OPTOCOUPLER DEVICES

Learn to use optocouplers in circuits that require high electrical isolation between input and output.

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OPTOCOUPLERS OR OPTOISOLATORS have applications in many situations where signals or data must pass between two circuits, but high electrical isolation must be maintained between those circuits. Optocoupling devices are useful in changing logic levels between the circuits, blocking noise transmission from one circuit to another, isolating logic levels from AC-line voltage, and eliminating ground loops.

DC level as well as signal information can be transmitted by an optocoupler while it maintains the high electrical isolation between input and output. Optocouplers can also replace relays and transformers in many digital interfaces. Moreover, the frequency response of optocouplers is excellent in analog circuits.

Optocoupler basics.

An optocoupler consists of an infrared-emitting LED (typically made from gallium arsenide) optically coupled to a silicon photodetector (phototransistor, photodiode or other photosensitive device) in an opaque light-shielding package. Figure 1 is a cutaway view of a popular single-channel, six-pin dual-in-line-(DIP) packaged optocoupler. The IR-emitting LED or IRED emits infrared radiation in the 900- to 940-nanometer region when forward biased current flows through it. The photodetector is an NPN phototransistor sensitive in the same 900- to 940-nanometer region. Both IRED and phototransistor are in chip or die form.

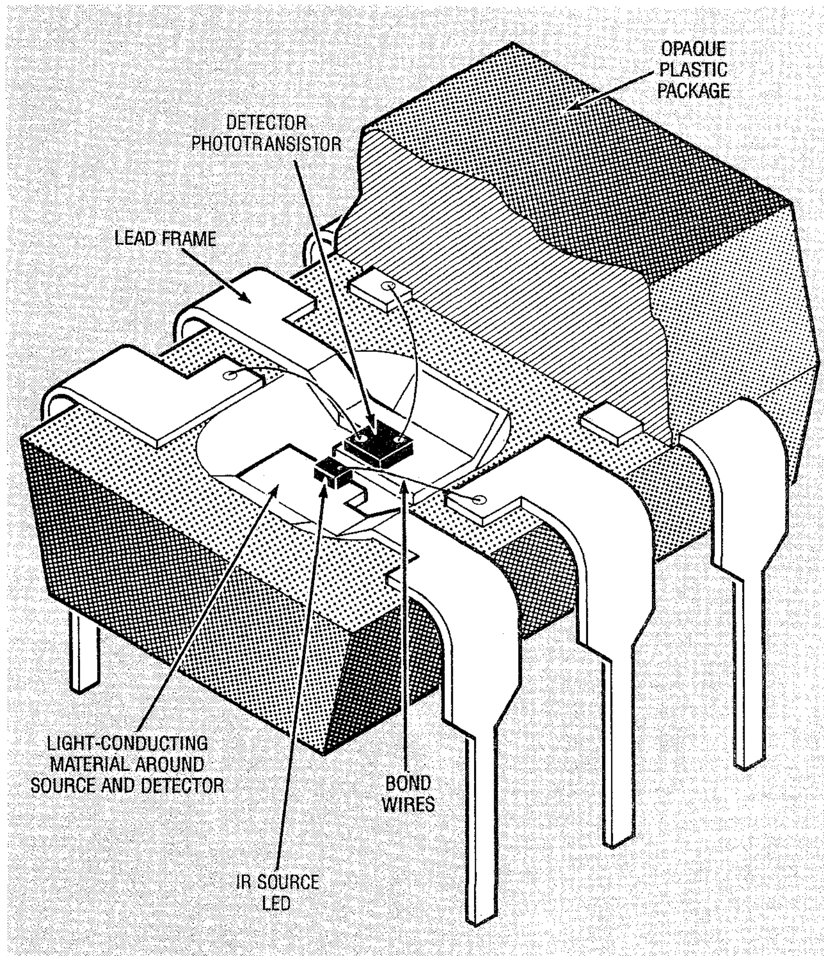

FIG. 1—CUTAWAY VIEW OF AN OPTOCOUPLER with a phototransistor output.

Most commercial optocouplers are made by mounting the IRED and phototransistor on adjacent arms of a leadframe, as shown. The leadframe is a stamping made from thin conductive sheet metal with many branch-like contours. The isolated substrates that support the device chips are formed from the inner branches, and the multiple pins of the DIP are formed from the outer branches.

After the wire bonds are made between the device dies and appropriate leadframe pins, the region around both devices is encapsulated in an IR-transparent resin that acts as a "light pipe" or optical waveguide between the devices. The assembly is then molded in opaque epoxy resin to form the DIP, and the leadframe pins are bent downward.

Figure 2 is a pin diagram of the most popular single-channel, 6-pin phototransistor optocoupler DIP. It is called an

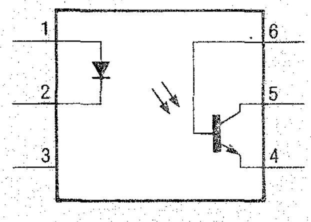

FIG. 2—TOP VIEW SCHEMATIC of a phototransistor-output optocoupler.

optocoupler because only infrared energy or photons couple the input IRED to the output phototransistor. The device is also an optoisolator because no electric current passes between the two chips; the emitter and detector are electrically insulated and isolated. These devices are also known as photocoupler or photon-coupled isolators.

