

to each board through a connector that is mounted on the bottom of the board and projects through the rear of the unit. Each line input first passes through a line filter. The first section of the filter is a common-mode choke, which attenuates EMI generated by the 14570A as well as noise generated by the devices being controlled. The second section contains a normal-mode filter and a pair of metal-oxide varistors. These components limit the magnitude of line spikes to less than 750 volts peak and reduce the rate of rise to less than 75 volts per microsecond. This relatively clean power is then distributed to the devices being controlled. The filtered power is also routed to a bias supply that is used to operate the timing circuits and to drive the relays and SCRs.

The 14570A turn-on cycle begins when an external logic signal is received for a channel to turn on. This signal goes through a digital delay circuit that filters out glitches shorter than two milliseconds. The logic circuit waits until one millisecond before the next positive transition of the ac line. The SCR is then given gate current and the relay coil is energized. The SCR is reverse-biased for a millisecond while the line is negative. As soon as the line goes positive, the SCR conducts. The SCR gate current is derived from a separate bias supply and does not flow through the load. A few milliseconds later, the relay contacts close and the relay takes the burden of the line current from the SCR. The SCR turns on and off every time the relay bounces, so the relay only has to switch the voltage drop in the SCR circuit. After the first half line cycle the gate current is removed from the SCR.

The turn-off sequence is nearly the reverse of turn-on. When the external command is received to turn the channel off, the logic signal is deglitched. Just before the next positive line peak, the SCR receives gate current and the relay coil is deenergized. A few milliseconds later, the relay contacts open and the SCR carries the line current until the SCR ceases to conduct at about zero current. When the relay opens, there is almost none of the destructive arcing that usually occurs when a relay opens, because it only has to break the low forward voltage of the SCR. The gate current is removed just after the line voltage goes to zero.

There were several reasons for choosing an SCR over a triac for the solid-state switching element. SCRs are generally more rugged; they will withstand greater di/dt and overcurrent. Because SCRs are unidirectional, they can be given gate current while the ac line is still negative and only a few milliamperes of parasitic remote base transistor current will flow. When the line forward-biases it, the SCR will start conducting immediately, giving zero-voltage turn-on. This eases the timing requirements on the solid-state device. To make the SCR even more immune to failure, it has a 0.5-ohm resistor and a 1-microhenry inductor in series with it. The resistor limits the peak current that the SCR will see under fault conditions, while the inductor limits di/dt to a value that the SCR can safely withstand. Since the SCR, the series resistor, and the series inductor conduct for only brief periods, the impedance of the protection network can be relatively large to afford the necessary protection, while the average power dissipated is very small in comparison to the peak.

Load Types

Having chosen an SCR for the switching device, there are some restrictions on the type of load to be switched, and on the operate and release time of the relay. The circuit described works for any type of load at turn-on. Any resistive, capacitive, or inductive load has zero current at turn-on if the line voltage is zero. It is only after the load has been on that the line current starts to lead or lag the voltage. At turn-off, for the SCR to conduct, both the voltage and the current must be positive. For a purely inductive load, the earliest that this happens in a given cycle is just after the line has hit its peak and the current is just starting to go positive. For a capacitive load, this point is when the line is just starting to go positive and the load current is at its peak. Inductive and capacitive currents are 180 degrees out of phase and the turn-off circuit can not effectively work under both sets of conditions.

It was decided to have the turn-off circuit optimized for inductive loads. This includes motors, solenoids, and similar types of loads. This timing is also suitable for resistive loads, since the relay can turn off in less than one-fourth cycle. This includes nonlinear resistive loads such as heaters or tungsten loads. Another common type of load is power supplies. Switching power supplies might seem to be capacitive, but a little analysis shows that they are not. At turn-on, they present almost a short circuit while the filter capacitors are being charged. This requires a switch that can withstand high surge currents, such as a 14570A. After one line cycle, the input capacitors are charged and look more like a battery load, drawing current only during that part of the line cycle when the line voltage is greater than the capacitor voltage. This time depends on the amount of droop that the input capacitors have. A circuit composed of rectifiers and capacitors (the input to a typical switching power supply) does not have a leading power factor. Putting a transformer in front of this (the input to a typical linear supply) makes little difference.

Because the load current starts to lead in the case of a capacitive load, the relay has to turn off faster to ensure that the load current has not gone negative before the relay contacts open. In practice, the 14570A is capable of handling a leading power factor of about 0.8. A capacitor-start motor may have a leading power factor at start-up; however, while running it is inductive and the 14570A has no problem turning it off. The 14570A is not recommended for this application.

Relay Considerations

With these constraints, the relay characteristics were established. The relay must operate in less than one-half ac line cycle and release in less than one-fourth cycle. The relays investigated would do this, but with little time to spare. It was found that by operating the relays at a higher-than-nominal potential, pull-in could be speeded up considerably. This had the undesirable effect of slowing their release time because of increased energy stored in the relay coil. This approach also made them less reliable because of increased power dissipation.

