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APPLIANCE CLINIC
(continued from page 26)

trol and speed regulation, with the RC networks and extra diodes, etc.

Once again, testing can be quite easy. If the motor runs at full speed at all times, the motor and SCR are OK.

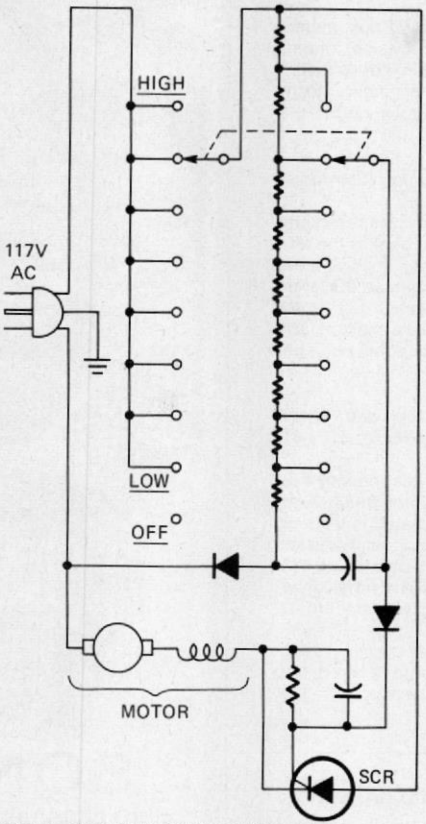

FIG. 2—SCR CONTROLS SPEED of motor. Gate voltage of SCR is controlled by a switch and resistors. This type has speed regulation.

The chances are that the selector switch, or one of the resistors in the gate voltage divider, or both, would be open. If the SCR is shorted, the chances are that the motor would run at a speed much faster than normal, since it would then have full-power full-wave ac applied to it. The SCR can be checked for shorts with an ohmmeter.*

Incidentally, you should be able to make a substitution test for a suspected SCR; just unhook it, and temporarily connect a standard silicon diode rectifier (with sufficient current capacity, of course!) into the circuit in its place. If the motor will run at full speed, the motor itself is OK, and you've got trouble in the SCR, switch, etc.

Here again, you may run into encapsulated or "Black Box" controls. The tests described can be made on the motor, and if these show that it is in working order, the entire control unit must be replaced. (You can't get into 'em—they're sealed.) **R-E**

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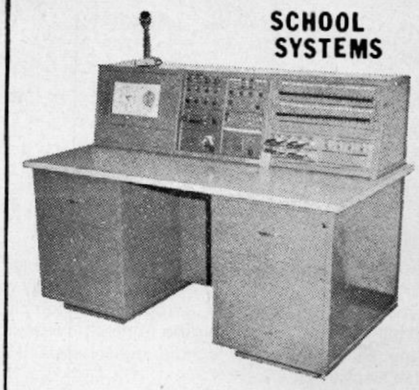
*Thanks very much to R. W. Fox of GE Applications Engineering Department, for the data on these control systems.



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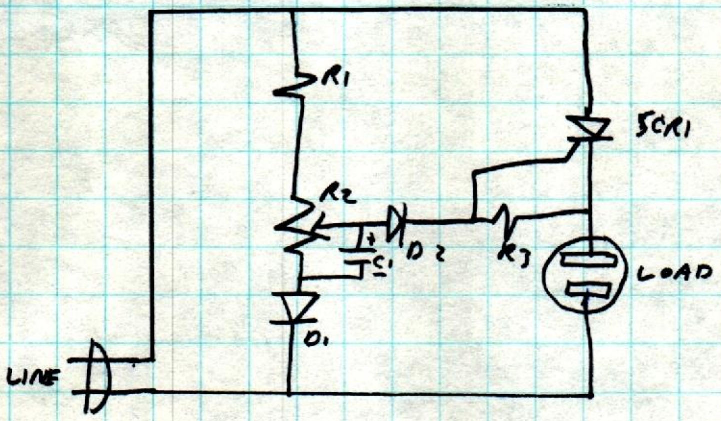
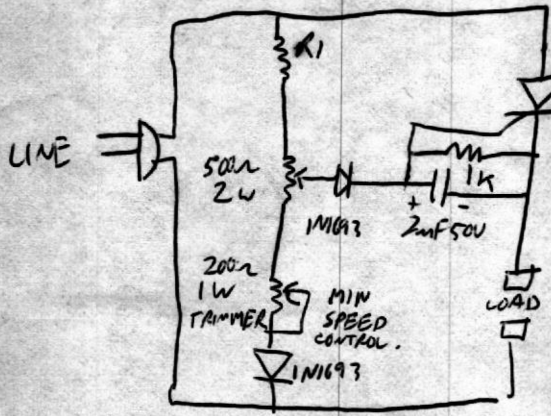


SCR1 - TRIAC OR SCR - ANY CURRENT - 200 PIV MIN.

