APPLICATION NOTE

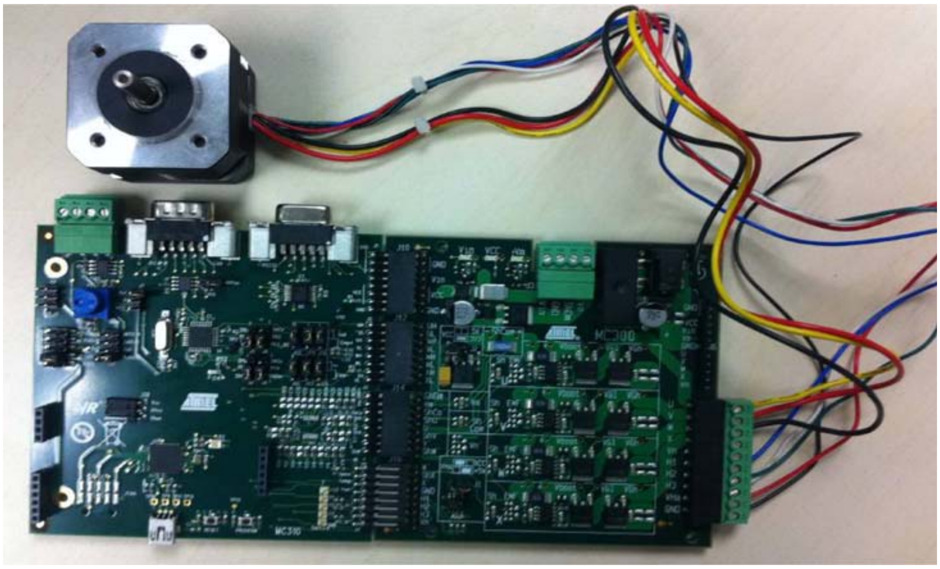
BLDC/BLAC Motor Control Using a Sinus Modulated PWM Algorithm with Atmel ATmega32M1

ATMEGA32M1 ON MC320

Features

- ATAVRMC300 Power Stage Board
- 1 ATAVRMC310 Device Board for the Atmel® ATmega32M1 AVR® Microcontroller
- 12V BLDC Motor Control with Sinus Waveform
- ISP and Emulator Interface

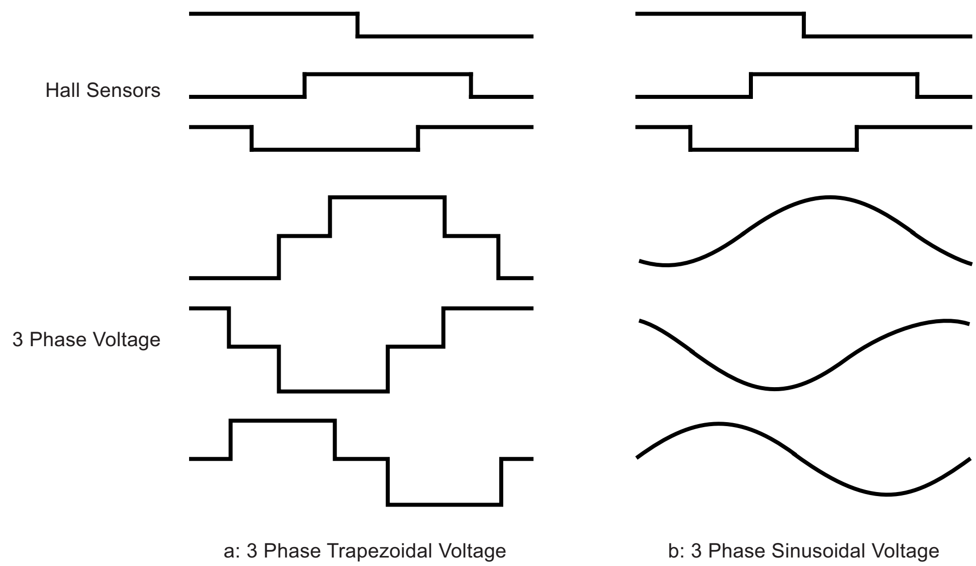
Figure 1. Demo Kit MC320



1. Introduction

Equipped with Hall effect sensors, permanent magnet motors are generally powered by currents of 'trapezoidal' shape (Figure 1-1a). In order to improve the system's performance (less noise, less torque ripple) it can be an advantage to power these motors using currents that have a ‘sinusoidal’ form (Figure 1-1b). BLDC motors are designed to be supplied with a trapezoidal shape current and BLAC motors are designed to be supplied with a sinusoidal shape current. This Application Note proposes implementation using the latter with an MC320 board mounted with an Atmel ATmega32M1.

Figure 1-1. 3 Phases Output Voltages vs. Hall Sensor Inputs



2. Operating Principle

2.1 Introduction

This implementation is based on the use of the Space-Vector Modulation (SVPWM) technique. The different sectors are determined and synchronized with the Hall sensors.

