SCRs, triacs and power control

Part two of Ray Marston's short series on these useful devices. In this part, he covers power switch circuits, electric heater controllers, lamp dimmers and motor speed controllers. A whole stack of applications circuits are given — as usual.

Ray Marston

LAST MONTH's Circuit File dealt at length with the fundamentals of SCR and triac circuitry and gave particular attention to the principles of synchronous and non-synchronous triggering. This issue we present a stack of practical circuits for use on 240 Vac power lines. In these designs, you simply select the triac or SCR rating to suit your own particular application.

Let's start off, then, by looking at some practical triac power switch designs for use in basic on/off ac power line switching applications.

TRIAC POWER SWITCHES

Non-synchronous designs

As was explained in part 1, triacs can be triggered (turned on) either synchronously or non-synchronously with the mains voltage. Synchronous circuits *always* turn on at the same point in each mains half-cycle (usually just after the zero-crossing point), and usually generate minimal RFI. The trigger points of non-synchronous circuits are not synchronised to a fixed point of the mains cycle, and the circuits may generate significant RFI, particularly at the point of initial turn-on. Triac turn-off is always automatically synchronised to the mains, as the device's main-terminal currents fall below the minimum-holding value at the end of each mains half-cycle.

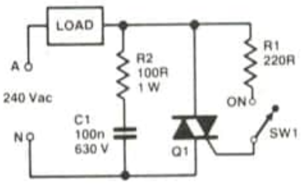

Figure 1. Simple ac power switch, ac line triggered.

Figures 1 to 8 show a variety of non-synchronous triac power switch circuits which can be used in basic on/off line switching applications. The action of the Figure 1 circuit was explained last month, being such that the triac is gated on from the mains via the load and R1 shortly after the start of each mains half-cycle when SW1 is closed, but remains off when SW1 is open. Note, in this circuit, that the trigger point is *not* synchronised to the mains when SW1 is initially closed, but becomes synchronised on all subsequent half-cycles.

Figure 2 shows how the triac can be triggered via a mains-derived dc supply. C1 is charged to +10 V on each positive half-cycle of the mains via R1-D1, and the C1 charge triggers the triac when SW1 is closed. Note that all parts of this circuit are 'live', making it difficult to interface to external electronic control circuitry.

Figure 3 shows how the above circuit can be modified so that it can easily be interfaced to external control circuitry. SW1 is simply replaced by transistor Q2, which in turn is driven from the 'phototransistor' side of an inexpensive optocoupler. The 'LED' side of the optocoupler is driven from a 5 V or greater dc supply via R4. The triac turns on only when the external supply is connected via SW1.

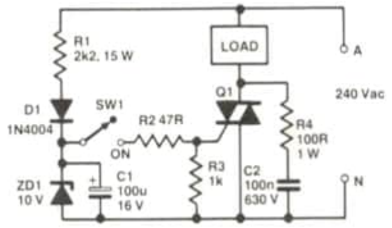

Figure 2. Ac power switch with line-derived dc triggering.

Optocouplers have typical insulation potentials of 500 to several thousand volts, so the external circuit is fully isolated from the mains, and can easily be designed to give any desired form of remote operation of the triac by replacing SW1 with an electronic switch.

Figure 4 shows an interesting variation of the above circuit. In this case the triac is ac-triggered on each half-cycle of the mains via C1-R1 and back-to-back zeners ZD1-ZD2.

Note that the mains impedance of C1 determines the magnitude of the triac gate current but that C1 dissipates virtually no power. Bridge rectifier D1 to D4 is wired

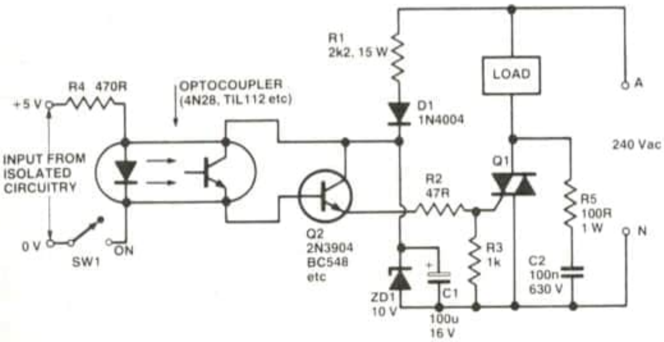

Figure 3. Isolated-input (optocoupled) ac power switch, dc triggered.

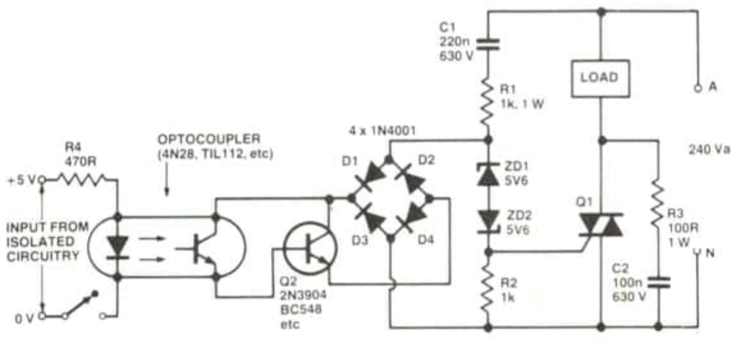

Figure 4. Isolated-input ac power switch, ac triggered.

