MOTOROLA
SEMICONDUCTOR APPLICATION NOTE

Order this document by
AN1627/D

AN1627

LOW COST HIGH EFFICIENCY SENSORLESS DRIVE FOR BRUSHLESS DC MOTOR USING MC68HC(7)05MC4

By Leos Chalupa
Roznov System Application Laboratory
Motorola, Roznov pod Radhostem, Czech Republic

1 INTRODUCTION

This application note presents a low-cost sensorless speed control system for Brushless DC (BLDC) motors. Especially suitable when high efficiency and low-price are required, the drive system is based on a high efficiency Brushless DC motor, sensorless rotor position detection, low cost components and the motor control dedicated low-cost microcontroller (the Motorola's MC68HC05MC4).

Today more and more variable speed drives are put in appliance products to increase the whole system efficiency and the product performance.The low dynamic drive is a solution in many cases for common appliance applications, whereby the load or speed is changed quite slowly in comparison with the system mechanical time constant. Quite simple algorithms can perform the control tasks. Moreover, the necessary computing power can be minimised by using a dedicated microcontroller and efficient use of its internal function blocks (such as A/D converter, dedicated PWM outputs, input capture and output compare functions...).

Three phase Brushless DC (BLDC) motors are good candidates because of their high efficiency capability and easy to drive features. The disadvantage of this kind of motor is the fact that commutation of motor phases relies on its rotor position. Although the rotor position is usually sensed by sensors, the requirement for sensorless solutions becomes more and more real.

The sensorless rotor position technique developed detects the zero crossing points of Back-EMF induced in the motor windings. The phase Back-EMF zero crossing points are sensed while one of the three phase windings is not powered. The obtained information is processed in order to control the phase voltage, using Pulse Width Modulation.

This application note tries to give a fundamental mathematical method for modelling, torque calculation and control concept of the presented drive. The drive was developed in order to drive simple applications (e.g. pumps, compressors, fans...) within certain ranges of speed and load. Results from simulation show the drive behaviour at different working conditions and better explains the drive strategy.

1.1 Classical System

As is well known, the Brushless DC motor (BLDC motor) is also named electronically commuted motor. There are no brushes on the rotor and the commutation is performed electronically at certain rotor positions. The three phase voltage system (see Figure 1-1.), with a rectangular shape, is used to create a rotational field. This easy to create shape of applied voltage ensures the simplicity of control and drive. The rotor position must be known at certain angles in order to align the applied voltage with the Back-EMF, which is induced in the stator winding due to the movement of the permanent magnets on the rotor. The alignment between Back-EMF and commutation events is very important. At this condition the motor behaves as a DC motor and runs at the best working point. The simplicity of control and good performance makes this motor a natural choice in low-cost and high-efficiency applications.

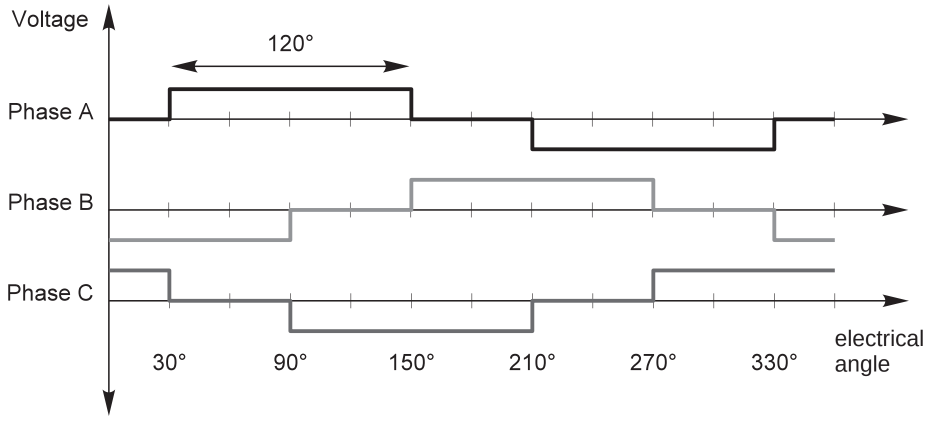

Figure 1-1. Three Phase Voltage System

1.2 Why Sensorless?

As explained in the previous section, the rotor position must be known in order to drive a Brushless DC motor. If any sensors are used to detect rotor position, then sensed information must be transferred to a control unit (see Figure 1-2.). Therefore additional connections to the motor are necessary. This may not be acceptable for some kind of applications. There are at least two reasons why you might want to eliminate the position sensors:

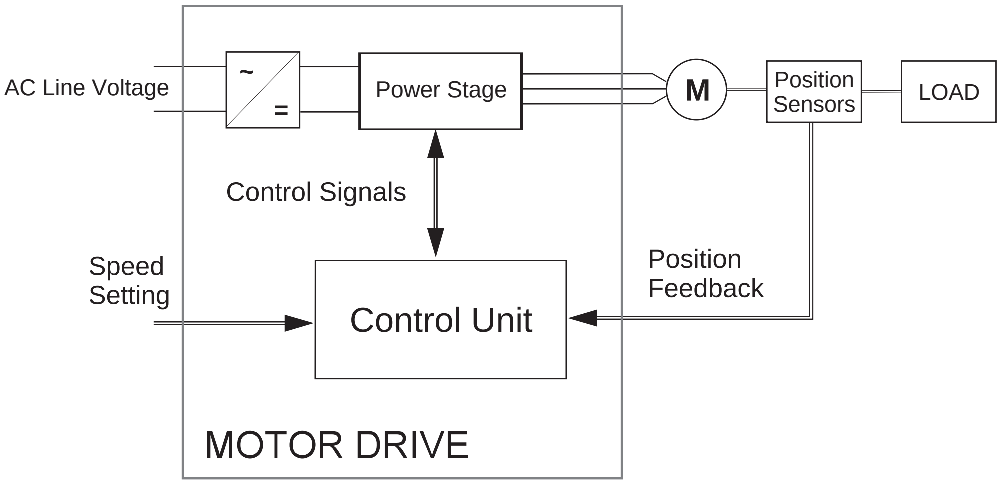

Figure 1-2. Classical System

1. Real impossibility to make additional connections between position sensors and the control unit
2. Cost of the position sensors & wiring

The first point might be solved by integration of the driver within the motor body. However a significant number of applications requiring a sensorless solution still remain.

2 THEORY

2.1 Power Stage - Motor System Model

In order to explain and simulate the idea of Back-EMF sensing techniques a simplified mathematical model, based on the basic circuit topology (see Figure 2-1.), has been created.

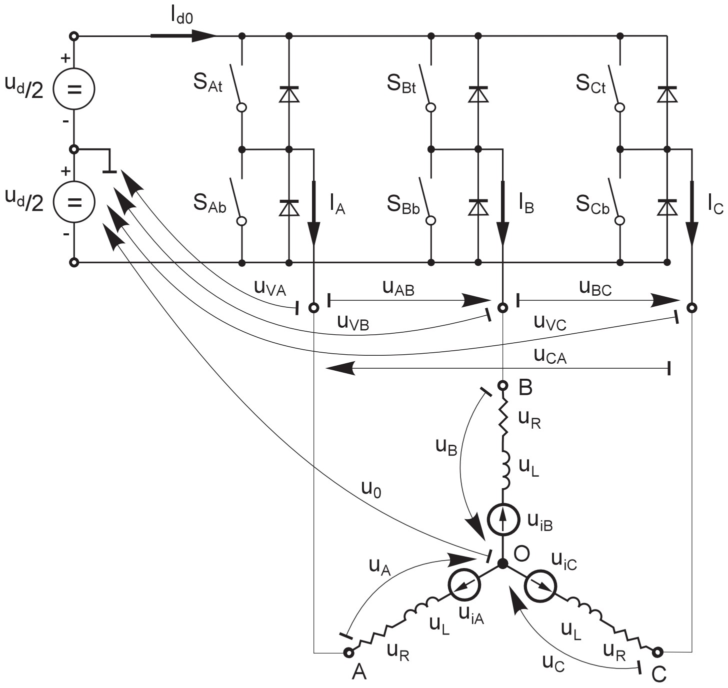

Figure 2-1. Power Stage - Motor Topology

The second goal of the model is to find how the motor characteristics depend on the switching angle. The **switching angle** is the angular difference between a real switching event and an ideal one (at the point where the **phase to phase** Back-EMF crosses zero).

The motor-drive model consists of a normal three phase power stage plus a Brushless DC motor. The power for the system is provided by a voltage source (U_d). Six semiconductor switches ($S_{A/B/C\ t/b}$), controlled elsewhere, allow the rectangular voltage waveforms (see Figure 1-1.) to be applied. The semiconductor switches and diodes are simulated as ideal devices. The zero voltage level of the whole model is put at one half of the DC-Bus voltage. This simplifies the mathematical expressions when output waveforms from the power stage are calculated.

2.1.1 Mathematical Model

The following set of equations is valid for the presented topology:

$$
\begin{aligned}
u_A &= \frac{1}{3}\left(2u_{VA} - u_{VB} - u_{VC} + \sum_{x=A}^{C} u_{ix}\right) \\
u_B &= \frac{1}{3}\left(2u_{VB} - u_{VC} - u_{VA} + \sum_{x=A}^{C} u_{ix}\right) \\
u_C &= \frac{1}{3}\left(2u_{VC} - u_{VA} - u_{VB} + \sum_{x=A}^{C} u_{ix}\right) \\
u_O &= \frac{1}{3}\left(\sum_{x=A}^{C} u_{Vx} - \sum_{x=A}^{C} u_{ix}\right) \\
0 &= i_A + i_B + i_C
\end{aligned}
\qquad \text{(EQ 2-1.)}
$$

where:

$u_{VA} \ldots u_{VC}$	are “branch” voltages; the voltages between one power stage output and its virtual zero.
$u_A \ldots u_C$	are motor phase winding voltages.
$u_{iA} \ldots u_{iC}$	are phase Back-EMF voltages induced in the stator winding.
u_O	is the voltage between the central point of the star and the power stage virtual zero
$i_A \ldots i_C$	are phase currents

The equations (EQ 2-2.) can be written taking into account the motor phase resistance and the inductance. The mutual inductance between the two motor phase windings can be neglected because it is very small and has no significant effect. In other words, the motor must be designed this way, otherwise sensing of the back-EMF would be almost impossible.

$$
\begin{aligned}
u_{VA} - u_{iA} - \frac{1}{3}\left(\sum_{x=A}^{C} u_{Vx} - \sum_{x=A}^{C} u_{ix}\right) &= R \cdot i_A + L\frac{di_A}{dt} \\
u_{VB} - u_{iB} - \frac{1}{3}\left(\sum_{x=A}^{C} u_{Vx} - \sum_{x=A}^{C} u_{ix}\right) &= R \cdot i_B + L\frac{di_B}{dt} \\
u_{VC} - u_{iC} - \frac{1}{3}\left(\sum_{x=A}^{C} u_{Vx} - \sum_{x=A}^{C} u_{ix}\right) &= R \cdot i_C + L\frac{di_C}{dt}
\end{aligned}
\qquad \text{(EQ 2-2.)}
$$

where:

R,L - motor phase resistance, inductance

The internal torque of the motor itself is defined as:

$$
T_i = \frac{1}{\omega}\sum_{x=A}^{C} u_{ix} \cdot i_x = \sum_{x=A}^{C} \frac{d\Psi_x}{d\theta} \cdot i_x \qquad \text{(EQ 2-3.)}
$$

where:

T_i - internal motor torque (no mechanical losses)

ω, θ - rotor speed, rotor position

Ψ_x - magnetic flux of phase winding x

It is important to understand how the Back-EMF can be sensed and how the motor behaviour depends on the alignment of the Back-EMF to commutation events. This is explained in the next sections.

