AVR448: Control of High Voltage 3-Phase BLDC Motor

Features

* **½ horsepower 3-phase BLDC motor**
* **Integrated Power Module controls motor currents**
* **Motor control via potentiometer wired to an ATmega48**
* **AC Line powered as found in White Goods and appliance applications**

1 Introduction

Three Phase AC motors have been in operation worldwide for decades. They offer relative simplicity of construction, low maintenance, and high efficiencies. Many of these motors require the minimum of control electronics; typically only a 3-pole single throw switch. However, one disadvantage is that their running speed varies with the mechanical load, and is not easily controlled.

With the addition of a microcontroller as a control device, 3-phase motors can be used for a far wider range of applications. Also, motor sizes below one horsepower and is efficiently controlled in speed, acceleration and power levels. This is the ideal situation for consumer appliances and white goods such as washing machines. Additional applications include battery-operated tools, air conditioners, vacuum cleaners, and toys. There are hundreds of additional applications too numerous to mention here.

Figure 1-1. 3-Phase Motor Examples

Motor,1 HP,60/50 Hz
Grainger 3 Phase Motor

2 Theory of Operation

2.1 Hall Sensors Detect Rotor Position

One very important detail in MCU motor control is rotor position. The control application must know the angular position of the rotor so that the proper voltages and currents are applied to the motor terminals. Hall magnetic sensors are typically installed within the motor. When 5VDC is applied to them, they provide a digital output signal that changes when the rotor turns. Three phase motors use three Hall sensors. This type of position detection is well suited for many 3-phase motors and in particular, those with high starting loads.

**Figure 2-1.** Hall Sensor Outputs as Related to Rotor position

Shaft Position in degrees
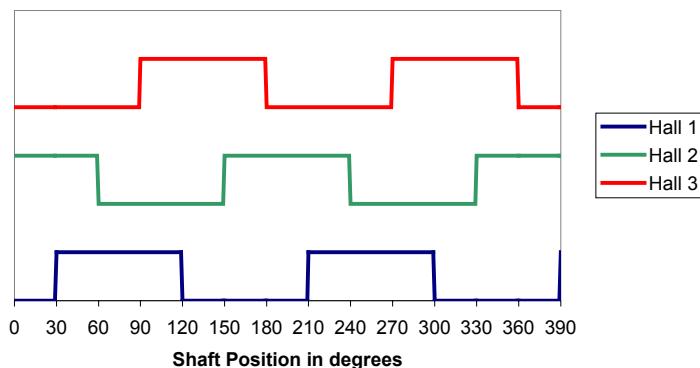
Figure 2-2. Motor winding schematic
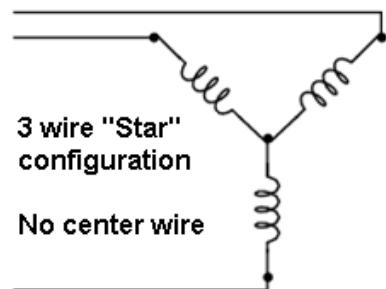
2.2 Electrical Requirements of a 3-Phase BLDC Motor

The motor used in this application note is a 120V 4A 3-phase design wired in a "star" configuration. It has a permanent magnet rotor and the 3 phases are wound in the stator. Hence, it has 3 wire connections to the windings, as is the case with many industrial 3-phase motors.

In addition, it has 5 additional connections for the 3 Hall sensors: 5VDC In, GND, and the 3 Hall sensor outputs. See schematic.

2.3 ATmega48 Firmware

The ATmega48 is running a C-program that reads an analog voltage from a potentiometer used as a speed control knob. This is done using pin ADC0 and 8 bits of the A-to-D converter (ADC).

The outputs of the ATmega48 are connected to an Integrated Power Module (IPM) from International Rectifier. This device accepts logic levels from the ATmega48, as well as 180VDC at up to 4A and applies this voltage to the motor windings.

