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LOW COST UNIVERSAL MOTOR 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 15,000 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. This mode requires a speed sensor on the motor shaft. Such a sensor is usually a tachometer generator. 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 features of a simple microcontroller. The microcontroller and this board may be used in a wide variety of applications.

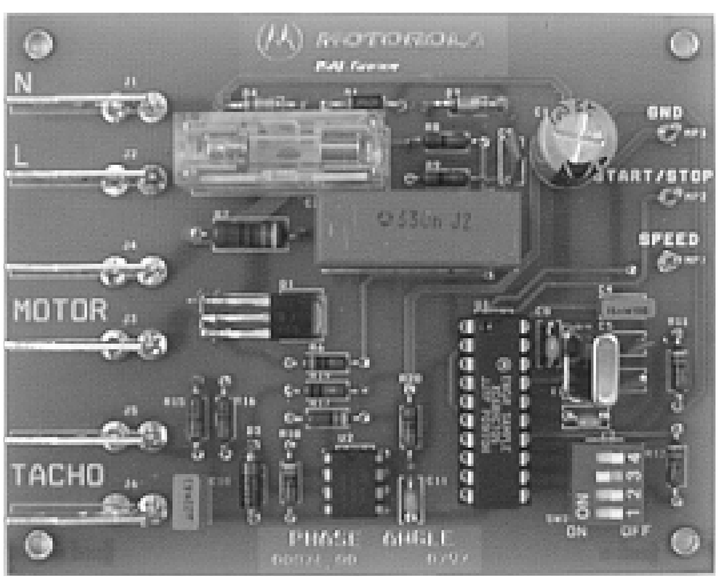

Figure 1. Low Cost Motor Control Phase Angle Board

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.

All 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.

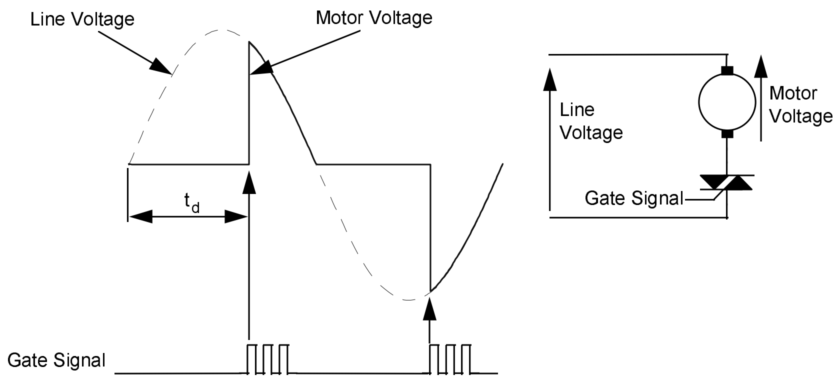

Figure 2. Phase Angle Control technique

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 phase angle system.

2 ADDED VALUE USING A MICROCONTROLLER

Compared to a poor analog solution, a microcontroller based drive shows many advantages. Some of them are listed below:

- choice between different control algorithms
- choice between any shape of speed command (phase acceleration and deceleration)
- choice between any type of tachometers
- software can make the hardware more simple
- diagnostic functions
- remote control by wire and communication protocol
- open for innovation

3 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 series MAC4 and MAC8-16 triacs 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

4 CIRCUIT

4.1 Description

In Figure 3. the schematic of a phase angle motor control board is shown. As can be seen, the phase angle drive needs only two integrated circuits - the microcontroller and one comparator. 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 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 determines 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 needs at least 25 mA typically in case of negative IGT - G(-). For an operational mode with positive IGT - G(+) the gate trigger current is much higher. Our choice is G(-). Three pins PA3-PA5 are connected together and are powerful enough to cover the amount of current needed by the gate and 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 comparator, the external control panel and also the triac.

WARNING

This circuit is powered directly from the line. 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 the control algorithm in closed loop mode there are some devices which allow connection of a tachometer. The most frequently used tachometer has 16 poles and an output voltage of 5 V to 20 V RMS for full scale of working speed. An input filter protects the comparator against high voltage at high speed and diode D3 protects the comparator against negative voltage. The output square wave signal from the comparator is connected to pin PB3. By means of this arrangement the input capture feature of the microcontroller can be used.

