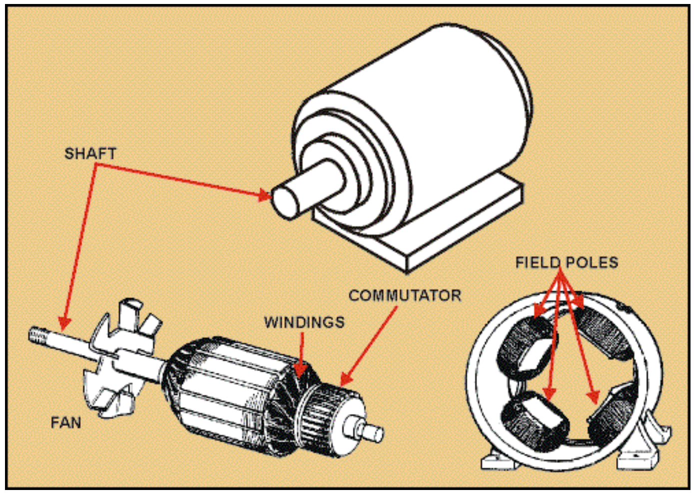
Motors and Variable Speed Drives

©Trevor Pope (tpope AT iafrica.com) – Feb 2005



Inside woodworking machines, you are likely to encounter two types of motors – Induction motors and Universal motors.

I'll deal with so-called "universal motors" first. A universal motor has an armature (the part that rotates) with copper windings on it and a commutator that conducts current to the armature. Typically the commutator has brushes of carbon that rub against a segmented copper ring that switches the current to the right armature windings for the position of the armature, to generate a magnetic field. The stator field is the stationary field generated by the field poles, to provide the opposing magnetic field that generates the torque (turning force) that makes the rotor want to turn. In smaller motors, the field is created by permanent magnets such as on your battery screwdriver. In bigger motors, the field is an electro-magnet – it has copper windings as shown in the diagram. (See http://www.claytonengineering.com/Training/myweb6/101basics.html for more explanations.)

Universal motors have high power-to-weight ratios and tend to turn fast (26000 rpm on your router) so they are well suited to portable power tools. They are also used in some stationary power tools such as the club's Ryobi thicknesser. They are noisy because they turn fast. They also have good low speed torque characteristics that make them less likely stall. Universal motors can operate on Direct Current (DC) from batteries and from the Alternating Current (AC) mains supply. Because of their small size they are inclined to overheat if worked at their maximum ratings for extended periods. Over time, the brushes wear out and need attention. To keep them cool, they need lots of air blowing through them, so they are vulnerable to clogging with sawdust.

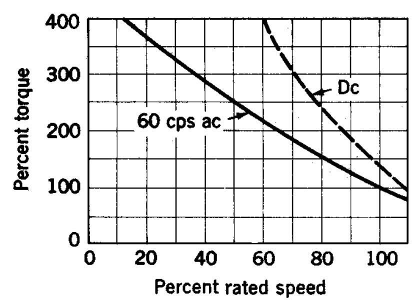
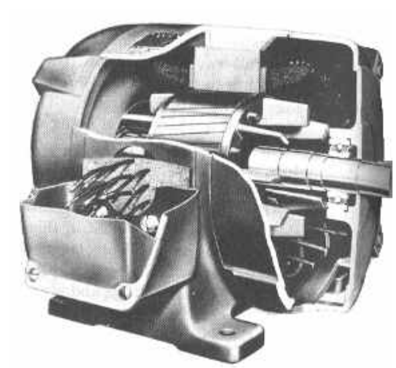


Fig. 11-12. Typical torque-speed characteristics of a universal series motor.

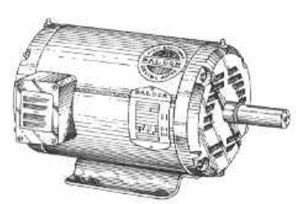
For the technically minded, I have included a graph that shows the torque – speed characteristic for a series wound universal motor (taken from: Electric Machinery 3rd Ed, Fitzgerald, Kingsley and Kusko which was the text for my 3rd year course in 1978).

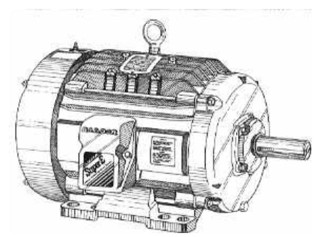
The torque and speed are given in percentages, so the rated torque and speed are 100%. This motor works better with DC, due the lower impedances of the windings at DC, so a separate curve is shown for DC operation. You can see that at lower speeds, the motor is able to develop considerably more torque, which is helpful to prevent stalling and to start up heavy loads more quickly. Due to heating effects, the motor will not be able sustain low speeds and high torque demands for very long without damage. So you can expect high torques for short periods to help through a sticky patch, but don't overdo it or you will smell an expensive electrical-insulation-burning smell! Better machines will have some sort of thermal fuse or resettable cutout to prevent this.