R_1 - 3.3K 2W
R_2 - 500Ω → 1K
R_3 - 150Ω ½W
C_1 - 100/12V.
D_1, D_2 - ½A 200 PIV RECTIFIERS.

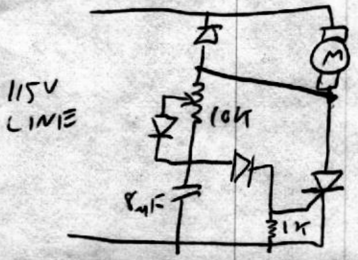
MOTOR SPEED CONTROL

#1



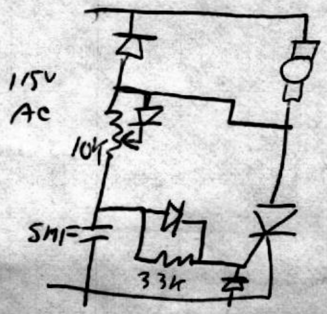
	GEN. PUR. (2A).	HEAVY DUTY
SCR.	GE C15B	2N1846
R1	4K 2W	1K 5W.

#2



DIODES - 1N3072.

#3



Motor Controller Project

Electric drills, saws, grinders, food blenders etc., all benefit from having some sort of control over their speed. Simple electric motor speed controllers, while proving speed control, have limited ability to maintain motor speed constant over widely varying loads. This project overcomes the limitations of these simple units and, despite its simplicity and low cost, is remarkably effective.

By Jonathan Scott

JUDGING BY users' remarks on the shortcomings of speed controllers on a variety of electrically driven appliances, and from much personal experience and observation, there is a *considerable need* for a well-designed speed controller for use with electric drills, grinders, saws, food blenders and other appliances driven by 'universal' electric motors.

The more expensive power drills now come with a variable control built into the trigger. Food blenders come *festooned* with an array of buttons marked with a ludicrous range of words with every synonym from 'mix' to 'masticate' represented!

These gadgets all have a severe limitation, namely, that they really only have voltage controllers, not speed controllers, for the motor in the unit. They vary the speed but provide little or no feedback speed control.

In the case of the power drill with a speed control in the trigger, the operator is in a position to adjust the trigger continuously in response to variations in the speed of the shaft, thus effectively becoming part of a feedback loop and serving as the speed *regulating* element.

The variable speed function of these latest drills is really not designed to allow the slow steady pace needed for delicate or laborious jobs, but to allow the unit to act as an electric screwdriver, when fitted with the appropriate bit, where constant speed is not necessary.

Blenders, however, are items which you typically want to turn on and add more and more ingredients (adding more load) as the process progresses. What happens? The blender slows down as the load increases and it's real pain to have to keep adjusting it. If you're not careful, or in too much of a hurry, you can stall the motor quite easily.

Older electric drills and most high rpm grinder never had any sort of variable speed adjustment, electrical or mechanical. Grinders fitted with a special 'pad' wheel are used for building, too. But you have to be quite deft, otherwise it's easy to buff right through the undercoat of a painted object because of the ferocity of the thing.

If you need to drill a particularly tough substance with an older drill, then you have to be prepared to wear out the fine, sharp drill tip very quickly.

So, there is a distinct requirement for some device which can be placed between the appliance plug and the power that can be used to not only *set* the motor speed, but to *regulate* it as well.

The perils of simplicity

There seems to be fundamentally three degrees of complexity in the way one can design these circuits, each with advantages and disadvantages. All techniques employ some method of sensing the motor back-emf and adjusting the power delivered to keep the back-emf relatively constant.

For the sake of attaching 'handles' to each fundamental technique, I shall dub them — the *crude/economical* method, the *refined/economical* method and the *complex/ultimate* method.

For this project I have chosen the middle course for reasons which will become apparent shortly.

The crude/economical method is the simplest and for that reason has an extraordinary advantage in that it has a low parts count. This sort of circuit requires a diode or two, a pot, a couple of resistors and little else apart from the SCR switching element (see Figure 1). Now, it is hard to beat this sort of economy, but such circuits have a few annoying limitations.

Firstly, they will not usually drive anything but the most sensitive SCRs because they deliver very low gate currents.