Figure 2-3. Integrated Power Module

There are numerous algorithms for control of 3 phase motors using a MCU: Trapezoidal, Sine Wave, and Proportional Integral Derivative (PID) are three common methods.

In this application note, Trapezoidal control has been implemented because it is the simplest yet very effective at controlling motor speed and power. The Trapezoidal method simply applies On-Off digital signals to the IPM. These signals are Pulse Width Modulated from 0% to 100% at a frequency of 20kHz. The 20kHz frequency is constant, and chosen to be out of the range of human hearing.

The Hall sensor outputs are used by the program to determine which IPM inputs to set high and low. The signals to the IPM are pulse width modulated, which effectively varies the average voltages and currents to the windings. To clarify, consider the case where power is first applied to the motor with the rotor stopped. Only one H input and one L input will be active; the remaining 4 IPM inputs will be high (inactive). Look at the schematic to see the 6 IPM inputs.

For the first millisecond, the rotor may rotate a very small amount. Most likely, the Hall outputs will remain unchanged, which tells the program to continue with the same H and L inputs. However, these inputs are pulse-width modulated, otherwise full power would result, and this would likely blow the fuse or circuit breaker. The duty cycle of these signals would be 20-30%, (at 20kHz frequency) which limits the starting current.

As the rotor begins to turn, the Hall sensors change their outputs, and the program reacts by choosing a different pair of H and L inputs to the IPM. From 0 to 10,000 RPM, this motor exhibited good starting torque, smooth acceleration and abundant torque. The variable speed and high speeds are achieved by varying the frequency of field excitation, under program control, in response to Hall Sensor position feedback.

This is a demonstration program that reads the voltage on a potentiometer and adjusts the power to the 3-phase motor. This resultant motor speed is running open

loop, in the sense that there is no provision to measure the RPM in this program. Open loop speeds range from 0 to >>5000 RPM and one must use caution to not damage the motor with excessive speed or current.

2.3.1 Main Loop

After the MCU is reset, the I/O ports, ADC and Timers are initialized. Next, the Top of Main Loop is reached. The Main Loop is a very short fast loop that essentially reads the PWM Output on Port C bit 3, and sets a variable IPM_B4_PWM to all 1's or to a value assigned in the Pin Change Interrupt Service.

Figure 2-4. Flowchart for Main Loop

```
                        ┌─────────────┐
                        │    START    │
                        └──────┬──────┘
                               │
                   ┌───────────▼───────────┐
                   │   Initialize I/O Port B │
                   └───────────┬───────────┘
                               │
                   ┌───────────▼───────────┐
                   │    Initialize ADC      │
                   └───────────┬───────────┘
                               │
                   ┌───────────▼───────────┐
                   │ Initialize Timer 2 in  │
                   │ Phase Correct PWM Mode │
                   └───────────┬───────────┘
                               │
                   ┌───────────▼───────────┐
                   │  Initialize Port C Pin │
                   │   Change Interrupts    │
                   └───────────┬───────────┘
                               │
          ┌────────────────────┴────────────────────┐
          │                                          │
┌──────────────────┐      ╱ Is pin PD3 ╲      ┌──────────────────┐
│ Set all IPM signals│◄─N─◄  (PWM Output) ►─Y─►│  Set IPM signals to│
│ to high (inactive) │      ╲   high ?   ╱      │  IPM_BW_PWM value  │
└──────────────────┘        ╲         ╱        └──────────────────┘
```
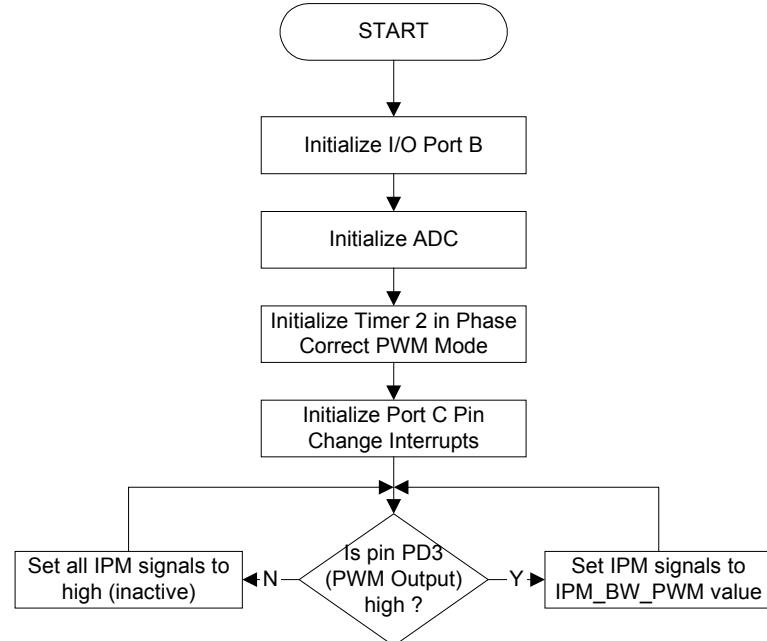
2.3.2 Pin Change Interrupt Handler

