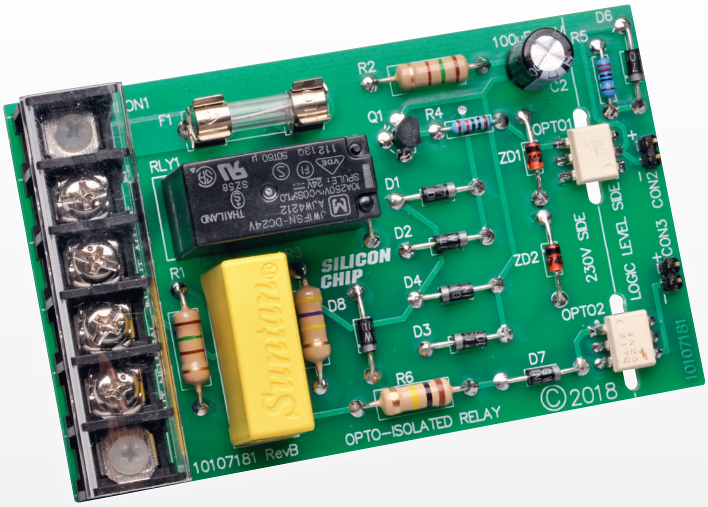
174 Roe Street, PERTH. Western Australia. 6000
Phone: (08) 9428 2188 Fax: (08) 9428 2187
E-mail: kits@altronics.com.au

K 2930



Opto-Isolated Mains Relay

If you need to switch mains voltages, say from a micro's output or any other low voltage source, you need to isolate them from each other. That's what this project does – it's easy to build and keeps mains voltages locked away from the controller . . . and you! Virtually any low voltage source will do – from 2.7 to 10V.

Reprinted with kind permission of Silicon Chip Magazine

Arduino and Raspberry Pi modules are popular because it's so easy to get into them, even if you're a beginner. But many people do not like working with mains, and with good reason – it's easy to create an unsafe situation if you don't know better. Incorrect wiring or inadequate insulation is a hazard not just to you but to anyone who comes in contact with your invention. This project is an ideal way of switching mains power, whether you are a beginner or not. If you follow the instructions in this article carefully, within an hour or two, you will have a working and importantly, safe, mains switch. You could control a heater, light, fan, pump, television, amplifier, computer – just about anything that plugs into a mains socket. You can use a wide range of sensors to decide when to switch those devices on and off; we've covered many easy-to-use sensors in our El Cheapo Modules series.

Other versions

There are some existing designs which do this job but they all seem to be designed for 110-120VAC mains, as used in the USA and some other countries. For example, Adafruit's PowerSwitch Tail performs a similar function to our design. But you definitely wouldn't want to use these with 230VAC mains as used in Australia, Europe and elsewhere. It would probably blow up and even if it didn't, it wouldn't be safe. In the past, when we needed to control mains outlets using a microcontroller, we modified a 433MHz remote mains switch to do the job. The last time we did this was in the November 2014 issue. While simple and elegant, it's more expensive and more work, as you need to buy and modify the remote mains switch units. So we have designed this unit which is simple, cheap, reliable and able to switch just about any mains device, up to 10A rating. You could even connect several units to one micro to switch multiple devices.

How it works

The 230V Opto-Isolated Relay uses a logic signal (eg, 3.3V or 5V or up to 10V) and switches a mains-rated relay on or off based on the state of that signal. The optical isolation ensures that there is no chance that mains voltages could appear on the logic input and cause a shock hazard, or damage the driving circuitry. The 4N25 optocouplers we are using have an isolation rating of 5300V RMS.
It also has a logic signal output which can be used by the driving circuitry to detect whether mains power is present and also allows the phase and frequency of the mains waveform to be sensed. This output uses the same type of optocoupler for safety. An optocoupler consists of a LED (usually infrared) and phototransistor in a plastic package. The LED shines on the phototransistor junction through an insulating clear plastic section, so that the phototransistor conducts when the LED illuminates it. It behaves like a transistor with separate base-emitter and collector-emitter junctions.

But the gain (called the "current transfer ratio" or CTR) is much lower than a standard transistor, so the collector current is generally of a similar magnitude to the LED drive current. The CTR may be above or below 100%, depending on the particular optocoupler used (it can vary from sample to sample) and on the LED current; the CTR tends to peak at a few milliamps of LED drive current. Take a look now at the circuit diagram, shown in Fig.1. The control signal is applied to pin header CON2. When a sufficient voltage is applied, current flows through the 220W current-limiting resistor and through OPTO1's internal LED, which usually has a forward voltage of around 1V. So with 3.3V across CON2, around 10mA flows through it.

