VARY THE SPEED OF SYNCHRONOUS MOTORS WITH THIS PROGRAMMABLE CONTROL

BY GARY McCLELLAN

BECAUSE of their performance, reliability, and relatively low cost, synchronous ac motors are found in many turntables, tape decks, electrical timepieces, and even in the clock drives of amateur telescopes. The rotational speed of such a motor depends largely on the frequency of the ac source that powers it. In most applications, utility-generated ac powers a synchronous motor, making for an operational speed that is accurate and stable but difficult to vary.

Sometimes it is desirable to vary the speed of a synchronous ac motor. This article describes a project, the Programmable Speed Control, that provides this capability. It converts +12-volt dc into line-voltage, square-wave ac whose frequency is crystal-controlled and selectable in 0.1-Hz increments from 10.0 to 100.0 Hz. The project can provide up to 15 watts of output power, and can be modified to provide more. When properly calibrated, it has a rated frequency accuracy six times greater than that of the U.S. ac power grid. The Programmable Speed Control also has a moderate parts count and a relatively low construction cost.

About the Circuit. The heart of the system (Fig 1.) is a phase-locked loop comprising *IC1*, *IC2*, *IC3*, BCD thumbwheel switches *S1* through *S3*, and a quartz crystal. An oscillator in MOS LSI chip *IC1* generates a 3.5795-MHz signal whose frequency is controlled by the quartz crystal *XTAL*. Also included in this chip is a programmable-modulo counter. For this application, the counter is programmed so that a 100-Hz square wave appears at its output. This signal is used as a stable reference input for the phase-comparator section of CMOS phase-locked loop *IC2*.

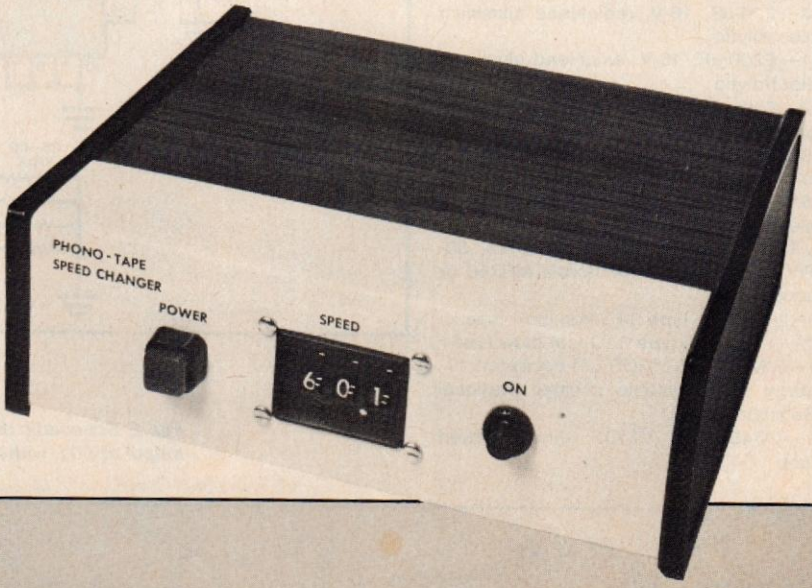
Applied to the other input of the phase comparator is a square wave derived from the output of the voltage-controlled-oscillator (vco) section of *IC2*. The output of the vco is a square wave whose frequency can vary from 10 to 100 kHz. In the example shown, it is nominally 60 kHz. This signal is applied to programmable-modulo counter *IC3*, which divides its frequency by a factor determined by the settings of thumbwheel switches *S1*, *S2*, and *S3*. These switches generate twelve BCD bits which are applied to the programming inputs of *IC3* and whose decimal equivalent is read off the faces of the switches.

In Fig. 1, the switches are shown set to read 60.0, but the decimal equivalent of the BCD number actually applied to the counter is 600. Accordingly, the vco output frequency is divided by 600, and a 100-Hz square wave appears at the output of *IC3*. The phase comparator accepts the two square-wave inputs. If they are not in phase the comparator sends a dc *error voltage* to the control input of the vco. In response, the vco shifts its frequency of oscillation until the square wave generated by *IC3* is in phase with the quartz-derived reference. (Frequency can be considered the rate of change of phase.) At this point, the output of the vco is phase-locked to the reference.