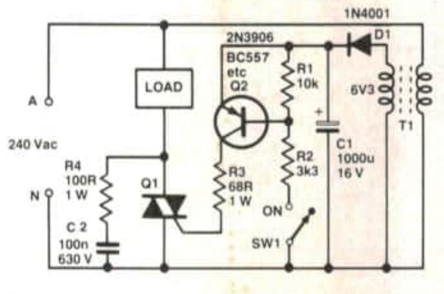

Figure 5. Ac power switch with transistor-aided dc triggering.

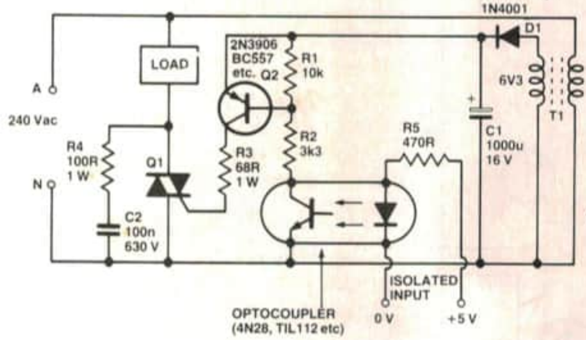

Figure 6. Isolated-input ac power switch with dc triggering.

across the ZD1-ZD2-R2 network and is loaded by Q2. When Q2 is off, the bridge is effectively open and the triac turns on shortly after the start of each mains half-cycle: when Q2 is on, a near-short appears across ZD1-ZD2-R2 inhibiting the triac gate circuit, and the triac is off.

Transistor Q2 is actually driven via the optocoupler from an isolated external circuit, so the triac is normally on but turns off when SW1 is closed.

CONSTRUCTION OF T1, FIGS 7, 8

The core is a 30 mm long piece of 9.6 mm dia. ferrite aerial rod. The primary and secondary are each 30 turns of 0.4 mm dia. enamelled wire (26 B&S) closewound on the centre 15 mm of the core. Use two layers of plastic insulation tape between the two windings and cover complete unit with a further two layers of tape. Bring the primary and secondary leads out opposite ends of the core. Mark the starts of each winding (spots on circuit).

Figures 5 and 6 show a couple of ways of triggering the triac via a transformer-derived dc supply and a transistor-aided switch. In the Figure 5 circuit, the transistor and the triac are both driven on when SW1 is closed, and are off when SW1 is open.

In practice SW1 can easily be replaced by an electronic switch, enabling the triac to be operated by heat, light, sound, etc. Note however, that the whole of the Figure 5 circuit is 'live'.

Figure 6 shows how the circuit can be modified for optocoupler operation, so that it can be activated via fully isolated external circuitry.

Finally, to complete this section, Figures 7 and 8 show a couple of alternative ways of obtaining triacs triggering from a fully isolated external circuit. In these two circuits the triggering action is obtained from a unijunction (UJT) oscillator (Q2) which operates at a frequency of several kilohertz and has its output pulses fed to the triac gate via pulse transformer T1, which provides the desired 'isolation'.

In the Figure 7 circuit, Q3 is wired in series with the UJT's main timing resistor so the UJT and triac turn on only when SW1 is closed. In the Figure 8 circuit, Q3 is wired in parallel with the UJT's main timing capacitor so the UJT and triac turn on only when SW1 is open. In both of these circuits, SW1 can easily be replaced by an electronic switch.

Synchronous designs

Synchronously-triggered triac circuits *always* turn on at the same point in each mains half-cycle. Usually, the trigger point occurs just after the 'zero-crossing' point at the start of each half-cycle, in which case the triac generates absolutely minimal RFI.

Figures 9 to 18 show a number of on/off power switching circuits that use this form of triggering.

Figure 9 shows the practical circuit of a 'transistorised' synchronous line switch that is triggered near the zero-voltage crossover points of the mains. The triac gate trigger current is obtained from a 10 Vdc supply that is derived from the mains via R1-D1-ZD1 and C1, and this supply is switched to the gate via Q5, which in turn is controlled by SW1 and zero-crossing detector Q2-Q3-Q4.

The action of Q5 is such that it can only turn on and conduct gate current when SW1 is closed and Q4 is off. The action of the zero-crossing detector is such that Q2 or Q3 are driven on whenever the instantaneous mains voltage is positive or negative by more than a volt or two (depending on the setting of RV1), thereby driving Q4 on via R3 and inhibiting Q5.

Thus, gate current can only be fed to the triac when SW1 is closed and the instantaneous mains voltage is within a few volts of zero. The circuit thus provides minimal switching RFI.

