AN1663

LOW COST UNIVERSAL MOTOR SENSORLESS PHASE ANGLE DRIVE SYSTEM

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1 INTRODUCTION

This application note describes the design of a low cost phase angle motor control drive system based on the MC68HC05JJ6/MC68HC705JJ7 microcontroller and the MAC4DC snubberless triac. The low cost single-phase power board is dedicated for universal brushed motors operating from 1000 rpm to 10,000 rpm. This universal motor is today the most widely used motor in home appliances such as: vacuum cleaners, washers, hand tools, and food processors. The operational mode, which is used in this application, is closed loop and regulated speed. Compared to the conventional solution with a tachometer on the shaft of the motor, this application note describes a solution **without** any tachometer. The speed sensing is performed indirectly by the microcontroller measuring the motor current. The kind of motor and its drive have a high impact on many home appliance features like: cost, size, noise and efficiency. Electronic control is usually necessary when variable speed or energy savings are required.

Microcontrollers offer the advantages of low cost and attractive design. They can operate with only few external components and reduce the energy consumption as well as cost. This circuit was designed as a very simple schematic using all the features of a simple microcontroller. The microcontroller and this board may be used in a wide variety of applications.

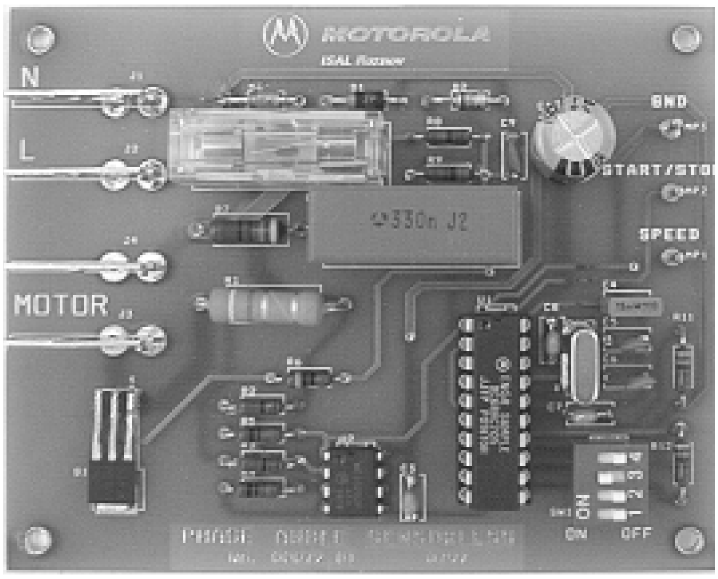

Figure 1. Low Cost Motor Control Phase Angle Board

MOTOROLA

The Phase Angle control technique is used to adjust the voltage applied to the motor (refer to Figure 2). A phase shift of the gate's pulses allows the effective voltage, seen by the motor, to be varied.

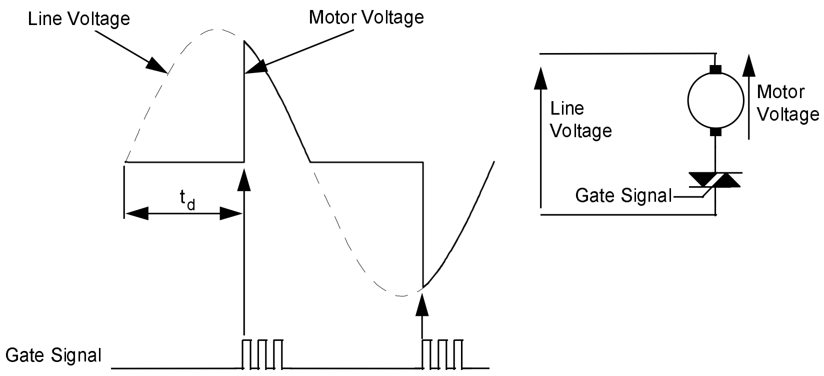

Figure 2. Phase Angle Control technique

All the required functions are performed by just two integrated circuits and a small number of external components. This allows a very compact printed circuit board design and a very cost effective solution.

This application note also explains how to design the software implementation using an HC05 microcontroller. Such a low cost microcontroller is powerful enough to do the whole job necessary for driving a closed loop sensorless phase angle system.

2 DEVICES

Universal motors are still used where brushes are accepted and universal motors driven by triacs are used where a low price is required. This section contains information and descriptions about all features of suitable microcontrollers and triacs.

MC68HC05JJ6/MC68HC705JJ7

The 68HC05JJ6 is an HC05-based MCU designed for low-cost applications. General features include 6.1k bytes of ROM, 224 bytes of RAM, a 16-bit timer including an output compare and an input capture, 14 general-purpose I/O pins, and a simple serial input/output (SIOP) port in a 20-pin SOIC or a DIP package. In addition the JJ6 has specific features including two comparators which can be combined with the 16-bit programmable timer to create a 4-channel single slope A/D converter. It also includes a high current source/sink port and an on-chip temperature measurement diode. The high current source pins are very important for this application. The JJ6 has 6 pins with 10 mA sink capability.

The MC68HC705JJ7 has the same features but replaces the ROM with a 6.1k EPROM and is more suitable for program development.

Triac MAC' Family

The MAC4 and MAC8-16 series are specially designed for efficient motor drives. Triacs with low-enough trigger current for direct drive by a microcontroller (MAC4DS, MAC8S, MAC15S) usually have a low dv/dt capability and may need to be snubbed. The MAC15S is the largest sensitive-gate triac in the market today. High dv/dt devices such as the MAC4DC, MAC9 and MAC16 are ideal for snubberless applications. They can turn off inductive loads without a snubber turn-off circuit, thereby saving the cost and space of extra components. The **MAC4DCN** triac is designed for low cost, industrial and consumer applications such as temperature, light and speed control. The main parameters are the following:

Table 1. Electrical characteristics of the MAC4DCN

Parameter	Value
Peak repetitive reverse voltage VRRM	800 V Max
RMS current IT(RMS)	4 A Max
Peak On-state voltage (ITM = 6 A peak) VTM	1.3 V Typ
Continuous gate trigger current IGT MT2(-), G(-) IGT	25 mA Typ
Critical rate of rise Off-state voltage dv/dt	1700 V/μs Typ

3 CIRCUIT

3.1 Description

In Figure 3. a schematic of a sensorless phase angle motor control board is shown. As can be seen, the phase angle drive needs only two integrated circuits - the microcontroller and one operational amplifier. The snubberless triac MAC4DC is used as the power device. This triac has a very high dv/dt immunity and therefore there is no RC circuit around the triac. The MT1 pin of the triac is connected to VCC and the GATE pin directly to the microcontroller. The triac's turn-on level on pins PA3-PA5 is 0 V. This configuration was chosen due to two reasons. The first is the current capability of the pins of port A. In the data-sheet it can be found that the source capability is 5 mA and the sink capability is 10 mA. Our choice is the sink mode. The second reason is determined by the triac. There is a common law stating that snubberless triacs with high dv/dt immunity need a higher gate trigger current IGT. The MAC4DC typically needs at least 25 mA, in the case of negative IGT - G(-). For an operational mode with positive IGT - G(+), the gate trigger current is much higher. Our choice is G(-), commonly called "3rd quadrant operation". Three pins PA3-PA5 are connected together and are powerful enough to cover the amount of current needed by the gate and to turn on the triac reliably.

