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# Applications of Digital and Optoelectronic Circuits to Electrothermal-Chemical Gun System Facilities

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Electrothermal-chemical (ETC) gun systems require highly specialized control and diagnostics hardware due to their extraordinary electrical pulsed-power requirements. Specifically, the initial electrical energy level of the power supply should be measurable and the means for operators to safely control high-voltage equipment must be available. As a result, several control systems needed to perform the stated functions have been studied, developed, and experimentally proven in the ETC gun facilities of the Army Research Laboratory. One recent experimental program involving a Navy-owned 60-mm ETC gun relied heavily upon some of the techniques which are introduced here. Problems associated with laboratory operations lacking appropriate hardware are addressed and the fundamental behavior of the control systems investigated are described.

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TABLE OF CONTENTS

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## LIST OF FIGURES

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## 1. INTRODUCTION

The use of digital electronic and optical electronic circuits for controlling various aspects of pulse-forming networks (PFNs) in electrothermal-chemical (ETC) gun facilities at the U.S. Army Research Laboratory (ARL) are described. A design of a digital sample and hold circuit used to retain, in digital memory, the initial voltage (and energy) of PFNs is considered. In addition, various uses of optical electronic circuits to control PFN safety network function, amplifier operations, and power supply switching are described.

## 2. BACKGROUND

ETC gun systems are a novel propulsion concept that requires the injection of an electrical plasma into a propellant chamber to initiate and perhaps control the interior ballistic combustion process. The plasma is generated in a specialized chamber that consists of a small diameter fuse wire connecting the output terminals of a PFN. The plasma is intended to interact with stored propellant in the adjacent combustion chamber of the gun. The typical ETC laboratory system consists of several major subsystems, including a high-voltage power supply, PFN, switches, high-power coaxial cable, plasma cartridge, working fluid chamber, and a gun tube. The Weapons Technology Directorate (WTD) of the ARL employs several pulsed-power facilities in support of ETC (and electromagnetic) gun technology. All such facilities incorporate capacitor-based, PFNs that are typical of the configuration shown in Figure 1. These networks discharge through high-power switches in a very short time frame (1-4 ms typically). The capacitors in this circuit have an electric charge placed on their terminals with an external dc power supply. Typically, systems operate at a maximum initial voltage of about 10–20 kV. Usually, this correlates to initial PFN energy levels in the range of hundreds of kilojoules or more. The PFN discharge and resulting plasma are initiated by the closure of the circuit switches which begins the flow of electrical current to the fuse wire located in the plasma gun chamber. More technical details of the PFN can be found in other publications (Bunte et al. 1991; Pfenning et al. 1991; Katulka et al. 1991; Zielinski and Renaud 1992; Powell and Zielinski 1992; Hummer et al. 1992). The electrical plasma is formed on the inside of a cylindrical cartridge which is in the form of a polyethylene capillary. As power from the PFN continues to feed the plasma, there is a tremendous increase in the temperature and internal pressure of the cartridge. Due to the large pressure gradient, plasma is ejected from the nozzle at the muzzle end of the capillary into the working fluid chamber where the combustion process is initiated. It is important to note,

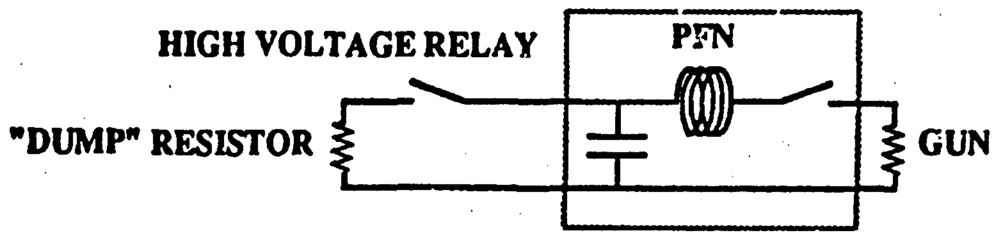



Figure 1. Diagram of typical ETC PFN with safety network in place.

however, that the initial energy of the system is equal to one half the total capacitance multiplied by the square of the initial capacitor voltage. This relation is shown in Equation 1.

$$E = 1/2 * C * V^2 \tag{1}$$

Also, it has been demonstrated by Tran and Wren of the ARL that total plasma-dissipated energy and mass are most sensitive to changes in initial capacitor voltage (Tran and Wren 1992). For these reasons, it is very desirable to know the initial capacitor voltage of the PFN to a high degree of accuracy. A technique that accomplishes this through the use of standard digital voltmeters and a triggerable latching circuit, which was designed at the ARL, is described within.