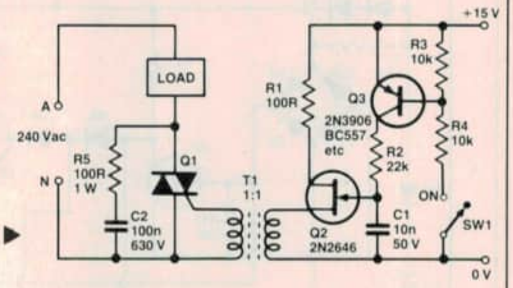

Figure 7. Isolated-input (transformer-coupled) ac power switch.

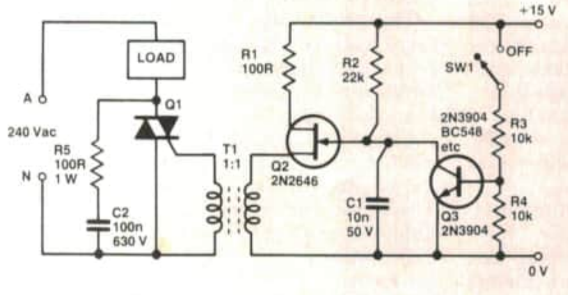

Figure 8. Isolated-input ac power switch.

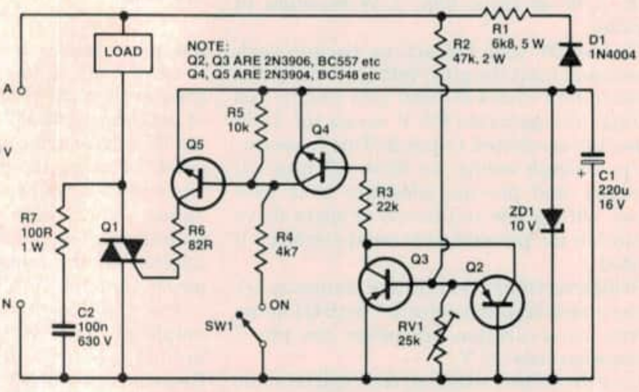

Figure 9. 'Transistorised' synchronous line switch.

Figure 10 shows how the circuit can be modified so that the triac can only turn on when SW1 is open. Note in both of these circuits that, since only a narrow pulse of gate current is sent to the triac, the *mean* consumption of the dc supply is very low (1 mA or so). Also note that SW1 can easily be replaced by an electronic switch to give automatic operation via heat, light, etc, or by an optocoupler to give fully isolated operation from external circuitry.

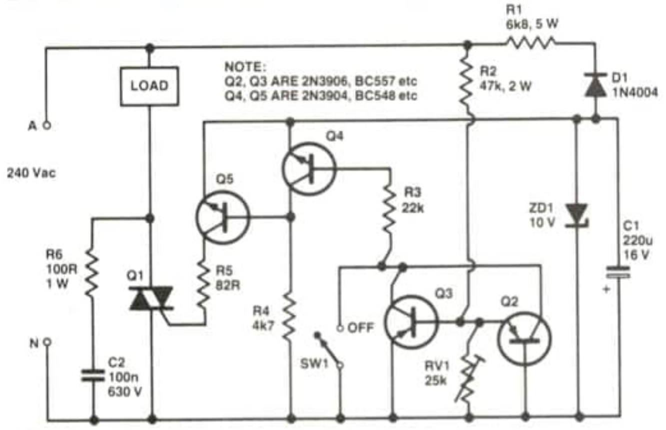

Figure 10. Alternative version of the 'transistorised' line switch.

