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Water Jet with Electronically Controlled Flow and Temperature Settings

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Abstract
The main objective of this design project is to design a water jet where the temperature and flow of the jet can be controlled electronically through up-down buttons. The temperature of the jet coming out of heater is continuously checked against the set temperature, and heating level of the heating unit is adjusted by a feedback system. Both the controls have been implemented using microprocessor based integer cycle power control.

1. INTRODUCTION

The motivation behind creating a water jet is to provide user with more flexibility in terms of controlling the temperature and flow of the water coming out of the jet, for various applications. The process that is used in normal household is heating the water in geysers and then mixing the hot and cold water to obtain the required temperature. Some prototypes of this equipment exists in foreign markets but they are too expensive for an Indian household use [12].
The flow and temperature of the jet are controlled by the speed of the pump motor and the current supplied to the heating coil respectively. Both of them can be controlled by using microcontroller based integral cycle power control.

Temperature of the jet can change in two ways:-
1. When the user gives the required instruction to do so.
2. When the flow of the jet changes, since the amount of water getting out

per second changes, whereas energy supplied to the heater, if not changed, remains the same.

This change of temperature is measured by a thermistor, whose resistance changes with temperature. This change of resistance of thermistor is being fed to the ADC (analog to digital converter), which then generates the appropriate signals, which in return is fed to the microcontroller and the microcontroller then adjusts the amount of current given to the heater coil accordingly, in order to keep the temperature as set by the user, through integer cycle control.

2. INTEGRAL CYCLE CONTROL

In integral cycle control, control is achieved by periodically applying supply voltage to the load for certain cycles. Where the on and off durations are T_{on} and T_{off} respectively, which may be varied over the control range to control the effective values of voltage, current, and power applied to the load. Since sinusoidal current will flow in the load during the ON period, this method of control has the advantage over phase control in that radio frequency interference is minimized [1]. Integral cycle control may be used in applications such as heating, lighting, and ac and dc motor control. For inductive loads, as is our case, a dc offset component will appear in the load current depending on the triac firing angle [1]. This component is undesirable since it may cause magnetic saturation and large peak load current. We have used a feedback-controlled digital circuit that provides for integral cycle control of power in RL loads. The circuit eliminates the dc offset component of load current, for our application we have developed a self-adjusting microcontroller-based system for ac power control of RL loads.

Fig. 1 shows the circuit components of the system under investigation. It consists of a static RL load connected to an ac supply via a triac. The microcontroller system provides the firing pulses for the triac. During conduction, the load current *i* can be expressed as

$$i\,(t) = \sqrt{2}\,V/Z\,[\sin(\omega t - \varnothing) - \sin\,(\alpha - \varnothing)e^{(R/L)(\alpha/\omega - t)}] \qquad (1)$$

where V is the r.m.s. supply voltage, α is the triac firing angle with respect to the supply voltage zero crossing, and $Z\,L\varnothing$ is the load impedance. It is clear from (1) that in order to eliminate the dc offset component, α should be very close to $\varnothing$**.** The angle α can be set to an arbitrary value α_i (initial); during the first burst of conduction. The microcontroller adjusts α closer to $\varnothing$ at every succeeding burst. If α_i (initial) is not chosen properly, high peak current value is obtained.

The microcontroller is programmed to measure the angle $\varnothing 1$ (Fig. 2) at the last supply voltage cycle during the ON period. This will make $\varnothing 1$ closer to $\varnothing$ since the dc component is allowed to decay before measurement. We were not able to implement the zero crossing detector circuit for load current but provision has been made on the microcontroller to add this circuitry in the subsequent versions of the product.