Another concern in the ETC laboratory is that of electrical isolation of personnel and equipment. Electrical isolation is a serious problem due to the very high electric potentials involved in operating PFNs for ETC applications. Most PFNs are capable of delivering very large amounts of electrical energy in a short time. Consequently, a tremendous peak power capability is inherently built into the ETC facility. With this in mind, it is important to utilize control systems for PFN operations that will allow for safe control of the PFN components with respect to electrical hazards. One obvious choice for electrical isolation of PFN controls is in the use of optical electronics and fiber optic transmission links. The design of a particular optoelectronic circuit used for PFN safety relay control is described here. For this application, PFN relays are used as a means for discharging initially charged PFN capacitors to a safety network that will bleed off the stored energy over a longer time frame (see Figure 1). Such a situation will occur if it is decided to abort the gun firing after the PFN is energized. In this case, the alternate safety resistors or "dump" resistors are used to dissipate the initial PFN energy. The resistors are switched into the PFN capacitor circuit via the deactivation of the high-voltage relays, which are of the normally closed type (i.e., shorted when deactivated). The method of controlling the safety relay through an optical control circuit is also described. Finally, it is explained how components such as uninterruptible power supplies and charge amplifiers can be controlled with similar optoelectronic approaches. These methods will alleviate the problem of operators contacting high-voltage (and possibly high-energy) devices while working with the PFNs.

## 3. DIGITAL SAMPLE AND HOLD CIRCUIT

For simplicity, Protek Model D-990 digital volt-ohm meters (DVOM) are used to measure initial capacitor voltage in the PFN circuit. These meters are convenient since they already contain an analog-to-digital (A/D) converter, a bar graph-integrated circuit, a 3.5-digit, seven-segment display, and are of a reasonable cost. In the schematic diagram (Figure 2), it can be seen that when pin No. 57 is of a low state (i.e., grounded through manual switch s3), the A/D converter is placed in a memory or a "hold" mode.

In this state, the meter retains the last digital information that was sampled by the A/D prior to the closure of switch s3. For this application, the A/D converters are used to sample (at a rate of two times per second) the initial PFN capacitor voltage as measured through a 1000:1 voltage divider (Fluke Model No. 80k). The instant the PFN begins to discharge to the circuit load, the converter must be transferred to the hold mode by the actuation of switch s3. In this manner, the voltage of the PFN just prior to discharge will be retained in the memory of the DVOM. To accomplish the automatic closure of switch s3 on the event initiation (i.e., PFN discharge), a TTL circuit was designed to provide power to a mechanical relay which takes the place of switch s3 (see Figure 3). The circuit consists of a set-reset (SR) latch (chip No. 4013), a 2N2222 NPN bipolar junction transistor, an LM44B00 magnetic relay, a 12-V power supply, and several 1/4-W resistors.

The SR latch, a memory logic chip used to store binary information in digital systems, is used here as a temporary memory that can be set or reset depending upon the condition desired. In Figure 4, information is provided for a typical SR latch including the logic diagram, symbol, and the truth table. When the latch is set, pin No. 6 in an active high state, and pin No. 2 (Q bar) output is in an active low