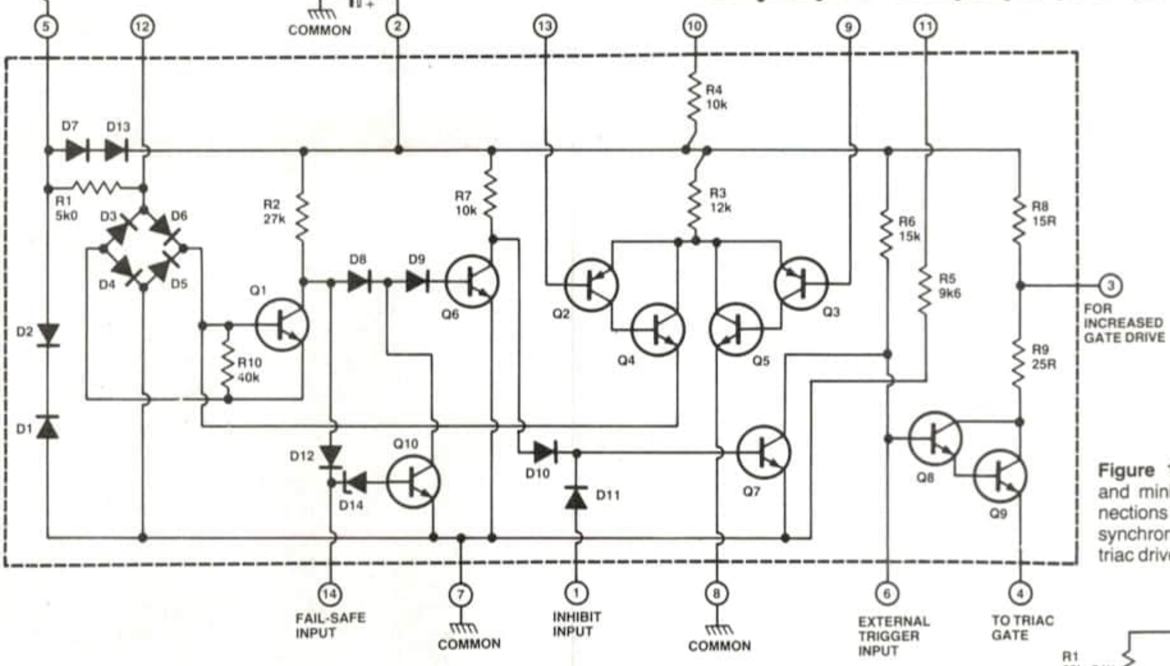

Figure 11. Internal circuit and minimal external connections of the CA3059 synchronous 'zero-voltage' triac driver.

A number of special-purpose synchronous zero-crossover triac-gating ICs are available, the best known examples being the CA3059 and the TDA1024. These devices incorporate mains-derived dc power supply circuitry, a zero-crossing detector, triac gate drive circuitry, and a high gain differential amplifier/gating network.

Figure 11 shows the internal circuitry of the CA3059, together with its minimal external connections. Mains power is connected to pins 5 and 7 via limiting resistor R_S (22k, 5 W or three 68k, 1 W resistors in parallel).

Diodes D1 and D2 act as back-to-back zeners and limit the pin 5 voltage to ±8 V. On positive half-cycles D7 and D13 rectify this voltage and generate 6.5 V across the 100u capacitor connected to pin 2. This capacitor stores enough energy to drive all internal circuitry and provide adequate triac gate drive, with a few milliamps of spare drive available for powering external circuitry if needed.

Bridge rectifier D3 to D6 and transistor Q1 act as a zero-crossing detector, with Q1 being driven to saturation whenever the pin 5 voltage exceeds ±3 V.

Gate drive to an external triac can be made via the emitter (pin 4) of the Q8-Q9 Darlington pair, but is available only when Q7 is turned off. When Q1 is turned on (pin 5 greater than ±3 V) Q6 turns off through lack of base drive, so Q7 is driven to saturation via R7 and no triac gate drive is available at pin 4. Triac gate drive is available only when pin 5 is close to the 'zero-voltage' mains value. When gate drive is available, it is delivered in the form of a narrow pulse centred on the crossover point, with pulse power supplied via C1.

The CA3059 incorporates a differential amplifier or voltage comparator, built around Q2 to Q5, for general purpose use. Resistors R4 and R5 are externally available for biasing one side of the amplifier. The emitter current of Q4 flows via the base of Q1 and can be used to disable the triac gate drive (pin 4) by turning Q1 on.

The configuration is such that the gate drive can be disabled by making pin 9 positive relative to pin 13. The drive can also be disabled by connecting external signals to pin 1 and/or pin 14.

Figures 12 and 13 show how the CA3059 can be used to give manually-controlled 'zero-voltage' on/off switching of a triac. These two circuits use SW1 to enable or disable the triac gate drive via the internal differential amplifier of the IC. Remember, the drive is enabled only when pin 13 is biased above pin 9.

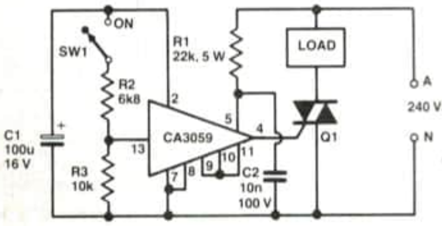

Figure 12. Direct-switched IC-gated 'zero-voltage' line switch.

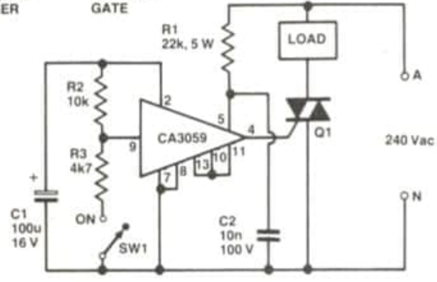

Figure 13. An alternative method of direct-switching the CA3059 IC.

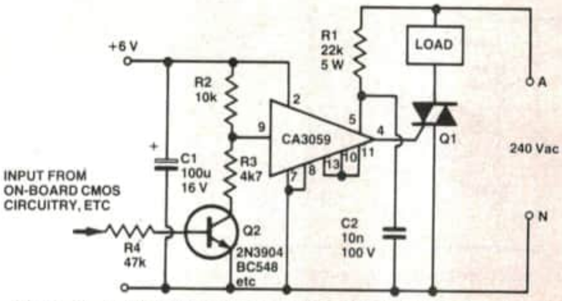

Figure 14. Method of transistor-switching the CA3059 via on-board CMOS circuitry, etc.