Assuming the 24V mains-derived power supply on the other side of the optocoupler is present, the phototransistor then acts as an emitter-follower, supplying voltage to the base of NPN transistor Q1 via a 10kW current-lim-

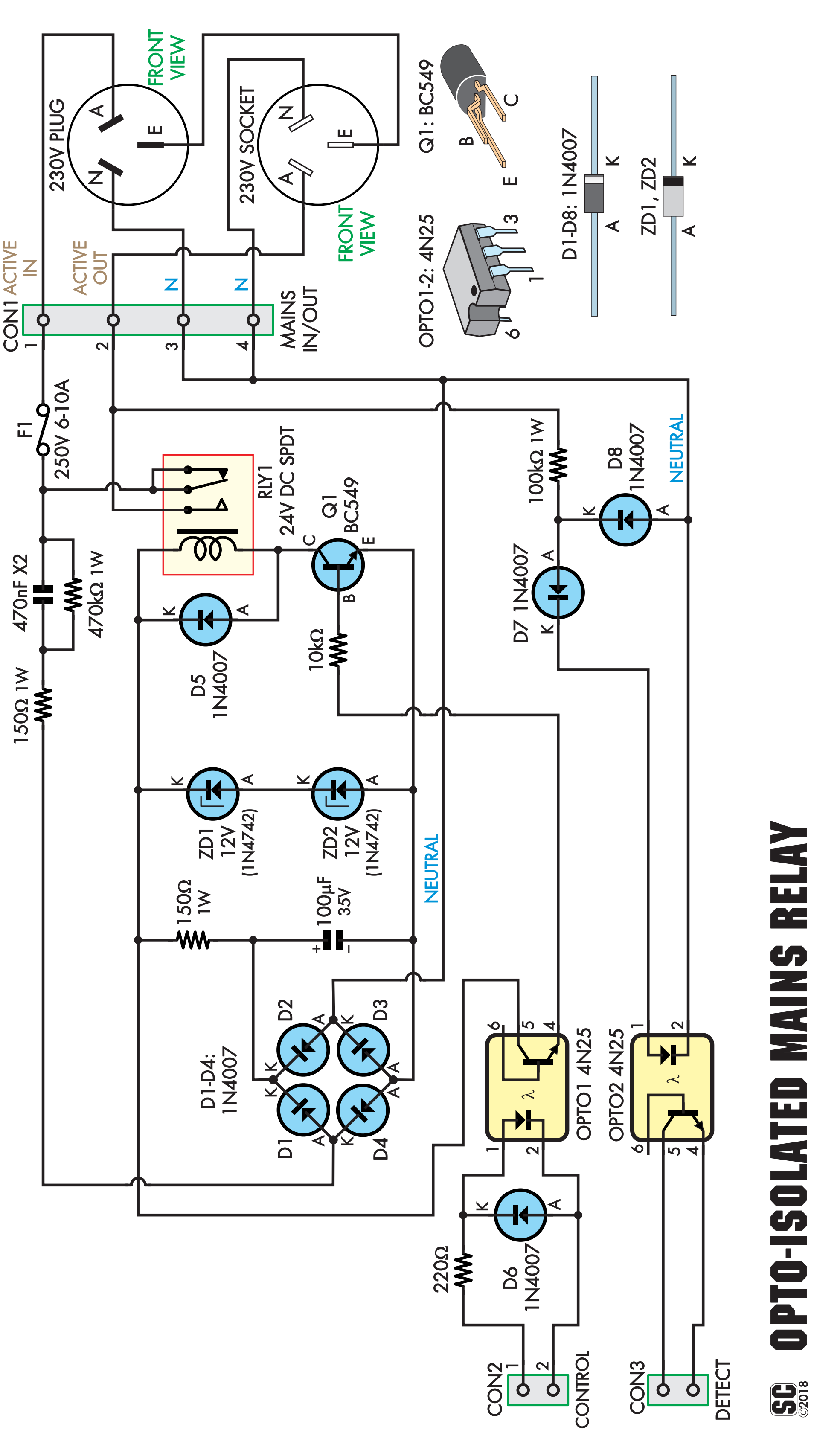


Figure 1: The complete circuit and wiring diagram for the Opto-Isolated Relay. The control signal at CON2 drives the LED in OPTO1 which switches NPN transistor Q1 to activate relay RLY1. The incoming mains Active voltage is applied to a 470nF X2 capacitor and then rectified by diodes D1-D4 and filtered by a 100µF capacitor to provide around 25V DC for the relay coil. OPTO2 allows mains phase sensing and indicates when the load has mains power.

iting resistor. Q1 provides some gain so that sufficient current flows through the coil of RLY1 to latch its armature, connecting pins 1 and 2 of CON1, the mains terminal and connecting the Active pin of the mains output socket to the mains input.