The power supply includes only a few components (D1, D4, R7, C1, C2). The output voltage is +5V and despite its simplicity it is able to supply the microcontroller, the operational amplifier, the external control panel and also the triac.

WARNING

This circuit is powered directly from the line and contains HIGH VOLTAGES. Do not touch any parts of this board. When working with such board, do not connect any computer, scope or development system. In this case it is necessary to use an isolation transformer.

The circuitry connected to pin PB6 is needed for the acquisition of a synchronization signal. This signal provides the most important information to the microcontroller, which is the zero crossing of the line voltage. The point of the zero crossing is fundamental for the calculation of any triac's action. All actions and the functionality concerning the triac are controlled by software and will be discussed later.

Because this board provides a sensorless control algorithm there are some devices which allow the measurement of a current. The current measurement consists of the voltage drop resistor R1 and the differential amplifier U2A. In this part the low voltage rail-to-rail operational amplifier MC33202 is used. The MC33202 is device with rail-to-rail operation on both the input and output. The output can swing within 50 mV of either supply. Such a device makes it possible to build a low cost circuit in order to amplify the signal from the voltage drop resistor. The only errors exist for very low currents and can be eliminated by the software. The analog signal from the output of the amplifier U2A is connected to pin PB1.

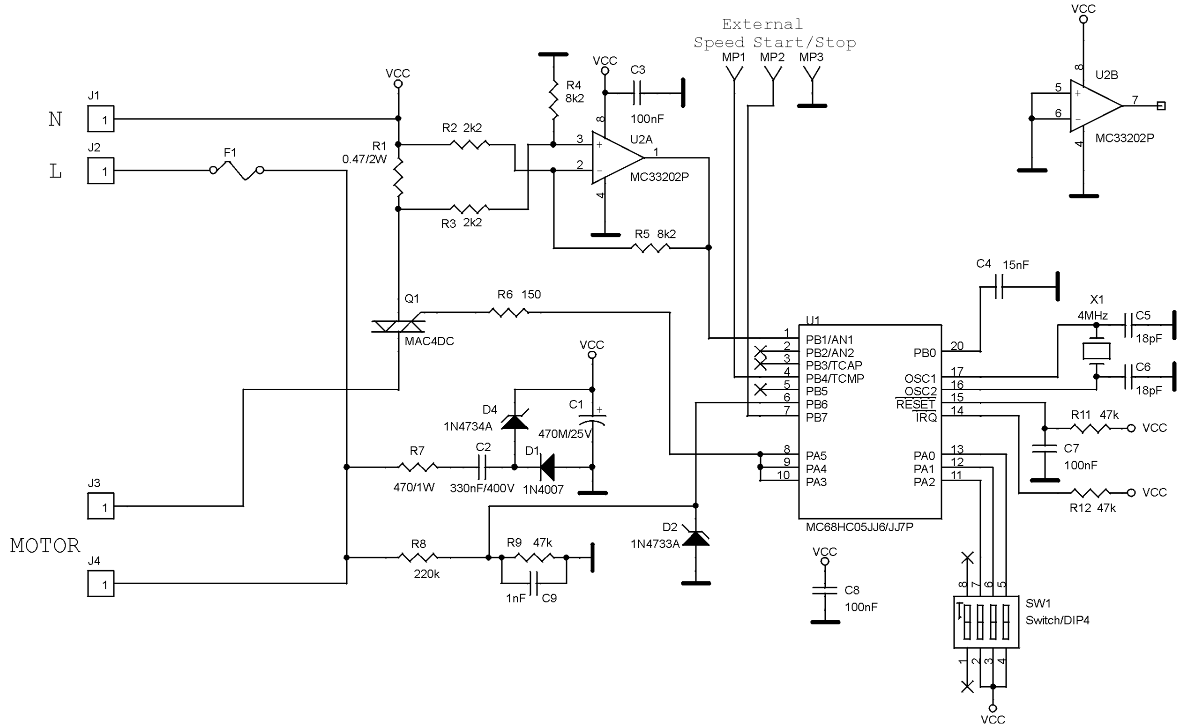

Figure 3. Low Cost Motor Control Phase Angle Sensorless Drive

The speed command can be set externally in the range of 0 V to 3.5 V. A simple external control panel (refer to Figure 4.) should be linked with the phase angle power stage when external commands are needed. The limits for the analog speed command (max 3.5 V) are given by an internal A/D convertor limitation. The connectors MP1-Speed, MP2-Start/Stop and MP3-GND are provided on-board.

WARNING

Because of HIGH VOLTAGES, the control panel must be isolated from the user under all possible circumstances.

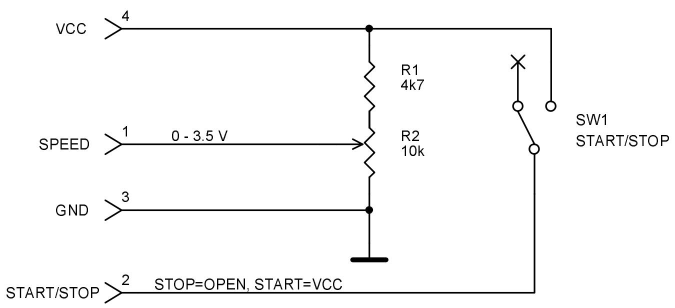

Figure 4. External Control Panel

The DIP switch SW1 allows an option of the drive’s functionality and will be discussed later.There are no pulldown or pullup resistors because these devices are provided directly on the chip. The appropriate resistors are enabled in a mask option register.

3.2 Synchronization

As is well known, the phase angle drive system needs to have information about the line voltage and its zero crossing points. The appropriate signal is connected to pin PB6. Only two resistors R8, R9, one capacitor C9 and a diode D2 (as an overvoltage protection) are used. Due to its simplicity and its low cost solution, the output signal is not a real square wave. In Figure 5 the relationship between the line voltage and the synchronization signal can be seen. The positive half period and the negative half period are not identical. This situation causes a distortion of the motor current. Under this condition the phase angle drive works but the triac is overloaded during one half period. Figure 5 also shows the current of the motor including the software adjustment. A very fine correction can be done by software to avoid unequal half periods of the current.