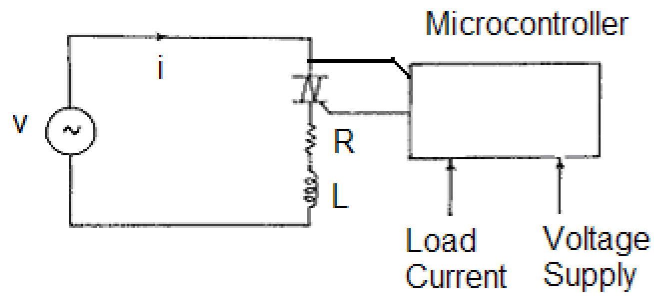


Fig. 1 System under study

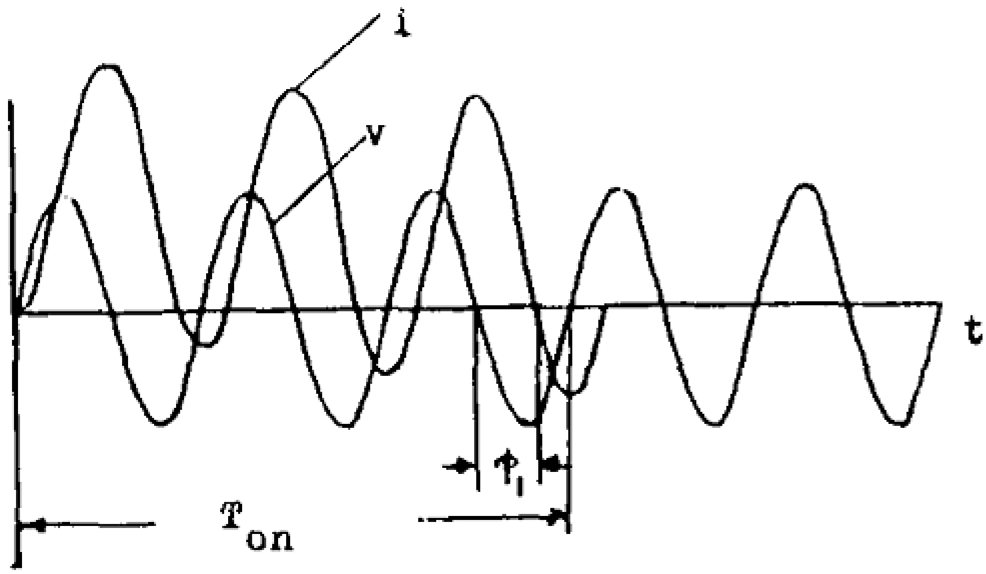


Fig. 2 Waveform of current and voltage

3. THERMODYNAMIC EQUATIONS

By equating the enthalpy of the system, we get

$$M_1 C_p T_1 + Q = M_1 C_p T + V C_p \, (\mathrm{d}T/\mathrm{d}t) \tag{2}$$

where, C_p= heat capacity of water and T_1= initial temperature of water.

Also on LHS we have the initial enthalpy of the water flowing at the set rate into the heater (M_1), added to the amount of heat delivered by the heater (Q), which is equal to the power of heater. On RHS we have final enthalpy of the water, which is proportional to the final temperature of the water flowing out of the heater (*T*). Added to the heat transferred to the water in the heater, which is proportional to the capacity of the geyser (*V*) and rate of change of temperature. On solving this, we get a differential equation in which we get the final temperature of the water flowing of the heater, as a exponential function of time. Related through variables like flow rate and capacity of the heater.

On putting values for different flow rates, we get a differential equations each showing a direct relation between temperature (*T*) and time (*t*), depending only upon the capacity of the heater.

For flow rate = x litre/min, we get the temperature in K as

$$T = (300+14/x) - (14/x)\exp(-t/30V) \quad (3)$$

The relationship is plotted in Fig. 3 for x=1litre/min and 2litre/min.

