Optocoupler devices and their applications

Ever wanted to control one circuit with another without having any intermediate electrical connection? Devices that provide coupling via a beam of infra-red light are called 'optocouplers' and they're just perfect for the job. Here's a run down on a host of popular optocouplers and how to use them in practical circuits.

Brian Dance

THE ELECTRONIC circuit designer is often faced with the problem of providing a high degree of isolation between two circuits which must nevertheless be able to pass alternating signals from one part of the circuit to the other.

For example, one may wish to have one part of the circuit completely isolated from the mains, yet use signals from this part of the circuit to control the flow of the mains current through a load. Another example occurs in patient monitoring equipment where the small voltages developed by the beating of a heart can be coupled into mains powered equipment without any danger of the equipment causing a current to flow through the heart.

Optocouplers

Optocouplers use a beam of infra-red radiation (or occasionally, visible light) to convey the signal from one part of the circuit to the other without any electrical connection whatsoever between the two parts. They are sometimes known as photon-coupled devices or as opto-isolators. They may be employed to replace conventional relays when a fast response is required or when sparking at relay contacts must be avoided in an explosive atmosphere.

An optocoupling device consists of an infra-red emitting device or other lamp on its input side and some form of detector for the radiation on the output side, both the emitter and detector being in a light-tight enclosure. The silicon detector itself may be a phototransistor, a photo-Darlington device, an opto-triggered triac or even a field effect phototransistor.

No matter which of these device types is employed, the silicon detector has its maximum sensitivity at a wavelength quite near to that at which the gallium arsenide device emits with its maximum intensity. In other words, the devices are spectrally well matched so that a small emitter device current can produce a reasonably large response in the detecting device.

Types

A very large number of types of optocoupler have been marketed with the electrical characteristics of both the emitter and the detector having to be specified in every type. Rather than involve readers with a mass of type numbers, this article will concentrate on a limited number of readily-available devices.

The 4N26, 4N28 and MCT2 devices are examples of those using a phototransistor as a detector, the 4N33 has a Darlington output stage, the 6N139 (equivalent to the MCC671) has a 'split-Darlington' fast output device, the MCT6 is a dual device and the MOC-3020 has a triac output for 240 V mains supplies.

Dual-in-line

Although some optocoupled devices are fabricated in circular metal packages, the most common types, including those listed above, are produced in dual-in-line (DIL) packages with a typical construction like that shown in Figure 1. The emitter and detector are placed fairly close together with a clear insulating material between them. The black silicon body of the device prevents stray radiation from falling on the detector. A circuit symbol is shown in Figure 2.

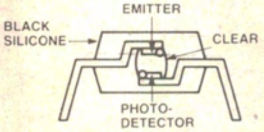

Figure 1. Cross-section through an optocoupler.

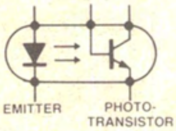

Figure 2. Symbol for an optocoupler having a transistor output stage.

In most DIL devices the radiating emitter is connected to pins on one side of the device, while the detector is connected to pins on the other side. This arrangement provides the maximum possible electrical isolation between the input and output circuits. Many of the simpler optocoupled devices differ from most other dual-in-line devices in that they have a total of only six connecting pins.

The basic internal circuitry of the devices under discussion is shown in Figures 3 to 7 inclusive. The three devices 4N26, 4N28 and MCT2 with a single phototransistor output all have the connections shown in Figure 3. The dual device type MCT6 is housed in the 8-pin package of Figure 4 so that the additional pins required are available.

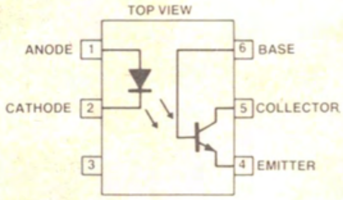

Figure 3. Pinout for the 4N26, 4N28 and MCT2 devices.

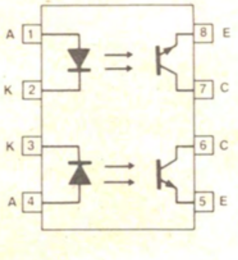

Figure 4. Pinout of the MCT6 dual optocoupler device.