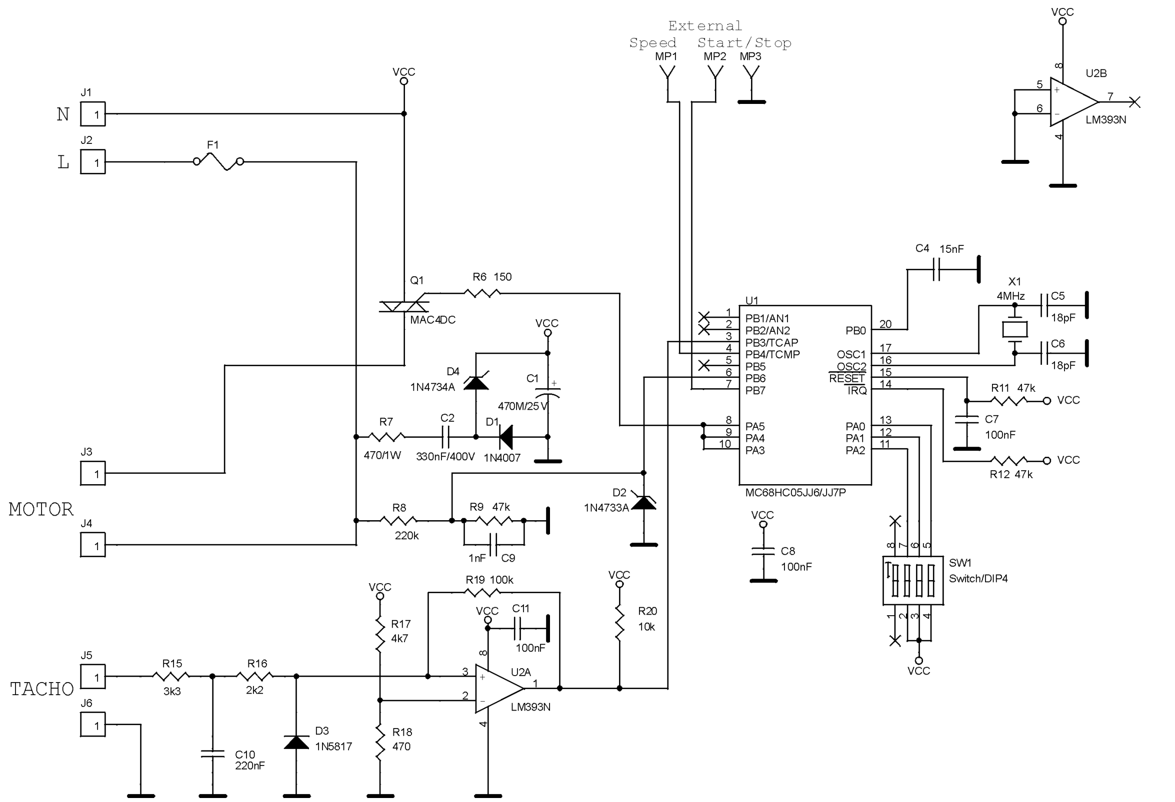

Figure 3. Low Cost Motor Control Phase Angle Drive

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 the 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

The control panel must be isolated from the user under all possible circumstances.

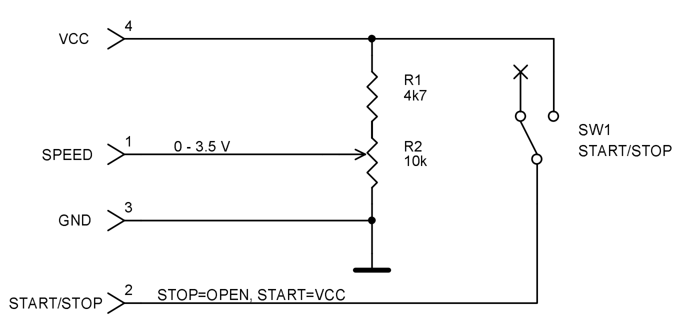

Figure 4. External Control Panel

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.

4.2 Synchronization

As it 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 overvoltage protection) are used. Due to its simplicity and its low cost solution, the output signal is not a real square wave. In Figure 4 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.