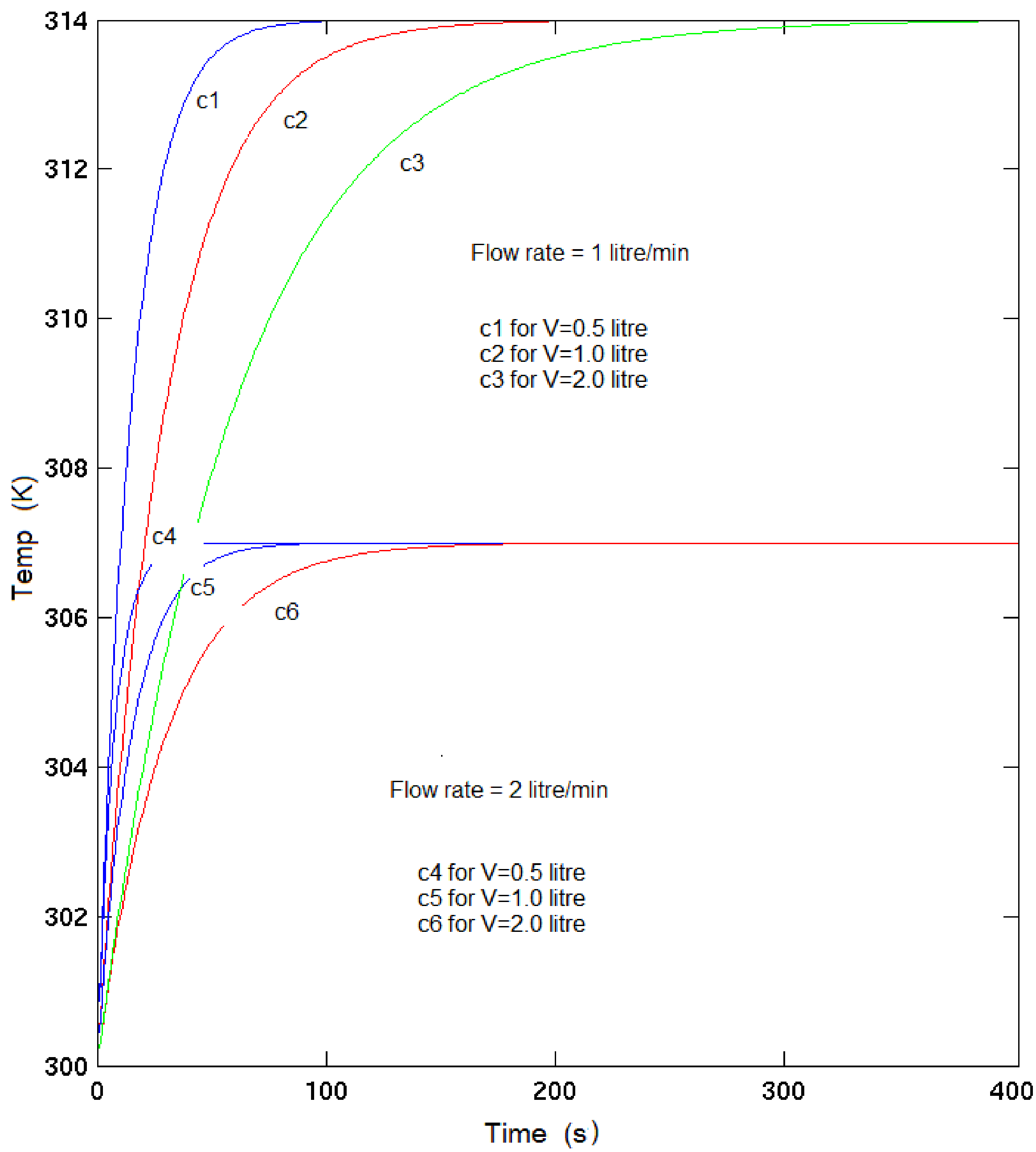


Fig. 3 Temperature versus time graph for diff. Flow rates and diff. *V*

Hence we can deduce from the figure that smaller is the capacity (*V*) of the heater, more quickly it will reach the required temperature. But since we were constrained from the minimum dimensions of heater, the geyser (container for storing the water) has the capacity (*V*=0.62litre).

4. FEEDBACK MECHANISM TO CONTROL HEATING

Prime component of the feedback system is the temperature sensor. Thermistor (NTC-1k) has been used for the sensing the current temperature and giving this feedback to the system so that it can adjust its power level accordingly as required by the user. Resistance of the thermistor decreases with increase in the temperature. To know the correct temperature we need to know the resistance of thermistor in our temperature range. Fig. 4 shows the resistance versus temperature curve for NTC-1k which has been obtained using the water bath technique.

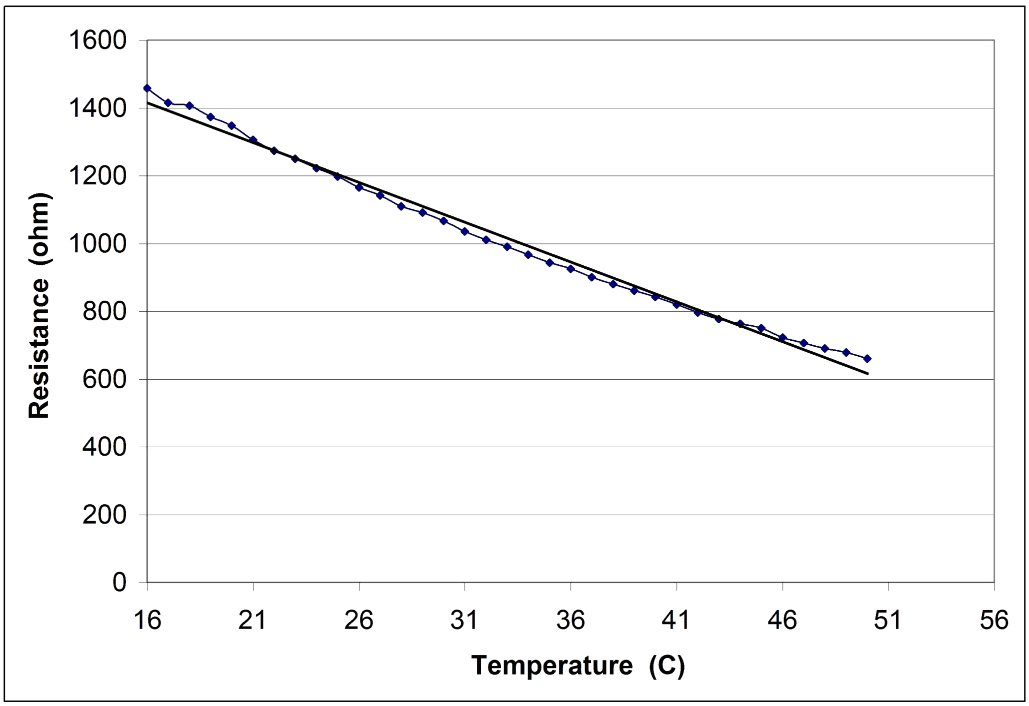


Fig. 4 Resistance of the thermistor NTC-1k as a function of temperature. The straight line is a linear interpolation through the observed points.

5. HARDWARE IMPLEMENTATION

5.1 Zero crossing detector circuit

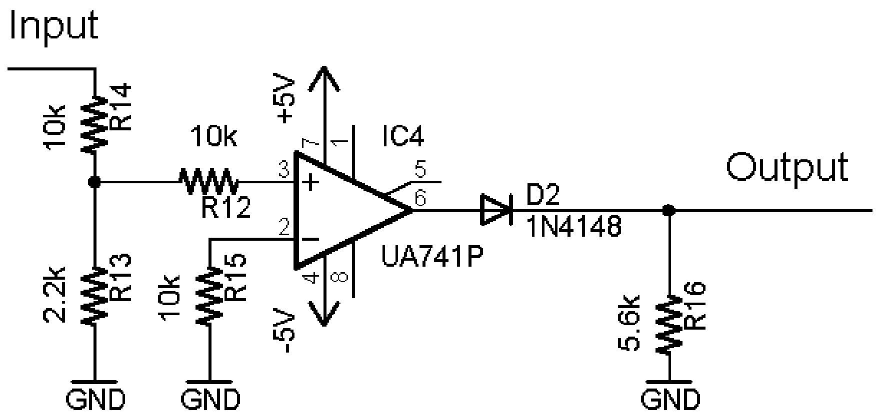


Fig. 5 Zero Crossing Detector Circuit

As shown in Fig. 5, circuit consist of a op amp IC4 based comparator circuit which converts the sinusoidal waveform into the square waveform such that zero crossing points of the square wave are at the same location as that of original sinusoidal signal. The op amp is powered by +5v and -5v supplies. Diode D1 is used to rectify the comparator output for interfacing it to the microcontroller. These square waves (one each of voltage and current is given to microcontroller at pin p1.6 (current) and pin p1.7 (voltage). In our implementation both the pins have been given the same input that of voltage square waveform. From these signals, the microcontroller calculates the lag between the voltage supply and the current flowing in the circuit and to trigger the gate of triac exactly at the point where current and the circuit crosses the zero line

