AVR493: Sensorless Commutation of Brushless DC Motor (BLDC) using AT90PWM3 and ATAVRMC100

AVR Microcontrollers

Application Note

1. Introduction

This application note describes how to implement a sensorless commutation of BLDC motors with the ATAVRMC100 developement kit. Starting with a simple model of the BLDC motor, the basis of sensorless commutation will be explained. Technical constrains and outcoming requirements for the implementation will be described. The goal of this application note is to give all information that are relevant for an implementation of sensorless commutation using the AT90PWM3. The AT903PWM3 is equipped with integrated peripherals that reduce the number of external components in a BLDC application.

Sensorless commutation saves the cost of position sensors, wiring, and connectors compared to BLDC motors driven in sensor mode using Hall sensors. Without Hall sensors, the assembly of the motor is simplified. This reduce the motor and system costs.

Due to physical constrainst, sensorless commutation requires a minimum speed to work. Sensorless commutation is suitable for those applications where a motor turns at speed beyond this limit. The AT90PWM3 is suitable for sensorless commutation and for commutation with Hall sensors as well.

This application note focuses on the sensorless commutation. Nevertheless, Hall sensors are referred in place of position sensors for clarification. Sensorless commutation is suitable for applications with speed beyond a speed limit like fans or pumps where the mechanical load does not change abruptly. These applications fit well with sensorless commutation.

7658B–AVR–12/06

2. BLDC Motor Theory

Brushless DC motors (BLDC) are more reliable than standard DC (mechanically commutated) motors. DC motors start turning when a supply voltage is applied, but BLDC motors require electronics for commutation. Speed control or remote control of a BLDC motor requires electronics as for mechanically commutated DC motors. BLDC motor are more suitable for control and regulation. Operating a BLDC motor in sensorless beyond its typical speed limit makes it similar to a BLDC motor equipped with Hall sensors.

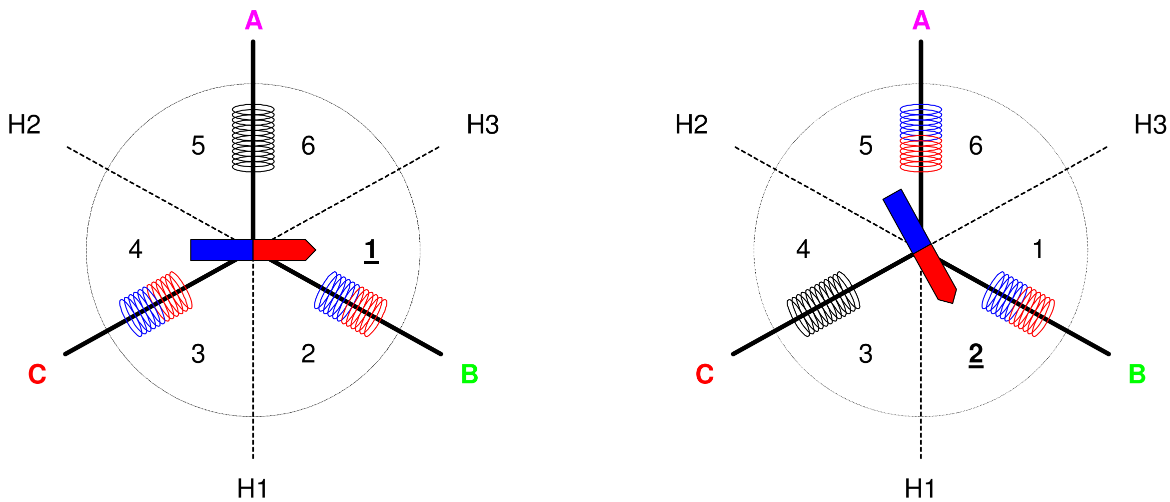
2.1 Simplified Model of a BLDC Motor

A simplified model of a BLDC motor consists of three coils arranged in three directions A, B and C (See Figure 2.1). A permanent magnet forms the rotor. Here the rotor is outlined as a bar magnet with its rotary axis at the intersection of the three axes A, B, C perpendicular to the plane of these axis. The orientation resp. position of the permanent magnet can be controlled by driving a configuration of currents through the three coils. The bar magnet comes to position **1** when a current is driven from C through B and it comes to the opposite orientation (4) when a current is driven from B to C. For a BLDC motor that is equipped with Hall sensors these give the actual rotor position.

The motion of the rotor induces alternating voltages called **B**ack **E**lectro**M**otive **F**orce (BEMF) within the coils. The amplitude of the BEMF is proportional to the angular velocity of the rotor. Hall sensors are mounted in such a way that the zero crossing of the BEMF occurs as close as possible to the zero crossing of the Hall sensor signal associated with the corresponding coil.

H1 is associated with A, H2 is associated with B, and H3 is associated with C. Alternatively, the connections A, B, C of BLDC motors are also labeled as U, V, W respectively. The BEMF can be modeled as a voltage source in series with each coil that has a voltage amplitude proportional to the speed of the rotor. The BEMF voltage varies with the angle between the coil axis and the angle of the rotor. Following, the shape of the BEMF is assumed to be sine wave. Alternatively, the shape can be triangular or trapezoidal or somewhat between these shapes.

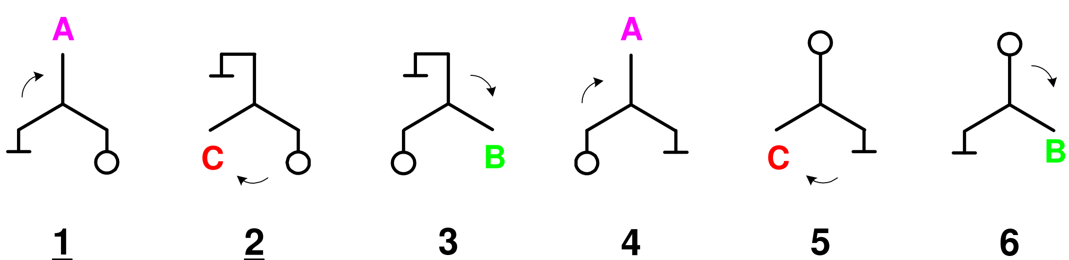
Figure 2-1. Simplified Model of a two-pole BLDC Motor (with two successive rotor positions 1, 2)