Switches *S1*, *S2*, and *S3*, together with *IC1*, *IC2*, and *IC3* form a frequency synthesizer that generates an extremely stable square wave. Its frequency will be between 10 and 100 kHz, the exact value determined by the settings of the thumbwheel switches. Counters *IC4* and *IC5* divide the vco output frequency by a factor of 1000. For the example shown, the output of *IC5* is 60.0 Hz. Counter *IC5* functions such that the duty cycle of its square-wave output is 50 percent.

This signal is inverted by buffer *IC6F*, whose output is simultaneously applied to driver *Q1* and to inverting

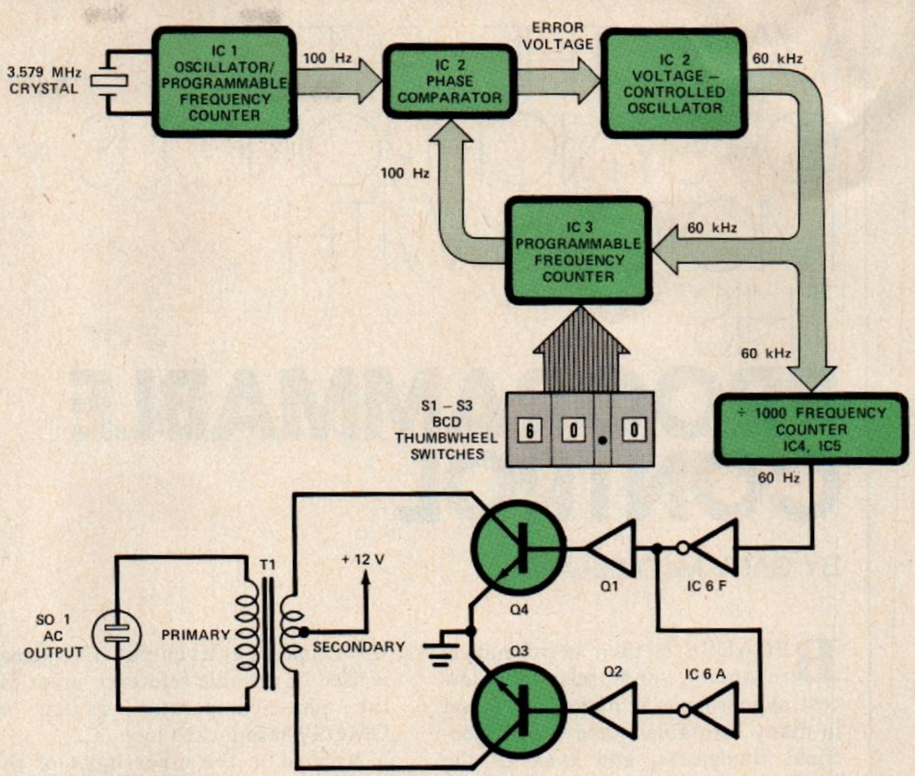
Crystal-controlled, frequency-synthesized dc-to-ac inverter has many useful applications



buffer *IC6A*. The output of the second inverting buffer is applied to driver *Q2*. When *Q1* is conducting, it provides base drive to power transistor *Q4*, but driver *Q2* and, hence, power transistor *Q3* are cut off. Similarly, when the output of *IC6A* causes *Q2* and *Q3* to conduct, *Q1* and *Q4* are cut off. The emitters of the power transistors are grounded, and their collectors are connected to the ends of the secondary winding of transformer *T1*. The center tap of the secondary is connected to +12 volts.

Power transistors *Q3* and *Q4* cause current pulses of opposite polarity to flow through the secondary of *T1*. Actually, the nominal secondary is used as a primary winding in this application, and vice versa. Line-voltage, square-wave ac appears across the primary of *T1* and is routed to power socket *SO1*. There it is available to the synchronous ac motor whose speed is to be controlled.

The schematic diagram of the Programmable Speed Control (Fig. 2.)



PARTS LIST

Components denoted by an * are needed only if the optional line-powered supply is built.