5.2 Triac-Load circuit

The neutral, of the power mains, goes to the common ground. The line of the power mains goes to one end of the load, the other end of the load being connected the pin A2 of the TRIAC (Fig 6). TRIAC is a three terminal semiconductor for controlling current in either direction [7]. The main or power terminals are designated as MT1 and MT2. When the voltage on MT2 is positive with regard to MT1 and a positive gate is applied, the left SCR conducts. When the voltage is reversed and negative voltage is applied to the gate, the right SCR conducts. Minimum holding current must be maintained in order to keep a TRIAC conducting. A TRIAC operates in the same way as the SCR; however, it operates in both the forward and reverse direction. Major considerations, when specifying a TRIAC, are:

a) Forward and reverse break-over voltage
b) Maximum current
c) Minimum holding current
d) Gate voltage and gate current trigger requirements
e) Switching speed

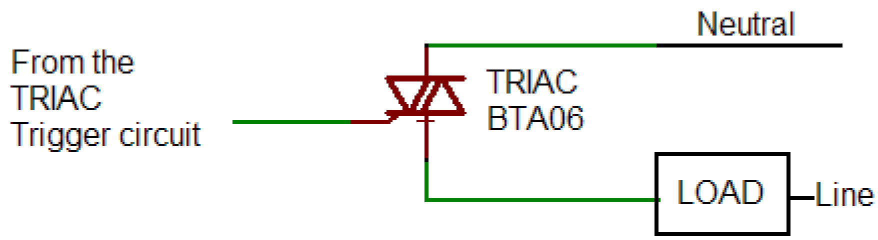


Fig. 6 A general connection between a load and the TRIAC (BTA06B)

5.3 Temperature sensor circuit

As shown in Fig 7, voltage across the thermistor will change with the change in the temperature. This voltage is then amplified using a simple operation amplifier circuit. The amplified voltage is given as input to analog-to-digital Converter (ADC 0804). ADC then converts the analog voltage to corresponding digital value. Digital value is then given to microcontroller.

5.4 Circuit for temperature display

The circuit is shown in Fig. 8. This part of the circuit deals with the display of the temperature set by the user. A second microcontroller is used here and with the help of key detection and the 7447 logic plus multiplexing of the 2 seven segment displays we are able to achieve the desired display.