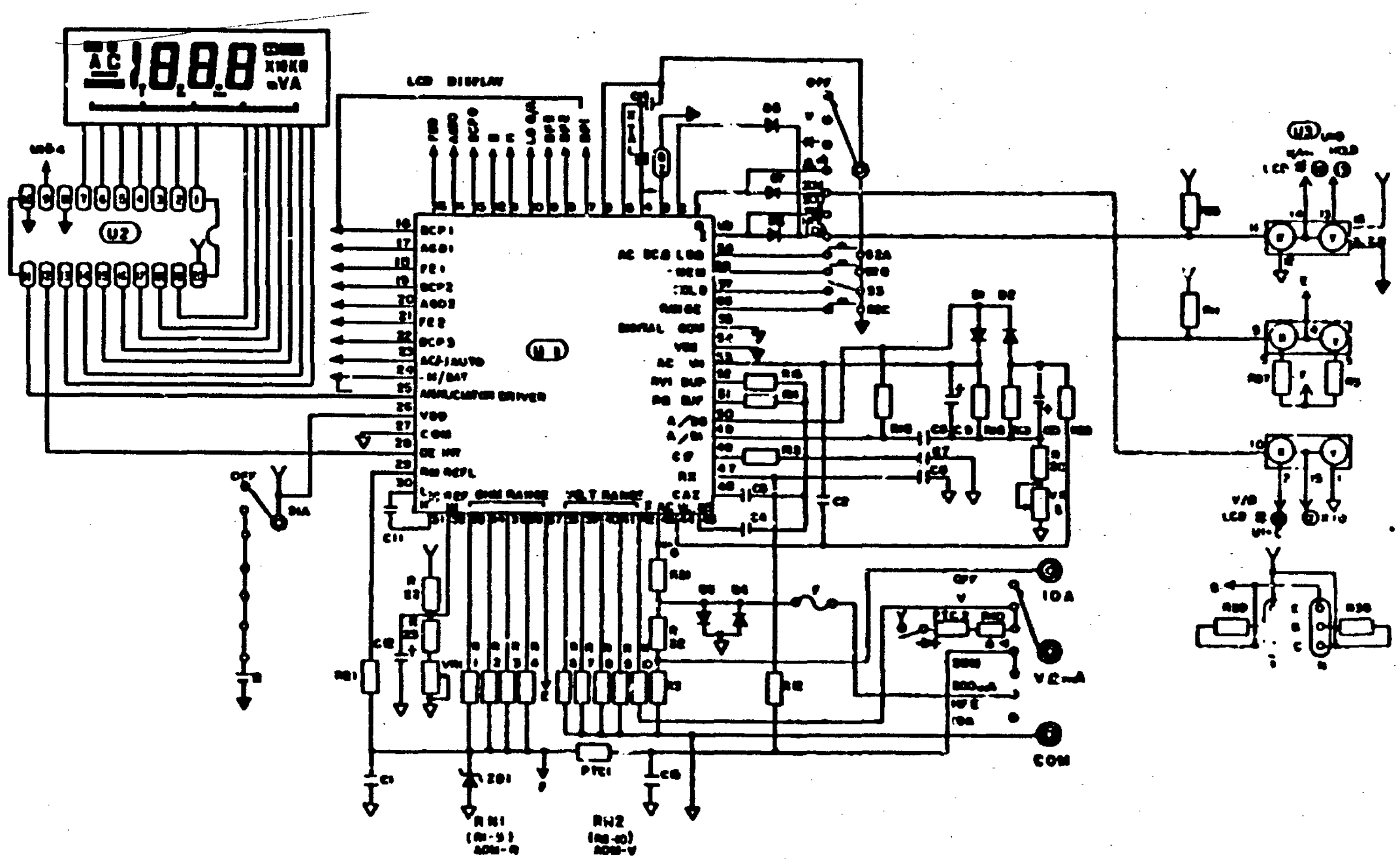



Figure 2. Schematic diagram of Protek Model D-990 digital multimeter.