C1—30-pF NPO disc ceramic or silver mica capacitor
C2—15-pF NPO disc ceramic or silver mica capacitor
C3—6-to-20-pF air-dielectric trimmer capacitor (E.F. Johnson 275-0320-005 or equivalent)
C4, C6, C8—0.1-µF disc ceramic capacitor
C5—1-µF, 16-volt tantalum capacitor (do not make substitutions)
C7—47-pF NPO disc ceramic or silver mica capacitor
C9—10-µF, 16-V, radial-lead aluminum electrolytic
C10—220-µF, 16-V, radial-lead aluminum electrolytic
C11—2200-µF, 16-V, axial-lead aluminum electrolytic
C12—0.47-µF, 600-V, Mylar tubular capacitor
C13*, C14*—0.01-µF, 250-V, disc ceramic capacitor
C15*—4700-µF, 25-V, axial-lead aluminum electrolytic
D1, D2*, D3*, D4*, D5*—6-ampere, 50-PIV silicon rectifier (Motorola MR750 or equivalent)
F1—2-ampere, type 3AG fast-blow fuse
F2*—1-ampere, type 3AG fast-blow fuse
IC1—MM5369EST MOS LSI oscillator/17-stage programmable counter (National Semiconductor)
IC2—CD4046BC CMOS phase-locked loop

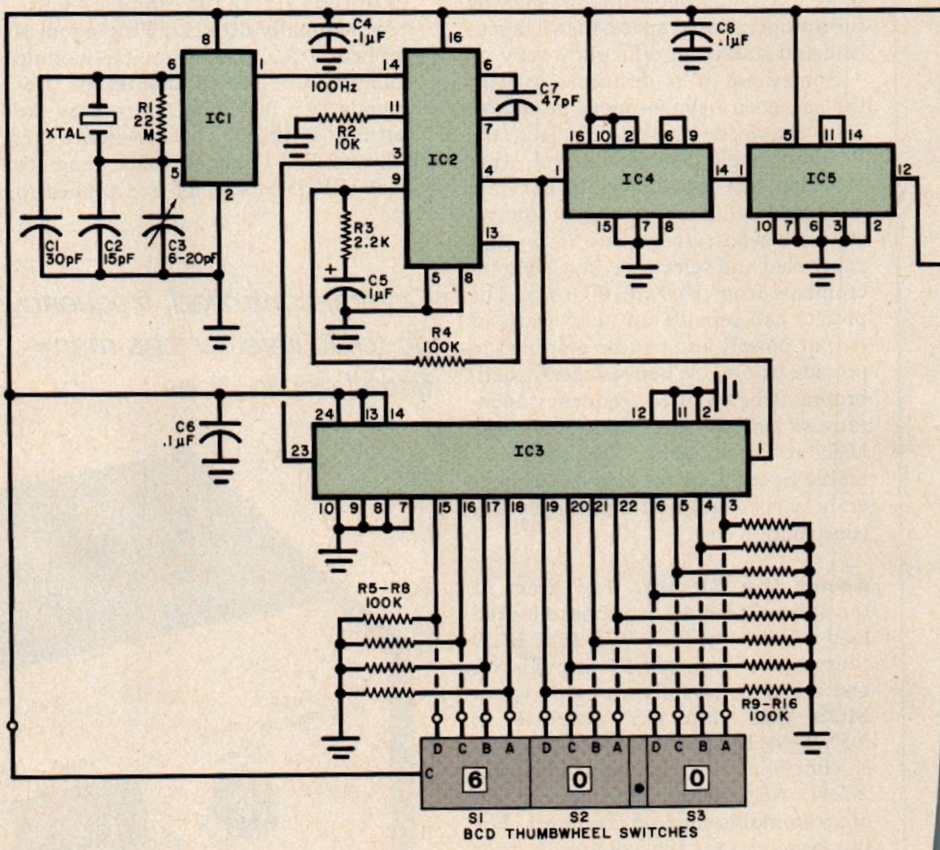


Fig. 2. Schematic diagram of the system. It can provide up to 15 watts of output at SO1, with frequency variable from 10 to 100 Hz.

closely resembles the block diagram. Components *C5*, *R3*, and *R4* comprise a loop filter—a low-pass filter that processes the error-voltage output of the phase-comparator in *IC2*. It ensures that clean dc is applied to the control input of *IC2*'s vco and that the vco's output frequency is stable. A tantalum capacitor is specified for *C5*. Using a standard aluminum-electrolytic capacitor for *C5* can cause circuit instability.