The base terminal of the phototransistor is available at pin 6 on the six-pin DIP, but in normal ues it is left open-circuited. Also, no connection (NC) is made to pin 3. The phototransistor can be converted to a photodiode by shorting together base pin 6 and emitter pin 4. That option is not available in four-pin optocoupler DIP's and multi-channel optocouplers. There are, however, photodiode-output optocouplers optimized for the wider bandwidth and higher speeds needed in data communications, but they are far less efficient as couplers.

Large-volume producers of commercial optocouplers include Motorola, Sharp Electronics Corp., and Siemens Components, Inc. Optek Technology concentrates on optointerrupters and optoreflectors while Hewlett-Packard's optocouplers are focused on high-speed communications and special applications.

Optocoupler characteristics

One of the most important characteristics of the optocoupler is its light-coupling efficiency specified as current transfer ratio, CTR. That ratio is maximized by matching the IRED's IR emission spectrum closely with its detector/output device's detection spectrum. CTR is the ratio of output current to input current, at a specified bias, of an optocoupler. It is given as a percent:

$CTR = (I_{CEO})/(I_F) \times 100\%$

A CTR of 100% provides an output current of 1 milliampere for each milliampere of current to the IRED. Minimum values of CTR for a phototransistor-output optocoupler such as that shown in Figs. 1 and 2 can be expected to vary from 20 to 100 %. CTR depends on the input and output operating currents and on the phototransistor's supply voltage.

Figure 3 is a plot of phototransistor output current (I_{CB}) vs. input current (I_F) for a typical phototransistor optocoupler at a collector-to-base voltage (V_{CB}) of 10 volts.

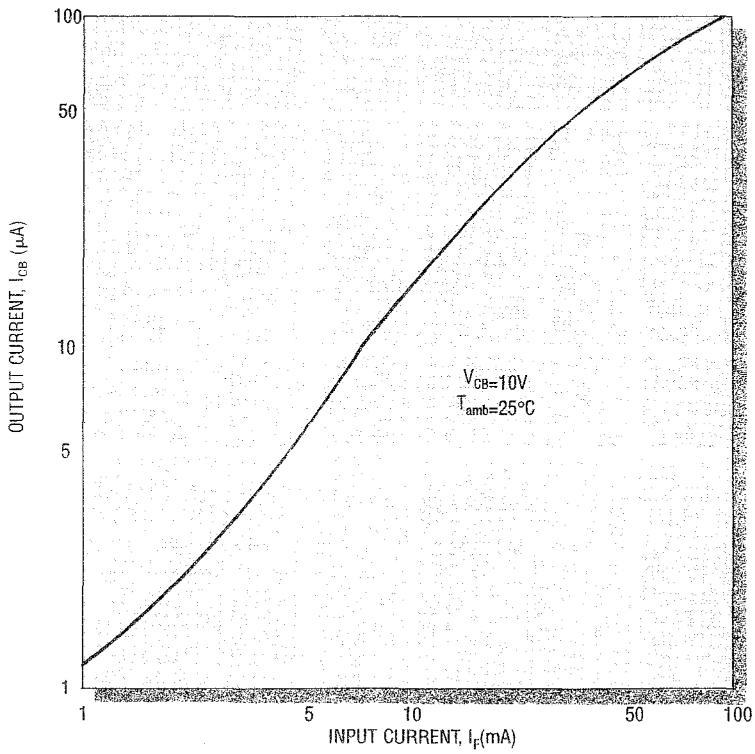

FIG. 3—TYPICAL OUTPUT CURRENT vs. input current for a phototransistor-output optocoupler with a V_{CB} of 10 volts.

Other important optocoupler specifications include:

- *Isolation voltage* (V_{ISO}). The maximum permissible AC voltage that can exist between the input and output circuits without destruction of the device. Those values typically range from 500 volts to 5 kilovolts RMS for a phototransistor-output coupler.
- V_{CE}. The maximum DC voltage permitted across the phototransistor output. Typical values for a phototransistor - output coupler range from 30 to 70 volts.
- I_F. The maximum continuous DC forward current permitted to flow in the IRED. Typical values for a phototransistor-output coupler range from 40 to 100 milliamperes.
- *Rise/fall time* for a phototransistor-output coupler is typically from 2 to 5 microseconds for both rise and fall. Those determine device bandwidth.

Industry-standards

A wide variety of optocouplers is produced by many manufacturers throughout the world. Some of the suppliers of commodity optocouplers include Motorola, Sharp Electronics, Toshiba, and Siemens. In addition to the industry standard six-pin DIP shown in Figs. 1 and 2, some transistor-output optocouplers are packaged in four-pin DIP's and surface-mount packages.

Multi-channel configurations of the popular optocouplers are also available with dual and quad emitter-detector pairs per package. Those optocouplers repeat the basic schematic of

Fig. 2 except that they lack external base pins. It is important to note, however, that certain electrical and thermal characteristics are derated in those packages because of the closer spacing of the semiconductor dies.