DEVICE TYPE	4N26	4N28	MCT2	MCT6 (dual)	4N33	6N139	MOC-3020
Output device	←——— Phototransistor(s)			———→	← Darlington	→	Triac
CTR (%) Min.	20	10	—	5	—	400	—
Typ.	50	30	—	50	500	—	—
Isolation (kV) (min.)	1.5	0.5	1.5	1.5 (0.5 between channels)	1.5	3	7.5 (max 5 sec)
Isolation resistance (Typical ohms)	10^{11}	10^{11}	10^{12}	10^{12}	10^{11}	10^{12}	—
Isolation capacitance at 1 MHz (pF)	1.3	1.3	0.5	0.5	0.8	0.6	—
Maximum emitter current (mA)	80	80	60	60 per emitter	80	20	50
Typical emitter voltage at 50 mA	1.2	1.2	—	—	1.2	1.5 (at 1.6 mA)	—
Maximum reverse input voltage (V)	3	3	3	3	5	5	3
Input capacitance (pF)	150	150	250	—	150	—	—
Maximum power Total (mW)	250	250	250	400	250	—	300
Input	150	150	200	100	150	35	
Output	150	150	200	150	150	100	
Output transistor:							$V_{DRM} = V_{RRM} = 400$ V Trigger current 5 mA (typ.), 20 mA (max.) Holding current 100 uA (typ.) at $V_{AK} = 3$ V Maximum output current 100 mA RMS
BV_{CEO} (min.)	30	30	85	85	30	—	
BV_{CBO} (min.)	70	70	165	—	50	—	
BV_{ECO} (min.)	7	7	14	13	5	—	
h_{FE} (typ.)	250	250	60	—	5000	—	
I_{CEO} (nA typ.)	50	100	50	50	100	1000	
$V_{CE(SAT)}$ (typ.)	0.2	0.2	0.24	0.24	1.0	—	
Typical I_c for $I_F = 10$ mA	5	3	—	—	—	—	
Typical bandwidth (kHz)	300	300	150	150	30	—	
Package	Figure 3	Figure 3	Figure 3	Figure 4	Figure 5	Figure 6	Figure 7

TABLE 1. Basic data on the types of optocouplers discussed.

The 4N33 with its high-gain photo-Darlington output device is encapsulated in a 6-pin package with the same type of connections as the phototransistor output types of Figure 3; except for the performance differences, these devices are pin-for-pin replaceable.

The 6N139 'split-Darlington' output device has its output transistor base brought out to a separate pin, so the 8-pin dual-in-line package of Figure 6 is employed; this enables the input diode connections to be kept on the opposite side to all of the output connections.

Finally, the MOC-3020 with its triac output stage, is housed in a 6-pin dual-in-line package with the connections shown in Figure 7.

The basic parameters of these devices are listed in Table 1, but it cannot be overemphasised that some of these values apply only under certain operating conditions stated on the data sheet which cannot all be shown in a table of a reasonable size.

It can be seen that most of the specifications required for the MOC-3020 differ from those of the other devices in their nature owing to the fact that the output triac must be specified in a different way to transistors and Darlingtons.

Which type?

If one wishes to use an input signal to control alternating current from the mains in a load, the MOC-3020 will generally be the best device from those under discussion. This optocoupler will be discussed separately from the others.

If one has to design a circuit which requires two separate control coupling systems, this can be done using the dual MCT6 device provided that phototransistor outputs are suitable for the particular application concerned. Indeed, two of these MCT6 devices can be inserted into a 16-pin dual-in-line IC socket so that one has a quadruple coupling system. (Quad devices in a single package are manufactured, but are not so common as the types under discussion.)

This leaves us with a choice, in the case of single devices, of those using a phototransistor or those employing a photo-Darlington output stage. The types using a phototransistor are most commonly employed, since they provide a fast response and can usually handle input signals with frequencies of over 100 kHz (see Table 1).

Photo-Darlington output devices provide a higher gain, but the bandwidth (or maximum usable signal frequency) is about an order of magnitude less than devices which use a simple phototransistor output; in addition, devices using a photo-Darlington output stage may be priced some 50% higher than those employing a phototransistor output, although this is not always the case. ▶

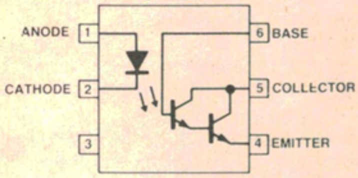

Figure 5. Pinout of the 4N33, an optocoupler having a photo-Darlington output stage.