Inverting buffers *IC6A* and *IC6F*, because they are CMOS stages, can source only a few milliamperes of current. Driver transistors *Q1* and *Q2* function as emitter followers and provide base drive for power transistors *Q3* and *Q4*. The amount of base drive, nominally 20 mA, is determined by the values of resistors *R17* and *R18*. It can be adjusted if necessary by changing the values of these components.

In line-powered applications, synchronous ac motors are driven by a sinusoidal waveform. The output waveform of the Programmable Speed Control, however, is a square wave. Capacitor *C1* is wired in parallel with the transformer's primary winding (functionally the secondary winding) to damp the square wave and to protect the transformer and the synchronous ac motor from transient spikes. Also wired in parallel with the primary winding is neon pilot indicator *I1*. This lamp glows to alert the user that line-voltage ac is present at output power socket *SO1* and that the project is ready for use.

The Programmable Speed Control is designed to be powered by a +12-volt dc source. Diode *D1* protects the polarity-sensitive components in the project from application of reverse-polarity dc. Voltage regulator *IC7* enhances the stability of the frequency synthesizer by isolating it from voltage fluctuations in the dc power source.

Using a dc power source makes the project ideal for applications such as powering the clock drive of an amateur telescope during an outdoor viewing session. However, there are applications for the Programmable Speed Control in which ac line power is readily at hand. Two alternatives suggest themselves. One is to use a 12-volt rechargeable battery connected to a line-powered trickle charger. The other is to use a +12-volt, 3-ampere battery eliminator or the power supply shown in Fig. 3. This unregulated full-wave dc supply is more than adequate to power the circuit. It can be incorporated into the main project enclosure if the Programmable Speed Control will always be used in line-powered applications. Power switch *S4* then becomes superfluous.

Construction. Fashion a printed-circuit board using Fig. 4 as a guide. Referring to the component-placement guide in Fig. 5, install IC sockets or Molex Soldercons at locations *IC1* through *IC6* and add the two bare-wire jumpers between locations *IC2* and *R13*. Next, install the on-board capacitors, observing polarity

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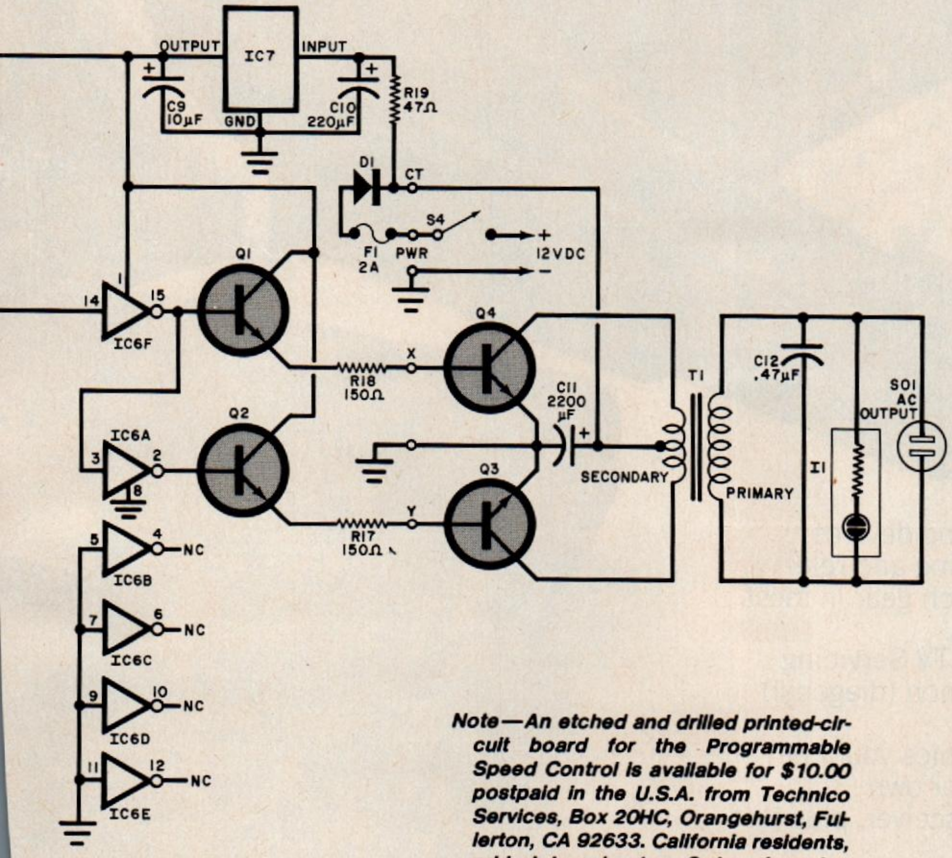

