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# AVR1607: Brushless DC Motor (BLDC) Control in Sensor mode using ATxmega128A1 and ATAVRMC323

## Features

- BLDC Motor Basics
- Hardware Implementation
- Code Example

## References

- [1] ATxmega128A1 Data sheet
- [2] AVR430: MC300 Hardware User Guide
- [3] AVR1014: MC303 Hardware User Guide
- [4] AVR601: Atmel Modular Evaluation Kits for Motor Control Applications

## Glossary

BLDC : Brushless DC

PWM : Pulsed Width Modulation

IGBT : Insulated Gate Bipolar Transistor

AWEX : Advanced Waveform Extension

## 1 Introduction

This application note describes how to implement a control of Brushless DC motor (BLDC) in sensor mode using the ATxmega128A1, Atmel® AVR® microcontroller and the ATAVRMC323 development kit.

This application note deals only with BLDC motor control application using Hall effect position sensors to control commutation sequence.

In this document, we will give a short description of brushless DC motor theory of operations. We will detail how to control a brushless DC motor in sensor mode and we will also provide a short description of the ATAVRMC303 and ATAVRMC300 boards used in this application note.

Software implementation is also discussed with software control loop using a PID filter.



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Microcontrollers

Application Note

Rev. 8311A-AVR-07/10



## 2 Brushless DC motor Theory of Operation

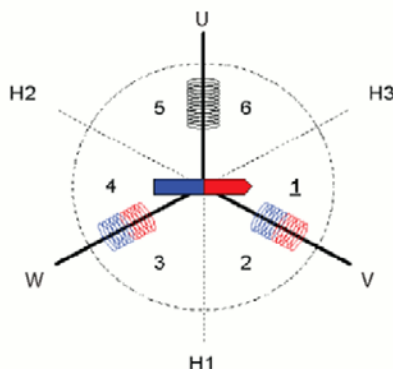
### 2.1 Simplified Model of a BLDC Motor

A simplified model of a three phases BLDC motor stator consists of three coils arranged in three directions U, V and W (Figure 1).

A permanent magnet forms the rotor. The rotor in a BLDC motor consists of an even number of permanent magnets. The number of magnetic poles in the rotor also affects the step size and torque ripple of the motor. More poles provide smaller steps and less torque ripple. The permanent magnets go from 1 to 5 pairs of poles. In certain cases it can go up to 8 pairs of poles.

Here the rotor is outlined as a bar magnet with its rotary axis at the intersection of the three axes U, V, W perpendicular to the plane of these axes. The orientation/position of the permanent magnet can be controlled by driving a configuration of currents through the three coils. The bar magnet comes to position sector 1 when a current is driven from W through V and it comes to the following orientation (sector 2) when a current is driven from W to U.

**Figure 1. Simplified Model of a BLDC Motor**



### 2.2 Six-step commutation

The method for energizing the motor windings in the sensor method described in this application note is the six-step commutation. Each step, or sector, is equivalent to 60 electrical degrees. Six sectors make up 360 degrees, or one electrical revolution.

The arrows in the winding diagram Figure 2 show the direction current flows through the motor windings in each of the six sectors.

The graph (Figure 3) shows the voltage applied at each lead of the motor during the six sectors. Sequencing through these six sectors moves the motor one electrical revolution.

For every sector, two windings are energized and the third winding is floating (not energized).

Connecting the coils to the power and neutral bus induces the current flow. This is referred to as trapezoidal commutation or block commutation.

Figure 2. Model of a BLDC Motor with current flows versus rotor positions

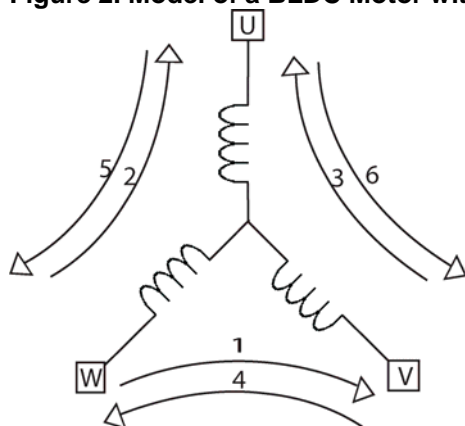
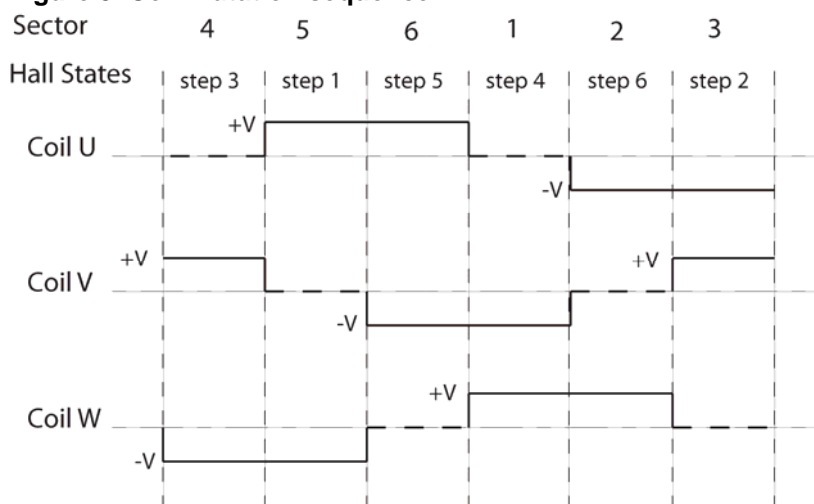