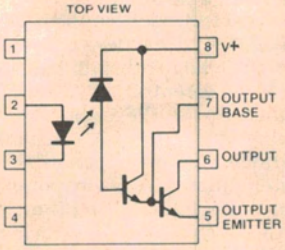

Figure 6. Pinout for the 6N139 (or MCC671) device which has a separate photodiode for maximum speed and a Darlington output for high gain.

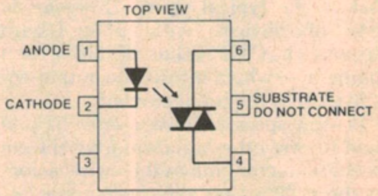

Figure 7. Pinout of the MCO-3020, which has a triac output stage.

The single devices of Figures 3 and 5 (but not the dual device of Figure 4) have the transistor base connected to a separate pin so that suitable circuitry may be used to trade-off gain in order to obtain a better high frequency response. The maximum usable frequency will be obtained when the output phototransistor is connected as a photodiode using only the base and collector connections of Figure 3, but a relatively large input current will then be needed to produce a small output current; the CTR value may be under 0.1%.

Apart from the more limited response speed of a device with a photo-Darlington output stage, it can be seen from Table 1 that the saturation voltage (under high input conditions) is much greater for the photo-Darlington device than for a simple phototransistor. Both the speed of response and the saturation differences are inherent properties of photo-Darlington devices and are not limited to optocouplers.

CTR

In order to understand some of the figures quoted in Table 1, we must first examine the ways in which certain device parameters are specified. The user need not consider any of the internal optical design points, since the manufacturer takes care of such considerations when he is designing the devices concerned.

Optocouplers are supplied as sealed units, although opto-interrupter modules are also manufactured in which there is a slot between the emitting diode and the detector so that a metal vane passing through the slot can interrupt the beam; such opto-interrupters can, for example, be used in car ignition timing systems.

One of the most important parameters of an optocoupled device is its *current transfer ratio* (CTR) which is the ratio of the output current to the input current under certain conditions specified by the manufacturer; it is usually expressed as a percentage and, broadly speaking, may be considered as the 'gain' of the device. It may be noted that devices with a triac or a thyristor output do not have a CTR value.

It can be seen from Table 1 that typical values of the CTR in the case of devices which have a simple phototransistor output stage is of the order of 50% — which means the collector current in the output phototransistor will be about half that to the input diode emitter.

The minimum value in a device of any specified type may be considerably less than that of the typical value. However, in the case of devices with photo-Darlington outputs, a CTR value of 500% is more common — which means the output current is five times the input current.

In some special devices a short light pipe is used to carry the radiation from the emitter to the detector, inevitably with some loss, so the CTR value may be reduced in such devices which may be able to withstand a much higher voltage between their input and output sides.

Unfortunately, the CTR does not have a constant value but varies widely with the diode input current and with the device temperature. Figure 8 shows the typical variation of the CTR value of the MCT2 device (which has a simple phototransistor output stage) with the forward input current passed through the emitter diode.

Each curve is for a different MCT2 device, the wide spread being due to variations in the phototransistor gain, the emitter efficiency and the coupling efficiency between the two internal components. The percentage values quoted on each curve are those for a 10 mA input current.

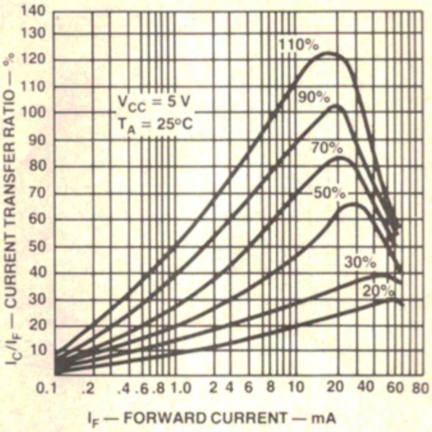

Figure 8. Variation of the current transfer ratio (CTR) with forward current in typical MCT2 devices.

The CTR value of a 4N26 or 4N28 can vary by a factor of about 2.5 between high temperatures (where it is relatively low) and very low temperatures, while devices with Darlington outputs may show variations of double this factor between temperature extremes. Rather smaller variations are more commonly found.

Isolation

Manufacturers of optocoupled device specify a maximum voltage which may be safely applied between the input and output sides of the device. In most devices this is in the range 500 to 8000 V, depending on the device type, but special types can be obtained for higher voltage isolation.