Note—An etched and drilled printed-circuit board for the Programmable Speed Control is available for $10.00 postpaid in the U.S.A. from Technico Services, Box 20HC, Orangehurst, Fullerton, CA 92633. California residents, add state sales tax. Orders from foreign countries must be accompanied by remittance of U.S. currency and a $3.00 postage-and-handling charge.

IC3—CD4059AE CMOS 4-decade programmable counter
IC4—CD4518BC CMOS dual-synchronous BCD up counter
IC5—MM74C90 CMOS 4-bit decade counter
IC6—CD4049C hex inverting buffer
IC7—LM78L05CZ 5-V, 100-mA regulator
I1—Neon pilot indicator with integral series resistor
Q1, Q2—2N3904 npn silicon switching transistor
Q3, Q4—2N3055 npn silicon power transistor
The following are ½-watt, 5% tolerance, carbon-composition fixed resistors.
R1—22 MΩ
R2—10 kΩ
R3—2.2 kΩ
R4 through R16—100 kΩ
R17, R18—150 Ω
R19—47 Ω
S1, S2, S3—Ten-position thumbwheel switch with BCD outputs
S4—Spst toggle switch (not needed if optional line-powered supply is built)
S5*—Spst toggle switch
SO1—Ac power socket
T1—20-V, 1.5-A, center-tapped transformer (Signal Transformer Co. No. 241-6-20 or equivalent)
T2*—25-V, 3-A, center-tapped transformer
XTAL—3.579545-MHz quartz crystal
Misc.—Heat sink, mica insulators, silicone thermal compound, IC sockets or Molex Soldercons, printed-circuit board, suitable enclosure, fuseholder*, pc-mount fuse clips, line cord*, strain relief, power cable, heavy-duty alligator clips (used only if optional line-powered supply is not built), ac power plug*, hookup wire, hardware, solder, etc.

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where appropriate. Make sure to install trimmer capacitor *C3* with the pin connected to the rotor plate and the adjustment screw soldered to the ground foil at the edge of the pc board. Before installing *C5*, double-check that it is a tantalum capacitor—not an aluminum electrolytic.

Next, mount quartz crystal *XTAL*. It might be necessary to drill another hole in the pc board to accommodate one of the crystal's pins. There are many such crystals on the market, and not all have the same pin spacing. Then install regulator *IC7* and transistors *Q1* and *Q2*, making certain their leads are oriented correctly. Use of transistor sockets at these three locations is optional, but will simplify replacement in the event of device failure. Mount copper fuse clips for *F1* and, when they have cooled, snap in the fuse. Install diode *D1* so that its polarity is correct. Finally, mount the fixed resistors on the board.

The remaining components mount off the board and are connected to it by means of flexible, stranded hookup wire or by the attached leads (*T1*, for example). Thumbwheel switches *S1*, *S2* and *S3* are best connected to the pc board using suitable lengths of multiconductor ribbon cable.

When all leads and wires have been soldered to the appropriate pc foil pads, the board should be installed in the project enclosure using standoffs. If a metallic enclosure is used (and this is recommended), it will probably not be necessary to employ heat sinks for power transistors *Q3* and *Q4*. They can be bolted directly to the enclosure using suitable hardware, mica insulating washers, and silicone thermal compound. After the transistors are fixed in place, the leads running from the pc board can be soldered to the appropriate transistor leads. Remember to keep the case or tab of the power transistors isolated electrically from the project enclosure if it is metallic or from any heat sink that is used.