Figure 3. Commutation sequence



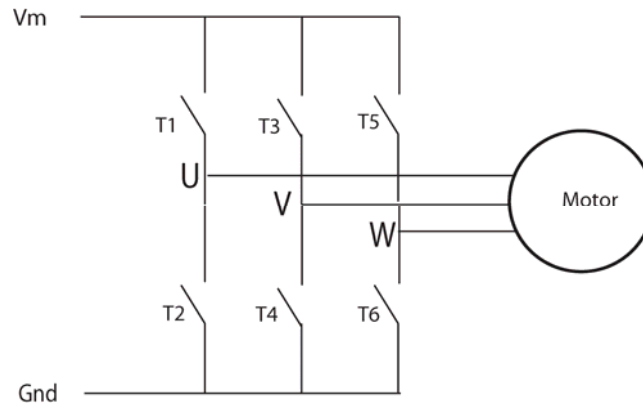
Notes :

- Open phase is the one shown with dotted line.
- Hall states are detailed in 2.4 section

## 2.3 Power Stage

The commutation pattern is controlled with a 3-phase bridge (see Figure 4). The 3 half bridges have 6 power switches (IGBT or MOSFET transistors) which are switched according to the defined commutation pattern.

Figure 4. 3-phases bridge

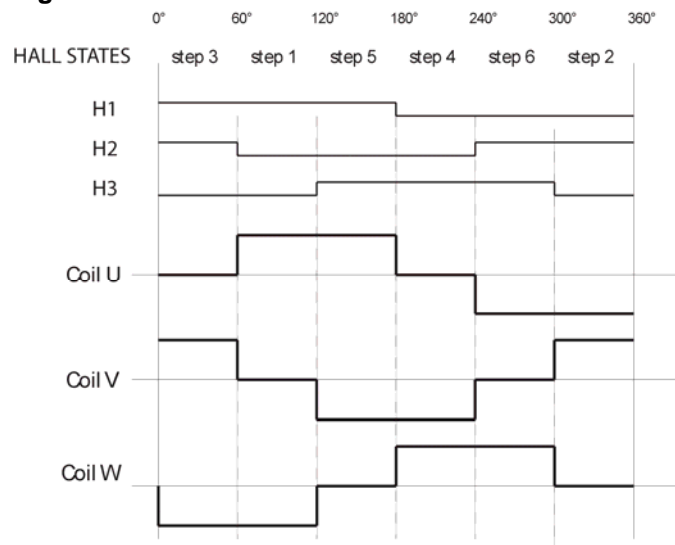


## 2.4 Hall sensors

For the estimation of the rotor position, the motor is equipped with three hall sensors. These hall sensors are placed every 120°. With these sensors, 6 different commutations are possible. Phase commutation will depend on these hall sensor values.

Figure 5 shows the three Hall sensors signals H1,H2,H3 as motor turns using sensor control. Hall states are the combination result of H1,H2,H3 signals.

**Figure 5. Hall states versus Motor leads in Sensor mode**



With a motor of  $n$  pairs of poles, the hall sensors frequency is  $n$  times faster than the motor rotation.

## 2.5 Phase Commutations

Power supply to the coils must be changed when hall sensor values change. With right synchronized commutations, the torque remains nearly constant and high.

Reading hall sensors values (HS\_XXX variable) indicates which new scheme should be switched.(see following table)

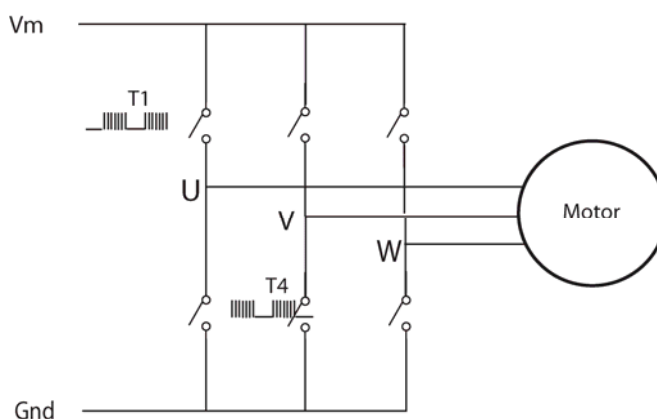
**Table 1-1.** Switches commutation for CW rotation