Diode D6 prevents OPTO1's internal LED from being reverse-biased if the voltage at CON2 is reversed, mainly to protect against damage from static electricity. The outgoing Active line also drives the LED in OPTO2 via a 100kW 1W mains-rated resistor and a simple half-wave rectifier consisting of diodes D7 and D8. So when the Active voltage is above about 2V, D7 is forward-biased and current flows through the LED in OPTO2.

As a result, current flows between the pins of CON3 during the positive half of the mains waveform, if RLY1 is latched on. CON3 can be connected between a microcontroller digital input pin and ground so that the micro's pin is pulled low in this case. A pull-up of some sort is required on that pin, to ensure its state changes when OPTO2's output switches off; many micros have built-in pull-ups which can be enabled in software. That micro can also measure the frequency of the pulses from CON3 to determine the mains frequency (this is usually pretty accurate, so it could be used as a reference) and the transitions are near the zero crossings. There will be a slight phase shift due to the threshold being 2V rather than 0V but this can be compensated for in software if accurate detection of zero crossings is necessary.

Mains power supply

RLY1 has a 24V DC coil because a higher coil voltage means a lower coil current for the same power, and we have limited current available to drive it with such a simple power supply. Neutral is connected directly to the circuit ground and the supply current comes from the Active conductor via a 470nF X2-class capacitor which limits the average current and a 150W series resistor which limits the inrush current. The resulting voltage is then rectified by a bridge rectifier comprising diodes D1-D4 and filtered to pulsating DC using a 100µF electrolytic capacitor.

A 470kW resistor across the X2 capacitor discharges it when the unit is unplugged, to minimise the risk of getting a (small) shock from the circuit. If you consider what happens starting at a zero crossing, when the Active