Secure transformer *T1* and power socket *SO1* firmly in place inside the project enclosure. Install a strain relief on the enclosure where the dc power cable leaves it. Connecting large color-coded alligator clips to the free ends of these leads will ease connection to a 12-volt battery.

Checkout and Operation. First, plug the device to be controlled into *SO1*. An electric clock is a good test load. Always remember to connect the device to be controlled to the project before applying power to the project. Running the project without a load can damage *C12* or *T1*. Next, set the thumbwheel switches to read "60.0" to select an ac output frequency of exactly 60.0 Hz. Then apply power to the Programmable Speed Control. Upon closure of the power switch, the project should come to life and the clock start to run. If this isn't the case, refer to the "Troubleshooting" section. Compare the operation of the clock with another being powered by the ac line to see how accurate the frequency generated by the Programmable Speed Control is. (Note that two accurate clocks are required for this!) Change the setting of the thumbwheel switches and note how you can apparently speed up or slow down the passage of time.

The Programmable Speed Control can now be used as is or can be calibrated for more accurate output using a frequency counter. Connect the ground of an oscilloscope probe to the case of the project or to circuit ground. Then touch the "hot" side of the probe to pin 7 of *IC1*. Carefully adjust trimmer capacitor *C3* for a reading of 3.579,545 MHz. Then touch the probe to pin 4 of *IC2*, and you should read almost exactly the significant digits of the setting of the thumbwheel switches. For example, if the switches are set for 60.1 Hz, you should read 60.101 kHz. That completes the calibration. It's an optional, but useful step. Uncalibrated, you can expect the project to be accurate to within ±0.01% with the rotor of trimmer *C3* set to midposition. For many applications, that's good enough.

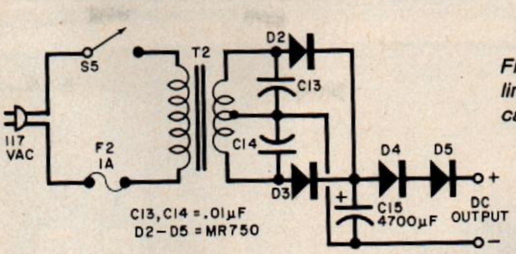
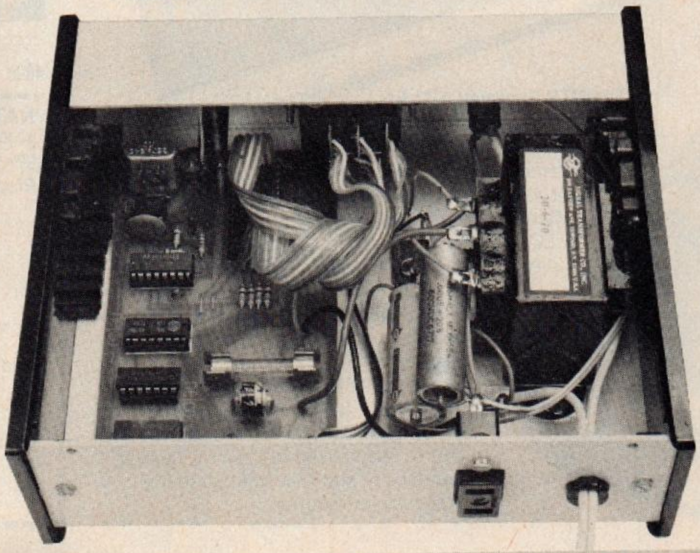


Fig. 3. Schematic diagram of a line-powered supply that can be used with the project.

Troubleshooting. Here's a simple procedure you can use to troubleshoot the project. A multimeter and a counter are needed. First, note whether the fuse blows. If it does, disconnect the wire running to board location *CT*. This should stop the fuse from blowing, and reduce the current drain from the dc source to approximately 30 mA.

Measure the voltage on pin 16 of *IC2*. If it is not +5 volts ±5%, suspect *IC7* or the presence of inadvertently created shorts. When the correct reading is obtained, use the counter to measure the frequency at pin 1 of *IC1*. You should read 100 Hz. If you measure 60 Hz and can't obtain the desired ac output frequency, chances are you've used the wrong version of the MM5369! Replace it with the EST-suffix version specified in the parts list. When you've obtained the desired 100-Hz reading, move the counter probe to pin 4 of *IC2* and set thumbwheel switches to read "55.5". The counter should read

Photo of the interior of the author's prototype.