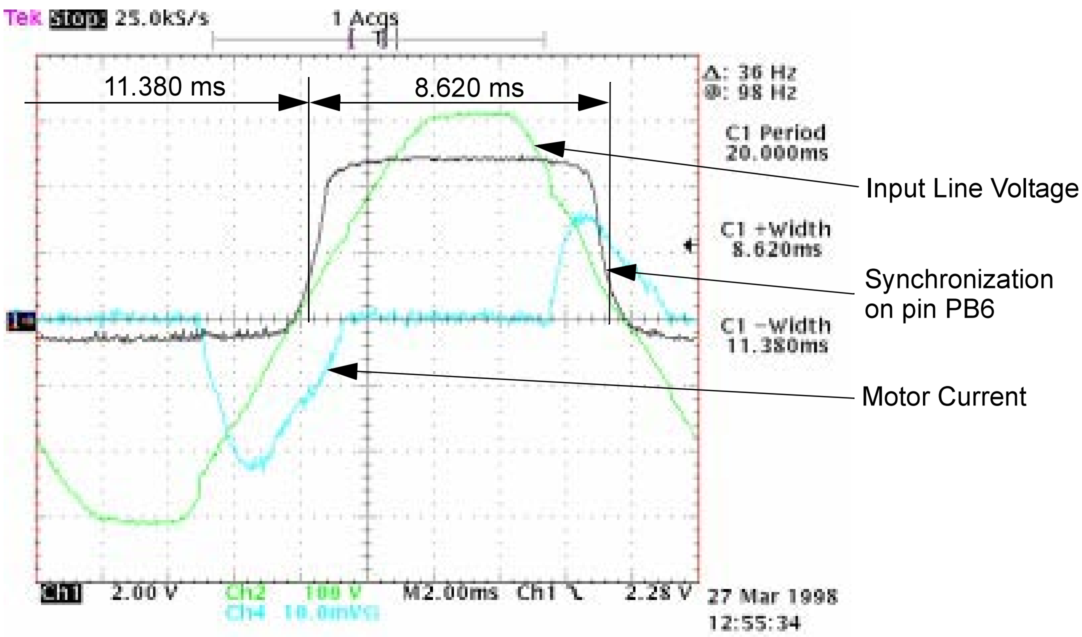

Figure 5. Synchronization Signal

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 four interrupts has been chosen to assure proper functionality and some additional performance capacity of the CPU.

Figure 6 shows a state diagram. The software consists of a Control block and some subroutines like: MAKE_ZERO, MAKE_PI, RAMPE, Watch-Dog 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.

A DIP switch with three connected switches (refer to Figure 7) 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.