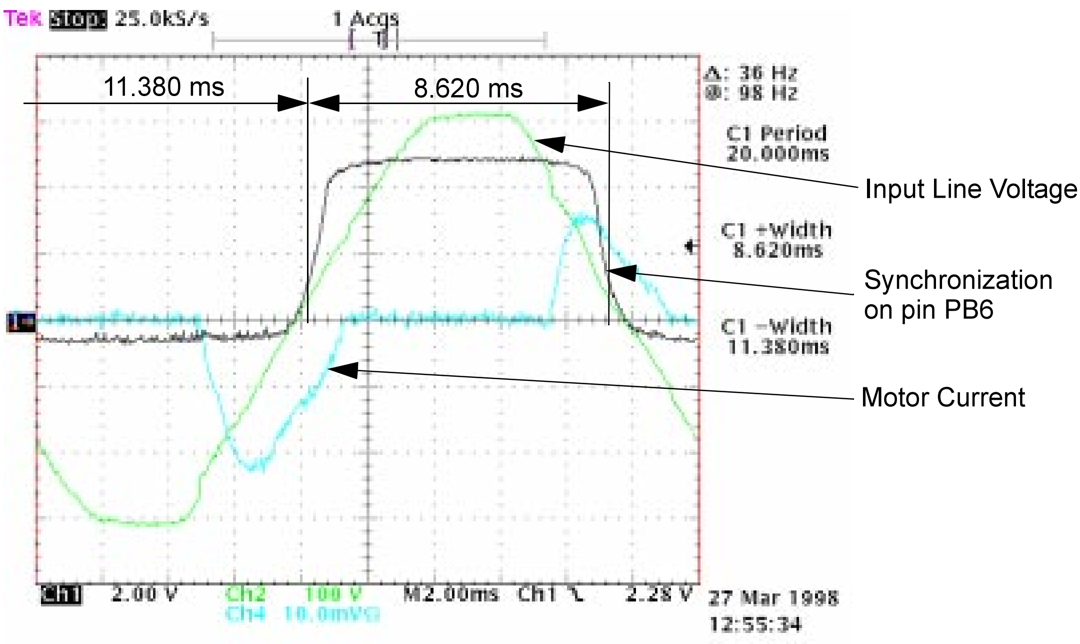

Figure 5. Synchronization Signal

4 SENSORLESS ALGORITHM

The universal motor is a serial excitation motor. Therefore the motor torque is proportional to the square of the motor current:

$$T = k.i^2 \quad \text{(EQ 4-1.)}$$

The equations for the universal motor driven by a triac have to be split into two phases:

a) while the triac is off

$$i = 0 \quad \text{(EQ 4-2.)}$$

b) while the triac is on

$$v = e + z.i \quad \text{(EQ 4-3.)}$$

Where

e	= back electromotive force (bemf) $k.i.\Omega$
z	= motor impedance $r + j.L.\omega$
ω	= mains frequency
Ω	= motor speed
k	= constant depended upon motor characteristics
r	= winding resistance

$$v = (k.\Omega + r).i + j.L.\omega.i \quad \text{(EQ 4-4.)}$$

The Saber™ analog simulator was used in order to calculate all necessary equations and run the virtual universal motor phase angle sensorless drive system. For a model of the universal motor the standard model from the library was used (dc_srs.sim). Customization was done according to the parameters of a 400 W universal motor from a washing machine. All the following results and figures are taken directly from the simulation. The schematic of the simulation circuitry is shown in Figure 6. The circuitry consists of the AC power supply, the universal motor, the triac, the load, and the pulse source.

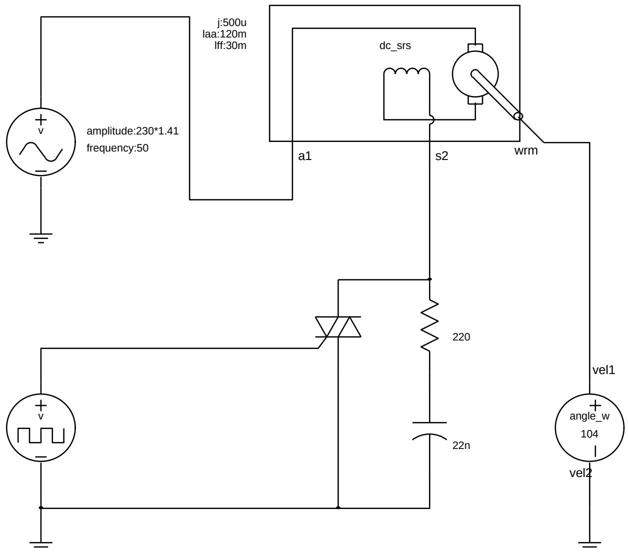

Figure 6. Schematic for Simulation

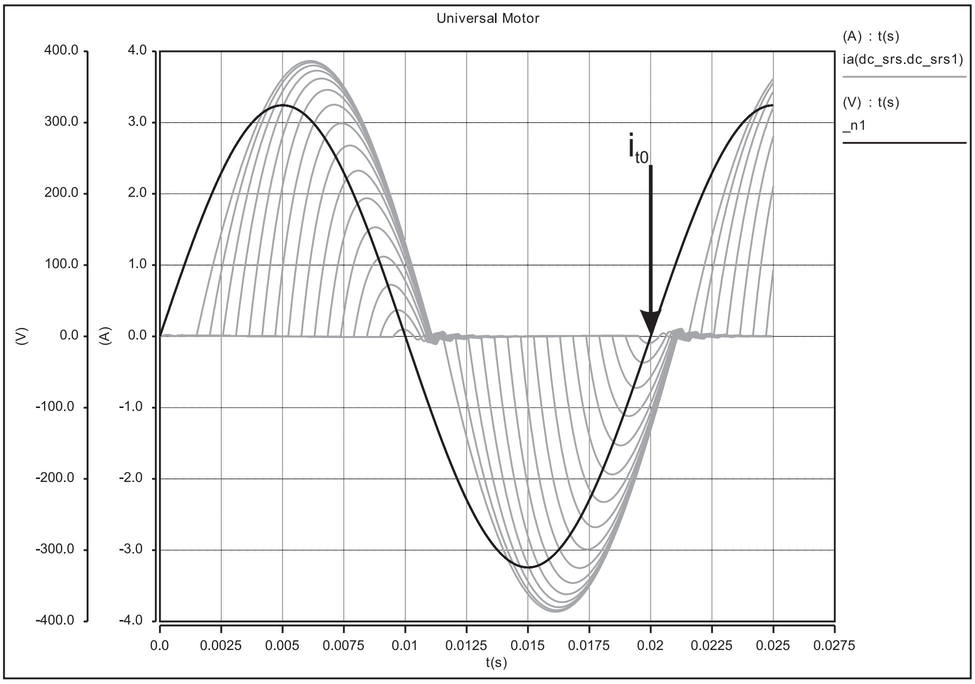

Figure 7. Set of Current Curves for Different t_d in the Range of 1.5 ms - 9.5 ms at 1000 rpm