2.2 Back-EMF Sensing

The Back-EMF sensing technique is based on the fact that only two phases of a DC Brushless motor are connected at a time (see Figure 1-1.), so the third phase can be used to sense the Back-EMF voltage.

Let us assume the situation when phases A and B are powered and phase C is free. No current is going through this phase. This is described by the following conditions:

$$\begin{aligned} & S_{Ab}, S_{Bt} \leftarrow PWM \\ & u_{VA} = \mp\frac{1}{2}u_d,\ u_{VB} = \pm\frac{1}{2}u_d \\ & i_A = -i_B,\ i_C = 0,\ di_C = 0 \\ & u_{iA} + u_{iB} + u_{iC} = 0 \end{aligned} \qquad \text{(EQ 2-4.)}$$

The branch voltage C can be calculated when considering the above conditions:

$$u_{VC} = \frac{3}{2}u_{iC} \qquad \text{(EQ 2-5.)}$$

It is seen from the Figure 2-1. that the branch voltage of phase C can be sensed between the power stage output C and the zero voltage level. Thus the Back-EMF voltage is obtained and the zero crossing can be recognized.

The same expressions can also be found for phase A and B:

$$u_{Vx} = \frac{3}{2}u_{ix} \ldots x = A,B,C \qquad \text{(EQ 2-6.)}$$

There are two necessary conditions which have to be met -

- Top and bottom switch (in diagonal) have to be driven with the same PWM signal
- No current is going through the phase used to sense the Back-EMF

The Figure 2-2. shows branch and motor phase winding voltages during a 0-360°electrical interval. Shaded rectangles designate the validity of the equation (EQ 2-6.). In other words, the Back-EMF voltage can be sensed during designated intervals.

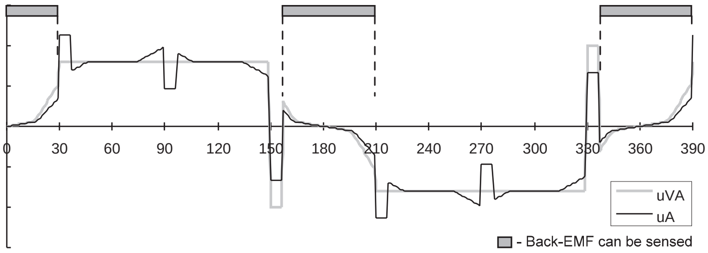

Figure 2-2. Phase Voltage Waveforms

2.3 Motor Behaviour at steady state condition

The previously described model is used to obtain the typical waveforms at different switching angles. See Figure 2-3., Figure 2-4. and Figure 2-5.

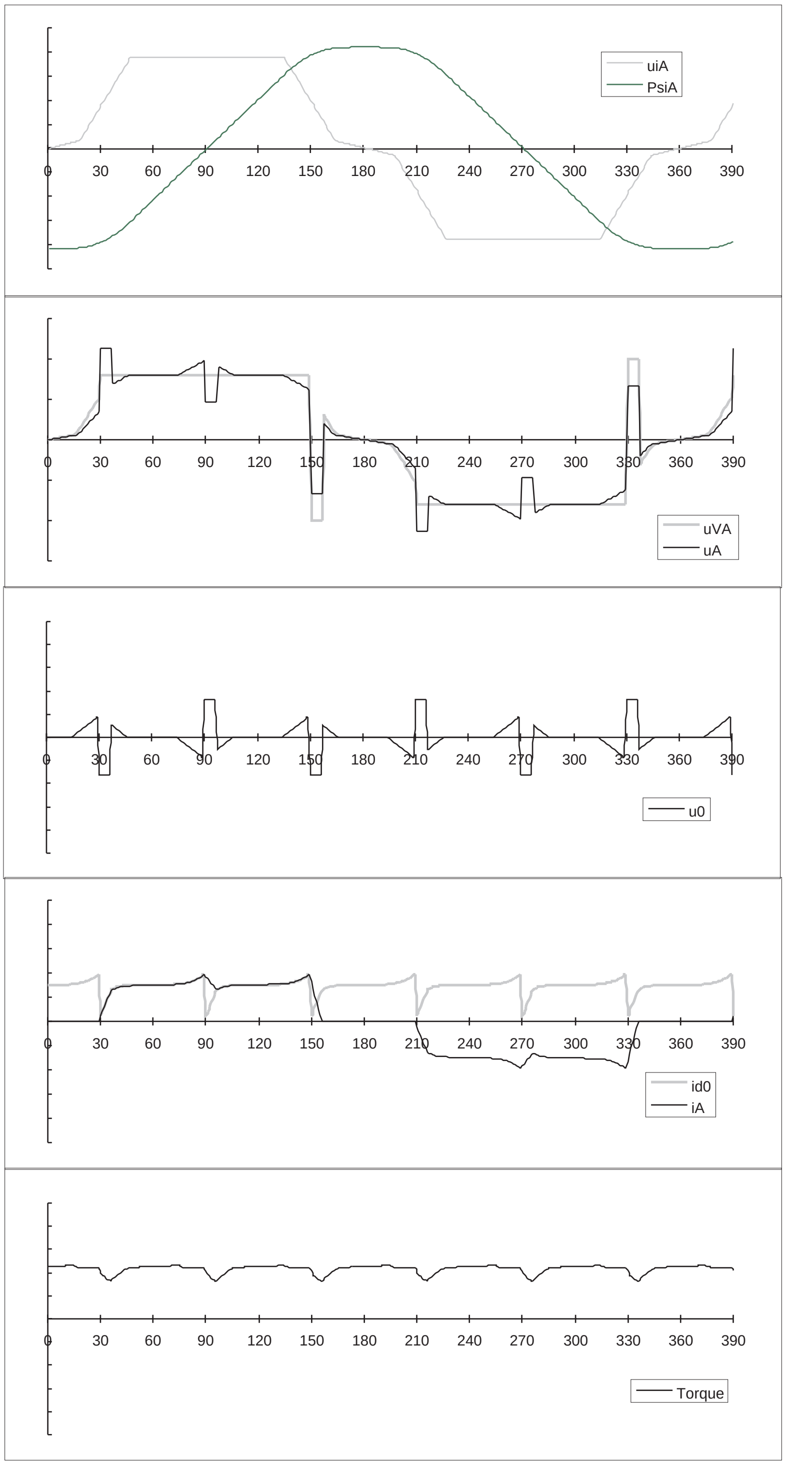

Figure 2-3. 0° switching angle

The x-axis represents electrical degrees of rotation. The y-axis represents relative amplitudes only. u_{VA} is voltage created by the power stage and applied to the motor. u_A is the voltage across the motor phase winding. A detailed look at waveforms u_{VA} and u_A shows one interesting fact. These voltages can differ quite a lot because the three phase system, created by the power stage, is not symmetrical. If it was symmetrical, u_0 would equal zero. The expression of u_0 (see (EQ 2-1.)) explains how this depends on the motor construction ($u_{iA,B,C}$) and the implemented three phase system ($u_{vA,B,C}$). The Back-EMF of phase A can be sensed within the following intervals: 330°-30° and 150°-210°.