Hall Sensors Value (H1 H2 H3) = HS_XXX	Hall States	Previous Phases	Previous scheme	Next Phases	Next scheme
110	3	V-W	T3 ; T6	U-W	T1 ; T6
100	1	U-W	T1 ; T6	U-V	T1 ; T4
101	5	U-V	T1 ; T4	W-V	T5 ; T4
001	4	W-V	T5 ; T4	W-U	T5 ; T2
011	6	W-U	T5 ; T2	V-U	T3 ; T2
010	2	V-U	T3 ; T2	V-W	T3 ; T6

For motors with multiple poles the electrical rotation does not correspond to a mechanical rotation. A motor with n pair of poles BLDC motor uses n electrical rotation cycles to have one mechanical rotation.

The strength of the magnetic field determines the force and speed of the motor. By varying the current flow through the coils, the speed and torque of the motor can be adjusted. The most common way to control the current flow is to control the average current flow through the coils. PWM (Pulse Width Modulation) is used to adjust the average voltage and thereby the average current, inducing the speed. For example, the PWM frequency selected is the range from 10kHz to 200kHz according to the application (commutation losses, audible frequency...).

**Figure 6.** PWM scheme



Commutation creates a rotating field.

For instance at Step 5, Phase U is connected to the positive DC bus voltage through T1 and Phase V is connected to ground through T4, Phase W is unpowered. Two flux vectors are generated by phase U and phase V. The sum of the two vectors creates the stator flux vector. Then the rotor tries to follow this stator flux.

As soon as the rotor reaches the given position, the hall sensors state changes its value from "101" to "001" a new voltage pattern is selected and applied to the BLDC



motor. Then Phase U is unpowered and Phase W is connected to the positive DC bus, resulting in a new stator flux vector 'Step 4'.

Following the commutation schematic Figure 5 and Table 1-1, we get six different stator flux vectors corresponding to the six commutation steps. These six steps provide one electrical revolution.

### 3 ATxmega128A1 microcontroller

Based on the high performance AVR 8-bit RISC architecture, the ATxmega128A1 integrates all of the basic peripherals necessary to satisfy the needs of complex algorithms.

The ATxmega128A1 has all necessary resources to provide an integrated solution to control BLDC motors in their system environments.

#### 3.1 Timer/Counters

ATxmega128A1 provides 16-bit timers/counters with :

Four Compare or Capture (CC) Channels in Timer/Counter 0

Two Compare or Capture (CC) Channels in Timer/Counter 1

To generate PWM frequency, this Application Note uses three compare channels (A,B,C) of Timer0 and the Advanced Waveform Extension (AWEX) additional feature to Timer 0. AWEX function is available for ports C and E (Port C is used in this Application Note).

The benefits of AWEX features for motor control are :

- Complementary outputs from each Capture channel
- Four Dead Time Insertion (DTI) which avoid cross conduction
- **Separate High and Low Side Dead-Time Setting**
- Double Buffered Dead-Time
- Event Controlled Fault Protection
- Single Channel Multiple Output Operation
- Double Buffered Pattern Generation

The output pairs go through a Dead-Time Insertion (DTI) unit that enables generation of the non-inverted Low Side (LS) and inverted High Side (HS) of the WG output with dead time insertion between LS and HS switching. The DTI output will override the normal port value according to the port override setting.

The Fault Protection unit is connected to the Event System. This enables any event to trigger a fault condition that will disable the AWEX output. Several event channels can be used to trigger fault on several different conditions.

#### 3.2 Analog features

ATxmega128A1 integrates also analog blocks like :

- Two Eight-channel, 12-bit, 2 Msps Analog to Digital Converters, with programmable gain options.

The inputs per ADC are :

- 8 single ended inputs

- 8x4 differential inputs with selectable 1/2/4/8/16/32/64x gain
- Four Analog Comparators with Window compare function, with selectable comparison levels, and interrupts on pin change I/Os.

The ATxmega128A1 includes independent positive and negative comparator inputs available for over-current detection. The Input selection can be achieved from pins :

- Pins 0, 1, 2, 3, 4, 5, 6 for positive input
- Pins 0, 1, 3, 5, 7 for negative input

Its reference (comparison level) can be fixed via the DAC output or any external reference voltage :

- Output from 12-bit DAC
- 64-level scaler of the VCC, available on negative analog comparator input
- Bandgap voltage reference