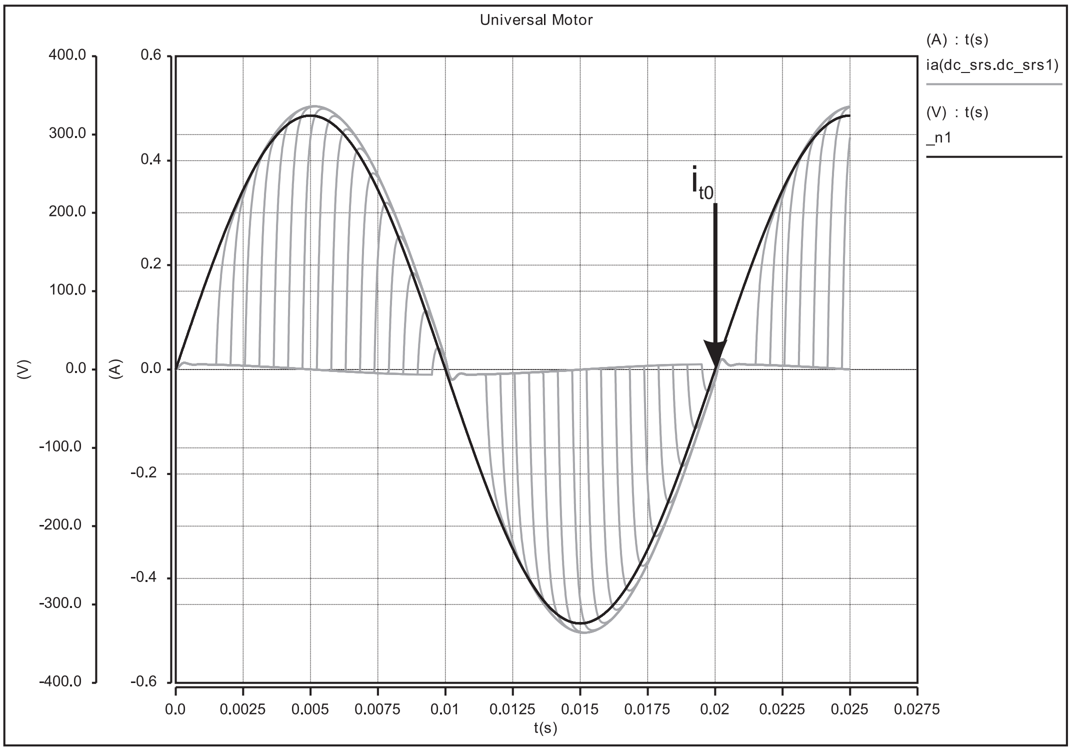

Figure 8. Set of Current Curves for Different t_d in the Range of 1.5 ms - 9.5 ms at 10 000 rpm

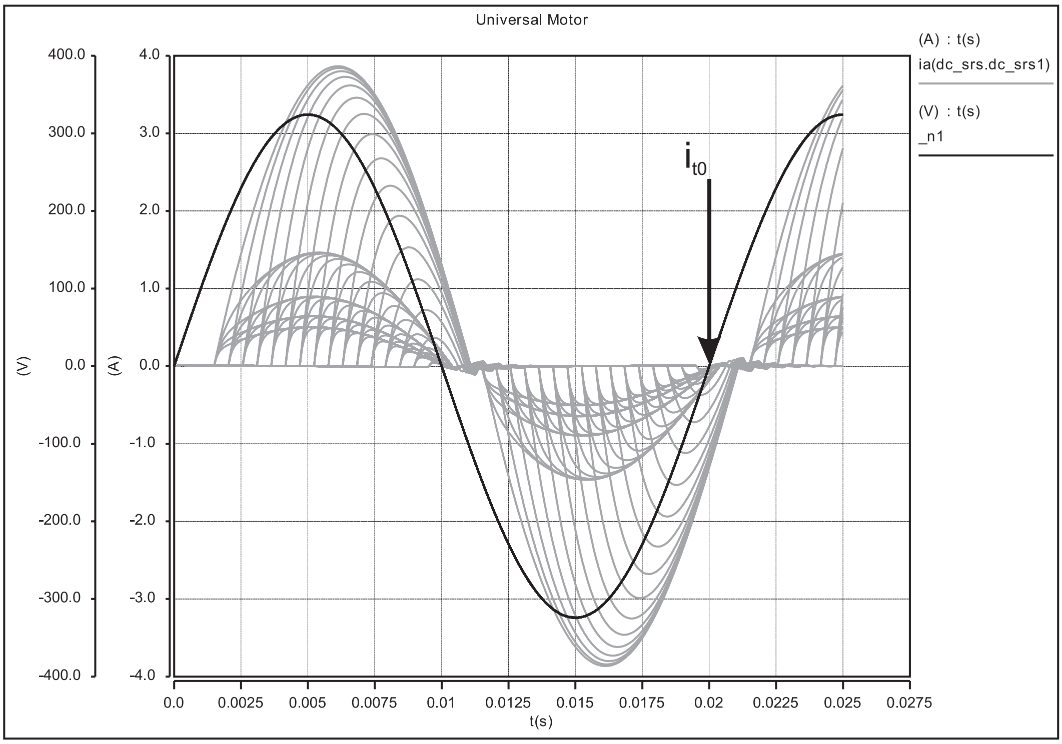

Figure 9. Sets of Current Curves for 1000, 3250, 5500, 7750 and 10 000 rpm

Figures 7, 8 and 9 show sets of the currents for firing delay t_d (refer to Figure 2) in the range of 1.5 ms - 9.5 ms at different speeds. Certain sets of the current are given at a constant speed, e.g. in Figure 7 at 1000 rpm. The firing delay t_d varies in a wide range and represents the varying load.

From Figures 7, 8 and 9 it can be also seen that the current $i_{t0,}$ which is measured at the mains zero crossing point, depends only upon the speed except at the largest firing delay of 8 ms. Figure 10 gives the best explanation. For speeds faster than 3000 rpm and a firing delay less than 8.5 ms, the current at the mains zero crossing point is constant at the given speed for a wide variety of loads. For speeds less than 3000 rpm or a firing delay more than 8.5 ms, a correction needs to be done. Units used for the speed are radians per second (rps). Table 2 shows the recalculation between radians per second (rps) and revolutions per minute (rpm).

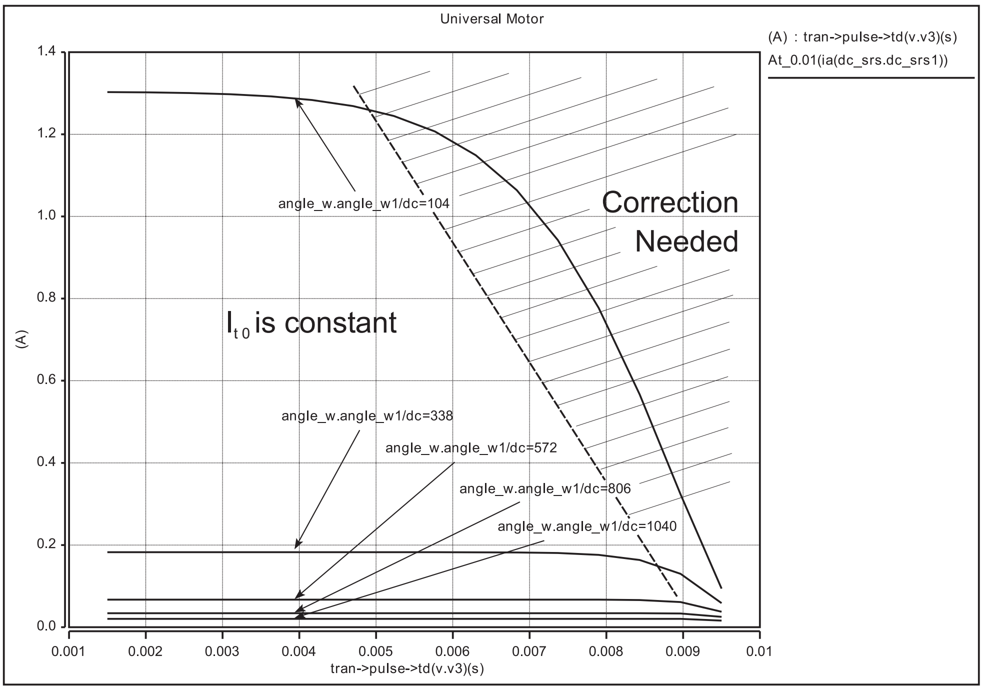

Figure 10. Current i_{t0} at Mains Zero Crossing versus Firing Delay t_d for Various Speeds