2.2 Principle of the Space-Vector Modulation

Figure 2-1. Typical Structure of the Application

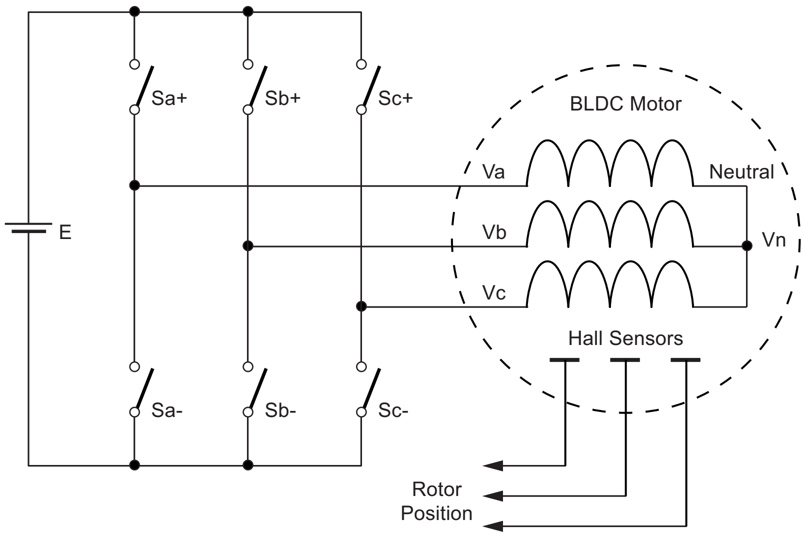


Figure 2-1 shows the typical structure of a BLDC/BLAC motor connected to a voltage source inverter. The motor is considered to have a balanced load with an unconnected neutral as follows:

Vn = (Va + Vb + Vc)/3

Van =Va – Vn = (Vab – Vca)/3

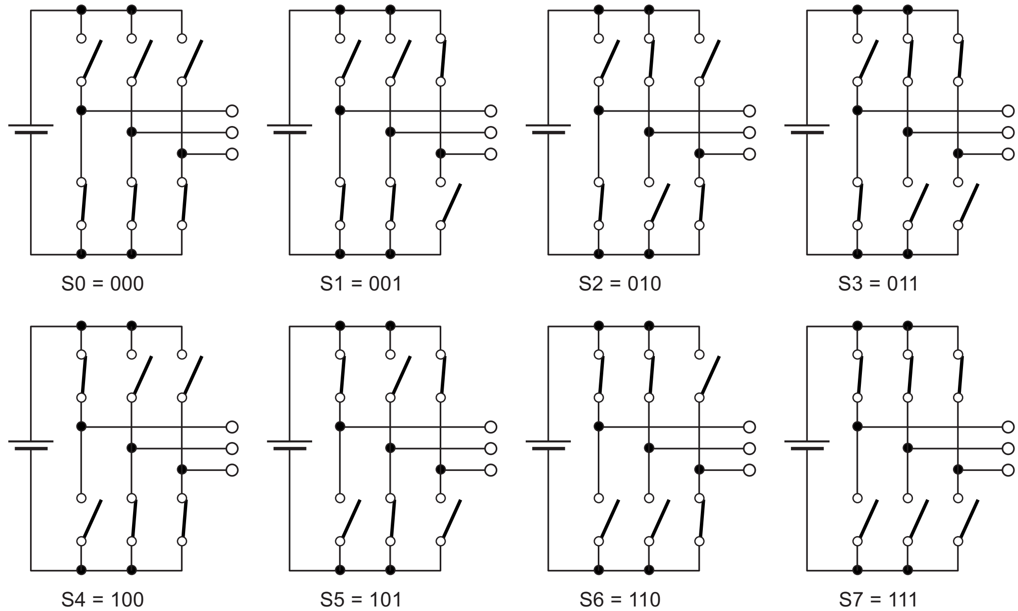
Vbn =Vb – Vn =(Vbc – Vab)/3

Vcn =Vc – Vn = (Vca – Vbc)/3

Because the upper power switches can only be ON or OFF, and because the lower ones are supposed to always be in the opposed state (the dead times of the inverter legs are neglected), there are only eight possible switching states, as shown in Table 2-2 on page 5. Six of them lead to non-zero phase voltages, and two interchangeable states lead to zero phase voltages. When mapped in a 2D frame fixed to the stator using a Concordia transformation [1,2], the six non-zero phase voltages form the vertices of a hexagon (see Figure 2-3 on page 4).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} = \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

Figure 2-2. Possible Switching Configurations of a 3-phase Inverter



As shown in Figure 2-3, the angle between two successive non-zero voltages is always 60°. In complex form, these non-zero phase voltages can be written as

$V_k = Ee^{j \times (k-1) \times \frac{\pi}{3}}$, with k = 1 to 6 and V0 = V7 = 0V.