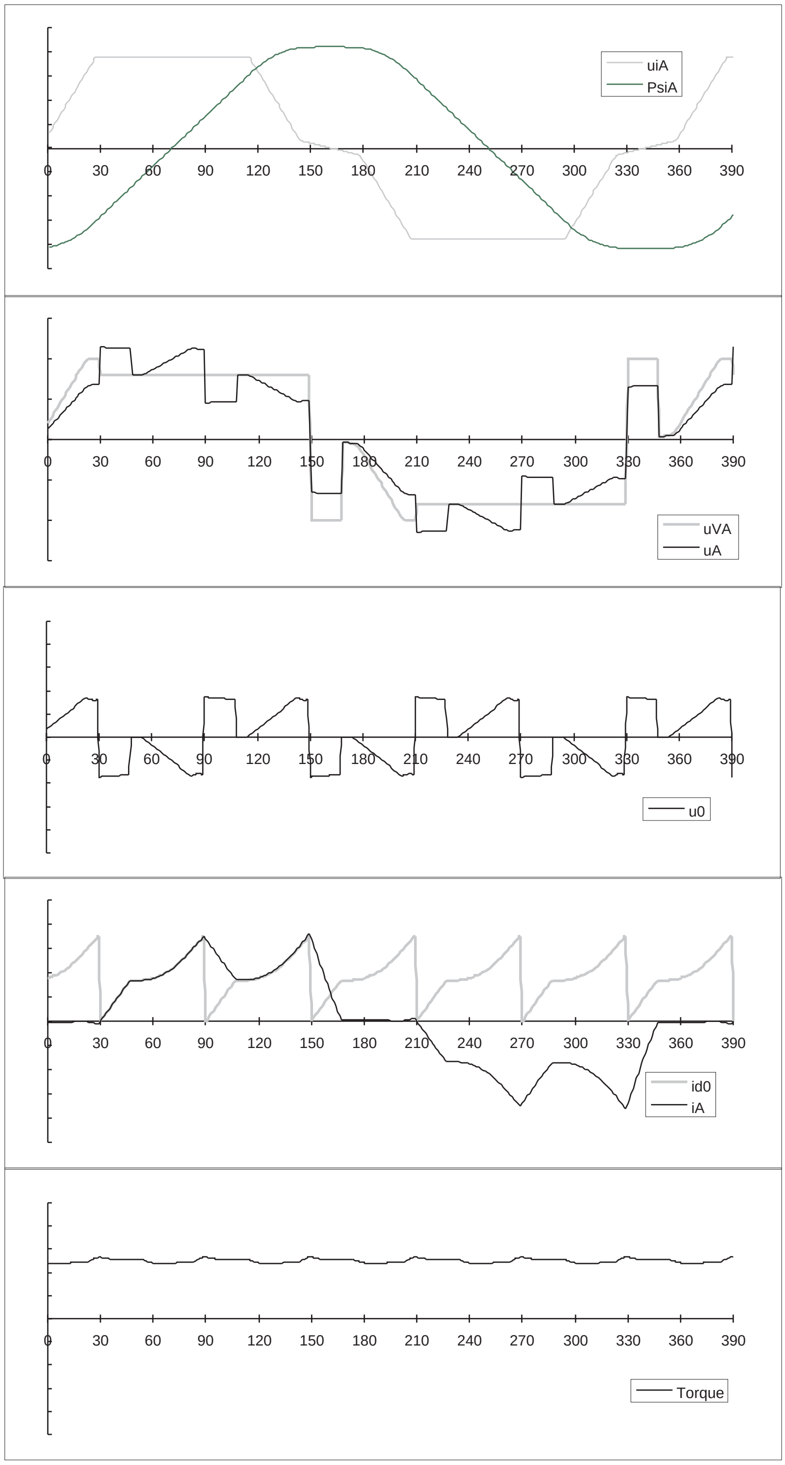

Figure 2-4. -20° switching angle

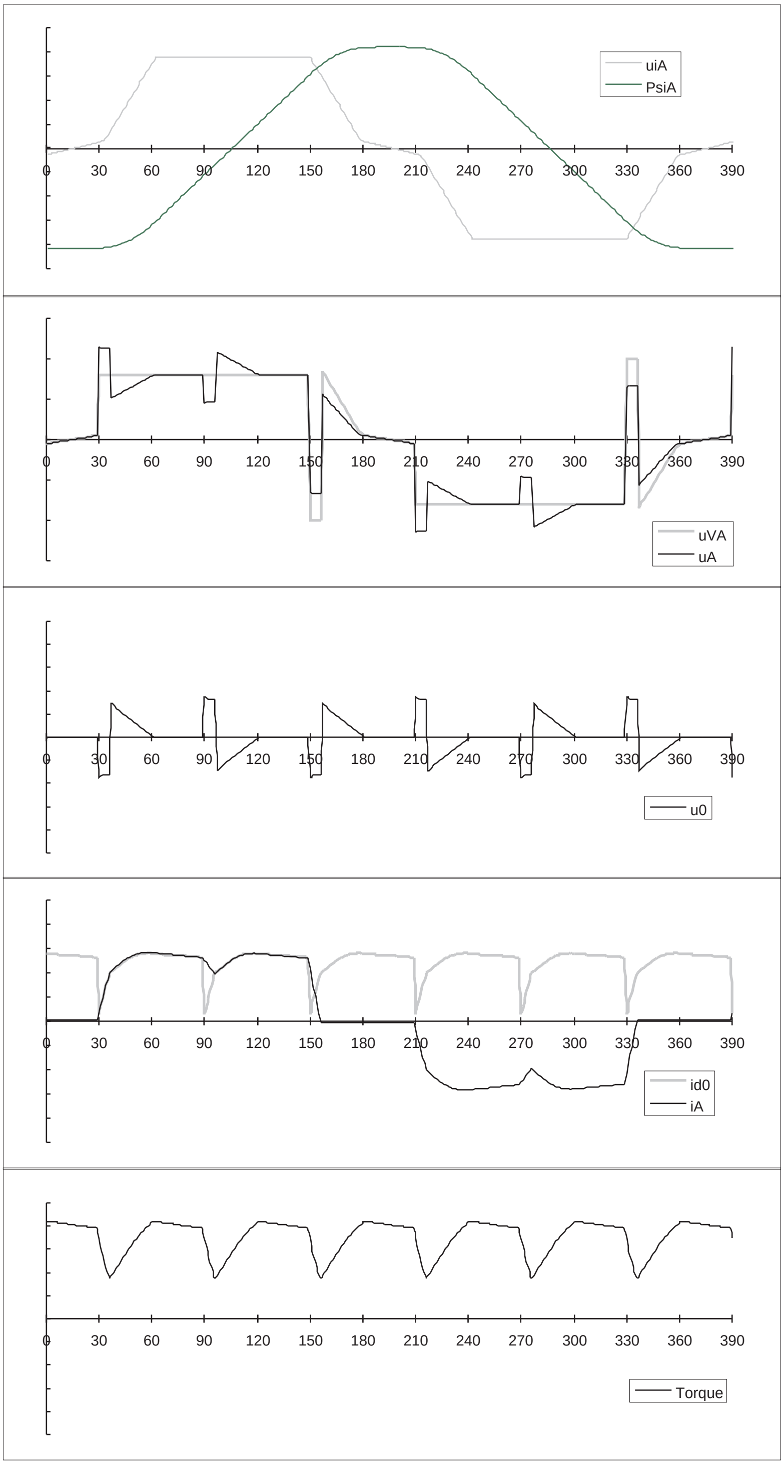

Figure 2-5.   15° switching angle

Let's suppose that the motor is fed from a voltage source, the fundamental frequency created by the power stage is constant. Figure 2-6. shows how the average motor torque (y-axis, relative amplitudes only) depends on the switching angle (x-axis) at constant speed and applied voltage (PWM duty cycle value) as a parameter. The working point can be found for a certain load torque and PWM duty cycle. If the load torque changes and the PWM duty cycle remains constant, the switching angle changes accordingly. The zero crossing event is used to calculate the actual switching angle. Once it is known, a corrective action can be made to keep the switching angle within the desired interval. This will allow control of the motor at the best efficiency point without need of position sensors.

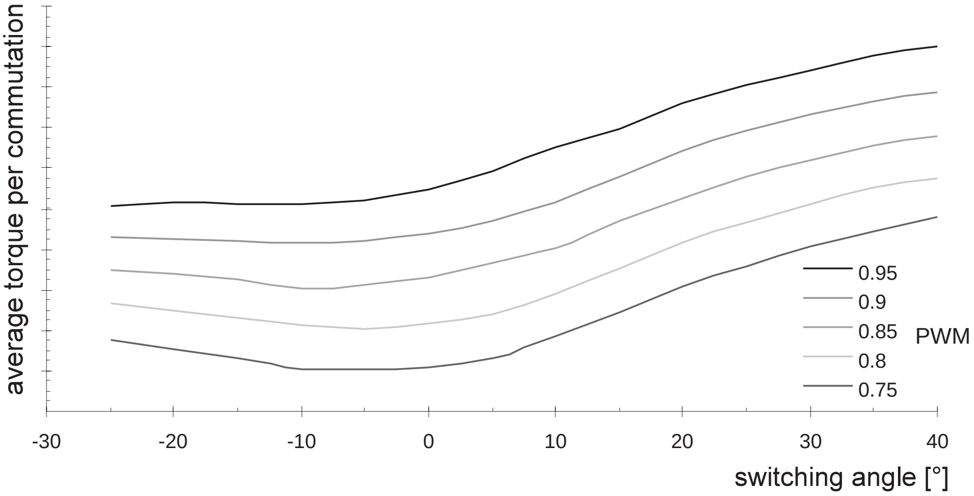

Figure 2-6. The Average Motor Torque

3 USUAL REQUIREMENTS

As was shortly introduced in the previous sections, the low-dynamic application is the field where this drive can be used. The speed and load vary during a much longer time than the system mechanical time constant.

The Table 3-1. summarizes the requirements of a typical (low-cost high-volume) application with a Brushless DC motor.

Motor type:	6 stator poles, three-phases, four rotor poles, EC PM DC Motor	Specifications
Motor characteristic:	Speed range:	300-3000 RPM
	Torque range:	10%-120% of nominal
	Max. electrical power:	<300W
Drive input characteristic:	Input “inrush” max.:current	<30A
	Target efficiency:	0.9
	Min efficiency:	0.8 over whole range
	Fulfill European Community Regulation IEC555-1	
Load characteristic:	Type	Varying
	Start-up torque	Max. 150% of nominal
	Max. acceleration time: (0 to rated speed)	10sec

Table 3-1.

4 SYSTEM CONCEPT

The concept below was chosen. The cost target, especially, forced the design to be as simple as possible.

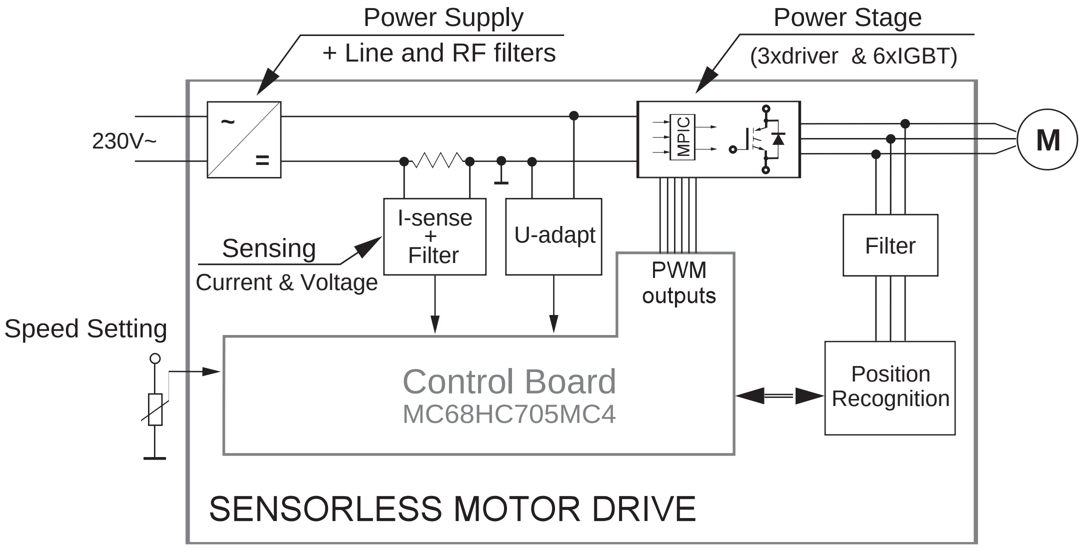

Figure 4-1. System

The 68HC705MC4 is an HC05-based MCU designed for three-phase Brushless DC motor (permanent magnet) drive applications. General features include 3.5 kb of EPROM, 176 bytes of RAM, a 16-bit timer including an output compare and two input captures, 4 general-purpose I/O pins, and an SCI (UART) port in a 28-pin SOIC or DIP package. In addition the MC4 has specific features that target Brushless DC motor control, including a 2-channel, 8-bit PWM module, a high current source port, and a 6-channel, 8-bit A/D module.