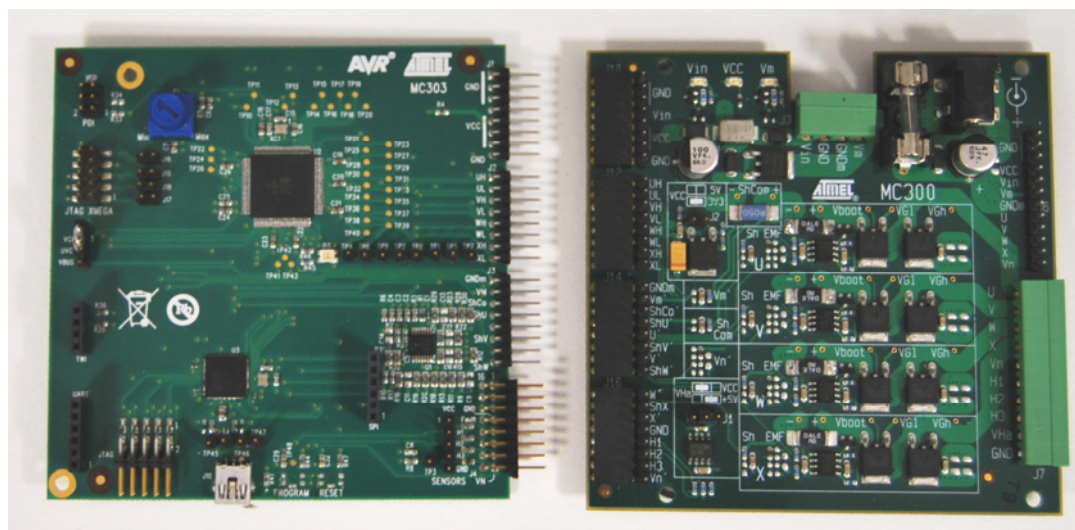
Refer to the ATxmega128A1 Data sheet for the complete description of the ATxmega128A1 microcontroller.

## 4 Hardware description

This application has been developed with ATAVRMC300 and ATAVRMC303 boards which are the two parts of the ATAVRMC323 Starter kit..

The ATAVRMC300 board is the power board which embeds the power bridge is connected (see below) to the ATAVRMC303 which is the processor board built around the ATxmega128A1 processor.

**Figure 7. MC303 and MC300**



Please refer to the ATAVRMC300 and ATAVRMC303 Application Notes :

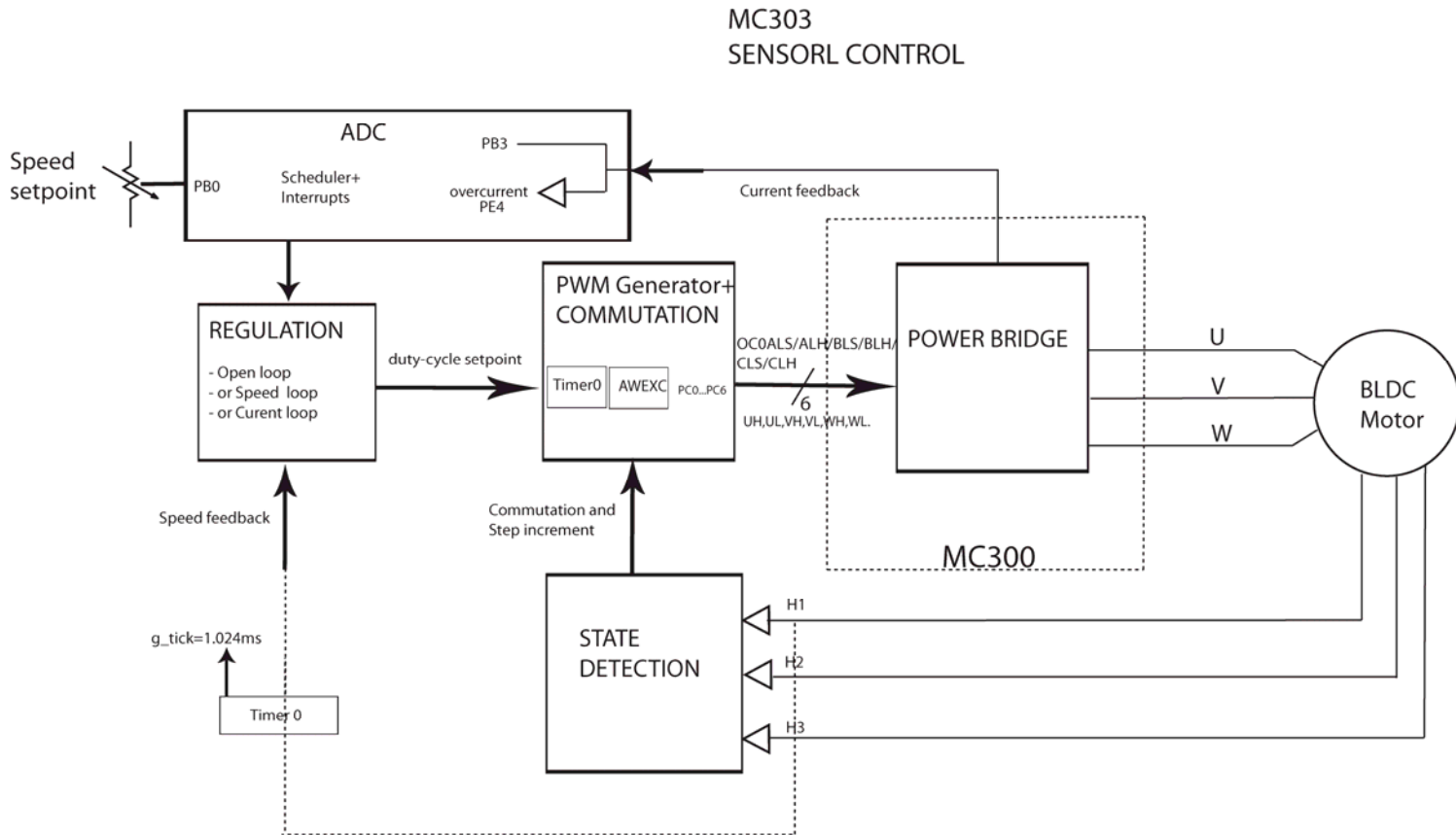
- AVR430: MC300 Hardware User Guide
- AVR1014: MC303 Hardware User Guide