The resistance between the input and output sides of a typical device is often around 10^{11} to 10^{12} ohm. Although this seems very high, if a potential of a few kilovolts is applied across the device, a current of somewhat under 100 nA can flow. This is comparable with the current through the output of a high gain device when the input current through the emitter is under 1 mA.

If an optocoupler fails under a high applied voltage between its input and output sides, a short circuit will normally develop as a track is formed between the emitting and detecting devices. The problem can be reduced by the use of suitable current limiting resistors or protective devices in either the input or output circuit.

The stray capacitance between the input and output circuit of an optocoupler is typically of the order of 1 pF (Table 1). It can provide some unwanted coupling in circuits designed to be able to operate at high speeds, especially when inductive loads are being switched.

The emitter

The emitting diode will have a maximum continuous current rating, normally some tens of milliamps as indicated in Table 1. In some devices, pulsed currents above the maximum continuous current are permissable.

A maximum value is also imposed on the reverse voltage which may appear across the emitter diode. The application of a higher reverse voltage can cause it to breakdown and perhaps pass a destructive current; however, this problem is easily avoided by connecting an external diode across the emitter diode as shown in Figure 9.

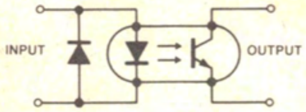

Figure 9. If a reverse voltage is likely to appear across the optocoupler emitter an external diode can be used to 'clip' it.

Although gallium arsenide diodes have been the main type used in optocouplers, there is an increasing trend to employ gallium-aluminium-arsenide types, since the latter not only emit photons more efficiently, but also provide a slightly better spectral match to the silicon detector. Thus an appreciable increase in the CTR value can be obtained.

In many optocouplers one must be careful to observe not only the total power dissipated in the complete package, but also the power dissipated in the separate input and output devices, as indicated in Table 1.

The detector

As with any other phototransistor or photo-Darlington, there is a certain value quoted for the maximum voltage which may be applied between the collector and the emitter with the base unconnected without risk of the device undergoing breakdown; this is BV_{CEO}. Similarly, values may be quoted for BV_{CBO} and BV_{ECO}.

A maximum collector current may also be quoted together with a maximum collector leakage current with base unconnected, I_{CEO}, under specified conditions.

The characteristics of the detector determine the speed of response and the bandwidth, since the emitting diodes are fast. The response time can be reduced by the use of a smaller value of load resistor, but many manufacturers quote rise and fall times and bandwidths with load resistors which are so small that the circuit would have an inadequate gain for most applications.

The response speed of an optocoupler can be improved by using the circuit of Figure 10 in which the collector load is effectively reduced to a very low value by the virtual earth input impedance of the operational amplifier.

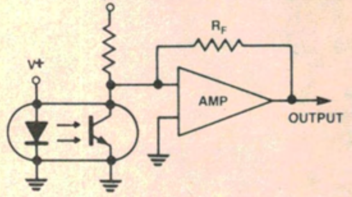

Figure 10. Response speed may be increased by the use of the virtual earth input of an op-amp.

An even simpler way of obtaining a faster response at the expense of a reduced value of the CTR involves connecting a resistor between the base and emitter of the output transistor. As the value of this resistor is reduced, the response becomes faster until in the limit, when the resistor is a short circuit, one is using the detector as a photodiode.

If one expects to be working with a very small input current, one might expect the use of a high gain device with a photo-Darlington output would be ideal. This is not necessarily true, since the overall efficiency can fall at such currents to the point where a device with a phototransistor would be better.

APPLICATIONS

Optocoupling devices can be employed to replace relays and pulse transformers in a wide variety of applications in which high isolation may be desirable or essential. They provide fast signal transfer with excellent noise immunity. They are suitable for interfacing with TTL and CMOS circuits and can also be used for analogue signal coupling.

Circuits designed for use with single phototransistor output optocoupled devices can generally employ the 4N26, 4N28 or MCT2, but note should be made of the individual differences listed in Table 1.

For example, the 4N28 is limited to applications in which the voltage across the device does not exceed 500 V, while when the other devices are selected, it may be as great as 1.5 kV.

The phototransistors in the MCT2 and in the dual MCT6 outputs are much higher voltage devices than those used in the 4N26 and 4N28.

The bandwidth of the 4N26 and 4N28 is typically greater than that of the other two types, but so is the isolation capacitance between the input and output. However, these points are not likely to be of any great importance in most applications.