Table 2-1 on page 5 shows the line-to-line and line-to-neutral voltages in each of the eight possible configurations of the inverter.

Figure 2-3. Representation of Eight Possible Switching Configurations in the Concordia Reference Frame

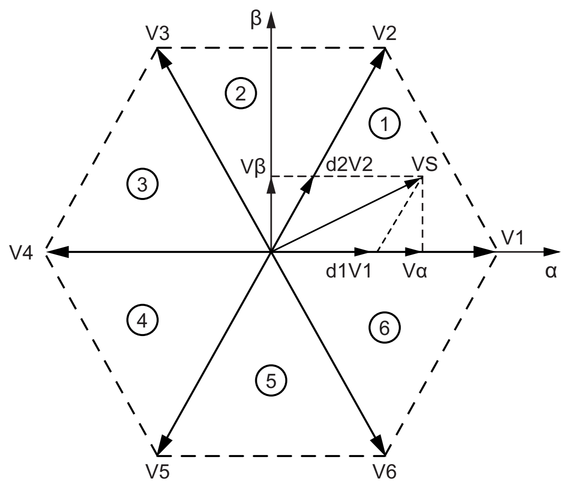


Table 2-1. Switching Configurations and Output Voltages of a 3-phase Inverter

S_{a+}	S_{b+}	S_{c+}	S_i	V_{ab}	V_{bc}	V_{ca}	V_{an}	V_{bn}	V_{cn}	V_α	V_β	V_i
0	0	0	S_0	0	0	0	0	0	0	0	0	V_O
0	0	1	S_1	0	–E	E	–E/3	–E/3	+2E/3	–E/2	$-E\sqrt{3}/2$	V_5
0	1	0	S_2	–E	E	0	–E/3	+2E/3	–E/3	–E/2	$E\sqrt{3}/2$	V_3
0	1	1	S_3	–E	0	E	–2E/3	–E/3	–E/3	–E	0	V_4
1	0	0	S_4	E	0	–E	+2E/3	–E/3	–E/3	E	0	V_1
1	0	1	S_5	E	–E	0	E/3	–2E/3	E/3	E/2	$-E\sqrt{3}/2$	V_6
1	1	0	S_6	0	E	–E	E/3	E/3	–2E/3	E/2	$E\sqrt{3}/2$	V_2
1	1	1	S_7	0	0	0	0	0	0	0	0	V_7

Table 2-2. Expression of the Duty Cycles in Each Sector

Sector Number	θ	d_k	d_{k+1}
1	$\left[0,\frac{\pi}{3}\right]$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{\pi}{3}-\theta\right)$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin(\theta)$
2	$\left[\frac{\pi}{3},\frac{2\pi}{3}\right]$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{\pi}{3}+\theta\right)$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{5\pi}{3}+\theta\right)$
3	$\left[\frac{2\pi}{3},\pi\right]$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin(\theta)$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{4\pi}{3}+\theta\right)$
4	$\left[\pi,\frac{4\pi}{3}\right]$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{5\pi}{3}+\theta\right)$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin(2\pi-\theta)$
5	$\left[\frac{4\pi}{3},\frac{5\pi}{3}\right]$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{4\pi}{3}+\theta\right)$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{\pi}{3}-\theta\right)$
6	$\left[\frac{5\pi}{3},2\pi\right]$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin(2\pi-\theta)$	$\frac{2}{\sqrt{3}}\times\frac{V_S}{E}\times\sin\left(\frac{\pi}{3}+\theta\right)$

In the Concordia frame, any stator voltage $V_S = V_\alpha + jV_\beta = V_{sm}\cos(\theta) + jV_{sm}\sin(\theta)$ located inside this hexagon belongs to one of the six sectors and can be expressed as a linear combination of the two non-zero phase voltages which delimit this sector: $V_S = d_kV_k + d_{k+1}V_{k+1}$. Equating $d_kV_k + d_{k+1}V_{k+1}$ to $V_{sm}\cos(\theta) + jV_{sm}\sin(\theta)$ in each sector leads to the expressions of the duty cycles shown in Table 2-2. Because the inverter cannot generate instantaneously the space vector PWM principle consists in producing a T_S-periodic voltage whose average value equals V_S, by generating V_k during $T_k = d_kT_s$ and V_{k+1} during $T_{k+1} = d_{k+1}T_s$. Because $d_k + d_{k+} \le 1$, these voltages must be completed over the switching period T_s by V_0 and/or V_7. Several solutions are possible, and the one which minimizes the total harmonic distortion of the stator current consists in applying V_0 and V_7 during the same duration

$$T_0 = T_7 = \frac{1 - d_k - d_{k+1}}{2}\times T_s$$

V_0 is also applied at the beginning and at the end of the switching period, whereas V_7 is applied at the midpoint. As an illustration, the upper side of Figure 2-4 on page 6 shows the waveforms obtained in sector 1.