2.2 Block Commutation

The polarities of two coil currents with one coil left unconnected define six different positions for the rotor. Switching the currents in a way that the currents pull the rotor to the position next to the current position lets the rotor turn. Each position of the rotor is associated with a configuration of coil currents by a successive switching scheme configuration that pulls the rotor to its next position. The coil currents are driven by three voltage sources. The voltage sources are realized with fast switches (Power MOSFETs) that are PWM controlled for adjustment of effective voltage. The block commutation scheme is outlined by Figure 2.2. For each commutation step there is one terminal connected to ground (ground symbol), one terminal is connected to the power supply (circle), and one terminal is left open (terminal name A, B, C). Permanent connection to ground and power supply drives the maximum current though the coils of the motor and will turn it with maximum speed that is possible for a given motor with a given supply voltage.

Figure 2-2. Outline of Block Commutation Scheme (positions 1 & 2 correspond with Figure 2.1)



For the block commutation, each sector of the rotor is mapped to the successive sector concerning current switching. So, commutation via interrupts becomes simple if each change of a Hall sensor signal forces an interrupt. Then, the actual triple of Hall sensor signals defines the commutation sector. In other words, the block commutation can be described as a periodic sequence of 0Z11Z0 where 0 is connection to ground, Z represents an open terminal, and 1 is connection to the supply voltage source. This sequence is delayed by two steps for each successive terminal. The sequence 123456 of commutation steps is for A = Z00Z11, B = 11Z00Z, C = 0Z11Z0. For revolution into the opposite direction 654321 it is A = 11Z00Z, B = Z00Z11, C = 0Z11Z0.

The coils of the motor can be connected in star (Y connection) or triangle (Delta connection). Whatever is the type of connection, the idea is to get an access to the null point to be able to measure the BEMF, somes motors allow this access via an additional wire. Direct access to the null point N enable direct measurement of the BEMF. The voltage of the null point N is affected by the supply voltage together with a given PWM scheme. If needed, the voltage of the null point N over ground can be reconstructed electrically or for different PWM schemes it is possible to calculate it. With then ATAVRMC100 and the extension board (Figure 4-2) for sensorless commutation there is no need for the voltage of the null point. .

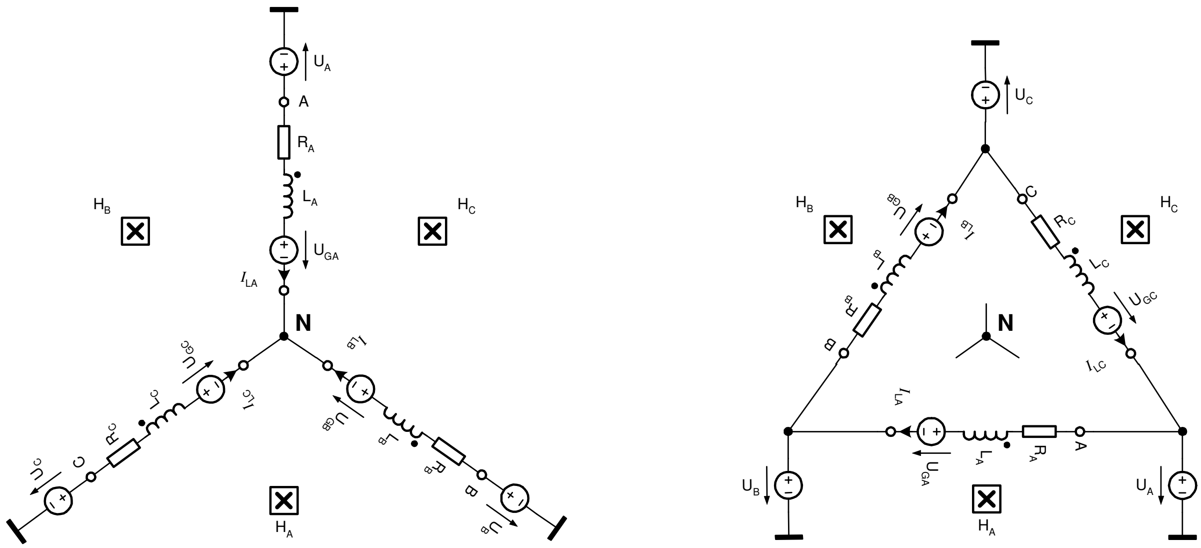
2.3 BEMF

Within each coil, the rotating permanent magnet induces an alternating voltage with an amplitude proportional to its angular velocity. Following, the shape of this voltage is assumed to have sine wave shape. A sine wave shape is valid for many motors and it is a good approximation if the shape of the BEMF differs for a given motor.

A zero crossing of the voltage induced within a coil occurs when the permanent magnet rotor – here modeled as a bar magnet is perpendicularly orientated to the axis of the coil. Two successive magnet positions are outlined by Figure 2.1. For coil **A** the zero crossing of the voltage induced occurs when the bar magnet is at position **1** (outlined by the drawing on the left side). For coil **C** the zero crossing occurs when the bar magnet is at position **2** (outlined by the drawing on the right side).

At a given supply voltage, the BEMF limits the speed of a motor. The BEMF constant for a BLDC motor is commonly given in unit [RPM / V] or within reciprocal unit [V / RPM]. Although this value does not directly represent the amplitude of the BEMF except if it is explicitly labeled to do so, it represents the range of the amplitude of the BEMF due to the fact that the speed at a given supply voltage depends on the amplitude of the BEMF but also on the shape of it.

Figure 2-3. BLDC Motor in Y connection (left side) and DELTA connection (right side)



BEMF= UGA, UGB, UGC

The BEMF constant given in unit [RPM/V] resp. [V/RPM] directly gives information that is relevant for the application's point of view. For example, a BEMF constant of 4100 [RPM/V] means, that the speed of that BLDC operating on a 12V supply voltage can go up to 12V * 4100 RPM / V = 49200 RPM. Within the context of motor physics, the BEMF constant is given within unit [V s / rad].