The lowest cost industry-standard phototransistor optocouplers with single channels have been designated by the JEDEC prefix "4N" and include the 4N25 to 4N28 and 4N35 to 4N37. However, many suppliers have developed their own proprietary parts with unusual features which are sold under their own designations. Popular phototransistor optocouplers are now available in small quantities for less than a dollar each.

Because optocouplers are used in AC-line powered circuits, they are subject to safety tests such as those of Underwriters Laboratories Inc. (UL) and Canadian Standards Assosiation (CSA). Most suppliers are offering UL-Recognized optocouplers and many make couplers that conform to the tighter Verband Deutsch Electrotechniker (VDE) specifications. Compliance with those specifications or the equivalent national specifications is a mandatory requirement for their use in Europe.

Figure 4 illustrates a simple optocoupler circuit. The conduction current of the phototransistor can be controlled by the forward bias current of the IRED although the two devices are separated. When S1 is open no current flows in the IRED so no infrared energy falls on the phototransistor, making it a virtual open-circuit with zero voltage developed across

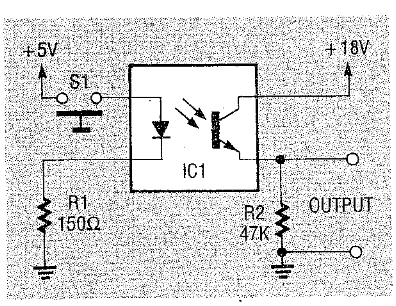

FIG. 4—CIRCUIT for phototransistor-output optocoupler.

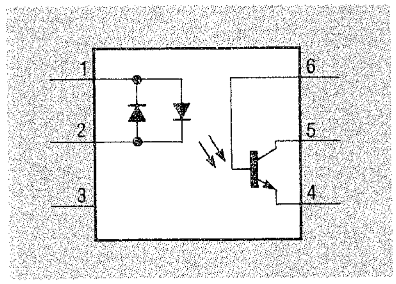

FIG. 5—AC INPUT PHOTOTRANSISTOR-output optocoupler schematic.

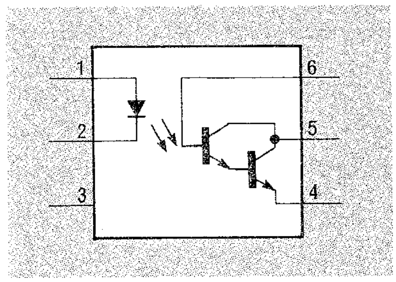

FIG. 6—PHOTODARLINGTON-OUTPUT optocoupler schematic.

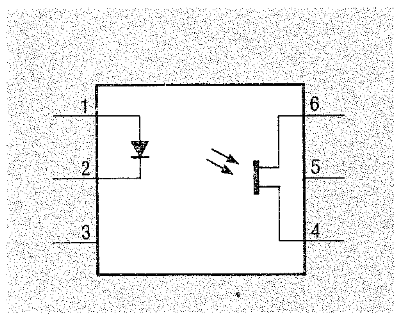

FIG. 7—BI-DIRECTIONAL LINEAR output optocoupler schematic showing MOSFET output.

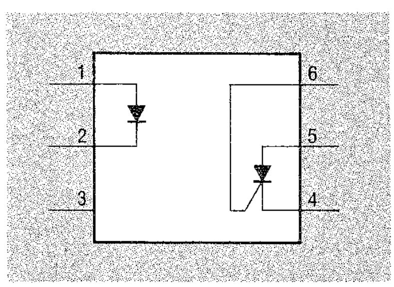

FIG. 8—PHOTOSCR-OUTPUT optocoupler schematic.

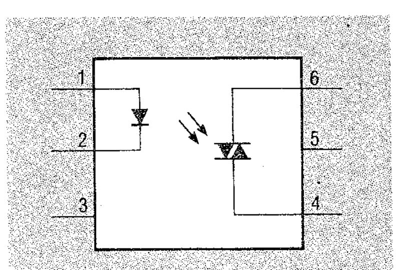

FIG. 9—PHOTOTRIAC-OUTPUT optocoupler schematic.

output resistor R2. When S1 is closed, current flows through the IRED and R1, and the resulting IR emission on the phototransistor causes it to conduct and generate an output voltage across R2.

The simple optically-coupled circuit shown in Fig. 4 will respond only to on-off signals, but it can be modified to accept analog input signals and provide analog output signals as will be seen later. The phototransistor provides output gain.

The schematics of six other optocouplers with different combinations of IRED and output photodetector are presented as Figs. 5 thru 10. Figure 5 is a schematic for a bidirectional-input phototransistor-output optocoupler with two back-to-back gallium-arsenide IRED's for coupling AC signals or reverse polarity input protection. A typical minimum CTR for this device is 20%.

Figure 6 illustrates an optocoupler with a silicon photodarlington amplifier output. It provides a higher output current than that available from a phototransistor coupler. Because of their high current gain, Photodarlington couplers typically have minimum 500% CTR's at a collector-to-emitter voltage of 30 to 35 volts. This value is about ten times that of a phototransistor optocoupler.