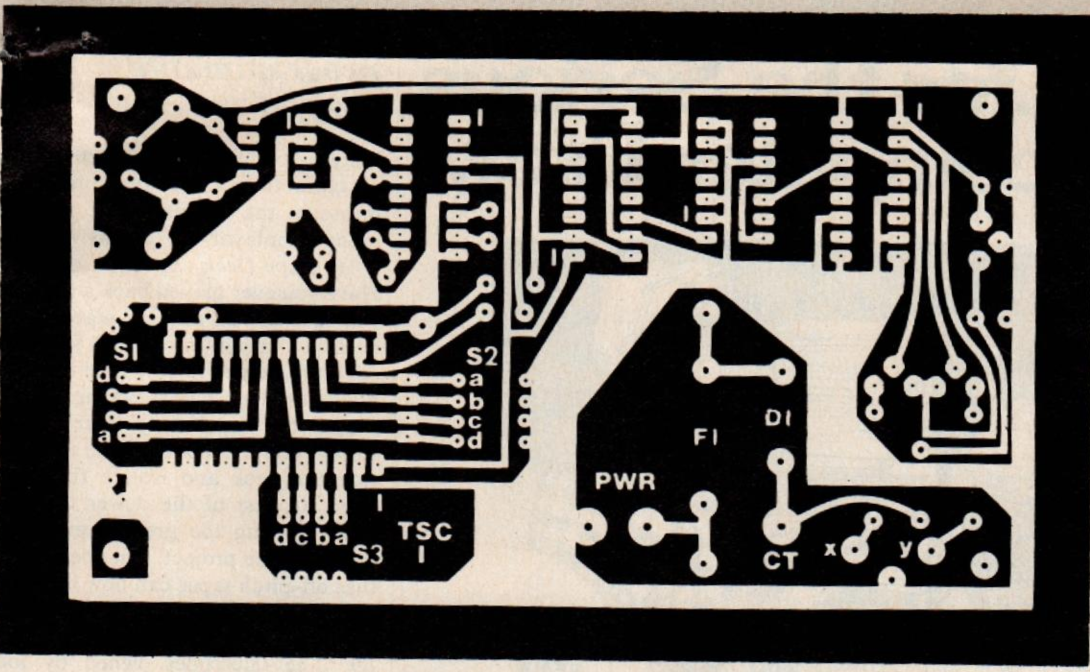


Fig. 4. Etching and drilling guide for a printed-circuit board for the project.

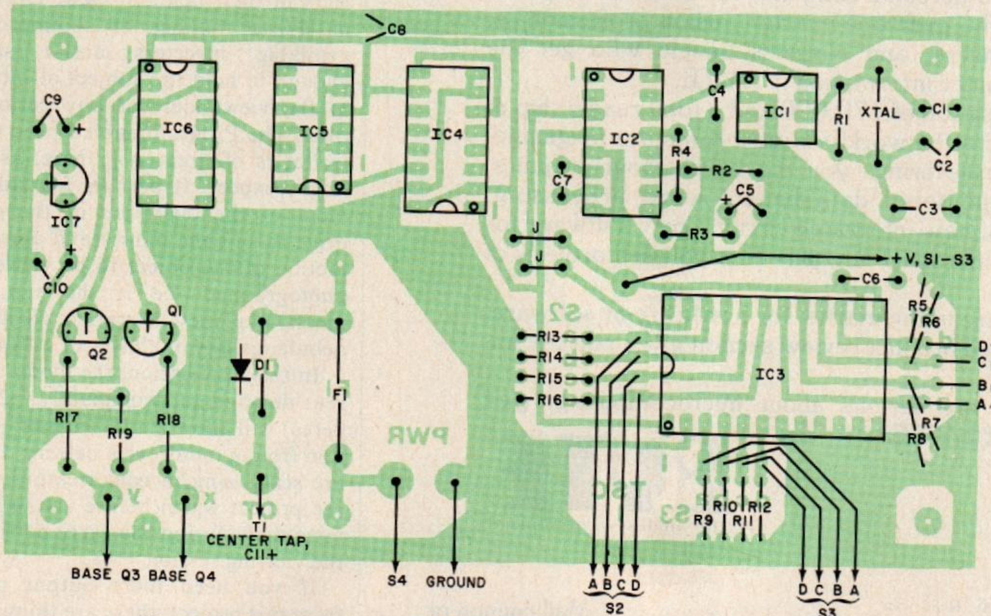


Fig. 5. Use this guide to assemble the components on the printed-circuit board.