2.3.1 BEMF vs. Hall Sensors

An important physical difference concerning determination of the rotor position via BEMF or using Hall sensors is that for the BEMF the change of the magnetic flux in time within the coil gives the BEMF where for the Hall sensor the magnetic flux is sensed. Because of this, for sensorless commutation based on the measurement of the BEMF the rotor has to move before one can determine its position. In contrast to that, Hall sensors always give a valid signal representing a position. The position of the rotor is represented by a three bit vector with a resolution of 60° within the electrical period. For most BLDC motors, the Hall sensors are mounted within the 120° scheme that is direct compatible to the BEMF. Nevertheless, there are BLDC motors with Hall sensors mounted within a 60° scheme resulting in a different Hall signal pattern. Those 60° Hall sensor BLDC motors are not taken into account here.

2.3.2 Zero Crossing Detection

For block commutation, the polarity of the BEMF changes within the coil that is perpendicularly oriented to the rotor. Hall sensors are mounted on those positions that their polarity changes in phase with the BEMF of the associated coils. In other words, Hall sensor signals represent the polarities of the BEMF of their associated coils. Three Hall sensor signals resp. BEMF polarities together represent the actual position of the rotor. For normal operation, the switching to the next commutation position is done with each zero crossing. Direct measurement of the BEMF is possible if there is direct access to the null terminal N of the BLDC motor. Although the N terminal is available at some Y connected BLDC motors, it is not available for DELTA connected motors. So for a flexible implementation, the zero crossing detection has to be realized without the N terminal. Other solutions reconstruct the voltage of the N terminal. The sensorless commutation is also possible without reconstruction of the N terminal voltage. Additionally, other solutions strongly focus on post processing of signals that are noisy due to PWM switching and self-induction of coils. With the right signal conditioning, the sensorless commutation becomes as simple as commutation based on Hall sensors.

2.3.3 Noise

Noisy signals that are used for determination of the rotor position leads to commutation faults. So, noise has to be avoided by adequate signal conditioning or filtered by the software that is doing the commutation. Digital filtering is a powerful method but it consumes much processing power that is not required if the signals are well conditioned without noise that could disturb the commutation.

2.4 PWM

BLDC motors that have a high efficiency might have a very low resistance and very low inductance. The final speed of a BLDC motor is determined by the applied supply voltage and by the BEMF constant of the motor. The speed can be adjusted by adjusting the applied supply voltage. Normally, one has a fixed voltage source e.g. a battery, a rechargeable battery, or a power supply unit – with a constant voltage. Doing the adjustment of the effective supply voltage by pulse with modulation (PWM) is a method of applying an effective voltage for speed control. The advantage of the PWM is its low power dissipation compared to voltage adjustment by a linear regulator. A current regulation can be achieved by adjusting the effective voltage by varying the PWM duty cycle depending on a measured current.

2.5 Principle of a BLDC Motor in Sensorless Mode

The challenge of sensorless commutation is to reconstruct the BEMF signals in a way that these signals are sufficient to represent the position of the rotor where switching pulses (PWM) overlay the BEMF signals. For block commutation there is always one terminal of A, B, C that is disconnected and where one can measure the BEMF signal. The zero crossing of the BEMF signal falls within the window where a terminal is disconnected. The zero crossing determines the next commutation step. A good signal pre-conditioning by low pass filtering simplifies the processing to be done by the processor. In best case, the BEMF signals are converted into Hall sensor like signals. Any noise on BEMF signal take effect on the commutation and may be taken into account into the firmware, but this might be acceptable due the low cost of the solution depending on the application.

2.6 Theory of Sensorless Mode

The BEMF induced by the rotation of the rotor within each coil can be modeled by three voltage sources UGA(t), UGB(t), UGC(t) according to BLDC Motor in Y connection (left side) and DELTA connection (right side). The amplitude of these voltage sources is given by the BEMF constant k_e of the BLDC motor that is proportional to the speed. With a BEMF shape assumed to be sine wave, one gets alternating voltages

UGA(t) = k_e[V/rpm] * v[rpm] * sin(360° * v[rpm]/60 * t[s])
UGB(t) = k_e[V/rpm] * v[rpm] * sin(360° * v[rpm]/60 * t[s] + 120°)
UGC(t) = k_e[V/rpm] * v[rpm] * sin(360° * v[rpm]/60 * t[s] – 120°)

With a function where sign(x)=1 if x is negative or sign(x)=0 if x is positive or equal to 0, binary signals (Hall sensor like signals) can be generated from sine wave shape BEMF signals

HA = sign(UGA(t))
HB = sign(UGB(t))
HC = sign(UGC(t))

The technical challenges of sensorless mode come from the fact that simple direct measurement of the BEMF voltages is not possible for all types of real BLDC motors.

2.6.1 Open Loop Ramp Up

As mentioned before, the sensorless commutation requires a minimum amount of speed to work. This is because the amplitude of the BEMF is proportional to the angular velocity of the rotor. Below the speed limit, the signal noise ratio of the BEMF signal that is superposed by the PWM signal is too low. The speed limit depends on the BLDC motor and the supply voltage. For example a BEMF amplitude of some hundred millivolt is not significantly different from the noise due to the PWM switching with a voltage amplitude of some volts. So, for sensorless commutation, the BLDC motor has to be ramped beyond this speed limit.

When commutating based on the position feedback by sensors the BLDC motor starts with high current and accelerates as fast as it can until the BEMF limits its speed for a given supply voltage. The current has to be limited during the ramp up. This is really important for BLDC motors with very low resistance and low inductance because they behave similar to a short cut if the rotor is at rest.

The current can be limited via open loop PWM control or via closed loop current control. Nevertheless, the open loop speed ramp up has to be done with a defined angular acceleration. This is because a current limit limits the available torque and Newton's law defines the relation between force, mass, and acceleration resp. torque, moment of inertia, and angular acceleration.

2.6.2 Ramp Up with Current Limit

One possibility is the measurement of the current and closed loop regulation of the current to limit it. The PWM duty cycle is tuned depending on the measured current. This regulation loop has to be very fast for BDLC motors with very low resistance and very low inductance because those BLDC motors behave like a short cut.