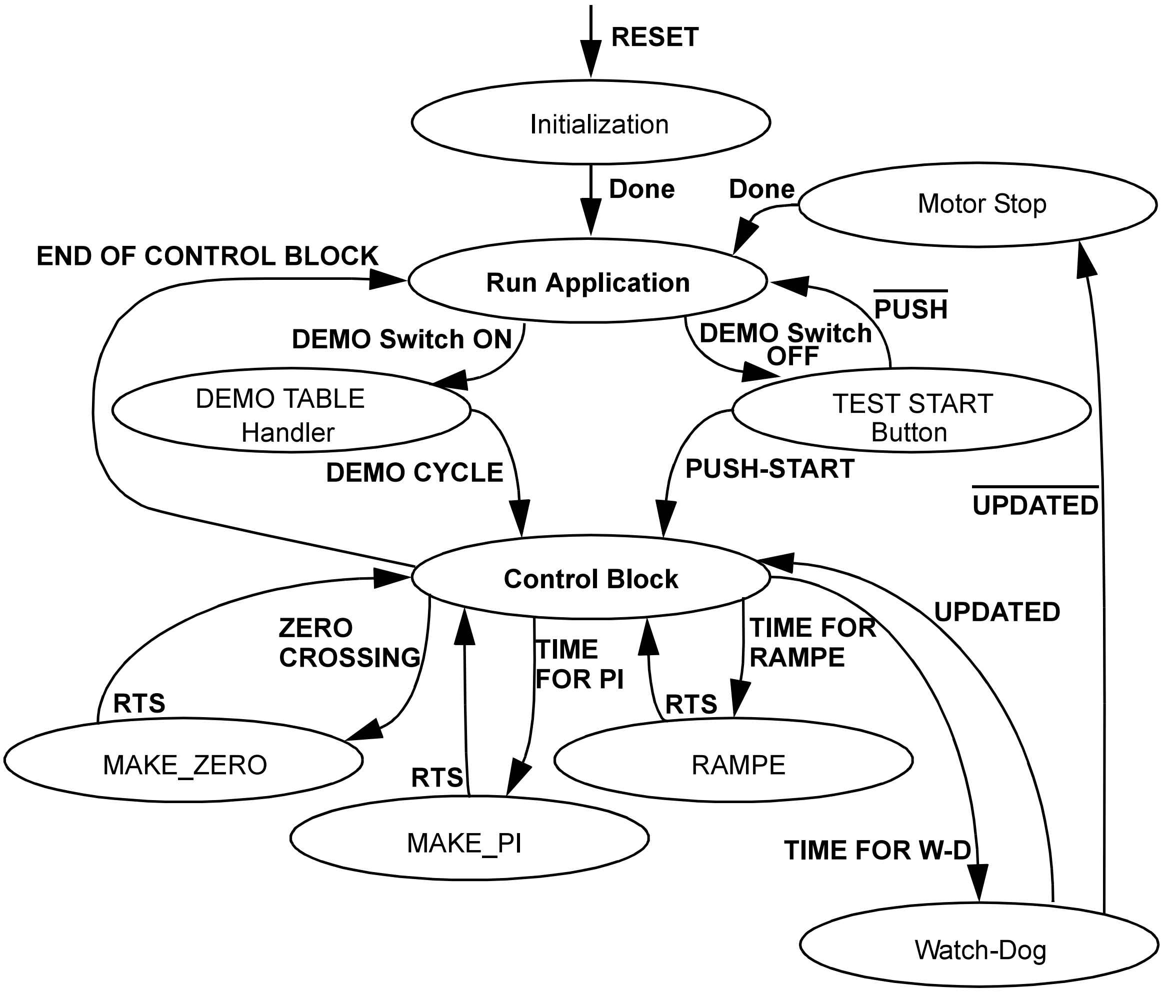

Figure 6. Program State Diagram

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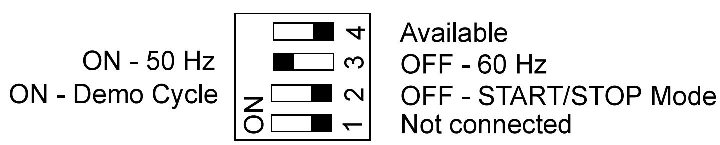

Figure 7. DIP Switch SW1

5.1 MAKE_ZERO subroutine

The MAKE_ZERO subroutine is entered when the zero crossing of the line voltage occurred. The 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 convertor is needed for the START/STOP mode when the external analog speed command, connected to 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 x I_{CHG} x P) / (V_X x 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

$C_{EXT} = (255 \times 100 \times 10^{-6} \times 8) / (3.5 \times 4 \times 10^{6}) = 14$ 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 result easy.

5.2 MAKE_PI subroutine

The MAKE_PI subroutine is entered only when two conditions are fulfilled: the time condition occurred and the output compare occurred. Because the MAKE_PI subroutine is very time consuming part of the software (700 μs), it is placed in the time window where no important actions are expected (refer to Figure 10). The main job is the calculation of the actual speed and the calculation of the PI controller. The input value for the speed calculation is a good filtered 16-bit output value from the Input capture interrupt. A 32/16 bit division is used where the 32-bit number is a constant and the 16-bit number is the output from the input capture interrupt. The constant can be calculated from the following expression:

CONST = N x $INCAP_{MIN}$

Where:

CONST	= Constant for division
N	= Maximal number of result 255
$INCAP_{MIN}$	= Minimal number of counts between two edges of tachometer signal (250 for 15,000 RPM and 4 MHz crystal)

CONST = 255 x 250 = 63 750 (0000F906 Hex)

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 - actuel_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.

5.4 Watch-dog subroutine

The Watch-dog subroutine is entered when the watch-dog register has not been updated for approximately 4 s. The input capture interrupt service routine, as a result of the running motor, takes the responsibility for the watch-dog register. By this arrangement it is possible to protect the motor when the shaft is blocked. In this case the watch-dog will turn off the triac and will wait for a new START command.

6 INTERRUPTS

As was mentioned in section 5, four interrupts are used (refer to Figure 8). The simplest interrupt is the Timer overflow interrupt. The appropriate service routine is the Timer overflow interrupt service routine (TOISR) and it enables the Input capture interrupt. The Input capture interrupt service routine (ICISR) is allowed to run six times and it calculates an average value of the time interval between the rising edges of the tachometer signal. The Analog interrupt service routine (ANISR) reads and stores the new value from the A/D convertor. The Output compare interrupt service routine (OCISR) generates the pulses for the triac (refer to Figure 9).