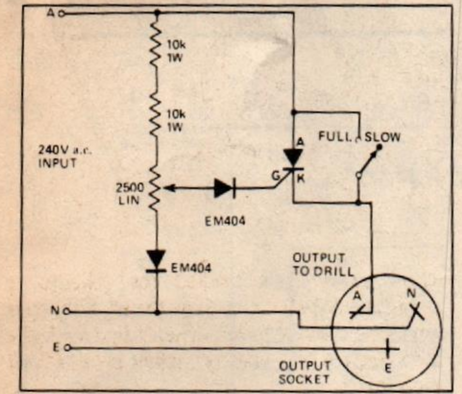


Fig. 1. An example of the crude/economical type of motor speed controller. This is the circuit of the ETI Speed Controller.

Secondly some component values can be critical, resulting in touchy or erratic response if tolerances are a bit out or the unit is driving an unusual motor. Lastly, the lack of an amplifying element in the feedback means that the speed regulation, while being above normal for a universal motor, is nowhere near perfect and the speed does drop under load.

To separate the two further types of controller requires a reasonable familiarity with what goes on when controlling a universal electric motor, so I will discuss the technique I have used in this project now and then go on to the explanation of further refinement.

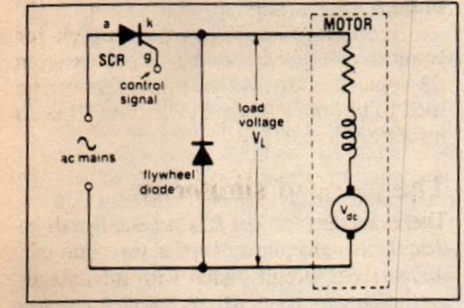


Fig. 2. Fundamental circuit elements of the controller used in this project. Note that V_{dc} is the back-emf of the motor.

Controller technique

A universal electric motor appears as a resistance, an inductance and a voltage source in series. The elements of the phase control system I have used — an SCR and a 'flywheel diode' — are connected as shown in Figure 2.

The voltage across the motor terminals during operation of this circuit will appear something like that shown in Figure 3. (Note that the vertical axis is not to scale.)

Considering the cycle from the peak onwards, let us examine the reason behind the appearance of each part of the waveform.

Say that, at some speed setting, the SCR is fired into conduction at about the 100° point of each positive half cycle. The load voltage jumps to a value very nearly equal to the mains voltage at that point (less the small drop across the SCR) and follows the mains cycle variation until the end of that half cycle (i.e. at the 180° point).

Thus, the point between 0° and 180°, of the positive half cycle, where the SCR fires, defines how much voltage is delivered to the load (the motor). Varying the delay before firing provides a means of varying the power delivered to the motor. This is known as phase control, for clearly obvious reasons.

At the point where the mains voltage falls below the back-emf voltage of the motor you would expect the current through the motor to become zero and the SCR to turn off. But, this is not quite the case as the load is not purely resistive. The inductive component of the motor forces its terminal voltage negative in an attempt to maintain motor current, and indeed, the load voltage would follow the mains negative for some way if it were not for the diode connected across the motor terminals.

This diode conducts as the motor voltage goes beyond about 0.7 volts negative and carries the 'flywheel' current from the motor's inductance, generated by the collapsing magnetic field, allowing the SCR to isolate.

The flywheel current persists until the energy stored in the motor's windings is exhausted. This takes typically two to five milliseconds.

Were the diode not there, a large negative-going pulse would result. This, in itself, is not a bad thing, but it is easy to block this and reduce the net dissipation in the SCR, allowing it to control a larger device for the same ratings and prevents the need to make the controller circuitry more complex to resist the negative-going voltage.

At any rate, some way into the negative supply half cycle, the inductance ceases to be the dominating voltage source within the motor and the back-emf becomes evident.

As you may see from the diagram, the motor voltage rises to a level defined by the apparent dc source within the motor equivalent circuit. (The 'back-emf generator'). This voltage is a result of residual magnetism in the metal of the armature and field coils and the relative motion of these two elements.

The actual back-emf developed depends on a number of factors, a major one being speed so it is a good representation of the motor's instantaneous speed.

There is some noise evident on the back-emf voltage, it is not a smooth dc level. This noise is partly due to commutation hash (high frequency spikes) and partly due to different amounts of residual magnetism in different armature segments etc. However, the noise is not sufficient to obscure the speed signal, or back-emf.

In a typical universal electric motor the back-emf would average around 10 volts at full rpm. The control circuitry in the controller looks at this dc signal and varies the point at which the SCR fires, increasing the delay if the motor attempts to speed up under decreasing load, or decreasing the delay if the motor attempts to slow down under increasing load.