which also provide boards schematics.

## 4.1 Hardware implementation

The block diagram of the sensor closed loop is following :

**Figure 8. System block diagram**



The outputs UH, UL, VH, VL, WH & WL of AVR303 are used to control the power bridge (see Table 1-2). As previously seen, they depend on the Timer0 and AWEX which generates PWM signals.

An external comparator on MC303 board provides a fault signal (Fault\_overcurrent) connected to PE4 input.:

The compared inputs are the shunt\_pos and AVCC/ 34. Shunt\_pos is the voltage monitored across the 0.05 ohm resistor, and equals the motor current divided per 20. So the comparator output will toggle as soon as motor current  $I_m$  will be :

$$I_m / 20 > AVCC / 34$$

So limit is :  $I_m > 2.94 \text{ A}$

**Table 1-2. Microcontroller I/O ports use (TQFP100 package)**

PORT A			
PA0	95	U_cond_neg	U Reference for zero-crossing <b>(Not used)</b>
PA1	96	V_cond_neg	V Reference for zero-crossing <b>(Not used)</b>
PA2	97	U_conditioned	= U / 6 <b>(Not used)</b>



PA3	98	V_conditioned	= V / 6 <b>(Not used)</b>
PA4	99	W_conditioned	= W / 6 <b>(Not used)</b>
PA5	100	Vn_conditioned	Neutral voltage / 34 <b>(Not used)</b>
PA6	1	Vm	<b>(Not used)</b>
PA7	2	W_cond_neg	W Reference for zero-crossing <b>(Not used)</b>
<b>PORTB</b>			
PB0	5	Speed_ref	Speed Potentiometer (MC303)
PB1	6		
PB2	7	Current_reference	= AVCC / 34
PB3	8	Shunt_pos	0.05 ohm shunt voltage ( = motor current / 20)
PB4	9	Shunt_neg	GND of Vmotor
PB5	10	Shunt_U	= Shunt_pos <b>(not used)</b>
PB6	11	Shunt_V	= Shunt_pos <b>(not used)</b>
PB7	12	Shunt_W	= Shunt_pos <b>(not used)</b>
<b>PORTC</b>			
PC0	15	UL	Drives T1 power transistor of MC300
PC1	16	UH	Drives T2 power transistor of MC300
PC2	17	VL	Drives T3 power transistor of MC300
PC3	18	VH	Drives T4 power transistor of MC300
PC4	19	WL	Drives T5 power transistor of MC300
PC5	20	WH	Drives T6 power transistor of MC300
<b>PORT E</b>			
PE0		H1	Hall sensor 1 signal
PE1		H2	Hall sensor 2 signal
PE2		H3	Hall sensor 3 signal
PE4		Fault_overcurrent	External comparator ( MC303)output
PE5		Fault_IPM	<b>(Not used)</b>
<b>PORT H</b>			
PH0		ZC_U	Zero crossing external comparator output : sensorless mode <b>(Not used)</b>
PH1		ZC_V	Zero crossing external comparator output : sensorless mode <b>(Not used)</b>
PH2		ZC_W	Zero crossing external comparator output : sensorless mode <b>(Not used)</b>

## 4.2 MC300 configuration and use

The power board must be supplied with a 12V, 2A, DC Power Supply.

**Table 1-3. ATAVRMC300 jumper settings**

Jumper	Position	Comment
J1(VHa)	Pin1 & 2 shorted	VHa = +5V
J2(VCC)	Open	Vcc = +5V

## 4.3 MC303 configuration and use

The jumpers configuration of the MC303 processor board is following :



**Table 1-4. ATAVRMC303 jumper settings**

Jumper	Position	Comment
J15	Open	Shunt_neg (Jumpers to be removed to enable JTAG Programming)
J16	Open	Shunt_U (Jumpers to be removed to enable JTAG Programming)
J17	Open	Shunt_V (Jumpers to be removed to enable JTAG Programming)
J18	Open	Shunt_W (Jumpers to be removed to enable JTAG Programming)

## 4.4 Power-supply

This firmware example has been configured according to a power-supply  $V_m=12V$ .