Key features of the 6-pin, 2-channel PWM module include 16 PWM rates between 122Hz and 23.4kHz for each PWM channel, buffered data registers with an interlocking mechanism for coherent updates of the pulse width outputs on each PWM channel, and a 3-output commutation MUX on each PWM channel for easy control of outputs to the motor drive. The six PWM outputs of the commutation MUX are connected to an output port with 10 mA current source capability per pin, thus reducing the cost of external components required for building motor drives.

The Back-EMF zero crossing detection enables position recognition, as explained in previous sections. The resistor network is used to divide sensed voltages down to a 0-15V voltage level. Simple filtering prevents the comparators being disturbed by high voltage spikes produced by the switching of the IGBT’s. The multiplexer selects the phase comparator output which corresponds to the current commutation stage. This signal is transferred to the microcontroller Input Capture pin (TCAP2).

The voltage drop resistor (0,6Ohm/2W) is used to measure the DC-bus current which is chopped by the PWM. The obtained signal is rectified and amplified (0-5V). The internal microcontroller A/D converter is synchronized with the PWM signal. This synchronization avoids spikes when the IGBT’s are switching and simplifies the electric circuit.

The A/D converter is also used to sense the DC-Bus Voltage and speed setting. The DC-Bus voltage is divided down to a 5V signal level by a resistor network.

The six IGBT’s (copack with built-in fly back diode) and high voltage gate drivers create a compact power stage. The drivers provide the level shifting that is required to drive high side bridge circuits commonly used in motor drives. PWM technique is used to the control motor phase voltage.

A Simple power supply (rectified mains) contains a Line and a RF filter in order to fulfil the European Community Regulation (IEC555-1).

As apparent, this concept uses a common ground (no isolation is used).

WARNING

It is strongly recommended to use opto-isolation (optocouplers and optoisolation amplifiers) during the development time to avoid any damage to the development equipment.

---

5 SOFTWARE

5.1 Control Algorithm

Two methods were tried. The first idea was to calculate the commutation events from the obtained zero crossing times. This method was shown to be not robust enough. Any disturbance to the feedback signal (due to noise or motor asymmetry) caused high torque ripples and motor stoppage.

Because of these problems, the second method was developed. Here, the motor is running as a synchronous motor. The operating value of the voltage is created in such a way, that the Back-EMF is aligned with the commutation. The phase Back-EMF zero crossing point is kept within a time window ($90° < \alpha < 180°$ see Figure 6-2.; this can be changed with respect to type of application). This principle is close to a simple vector control method. This does not require calculation of the next commutation event, directly based on the Back-EMF sensing. Therefore this is a more stable algorithm in case of feedback signal disturbance. No motor stoppage can occur. When using this algorithm the motor speed variation is very low.

The control flow consist of five phases: Alignment stage, Ramp-up stage, Stabilizing stage, PLL (Phase Locked Loop) Acquisition stage and Running (PLL Locked) stage.

5.1.1 Alignment

Before the motor starts, there is a short time (which depends on the motors electrical time constant) when two phases are supplied by power. The Current Controller keeps the current within predefined limits. This stage is necessary in order to create a high start-up torque (see (EQ 2-3.)).

5.1.2 Ramp-up

Here the motor is starting and ramped up (an “S” curve ramp creates a smooth transient) until it reaches the working speed. The Current Controller keeps current at the maximum limit in order to ensure that the rotor will not become locked. The Back-EMF sensing technique enables a sensorless detection of the rotor position, however the drive must be started without this feedback. It is caused by the fact that the amplitude of the induced voltage is proportional to the motor speed. Hence, the Back-EMF cannot be sensed at a very low speed and a special start-up algorithm must be performed.

5.1.3 Stabilizing

The motor is now running for a short time at constant speed. The motor speed is stabilized before the synchronization with the Back-EMF feedback takes place.

5.1.4 PLL Acquisition

The current controller is switched off. Only the over-current detection is left on. The motor is supplied from a voltage source. This transition must be done very carefully. The actual PWM duty cycle (phase voltage) is decreased until several zero crossing points can be sensed within the target time window ($90° < \alpha < 180°$ see Figure 5-2.). The rate of decrease must be tuned for the application and must not create oscillation of the whole drive.

5.1.5 Running (PLL Locked)

The following conditions have to be met to enter this stage:

1. Zero crossing events have to be sensed within a time window ($90° < \alpha < 180°$) several times (e.g. 6×).
2. Current peaks during one commutation period must be below a certain limit

Then the PLL controller keeps the phase shift α at the right value by controlling the phase voltage. The motor is now running with a good efficiency. Current measurement, over-current detection and motor stall detection is still continuously applied.

5.2 Main routines

The software is divided into several main routines: INIT, START, BODY and INTERRUPT SERVICE ROUTINES (ISR). Several common subroutines are called throughout these routines and are described in more details later in Section 5.2.4. The Figure 5-1. shows the sequence of the routines.

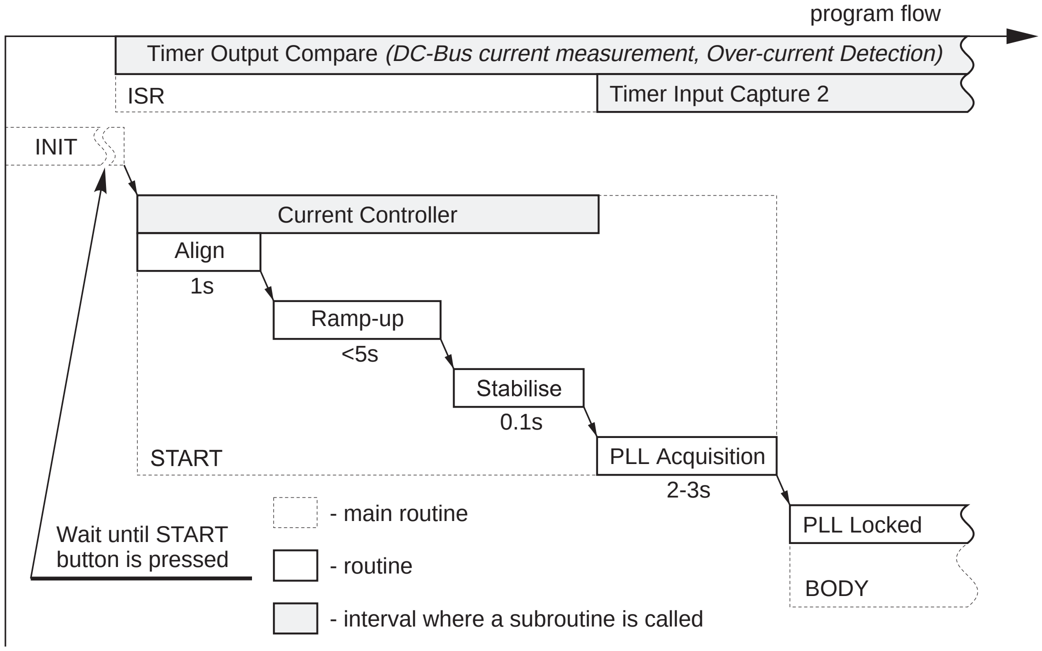

Figure 5-1. Program Flow

5.2.1 INIT

INIT does all necessary initialization before the drive is started.

Ports initialization:	PA1-6 - PWM output PB5-7 - output PC0-7 - inputs PD6-7 - inputs
A/D initialization:	The DC-Bus current zero value and DC-Bus voltage limits (high and low) are tested in order to prevent the drive from being damaged. The speed setting is sampled. After the START switch is turned on (see Figure 5-1.) the initialization continues.
PWM initialization:	Sets the PWM frequency (3.9kHz) and the PWM polarity (POLA=POLB=0). The time point for synchronization of the current measurement with the PWM is taken. The pointer for commutation look-up table is initialized.
Timer Output Compare Function initialization:	Software Timer1 is synchronized with PWM in order to handle the internal A/D converter. Software Timer2 (creates commutation period) is initialized.
Input Capture Function initialization:	The Input Capture Function and input pin (TCAP2) are initialized.
Current Controller initialization:	All registers used by PI type of Current Controller are cleared.

Finally, interrupts are enabled.

5.2.2 START

This routine performs the start algorithm and consists of the parts mentioned in the Control Algorithm Section.

5.2.2.1 Alignment

The required value of the current is set. The Current Controller keeps the current at the required value. The Current Controller subroutine is called every 512µs after new value of the DC-Bus current have been obtained. The PWM signals are applied onto only two motor phases (no commutation). The motor current and rotor position is stabilized.

5.2.2.2 Ramp-up

The commutation period is decreased in order to reach the maximal speed within 5 seconds (see Figure 5-4.).

The following subroutines are called: Current Controller (512µs period), Speed Setting & DC-Bus voltage sensing, Commutation and Ramp.

When finished ramping-up (the motor is running at the required speed), the program flow continues.

5.2.2.3 Stabilizing

Here, the motor speed is stabilized before the PLL Acquisition takes place. The motor is running with constant speed. After a certain time (which depends on the application), the program flow continues to the next stage.

The Current Controller (512µs period), the Speed Setting & DC-Bus voltage sensing and the Commutation subroutines are called from this part.