The Perils Of Complexity

It turns out that, in the case of most motors, a very satisfactory degree of speed regulation can be achieved with only a hint of hunting detectable at *very* low speeds. This is most fortunate as it means that one does not require to advance to the next step of complexity, namely using the third technique mentioned earlier — the *complex/ultimate* circuitry with its own compensating system incorporated to guarantee the stability of the system under *all* conditions, despite large loop gain.

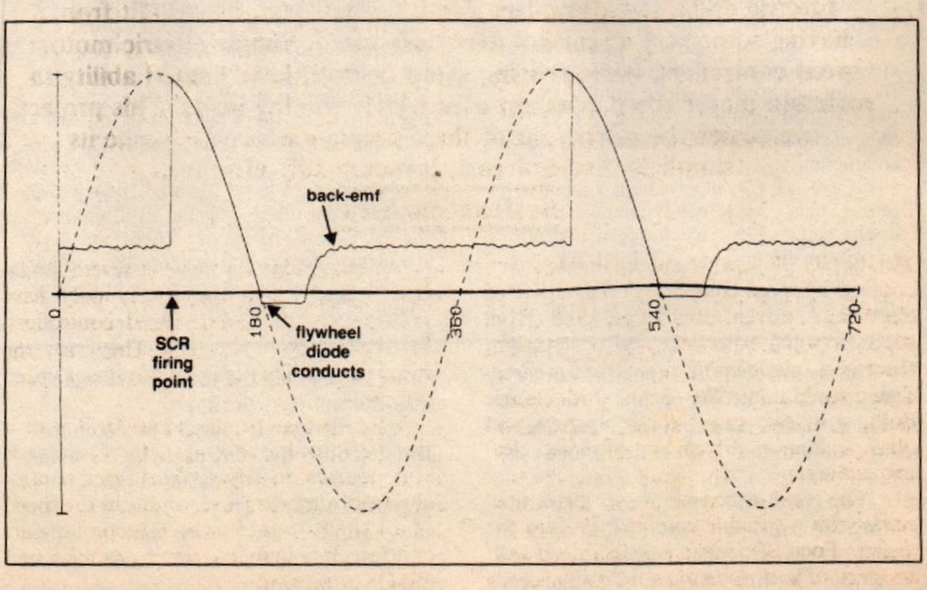


Fig. 3 Waveform of the voltage across the motor when using the ETI speed controller. (Vertical axis not to scale). The dashed line shows the power line input waveform.

HOW IT WORKS

The speed of an appliance's motor attached to the project, is controlled by applying the mains voltage to it at a set point of the mains positive half cycles, as seen in Figure 3. This is done by turning an SCR on at the appropriate point in the cycle. Turning on the SCR earlier in the cycle applies more voltage, increasing the speed, while turning the SCR on later applies less voltage, decreasing the speed.

The SCR (SCR1) is 'fired' by applying a positive pulse to its gate. This is effected by IC1, an optically-coupled triac driver containing a LED coupled to pins 1 and 2 and a bi-directional optically-operated 'switch' coupled to pins 4 and 6. When the LED in IC1 is off, the switch is off. When the LED is turned on, the switch conducts. If pin 4 is positive with respect to pin 6, it will forward-conduct from pin 4 to pin 6, and vice-versa if pin 6 is positive with respect to pin 4. So that only positive-going pulses are applied to the gate of SCR1, D3 ensures that the switch in IC1 can only conduct during mains positive half cycles.

Resistor R6 simply limits the current through IC1 pins 4 and 6, while R10 prevents false triggering of SCR1 due to small leakage currents.

The control electronics consists of Q1, Q2, PUT1, IC1, RV1 and associated components. The 'flywheel' diode is D6. Power supply for the control electronics is derived by a half-wave rectifier from the mains input. This consists of D2, R2 and C1. This supply is regulated by ZD1, a 33 V zener, R2 providing current limiting. C1 is charged up during the mains positive half cycles and substantially holds its charge during the negative half cycles.