This routine is initialized by forcing a pin change at the beginning of the main program. This first execution of the Pin Change Interrupt Routine reads the ATmega48 input pins connected to the Hall sensors, and determines what is the initial rotor position. Earlier in the program the variable Clockwise (CW) is defined, which determines direction of rotation. This direction decision and the Hall signals are used to look up the proper signals to output to the IPM via PORTB. This is, in effect, a Look Up Table of values that apply signals to the IPM that turn the motor 60 degrees.

This routine is entered 12 times per revolution of the motor. If the motor is running at 6000 RPM, that is 100 Rev/Sec, or 1 revolution in 10 msec, or 10,000 usec. So, 10,000 usec/12 = an interrupt every 833 usec.

Figure 2-5. Flowchart for Main Loop

```
                        ┌────────────────────┐
                        │ Pin Change Interrupt │
                        └──────────┬─────────┘
                                   │
                        ┌──────────▼─────────┐
                        │ Read Hall sensor signals │
                        │     from Port C      │
                        └──────────┬─────────┘
                                   │
┌───────────────────┐          ◇─────────◇          ┌───────────────────┐
│ Select current winding │◄── Y ──│ Clockwise │── N ──►│ Select current winding │
│ state from CW sequence │        │ rotation? │        │ state from CCW sequence │
└─────────┬─────────┘          ◇─────────◇          └─────────┬─────────┘
          │                         │                           │
          └─────────────────────────┼───────────────────────────┘
                                     │
                          ┌──────────▼─────────┐
                          │ Read ADC value from │
                          │    potentiometer    │
                          └──────────┬─────────┘
                                     │
┌───────────────┐             ◇──────────◇             ┌─────────────────┐
│ PWM value = 200 │◄── Y ──│ ADC value > │── N ──►│ PWM value = ADC value │
└───────┬───────┘             │    200?    │             └─────────┬───────┘
        │                     ◇──────────◇                         │
        └──────────────────────────┼────────────────────────────────┘
                                    │
                         ┌──────────▼─────────┐
                         │       RETURN        │
                         └────────────────────┘
```
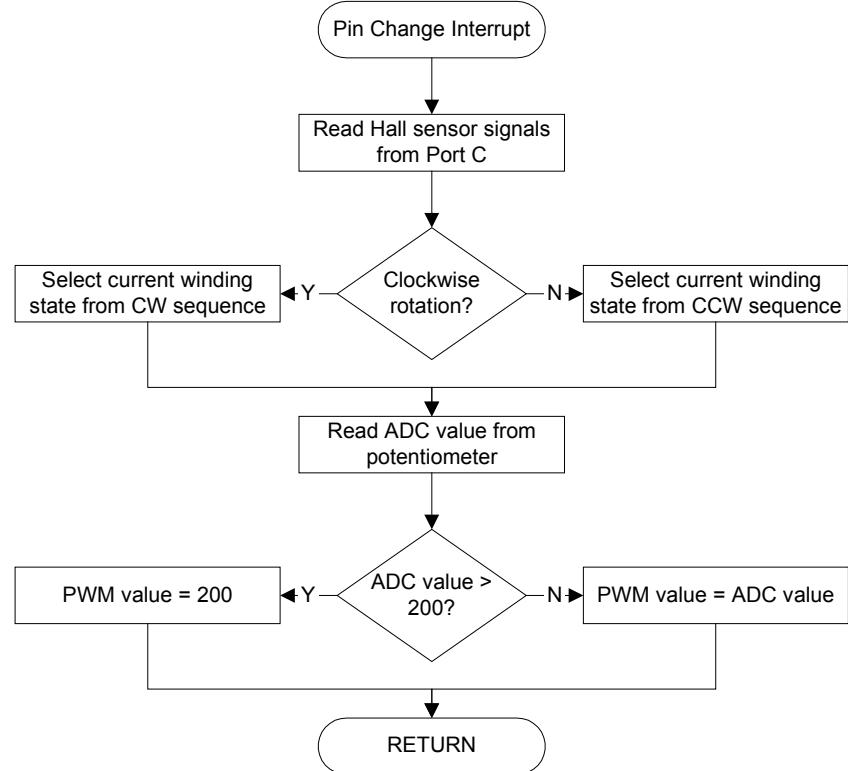
2.3.3 Analog-to-Digital Converter