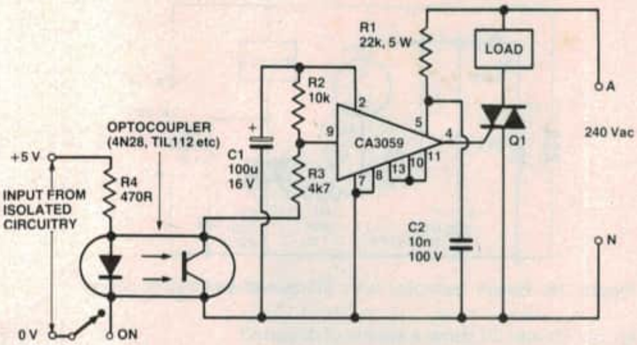

Figure 15. Method of remote-switching the CA3059 via an optocoupler.

In the Figure 12 circuit, pin 9 is biased at half-supply volts and pin 13 is biased via R2-R3 and SW1, and the triac turns on only when SW1 is closed.

In Figure 13, pin 13 is biased at half-supply and pin 9 is biased via R2-R3 and SW1, and the triac again turns on only when SW1 is closed. In both of these circuits, SW1 handles a maximum potential of 6 V and maximum current of only 1 mA or so.

Note, in these designs, that capacitor C2 is used to apply a slight phase delay to the pin 5 'zero-voltage detecting' terminal, and causes the gate pulses to occur slightly after (rather than to 'straddle') the zero-voltage point.

Note in the Figure 13 circuit that the triac can be turned on by pulling R3 low or turned off by letting R3 float. Figures 14 and 15 show how this simple fact can be put to use to extend the versatility of the basic circuit.

In Figure 14, the triac can be turned on and off by transistor Q2, which in turn can be activated by on-board CMOS circuitry (such as one-shots, astables, etc) that are powered from the 6 V pin 2 supply.

In Figure 15, the circuit can be turned on and off by fully-isolated external circuitry via an inexpensive optocoupler, which needs an input in excess of only a couple of volts to turn the triac on.

Alternatively, Figure 16 shows how the TDA1024 can be used in place of the CA3059 to give either directly-switched or opto-coupled 'zero-voltage' triac control.

Finally, to complete this section, Figures 17 and 18 show a couple of ways of using the CA3059 so that the triac operates as a light-sensitive 'dark-operated' power switch. In these two designs the built-in differential amplifier of the IC is used as a precision voltage comparator that turns the triac on or off when one of the comparator input voltages goes above or below the other.

Figure 17 is the circuit of a simple dark-activated power switch. Here, pin 9 is tied to half-supply volts and pin 13 is controlled via the R2-RV1-LDR-R3 potential divider.

Under bright conditions the LDR has a low resistance, so pin 13 is below pin 9 and the triac is disabled. Under dark conditions the LDR has a high resistance, so pin 13 is above pin 9 and the triac is enabled and power is fed to the load. The precise threshold level of the circuit can be preset via RV1.

Figure 18 shows how a degree of hysteresis or 'backlash' can be added to the above circuit, so that the triac does not switch annoyingly in response to small changes (passing shadows, etc) in ambient light level. The hysteresis level is controlled via R3, which can be selected to suit particular applications.

ELECTRIC-HEATER CONTROLLERS

Non-synchronous circuits

Triacs can easily be used to give automatic room-temperature control by using electric heaters as the triac loads and either thermostats or thermistors as the thermal feedback elements.

Two basic methods of heater control can be used, either simple on/off power switching or fully automatic proportional power control. In the former case, the heater switches fully on when the room temperature falls below a preset level and turns off when the temperature rises above the preset level.

In the latter case, the *mean* power to the heater is automatically adjusted so that, when the room temperature is at the precise preset level, the heater output power self-adjusts to balance the thermal losses of the room.

Because of the high power requirements of electric heaters, special care must be taken in the design of triac controllers to keep RFI generation to minimal levels. Two options are open to the designer, to use either continuous dc gating of the triac, or to use synchronous pulsed gating.

The advantage of dc gating is that, in basic on/off switching applications, the triac generates zero RFI under normal (on) running conditions. The disadvantage is that the triac may generate very powerful RFI as it is initially switched from the off to the on condition.

The advantage of synchronous gating is that no high-level RFI is generated as the triac transitions from the off to the on condition. The disadvantage is that the triac generates continuous very-low-level RFI under normal (on) running conditions.

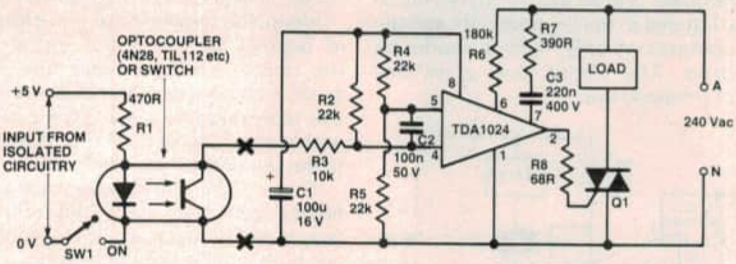

Figure 16. The TDA1024 used to give either directly switched or optocoupled 'zero-voltage' triac control.