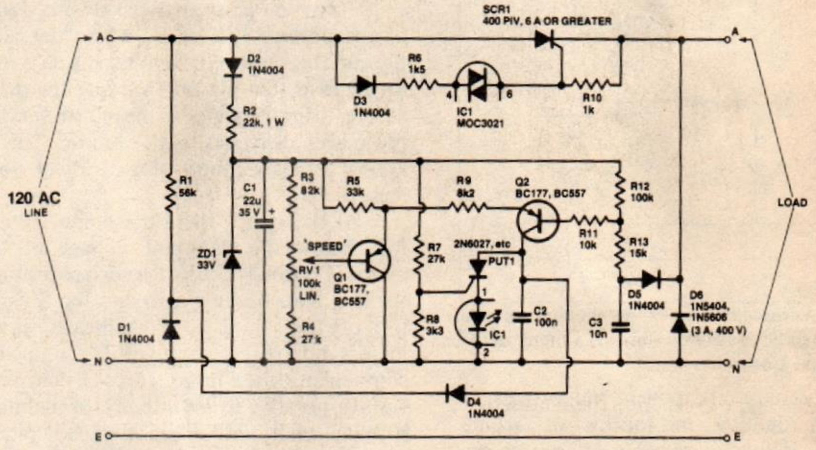
The SPEED control, RV1 is part of a potential divider — R3/RV1/R4. The wiper of RV1 sets a reference level on the emitter of Q1. This can be anywhere between about 4 V and 15 V (with respect to the neutral line), depending on the setting of RV1.

Now, let us see what happens from the point where the mains positive half cycles crosses through the zero point, going negative, at 180°, assuming SCR1 has been fired during the preceding half cycle.

Referring to Figure 3, as the mains crosses through zero, going negative, D6 (the flywheel diode) will conduct, holding the active (A) load terminal at about -0.6 V. The SCR then becomes reverse biased and ceases conducting.

Capacitor C3 will have been charged to a certain voltage (via R12/R13), but will now be discharged via D5. Any charge on capacitor C2 will be discharged via D4/D1/R1.

Diode D6 remains conducting until the inductive backlash of the motor (as explained in the text) dissipates. The voltage at the load active terminal (with respect to the neutral line) then rises to the back-emf level. D5 is now reverse biased, allowing C3 to charge again via R12/R13 until it reaches the level of the back-emf +0.6 V (D5's forward conduction voltage). Small positive-going 'spikes' on the back-emf level are ignored (momentarily reverse biasing D5) due to the time constant of R12/R13 and C3. This prevents erratic control circuit operation due to this noise. Nevertheless, small fluctuations are still present in the negative peak level held by C3.



Transistor Q2 is forward biased by the voltage drop across R12. The collector of Q2 sources charging current to C2, but this is held discharged via D4/D1/R1 until the mains negative half cycle crosses the zero point and the next positive half cycle begins. When it does, and D1/D4 are reverse biased, C2 will commence charging at a rate determined by the collector current of Q2.

The programmable unijunction transistor (PUT1) has its gate held at about 4 V (with respect to the neutral line) by the potential divider of R7-R8. When C2 charges to 0.6 V above this level, the PUT will 'fire', delivering a current pulse to the LED in IC1. This will operate the switch in IC1 and SCR1 will fire.

The rate at which C2 charges, determines at what point in the cycle the PUT and thus the SCR will be fired. There are two mechanisms for determining the rate at which C2 charges, and thus the point in the cycle at which SCR1 is fired.

Firstly, a reference level is set at the emitter of Q1 by the setting of RV1, the speed control. The collector-emitter current of Q2 will depend on the value of the voltage at this point and the value of R9, assuming the base voltage is held constant. Thus, varying RV1 varies the charging rate of C2, setting the point at which SCR1 fires.

Secondly, the base current of Q2 varies (and thus the collector current) depending on the voltage drop across R12. If the back-emf of the appliance motor falls, such as with an increase in motor loading, the voltage held on C3 will decrease (pulled down by D5 conducting current through the load) until it reaches the new value of the back-emf plus 0.6 V (D5 forward drop). This will increase the voltage drop across R12 and thus increase the base and collector current of Q2. Thus, C2 will charge more rapidly each mains positive half cycle, firing the PUT and SCR1 earlier in the cycle. This applies more power to the motor so that its speed is maintained.

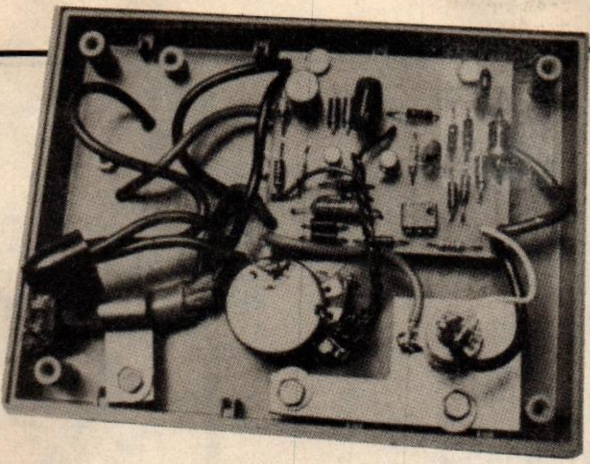
If the back-emf rises, such as it would from a decrease in motor loading, the voltage on C3 will rise and the voltage drop across R12 will decrease, decreasing the collector current of Q2. Thus, C2 in this case will charge more slowly, causing the SCR to fire later in the cycle. This will reduce power to the motor so that the set speed is maintained.