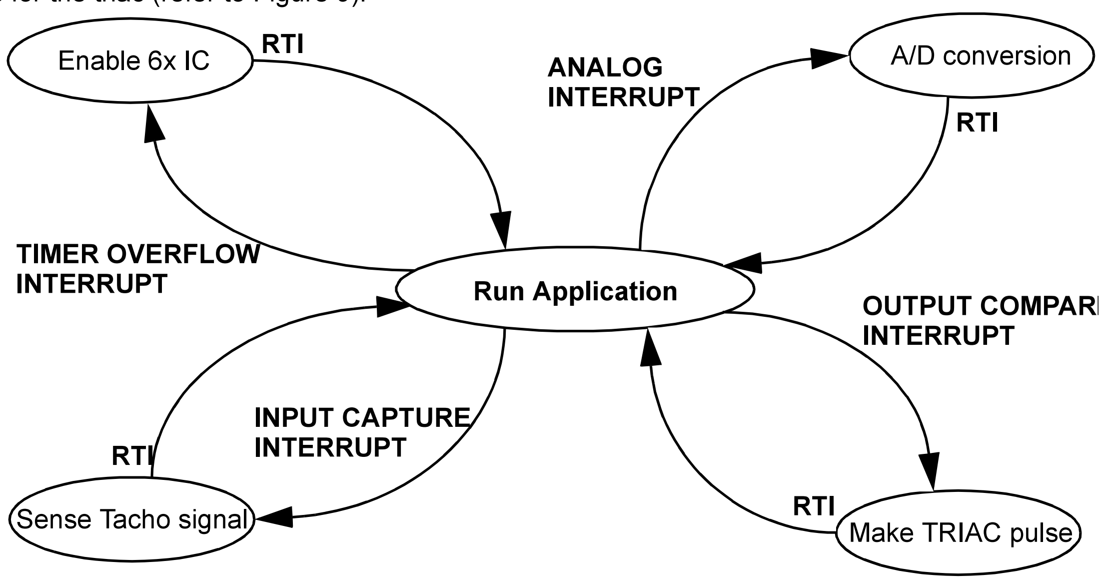

Figure 8. Interrupt Service Routines

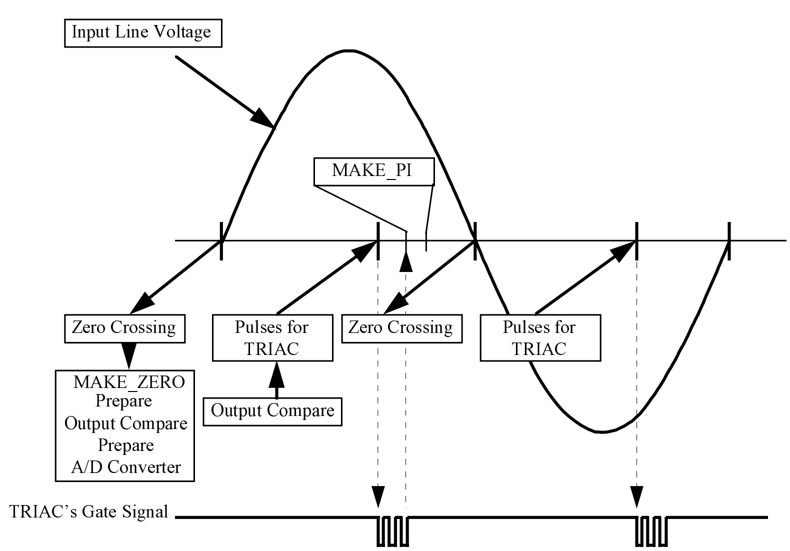

Figure 9. Timing of SW Subroutines

7 MICROCONTROLLER USAGE

7.1 Total RAM & ROM used

Table 2 shows how much memory was needed to run the phase angle drive. A significant part of the memory is still available.

Table 2.

Memory	Available	Used
SRAM	224Bytes	54Bytes
ROM	6.1kBytes	1.17kBytes

7.2 I/O use

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

Table 3.

I/O	Available pins	Used pins	Purpose
Port A	PA0-PA5	PA0-PA2 PA3-PA5	DIP switch Triac
Port B	PB0-PB7	PB0 PB3 PB4 PB6 PB7	Ext. capacitor Tachometer Ext. speed Synchronization Ext. START

8 PARTS LIST AND PCB

The list of components is listed in Table 4. and Figure 10 and Figure 11 show the PCB layout.