2.6.3 Open Loop Speed Up

Another possibility is to control the PWM duty cycle open loop as a function of the actual velocity during acceleration. This open loop regulation can be done based on the known parameters of the BLDC motor.

The open loop speed up has been realized (refer to Figure 2.5). The goal of open loop ramp up is to bring the BLDC motor into the range of BEMF amplitude sufficient for sensorless commutation based on the comparator signals used for BEMF zero crossing detection. To achieve this, the torque has to be almost constant during open loop ramp up.

A current commutation state represents a target position for the rotor by defining the current flow direction, where the PWM duty cycle scaling represents an effective voltage scaling of the motor supply voltage. So, changing the PWM duty cycle changes the amount of current flowing through the windings of the motor and that changes the torque of the motor.

To achieve an almost constant torque during ramp up, the PWM has to be tuned during open-loop speed-up as a function of the actual commutation velocity as outlined by figure 2.5

pwm(v) = c0 + c1 * v

The constant c0 and c1 scale with the supply voltage VBAT, where c0 and c1 can be chosen in a way that the resulting PWM is

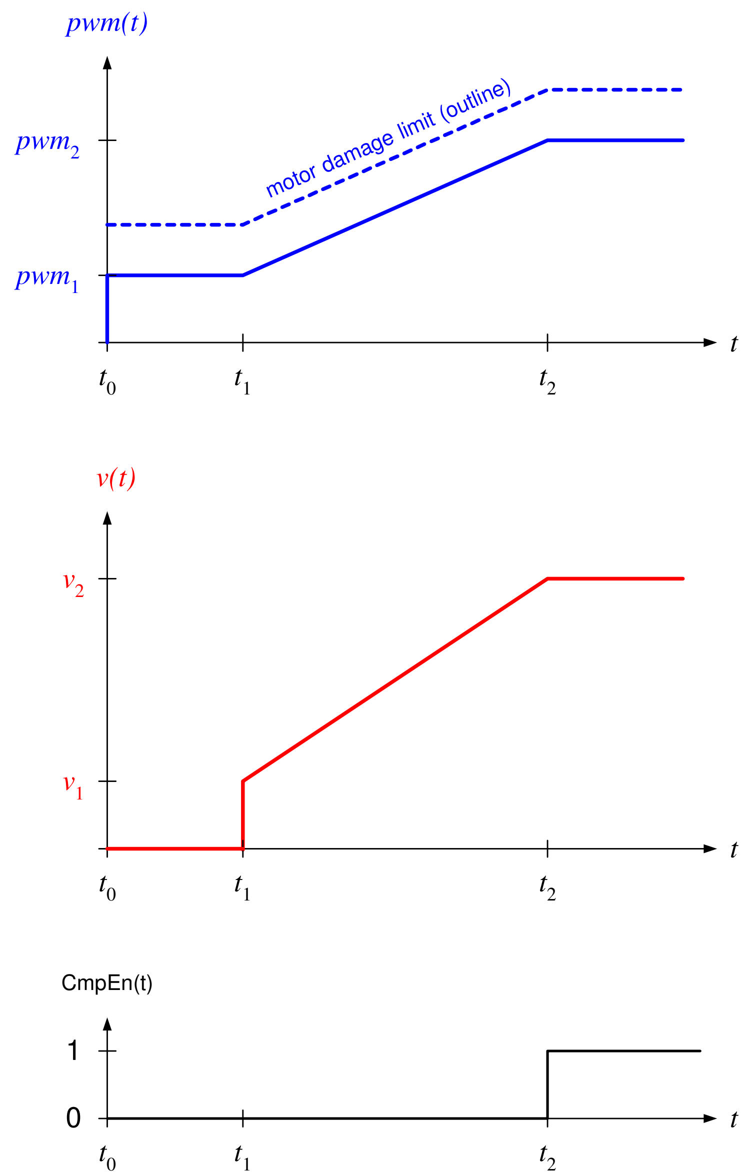
pwm(v) = (c0 + c1 * v) / VBAT.

Before accelerating with constant acceleration a = dv / dt, first a PWM offest pwm0 is applied. Then a waiting phase is inserted to give the rotor enough time to move to the given initial commutation position. After the rotor reaches the initial target commutation position, it comes to rest doing a damped oscillation – similar to a harmonic damped oscillator. The oscillation frequency is defined by the moment of inertia of the rotor and the toque constant of the motor. The damping constant determined by friction of the motor slightly influences the oscillation frequency. From the application's point of view, the damping constant determines the duration of an oscillation. The duration of oscillation is important for the time to wait before starting speed up.

The BEMF zero crossing comparators are disabled during open-loop sped-up until the target velocity is reached. When the target velocity is reached, the BEMF zero crossing comparators are enabled before leaving the open-loop speed-up subroutine.

With the right pwm0 and pwm1 one can accelerate slow enough that the rotor is able to follow the magnetic field. The constant c0 compensates the voltage drop caused by ohmic loss. The constant c1 compensates the reduction of the effective supply voltage due to the BEMF of the motor. A PWM offest that drives a current below the motor current limit ensures that the BLDC motor does not get damaged.

Figure 2-4. PWM vs. Speed v vs. Comparator Enabling CmpEn during Open-Loop Ramp-Up



2.6.4 Constants c0 and c1 resp. pwm0 and pwm1

For a given motor supply voltage, the constant offset pwm0 represents a voltage offset that drives a current through the windings according to U = R * I, where R is the ohmic resistance of the coils, the MOSFETs, and all resistances taking effect on the coil current for a given supply voltage are scaled by a PMW with a given duty cycle. This results in a torque proportional to the absolute value of the current. The torque depends on both the current and the load angle. A given current defines a maximum torque tau that is available with:

VBAT * pwm0 = R * I

with tau = k_tau * I.

The constant k_tau is the torque constant for a given motor. By choosing pwm0 in a way that the resulting current does not exceed the maximum nominal current of a given motor, one can accelerate during ramp up as slows as desired. A current larger than the maximum nominal current might be allowed for a short time as long as the temperature of the windings and the temperature of the motor does not exceed a given limit.