The function of R11 is simply to limit the currents in Q2 during those parts of the cycle when Q2 is not responding to the back-emf signal.

The reason that this type of circuitry is to be avoided, for the applications considered in the introduction to this article, is that it would require a great deal more electronics (and cost!). This would basically entail a mechanism capable of smoothly holding the back-emf signal so it could be further processed, which means some kind of sample-and-hold gate plus some synchronizing signal. Once isolated, the signal is easily dealt with, but the process is much more complex than the simple instantaneous method employed in Fig. 1.

One further refinement in a complex/ultimate controller may occur to the astute reader: namely, having the circuit capable of using the full 360° (or very nearly) of the mains supply cycle. The systems described so far, all assume that an SCR will be used to control the current delivered and not a triac. Hence, at most, only 180° of the mains cycle is available as the SCR must remain in a blocking state during the negative half cycle. Although a triac would permit use of the negative cycles, as would full-wave rectifying the mains before applying it to the SCR, these methods have one problem.

The sensing of speed, so that the speed may be regulated, requires access to the back-emf voltage, blanked immediately after a current zero. Hence, any attempt to employ near-continuous power application



Inside. Construction is quite straightforward — but take heed of the safety precautions mentioned in the text! Note that in use there may be a slight 'dead band' at either end of the speed control rotation where nothing happens.

would be hampered by the inductive 'backlash' concealing the motor's true back-emf value. Any such system would have to be capable of operating in a mode which left only every fourth or sixth half cycle unemployed for the purpose of 'getting at' the back-emf for speed sensing.

While possible, this would not only require considerable circuitry, but would also tend to impart some roughness to the torque delivered. Hence, such methods are well abandoned for the applications for which the controller has been designed. It is a realm of circuit complexity which returns benefits only with physically large machines.

Back To The Project

The controller has been deisnged to be a good compromise between the crude/economical and complex/ultimate controller. Speed can be set from full rpm on no load (at 'half power') down to less than one-tenth normal. This is lower than you're ever likely to need. On low speeds and without any load there is a tendency for motors to 'hunt' about the set speed, power being applied in detectable jerks. But, even when only a light load is applied, this has the effect of damping the control loop, improving the control and smoothing out the variations.

The torque characteristics of the circuit are excellent, until you approach the 180° limit of the cycle — which is, in any case, *way* beyond what you will need in common situations.

A good 'worst case' example is that of making houmous, a particularly thick and pasty (tasty, too!) dip in a blender. Initially, the mixture is oily, but as the blending proceeds it changes to a very glutinous consistency and blenders invariably begin to labour agonizingly at this point. With the controller in control — no problems!

Construction

Safety is a major consideration in a project such as this. Choosing a box in which to house the components has to be done carefully because the project will be used in a work environment, and is likely to encounter more than the usual amount of rough treatment.

I chose a strong, but not brittle, plastic case which comes in two halves, secured by recessed self-tapping screws that set into plastic pillars in the bottom half of the case.

Shape is unimportant, along with size, just so long as all the components can be fitted with ease and the box is not overlay large. If you choose a box with a metal fascia or panel, make sure this is *securely* grounded. If you can, get a box which provides internal posts to which the pc board and SCR mount can be secured with self-tapping screws so that no metal parts attached to these can protrude through the exterior of the case. If you must use a case that doesn't meet this requirement, secure 'the workings' with nylon nuts and bolts. All this is for your own protection.

The potentiometer used was of the conventional type, having a metal case, bushing and shaft. I grounded the pot. case, as shown in the wiring and overlay diagram. If possible, it would be an even better idea to obtain a pot. with a plastic bushing and shaft.

The mains cable *must* be firmly secured with either a clamp-type grommet where it enters the case, or with an ordinary grommet followed by a cable clamp. I used both a clamp-type grommet and a cable clamp, for good measure. (*That's probably overdoing it, but, please yourself — Ed.*)

Best place to start assembling the project is by drilling the few necessary holes in the box. If you are making a direct copy of the prototype, then positioning of the major components is clear from the internal photograph. If you're using a different box, then arrange the major components first and determine where you have to drill holes. Don't crowd the parts against one another. Use the blank pc board as a template for marking its mounting hold positions.