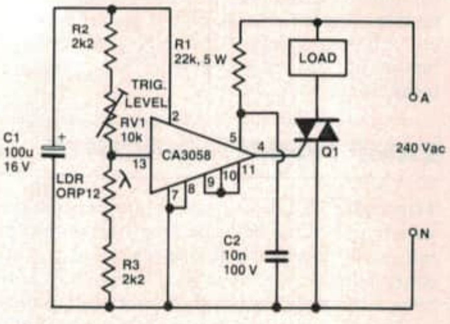

Figure 17. Basic 'dark-activated' zero-voltage switch.

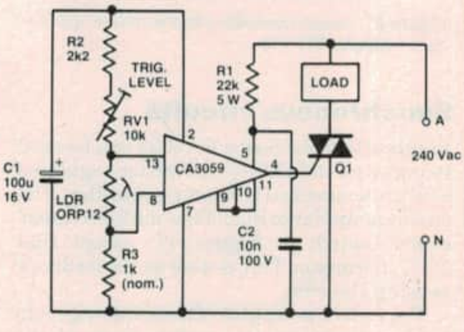

Figure 18. Dark-activated zero-voltage switch with hysteresis provided via R3.

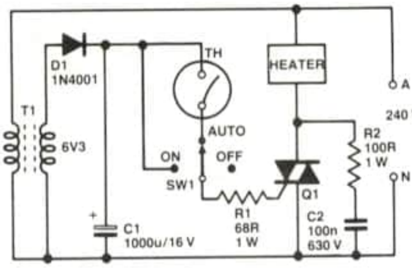

Figure 19. Heater controller with thermostat-switched dc gating.

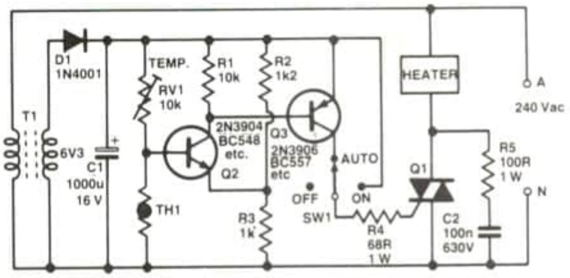

Figure 20. Heater controller with thermistor-switched dc gating.

Figures 19 and 20 show a couple of dc-gated heater-controller circuits, in which the dc supply is derived via T1-D1 and C1, and the heater can be controlled either manually or automatically via SW1. The Figure 19 circuit is auto-controlled via a thermostat.

The Figure 20 circuit on the other hand, is controlled by negative temperature coefficient (NTC) thermistor TH1 and transistors Q2-Q3, and calls for some explanation. RV1-TH1-R2-R3 are used as a thermal bridge, with Q2 acting as the bridge-balance detector. RV1 is adjusted so that Q2 just starts to turn on as the temperature *falls* to the desired preset level. Below this level, Q2-Q3 and the triac are all driven hard on, and above this level all three components are cut off.

Note, in the Figure 20 circuit that, since the gate-drive polarity is always positive but the triac main-terminal current is alternating, the triac is gated alternately in the I+ and III+ modes (or quadrants) and that the gate sensitivities are quite different in these two modes.

Consequently, when the temperature is well below the preset level Q3 is driven hard on and the triac is gated in both quadrants and gives full power drive to the heater, but when the temperature is very close to the preset value Q3 is only 'gently' driven on, so the triac is gated in the I+ mode only and the heater operates at only half of maximum power drive. The circuit thus gives fine control of temperature.

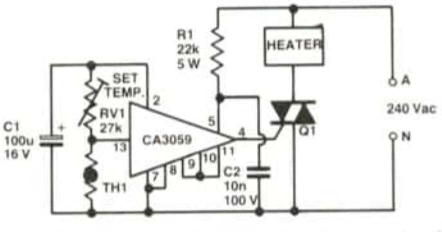

Figure 21. Heater controller with thermistor-regulated zero-voltage switching.

Synchronous circuits

Figure 21 shows how a CA3059 can be used to make an automatic thermistor-regulated synchronous electric heater controller. The circuit is similar to that of the 'dark-activated' power switch of Figure 17, except that NTC thermistor TH1 is used as the feedback sensing element.

The circuit is capable of maintaining room temperature within a degree or so of the value via RV1.

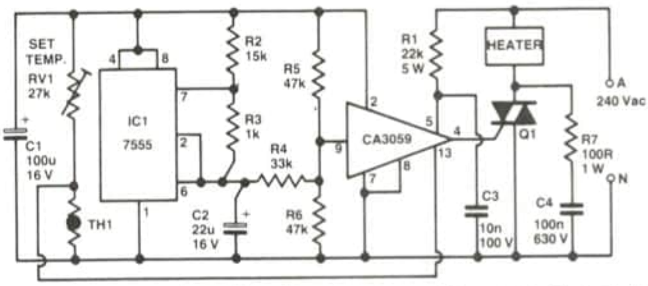

Figure 22. Heater controller giving integral-cycle precision temperature regulation.

Finally, to complete this 'heater controller' section, Figure 22 shows the circuit of a proportional heater controller which is capable of maintaining room temperatures within 0.5°C (depending on sensor placement). In this circuit a thermistor controlled voltage is applied to the pin 13 side of the CA3059's comparator and a repetitive 30 ms ramp signal, centred on half-supply volts, is applied to the pin 9 side of the comparator from CMOS astable IC1.