2.6.5 Calculation of Constants c0 and c1 from Motor Characteristics

Both constants c0 and c1 can be calculated from motor characteristics. One has to take care of the units of motor parameters, because different manufactures of BLDC motors use different ones. The pwm0 must range from 0% to 100% for a current I set to be valid. The constant offset PWM scaling constant is

pwm0 = R * I / VBAT.

For the current implementation for the AT90PWM3, the offset constant is c0 = c_pwm * pwm0, with pwm0 ranging from 0% to 100% and c_pwm = 255. The commutation frequency dependent PWM scaling constant is

pwm1 = (v_rpm + k_e * R*I) / (k_e * VBAT)

where v_rpm is the velocity in unit [rpm] and k_e is the BEMF constant of the motor in unit [rpm/V]. The effect of the coil inductance L is ignored for this calculations. Additionally, one has to take into account, the velocity given in units RPM is for two-pole-motors where one electrical period is equivalent to one mechanical period. Without a gear, one mechanical period is equivalent to one revolution. The constants c0 and c1 depend on the supply voltage. So, these are constants if the supply voltage is constant. For applications with variable supply voltage, these constants have to be calculated taking the linear dependence of the supply of VBAT into account.

2.6.6 Interactive Adjusting of Constants c0 and c1

Alternatively, interactive adjusting of the PWM scaling constants is possible for open-loop ramp-up. First, the parameter pwm0 has to be determined. For this, one first sets pwm0 = 0 and pwm1 = 0 when the BLDC motor is at rest. Then one increments pwm0 until the target current is reached. Measuring the current allows automated adjusting of the pwm0 parameter.

2.6.7 Defining the Ramp-Up velocities v0 and v1

The start velocity v0 might be set to 0. To shorten the ramp up phase it might be set to a velocity greater than 0. The velocity v1 should be as high as possible, because the amplitude of the BEMF is proportional to the velocity and higher amplitude gives better signal noise ratio for the comparators. Ramping-up in that kind, as described before, the torque remains almost constant up to the velocity

v_rpm = (VBAT – R * I) * k_e.

For higher velocities, the voltage driving the current through the coils is not high enough to drive the specified current I. A free running BLDC motor with a BEMF constant k_e finally turns with a velocity

v_rpm = VBAT * k_e

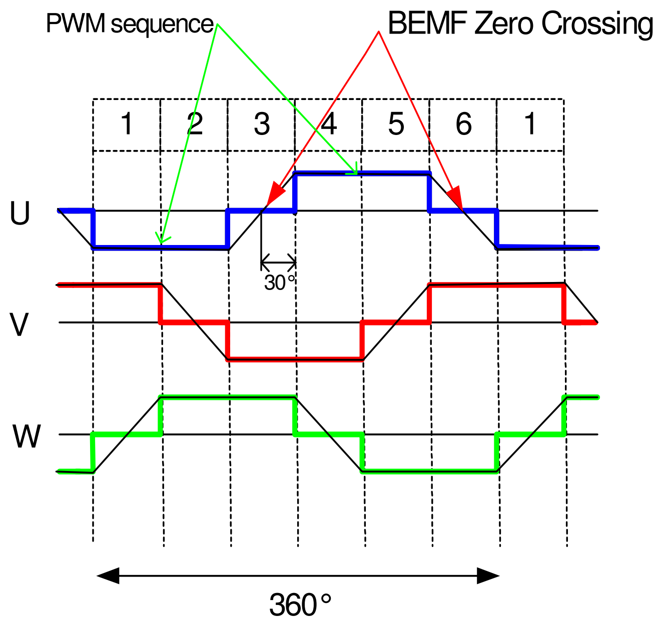
So, the choise in the range of v_rpm_max = (VBAT – R * I) * k_e is fine as end velocity v1. Depending on the motor, 10% to 100% of v_rpm_max is sufficient.

2.6.8 How to Set the Acceleration to be Applied

From the theoretical point of view, without friction, the maximum acceleration is defined by Newton's equation F = m * a with a = tau /J, where tau is the torque, J is the moment of inertia, and a is the angular acceleration. If a ramp up of 1 second is sufficient, the resulting acceleration a_rpm_per_s to come to the velocity v_rpm_max is v_rpm_max / 1 s would be sufficient. As opposed to the physical (SI) unit of angular acceleration [rad/s2] the unit [rpm/s] has been chosen as the unit for angular acceleration. This has two main advantages. First, the unit of [rpm/s] is more intuitive for velocities given in unit [rpm]. Second, the numeric range for typical velocities and accelerations is more compatible with integer representation using the unit [rpm/s] compared to the SI unit [rad/s^2].

3. Thirty degree phase angle

The optimum drive sequence is to drive PWM at 30° after zero crossing to be in phase with the rotor position as shown by the figure below. Driving earlier or later to this 30° will increase the current comsumption of the motor.



4. Zero Crossing Detection

The Zero crossing detection is done using the following circuit. it is using external analog comparator and low cost components. The values of the components are adapted to the BEMF level of motor of the ATAVRMC100 kit.

Figure 4-1. One phase and the corresponding comparator output (30° not implemented)