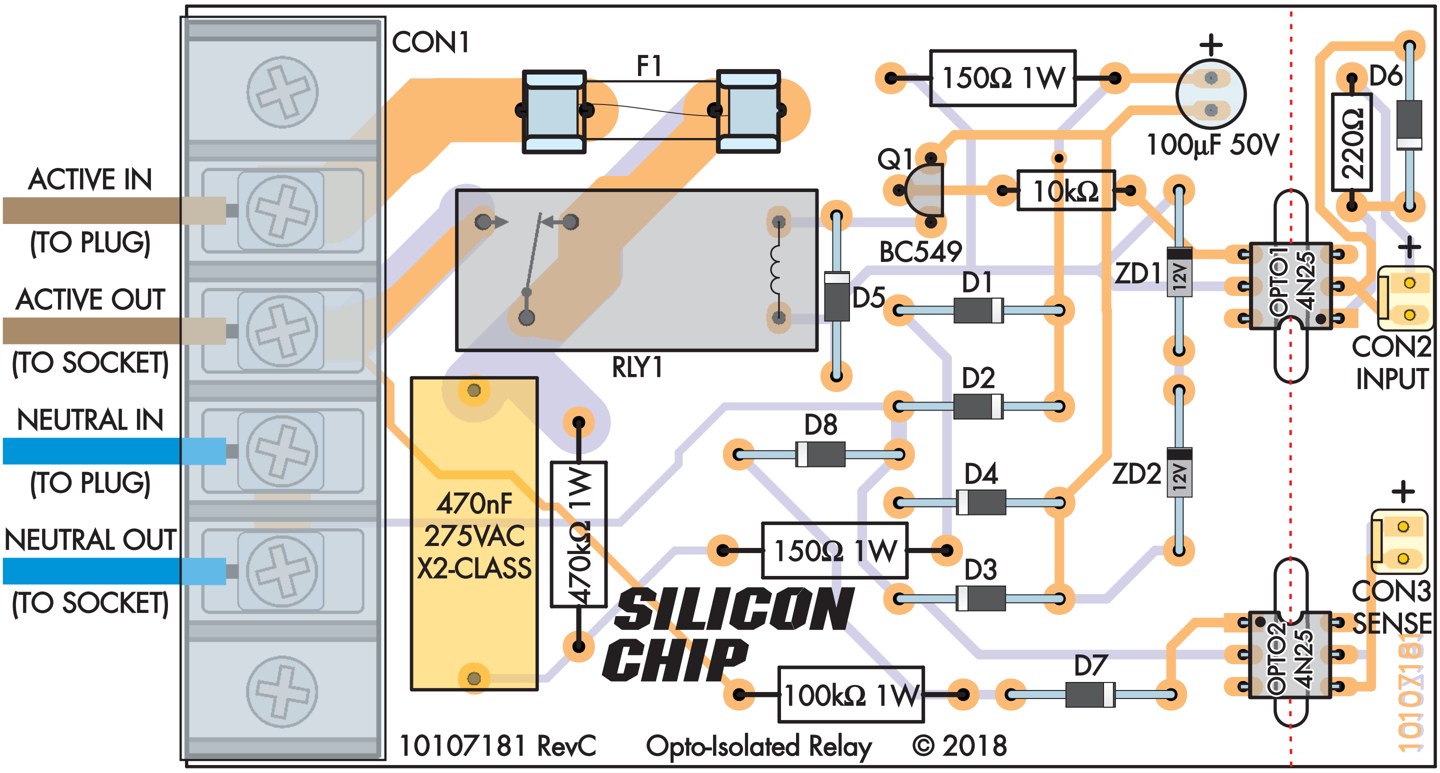


Figure 2: Use this overlay diagram to assemble the PCB. The safe, low-voltage side is at the right while the rest of the board is connected directly to the mains. During construction, take care with the orientation of the diodes and the electrolytic capacitor. The PCB should be sealed in its box before plugging it in. The layout has changed slightly since the prototype was built, to increase track clearances.

voltage is rising, the right-hand side of the X2 capacitor rises to around 350V DC while the left-hand side is limited to around 25V, due to zener diodes ZD1 and ZD2 which are effectively across the output of the bridge rectifier. Thus, the X2 capacitor charges up to around 325V DC. When the Active voltage starts to drop again, current flow through this part of the circuit ceases, until the Active voltage drops to around 300V DC. The left-hand side of the X2 capacitor will then be at about -25V and so current will flow through the other half of the bridge rectifier and the X2 capacitor will start to discharge.

It will have fully discharged when the Active voltage is around -25V and then it will start to charge in the opposite direction and the whole process will repeat as Active reaches -350V and then starts heading back towards 0V. This process repeats continually, maintaining the charge across the 100µF capacitor at around 30V while drawing just a few milliamps from the mains.

Voltage regulation

When there is no signal at CON2 and RLY1 is off, the two zener diodes keep the positive end of RLY1's coil at around 24V; this is more than enough voltage to allow its armature to latch. When Q1 does pull in, it diverts some but not all of the current that was flowing through the zener diodes to the relay's coil instead. At 50Hz, the 470nF capacitor has an impedance (reactance) of about 6.8kW, limiting the current drawn from the mains (230VAC) to around 33mA. The 24V relay draws around 22mA at 24V, so the current through the zener diodes drops from around 33mA to around 11mA. This assumes the mains is at the nominal 230V. These numbers change if the supply voltage changes, and so the extra current means the relay will work reliably even with mains voltages slightly below 230V.

ZD1 and ZD2 also limit the voltage across the 100µF filter capacitor to a safe level. We have used two 12V zeners rather than one 24V zener as the total dissipation with RLY1 off is not much below 1W and could be higher if the mains voltage is elevated. The second 150W series resistor, between the 100µF capacitor and relay coil, helps to prop up the coil voltage for the first few milliseconds after Q1 switches on, ensuring that it latches correctly.

This works because the 100µF capacitor can charge a to a slightly higher voltage initially, due to the voltage across this added resistor. Diode D5 protects Q1 from voltage spikes from back-EMF when RLY1 switches off, while fuse F1 blows if there is a fault on the mains side of this circuit, or if the load goes short-circuit, preventing any further damage. As noted, RLY1 requires around 22mA to operate. Q1's h_{FE} is typically over 400, meaning a base current of 55µA is needed to activate the relay. Assuming that OPTO1's CTR is at least 20%, that means the driving circuitry needs to be able to supply around 0.3mA at a minimum voltage of about 2.2V, to switch on the relay.