Table 4. Parts List

Component	Quantity	Value/Rating	Description
U1	1	-	IC, MC68HC05JJ6P or MC68HC705JJ7P
U2	1	-	IC, LM393N
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
D3	1	1.0 A, 20 V	Schottky Diode 1N5817
D4	1	5.6 V, 1.0 W	Zener Diode, 1N4734A

Table 4. 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
R15	1	3.3 kΩ, 1/4 W	Resistor
R16	1	2.2 kΩ, 1/4 W	Resistor
R17	1	4.7 kΩ, 1/4 W	Resistor
R18	1	470 Ω, 1/4 W	Resistor
R19	1	100 kΩ, 1/4 W	Resistor
R20		10 kΩ, 1/4 W	Resistor
C1	1	470 µF, 25 V	Capacitor Electrolytic
C2	1	330 nF, 400 V	Capacitor
C4	1	15 nF, 50 V	Capacitor
C5, C6	2	18 pF, 50 V	Capacitor
C7, C8, C11	3	100 nF, 50 V	Capacitor
C9	1	1 nF, 50 V	Capacitor
C10	1	220 nF, 50 V	Capacitor
F1	1	4 A	Fuse
J1-J6	6	-	Connector
SW1	1	-	DIP Switch
MP1-MP3	3	-	Connector

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

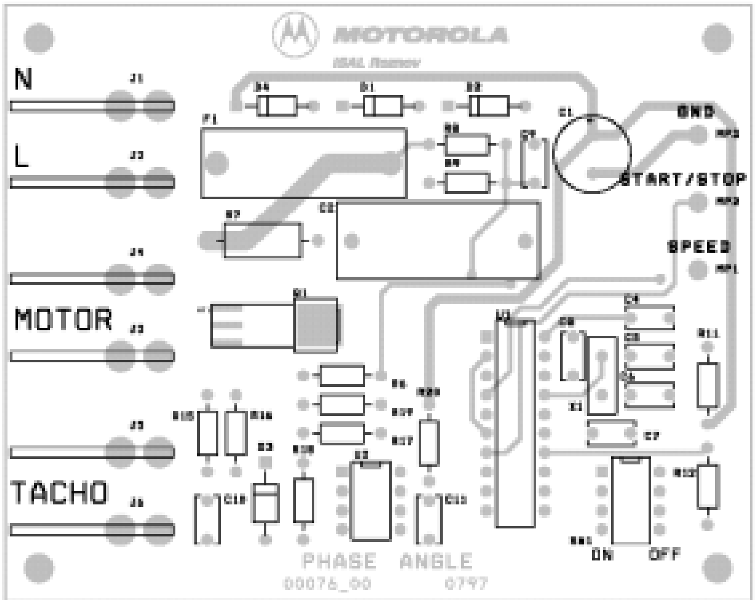

Figure 10. PCB layout Component Side

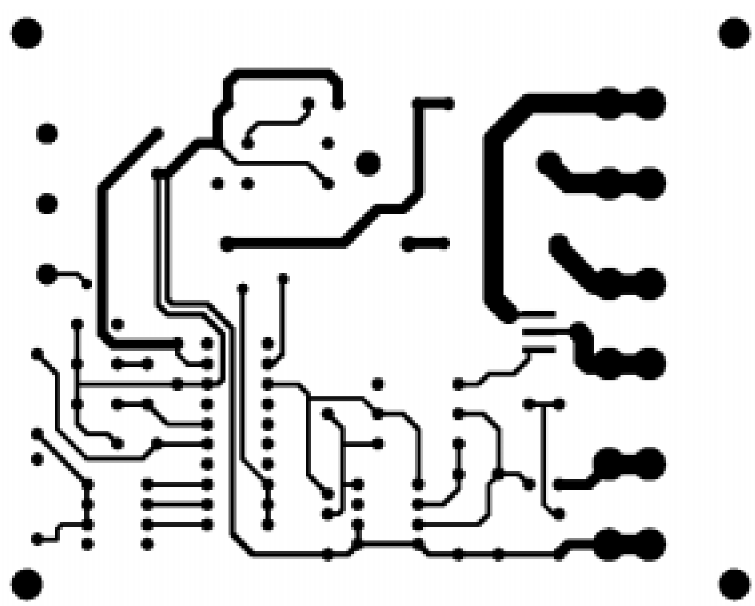

Figure 11. PCB Layout Copper Side

Performance of the Sample Design

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

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

Motor:.......................................400 W with tachometer

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 15,000 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.

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

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