The action of the circuit is such that the triac is synchronously turned fully on if the ambient temperature is more than a couple of degrees below the preset level, or is cut fully off if the temperature is more than a couple of degrees above the preset level.

When the temperature is within a couple of degrees of the preset value however, the ramp waveform comes into effect and synchronously turns the triac on and off (in the 'integral cycle' mode) once every 300 ms, with a mark/space ratio that is proportional to the temperature differential.

Thus, if the mark/space ratio is 1:1, the heater generates only half of maximum power, and if the ratio is 1:3 it generates only one quarter of maximum power.

The net effect of this action is that the heater output power self-adjusts to meet the room's heating requirements. When the room temperature reaches the preset value, the heater does not switch off, but generates just enough output power to match the thermal losses of the room, giving very precise temperature control.

LAMP DIMMER CIRCUITS

Triacs can be used to make lamp dimmers, which vary the brilliance of incandescent lamps, by using the phase-triggered power control principles described in part 1. The triac is turned on and off once in each mains half-cycle, the mark/space ratio controlling the mean power fed to the lamp. All such circuits require the use of a simple LC filter in the lamp feed line, to reduce RFI problems.

The three most popular methods of obtaining variable phase-delay triggering are to use either a diac plus RC phase delay network, or to use a line-synchronised variable delay UJT trigger, or to use a special purpose IC as the triac trigger.

Figure 23 shows the practical circuit of a diac-triggered lamp dimmer, in which R1-RV1-C1 provide the variable phase delay. This circuit is similar to that described in part 1, except for the addition of on/off switch SW1 which is ganged to RV1 and enables the lamp to be turned fully off.

A defect of the simple Figure 23 design is that it suffers from considerable control hysteresis or backlash. If the lamp is dimmed by increasing the RV1 value to 470k, it will not go on again until RV1 is reduced to about 400k, and it then burns at a fairly high brightness level. This 'backlash' is caused by the diac partially discharging C1 each time the triac fires.

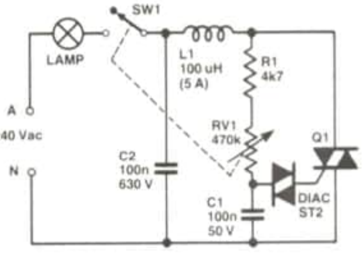

Figure 23. Practical circuit of a simple lamp dimmer.

The 'backlash' effect of the Figure 23 circuit can be reduced by wiring a 47R resistor in series with the diac, to reduce its discharge effect on C1. An even better solution is to use the gate slaving circuit of Figure 24, in which the diac is triggered from C2, which 'copies' the C1 phase delay voltage. But here, R2 protects C1 from discharging when the diac fires.

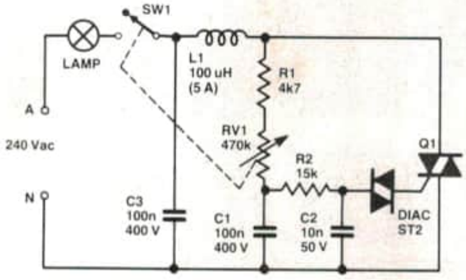

Figure 24. Improved lamp dimmer with gate slaving.

CONSTRUCTION OF L1, FIGS 23 TO 26

The core is a 30 mm long piece of 9.6 mm dia. ferrite aerial rod. Wind two layers of 20 turns, closewound, using the centre 15 mm of the core, with 0.63 mm dia. (22 B&S) enamelled wire. Cover with two layers of plastic insulation tape.

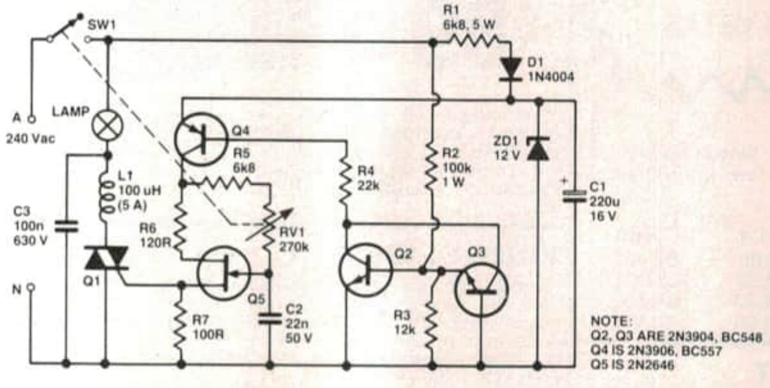

Figure 25. UJT-triggered zero-backlash lamp dimmer.

If absolutely zero backlash is needed, the UJT-triggered circuit of Figure 25 can be used. The UJT is powered from a 12 Vdc supply derived from the ac line via R1-D1-ZD1-C1. The UJT is synchronised to the mains via the Q2-Q3-Q4 zero-crossing detector network, the action being such that Q4 is turned on (applying power to the UJT) at all times other than when the mains is close to the zero-crossover point at the end and start of each mains half-cycle.