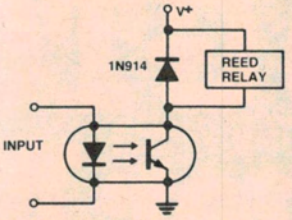

Figure 11. Using an optocoupler to isolate a reed relay.

Relay control

The simple circuit of Figure 11 shows how a small input current may be employed to control a reed relay. The inductive back-emf from the relay coil formed when the current ceases to flow through it is by-passed by the 1N914 diode so that this relatively high voltage pulse cannot damage the output transistor of the optocoupler.

The supply voltage used, V^+, should have a value about equal to the voltage required by the relay, but should not exceed the V_{CEO} value of Table 1 for the optocoupler used.

Although the use of a reed relay is suggested so that the output current of the optocoupling device is kept quite small, other types of small relay can be controlled with careful circuit design. Obviously this type of circuit provides better isolation than many types of relay.

The circuit can easily be modified so that the relay does not close until the input has been applied for a short time. One merely connects a capacitor across the input diode and feeds this diode through a series resistor. The delay time before the relay closes will be dependent on the time taken for the capacitor to charge through the series resistor.

Isolated audio

The circuit of Figure 12 shows how an audio output completely isolated from the audio input signal may be obtained. A positive bias is applied to the input signal, V^+_s so that the emitter diode polarity is satisfied.

The value of the input resistor R1 should be chosen so as to limit the modulating input current to a maximum of 5 mA. The 100 ohm load resistor of the phototransistor results in rather a low gain, but the 741 stage provides a gain of about ten so that a reasonably large output voltage is obtained.

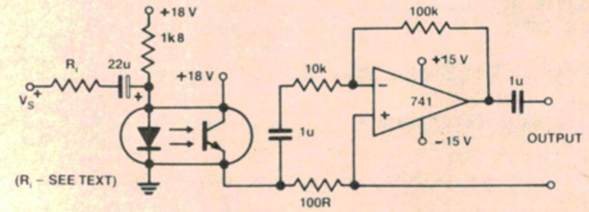

Figure 12. An isolation circuit covering the whole audio range.

The low value of the collector load resistor enables an upper frequency up to 20 kHz to be obtained, while the lower frequency response is determined by the values of the coupling capacitors employed — about 25 Hz in the case of the values shown.

Two separate +18 V supplies are required if complete isolation between the two parts of the circuit is needed. The input resistor R_i may consist of a variable resistor in series with a fixed resistor if it is required to alter the output signal voltage without any danger of receiving an electrical shock from the output circuit when the latter is at a relatively high voltage.

TTL interface

Optocouplers are widely used in interface logic circuits where the logic signal must be transferred from a circuit at either a high or a low voltage level to a circuit at a very different voltage level.

The circuit of Figure 13 shows how an optocoupling device employing a simple output transistor may be employed to couple the output of a TTL gate to one of the inputs of a TTL 7413 device at a very different voltage level. The 7413 Schmitt circuit provides switching.

A Fairchild report suggests that the base of the output phototransistor of the optocoupling device should be connected to the emitter through a resistor of about 200 kilohm to prevent false triggering of the outputs.

Another logic circuit for coupling an input to a 7413 device is shown in Figure 14, but in this case the 4N33 with its photo-Darlington output device is used.

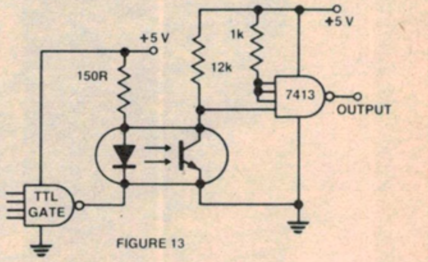

FIGURE 13

Figure 13. Isolating TTL circuits with an optocoupler.

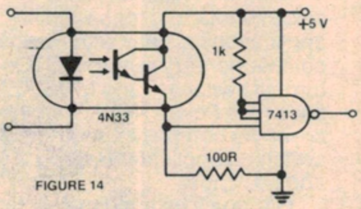

FIGURE 14

Figure 14. Control of a TTL Schmitt trigger circuit from a 4N33 photo-Darlington device.

It may be noted that in Figure 13 the load resistor (12 kilohm) is much higher than in Figure 14 (100 ohm), but the use of the higher gain of the 4N33 makes up for the lower value of load resistor. ▶

Simple latch

The very simple latching circuit of Figure 15 can employ a pair of 4N33 photo-Darlington output devices. Initially, S1 is open and no current flows through either 4N33. If S1 is then closed, a current flows from the positive supply through the diode emitter in the upper 4N33 and through the emitter in the lower 4N33, the output of the upper device being shorted out by S1 during this time.