55.500 kHz. If not, check *IC2* and its associated components. Then switch to "60.0." You should read 60.000 kHz. Obtaining any other frequency means that the thumbwheel switches may be miswired or that counter *IC3* is defective.

Once the desired 55.5 Hz is obtained, shift the probe to pin 15 of *IC6*—the reading should be 55.5 Hz. If it is not, *IC6*, *IC5*, and *IC4* are suspect. There should also be 55.5 Hz present at pin 2 of *IC6*, so check it out. At this point, the only problems remaining on the board can be a defective or incorrectly installed transistor at *Q1* or *Q2*. If these components are operating correctly, the problem lies in the off-board section of the project—most likely in *Q3*, *Q4*, or *T1*.

Applications. There are many different applications for this project. Let's detail the few mentioned earlier. Doubtlessly, you'll be able to come up with ones of your own.

A Turntable Speed Controller. The Programmable Speed Control was originally designed for this application, so I have many application hints to offer. First, if your turntable has an incandescent pilot lamp wired in series with the motor like my Empire unit, remove it. The lamp reduces the current flowing through the motor and thus its torque. You'll find that the turntable platter comes up to speed more quickly. Besides changing the turntable speed to correct for off-speed recordings, this project can be used in portable applications.

On the other hand, if you have damaged 78-rpm records that you want to copy on tape, this project can be very helpful. As you might already know, warped 78s will often play at reduced speeds. That's the key to success here. Set your turntable to 45 rpm and the Programmable Speed Control to 50.0 Hz. Then record the music using a tape recorder running at 3¾ ips. When the recording has been completed, play the tape back at 7½ ips, and you'll hear the program material being played at normal speed or close to it. Use an equalizer to improve the sound. I've salvaged many "unplayable" 78s this way.

A Tape-Deck Speed Controller. Have you ever played back a tape that was recorded on another machine and noticed a speed difference? This project can compensate for this if the playback deck has a synchronous ac motor that requires no more than 15 watts. You'll probably have to dig inside the deck and isolate the motor from the rest of the power wiring to avoid placing too great a power demand on the project. But the result is that off-pitch tapes can now be played so that they sound right!

A Telescope Clock-Drive Controller. The telescopes owned by most amateur astronomers use synchronous ac motors to keep astronomical objects in their fields of view. Unfortunately, a number of commercially available inverters aren't stable enough to hold the subject of interest in the viewfinder for any period of time. The Programmable Speed Controller is of great help here, as you might expect. It permits fine adjustment of the operation of the clock drive to suit the nature and apparent motion of the object to be viewed or photographed—be it the sun, the moon, a planet, a star, a cluster, a nebula, galaxy or cluster of galaxies.

In this application, the modest current demand (approximately 1.2 amperes) will allow many hours of operation from a motorcycle battery. If you are stargazing in cold weather, keep the project warm before use to minimize drift during the early portion of the viewing session.

If you need more output power from this project, there are things that you can do. A slight increase can be had by decreasing the values of *R17* and *R18*. Right now they provide approximately 25 mA of base drive to power transistors *Q3* and *Q4*. However, don't exceed a dc current drain of 1.5 amperes from the power source or you'll overload *T1*. A heavier-duty transformer can replace the device specified as *T1*—it is a 20-volt, center-tapped transformer rated to handle 1.5 amperes of secondary current. You might use a 12.6-volt, center-tapped, 10-ampere unit and four power transistors (two each connected in parallel using current-balancing resistors) for increased output. It is possible to get up to 100 watts this way. Be sure to use heavy wire for the power cable and transistor wiring if this approach is taken. ◇