If you're using an SCR type that is not in a stud-mount package, then you'll have to arrange a suitable mount for it. I used a C220D type in a stud-mount, screwing it to a small piece of aluminum which also serves as a heatsink of sorts. SCR dissipation is small, so this heatsink/mount need only be small.

PARTS LIST

Resistors (all ½W, 5% unless noted)

R1	56k
R2	22k, 1W
R3	82k
R4	27k
R5	33k
R6	1k5
R7	27k
R8	3k3
R9	8k2
R10	1k
R11	10k
R12	100k
R13	15k
RV1	100k/A linear pot.

Capacitors

C1	22*u*/35 V RB electrolytic
C2	100n
C3	10n

Semiconductors

D1-D5	1N4004, EM410 etc.
D6	1N5404, 1N5606 etc.
IC1	MOC3021 triac opto-isolator
PUT1	2N6027, D13T1 etc.
Q1,Q2	2N3905
SCR1	any type, 400 PIV/6A or greater

Miscellaneous

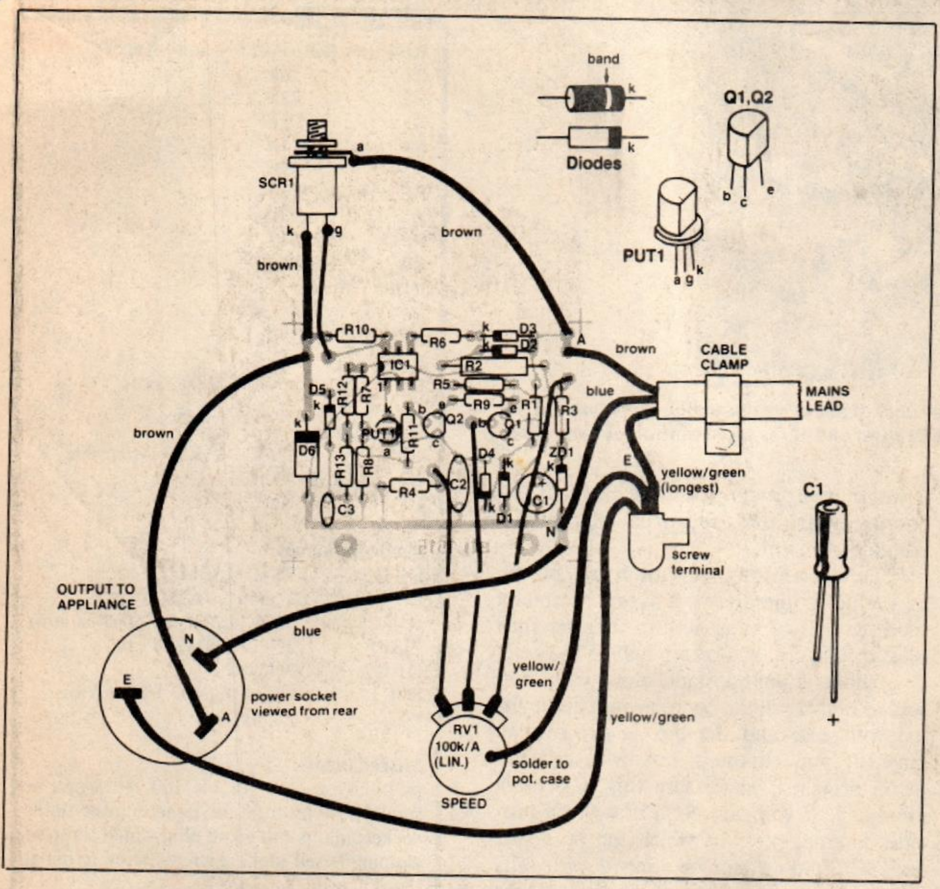
pc board; case — 135 × 100 × 38 mm or similar size to suit; 3-pin panel-mount mains socket; mains cable and plug; small scrap of aluminum, self-tapping screws; screw terminal block; etc.

Just bolt the SCR to the heatsink without any insulator, and use some thermal compound to improve thermal contact between the body of the device and the heatsink. REMEMBER — the heatsink will be at MAINS POTENTIAL, so make sure when mounting it that no securing bolts protrude through the case or use nylon nuts and bolts.

