure 37 were effected without the approximation method described in chapter 5.1.

6.3 CPU Performance

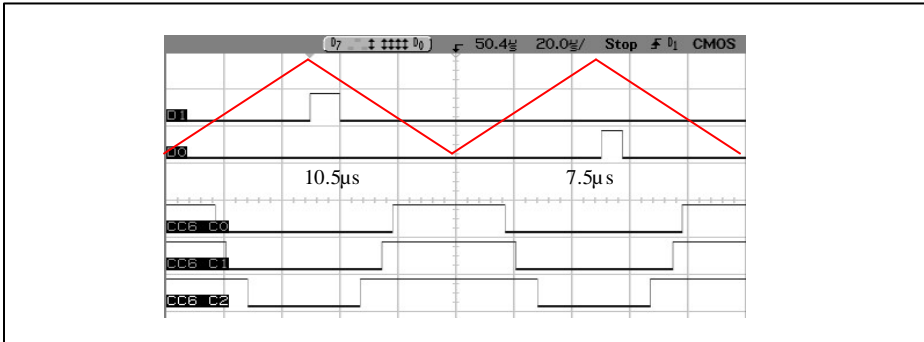


Figure 38 CPU Performance Test with PWM Cycles and Timer 12 states (red), D0 = Execution Time for Period 1 = 7.5 µs⁹, D1 = Execution Time for Period 2 = 10.5µs

The timing benchmarks for the most important modules are given below:

Function	Period	Time
GetRotorPosition()	1	2.15µs
GetSpeed(), executed each 4.2ms	1	1.8µs
PI_Controller(speed) (ASM)	1	2.05µs
ClarkeParkTrans()	1	2.2µs
PI_Controller(Id) (ASM)	2	2.05µs
PI_Controller(Iq) (ASM)	2	2.05µs
ParkInverse()	2	1.45µs
SVM()	2	4.2µs

Table 3 Timing Benchmarks @ 40MHz CPU Clock

Note: All functions was implemented in the programming language C (except the PI Controller function), without performance-enhancement e.g. by software implementation in assembler or by using the MAC-Unit.

⁹ Without speed controller execution

6.4 Pictures

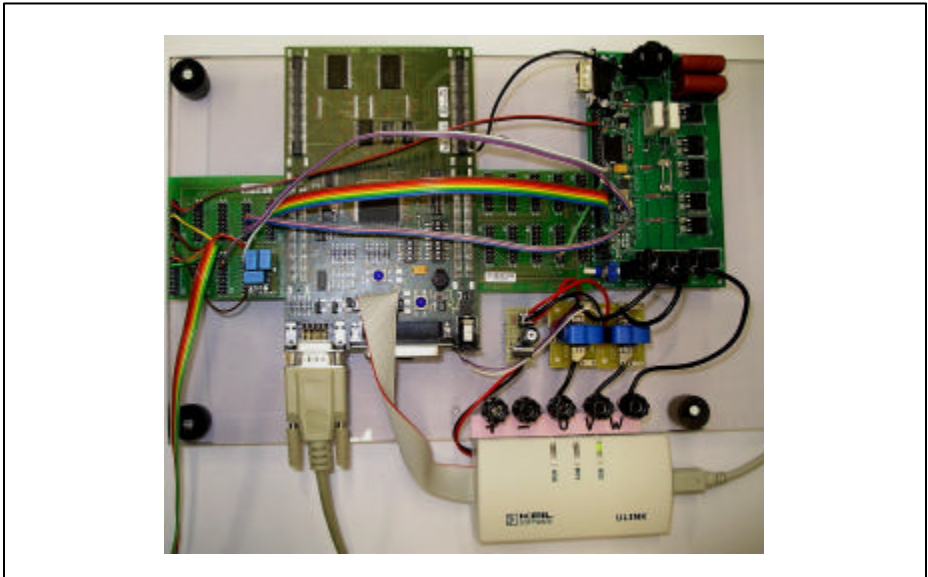


Figure 39 Inverter and XC167CI Board

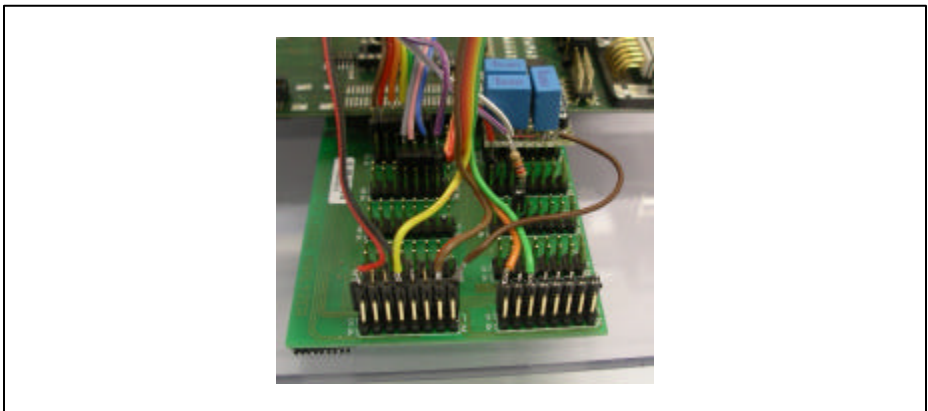


Figure 40 stencils

7 Conclusions

This paper discussed with the Field Oriented Control of a Permanent Magnet Synchronous Motor with a single dc link shunt current measurement.

The Field Oriented Control provides the smooth motion at slow speeds as well as efficient operation at high speeds high speeds. The presented option to measure the dc link current with a shunt is the cheapest method to become information about the current in the phases. The drawback of this method is that the current cannot be measured in defined machine states. If there is no special handling of the measurement in these problematic sectors (chapter 5.1), the current in the PMSM has more noise.

It has been shown that the Infineon XC167CI Microcontroller provides all peripherals in one single chip for an efficient implementation of a Field Oriented Control, e. g. the triggering automatism of the ADC by the 6 unit.

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Glossary

a, β -frame	Static co-ordinate system
A/D	Analog to Digital
ADC	Analog to Digital Converter
CC6	Capture Compare Unit on XC167
D/A	Digital to Analog
d,q-frame	Rotating co-ordinate system
FOC	Field Oriented Control
IM	Induction Motor
LEM	Trade name for a current transducer producer
MAC-Unit	Multiply Accumulate Unit on XC167CI
PEC	Peripheral Event Controller
PI	Proportional plus Integrative
PM	Period Match of a Timer
PMSM	Permanent Magnet Synchronous Motor
p. u. Quantities	Per Unit Quantities
PWM	Pulse-Width Modulation
SVM	Space Vector Modulation
SVPWM	Space Vector Pulse Width Modulation
U,V,W	Identifier of the three phase of an electric motor, in literature you can find also A,B,C, 1,2,3, etc.

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