However, there is a speed-output current tradeoff when using a photodarlington coupler. Effective bandwith is reduced by about a factor of ten. Industry standard versions of those devices include the 4N29 to 4N33 and 6N138 and 6N139. Dual- and quad-channel photodarlington couplers are also available.

The schematic of Fig. 7 illustrates a bi-directional linear-output optocoupler consisting of an IRED and a MOSFET. Those couplers typically have isolation voltages of 2500 volts RMS, breakdown voltages of 15 to 30 volts, and typical rise and fall times of 15 microseconds each.

Figure 8 is the schematic for one of two basic types of opto-thyristor-output optocouplers,

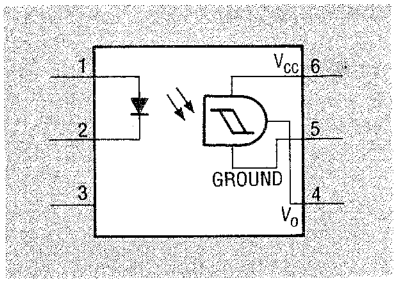

FIG. 10—SCHMITT-TRIGGER-OUTPUT optocoupler schematic.

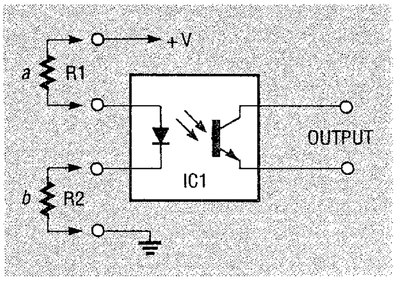

FIG. 11—SERIES RESISTOR must limit IRED current. It can be R1 at (a) or R2 at (b).

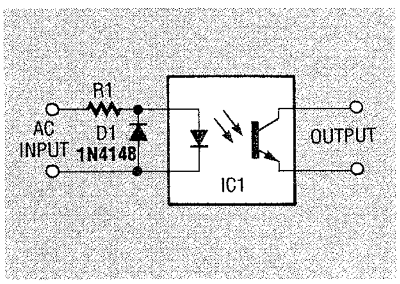

FIG. 12—IRED IS PROTECTED against reverse voltage with external diode D1.

one with an SCR output. OptoSCR couplers have typical isolation voltages of 1000 to 4000 volts RMS, minimum blocking voltages of 200 to 400 volts, and maximum turn-on currents (I_{FT}) of 10 milliamperes. The schematic in Fig. 9 illustrates a phototriac-output coupler. Thyristor-output couplers typically have forward blocking voltages (V_{DRM}) of 400 volts.

Schmitt-trigger outputs are available from optocouplers. Figure 10 is the schematic for an optocoupler that includes a Schmitt-trigger IC capable of producing a rectangular output from a sine-wave or pulsed input signal. The IC is a form of multivibrator circuit. Isolation voltages are from 2500 to 4000 volts, maximum, turn-on current is typically from 1 to 10 milliamperes, the minimum and maximum operating voltages are 3 to 26 volts, and the maximum data rate (NRZ) is 1 MHz.

Coupler applications

Optocouplers function in circuits the same way as discrete emitters and detectors. The input current to the optocoupler's IRED must be limited with a series-connected external resistor which can be connected in one of the two ways shown in Fig 10,

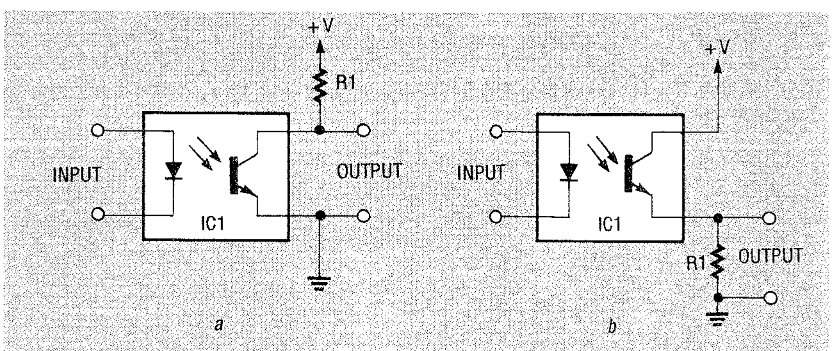

FIG. 13—EXTERNAL RESISTOR wired at phototransistor collector (a) or emitter (b).

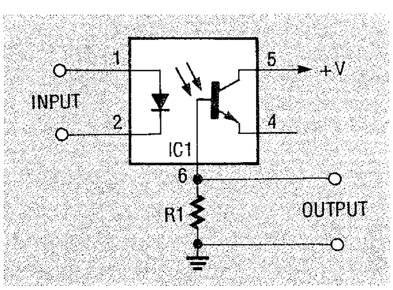

FIG. 14—PHOTOTRANSISTOR-TO-photodiode conversion with base pin connection.

either on the anode side *(a)* or cathode side *(b)* of the IRED.