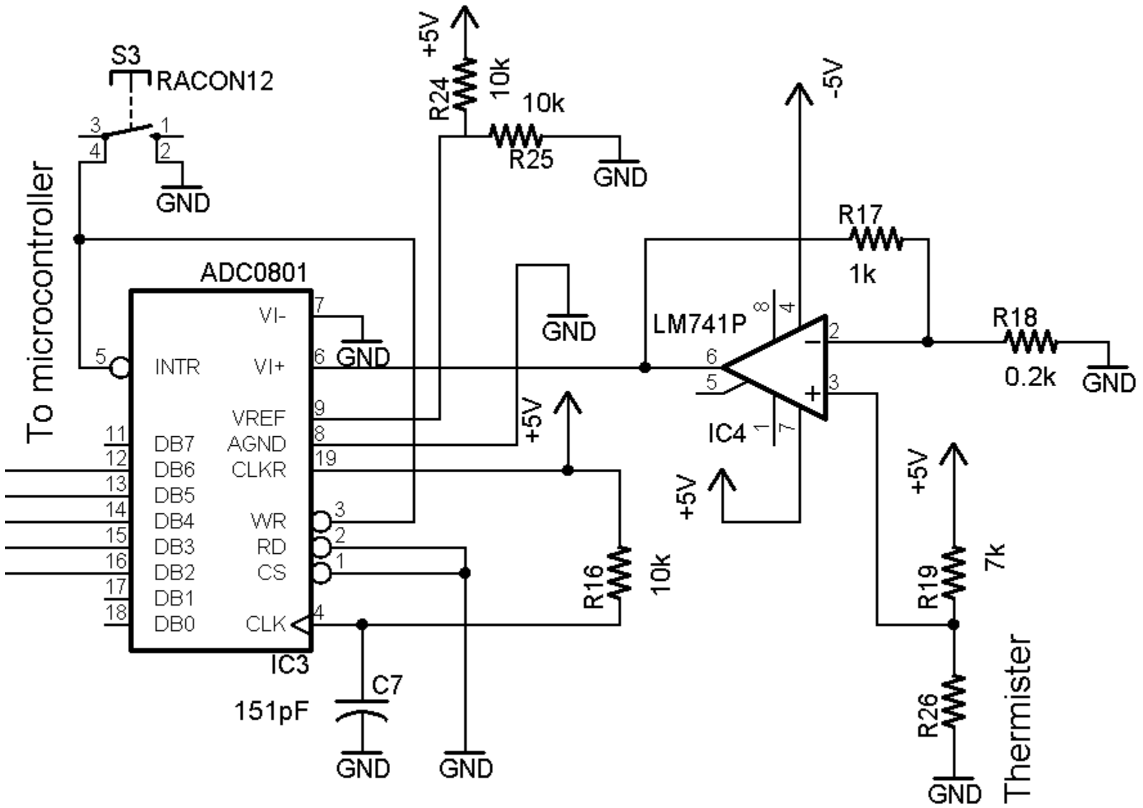


Fig. 7 Temperature sensor circuit

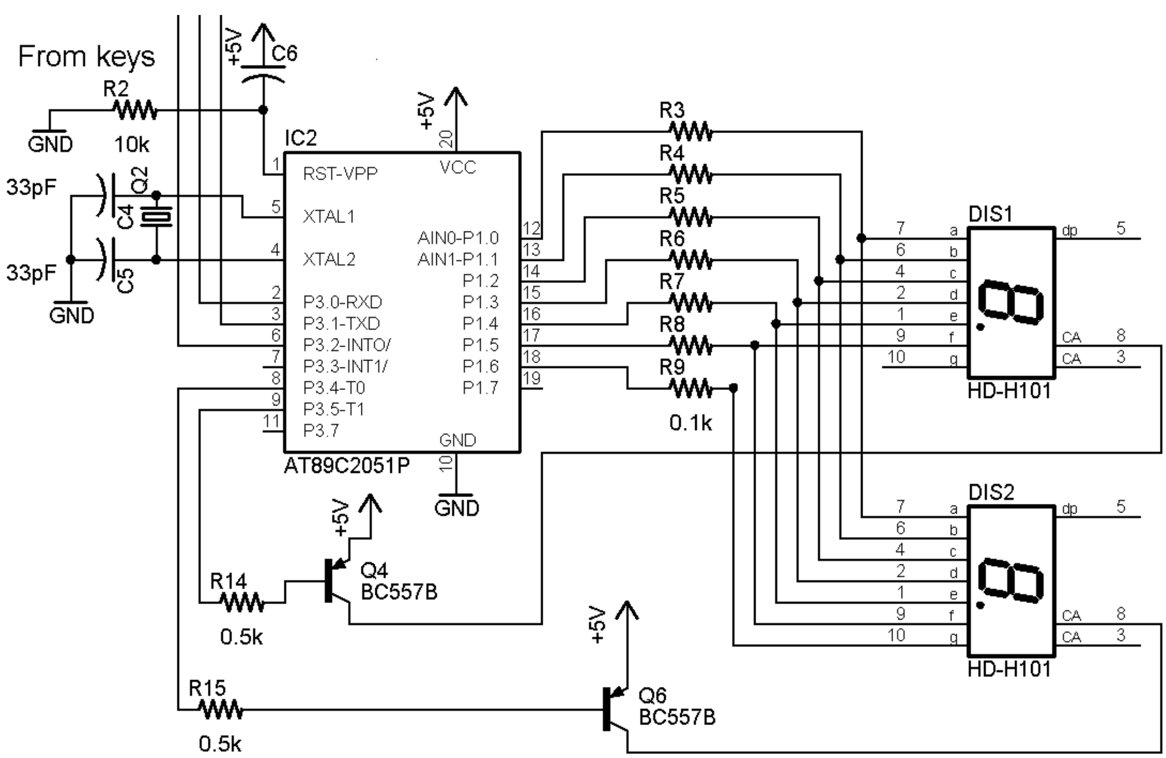


Fig. 8 Circuit to display temperature set by user

5.5 Circuit for flow control

Flow control circuit consists of following three parts:

1 Microcontroller

2 Keys

3 Triac firing circuit

The circuit is shown in Fig 9. Microcontroller takes the input from voltage squarer circuit as shown in Fig. 5 and generates the gate triggering pulse on pin 3.7. Keys are continuously checked by the microcontroller if they are pressed or not. If a key press is detected then the action is performed as described in section 6.2. The gate triggering circuit then generates the voltage level required to trigger the triac BTA06.