2.3 Efficient Implementation of the SV-PWM

Table 2-2 on page 5 indicates that the duty cycles have different expressions in each sector. A thorough study of these expressions show that because sin(x) = sin(π – x) all these duty cycles can be written in a unified way as

$$d_k = \frac{2V_{sm}}{E\sqrt{3}}\sin(\theta'') \text{ and } d_{k+1} = \frac{2V_{sm}}{E\sqrt{3}}\sin(\theta') \text{, with } \theta'' = \frac{\pi}{3} - \theta' \text{ and } \theta' = \theta - (k-1)\frac{\Pi}{3}.$$

Because these expressions no longer depend on the sector number, they can be denoted as d_a and d_b. Because θ' is always between 0 and π/3, computing d_a and d_b requires a sine table for angles inside this interval only. This greatly reduces the amount of memory required to store this sine table.

The Atmel ATmega32M1 provides the 3 Power Stage Controllers (PSC) needed to generate the switching waveforms computed from the space vector algorithms.

The counters will count from zero to a value corresponding to one-half of the switching period (as shown on the lower side of Figure 2-4), and then count down to zero. The values that must be stored in the three compare registers are given in Table 2-3 on page 7.

Figure 2-4. Inverter Switch Waveforms and Corresponding Compare Register Values

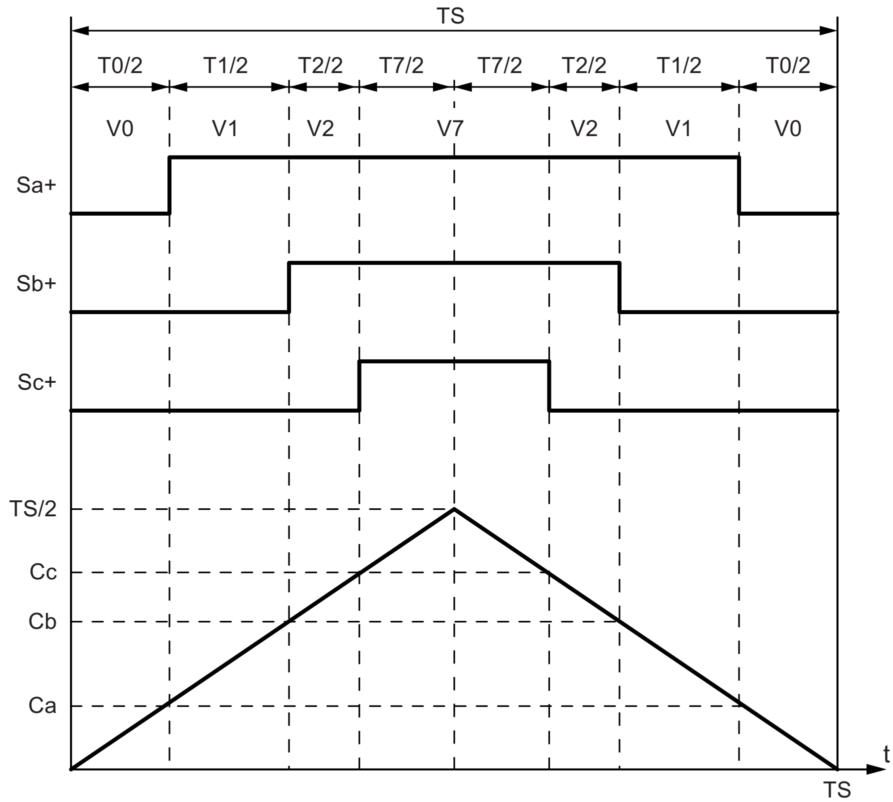


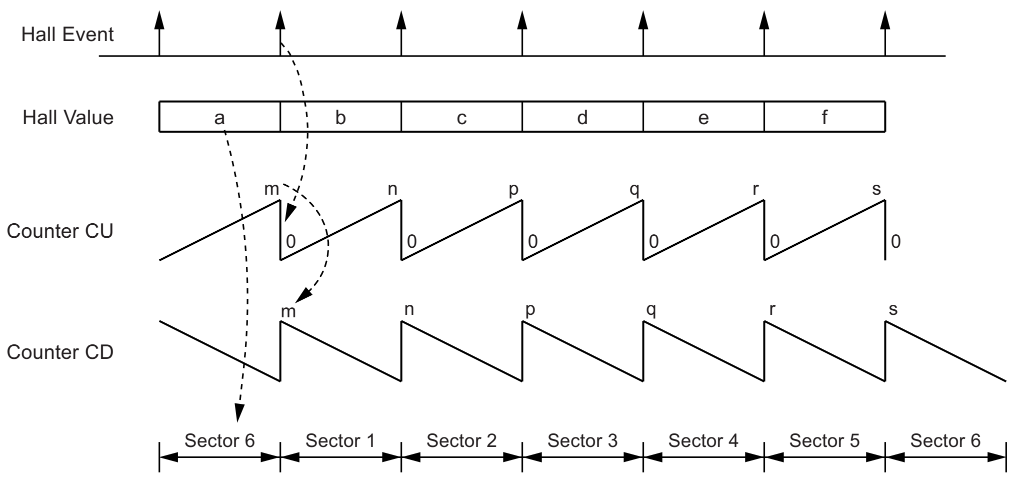
Table 2-3. Compare Register Values vs. Sector Number