5.2.2.4 PLL Acquisition

The current peak during one commutation is detected, if it is higher than the preset limit (2.5A), then the PWM duty cycle is decreased. The Timer Input Capture interrupt is enabled ~20µs after

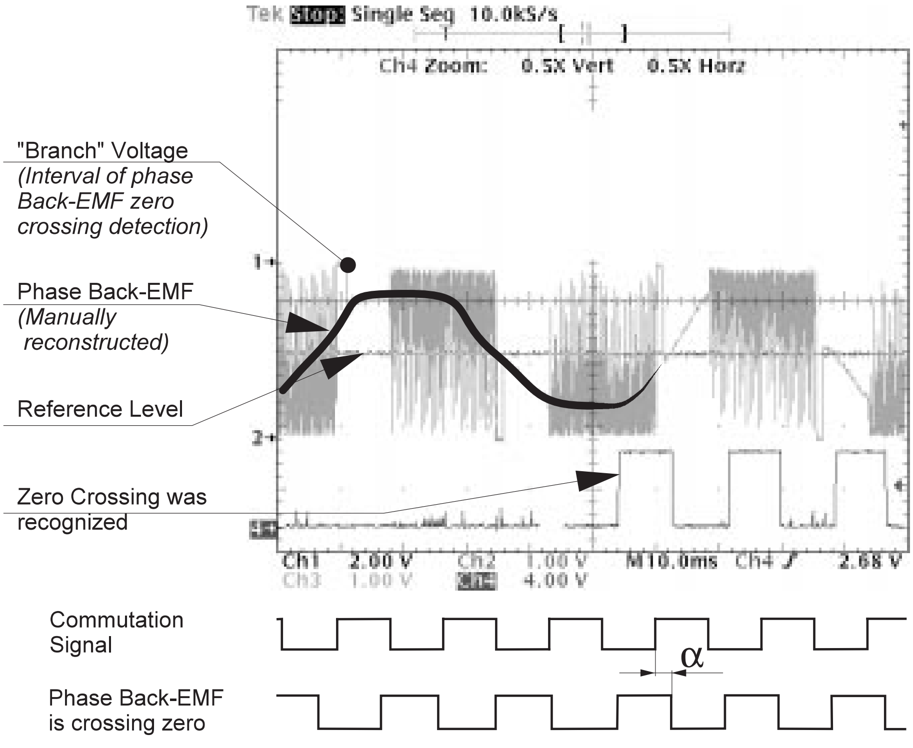

Figure 5-2. PLL Acquisition

the commutation, disabled before the successive commutation (OC ISR) or disabled when the edge of the Zero Crossing signal is detected by the IC function (see Figure 5-3.). If a zero crossing edge is detected, then the time interval from the commutation is calculated and condition the 90°<α<180° is evaluated. If this condition is met six times and the current peak is within the limit then the program flow continues. The following subroutines are called: Speed Setting & DC-Bus voltage sensing, Commutation.

The Figure 5-2. shows the moment when the zero crossing points can be sensed. The actual angle α is less than 90°, so the entry condition to the Running stage is not met and the DC-Bus voltage is decreased further.

5.2.3 BODY

This routine performs the Running stage. Speed Setting & DC-Bus voltage sensing and Commutation subroutines are called. The zero crossing feedback is handled and the angle α is evaluated. If no feedback is captured between commutations, then the zero crossing comparator feedback (TCAP2 pin) is sampled directly, just before the commutation takes place (see Figure 5-3., ⓪ samples).

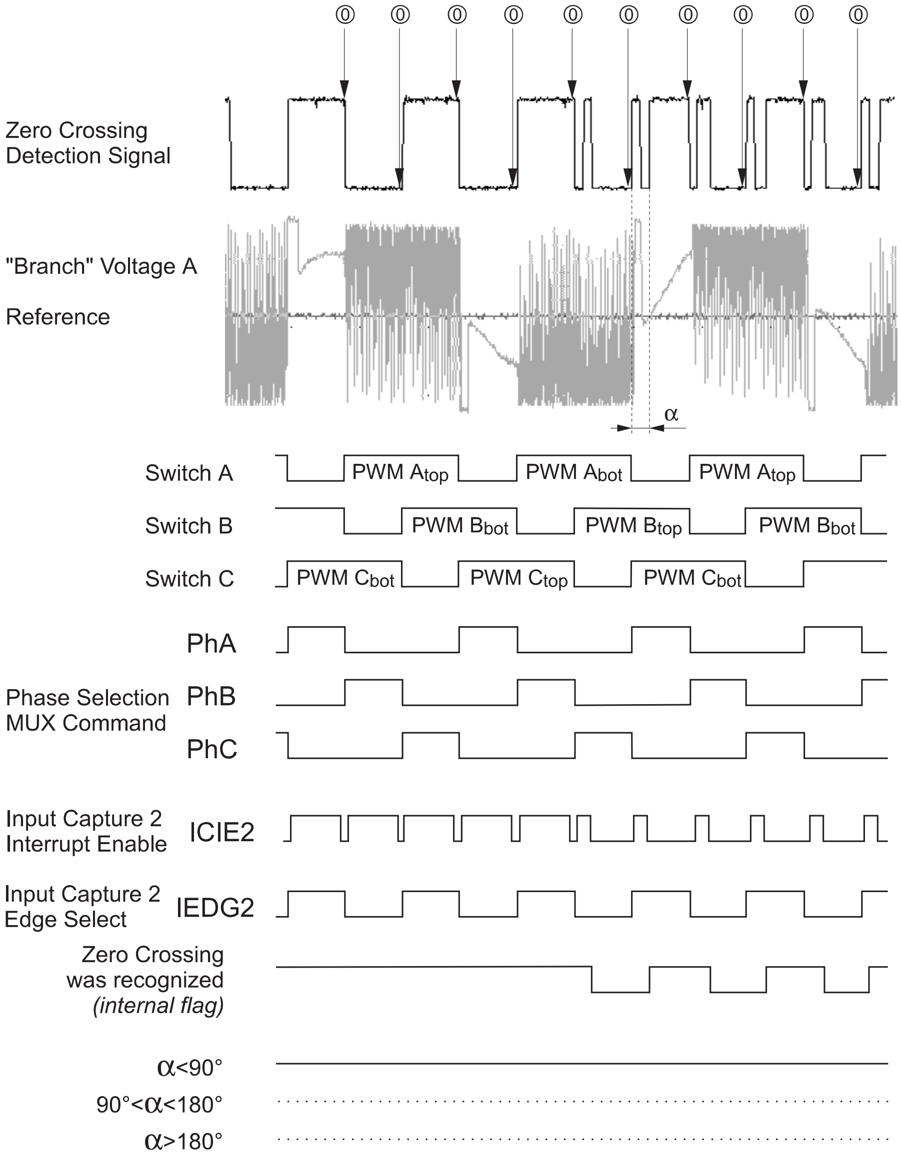

Figure 5-3. Control signals

The following formula is then used to evaluate if $\alpha<90^\circ$ or $\alpha>180^\circ$:

`if` (((Rising edge is expected) `AND` (TCAP2 pin is Hi)) `OR` ((Falling edge is expected) `AND` (TCAP2 pin is Lo))) `then` $\alpha<90^\circ$

`if` (((Rising edge is expected) `AND` (TCAP2 pin is Lo)) `OR` ((Falling edge is expected) `AND` (TCAP2 pin is Hi))) `then` $\alpha>180^\circ$

All three cases ($\alpha<90^\circ$, $90^\circ<\alpha<180^\circ$ and $\alpha>180^\circ$) are counted (by EMF_Lo, EMF_OK and EMF_Hi counters) during one revolution (18 commutations per revolution). The results are then used in the PLL Controller.

The stall detection is performed using another formula:

`if` (EMF_Lo>Stall limit) `then` call Emergency Service routine.

5.2.3.1 PLL Controller

Based on above counters values the PLL Controller changes PWM duty cycle (PWMA and PWMB registers)

```
if (EMF_OK>6)   then stay with the same PWM duty cycle
                else if (EMF_Lo>EMF_Hi)   then decrease PWM duty cycle
                                          else  increase PWM duty cycle
```

The PLL Controller can be more sophisticated for other applications (the time window can be divided into several subintervals etc.). In any case some kind of statistical evaluation is strongly recommended.

NOTE

If the current is higher, then the alignment of electrical and magnetic fields should be adjusted. The best α is no longer 90° but higher. The used algorithm does this improvement automatically.
Explanation: When load torque is increased, the phase current is also increased automatically and the fly-back diodes are open for a longer time. Thus the time window (when zero crossing can be sensed) is shrunk. This reduction can be so big that the time window becomes less than 30° long (also $\alpha>90^\circ$). If the previously explained control algorithm is applied, then the switching angle is increased so that the alignment of electrical and magnetic fields is improved (see Figure 2-3., Figure 2-4. and Figure 2-5.).

5.2.4 Subroutines

5.2.4.1 Emergency Stop Subroutine

This routines turns OFF all PWM outputs and waits. After some time the drive tries to start again (optional).

5.2.4.2 Speed Setting & DC-Bus Voltage Measurement

The result from an A/D conversion of either the Speed Setting or the DC-Bus voltage is stored into memory. The successive A/D channel is selected and an A/D conversion is started.

5.2.4.3 Current Controller Subroutine

The Current controller subroutine is called every 512µs. The PI controller calculates the PWM value based on the required and measured values of the DC-Bus current. The result from the PI controller is a scaled value of the duty cycle which is directly used by the PWM registers.

5.2.4.4 Commutation Subroutine

The values for the PWM control registers and the MUX command are found in look-up tables. The MUX command is a three bit word which controls the multiplexer (MUX). The multiplexer handles the phase zero crossing signals (see Figure 6-1.). The values obtained from the tables are stored into internal temporary variables in order to be ready when commutation is performed. The polarity edge sensitivity (IEDG2) of the Timer Input Capture 2 Function is toggled (see Figure 5-3.) in order to detect the rising or falling edge of the zero crossing signal. The edge polarity corresponds to the rotor position and the actual commutation stage.

5.2.4.5 Ramp Subroutine

The Ramp routine calculates commutation period (Timer1) such that an "S" speed ramp is achieved. No arithmetic division is required.

The formulas implemented are given below:

Acceleration: $$Period_{\{n+1\}} \leftarrow Period_{\{n\}} - \frac{(Period_{\{n\}} - PeriodStop) \cdot Const}{100\mathrm{hex}} - 1 \quad \text{(EQ 5-1.)}$$

Deceleration: $$Period_{\{n+1\}} \leftarrow Period_{\{n\}} + \frac{(Period_{\{n\}} - PeriodStart) \cdot Const}{100\mathrm{hex}} + 1 \quad \text{(EQ 5-2.)}$$

$Const$ is a parameter which changes the slope of the Ramp

$PeriodStart$ is the value of the commutation period when ramping is started.

$PeriodStop$ is the value of the commutation period when ramping is finished.