The solution is to charge a small capacitor up to twice the nominal voltage of the relay. This charge is used to switch the relay rapidly, while the current to hold the relay is

Testing the 14570A

The production test set for the 14570A checks all the normally tested parameters, such as high and low line operation, off-state leakage current, and isolation. In addition, it checks the operate and release time on each relay in the working unit. This is done by observing the voltage drop across the relay. Since the SCR has about a 1.6-volt drop and the relay drop is only a few hundred millivolts, it is very easy to distinguish between relay conduction and SCR conduction. It is also easy to see the relay contacts bouncing, when the SCR and relay are alternately conducting. A typical trace is shown in Fig. 1.

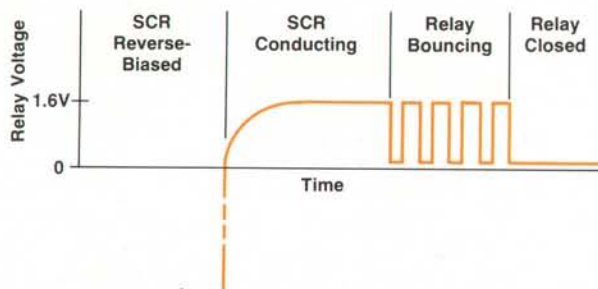


Fig. 1. Typical voltage waveform across one of the 14570A's relays during turn-on.

To check relay operate and bounce times it is only necessary to see if the voltage drop across the closed switch is above or below one volt. When it is above one volt, the SCR is conducting. When it is below one volt, the relay contacts are closed. The one-volt threshold can be raised to two volts to check whether the forward drop of the SCR is within limits.

A block diagram of the 6942A Multiprogrammer system designed to measure the timing and the voltage drops of the switch is shown in Fig. 2. The 69771A Digital Input card has an



Fig. 3. Photograph of the production test system.

analog comparator for each of its 16 inputs. The reference voltage for these comparators is derived from a 69720A Digital-to-Analog Converter (DAC) card. For instance, if the DAC card is set to one volt, the output of the digital input card will follow the position of the relay contacts. With five-microsecond response time, the 69771A is able to follow very fast bounces. The 69790A Memory card is connected to the input card, so that up to 4095 sequential readings can be taken on the state of the 12 relays. A 69735A Pulse Train Output card is connected to the handshake lines of the memory card. This is used to pace the readings taken by the memory card. The pulse train card is set to provide 4095 pulses with a period of 10 microseconds, allowing over 40 milliseconds of

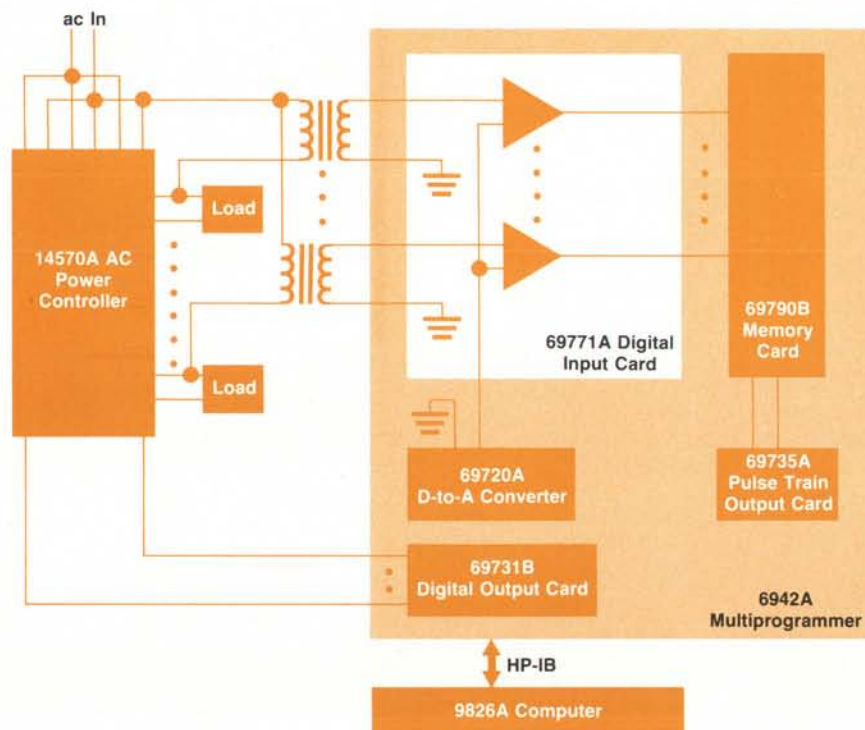


Fig. 2. This system is used for production testing of the 14570A AC Power Controller. Another 14570A switches ac power to the unit under test.

data to be stored. The pulse train card is triggered when all the channels on the 14570A are programmed to close.