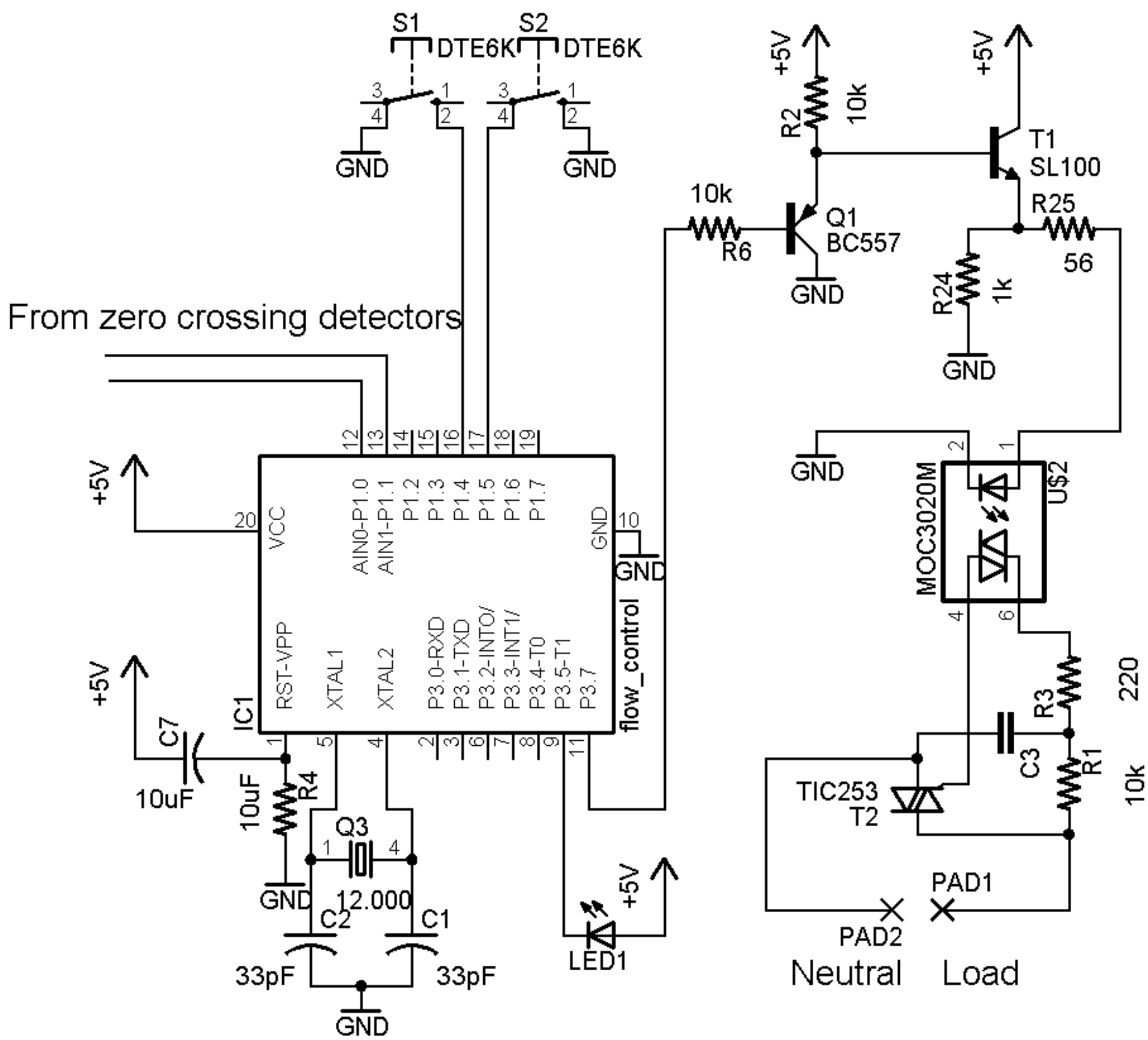


Fig 9 Circuit for flow control

5.6 Circuit for heating control

The circuit for heating control is shown in Fig. 10. The circuit is very similar to the circuit used in Section 5.5 (flow control). The difference here is that the microcontroller uses the output of the ADC to get the feedback of current temperature of the water. Triac used for controlling the power flow in heater is BTA16 instead of BTA06 which is a low current triac.