Figure 5 showed an optocoupler optimized for AC operation, but a conventional phototransistor coupler can also be driven from an AC source with the addition of an external conventional diode as shown in Fig. 12. That circuit also provides protection for the IRED if there is a possibility that a reverse voltage could be applied accidentally across the IRED.

The operating current of the coupler's phototransistor can be converted to a voltage by placing an external resistor in series with the transistor's collector or emitter as shown in Fig. 13. The collector option is shown in *(a)* and the emitter option is shown in *(b)*. The sensitivity of the circuit will be directly proportional to the value of either of the series resistors.

A phototransistor-output optocoupler in a six-pin DIP can be converted to a photodiode-output optocoupler by using the base pin 6 as shown in Fig. 14 and ignoring the emitter pin 4 (or shorting it to the base). This connection results in a greatly increased input signal rise time, but it sharply reduces CTR to a value of about 0.2%.

Digital interfacing.

Optocouplers are ideally suited for interfacing digital signal circuits that are driven at different voltage levels. They can interface digital IC's within the same TTL, ECL or CMOS family, and they can interface digital IC's between those families. The devices can also interface the digital outputs of personal computers (or other mainframe computers, workstations and programmable controllers) to motors, relays, solenoids and lamps.

Figure 15 shows how to interface two TTL circuits. The optocoupler IRED and current-limiting resistor R1 are connected between the 5-volt positive supply bus and the output driving terminal of the TTL logic gate. This connection is made rather than between the TTL gate's output and ground because TTL outputs can sink fairly high current (typically 16 milliamperes). However, TTL outputs can only source a very low current (typically 400 microamperes).

The open-circuit output voltage of a TTL IC falls to less than 400 millivolts when in the logic 0 state, but it can rise to only 2.4 volts in the logic 1 state if the IC does not have a suitable inter-

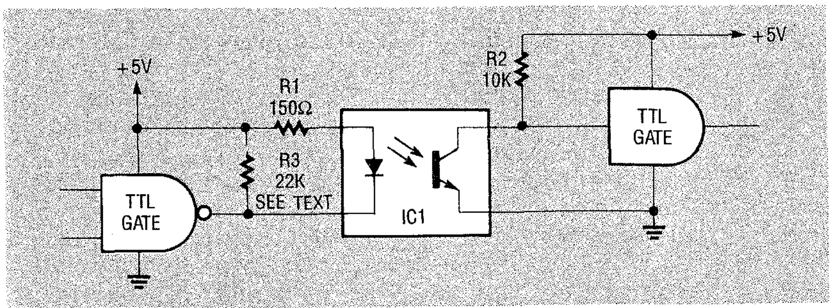

FIG. 15—TTL-GATE INTERFACE provided by a phototransistor, output optocoupler.

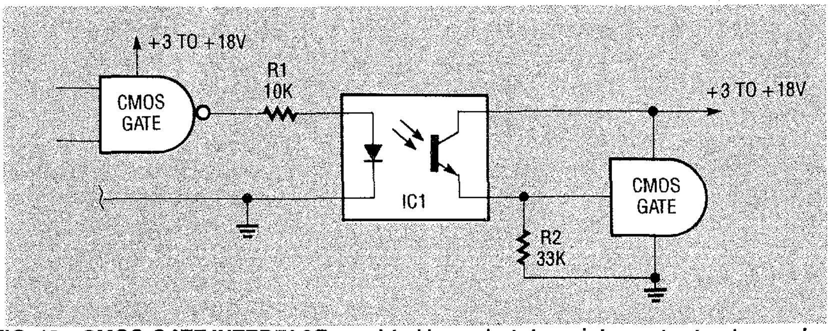

FIG. 16—CMOS-GATE INTERFACE provided by a phototransistor-output optocoupler.

nal pull-up resistor. In that case, the optocoupler's IRED current will not fall to zero when the TTL output is at logic 1. This drawback can be overcome with external pull-up resistor R3 shown in Fig. 15.

The optocoupler's phototransistor should be connected between the input and ground of the TTL IC as shown because a TTL input must be pulled down below 800 millivolts at 1.6 milliamperes to ensure correct logic 0 operation. Note that the circuit in Fig. 15 provides non-inverting optocoupling.

CMOS IC outputs can source or sink currents up to several milliamperes with equal ease. Consequently, these IC's can be interfaced with a sink configuration similar to that of Fig 15, or they can be in the source configuration shown in Fig. 16. In either case, R2 must be large enough to provide an output voltage swing that switches fully between the CMOS logic 0 and 1 states.

Figure 17 shows how a phototransistor-output optocoupler can interface a computer's digital output signal (5 volts, 5 milliamperes) to a 12-volt DC motor whose operating current is less than 1 amp. With the computer output high, the optocoupler IRED and phototransistor are both off, so the motor is turned on by Q1 and Q2. When the computer output goes low, the IRED and phototransistor are driven on, so Q1, Q2 and the motor are turned off. Note the 1-ampere current limitation.