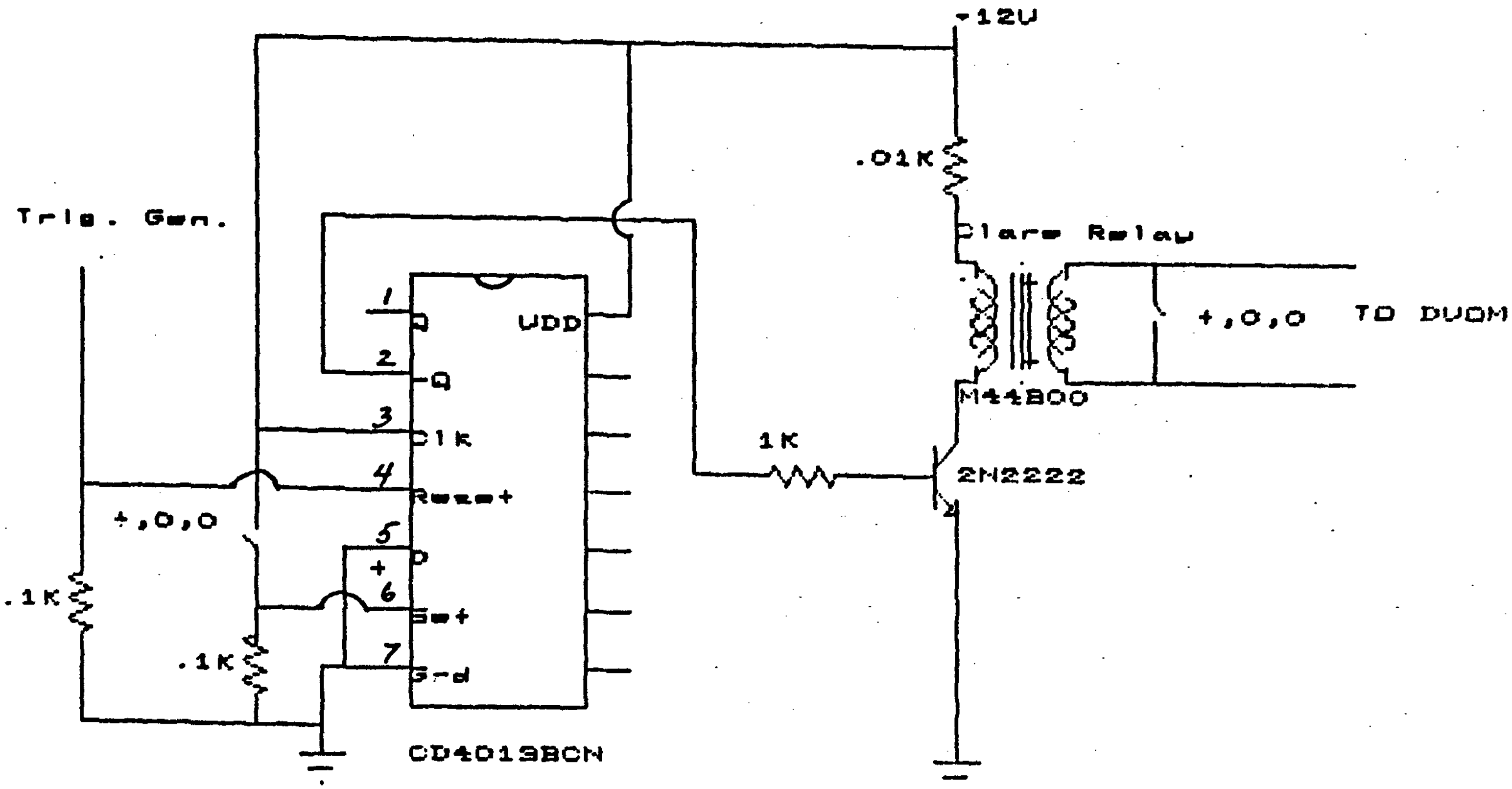



Figure 3. Diagram of digital latching network.

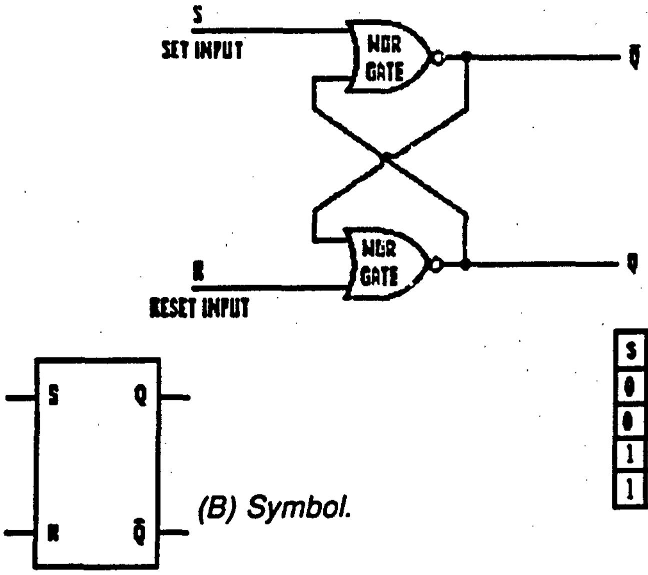
state (see Figure 4). In this condition, the base of the NPN transistor is not drawing any current; therefore, the transistor remains nonconductive. If this is true, the resistance of the transistor as seen from collector to emitter is very large and, as a result, the LM44B00 relay cannot be energized or closed. With this condition present, the DVOM A/D converter is in the sampling or "live" mode and not in a hold condition. The DVOM will remain "latched" in this mode until the state of the SR latch is changed. Changing the state of the SR latch is accomplished by providing a pulsed signal to pin No. 4 (reset) of the chip.