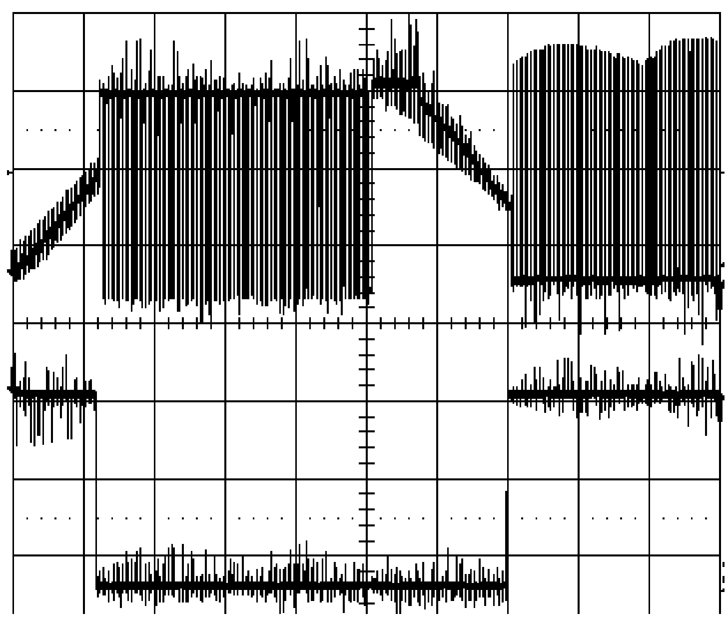
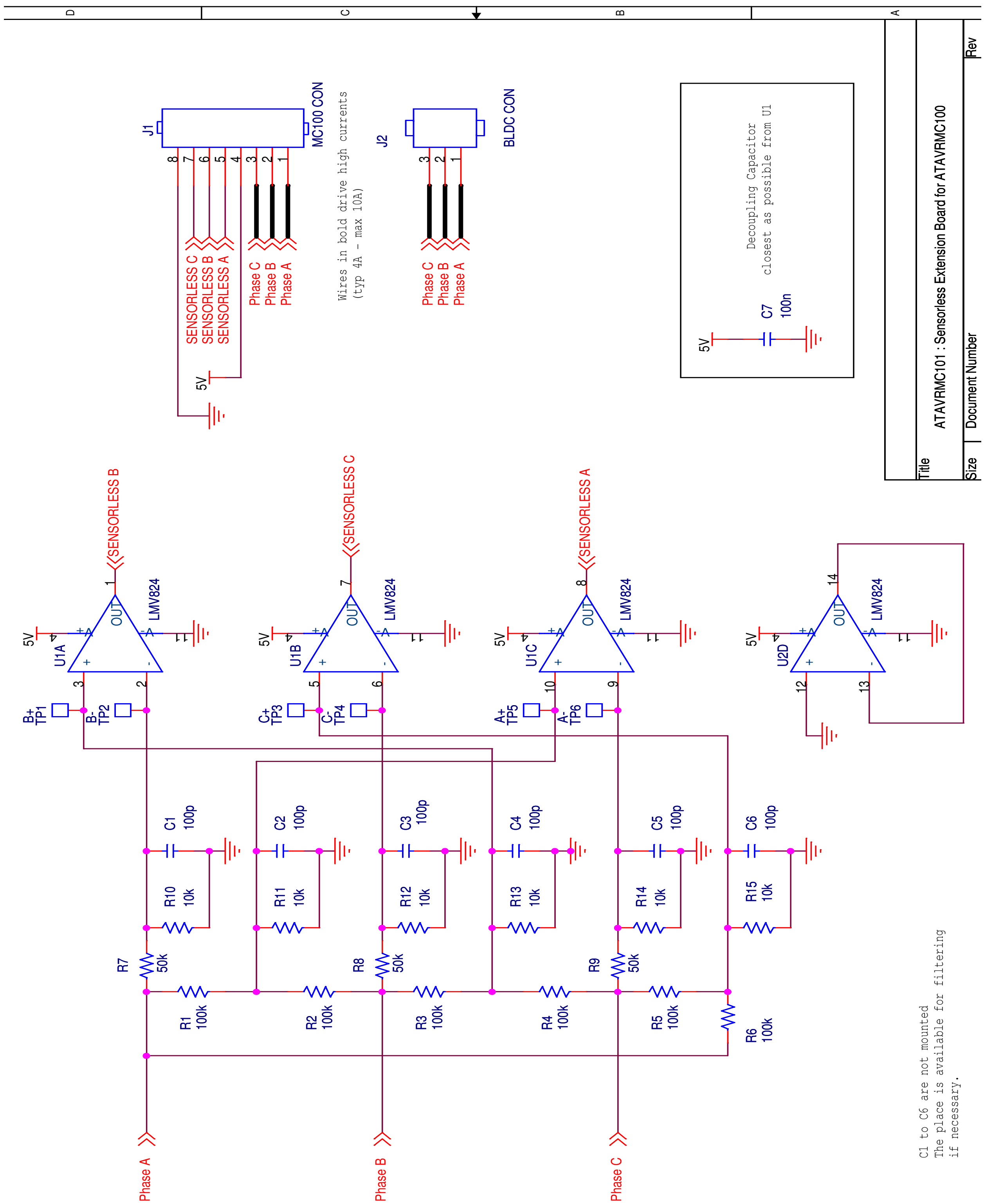


Figure 4-2. Extension board for sensorless detection using ATAVRMC100.i



4.1 Signal Conditionning

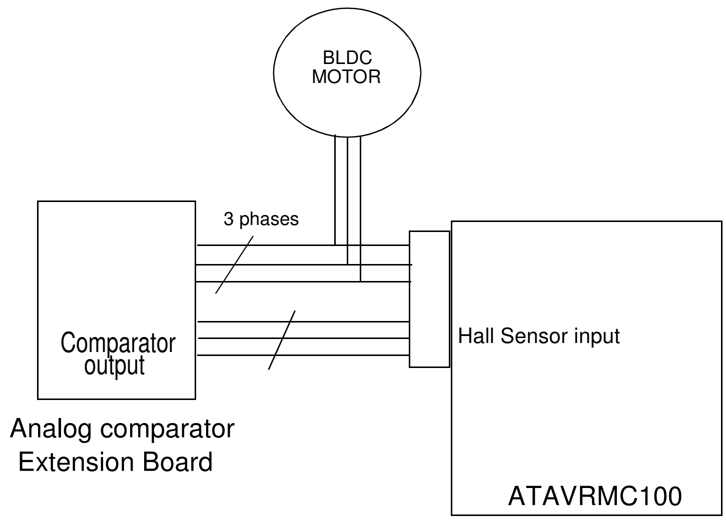
Signal conditioning is done to adapt BEMF level (depending of the motor caracteristics and speed) to input range of analog comparator. Low pass filter is used to filter PWM frequency on the BEMF signal.

Low pass filter introduce a delay between Zero crossing time and analog comparator output toggle. This time must be taken into account for 30° calculation. With the above schematic the delays generated by low pass filter is close to 125 us.

5. Hardware

The hardware used is the ATAVRMC100 board with analog comparator extension board. for ATAVRMC100 details please refer to ATAVRMC100 hardware user guide.