Construction

As with any circuit involving mains voltages, it is imperative that the case and mechanical construction are completed correctly to ensure the safety of the completed circuit. Attention to detail when building the PCB is critical too, as a single reversed diode could destroy other components in the circuit before the fuse has a chance to blow. The Opto-Isolated Mains Relay is built on a PCB coded 10107181 which measures 99 x 60mm. The PCB is designed to

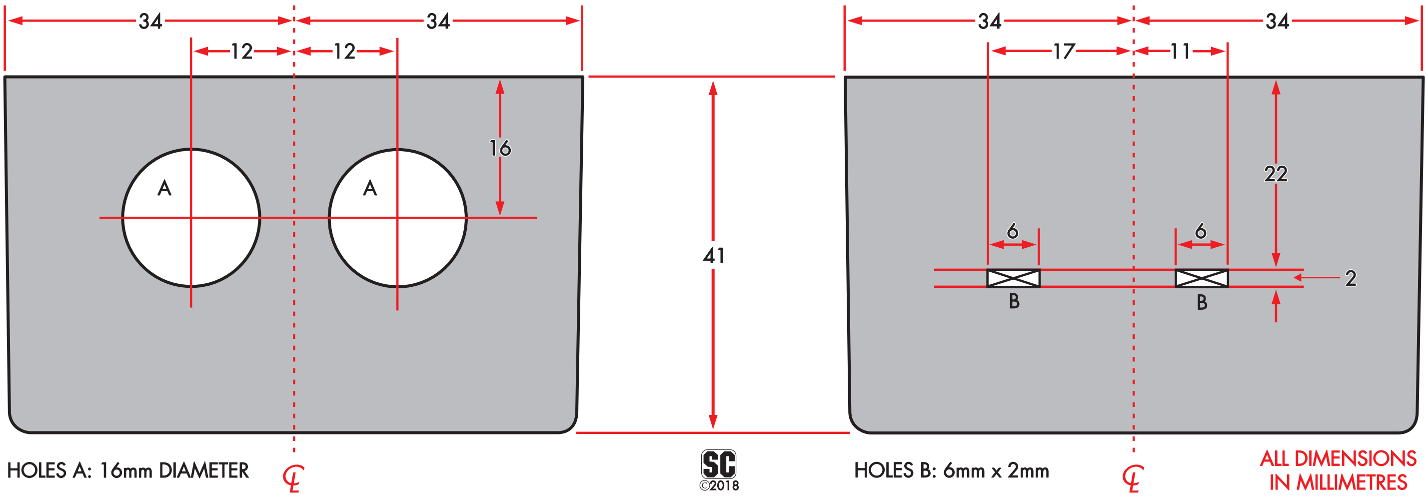
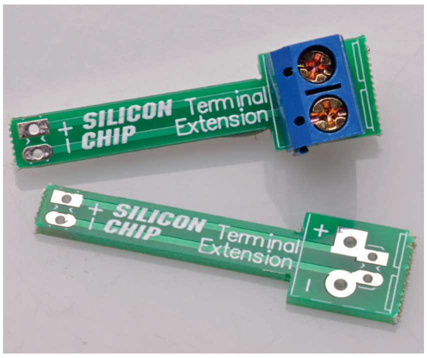


Figure 3: Drilling and cutting diagram for the UB3 plastic Jiffy box, reproduced same size. The two 16mm holes are for the cable glands that clamp the mains cords while the slots are for either figure-8 wires or extension PCBs to give access to the isolated control and feedback signals. The slots can be made by drilling a series of small holes which are then joined and shaped using a needle file.



Photographs: The Opto-Isolated Relay mounted inside a UB3 Jiffy box with the mains power plug and power socket wired up. Note the terminal extension boards, as shown above, are wired positive (+) to positive. These are optional attachments to make connecting your control module easier.

clip into the internal side rails of a UB3 Jiffy box, leaving just enough room at the end of the box to fit two cable glands, which are used to secure the mains cables. Use the PCB overlay diagram, Fig.2, as a guide during assembly. The first step is to fit the low-profile passive devices, starting with the resistors. Table.1 shows the colour coding used on the resistor bodies but it's best to double-check the values with a multimeter before soldering them in place where shown in Fig.2. Fit diodes D1-D8 next. Take care to insert them with the cathode stripe in the orientation as shown in the overlay diagram. Note that D1 and D2 face the opposite direction to D3 and D4. Then mount the two identical zener diodes. Again, ensure that the cathode band is orientated correctly.