The ADC converts the POT voltage to a digital number used by the Pin Change Interrupt Routine. This 10-bit value is converted to 8 bits, and limited under software control to 200. It is then sent to the PWM Output Compare register, where it sets the PWM duty cycle. If 0 is written to the OCR2B register, this will result in 0% PWM or no voltage applied to the motor. Conversely, if 200d = 0xC8 is written to OCR2B, this will result in 200/255 = 78.4% PWM or 78.4% of full voltage.

3 Schematic

The schematic contains circuitry for a demo board, and includes the necessary power supplies, ATmega48, IPM and the 3-phase motor.

3.1 4.1 Safety Precautions with Line Operated Power Supply

This power supply was designed to run from 120VAC, 50-60Hz. Notice that the negative side of the two bridge rectifiers is connected to a common ground. This IS NEITHER chassis ground NOR Earth Ground. DO NOT connect this ground to your oscilloscope ground wires! An Isolation transformer must be used. An example is shown here, along with a voltage variable transformer; the voltage variable transformer is highly recommended while developing code, because programming bugs could apply maximum voltage to the motor and damage some components.

Figure 3-1. BK Precision Variable AC supply

Figure 3-2. BK Precision Isolation Transformer

These are two of many available devices to aid in development and increase the level of safety. The above equipment is for 120VAC operation. For 220-240VAC operation, similar equipment rated for 220-240VAC must be used.

If it is desired to run this demo on 220-240VAC, the power supply must be modified with higher voltage components, not shown here. The IPM shown is rated up to 600VDC. It is the responsibility of the reader to use safe development procedures to prevent electric shock and equipment damage.

Note that there is a transformer on the schematic. This reduces the incoming AC to approximately 15VAC, which is then rectified and filtered for use by the 15VDC and 5VDC regulators.

The ATmega48 is shown connected for demonstration purposes. It has many additional I/O and ADC inputs, as well as additional features that are beyond the scope of this application note.

The IPM is wired sufficiently to operate the motor from 0-5000+ RPM. The IPM has built in protection circuits that protect itself and the motor. However, a bug in programming can cause full voltage to be applied to the motor, and may damage the motor and/or the IPM. This is why the Variable AC Supply is HIGHLY RECOMMENDED. Start your program development at much lower voltages, and apply 25-50VDC to the IPM at first. Also, the transformer shown in the schematic may have to be connected to 120VAC (not through the variable AC supply) so that the 5 and 15VDC voltages will be present while the Variable AC Supply controls the high DC voltage.