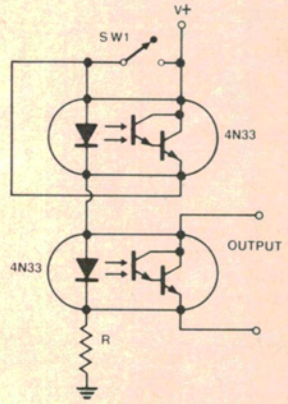

Figure 15. A latching circuit using two 4N33 devices.

When S1 opens, the short is removed from its output circuit, but the response time of the latter is longer than that of the emitter. The current therefore flows through the output of the upper 4N33, through the diode emitter of this same device to maintain the output in its conducting state and through the emitter of the lower 4N33. Thus the output of the lower device remains in its conducting state after S1 has re-opened.

The voltage across the two forward-biased emitting diodes is around 3.5 V and it is convenient to operate these diodes at about 5 mA. Thus, a suitable value for the resistor R is $(V^+ - 3.5)/0.005$ or about 3.9 kilohm with a 24 V supply.

Bidirectional control

The output current of an optocoupler using a phototransistor or a photo-Darlington device must flow only in one direction, so such a device cannot control alternating current.

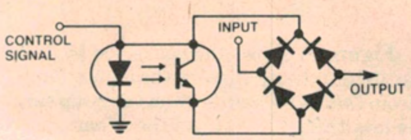

Figure 16. Controlling a bi-directional current using an optocoupler.

This problem can easily be overcome by the use of the circuit of Figure 16, in which the input-to-output current is rectified by a diode bridge circuit before being fed to the output stage of the optocoupled device.

The control signal which switches the output on and off must be unidirectional.

Power supply

Optocoupling devices can be used to isolate the control voltage of a regulated high voltage power supply from this supply line. The basic circuit which may be used is shown in Figure 17.

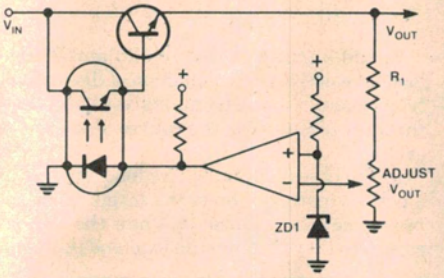

Figure 17. Using an optocoupler in a high voltage series-pass regulator.

A current flows from the stabilised output supply through the high value resistor R1 so that the variable resistor taps off a voltage proportional to the output voltage. This is compared with that across the zener diode D1 using the operational amplifier.

The output signal from this amplifier is fed to the emitter of the optocoupled device which is used to control the series pass transistor and hence to keep the output voltage constant. Thus, the amplifier device output is isolated from the high voltage supply.

A photo-Darlington device may be used in this type of circuit for higher feedback loop gain, but an external pass transistor is always required, since the output devices incorporated into optocouplers can handle only very limited power.

Fast interface

The 6N139 with its 'split photo-Darlington' output device enables the high speed of the separate photodiode to be combined with the high gain of the Darlington connected internal transistors. Although the CTR has a minimum value of 400% at a 500 mA input current, the device output can switch in a few microseconds.

A fast non-inverting logic interface circuit using this device is shown in Figure 18. The maximum switching speed depends on the load resistor, R2, and the input resistor, R1. If R1 has a value of 180 ohm a current of about 17 mA will flow to the output of the TTL input device from the internal emitter diode and the use of a 100 ohm load resistor for R2 will then enable data rates of about 300 kbit/s to be obtained. On the other hand, R1 may be increased to 1k8 for a 1.7 mA diode current with R2 2k2 for a maximum data rate of nearly 50 kHz.

Electrocardiograph amplifier

The use of an optocoupled device to provide complete isolation of a patient from electrocardiography equipment is shown in Figure 19. The electrodes from the patient are connected to the programmable 4250 preamplifier stage which operates from +/−3 V battery supplies, nulling facilities being provided by the variable resistor connected between pins 1 and 5.

The same +3 V battery supply provides the bias for the high gain BC109 transistor which drives the diode emitter of the optocoupling device.

The output phototransistor of the optocoupler receives a base bias so that some current is always passing through its collector circuit. This enables the positive and negative parts of the signal waveform to be obtained at the output.