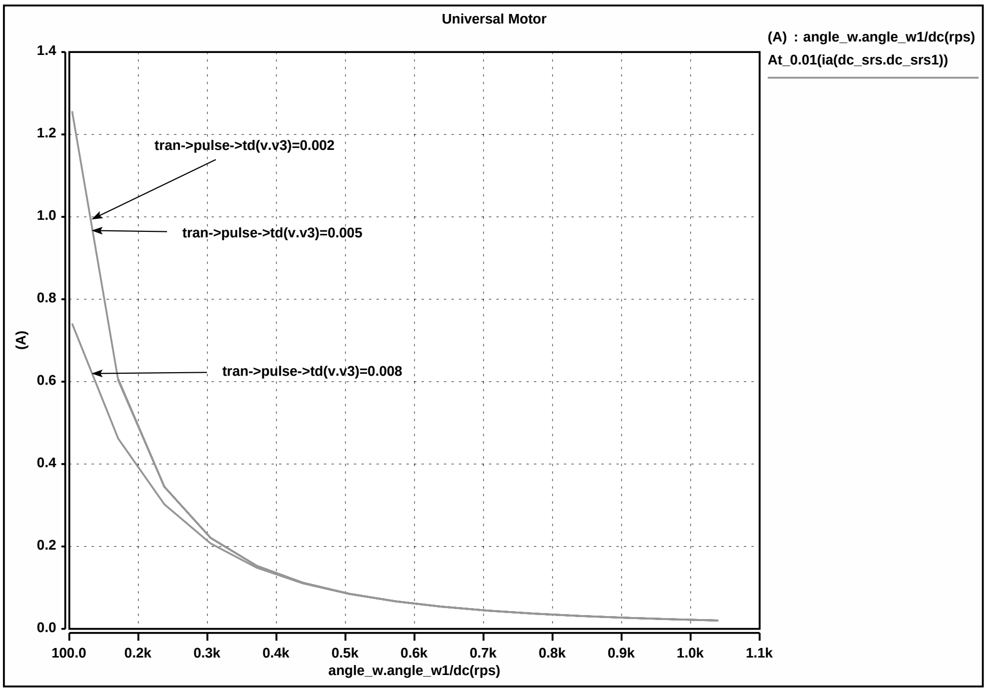

Figure 11. Current i_{t0} at Main Zero Crossing Versus Speed for Various Firing Delays t_d

Table 2. Recalculation rps - rpm

rps	rpm
104	1000
338	3250
572	5500
806	7750
1040	10 000

The relationship between the speed and the current is shown in Figure 11. This characteristic is used in the program and it determines that a certain current corresponds to unique speed. It is valid for the range of speed of 3000 to 10 000 rpm and t_d less than 8.5 ms. The representation of the curve from Figure 11 is expressed in the table and it is included in the program. The correction for the speed less than 3000 rpm and the firing delay more than 8.5 ms is shown in Figure 12. The representation of this curve is expressed in the table and it is also included in the program

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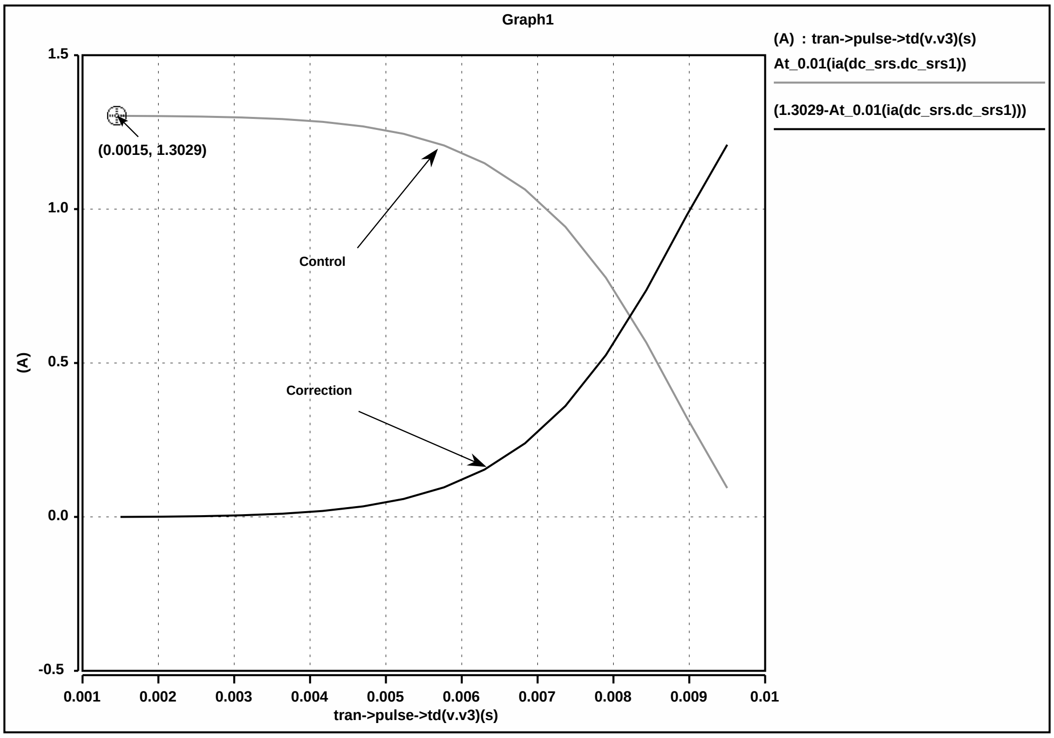

Figure 12. Current i_{t0} at Mains Zero Crossing versus Firing Delay at 1000 rpm and Suitable Correction Curve

5 CONTROL ALGORITHM

The basic principle of the phase angle control algorithm is very simple: match the firing pulse time of the triac in relation with the zero crossing of the line voltage. A phase shift of this firing pulse produces a variable output voltage on the load. A structure with three interrupts has been chosen to assure proper functionality and some additional performance capacity of the CPU.

Figure 13 shows a state diagram. The software consists of a Control block and some subroutines like: MAKE_ZERO, MAKE_PI, RAMPE and Interrupt Services Routines. The Control Block is in fact a relatively short loop which makes a decision on which subroutines will be called. There is also a universal timing routine, which works with the HW timer and a unique register for every timed subroutine. The timing routine calculates the difference between the HW timer and a particular register and, in case of coincidence with the given number (time interval), it calls the appropriate subroutines. The same principle is used for all time conditions.