The Hall sensors operate on 5VDC. Their 3 digital outputs are connected directly to the ATmega48 Port C.

Atmel offers the debugging/programming tool JTAG ICE mk II. It is an ideal tool for program development and debugging. When used with the ATmega48/88/168, the debugger uses only one pin: the Reset pin. This tool is designed to work with Atmel's AVR Studio 4.

4 Alternative Solutions

The application described above enters an eternal loop, polling the PWM output and setting the IPM signals. This leaves no CPU time for other tasks, such as external communication or safety functions (thermal shutdown etc). For such applications, two alternative solutions are given in the following.

4.1 External OR gates

The raw PWM signal is already present on the OC2B pin (PC3). Instead of polling this bit in software, it could be wired to an array of external OR gates. The gates use the PWN output as an inverted ENABLE signal for passing through the IPM signal or not. If the PWM output is low, the IPM signal is passed unchanged through the gate. When the PWM output is high, the gate output is always high, meaning 'inactive' to the IPM input. This solution requires the OC2 output to be inverted by setting the appropriate bits in the Timer/Counter Control Register.

Figure 4-1. Using external OR gates
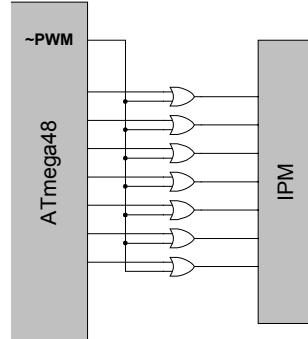
4.2 Utilizing more PWM channels

The two 8-bit Timer/Counters in ATmega48 provide three PWM channels each. However, when limiting the PWM base frequency to 20kHz, the register controlling channel A is used to set the timer TOP value. This leaves two PWM channels on each timer. The IPM is always used with one High-side and one Low-side input activated. By choosing to only Pulse-Width-Modulate the Low-side inputs, three PWM channels are enough and can be used to drive the Low-side inputs directly, thereby eliminating the eternal loop in software.

5 Literature

- The datasheet for the IPM is available at:
  http://www.irf.com/product-info/datasheets/data/irams10up60a.pdf
- The datasheet for the motor used is available at:
  http://www.newmotech.com/dws.html
- More information on motor technology:
  http://www.freescale.com/webapp/sps/site/overview.jsp?nodeId=02nQXGrrIP

Figure 5-1. Schematic diagram
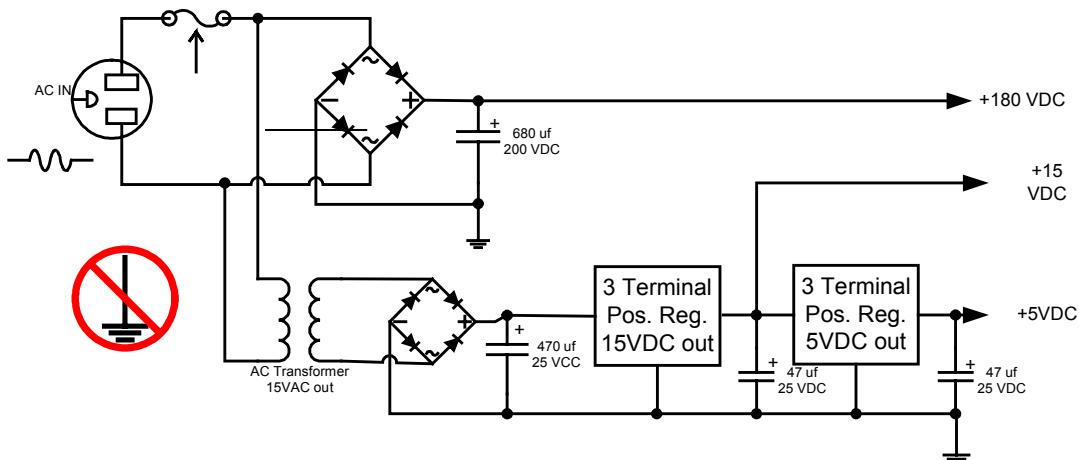
Shock Hazard! Dangerous voltages connected to GROUND on this schematic.