Q1 is the only transistor, and it should be orientated as shown in Fig.2. You may need to bend and adjust the legs to fit the holes on the PCB (eg, using smaller pliers). The two optocouplers, OPTO1 and OPTO2, should be soldered next. Note that the notches on the packages both point in towards the centre of the board. The PCB has been slotted to reduce the chance of leakage between the two halves of the board (ie, increase the creepage distance), so we have added a dot adjacent to the number one pin in each case. Align this with the dot on the optocoupler packages.

If you are going to install header terminals for CON2 and CON3, now is a good time to do so. You could instead solder wires directly to these pads later. If you are installing the extension pieces, fit the header terminals with the long pins down. Next, fit the fuse holder clips to the board. Make sure the retention tabs are facing towards the outside or else the fuse will not fit. You can temporarily install the fuse to make sure the holder clips are placed correctly but be careful if you solder the clips with the fuse in place, as the heat could damage the fuse (eg, you could accidentally desolder the end caps). Remove the fuse after soldering. Install the electrolytic capacitor next. It is polarised, so it must be fitted the right way around. The stripe on the capacitor body indicates the negative lead while the positive lead is longer. The positive lead should go into the pad marked with a + sign. We have specified a 50V capacitor, but a 35V or 63V rated capacitor would work fine. Solder the barrier terminal in place now.

These screws prevent any stress on the solder joints. But the cable glands we're going to use to clamp the mains cords should also prevent stress so the Altronics version without the moutning screw holes should be OK too. The terminals on the barrier terminal are quite large, so you may need a bit of extra solder and heat to ensure a good mechanical and electrical connection. Finally, fit the X2 capacitor and relay. Both should be pushed down fully onto the PCB before soldering. The capacitor is not polarised while the relay can only go in one way.

Putting it in the box

You must mount the PCB in the Jiffy box to provide sufficient insulation to make it safe. Start by drilling two holes at the end of the UB3 Jiffy box to suit the cable glands. The specified glands require 16mm holes. If you are using a different gland, you may need a different hole size. Use the cutting template, Fig.3, as a guide. The two slots on one end of the box are designed to provide access to CON2 and CON3. You could simply solder some light-duty figure-8 wires to those pads, or use twin leads with DuPont headers on the end to plug into the pin headers.

We've also prepared two slim PCBs which are supplied along with the main PCB and these can be soldered to the board in place of CON2 and CON3. They then pass through slots in the case and have mounting pads for small terminal blocks, which sit just outside the plastic case and make it easy for you to attach wires for connection to your control module. Regardless of which approach you take, we suggest you make the slots anyway since you need some way to get the control signals into the case. They can be made by drilling a few small holes in a row (eg, using a 2mm drill bit) and then joining and shaping them with a needle file.You could drill a larger hole but that would make it easier for dust and debris to get inside the box. You certainly shouldn't make these holes any larger than necessary to prevent wires from accidentally poking inside the case, which could (in an admittedly unlikely scenario) make contact with live portions of the board. A step drill is handy for drilling the larger holes for the cable glands but if you don't have one, you can use a tapered reamer instead. Fit the cable glands to the enclosure and make sure the nuts are done up tight.

We found that the lips on the mounting nuts overlapped slightly, so we trimmed them with a sharp pair of sidecutters.

Preparing the mains cable

It's up to you where to cut the mains cable to form the two leads. You could cut it in the middle to get two equal-length cords, or you could make the plug or socket end longer, depending on your application. Make sure there is at least 30cm of cable left at each end after cutting it. Once you have cut the cable, there are exposed ends that present an electrocution risk if the plug is connected to a socket. Take great care to ensure that the plug cannot be plugged into a socket while you are working on it (or if you leave it unattended). It helps to plug the plug end into the socket end until you have finished wiring it up.

Feed the cut ends of the cable through the glands. The plug end should go through the gland closest to the fuse. Make sure to thread the domed nut onto the cable first, if you had to remove it. Strip back the outer insulation by 25mm on both ends, then strip the insulation back by 5mm on the Active (brown) and Neutral (blue) wires. The Earth wires (green and yellow stripes) should be stripped back about 15mm. Remove the clear barrier from the terminal barrier and attach the wires as shown in Fig.2. The top screw terminal takes the incoming Active (brown) from the plug lead. The next screw terminal is for the outgoing Active wire to the socket, also brown. Ensure both of these are firmly screwed down.