In contrast, induction motors don't have brushes and copper windings on the rotor. The opposing magnetic fields in the rotor are induced by the changing fields in the stator causing currents to flow, using the same principle of magnetic coupling as a transformer. Hence the term: Induction Motor. On smaller motors, the rotor is a composite iron and aluminium assembly (with copper used on bigger motors) that is one solid piece as shown in the picture on the right. The stator is a set of copper field windings that are arranged around the rotor in the body of the motor. The current that flows in the windings is organised so that it creates a rotating magnetic field that rotates at the speed of the frequency of the supply current (50 cycles per second in South Africa). This rotating magnetic field induces currents in the armature that flow in the aluminium (or copper) parts in the rotor. These currents create opposing magnetic fields that act against the rotating magnetic field from the stator, thereby creating the torque that tends to turn the rotor. The induction motor is mechanically simpler than the universal motor, with only the bearings subject to wear on most motors. Some also have a speed sensitive switch that is used during starting.



Open frame motors (see left) have holes for air to flow through for cooling – these are subject to clogging with sawdust like universal motors. Better motors for a dusty environment are the so-called TEFC (Totally Enclosed, Fan Cooled) motors (see right) that are sealed against dust and have a fan at the non-driving end that blows air over the motor to cool it. Some have fins on the outside, to help conduct heat away. TEFC motors are larger than open-frame motors for the same power output, but because they don't get clogged with sawdust, they need less maintenance. In the right conditions, a TEFC motor should last almost indefinitely.





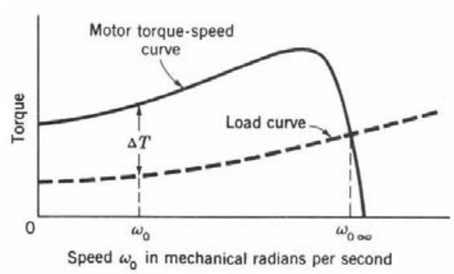
Because of their need for a rotating magnetic field, induction motors only work on AC. The maximum speed of the motor is governed by the frequency of the AC field and the number of poles of the motor. Common motors you will encounter have two poles such as in an electric bench grinder or four poles such as in a lathe. An induction motor operates with slip, which means that it can only approach the speed of the rotating magnetic field and cannot exceed it.

The field in a two-pole motor rotates at 3000 rpm (50 cycles per second x 60 seconds per minute = 3000). With slip, the motor rotates at about 2800 rpm when loaded. In a four-pole motor, the field rotates at 1500 rpm, so the motor rotates at about 1400 rpm when loaded. In bigger industrial applications, you will encounter 6 and 8 pole motors, but these are not common in smaller machines.

As the load on the motor increases, it slips more and slows down, until the limiting torque is reached and the motor quickly stalls. Compared to a universal motor, the limiting torque is lower, so the induction motor is better suited to constant speed applications.

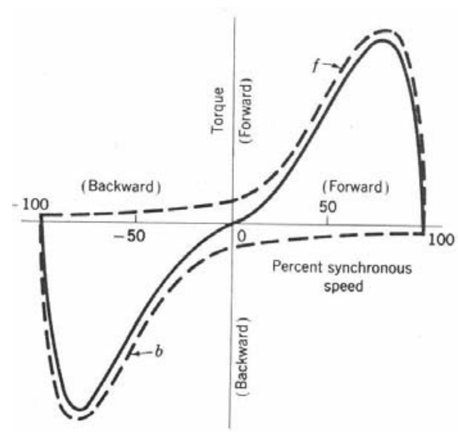
In a three-phase induction motor, the windings are arranged around the stator in three sets, so that the rotating magnetic field rotates clockwise or counter-clockwise, depending on how the phases are wired to the motor. Swapping two of the three wires changes the direction of phase rotation and hence the motor.

When a motor starts, the excess torque (if any) over that absorbed by the load accelerates the motor until the torque demanded by the load exceeds that available from the motor and a steady speed is reached. This is shown in the graph for an induction motor, where the motor has reached close to the synchronous speed, where the torque drops off steeply. The speed settles at the intersection of the two curves at $\omega_{0\infty}$. Should the load demand a lot more torque, the speed will drop slightly and the motor will be able to deliver it – a fair approximation to a constant speed is achieved over a wide range of loads. When the torque demanded exceeds that available from the motor, the motor will quickly stall.

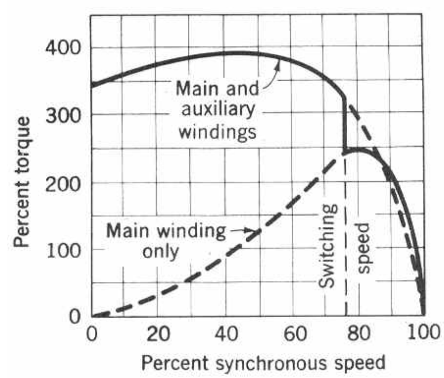


The rotating field is not so easily arranged in a single-phase motor, so extra windings are used to simulate the phase rotation, sometimes with a capacitor to induce a phase shift. To change the direction of single-phase motor, the sense of one of the windings needs to be changed, but this is not as simple as for three-phase, due to the variety of motors types. Consult with the supplier to confirm the required wiring changes.