After 4095 data points have been acquired, they are sent to the HP 9826A Desktop Computer for analysis. Transitions on the 12 channels are found by comparing each data point with the previous one. If it is the same, then no transition occurred during that ten-microsecond interval. If any data point is different from the previous one, the twelve bits are EXCLUSIVE-ORed with the last point to determine which bits are different. When the times of the transitions are known, it is a simple task to calculate the operate and bounce times for each relay. This method calculates these values for the 12 relays simultaneously, using a single set of

hardware.

Since we were concerned with operator safety, we wanted to turn the power off when the unit under test was being connected to the ac line or removed from it. It was also necessary to connect the unit to either 115 or 230 volts. For the first time in the history of our lab, it was not necessary to build a special box to control the ac power. The 14570A is used to test the 14570A. One section of the 14570A is set for 115-volt operation and a second section is set for 230 volts. Thus, it is possible to select either 115 or 230 volts under program control.

Fig. 3 shows the 14570A test set.

drawn through a series resistor. The resistor has a value that allows the relay to remain energized with less current than it needs to operate. The lower current means that there are fewer watt-seconds of energy stored in the coil. The initial energizing current forced by the high operating voltage is well within the rated surge current for the coil. Even with the increased operate current, the reduced holding current brings the average power in the coil to less than the rated power. In addition, the circuit has a Zener protection diode across the drive transistor instead of the usual flyback diode across the relay coil. The smaller amount of energy stored in the coil, in conjunction with the higher flyback voltage for the coil, greatly speeds up the release time. With these measures, it was possible to make the relay operate reliably in less than one-fourth line cycle and release in less than one-eighth line cycle.

Safety Considerations

The 14570A is designed to meet the safety requirements of UL 1092, CSA 584A, IEC 348, ANSIC39.5, VDE 0411, and the HP product safety manual. One major safety problem that was overcome was meeting the physical spacing requirements. There are three places that require isolation: across the bias transformer, from coil to contacts on each relay, and from the gating circuit to the SCR.

The bias transformer is of a split-bobbin construction. A rib, molded into the bobbin between the primary and the secondary of the transformer, makes it easier to obtain the required physical separation. The relay chosen has an eight-millimeter separation from coil to contacts. The SCR isolation could have been handled with an optoisolator. This would have required either stealing the gate current from the load and not having zero-current turn-on as in the conventional solid-state relays, or putting in another isolated supply to provide gate current. Even though most optoisolators have sufficient breakdown voltage, they do not provide very much physical separation between the emitter and the detector. This can be a problem if there is a fault in either the emitter or the detector that causes the optoisolator to overheat. This failure can result in destruction of the thin insulation between the circuits that are supposed to be isolated. This failure mode would connect the ac line to the logic circuits. A further problem with optoisolators is that a failure in the gating logic can cause the SCR to become stuck in the on position. This would result in feeding half-wave dc to the load. This could damage certain loads, such as an ac motor. The solution to the

optoisolator problem was to use a split-bobbin pulse transformer similar in construction to the power transformer. This provides physical separation between the logic circuits and the ac line. If there should be a failure in the logic circuits, the pulse transformer saturates and no more gate current flows.

Connectors

The power connections to the 14570A posed a problem. The initial solution was a barrier block, but this had many problems. Safety covers that are not permanently attached are frequently discarded, and a way to make them captive eluded our best mechanical designer. We felt that all the input and output cables required strain relief, but fifteen cable clamps on the rear of the unit made wiring very difficult and required a 5-inch-high box to accommodate them. Screw connections made wiring in the rack inconvenient, and changes in field wiring were time-consuming. The idea of using standard ac plugs and receptacles was rejected because the product is designed for 120 or 240-volt operation.

The connector that was finally selected has many advantages (Fig. 4). Both male and female connectors have their mating surfaces and the screws for tightening the connections recessed from touch. Each connector has built-in strain relief. The center ground pins are longer, so they make contact first. The connector was easily adapted for circuit board mounting. The fact that the connector can be assembled to the field wiring outside the rack permits easy assembly and simplifies later modifications.

Applications

To ship more reliable equipment and keep warranty costs down, many vendors have instituted a burn-in policy. The equipment is run from a few hours to several weeks so that early failures occur before the equipment is shipped. However, it is costly to tie up inventory and pay the electric bill for the burn-in procedure. To reduce these costs, the same amount of stress can be induced by cycling the equipment. The cycles can be timed on-off cycles or a combination of time and temperature cycling. The latter method produces more stress in a shorter period. The 14570A, an HP-85 Computer, and a 6940B Multiprogrammer are ideally suited for this application. For small installations, a 14750A could be driven directly from a 16-bit GP-IO interface installed in an HP 9915A Modular Computer.

When a computer is used to control ac power, there are