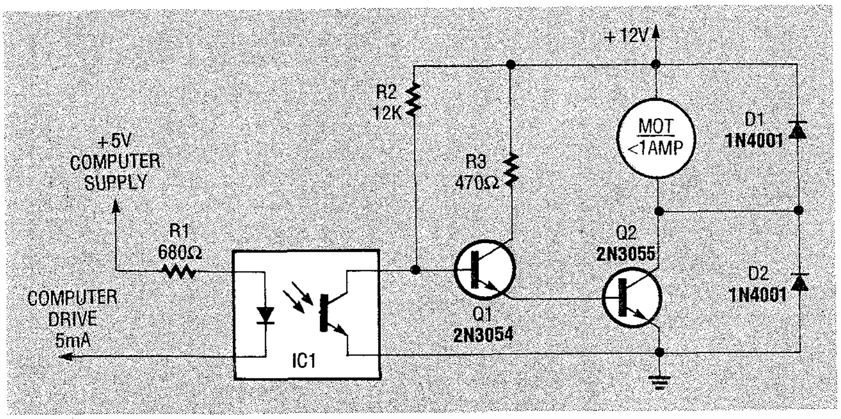

FIG. 17—COMPUTER TO DC-MOTOR INTERFACE provided by a phototransistor-output optocoupler.

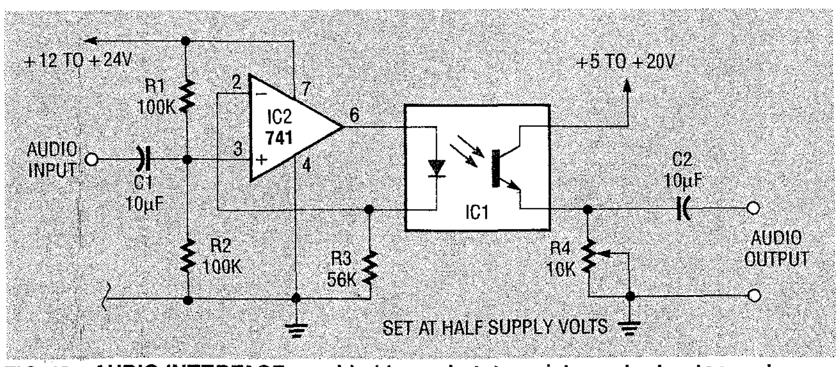

FIG. 18—AUDIO INTERFACE provided by a phototransistor-output optocoupler.

Analog interfacing

An optocoupler can interface analog signals from one circuit to another by setting up a "standing" current through its IRED and then modulating that current with the analog signal. Fig 18 shows this method applied to audio coupling. The operational amplifier IC2 is connected in a unity-gain voltage-follower mode. The optocoupler's IRED is wired into the op-amp's negative feedback loop so that the voltage across R3 (and thus the current through the IRED) precisely follows the voltage applied to non-inverting input pin 3 of the op-amp. This pin is DC biased at half-supply voltage with the R1-R2 voltage divider. The op-amp can be AC modulated with an audio signal applied at C1. The quiescent IRED current is set at 1 to 2 milliamperes with R3.

On the output side of the coupler a quiescent current is set up by its transistor. That current creates a voltage across potentiometer R4 which should have its value adjusted to give a

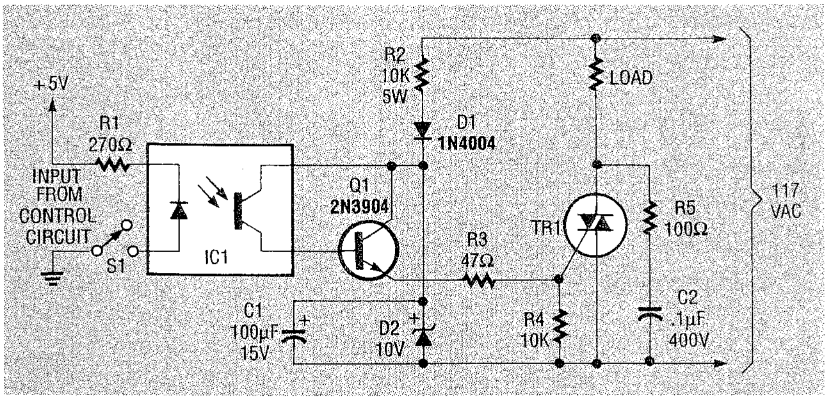

FIG. 19—NON-SYNCHRONOUS TRIAC power switch with optocoupled input.

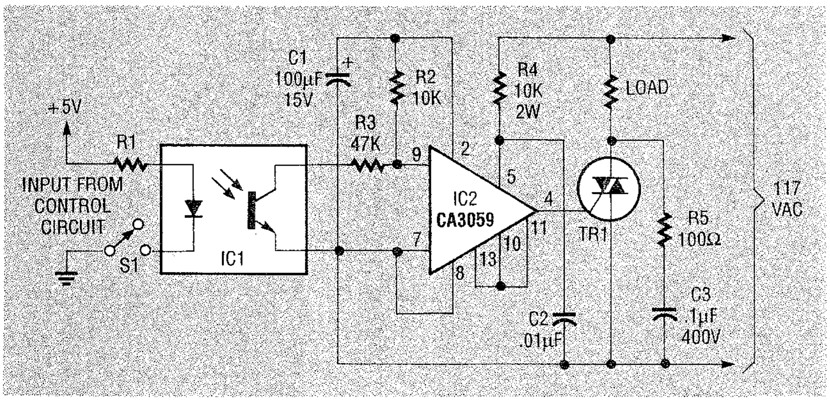

FIG. 20—SYNCHRONOUS TRIAC power switch with optocoupled input.