The bottom two screws are for the two Neutral wires (blue) and they are connected together on the PCB. While it will work regardless of which wire goes to which screw, it is neater to connect the incoming (plug) Neutral wire to the third terminal and the outgoing (socket) Neutral wire to the bottom screw terminal. The two Earth leads should now be joined using the BP-style double screw connector. Twist the wires together and then insert them into the connector, making sure that they both reach all the way to the end, then do up both screws tight and check that they have both clamped the wires.

Now check your work to ensure there are no exposed copper strands from any of the wires either floating around or touching the wrong terminals and then replace the transparent barrier strip over the barrier terminal. Check also that none of the wires can move around in their respective screw terminals. To test the unit insert a 100mA (or similar current) fuse in the holder and slot the PCB into the grooves in the enclosure, then tidy up the wires using cable ties. You can tuck the BP-style screw connector under the gland entry inside the box. Check that around 5mm of the outer mains cable insulation is visible inside the box before firmly tightening the glands. This ensures that the glands grip the cables securely.

Testing

Parts List

- 1 double-sided PCB, coded 10107181, 99mm x 60mm
- 2 double-sided PCBs, coded 10107182, 38mm x 10.5mm (optional)
- 1 230V 10A extension cord (or mains plug and socket with leads)
- 2 cable glands to suit mains cord Altronics (H4312A/H4313A)
- 1 UB3 Jiffy box (Altronics H0153/H0203)
- 1 4-way PC mount terminal barrier (CON1) (Altronics P2103)
- 1 BP-style double screw connector (Altronics P2125A)
1 250V-rated 24V DC coil relay (RLY1) (Altronics S4199 16A, recommended)
- 2 M205 PCB-mount fuse clips (F1) (Altronics S5983)
- 1 M205 slow-blow fuse to suit relay contact rating, no more than 10A (Altronics S5662)
- 1 M205 100mA or similarly rated fuse (for initial testing only)
- 2 2-way headers, 2.54mm pitch (CON2,CON3)
- 2 M3 x 20mm Nylon machine screws
- 2 M3 Nylon hex nuts
- 2 M3 Nylon flat washers

Semiconductors
- 8 1N4007 1A 1000V diodes (D1-D8)
- 2 12V 1W zener diodes, eg, 1N4742 (ZD1,ZD2)
- 2 4N25 optocouplers (OPTO1,OPTO2)
- 1 BC549 100mA NPN transistor (Q1)

Capacitors
- 1 470nF 275VAC X2-class MKT/MKP
- 1 100µF 50V RB electrolytic

Resistors (all 1W, 5% unless otherwise stated)
- 1 470kΩ: 4 Band Code (yellow violet yellow brown) 5 Band Code: (yellow violet black orange brown)
- 1 100kΩ: 4 Band Code (brown black yellow brown) 5 Band Code: (brown black black orange brown)
- 1 10kΩ: 4 Band Code (brown black orange brown) 5 Band Code: (brown black black red brown)
- 1 220kΩ: 4 Band Code (red red brown brown) 5 Band Code: (red red black black brown)
- 2 150kΩ: 4 Band Code (brown green brown brown) 5 Band Code: (brown green black black brown)

The first tests (with the low-value fuse in place) are to verify there are no problems with the PCB construction. Don't connect anything to the mains socket yet. Place the unit somewhere stable and during testing, stay well away from it – don't touch anything inside the box. Plug the unit into a switched-off GPO and then switch it on. If the fuse blows or the relay activates (you will hear it click), you may have mis-wired something. Turn off the power point and unplug the plug.

You can test for the presence of residual charge by carefully connecting a multimeter on a high DC volts range across the Active and Neutral pins of the mains plug. If there is voltage present after a few seconds, your bleed resistor may not have been fitted correctly.
If all is well, nothing obvious should happen. Turn off the power point, unplug the unit and connect a 3.3-10V DC voltage source to CON2 with the indicated polarity. Turn on the power again and check that the relay clicks as the armature pulls in. That shows that the circuit is working.