The figure below shows connection between both boards.



5.1 Technical Advices

5.1.1 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. A BLDC motor with a high moment of inertia is able to run for a relatively long time after setting the PWM duty cycle to 0%.

5.1.2 Ground Wiring and Power Wiring

One 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 due to high current. A ground plane within a multi layer PCB is recommended for proper function.

6. Firmware

The firmware proposed is based on the Sensor based demo using ATAVRMC100 board (AVR492 application note) with some modification including ramp up sequence and 30° implementation. It is woking in sensorless mode using the external comparator board described in previous chapter. Hall sensor wires of the BLDC motor must stay unconnected.

This demo need to be connected to RS232 using STK500.

6.1 Connecting STK500 to ATAVRMC100 to use the RS232 interface.

- **Ground of both board must be connected together using a simple wire.** (Ground can be connected using ISP connector cable on both boards)
- Connect the STK500 to ATAVRMC100 for uart control as described below.

Connect RXD and TXD pin of STK500 RS232 SPARE to pin 7 and 8 of I/O Connector of ATAVRMC100.(See connection table and/or pictures below)

Table 6-1. UART Connection Table

STK500	ATAVRMC100
TXD RS232 SPARE	Pin 7 of IO Connector (TXD)
RXD RS232 SPARE	Pin 8 of IO Connector (RXD)
GND	GND

Figure 6-1. Uart connection from STK500 side

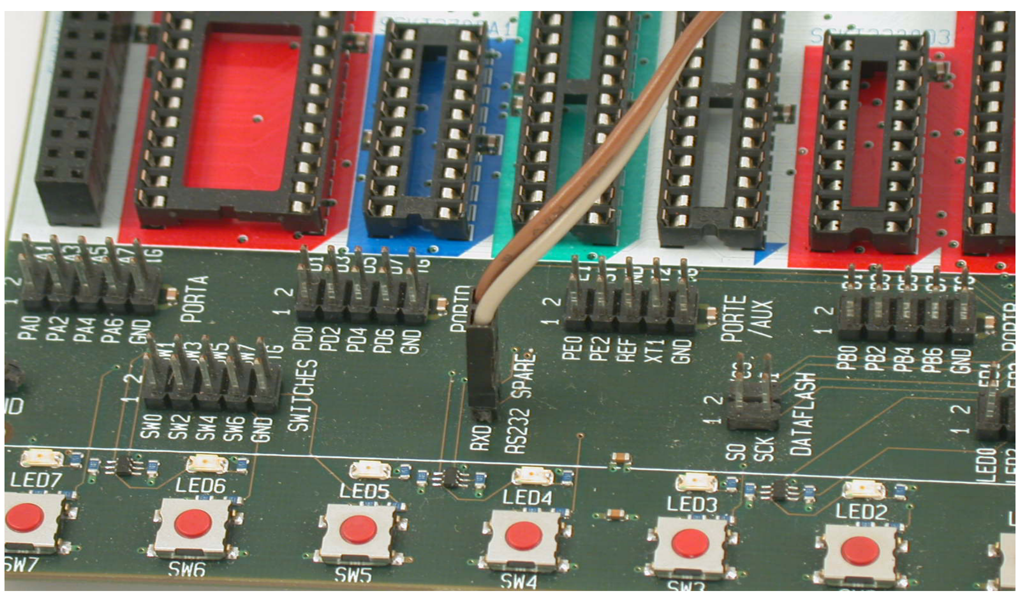
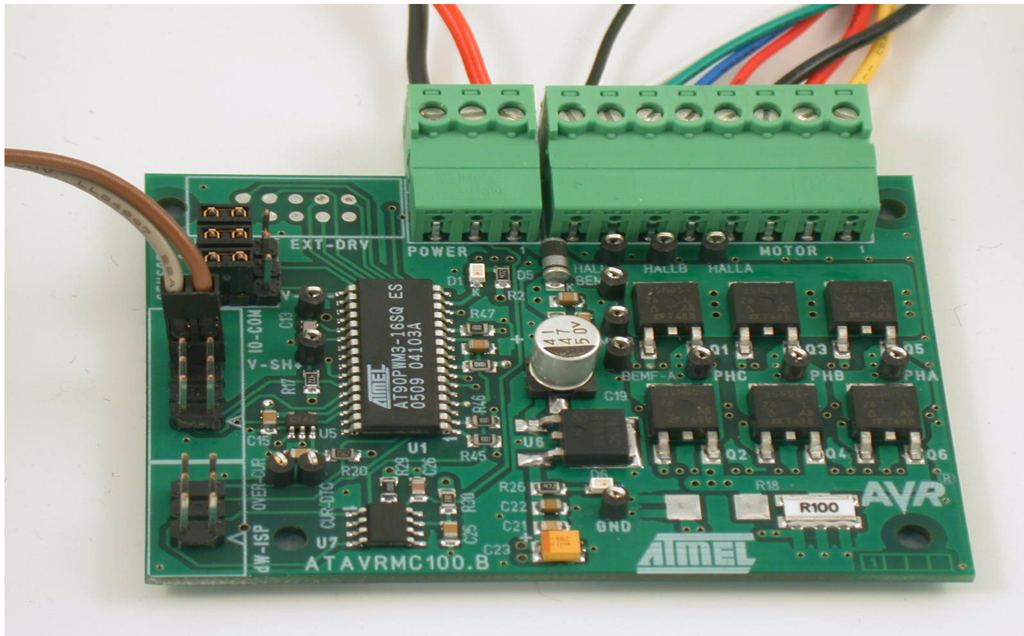
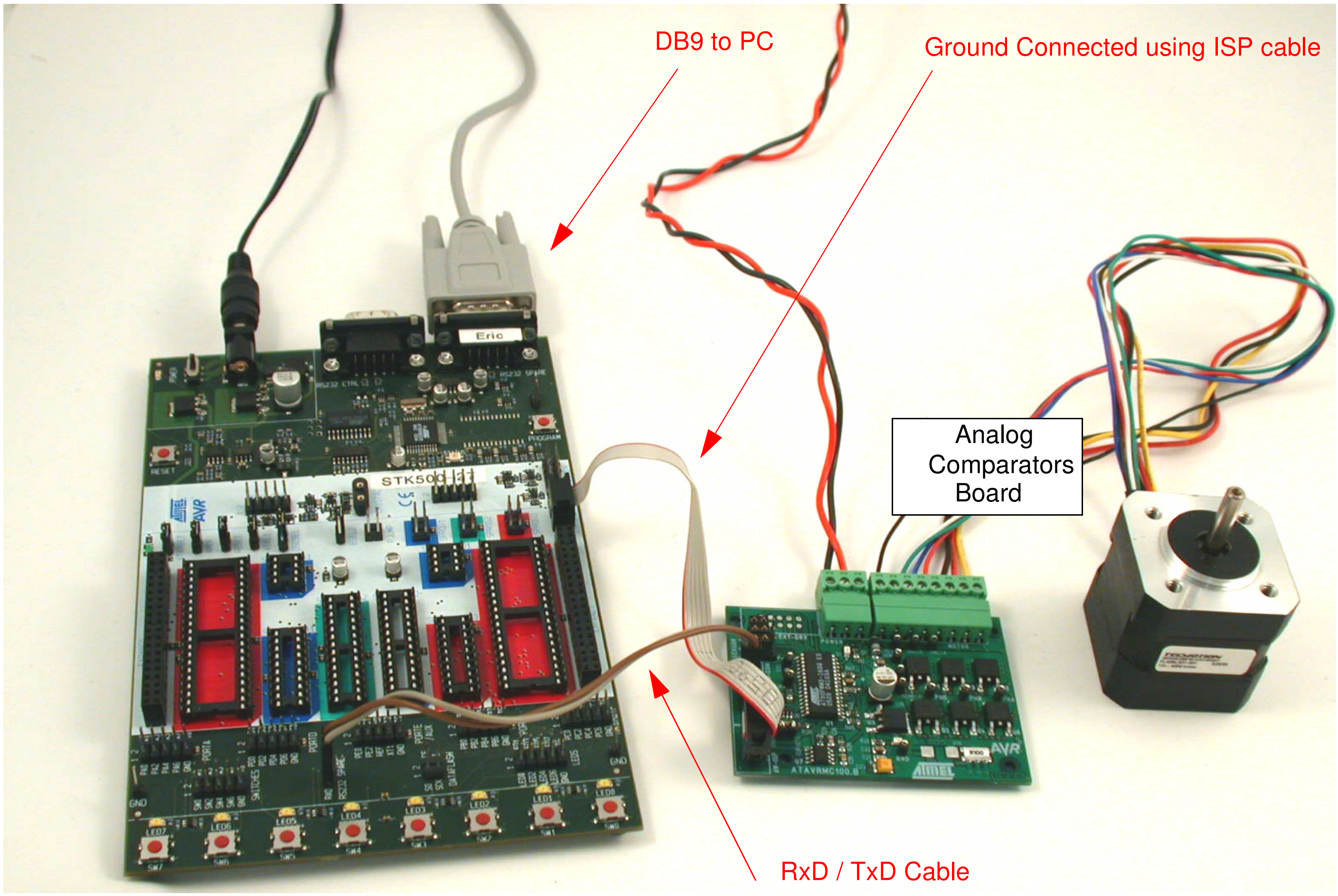