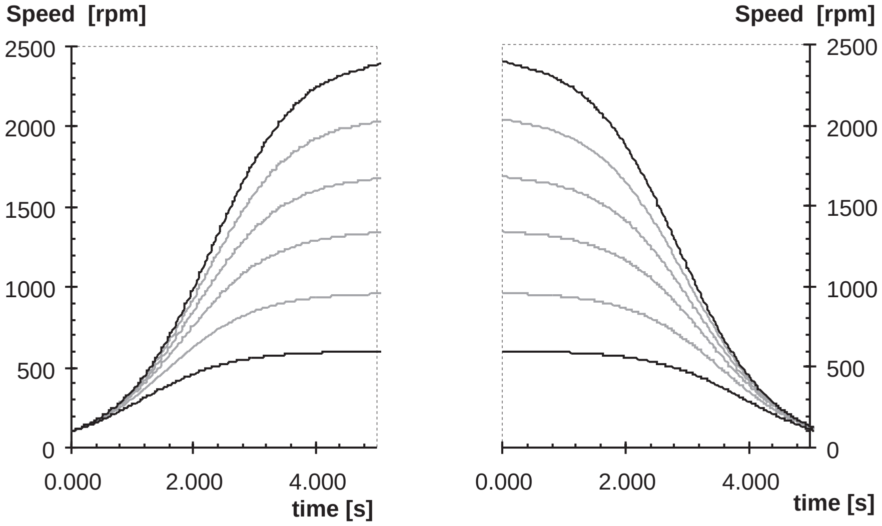

Figure 5-4. Ramp

5.2.5 ISR - Interrupt Services Routines

5.2.5.1 Timer Output Compare Interrupt Service Routine

Timer1 (A/D conversion) and Timer2 (commutation) are asynchronous software timers served by this routine.

If the OC Interrupt is caused by Timer1 the A/D conversion of DC-Bus current is done here first in order to be synchronized (within 4µs) with the PWM signal (see Figure 5-5.). The obtained value goes through the Over-current and Peak-current detection routines to make sure that it is within the limits. The flag for the Current Controller is set. This flag causes the Current Controller subroutine to be called with new data measured in this ISR.

On the other hand, if OC Interrupt is caused by Timer2, then the preset values (calculated in Commutation subroutine) are put into the PWM registers (CtlA, CtlB) and the MUX command is output too.

The IC Interrupt (ICIE2) is disabled here to preserve the Back-EMF detection from the disturbances produced during the commutation (see Figure 5-3.). It is enabled again after approximately 50µs.

If these two events are going to happen closer than 133µs, then Timer2 obtains priority and the commutation is performed at the right moment (no speed variation) while the A/D conversion is postponed by 256µs (see Figure 5-5.).

A new value for the Timer Output Compare Register (OCRH/L) is calculated, based on the states of Timer1 and Timer2.

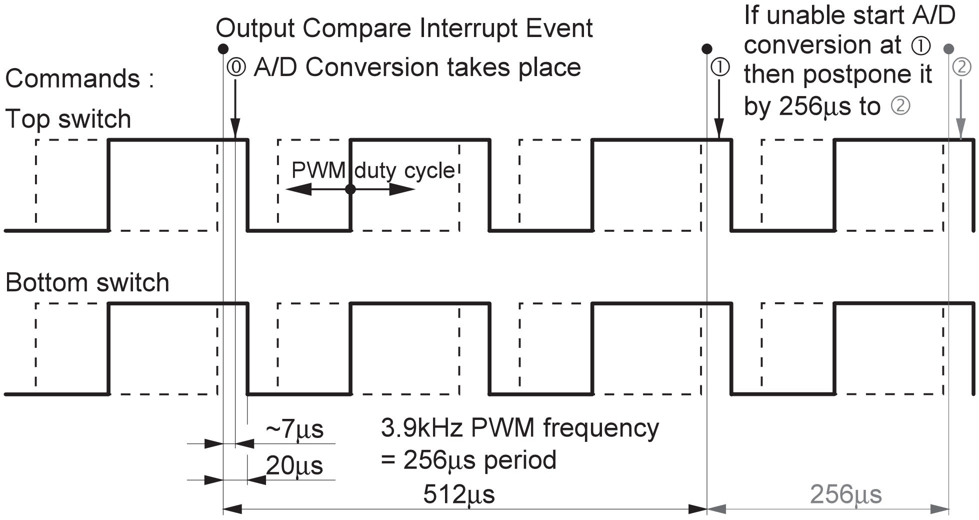

Figure 5-5. Measurement Synchronization with PWM

5.2.5.2 Timer Input Capture Interrupt Service Routine

The signal generated by the Position Recognition Logic causes this interrupt. Special care must be taken due to noise, which can disturb the incoming signal. The respective pin (TCAP2) is sampled in suitable places within the BODY and START routines. The period is less than 90µs and is typically 30µs. When this ISR is initiated, then another three samples of the TCAP2 are taken and the state of the TCAP2 pin is then evaluated. Based on the last sample before the ISR is executed, the selected edge sensitivity (IEDG2) and the samples after ISR is initiated, and the Input Capture event is verified. If it is acceptable then the captured time is stored in memory and the Input Capture Interrupt ISR is finished. The captured time is then used to calculate the angle α in the PLL.

5.2.5.3 IRQ

The wake up signal is serviced here. This allows the system to perform communication while the microcontroller is in the stand-by mode.

5.3 Program Load

The cycle time of the main routines was measured. The values obtained are given in the following table.

Routine	**Cycle time** (6MHz clock frequency)		
	Min.	**typical**	**Max.**
Start	22µs	~70µs	170µs
Body	25µs	~80µs	180µs
ISR-OC	55µs	84µs	90µs
ISR-IC	----	~25µs	----

Table 5-1.

5.4 Memory Map Usage

The figure below shows the overall memory usage for the system. It can be seen that very little ROM space is required by the system.

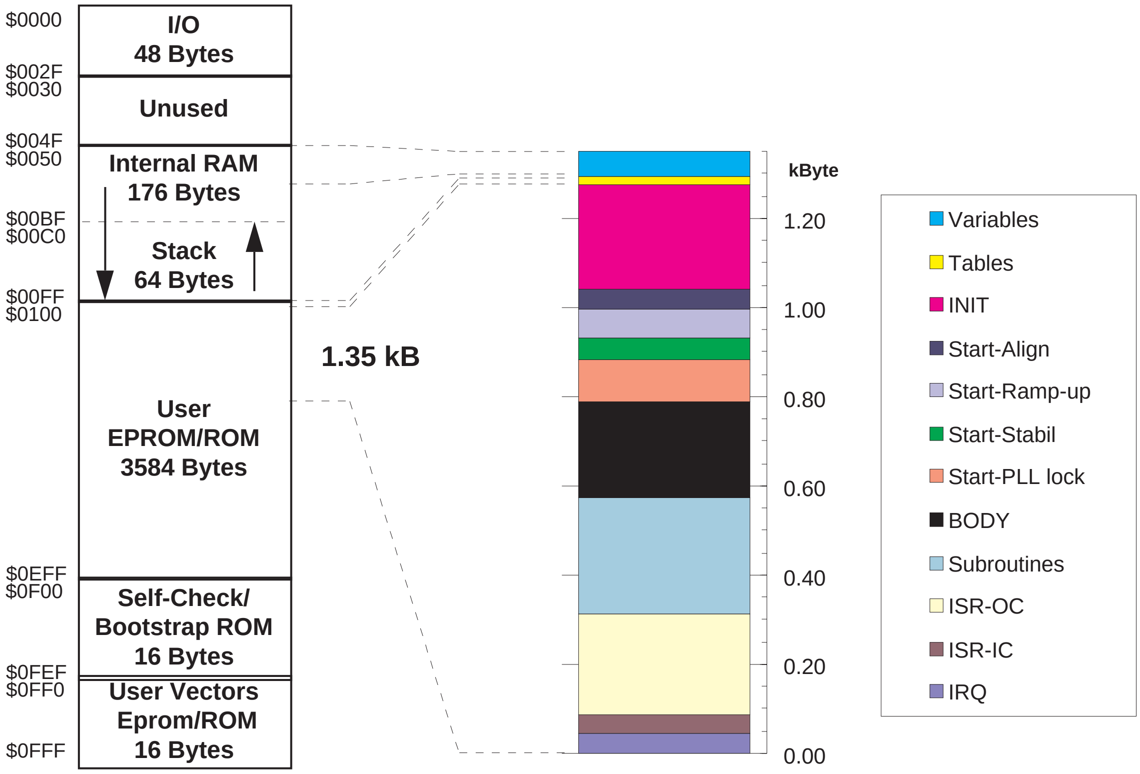

Figure 5-6. Memory Mapping

6 HARDWARE

6.1 Power Stage Board

6.1.1 Back-EMF sensing

An outline of the Back-EMF sensing circuit is shown below.

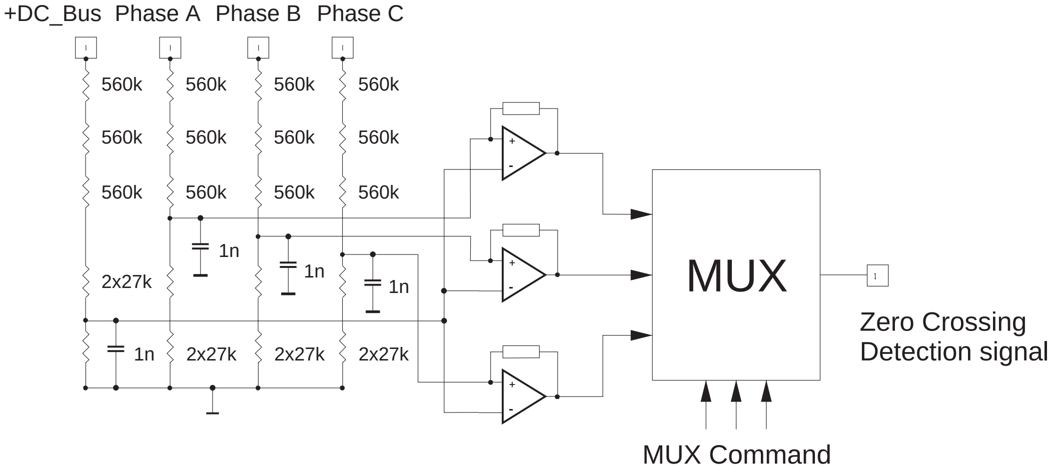

Figure 6-1. Back-EMF Sensing Circuit Diagram

As explained in the theoretical part of this application note, the phase zero crossing event can be detected at the moment when the branch voltage (of a free phase) crosses the half DC-bus voltage level. The resistor network is used to divide sensed voltages down to a 0-15V voltage level. The comparators sense the zero voltage difference of the input signal. The multiple resistors reduce the voltage across each resistor component to an acceptable level. A simple RC (54kΩ×1nF) filter prevents the comparators being disturbed by high voltage spikes produced by IGBT switching. The MUX selects the phase comparator output, which corresponds to the current commutation stage. This Zero Crossing Detection signal is transferred to the microcontroller's Input Capture pin (TCAP2).