Turn off the power, unplug the lead and replace the fuse with the final value. For example, if you are using the 16A relay from Altronics, use a 10A fuse, as the mains leads cannot safely carry a higher current. Testing the mains presence/phase output. The easiest way to test that the CON3 output is working is to connect a high-brightness LED with its cathode to pin 1 of CON3, then connect the anode to pin 1 of CON2 (the positive control signal input) and wire pin 2 of CON3 to pin 2 of CON2. You still need to apply the DC voltage to CON2 since the CON3 output is only active when the relay is latched. If you plug the unit back into mains and switch it on, you should find that the LED lights when the relay is engaged and switches off when you cut mains power. It will actually be flashing at 50Hz with a ~50% duty cycle but this may not be obvious to the naked eye. The LED current will be limited to one or two milliamps due to the limited CTR of OPTO2.

Finishing it off

Before you put the lid on, if you haven't already done so, make the control connections to CON2 and CON3. If using our small extension boards, fit the terminal blocks on the wider end, then feed the boards through the slots in the case (lining up + with + and – with –) and place the holes in the extension PCBs over the header pins. You can then solder them in place.

Note that once this has been done, they need to be desoldered to remove the PCB, so it is important that everything is working and the lid fits correctly before doing this. If soldering wires to the pads for CON2 and CON3, pull them tight and then glue them into the holes in the box with silicone sealant. This ensures that if the solder joints fail, the wires cannot come in contact with the high voltage section of the PCB. Now screw the lid on, to ensure that no live parts are exposed. Also, unwind the cable gland nuts and add a few drops of super glue to the threads, then do them up tight again. This stops anyone from undoing them while the device is plugged in. The 230V Opto-Isolated Relay is now complete and can be used for your intended purpose.

If you are planning to use the output/phase sense signal from CON3 with an Arduino, you can enable an internal pull-up current on the digital input pin using a command like this, within your setup() function: pinMode(3,INPUT_PULLUP);. In this example, connect digital pin 3 to the + terminal of CON3 and GND to the – terminal of CON3. When the mains is off, pin 3 will read high (1), while you would get a low reading (0) during the positive-going half of the mains cycle when the relay is on. You could use a pin change interrupt or counter function to detect the pin toggling if you simply need to know whether the load is powered.

In the event of a blackout or if, for some reason, the relay fails to close, that pin will remain high. You can detect that condition and flag an error (eg, by sounding a buzzer). Mains phase detection is possible using this signal but it's a little bit complicated due to the phase shift – you need to use a timer to measure the positive and negative times, calculate the delay between the zero crossing and the pin going low, then use another timer (or possibly the same one) to compensate. That's a bit too much detail to get into here. You don't necessarily need to use the output sensing function, though. You can leave CON3 disconnected if you do not need that feature.

What to use it for

Have solar panels and a pool? You can use a light sensor and a real-time clock (RTC) module to switch the pool pump on during the day when solar power is available, or during off-peak hours if the weather is bad.

Own a different type of pump? Use a float switch to control a pump. Turn it on when a storage tank is full or off when empty. Some float switches are light duty and may fail when switching high currents. Using the Opto-Isolated Relay to buffer the signal from a float switch will save its contacts from burning out

Need to control a heating/cooling system? Add a temperature sensor (and/or a RTC) to build a custom thermostat.

Own an amplifier (or other appliance) without a power switch? Add a remote-controlled on/off switch to an amplifier, by merely adding an IR decoder to a microcontroller module, hooking up our isolated relay, writing a few lines of code and using a spare TV remote.

Unreliable internet connection? Automatically reboot your router if your internet connection goes down, using a micro board with a WiFi module.

What about a wireless power switch? Controlled by a micro or handheld remote control; just wire up a remote control receiver to its logic-level control input (the receiver needs a separate DC power supply).

Or you can implement a complex light switching arrangement, with multiple light switches controlling the same set of lights. Wire the switches to perform low-voltage signalling and then use this signal to drive the lights via the Opto-Isolated Relay. You could even use switches that are not mains-rated, incorporate remote control etc. You don't even need a microcontroller to use the Opto-Isolated Relay. Any logic signal, from 2.7V up to about 10V can be used to activate the relay. This could come from an op amp output, logic gate, relay, switch, battery, plugpack or any other source of switched DC.

WARNING: this project involves mains voltages which can be dangerous if not handled correctly. Follow the instructions in this article carefully.

Dear Kit Constructor,

At Altronics we take great pride in the quality and presentation of our kits. If you find any deficiency in this kit or have any constructive comments whatsoever, please write to us at kits@altronics.com.au.

Important Note:
Please note that we can offer a warranty only on the components supplied with this kit. Because we are unable to guarantee your labour, there is no warranty on either partially or fully built kits. We are able to offer a repair service, but once construction has commenced, this service is chargeable.