An ISOLATION TRANSFORMER MUST BE USED during DEVELOPMENT and TESTING
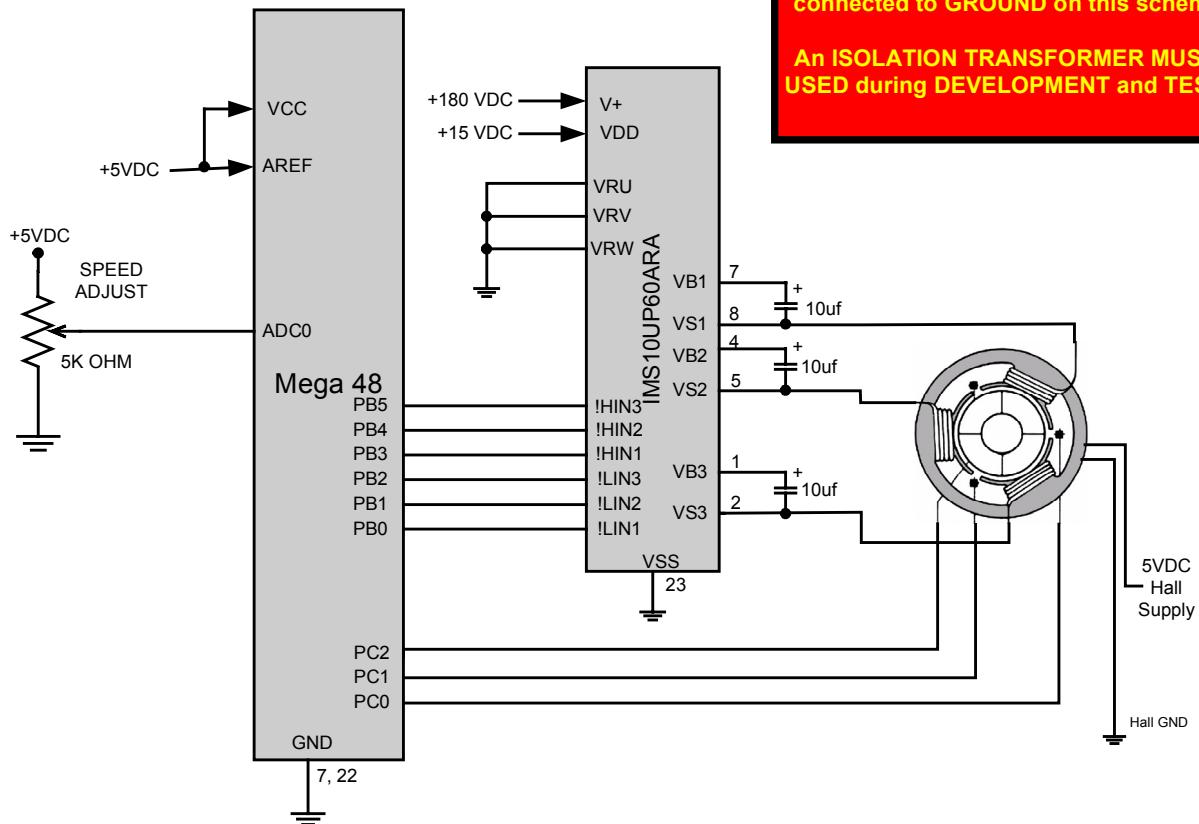
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