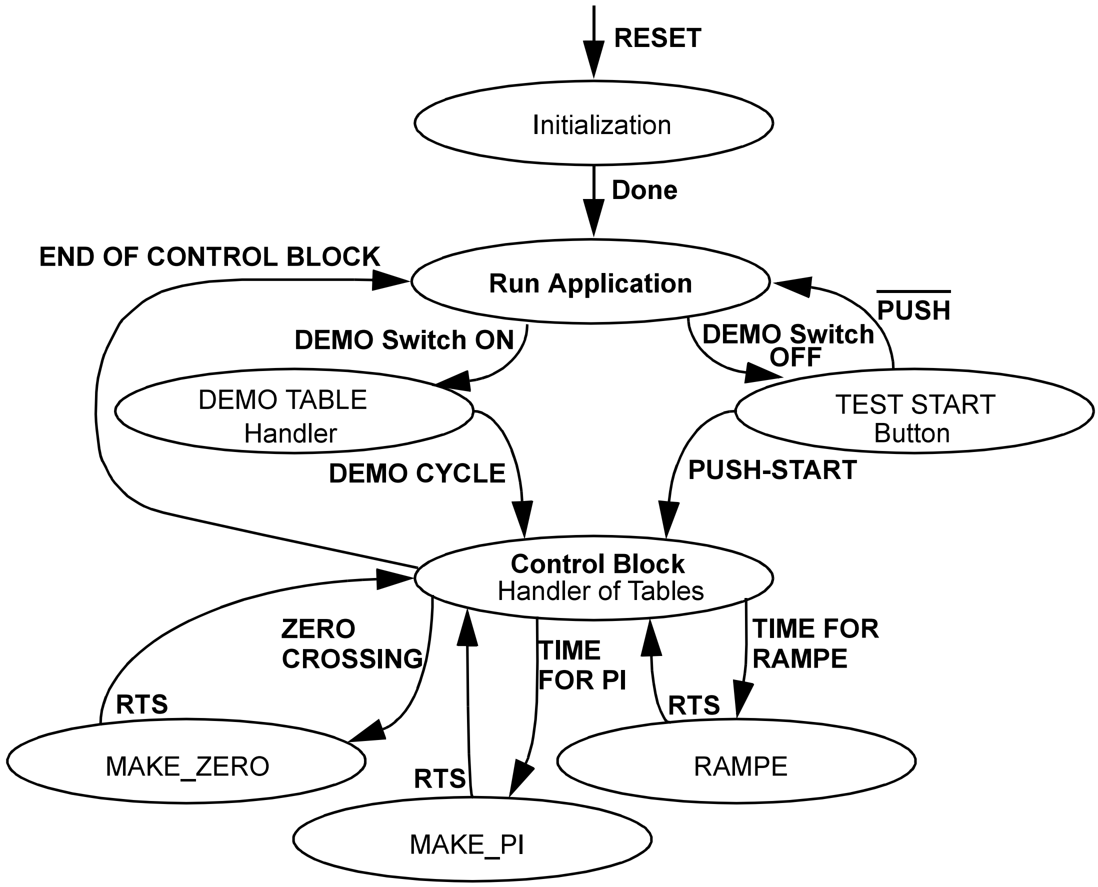

Figure 13. Program State Diagram

The requirements of this software dictate that it takes some of the values from the A/D converter (speed command and current), processes them and generates the pulses for the gate of the triac. The data flow diagram is shown in Figure 14.

The program deals with two tables - SPEED_TAB and CORRECTION. These tables contain data which correspond to the curves from Figure 11 and Figure 12. The speed command goes through the acceleration/deceleration ramp and the SPEED_TAB table. According to the speed and the load there is a correction process using the CORRECTION table. The speed command and the actual speed, which is represented by current i_{t0}, are brought to the PI control algorithm. Using the output compare feature of the microcontroller the pulses for the gate of the triac are generated.

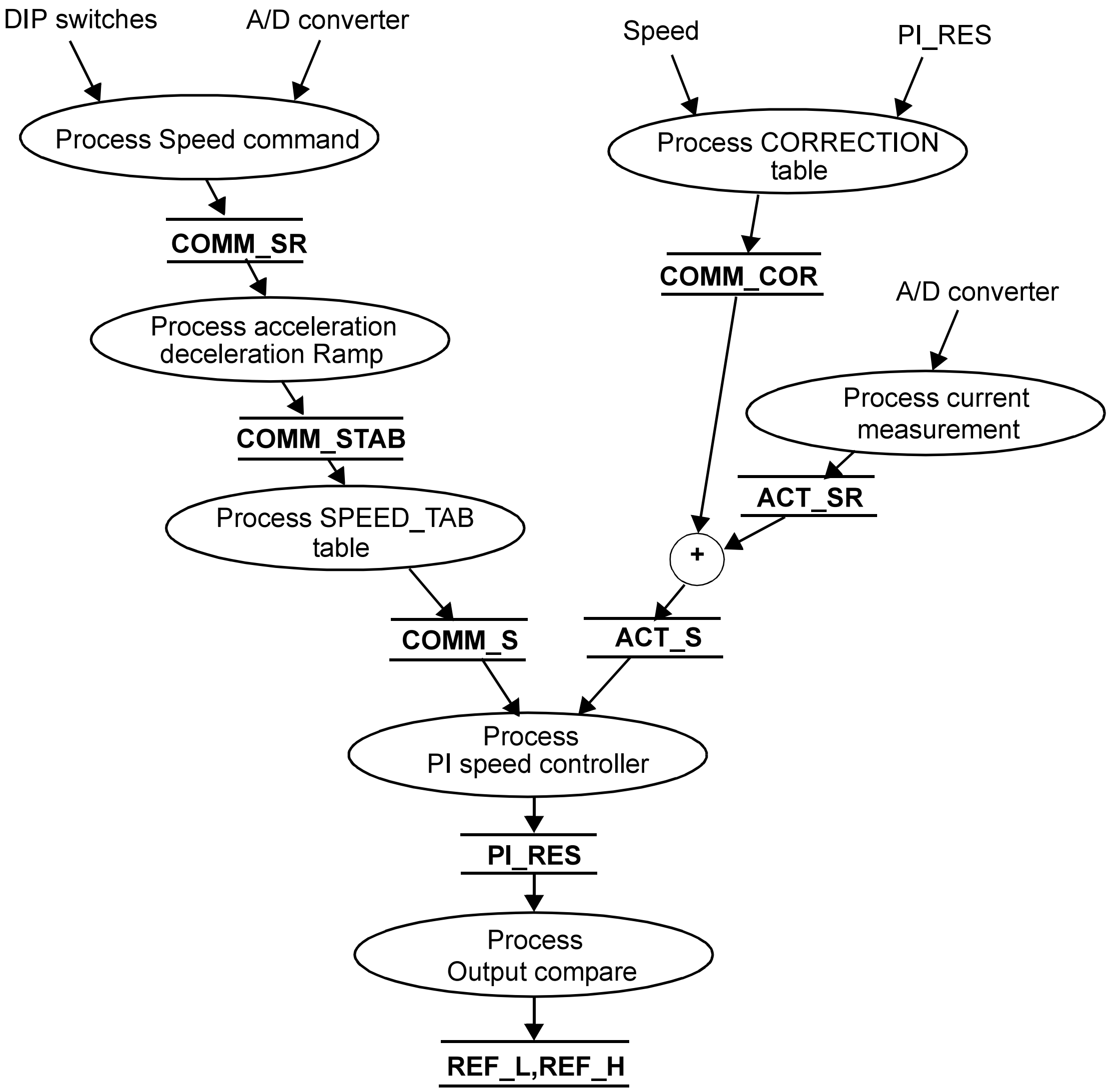

Figure 14. Main Data Flow

A DIP switch with three connected switches (refer to Figure 15) is available on the board. Two of them are tested by the discussed software (“2” and “3”) and one is free for customer use (“4”). The control block tests the switch number “2”. This switch selects the “Demo mode” or the “START/STOP” mode. In the Demo mode the drive starts automatically and runs in a three step endless loop. In the START/STOP mode both the external START command and the analog external speed command are necessary.