Sector Number	$4/T_s \times C_a - 1$	$4/T_s \times C_b - 1$	$4/T_s \times C_c - 1$
1	$-d_a - d_b$	$d_a - d_b$	$d_a + d_b$
2	$-d_a + d_b$	$-d_a - d_b$	$d_a + d_b$
3	$d_a + d_b$	$-d_a - d_b$	$d_a - d_b$
4	$d_a + d_b$	$-d_a + d_b$	$-d_a - d_b$
5	$d_a - d_b$	$d_a + d_b$	$-d_a - d_b$
6	$-d_a - d_b$	$d_a + d_b$	$-d_a + d_b$

2.4 Sector Determination Algorithm

The sector determination is based on readings from the three Hall sensors. All along one electrical revolution, the three Hall sensors generates six steps. These six steps divide the circle into six sectors which are used in the SVPWM (see Figure 2-5).

Figure 2-5. Sector Determination



Inside one sector the counter CU is incremented at a rate given by a high frequency reference clock. At the end of the sector the counter CU is copied into the counter CD. Then this counter CD is decremented by the same reference rate. This counter CD reflects the value of the angle ϑ of Vs vector inside a sector (see Figure 2-6 on page 8). For example, during sector 1 counter CU is incremented from 0 to n. At Hall event counter CU is copied into counter CD. Then during sector 2 counter CU is incremented and counter CD is decremented. Counter CD drives the rotation of the vector Vs (see Figure 2-6 on page 8).

Figure 2-6. Rotation of Vs Vector

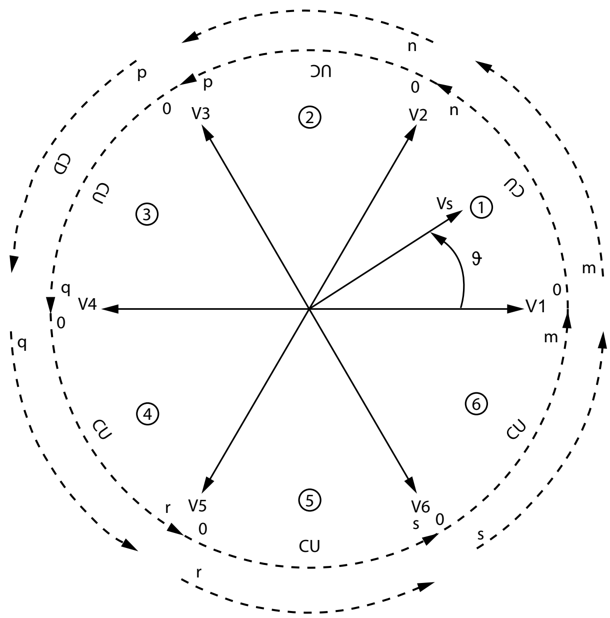
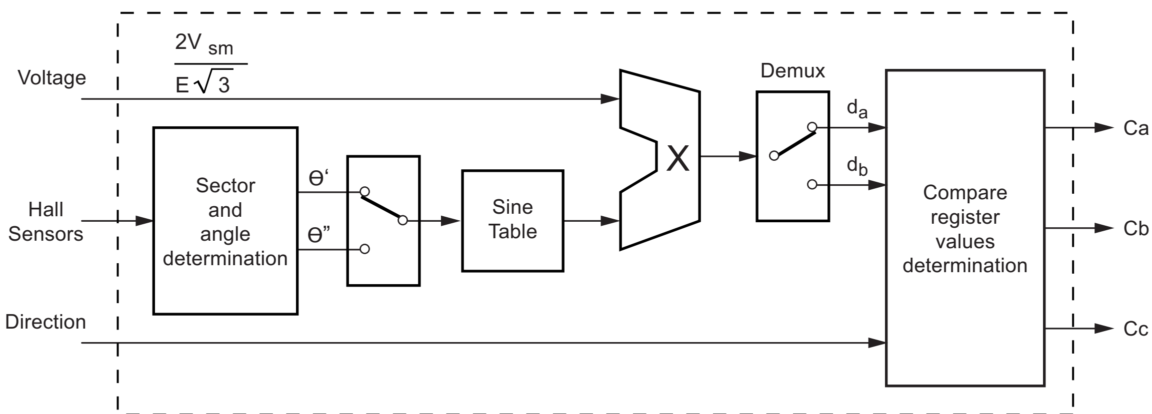