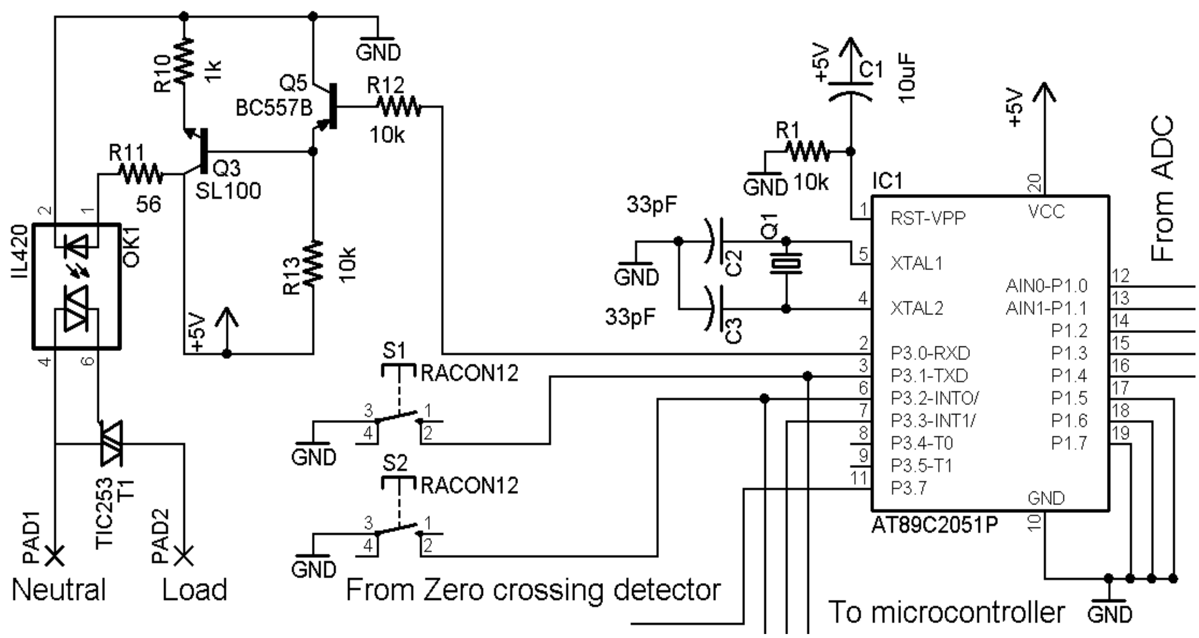


Fig. 10 Circuit for heating control

6. SOFTWARE

6.1 Algorithm for integral cycle control

Port p1 of the microcontroller is programmed to operate as an input port as well as output port (p1.4 and p1.5), whereas port p3 is programmed to operate as an output port. The flowchart of the program developed to control the system operation is shown in Fig. 11 When the system is started, the register R4 and R5 are loaded with its initial value. This initial value is a number representing a time delay that corresponds to an angle α initial at the voltage supply frequency. This angle is equal to the chosen initial value of the triac angle. Afterwards, the microcontroller outputs a logic level 0 through bit 7 of port 3. After performing an input high test on input

A (voltage square waveform) at pin p1.7*,* registers R7*,* R6*,* and R3 are loaded with their initial values. The initial values of R7 and R6 are, respectively, the values of the required ON and OFF supply cycles of the integral cycle power control circuit. The register R3 is used as a counter, and therefore, its initial value is always zero. The input *A* is then tested for a low input. The reason for doing an input high test followed by an input low one, at the beginning, is to assure that the system is operating correctly, irrespective of the instant of switching on. When input *A* goes high at the end of the input low test, the microcontroller starts a repeated loop of decrementing and testing R4 and R5*.* When both are zero, the microcontroller produces a logic level 1 through bit 7 of output port p3*.* Assuming that the loop time is equal to *D µs,*the number *N* to be loaded initially into R4 *and* R5 to produce a delay angle of α initial [1] ; degrees at 50 Hz is given by

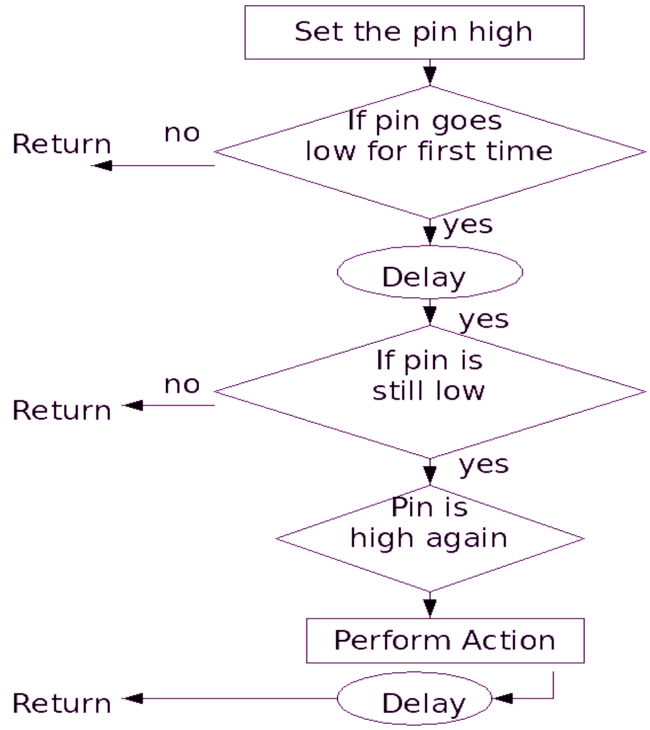
$$N = (5 \text{ ms} \times \alpha \text{ initial})/(D\ \mu s \times 90) = 500\ \alpha \text{ initial}/9D \qquad (4)$$

The above sequence means that bit 7 of port p3 will go low for a time corresponding to α initial and then goes high, producing a pulse with duration equal to the number of ON cycles stored in R7*.* This is achieved by a repeated delay loop that decrements R7 at every positive half supply voltage cycle. When R7 = 0, this indicates the end of the last positive half of the ON cycles. At this instant, the microcontroller starts testing input *B (current square waveform)* at pin p1.6*,* which represents the load current, to measure an approximate value *ø1* of the angle *ø* between the load voltage and current (Fig. 6). This is done by looping and incrementing R3 as long as input *B* is high. It is to be noted that this loop time must be equal to *D* to obtain correct results. The number obtained in R3 at the end of this test is copied into R4 *and* R5 to be its new initial value at the next cycle for executing the main program. An input low test is then performed on input *A* to indicate the completion of the required number of ON cycles. At this instant, bit 7 of port 3 goes low to end the triac triggering pulse. The output of bit 7 of port 3 is kept low for duration equal to the number of the required OFF cycles. This is done by another repeated delay loop that decrements R6 at every supply cycle. At the end of this test, the microcontroller jumps back to set the initial value of *R7,R6,* and *R3,* and the above sequence is repeated. However, we

Every new cycle will have a new value of α_i (initial)*,* which is equal to the value of ø1 measured at the preceding cycle. After a few cycles, the measured value *ø1* will be almost equal to the actual phase angle *ø* between load current and voltage, and hence, the dc component will be removed from the load current waveform.