The pulsed signal is taken from the trigger generator normally used to close the ignitron switches of the PFN. In this situation, the change in the state of the latch and the initiation of the DVOM hold mode, correspond with the closure of the PFN ignitron switches. The end result is the storage of the PFN capacitor voltage to the memory of the DVOM fractions of a second prior to the PFN discharge. Under these conditions, operators can determine (via Equation 1, to approximately the accuracy of the voltmeters used) the initial energy of the PFN. To place the circuit in the set state, a 12-V signal is applied to pin No. 6 via a push-button switch (see Figure 3). It should be noted that the 100-ohm resistors on pins No. 4 and No. 6 are used to keep those pins in the low state when the active high signals are not applied. Without these resistors, the electric potential of the latch may float high enough to change the state from low to high. This will cause random switching of the output states of the SR latch and will ultimately cause the DVOM to switch uncontrollably from live to hold mode. It should also be mentioned that the latch Integrated Circuit (IC) chip used here can serve as either an SR or Data (D) type latch. To operate in the SR latch mode, the clock must be kept in a high state while the D input is grounded.

## 4. OPTOELECTRONIC CONTROLLERS

Electrical isolation from high-voltage components of the PFN is a very important issue when dealing with systems that store large amounts of electrical energy as described here. Optoelectronic circuits provide a great deal of isolation and are inherently safer for operator use. One application of optoelectronics to control high-voltage discharge relays of a PFN, as shown in Figure 5, was designed at the ARL. In this arrangement, the optical circuit is used to activate, or open circuit, the PFN relays of the safety discharge network.

This system consists of a Hewlett Packard optical fiber, receiver Model 2524, transmitter Model 1523, and various other electronic components. The transmitter is made of a 660-nm light emitting diode (LED) and has a peak forward current rating of 750 mA. The receiver includes a monolithic dc-coupled, digital




| S | R | Q | $\bar{Q}$ |
|---|---|---|---|
| 0 | 0 | NO CHANGE | |
| 0 | 1 | 0 | 1 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | INVALID * | |

(C) Truth table.

* NOT USED
(UNPREDICTABLE)

Figure 4. Basic SR latch configuration: a) logic diagram; b) symbol; c) truth table.

IC receiver with an open collector Schottky output transistor. It has a maximum output current rating of 25 mA. The transmitter and receiver are displayed in Figure 6. A Schottky transistor is simply a rectifying device that contains a metal semiconductor junction (Jaeger 1988). The metal component allows electrons to move relatively unimpeded through the junction; therefore, the recombination time is quite fast (on the order of 10 ps), which makes this type of device of great value in high-speed applications (Savant et al. 1987). For this particular application, high speed is not an issue since only dc control signals are used to change the states of the digital circuitry involved. An internal pullup resistor is available for use in the receiver if desired. This feature allows the output at Pin No. 4 to remain high, or "pull up" to the power supply voltage (5-V) level when the transistor is not conducting. The transmitter and receiver are compatible with standard TTL circuitry, and a shield has been integrated into the receiver IC to provide additional, localized noise immunity. In the circuit of Figure 5, the base of the NPN transistor (2N2222) is grounded at pins No. 1 and No. 2 when the optical link is transmitting light. Electromagnetic radiation results in the movement of charge carriers through the photodiode in the optical receiver. This conduction current is amplified and applied to the base of an NPN (Schottky) transistor on the monolithically integrated receiver circuit. With current flowing to the base of the transistor, the resistance of the transistor from pin No. 2 to pin No. 1 is very small; thus, the large 2N2222 transistor