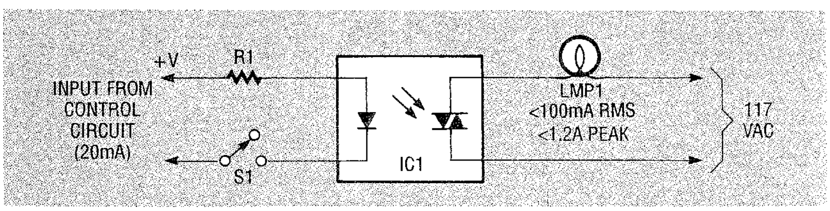

FIG. 21—INCANDESCENT LAMP CONTROL with a Triac-driver output optocoupler.

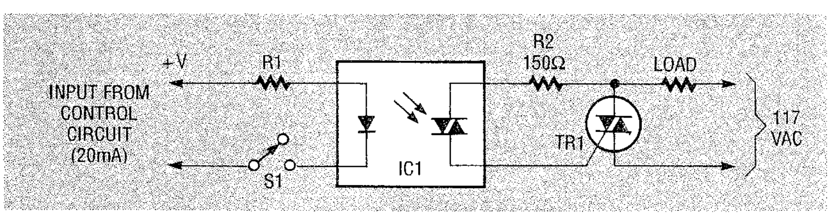

FIG. 22—HIGH-POWER LOAD CONTROL with Triac-driver output optocoupler.

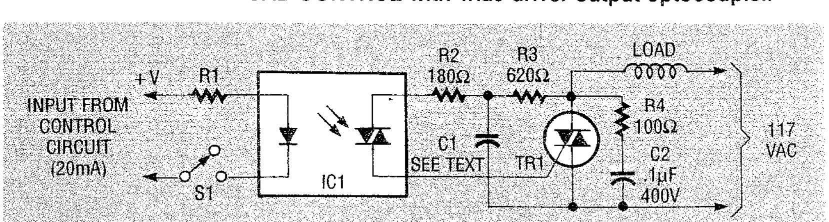

FIG. 23—INDUCTIVE LOAD CONTROL with Triac-driver output optocoupler and Triac slave.

quiescent output equal to half the supply voltage. The audio-output signal appears across potentiometer R4, and it is decoupled by C2.

Triac interfacing.

Interfacing the output of a low-voltage control circuit to the input of a Triac power-control circuit driven from the AC line is an ideal application for the optocoupler. (It is advisable that one side of its power supply be grounded.) That arrangement shown in Fig. 19 can control the power to lamps, heaters, motors and other loads.

Figures 20 and 21 show practical control circuits. The Triacs should be selected to match load requirements. The circuit in Fig. 19 provides non-synchronous switching in which the Triac's initial switch-on point is not synchronized to the 60-Hz voltage waveform. Here, R2, D1 Zener diode D2 and C1 develop a 10-volt DC supply from the AC line. This voltage can be fed to the Triac gate with Q1, which turns the Triac on or off. Thus, when S1 is open, the optocoupler is off, so zero base drive is applied to Q1 (keeping Triac and load off). When S1 is closed, the optocoupler drives Q1 on and connects the 10-volt DC supply to the Triac gate with R3, thus applying full line voltage to the load.

The circuit in Fig. 20 includes a silicon monolithic zero-voltage switch, the CA3059/CA3079, sourced by Motorola and Harris Semiconductor. That IC with a phototransistor-output optocoupler provides synchronous power switching. The gate current is applied to the Triac only when the instantaneous AC line voltage is within a few volts of the zero cross-over value. This synchronous switching method permits power loads to be switched on without generating sudden power surges (and consequent radio frequency interference (RFI) in the power lines). This scheme is used in many factory-made solid- state relay modules.

PhotoSCR's and PhotoTriacs

Both photoSCR and photo-Triac-output optocouplers have rather limited output-current ratings. However, in common with other semiconductor devices, their surge-current ratings are far greater than their RMS values. In the case of the SCR, the surge current rating is 5 amps, but this applies to a 100 microsecond pulse width and a duty cycle of less than 1%. In the case of the Triac, the surge rating is 1.2 amps, and this applies to a 10 microsecond pulse width and a maximum duty cycle of 10%.

The input IRED of optocoupled SCR's and Triac's is driven the same way as in a phototransistor-output optocoupler, and the photoSCR and photoTriac perform the same way as their conventional counterparts with limited current-handling capacity. Figures 21, 22, and 23 illustrate practical applications for the photoTriac-output optocoupler. In all circuits R1 should be selected to permit an IRED forward current of at least 20 milliamperes.

In Fig. 21, the photoTriac directly activates an AC-line-powered incandescent lamp, which should have an RMS rating of less than 100 milliamperes and a peak inrush current rating of less than 1.2 amps to work in this circuit.