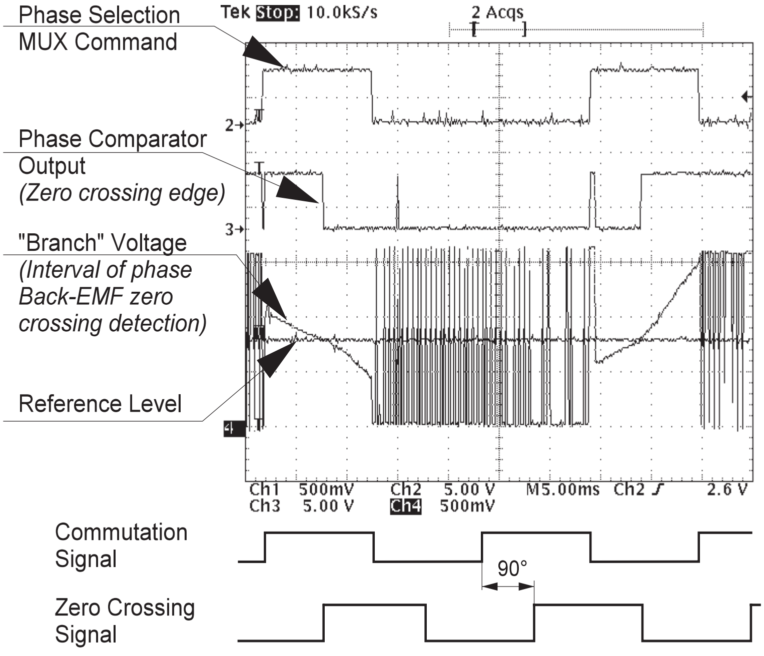

Figure 6-2. The Zero Crossing Detection

6.1.2 Current Sensing

In a star connected motor winding, the phase current can be sensed on the DC-Bus rail as each motor phase pair is energised. The voltage drop resistor (0,6Ohm/2W) is used to measure the DC-Bus current (0-4A), which is chopped by the PWM. The obtained signal is rectified and amplified (0-5V). The internal A/D converter is synchronized with the PWM signals (see Figure 5-5.). The current signal is converted 20µs before the end of the PWM “ON-time”. This synchronization avoids spikes when the IGBT’s are switching and simplifies the electric circuit. The over-current limit (3,6A) is detected by a comparator. This output is used to directly switch off the IGBT’s and for the IRQ interrupt input.

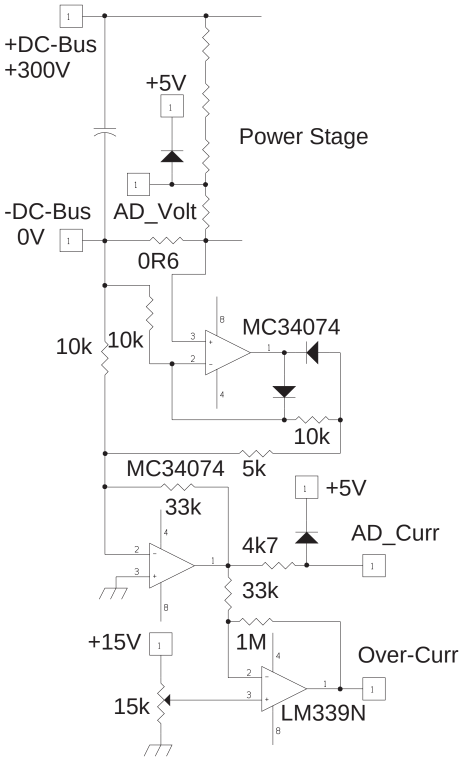

Figure 6-3. Current & Voltage Sensing

6.1.3 Voltage Sensing

The DC-Bus voltage is divided down-to a 5V signal level using a serial resistor network. This signal is used for over-voltage and under-voltage detection.

6.1.4 Power Devices

There are six MGP4N60ED IGBT’s (copack; with built-in fly back diode) driven by three IR2112 high voltage gate drivers.

Switching times, saturation voltage, and short circuit time of the IGBT’s have been optimized for motor drives. In addition, the gate threshold voltage is higher than usual for MOS gated power devices. The higher threshold eliminates the need for negative gate drive.

The high voltage driver IC's are designed to directly drive the gates of power MOS devices. They provide the level shifting that is required to drive high side bridge circuits commonly used in motor drives and other power applications. They are capable of withstanding floating supply offset voltages up to 600 volts. The Shut-down input of the IR2112 is used to switch off all IGBT’s when over-current detection is activated.

Detailed information about the power stage board can be found in the application note: AN1590 - “High Voltage Medium Power Board for Three Phase Motors”.

6.2 µC 68HC(7)05MC4 Board

The MC68HC(7)05MC4 is a low cost microcontroller especially dedicated for motor control. Due to this fact, the board schematic is very simple.

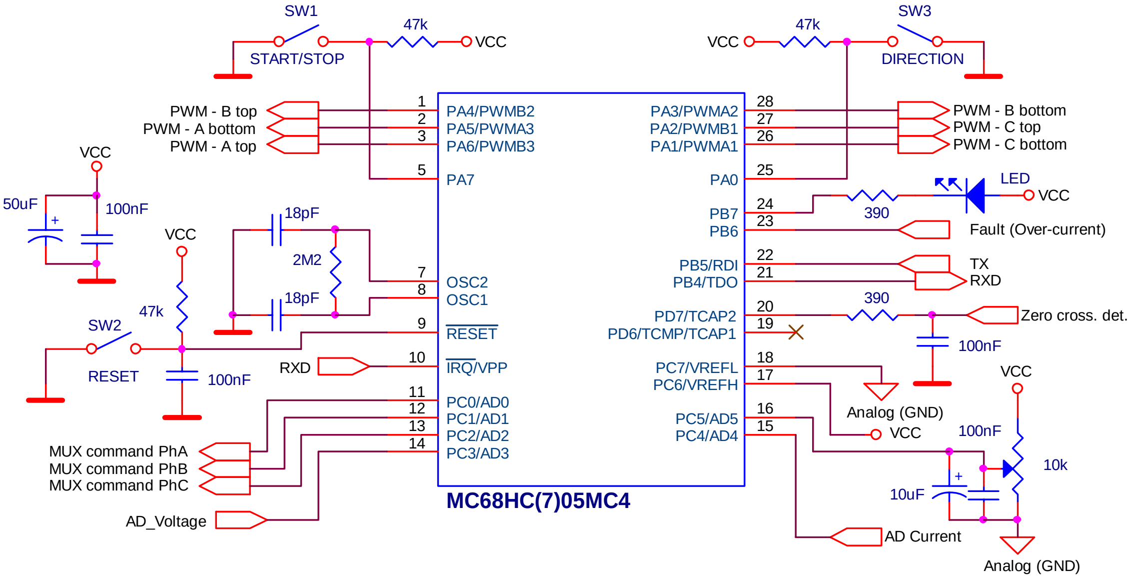

Figure 6-4. Microcontroller Board Schematic

There are no special requirements as long as common rules for microcontroller design are followed.

6.3 Power Supply Board

The rectified line voltage is filtered by a 100µF (400V) capacitor. The RFI filter and the Low-frequency (harmonic) filter are used to meet the new EMC regulation (IEC555-1).

Any type of power supply system (e.g. SMPS or classical centre-taped transformer) can be used to produce the auxiliary voltage levels (+15V, -15V and +5V).

This solution does have one limitation. The DC-Bus voltage can be 260V - 350V (the best case) which might not be sufficient for very large required speed range. The DC-Bus voltage should be three times higher (in star connection) than the phase Back-EMF voltage at maximal speed.

6.3.1 Meeting European Community Regulation IEC555-1

The application was designed to meet this regulation. The cheapest way often is to use one RF filter and one LF filter to improve the line current shape. The value of the inductance in the LF filter is a trade-off between power factor and current shape. It must be also kept in mind that any inductance before or after the mains rectifier decreases the DC-Bus voltage. This reduces the speed range this application can be used for.

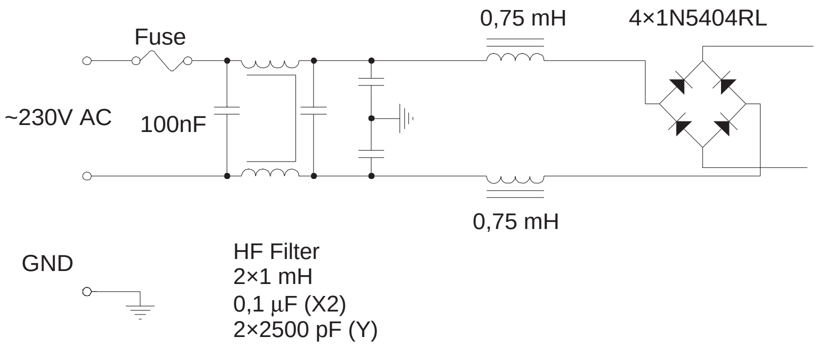

Figure 6-5. Main Power Supply Filters

6.4 Conclusion

The presented real application shows a typical system solution which was designed according to known market needs.

The microcontroller used is based on a HC05 core which is able to control such a low dynamic application and even more.The leftover memory space (>2kB) and performance capacity (free time is ~500µs each 1ms) are available for other application purposes. It allows one to design more sophisticated control algorithms or implement some customer code to perform other tasks (keyboard control, display control etc.) as well as serial communication.

But, a complete system solution depends not only on a microcontroller. Motor control design can be drastically simplified using integrated parts, such as co-pack IGBT's and integrated drivers, so that a low-cost target can be achieved.

APPENDIX A
MEASURED RESULTS

A.1 Power Stage Board

During the development it was important to find out if the power devices are suited for the application. Therefore a 30min test was performed. The temperature of the devices was checked to be within the range allowed by the manufacturer (105°C).

The gate resistance was 22Ohm. All IGBT's were in an upright position without heatsink and the temperature was measured on the central pin. The following table summarizes the obtained results. The maximal temperature does not exceed the allowed limit and the devices passed the test.