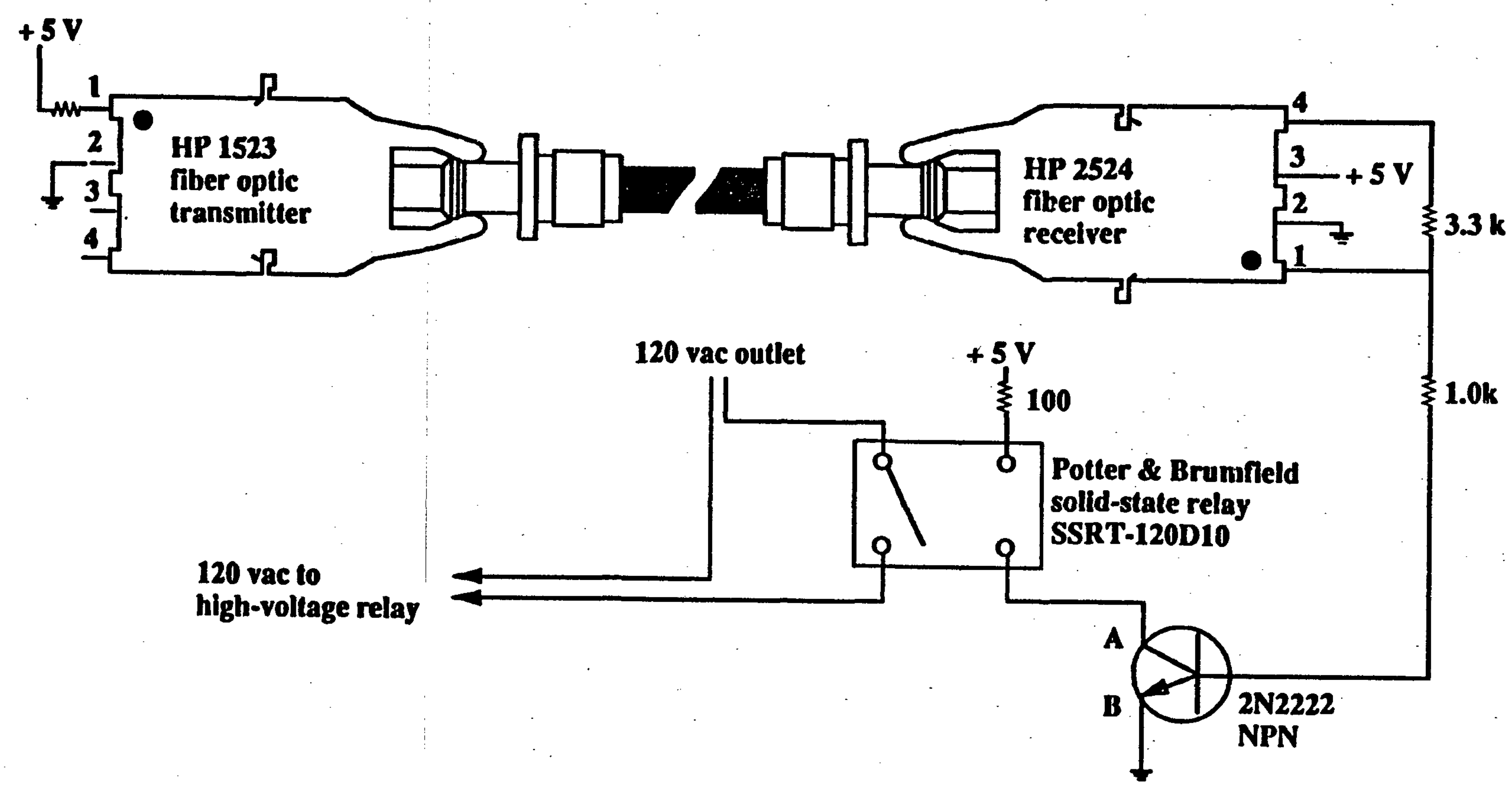



Figure 5. High-voltage relay optical control circuit.

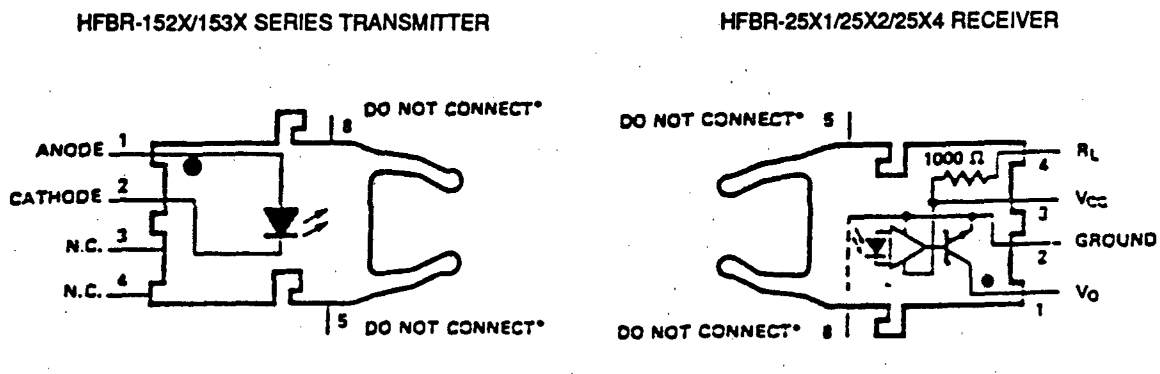



Figure 6. Hewlett-Packard optical transmitter/receiver pair (HFBR 1523/2524).