Figure 6-2. Uart connection from ATAVRMC100 side



Connect PC com port or PC USB-RS232 dongle to DB9 of SPARE RS232 on STK500 (See Figure below)

Figure 6-3. Complete Demo Connection



6.2 ATAVRMC100 Configuration

Jumpers must be set to sensor.

6.3 AT90PWM3 Configuration

AT90PWM3 must be programmed to run at 16MHz using PLL (set corresponding Fuse bits)

6.4 Hyperterminal configuration

The hyperterminal must be configured as followed : 38400 bauds,8 Data bit,1 Stop bit, no Handshake and no Parity

6.5 Supported Command

The following command are supported by the software:

Command	action
ru	Run motor
st	Stop Motor
help	Gives help
fw	Set direction to Forward
bw	Set direction to Backward
ss	Set Speed
gi	Get ID
g0	Get Status 0
g1	Get Status 1

6.6 Welcome Message

At power up the following welcome message is send by the board to the hyperterminal:

“ATMEL Motor Control Interface”.

Atmel Corporation

2325 Orchard Parkway
San Jose, CA 95131, USA
Tel: 1(408) 441-0311
Fax: 1(408) 487-2600

Regional Headquarters

Europe
Atmel Sarl
Route des Arsenaux 41
Case Postale 80
CH-1705 Fribourg
Switzerland
Tel: (41) 26-426-5555
Fax: (41) 26-426-5500

Asia
Room 1219
Chinachem Golden Plaza
77 Mody Road Tsimshatsui
East Kowloon
Hong Kong
Tel: (852) 2721-9778
Fax: (852) 2722-1369

Japan
9F, Tonetsu Shinkawa Bldg.
1-24-8 Shinkawa
Chuo-ku, Tokyo 104-0033
Japan
Tel: (81) 3-3523-3551
Fax: (81) 3-3523-7581

Atmel Operations

Memory
2325 Orchard Parkway
San Jose, CA 95131, USA
Tel: 1(408) 441-0311
Fax: 1(408) 436-4314

Microcontrollers
2325 Orchard Parkway
San Jose, CA 95131, USA
Tel: 1(408) 441-0311
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La Chantrerie
BP 70602
44306 Nantes Cedex 3, France
Tel: (33) 2-40-18-18-18
Fax: (33) 2-40-18-19-60

ASIC/ASSP/Smart Cards
Zone Industrielle
13106 Rousset Cedex, France
Tel: (33) 4-42-53-60-00
Fax: (33) 4-42-53-60-01

1150 East Cheyenne Mtn. Blvd.
Colorado Springs, CO 80906, USA
Tel: 1(719) 576-3300
Fax: 1(719) 540-1759

Scottish Enterprise Technology Park
Maxwell Building
East Kilbride G75 0QR, Scotland
Tel: (44) 1355-803-000
Fax: (44) 1355-242-743

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