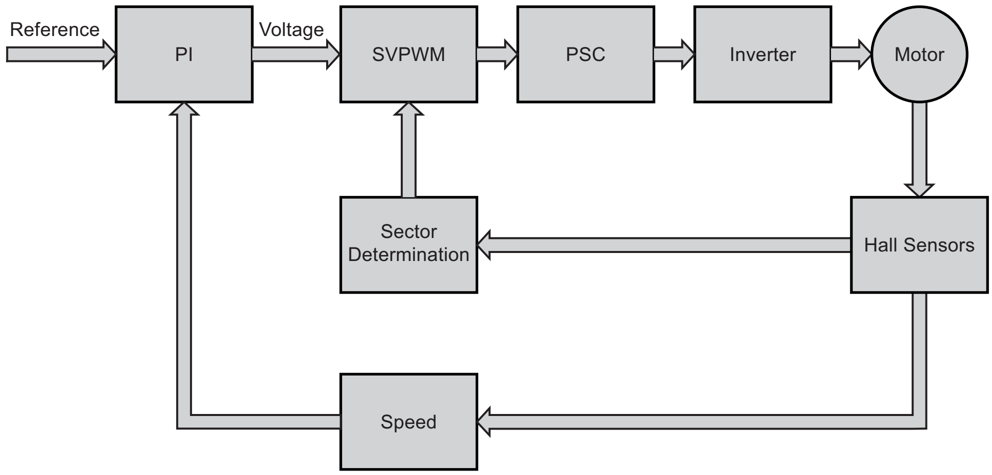
Figure 2-7 shows the data flow of the implementation of this SVPWM core. The Hall sensors indicate the sector number and the two angles ϑ' and ϑ''. These angles point to a sine table. The sine value is multiplied by the voltage to calculate d_a and d_b. Then d_a and d_b are used to determine the compare values sent to the PSC (see Figure 2-4 on page 6).

Figure 2-7. Space Vector PWM Data Flow Diagram



The resulting dataflow diagram, shown on Figure 2-7 on page 8, can be used to build a speed control loop (Figure 2-8 on page 9) in which the difference between the desired speed and the measured speed feeds a PI controller that determines the stator voltage frequency.

Figure 2-8. Block Diagram of the Complete System



3. Hardware Description

This application is available on the MC320 evaluation kit equipped with an Atmel ATmega32M1. This board provides a way to start and experiment with BLDC and BLAC motor control. The main features of the MC320 are:

- Atmel ATmega32M1 microcontroller
- 12VDC motor drive
- ISP and emulator interface

Figure 3-1. Connecting the BLDC Motor

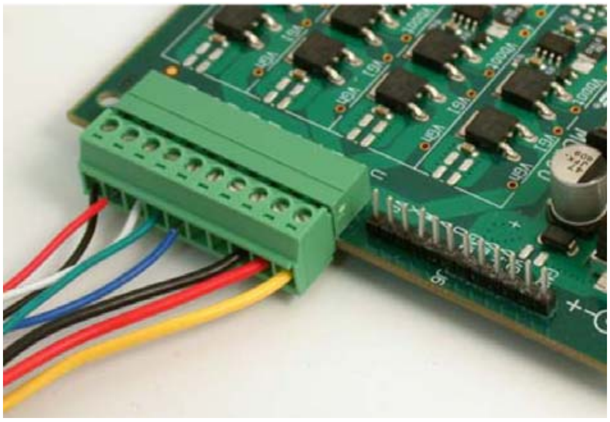


Table 3-1. Signals

J7 Signals	Motor Wires
U	Thin yellow
V	Thin red
W	Thin black
X	Not connected
Vn	Not connected
H1	Thin blue
H2	Thin green
H3	Thin white
VHa	Thin red
GND	Thin black

4. Software Description

All algorithms have been written in the C language using IAR Embedded Workbench® and AVR Studio® as development tools. For the space vector PWM algorithm, a table of the rounded values of