6.2 Polling mechanism to use keys

For making the device more user friendly, we have used 4 up and down keys two each for water flow control and water temperature control respectively. Once a key



press is detected by either of microcontroller the water flow/temperature level is increased or decreased according to which key is pressed.Fig.11 shows polling mechanism for detecting the keypress and performing the action associated with this.

Fig. 11 Keypress detection mechanism

6.3 Logic for temperature display

The display circuit is as shown in fig. 8 consists of microcontroller and the 2 multiplexed seven segment displays.

1. The microcontroller takes the input from the keys and detects a keypress. This will be an indicator of the number of times the key is pressed an hence the temperature stored by the user.
2. The micro processor converts the current temperature to BCD and from BCD a lookup table is made as follows for the output of the microcontroller ::

0	7E
1	30
2	6D
3	79
4	33
5	5B
6	5F
7	70
8	7F

9 73

The outputs are seven bits which are a b c d e f g LEDS of the seven segment display.

3. Two bits of the microcontroller are used to multiplex a port of the microcontroller to the 2 seven segment displays. They are connected to the Vcc of the Displays via transistors to ensure pullup.

6.4 Algorithm for heating control

The heating mechanism is a feedback system which allows the user to set the temperature thus making it independent on the flow rate.

The entire heating circuit consists of (1) microcontroller (core), (2) feedback part, and (3) display part.

Microcontroller: Microcontroller is responsible for the behavior of this system. The inputs to the microcontroller are the temperature set by the user and the current temperature of water which can be deduced by the resistance of the thermistor.

Feedback System: ADC gives the feedback of current temperature of water to the microcontroller as described in Section 5.3.

The output of this system is the gate trigger of the TRIAC BTA 16 that basically controls the number of ON cycles and OFF cycles in a period of 16 cycles. Integral cycle control mechanism similar to the flow rate control part is used except that here the number of on-off cycles is not predetermined but instead are computed based on the current temperature of water and temperature set by the user.

The logic of this circuit is as follows: If the user inputs a temperature higher than the current temperature of water then the rate of heating should increase. Hence for example if at the end of the previous cycle the TON/TOFF were 8/8 then the new TON/TOFF would be 9/7. and similar for the case if temperature set by the user is less than temperature of water. Such a system should have a maximum response time of about (16x16/50 Hz) = 5 s. The user uses a pair of keys to increase and decrease the temperature set (Polling mechanism).

Once the gate trigger is given the output of the microcontroller is given to a triggering circuit which sets the value of the Vgt and Igt to a maximum of 1.3V and 35 mA respectively. The TRIAC used here is of slightly higher current rating (16amps) because the power level that is going to be used while heating is more than that used for the pump (TRIAC BTA06, 6 A).

6.5 Algorithm for flow control

Algorithm used for flow control is exactly same as described in the integral cycle control section. Maximum number of on cycles are fixed to 7. Whenever the key to increase or decrease the TON cycle is pressed, number of TON cycles in R2 is incremented or decremented accordingly. After one TON and TOFF the value stored in R2 is used to update new number of TON cycles i.e. R7 and remaining TOFF cycles(after subtracting TON from 7) is stored in R6.

7. COMPONENTS & DESCRIPTIONS

1. Microcontroller: AT89C2051 [3]

It is a low power, high performance CMOS 8 bit microcomputer with 4K bytes of flash programmable and erasable read only memory (EPROM). It has 40 pins and 4 ports. Port 0 is an 8 bit, bi-directional I/O port. Each pin can sink 8 TTL inputs. Port 1 is an 8 bit bi-directional I/O port with internal pull-ups. Its output buffers can sink 4 TTL inputs. Port 1 is an 8 bit bi-directional I/O port with internal pull-ups. Its output buffers can sink 4 TTL inputs. Port 3 is an 8 bit bidirectional I/O port with internal pull-ups. Its output buffers can sink 4 TTL inputs.

Maximum Operating Voltage: 6.6 V

DC Output Current: 15.0 mA

Voltage on any pin (w.r.t., ground): -1.0V to 7.0V

2. UA741CN[4]

The UA741 is a high performance monolithic operational amplifier constructed on a single silicon chip.

Features:

8 Pin IC

Supply voltage	±22V
Differential Input Voltage	±30V
Input Voltage	±15V
Power Dissipation	500W
Output Short-circuit Duration	Infinite

3. *ADC0804[1]*

The ADC0804 is a 8-bit Microcontroller compatible A/D converter.

Features:

20 pin IC

Supply voltage	+6.5V
Voltage at any input	-0.3V to (V+ + 0.3V)

4. NTC-1k[1]

The NTC-1k is the negative temperature coefficient thermistor. The resistance of NTC-1k decreases with increase in the temperature. Its resistance at room temperature is 1k.

5. SEVEN SEGMENT DISPLAY[2]

8. FUTURE SCOPE

Fast heating to quickly reach the set temperature is restricted by the current that normal wiring can sustain. To overcome these limitations, 3 phase power supply may be used.

Also we spent quite some time on RF heating, which can also be done but one important constraint for that is the cost of the unit. One approach which is also viable from commercial and as well as power point of view is first heating the water through solar heating then using that water as a input to the heater where using thermistors the temperature can be measured and after comparing with the user specified temperature can be regulated upon which may also include mixing cold water with it based upon the instructions which microcontroller will generate. Other option is using a thermally insulated tank for pre-heating the water to a certain temperature, and used controlled heating for quickly reaching the set temperature.

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