remains at zero or ground potential. In this situation, the resistance as seen from points A to B on the 2N2222 is very large. This transistor acts as an open switch that impedes the flow of current from the 5-volt power supply through the solid-state relay (Potter and Brumfield SSRT-120D10 Relay). The solid-state relay, which is now closed, connects the high-voltage relay coil to its 120-vac power supply. Under these conditions, the high-voltage relay is energized (with open terminals) and the capacitors in the PFN can now be charged via an external dc power supply. Conversely, when the optical link is not transmitting light, the Schottky transistor offers a large impedance between pins No. 2 and No. 1 on the optical receiver. This effectively switches the base of the 2N2222 transistor from ground to the 5-V power supply. Under this condition, the 2N2222 allows current to flow; thus, the sclid-state relay is energized and in an open circuit position. The solid-state relay opens or removes power from the high- voltage relay coil. This condition causes shorting of the PFN capacitors through the high-voltage relay and the dump resistors. In this condition, the PFN is in a grounded or safe mode.

For another optical control circuit design, the goal is to remotely ground and unground charge amplifiers. The diagram in Figure 7 shows the details of the system components. Dymec optical links, consisting of transmitter Model 6723 and receiver Model 6722 are needed to transmit a dc control signal

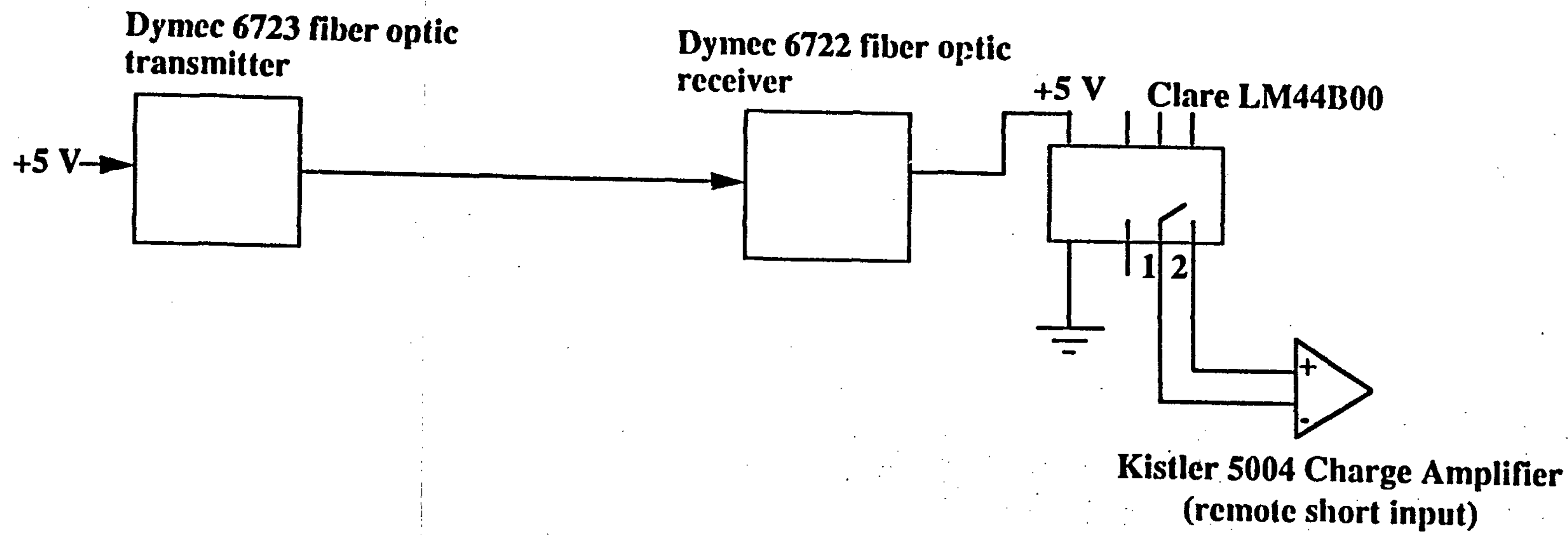



Figure 7. Charge amplifier optical control circuit.