This power-supply must be able to provide up to 4A output current.

## 4.5 Motor

The BLDC motor provided inside MC323 and MC300 Motor Control Kit has the following characteristics:

Manufacturer : TECMOTION

Number of phases : 3

Number of poles : 8 (4 pairs)

Rated voltage : 24V

Rated speed : 4000 rpm

Rated torque : 62.5 Nm

Torque constant : 35 Nm/A =  $k_{\tau}$

Line to Line Resistance : 1.8 ohm = R

Back EMF : 3.66 V/Krpm =  $k_e$

Peak current : 5.4A

Maximum speed is 6900 rpm.

## 4.6 Technical Advices

### 4.6.1 Disconnecting the BLDC Motor

The BLDC motor must not be disconnected while it is running or while its coils carry current. It is allowed to disconnect a BLDC motor if the PWM duty cycle is 0% and the rotor is at rest so that no current is driven through the coils. Be careful, when stopping the power supply or PWM, a BLDC motor with a high moment of inertia is able to run for a relatively long time.

#### **4.6.2 Ground and Power Wirings**

One design its own board has to take care of the ground wiring and power wiring. The power supply of the processor and additional signal conditioning components (e.g. additional fast comparators, operational amplifiers) has to be decoupled from the motor power supply. The ground connection has to be of low resistance and low inductance to prevent against voltage drop and noise due to high currents. A ground plane within a multi layer PCB is recommended for proper operation.

## **5 Firmware**

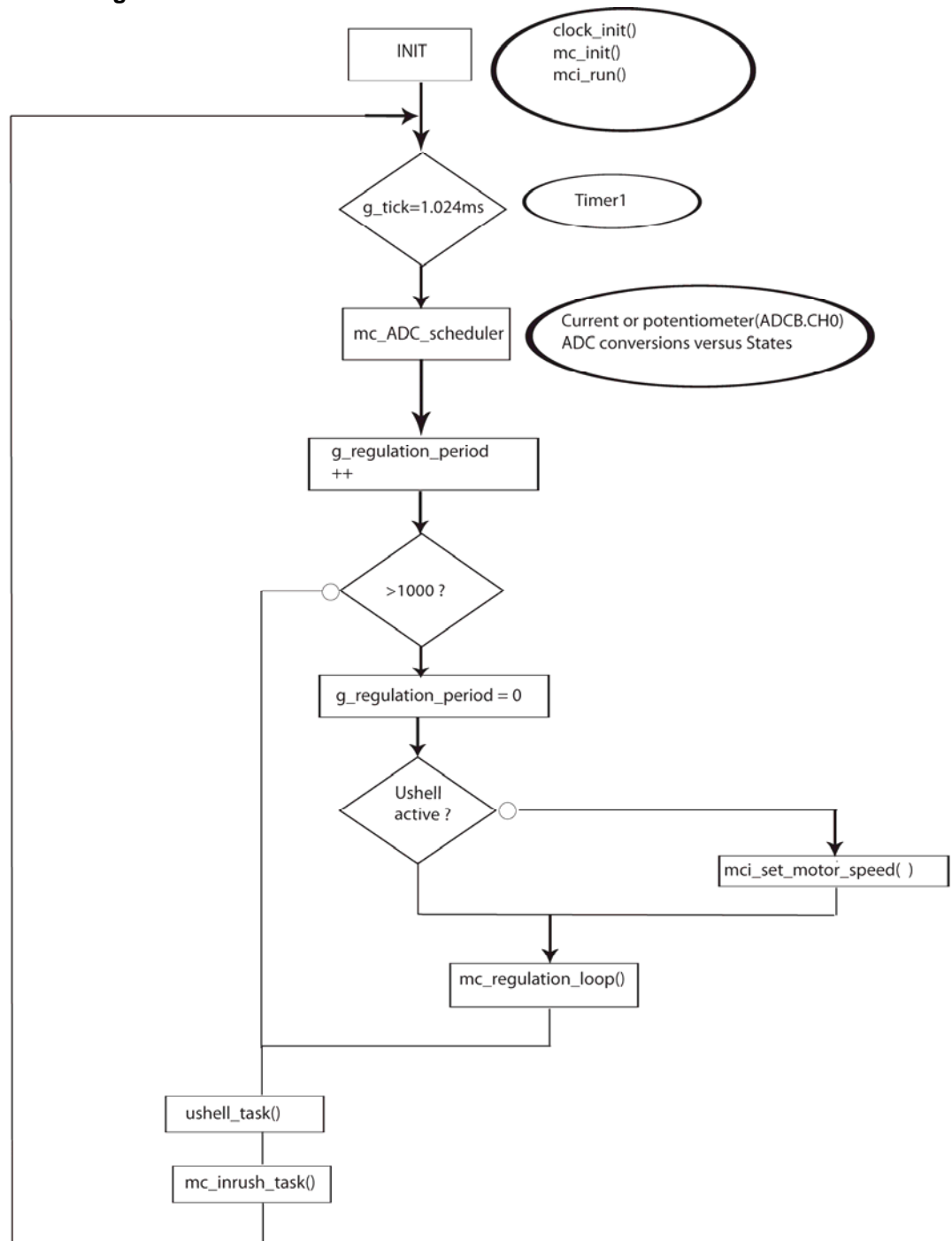
The source file directory embeds an html documentation which can be opened through the readme.html file.