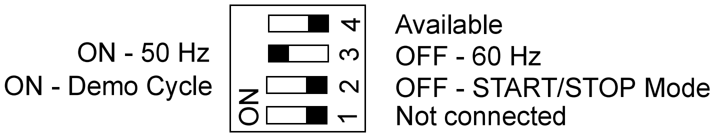

Figure 15. DIP Switch SW1

5.1 MAKE_ZERO subroutine

The MAKE_ZERO subroutine is entered when the zero crossing of the line voltage occurs. Its main job is to prepare the new value for the output compare interrupt service routine. The calculation is based on the half period of the line voltage. Since this time is different for 50 Hz and 60 Hz, there is a switch number “3” to distinguish between these two cases. The input value for the calculation is an output value from the PI controller. The recalculation is done according to the position of the switch number “3” and the known speed of the HW timer. The second task of the MAKE_ZERO subroutine is to start the A/D convertor. The A/D converter is needed for the measurement of the current (pin PB1) and for the START/STOP mode when the external analog speed command (pin PB4) needs to be converted. The A/D converter has several options and it is based on the two on-chip voltage comparators and a selectable charge/discharge function. Voltages are resolved by measuring the time it takes an external capacitor to charge up to the level of the measured unknown input voltage. The external capacitor can be calculated from the following expression:

$$C_{EXT} = (N \times I_{CHG} \times P) / (V_X \times f_{OSC})$$

Where:

N	= Number of counts during charge time 255
I_{CHG}	= Charge current 100 µA
P	= Prescaler value 8
V_X	= Maximum input voltage 3.5 V
f_{OSC}	= Oscillator clock frequency 4 MHz

$$C_{EXT} = (255 \times 100\text{x}10^{-6} \times 8) / (3.5 \times 4\text{x}10^{6}) = 14\ \text{nF}$$

From several working modes, option mode 1 with manual charge control and automatic discharge was chosen. The analog subsystem can generate some interrupts. An analog interrupt occurs when there is a match in the input conditions for the voltage comparator. This analog interrupt is used to make the achievement of the results easy.

5.2 MAKE_PI subroutine

The MAKE_PI subroutine is entered when the time condition occurred. Its main job is the calculation of the PI controller. The input value for the PI controller is the output value from the table SPEED_TAB. There is a need of correction in case the speed is smaller than 3000 rpm and the firing delay larger than 8.5 ms (refer to Figure 12 and Figure 14).

For the PI controller the well known equation is used:

V = VZ_1 + P_CONST x (E - EZ_1) + I_CONST x E

Where:

V	= Actual new value
VZ_1	= V in last step
P_CONST	= proportional constant
E	= command_speed - actual_speed
EZ_1	= E in last step
I_CONST	= integration constant

The output from the PI controller is the input value for the output compare interrupt service subroutine.

5.3 RAMPE subroutine

The RAMPE subroutine is entered when a time event occurred. This subroutine in fact changes the slope of the command speed’s signal. The slope is the same for the rising and falling edges. The slope can be modified through a change in the time interval for the RAMPE subroutine.

6 INTERRUPTS

As was mentioned in section 5, three interrupts are used (refer to Figure 16). The simplest interrupt is the Timer overflow interrupt. The appropriate service routine is the Timer overflow interrupt service routine (TOISR) and it produces a real time clock for the application. The Analog interrupt service routine (ANISR) reads and stores the new values from the A/D convertor (the current and the speed command). The Output compare interrupt service routine (OCISR) generates the pulses for the triac (refer to Figure 17).

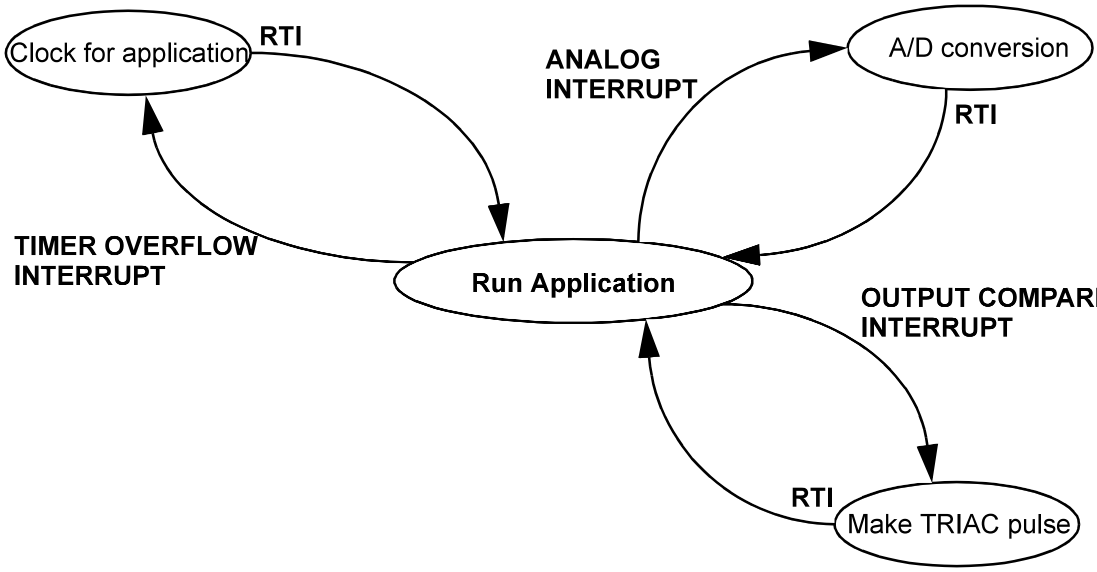

Figure 16. Interrupt Service Routines

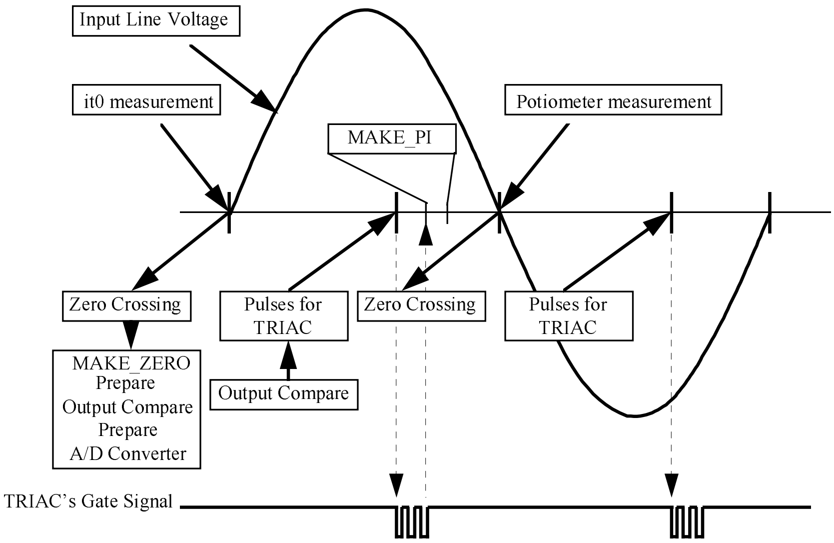

Figure 17. Timing of SW Subroutines

7 MICROCONTROLLER USAGE

7.1 Total RAM & ROM used

Table 3 shows how much memory was needed to run the phase angle drive. A significant part of the memory is still available.