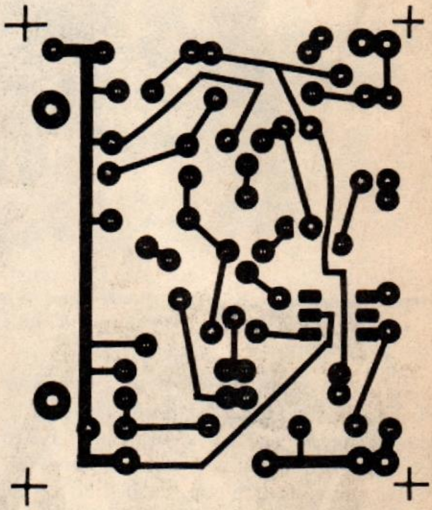
I mounted the SCR separately to the pc board so that a wide range of SCR types and packages could be readily accommodated, from the stud-mount C220D I used in the prototype, to small 6 A-rated, flange-mount plastic pack devices.

It is difficult to specify a 'load rating' for the project in terms of the SCR's characteristics, because of motor surge current characteristics and the range of motor ratings in appliances. A 6 A-rated SCR will happily handle an appliance rated to draw a nominal 2 A under 'normal' load. The C220D used in the prototype will reliably handle an appliance rated at four to five amps, right up to full revs setting under almost-stalled-rotor conditions.

Before attaching the 3-pin panel-mount mains outlet socket to the outside of the case, attach *colour-coded* wires to its terminals and thread these through the holes drilled for them in the case. Take care that



Overlay and wiring diagram. Follow this to assemble the pc board and wiring up of the external components.



you get the active (A), neutral (N) and ground (G) wires correct. Use wire from a short length of stripped-down mains flex.

When attaching the power cable, cut back the sheath so as to expose some 150 mm of the three wires to provide connections later. Make sure the cable is very firmly secured.

Mount the potentiometer using nuts on *both sides* of the case panel and lock the bushing tight so that there's no possibility of the pot. body coming loose and being rotated when the knob is turned.

Assemble the pc board next, according to the overlay diagram. You'll find it easier to solder the diodes in place first, followed by the resistors, capacitors and the rest of the semiconductors. As usual, watch the orientation of all the semiconductors and the electrolytic capacitor (C1).

Having done that check it. Make an especially careful examination of the soldering as diagnosis of problems will be dangerous and/or difficult later, because the board operates 'live'. In other words, if you are going to make only one project work first time this year, make it this one.

Attach the three wires that go to the potentiometer. Better colour code or mark these in some way to avoid confusion and wiring errors. Make sure they're long enough. Ordinary hookup wire will do for these. An ordinary piece of hookup wire can also be used for the lead to the SCR gate. The leads to the SCR anode and cathode carry mains potential and load current and should be wired using mains-rated wire. Get it from some stripped-down mains flex, like before.

Now wire up the mains input cable and the mains outlet socket to the pc board, then check it.

Note that the ground wire on the mains input cable should be longer than the active and neutral wires. Should the mains cable come adrift, the ground wire would then be the last to break.

The Try Out

When you're satisfied that the project is correctly together, it's time for a try-out. Just plug in your drill, blender, or whatever into the outlet socket, set the speed pot. a bit up from minimum, plug the controller into the mains, and switch on. See that the appliance's motor rotates at some low speed. Advance the speed control and see that the motor speed increases, as expected. If nothing's happening at this stage, switch off, unplug everything, and go over your wiring (this assumes you *know* the appliance works).

If that works, then try applying a load with the motor set at some convenient speed and see that the controller maintains the motor speed. If not, you've got troubles on the pc board and you'd better unplug everything and go over it.

If you are using the unit with an unusual motor, where the inertia of the armature may be greatly different to that expected by this circuit, you can vary the gain of the feedback amplifier by simply changing the value of R9. This can be varied between a minimum of about 150 ohms and a maximum of 22k.

Thus, if the motor hunts excessively (especially at low speed settings), R9 may be increased from the 8k2 value shown, reducing feedback loop gain and restoring stability at a small price in speed constancy. If the reverse is the case, you can acquire tighter regulation by reducing R9 — but check that hunting is kept to a minimum.

Finally, several words of caution are in order. The power bursts which are applied to the motor by the SCR switching and the control system variations with the motor armature running at low speed, applies a lot of stress to the motor's brushes and armature windings, so the controller should not be used in applications where it's not really necessary. Wear from the controller's use is unlikely to significantly shorten the life of an appliance, but it is never good practice to strain a mechanical device unnecessarily.

In addition, many appliance motors, particularly drills, employ a small cooling fan on the armature. The cooling effect of the fan is reduced, and extended periods of operation at low speeds should thus be avoided. **ETI**