This is a particularly important application of optocoupled devices, since without the isolation provided by such a device, small currents could be fed into the patient which in certain circumstances could produce death. ▶

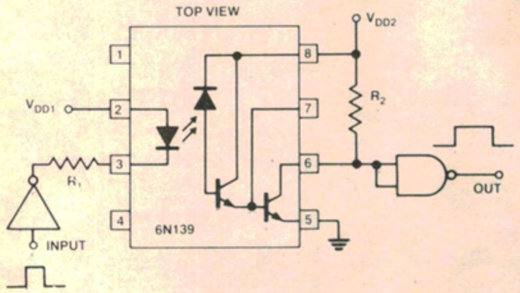

Figure 18. A fast TTL interfacing and isolating circuit using the 6N139.

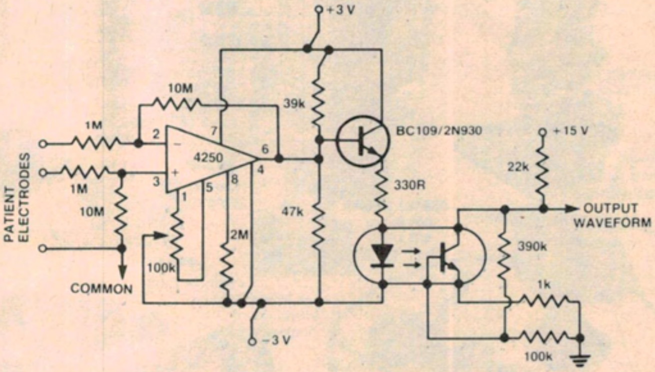

Figure 19. An electrocardiograph preamplifier circuit providing isolation of the patient from the equipment. (Litronix.)

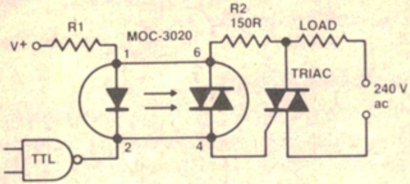

Figure 20. Control of ac power where there is a resistive load, using the MOC-3020.

The MOC-3020

The small triac in the MOC-3020 output can provide a current of up to 100 mA. This is too small for controlling the mains current passing through the load in almost all applications, but is adequate to trigger an additional external triac.

A circuit of this type is shown in Figure 20 in which the output of the TTL gate, controls the emitter current of the MOC-3020 which triggers the internal triac, the latter triggering the external triac.

The latter device should be selected so that it can hold-off the applied mains voltage and also pass whatever current is required by the particular load being used.

Figure 21 shows the use of the MOC-3020 to switch the ac current through a lamp fed from the 240 V mains when the lamp current is less than 100 mA. As the filament of the lamp has a much lower resistance when it is cold, care must be taken to ensure that the initial peak current is not excessive (about 1 A for a very short time is permissible).

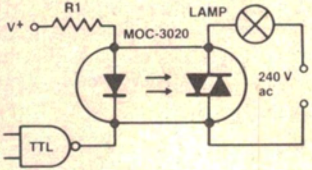

Figure 21. Controlling a lamp on the ac mains using a MOC-3020 (but watch the power rating).

In the circuits of Figures 20 and 21, the load is resistive and conduction of the internal triac ceases when the mains voltage passes through zero during the course of the mains cycle.

In the case of an inductive load (such as an electric motor), however, large back-emf pulses can be generated when the current ceases to flow through the load and this could cause the internal triac of the optocoupler to operate in an improper way.

This problem can be avoided through the use of the type of circuit shown in Figure 22, the values of the components of the 'snubber network' connected across the external triac being dependent on the load inductance and resistance.

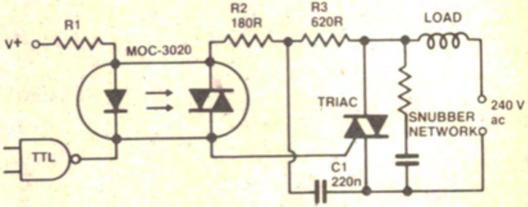

Figure 22. Control of ac power where the load is inductive (i.e: a motor), using the MOC-3020. Note the use of a 'snubber' network. Typical values for the RC network would be R=180 ohms, C=220n.

Conclusion

Simple optocoupler devices can be employed in a wide range of circuits from the simplest types to quite complex ones. At prices ranging from under one dollar up to a few dollars, they are excellent value! ●