Device: MGP4N60ED TO220 Copack			
Settings		**Results**	
Load torque	0.97Nm	Motor phase current	1.13A mean 1.36A RMS 2.14A peak
Motor speed	1002RPM		
DC-Bus voltage	305.5V	Temperature at the start of the test	30.8°C
PWM frequency	3.9kHz	Temperature at the end of the test	80.0°C
Ambient temperature	23°C	Max.temperature during 30min test	81.1°C

Table 1.

A typical oscillogram of the phase current (Ch1; 1A/10mV), the branch voltage (Ch3) and one half of the DC-Bus voltage (Ch2) waveforms (Ch2 and Ch3 are divided by resistor network) was taken during the test. In the points where the channel 3 is crossing the channel 2, the Zero Crossing points are

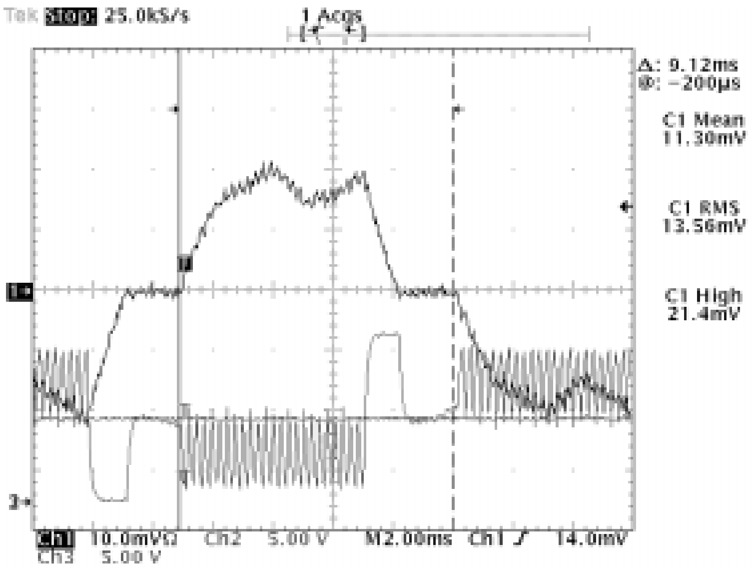

Figure 1. Measured waveforms

detected (see 2.2 Back-EMF Sensing). The alignment of the Back-EMF with the commutation events is good and the motor runs with high efficiency. The cursors define the time interval where the measurement of mean, RMS and peak values of the phase current are done. See results on the right side of the oscillogram.

A.1.1 Motor Load

The start-up capability of the drive was tested at more than 150% of the nominal load. The drive successfully reached the working speed (2400rpm) within 5s, as required. Figure 2. shows the obtained waveforms at the steady state condition.

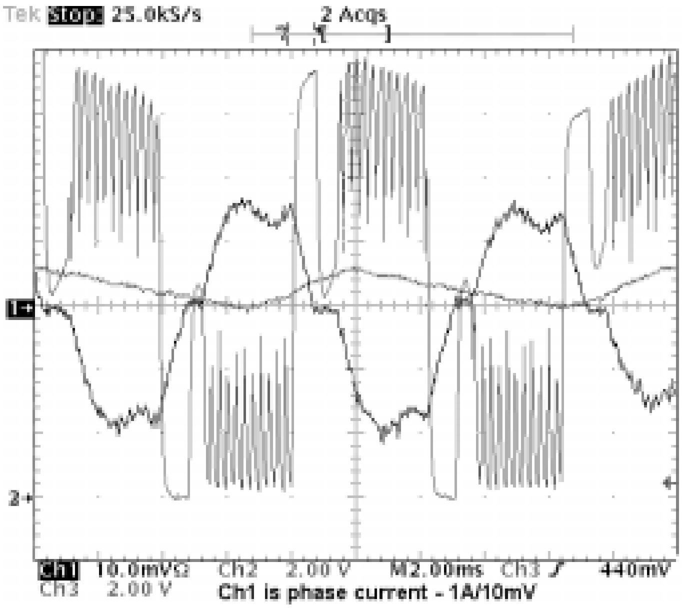

Figure 2.

Ch1 is the motor phase current, Ch2 is one half of the DC-Bus voltage and CH3 is the branch voltage Ch2 and Ch3 are divided by the resistor network down-to 0-15V level). The DC-Bus voltage is created by rectifying the mains and therefore channel 2 varies according to charging/discharging of the DC-Bus capacitor (10ms period). This variation has no impact on the Back-EMF zero crossing detection.

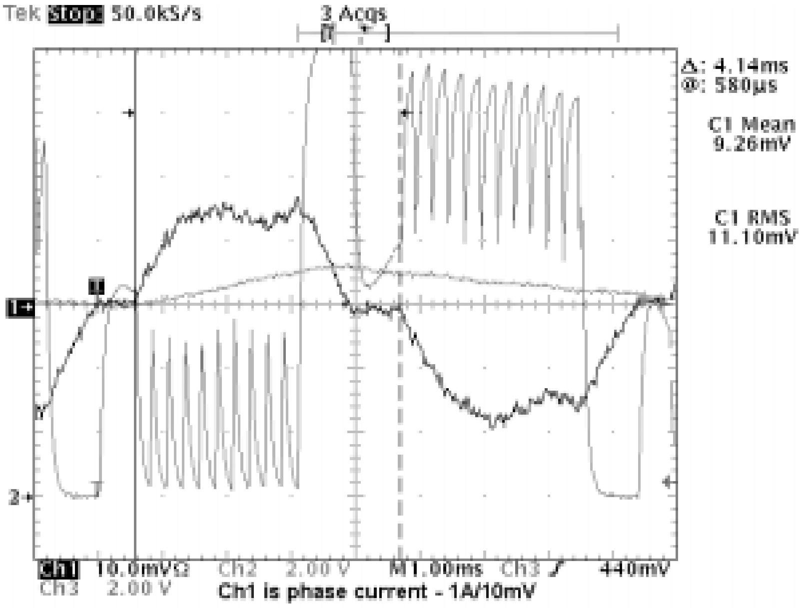

Figure 3.

A.2 Microcontroller Usage

The following tables show how much of the microcontroller MC68HC05MC4 was used to drive the sensorless application.

A.2.1 I/O Used

Table 2. summarizes the use of I/O pins. It can be found that six pins are still available.

I/O	Available pins	Used pins	Purpose
Port A	PA0-PA7	PA0	Direction command
		PA1-PA6	PWM
		PA	START/STOP command
Port B	PB4-PB7	PB4	Communication - TDO
		PB5	Communication - RDI
		PB6	Fault
		PB7	RUN LED
Port C	PC0-PC7	PC0-PC2	MUX command PhA-PhC
		PC3-PC7	AD3-AD5; VRefH/L
Port D	PD6-PD7	PD7	TCAP2 - Zero cross. detection
IRQ	IRQ	IRQ	Wake up signal
RESET	RESET	RESET	RESET

Table 2.

A.2.2 Modules Used

Motorola’s MC68HC05MC4 microcontroller offers many features which simplify the control of an application. The following table explains which function modules are used and their purposes.

Module	Used	Purpose
PWM	yes	PWM of motor phase voltage
A/D Converter	yes	Measurement of Speed Setting, DC-Bus current, DC-Bus voltage
Output Compare	yes	Commutation (software Timer2) and synchronization of A/D conv. with PWM (software Timer1)
Input Capture 1	no	
Input Capture 2	yes	Capture of edge of Zero Crossing Detection signal
SCI	no	
Core Timer	no	

Table 3.

A.2.3 Total RAM & ROM Used

The program was written with special care to reduce memory use in order to achieve the best result. Table 4. shows how much memory was needed to run the BLDC motor in the sensorless application. A significant part of memory is still available.

Memory	Available	Used
SRAM	176Bytes	60Bytes
User EPROM/ROM	3.5kBytes	1.35kBytes

Table 4.

Freescale Semiconductor, Inc.

All products are sold on Motorola's Terms & Conditions of Supply. In ordering a product covered by this document the Customer agrees to be bound by those Terms & Conditions and nothing contained in this document constitutes or forms part of a contract (with the exception of the contents of this Notice). A copy of Motorola's Terms & Conditions of Supply is available on request.

Motorola reserves the right to make changes without further notice to any products herein. Motorola makes no warranty, representation or guarantee regarding the suitability of its products for any particular purpose, nor does Motorola assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation consequential or incidental damages. "Typical" parameters which may be provided in Motorola data sheets and/or specifications can and do vary in different applications and actual performance may vary over time. All operating parameters, including "Typicals" must be validated for each customer application by customer's technical experts. Motorola does not convey any license under its patent rights nor the rights of others. Motorola products are not designed, intended, or authorized for use as components in systems intended for surgical implant into the body, or other applications intended to support or sustain life, or for any other application in which the failure of the Motorola product could create a situation where personal injury or death may occur. Should Buyer purchase or use Motorola products for any such unintended or unauthorized application, Buyer shall indemnify and hold Motorola and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that Motorola was negligent regarding the design or manufacture of the part. Motorola and Ⓜ are registered trademarks of Motorola, Inc. Motorola, Inc. is an Equal Opportunity/Affirmative Action Employer.

The Customer should ensure that it has the most up to date version of the document by contacting it local Motorola office. This document supersedes any earlier documentation relating to the products referred to herein. The information contained in this document is current at the date publication. It may subsequently be updated, revised or withdrawn.

Mfax is a trademark of Motorola, Inc.

How to reach us:

USA / EUROPE / Locations Not Listed: Motorola Literature Distribution;
P.O. Box 5405, Denver, Colorado 80217. 1–303–675–2140 or 1–800–441–2447

JAPAN: Nippon Motorola Ltd.; SPD, Strategic Planning Office, 141,
4–32–1 Nishi–Gotanda, Shinagawa–ku, Tokyo, Japan. 81–3–5487–8488

Customer Focus Center: 1–800–521–6274

Mfax™: RMFAX0@email.sps.mot.com – TOUCHTONE 1–602–244–6609
Motorola Fax Back System – US & Canada ONLY 1–800–774–1848
– http://sps.motorola.com/mfax/

ASIA / PACIFIC: Motorola Semiconductors H.K. Ltd.; 8B Tai Ping Industrial Park,
51 Ting Kok Road, Tai Po, N.T., Hong Kong. 852–26629298

HOME PAGE: http://motorola.com/sps/

MOTOROLA