The application to ATxmega128A1 is detailed in following sections.

### **5.1 Main Flow chart**

The firmware flowchart is described below :

Figure 9. Main flow chart



The tasks are scheduled thanks to the g\_tick produced each 1.024ms with Timer1.

## 5.2 INIT : Initialisation functions

The initialization functions are following

### 5.2.1 clock\_init()

- Oscillator : 32MHz RC oscillator and OSC oscillator
- PLL : clock source=32MHz and factor =16
- Prescalers: PSADIV=1 and PSB and PSCDIV=2 : means  $\text{clk\_PER4} = 128\text{MHz}$ ,  $\text{clk\_PER2} = 64\text{MHz}$  and  $\text{clk\_PER} = 32\text{MHz}$

### 5.2.2 mc\_init()

- Port C : pins 0 to 5 are in output mode and clear (DIRSET and OUTCLR=1) are the outputs connected to transistor power bridge
- Port E : The input pull up are activated to connect the Hall sensor signals
- External Interrupts are defined on Port E Pins0/1/2 (Hall signals)
- Timer 0 configuration is :

Clock prescaler /4 (8MHz)

PWM\_Init (255) configures a PWM frequency = 15686 kHz

- Timer1 configuration is :

No Clock prescaler and period=8000 produces a g\_tick each 1.024 ms

- ADCB configuration is :

- calibration/offset

- signed conversion mode and 12 bit resolution.

- ADC prescaler to a Sample rate of CPUFREQ/16. Allow time for storing data. \*/

- Set reference voltage to VCC-0.6 V

- Setup channel 0 to have single ended input and gain=1

- Set input to the channels in ADC B to be PIN 0

- Enable ADC B with free running mode

## 5.3 Regulation functions

The main loop functions are following.

### 5.3.1 mci\_set\_motor\_speed ()

This function updates the speed setpoint according to the potentiometer adjustment or the speed command received on serial transmission.

**mc\_get\_potentiometer\_value()** returns mc\_potentiometer\_value

### 5.3.2 mc\_regulation\_loop() :

The duty\_cycle variable controls the PWM generator. This variable is the result of following functions :

in Open loop mode : **duty\_cycle = mc\_get\_motor\_speed()**

in Speed loop mode : **duty\_cycle = mc\_control\_speed(mc\_get\_motor\_speed())**

in Current loop mode :





```
duty_cycle = mc_control_current(mc_get_potentiometer_value())
```

## 5.4 Commutation

The phase commutation has to be achieved according to the 3 Hall sensors. Commutation between steps is achieved when a rising or falling edge occurs on one of the 3 Hall sensor signals.

Hall sensor signals H1/H2/H3 are connected to PE0/PE1/PE2 which are configured as interrupt sources.

(Another solution could be using internal comparators to generate interrupts.)

Port Interrupt 0 Mask is defined as :

```
sfrb PORTE_INT0MASK = 0x068A
```

Are also defined :

```
#define PORTE_INT0MASK    PORTE.INT0MASK  
PORTE.INT0MASK = (PIN0_bm | PIN1_bm | PIN2_bm);
```

This means that PORTE\_INT0\_vect (HALL-A()) is executed if any of the three Hall sensor signal is changing.

This interrupt vector executes :

- The transistor commutation according to the HALL\_SENSOR\_VALUE :  
HALL\_SENSOR\_VALUE is the value of the 3 Hall sensor bits = PORTE.IN & 0x07  
The commutation is achieved by the function :  
**mc\_switch\_commutation(HALL\_SENSOR\_VALUE)**
- and estimation of speed on Rising edge of H1 (Hall A) sensor. This means the speed is evaluated one time per electrical cycle.

### 5.4.1 mc\_switch\_commutation()

This function achieves two operations:

- First, the update of the duty-cycle, thanks to function  
**mc\_duty\_cycle(mc\_get\_Duty\_Cycle())**

This is achieved with the update of the Output new compare value of the Timer:

**TC\_SetCompareA( &TCC0, level );** which updates CCABUF register with new compare value

**TC\_SetCompareB( &TCC0, level );**

**TC\_SetCompareC( &TCC0, level );**

The dead time insertion is achieved with **ConfigDTI()** function which configures a dead Time both sides equal to 3.