to an LM44B00 magnetic relay. The relay is used to attach the charge amplifier to ground when a 5-V signal is applied to pins No. 1 and No. 2, as shown in the figure. Without the control signal applied, the charge amplifier is ungrounded. This system accomplishes the task of remotely preparing the charge amplifier to accept either a charge mode or a voltage mode transducer signal, and it allows the operators to stay completely clear from contacting any possible high-voltage component of the system.

A system was designed that incorporates fiber optics for remotely controlling an uninterruptible power supply (UPS). Again, the optical approach is desired here for its capability of providing an excellent degree of electrical isolation. In this application, the Dymec optical link is used to control a solid-state relay (Potter and Brumfield SSRT-120D10). This relay is used to disconnect the UPS from the 120-vac utility network, so that it will begin to operate from the internal UPS battery supply. When power is not transmitted to the relay via the optical transmitter (located in the control room), the solid-state relay is inactive and in the normally closed position. Thus, the UPS is not in the battery power mode; instead, it is operating in the line power mode (see Figure 8).

## 5. SUMMARY AND CONCLUSIONS

Several criteria were discussed that exhibit the need for various digital and optoelectronic devices in the laboratory environment of the experimental ETC diagnostics facility. One need identified is in the form of a device that can store the initial voltage measured on PFN capacitors prior to an ETC gun firing. As a result, a digital circuit was designed to accomplish this task. This particular system was designed at the ARL using a digital-memory integrated circuit chip and other electronic components. This device is currently in operation at several ETC facilities at the ARL. In addition, optical electronic circuits and fiber optic links have been designed and incorporated into the ETC facilities for purposes of remotely controlling PFN components. The addition of optical control circuits has greatly increased the electrical isolation of high-voltage components; therefore, the risk of electrical safety problems has been greatly decreased. Specific applications of optical circuits used in the ETC laboratory environment include high-voltage relays, charge amplifiers, and UPS control systems.

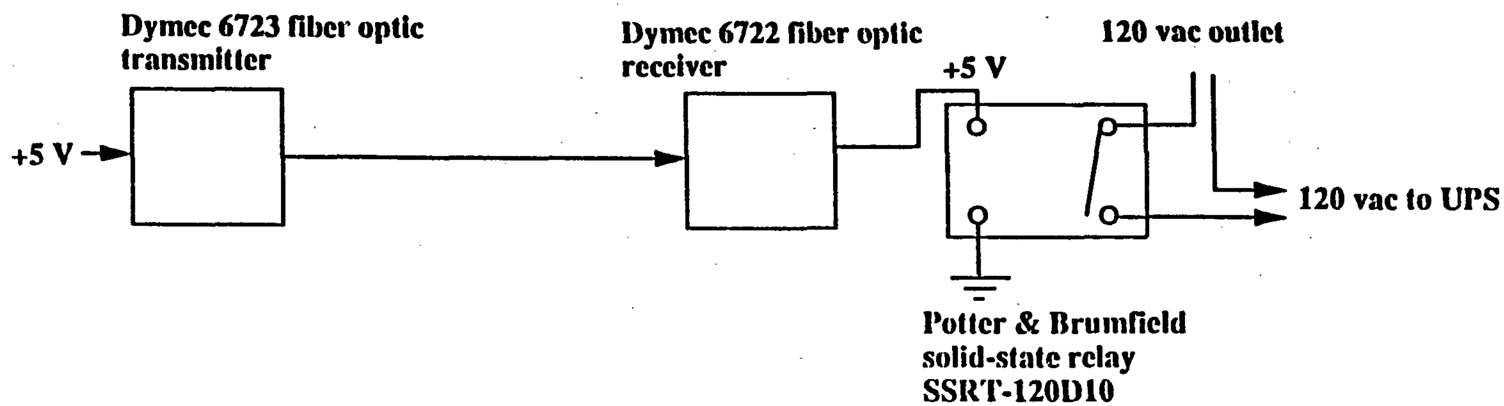



Figure 8. Uninterruptible power supply optical control circuit.

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