Thus, shortly after the start of each half-cycle, power is applied to the UJT circuit via Q4, and some time later (determined by R5-RV1-C2) a trigger pulse is applied to the triac gate via Q5. The UJT resets at the end of each half-cycle, and a new sequence then begins.

Finally, to complete this 'lamp dimmer' section, Figure 26 shows how a dedicated IC, the Siemens S566B 'Touch Dimmer' chip, can be used as a 'smart' lamp dimmer that can be controlled by either touch pads, push-button switches, or via an infra-red link.

The action of this chip, which gives a phase-delayed trigger output to the triac, is such that it alternately ramps up (increases brilliance) or ramps down (decreases brilliance) on alternate operations of the touch or pushbutton inputs, but 'remembers' and holds brilliance levels when the inputs are released.

The IC incorporates 'touch conditioning' circuitry, such that a very brief touch or push input causes the lamp to simply change state (from off to on, or vice versa), but a sustained (greater than 400 ms) input causes the IC to go into the ramping mode, in which the lamp power slowly ramps up from 3% to 97% of maximum and then down to 3% again, and so on.

The touch pads used with this circuit can be simple strips of conductive material; the operator is safely insulated from the mains voltage via R8 and R9.

UNIVERSAL-MOTOR CONTROLLERS

Domestic appliances such as electric drills and sanders, sewing machines and food mixers, etc, are almost invariably powered by series-wound 'universal' electric motors (so called because they can operate from either ac or dc supplies).

When operating, these motors produce a back-emf that is proportional to the motor speed. The *effective* voltage applied to such motors is equal to the true applied voltage minus the back-emf. This fact results in a degree of self-regulation of the speed of the motors, since an increase in the motor loading tends to reduce the speed and back-emf, thereby increasing the effective applied voltage and causing the motor speed to return towards its original value.

Most 'universal' motors are designed to give single-speed operation. Triac phase-controlled circuits can easily be used to provide these motors with variable speed control. A suitable 'diac plus phase-delay' circuit is shown in Figure 27. This circuit is particularly useful for controlling lightly-loaded appliances such as food mixers, sewing machines, etc. However, you only get a limited range of control.

Electric drills and sanders are subject to very heavy load variations, and are not really suitable for control via the Figure 27 circuit. Instead, the variable speed-regulator circuit of Figure 28 should be used.

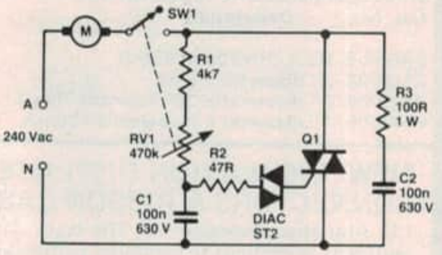

Figure 27. Universal-motor speed controller for use with lightly-loaded appliances (food mixers, sewing machines, etc).

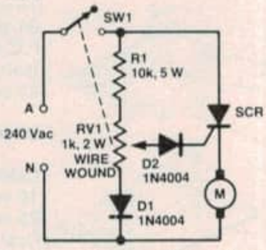

Figure 28. Self-regulating universal-motor speed controller for use with electric drills and sanders, etc.

This circuit uses an SCR as the control element and feeds half-wave power to the motor (this results in only a 20% or so reduction in available speed/power), but in the off half-cycles the back-emf of the motor is sensed by the SCR and used to give automatic adjustment of the next gating pulse, giving some speed regulation. The R1-RV1-D1 network provides only 90° of phase adjustment so all motor power pulses have minimum durations of 90° and provide very high torque.

At low speeds the circuit goes into a 'skip cycling' mode, in which power pulses are provided intermittently, to suit motor loading conditions. The circuit provides particularly high torque under low-speed conditions, but the motor 'chatters' somewhat. Like the previous circuit, only a limited range of control is provided. ●

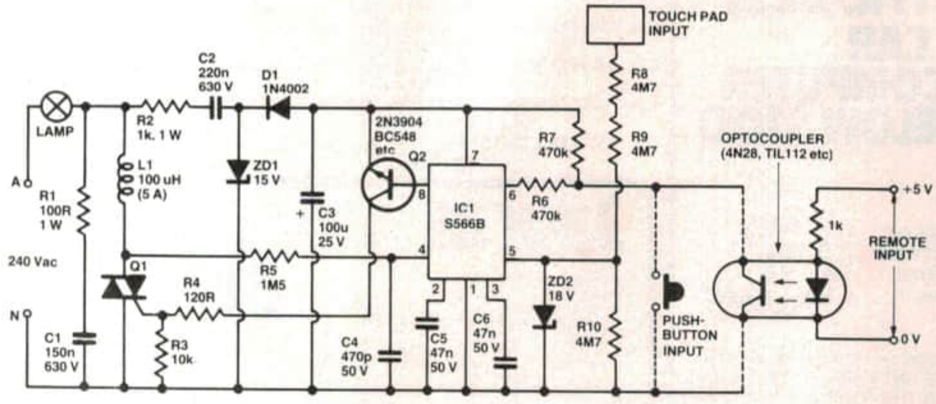

Figure 26. 'Smart' lamp dimmer controlled by a dedicated IC.