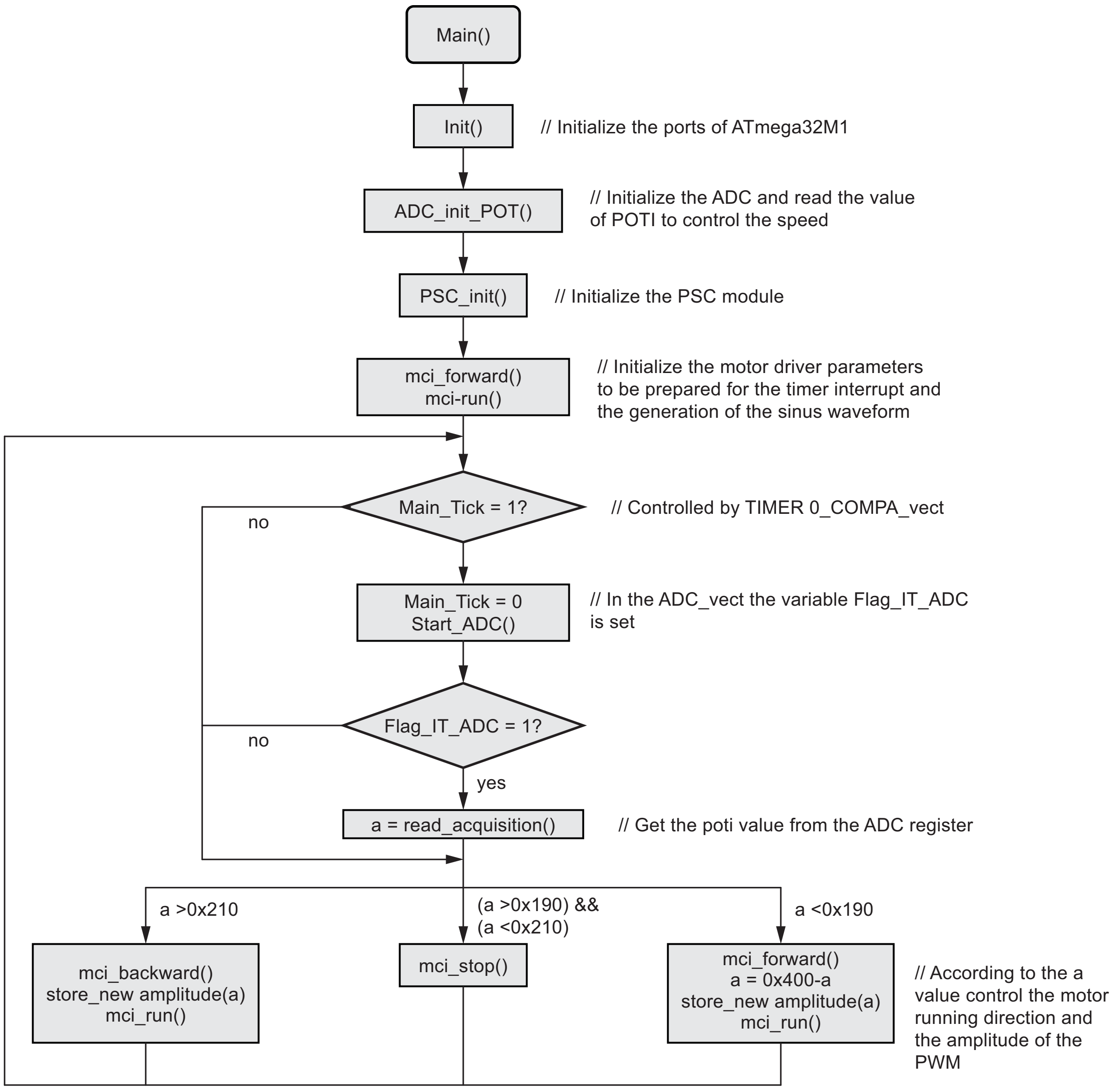
$$127\sin\left(\frac{2\pi k}{480}\right)$$

for k between 0 and 80 is used. The length of this table (81 bytes) is a better trade off between the size of the available internal memory and the quantification of the rotor shaft speed. For bi-directional speed control, the values stored in two of the comparators are interchanged when the output of the PI regulator is a negative number (see Figure 2-8 on page 9).