Table 3.

Memory	Available	Used
SRAM	224Bytes	43Bytes
ROM	6.1kBytes	1.5kBytes

7.2 I/O use

Table 4 summarizes the use of the I/O pins. It can be seen that 3 pins are still available.

Table 4.

I/O	Available pins	Used pins	Purpose
Port A	PA0-PA5	PA0-PA2 PA3-PA5	DIP switch Triac
Port B	PB0-PB7	PB0 PB1 PB4 PB6 PB7	Ext. capacitor Motor current Ext. speed Synchronization Ext. START

8 PARTS LIST AND PCB

The list of components is listed in Table 5. and Figure 18 and Figure 19 show the PCB layout.

Table 5. Parts List

Component	Quantity	Value/Rating	Description
U1	1	-	IC, MC68HC05JJ6P or MC68HC705JJ7P
U2	1	-	IC, MC33502P
Q1	1	4 A, 800 V	Triac, MAC4DCN-1
X1	1	4MHz	Resonator
D1	1	1.0 A, 1000 V	Diode 1N4007
D2	1	5.1 V, 1.0 W	Zener Diode, 1N4733A
D4	1	5.6 V, 1.0 W	Zener Diode, 1N4734A
R1	1	0.47 Ω, 2 W	Resistor
R2,R3	2	2.2 kΩ, 1/4 W	Resistor
R4,R5	2	8.2 kΩ, 1/4 W	Resistor

Table 5.   Parts List

Component	Quantity	Value/Rating	Description
R6	1	150 Ω, 1/4 W	Resistor
R7	1	470 Ω, 1 W	Resistor
R8	1	220 kΩ, 1/4 W	Resistor
R9,R11,R12	3	47 kΩ, 1/4 W	Resistor
C1	1	470 µF, 25 V	Capacitor Electrolytic
C2	1	330 nF, 400 V	Capacitor
C3,C7,C8	3	100 nF, 50 V	Capacitor
C4	1	15 nF, 50 V	Capacitor
C5,C6	2	18 pF, 50 V	Capacitor
C9	1	1 nF, 50 V	Capacitor
F1	1	4 A	Fuse
J1-J4	4	-	Connector
SW1	1	-	DIP Switch
MP1-MP3	3	-	Connector

All tolerances ±10% for capacitors, ±1% for resistors, unless otherwise specified.

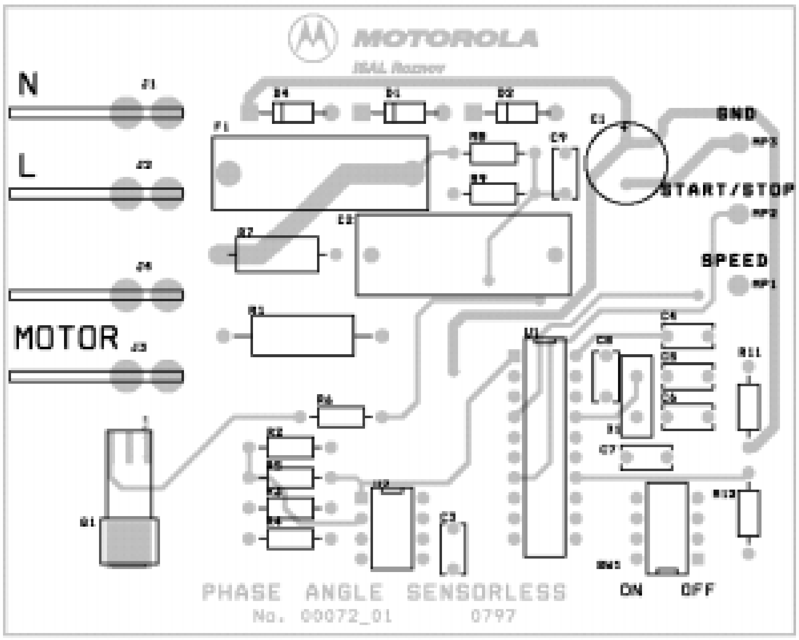

Figure 18.   PCB layout Component Side

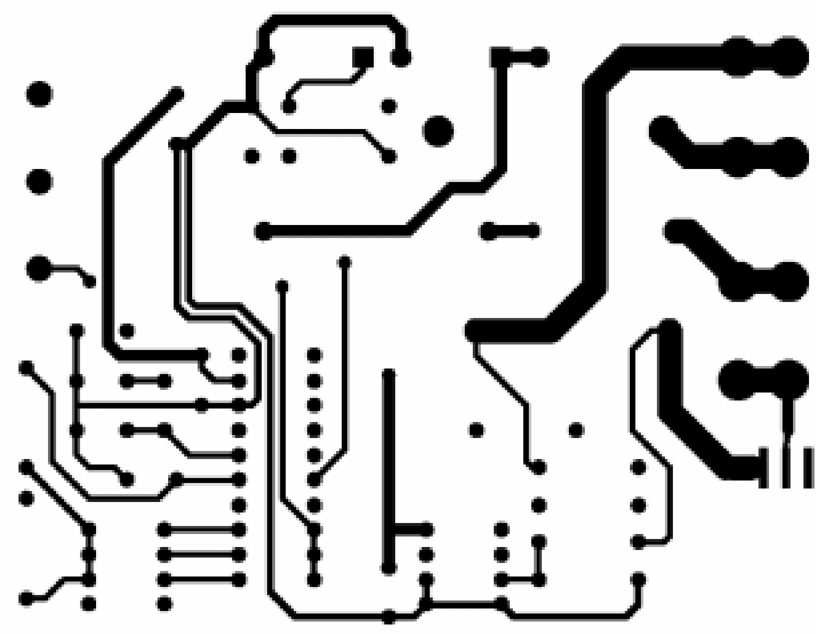

Figure 19. PCB Layout Copper Side

Performance of the Sample Design

Input voltage:............................220 V RMS

Input current:............................1 A RMS (without heatsink and without load)

Motor:.......................................400 W

Demo mode:............................Automatic START, no speed reference needed

START/STOP mode.................START-external +5 V, external speed reference 0 V to 3.5 V

Speed:.....................................1000 to 10,000 RPM

9 CONCLUSION

This application note describes a real application, which can be used in a low cost product. The unused memory and some performance capacity are still available for other customer’s purposes. These facts make this application especially suitable for the appliance market.

This application note also demonstrates how simulation can speed up and improve the design of the demo boards. From the simulation is taken the idea of the current measurement. This fact is important for the PCB design because the voltage drop resistor and the current amplifier must be placed on the PCB. Other parts of the sensorless algorithm are performed by the software.

The WWW page for this application can be found at address

http://Design-net.com/csic/

REFERENCES

1. MAC4DCN Data Sheet;
2. MC68HC05JJ6 Data Sheet; order from Motorola by HC05JJ6GRS/D
3. AN1708 Single-Slope Analog-to-Digital (A/D) Conversion; order from Motorola by AN1708/D
4. AN1662 Low Cost Universal Motor Phase Angle Drive System

NOTES

NOTES

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