- and secondly, a switch of the power bridge according to next expected position and the direction of the rotation.

AWEX feature, described previously is configured on PortC.

Port C0 to C5 are the UH/UL/VH/VL/WH/WL outputs.

An example of Hall detection and the resulting actions is described below:

```
case HS_001: if (direction==CCW) {Set_Q1Q6();}
              else                {Set_Q5Q2();}
```

According to Table 1-1, the scheme following the Hall state 001 is T5 and T2 transistors ON (in CW direction)

**Set\_Q5Q2()** instruction executes the AWEX operation :

AWEX\_SetOutoutOverride(AWEXC,PIN5\_bm | PIN0\_bm)

which drives the Pins 0 and 5 connected to gate of T5 and T2 transistors.

## 6 RS232 Communication with firmware

### 6.1 Connecting ATAVRMC303 to use the RS232 interface

Connect PC com port to the ATAVRMC303 RS232 connector through a direct cable.

The serial configuration is:

- 38400 bauds,
- 8 bit data bit,
- 1 stop bit,
- no handshake,

### 6.2 PC applications

User can communicate with firmware through RS232 with usual PC serial communication applications (i.e. Hyperterminal) or the Atmel "Motor Control Center" application which can be downloaded from Atmel web at url : <http://www.atmel.com>

#### 6.2.1 PC Terminal : RS232 Messages and Commands

At power up the following welcome message is received on terminal :

"ATMEL Motor Control Interface".

The following commands can be sent to the firmware:

**Table 1-5. List of commands**

Command	Action
<b>ru</b>	<b>Run motor</b>
<b>st</b>	<b>Stop Motor</b>
<b>help</b>	<b>Gives help</b>
<b>fw</b>	<b>Set direction to Forward</b>
<b>bw</b>	<b>Set direction to Backward</b>
<b>ss</b>	<b>Set Speed (followed with speed value)</b>
<b>gi</b>	<b>Get ID</b>
<b>g0</b>	<b>Get Status 0</b>
<b>g1</b>	<b>Get Status 1</b>

### 6.2.2 Motor Control Center

The User Guide is available in Install directory at URL :C:\Program Files\Atmel\Motor Control Center\help\Overview.htm

First, the communication must be achieved with the MC303 :

Select :

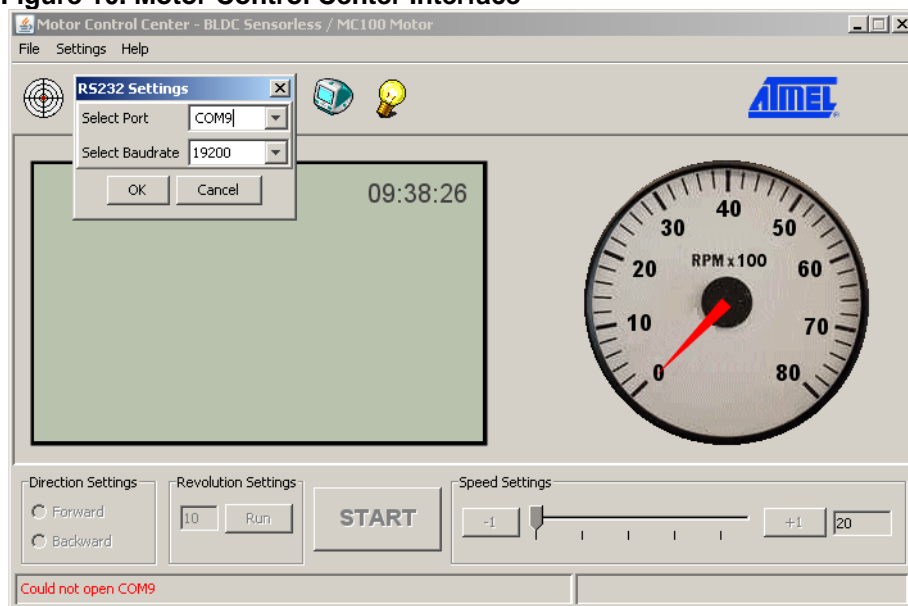
Settings -> Target communication -> RS232

Then force the COM port number to the one which has been enumerated as cdc (i.e. COM9 in Figure 10)

The AVR1607 Target must then be selected to get the right configuration : to

select, this target, execute the **File > Select Target** command or click the  button in the toolbar. The following dialog pops up:

**Figure 10. Motor Control Center Interface**





## **7 USB communication**

Communication can be achieved from PC to USB connector of MC303 board.

The AVR1014, MC303 Hardware User Guide details the configuration to be achieved.

Communication port becomes a Virtual Com port which must be forced in RS232 Settings window.

Same tools and commands as described in section 6 can be used through this Virtual Com port.



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