4.1 Project Description

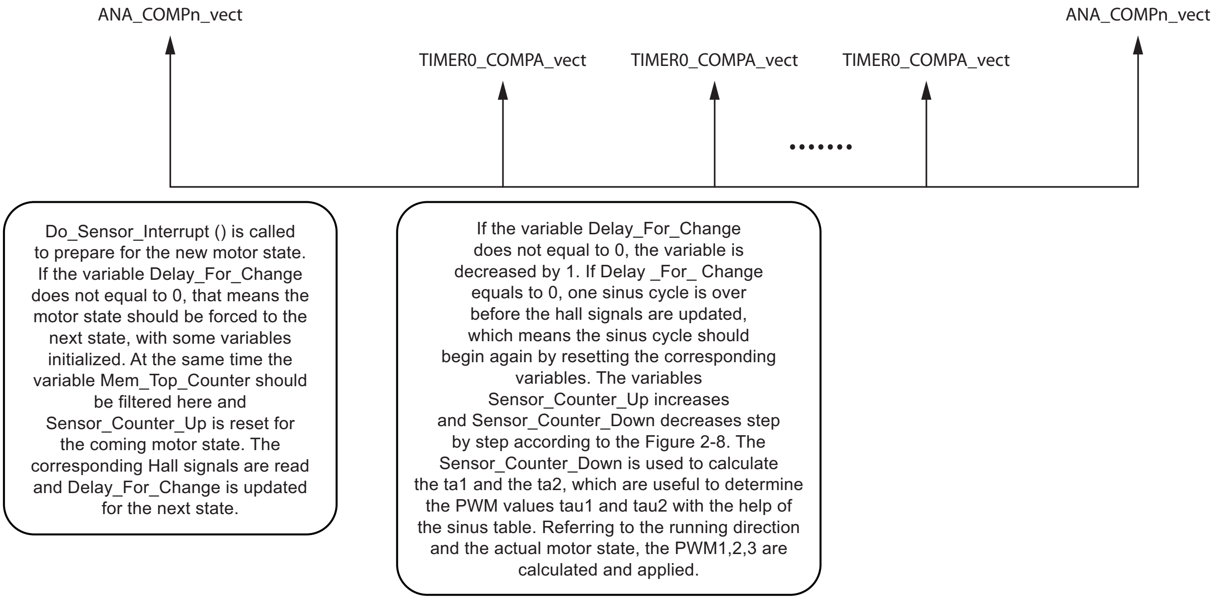
In Figure 4-1 the flow chart of the main routine is described. In the main() all the necessary modules are initialized and in the while(1) endless circle the value of the potentiometer is updated based on the Timer0 compare interrupt. The value of the potentiometer is used to control the motor, including the running direction and the speed.

Figure 4-1. Flow Chart of Main()



While the motor is running the comparator interrupts ANA_COMPn_vect and the timer0 A compare interrupts TIMER0_COMPA_vect play the most important role. The comparator interrupts are triggered by the Hall sensor signals to indicate the commutation time point. The timer0 A compare interrupts calculate the two variables tau1 and tau2 through the variables Sensor_Counter_Down, in order to select the corresponding values from the sinusoidal table. The following Figure 4-2 shows how the algorithm works.

Figure 4-2. Motor State Commutation



4.2 Resources

The values include all the application resources (main, serial communication,...)

2 472 bytes of CODE memory

1 684 bytes of DATA memory

Timer 0 is used for speed measurement/main tick/svpwm

Timer 1 is not used

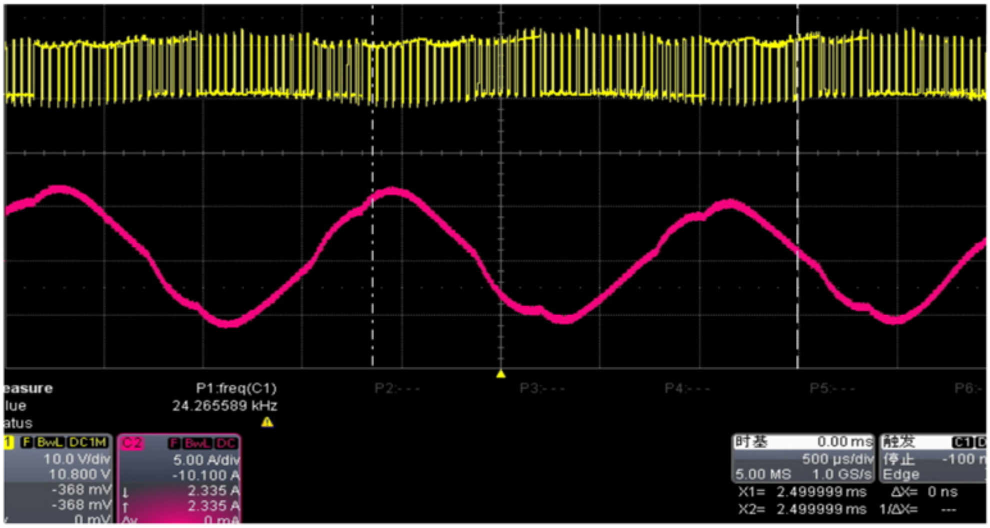
PSC0, 1, and 2 are used to generate PWM

ADC is used for current measurement. It is synchronized by PSC on the PWM waveform.

4.3 Experimentation

Figure 4-3 shows the voltage and the sinusoidal current on the U motor phase. With the SV-PWM algorithm presented above the sinus waveform BLDC motor control can be realized flawlessly on the MC320 with the Atmel ATmega32M1.

Figure 4-3. Voltage and Current on the U Motor Phase



5. Revision History

Please note that the following page numbers referred to in this section refer to the specific revision mentioned, not to this document.

Revision No.	History
9276B-AVR-04/15	• Put document in the latest template

Enabling Unlimited Possibilities®

Atmel Corporation 1600 Technology Drive, San Jose, CA 95110 USA **T:** (+1)(408) 441.0311 **F:** (+1)(408) 436.4200 | **www.atmel.com**