Figure 22 shows how the photoTriac optocoupler can trigger a slave Triac, thereby activating a load of any desired power rating. This circuit is only suitable for use with non-inductive (i.e.resistive loads) such as incandescent lamps and heating elements.

Finally, Fig. 23 shows how the circuit in Fig. 22 can be modified for inductive loads such as motors. The network made up of R2, C1, and R3 shifts the phase to the Triac gate-drive network to ensure correct Triac triggering action. Resistor R4 and C2 form a snubber network to suppress surge effects.

Figures 24 and 25 show two other variations on the optocoupler theme. A slotted coupler-interrupter module is shown in Fig. 23-a. The slot is an air gap between the IRED and the phototransistor. Infrared energy passes across the unobstructed slot without significant attenuation when the interrupter is "on". Optocoupling can, however, be completely blocked by opaque objects such spokes of a wheel or unpunched tape moving across the slot.

A typical slot width is about 3 mm (0.12 inch) wide, and the module has a phototransistor output that gives an "open" minimum CTR of about 10%. The schematic for this device is similar to that of Figure 2 except that the IRED and photodetector are enclosed in separate boxes.

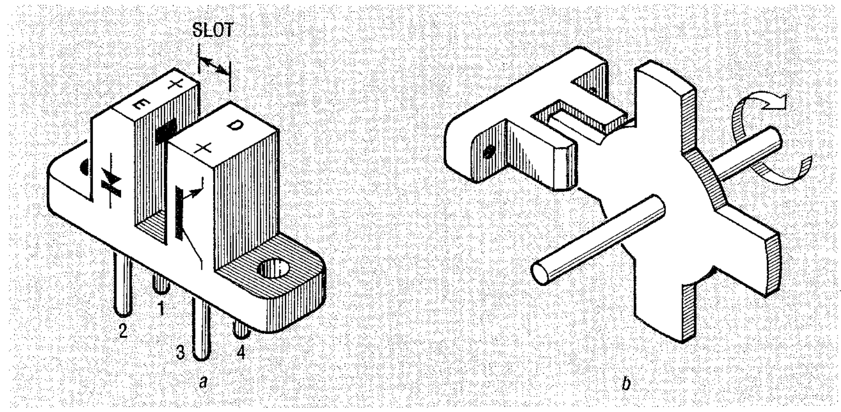

FIG. 24—OPTICALLY-COUPLED INTERRUPTER MODULE (a) and speed-counting application (b).

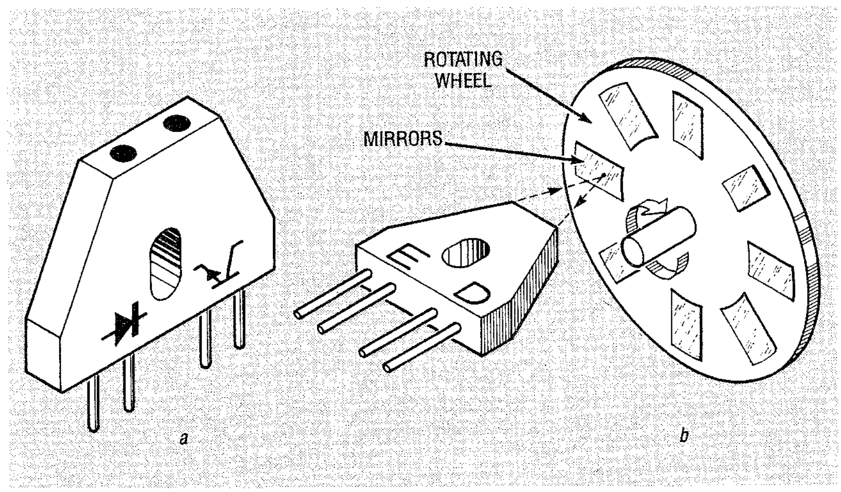

FIG. 25—OPTICALLY-COUPLED REFLECTOR MODULE (a) and revolution counting application (b).

Figure 24-b illustrates a method for counting revolutions with the interrupter. Each time a tab on the wheel blocks the optical path, a count is made. Other interrupter uses include end-of-tape detection, limit switching, and liquid-level detection.

A reflective optocoupler module is shown in Fig. 25-a. Direct infrared emission from the IRED is blocked from the phototransistor by a wall within the module, but both IRED and phototransistor face a common focal point 5 mm (0.2-inch) away. Interrupters are used to detect the presence of moving objects that cannot be easily passed through a thin slot. In a typical application, a reflector module can count the passage of large objects on a conveyor belt or sliding down a feed tube.

Figure 25-b illustrates a revolution counter based on reflecting IR from the IRED back to the phototransistor with reflectors mounted on the face of a spinning disk. The module-disk separation is equal to the 5-mm focal length of the emitter-detector pair. The reflective surfaces can be metallic paint or tape. Other applications for the reflective module include tape-position detection, engine-shaft revolution counting, and engine-shaft speed detection.

Photointerrupters and photoreflectors are also available with photodarlington, photoSCR, and photoTriac ouput stages. R-E