Induction motors generally have low starting torques, and single-phase motors are worse. Without a start winding, the torque – speed curve looks like the symmetrical one on the right. At zero speed there is no torque to start rotation. Without some rotation, the motor will just sit and hum. This is what happens when the start circuit fails. If the motor is given a small impulse forward or backwards, some torque is generated, and it will slowly accelerate up to speed.



Start windings can be arranged without or with capacitors, depending on the type of load. With a start winding, the torque – speed curve is a composite of the start (called auxiliary in the diagram) and the main winding. You can see from the curve on the right, for this particular motor, there is considerable starting torque. However, the motor cannot sustain this without being considerably larger, so to prevent overheating, the start winding is disconnected by a centrifugal switch when the motor gets up to speed, as shown in the diagram. This high starting torque is useful to get a machine with a lot of inertia up to speed quickly, however a lot of current will be drawn for a short time, dimming the lights, or even tripping a circuit breaker. Also a lot of heat will be dissipated in the motor, which is why you may need to be cautious about starting and stopping too frequently. This sort of motor would be suitable for starting a load like a compressor or a lathe.



If the centrifugal switch fails, you may see starting problems or overheating of the motor, depending on whether it fails in the open or closed position.

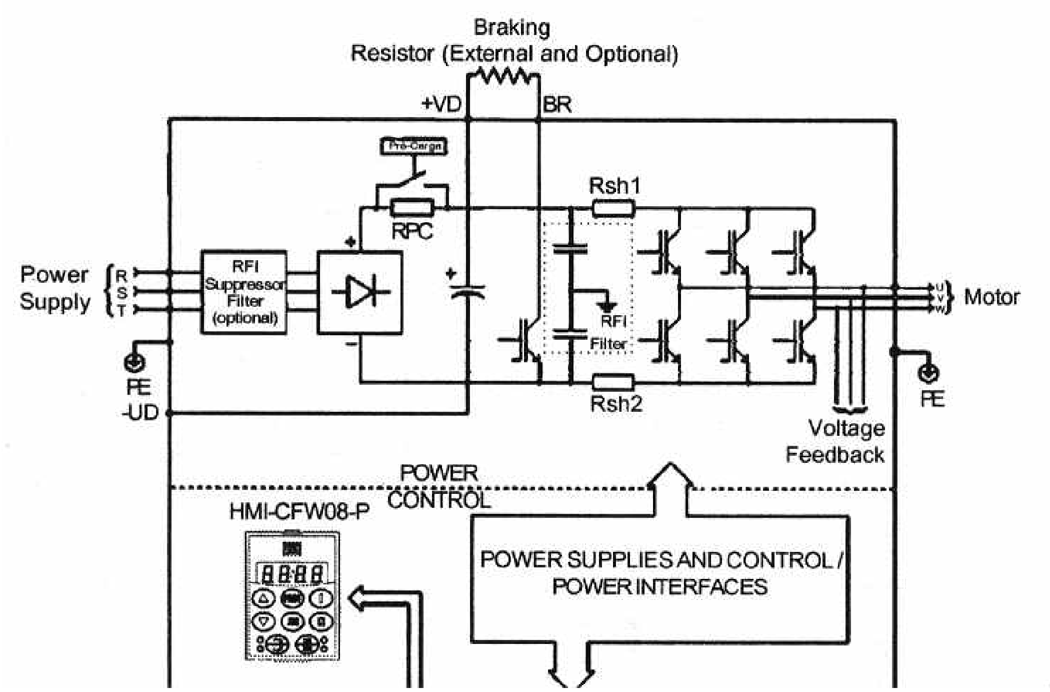
Single-phase motors generally have two sets of windings, as opposed to the three in three-phase motors, so they are less smooth. They have lower starting torques and are generally bigger and more expensive for the same power output. This is why, when three phase supplies are available in industrial situations, three-phase motors are always used.

> Consult the nameplate of the motor to see all the vital information on the motor – voltage, current, power, speed, insulation and duty cycle ratings.
>
> The type of speed control used depends on the motor type.
>
> Universal motors are mostly insensitive to the frequency of the supply, operating off DC or AC mains, or a battery, so simply limiting the voltage to them controls the speed of these motors. In the past, a

variable resistor was used, which was rather inefficient and resulted in the loss of low speed torque. Nowadays, an electronic circuit is used that uses AC phase control or DC pulse-width modulation (PWM). This is much more efficient and preserves the low speed torque of the motor. Even the most simple battery drill or screwdriver can boast such a circuit that allows you to control the speed from almost zero to full speed with excellent torque.

Induction motors are more difficult to control. They respond to the frequency of the supply and only slightly to the voltage changes, so to change the speed, you need give them a variable frequency supply. In the past, this was difficult, as the mains supply frequency is fixed. However, nowadays, we have that electronic marvel called an inverter.

So how does an inverter work? Basically it feeds the induction motor with a variable frequency input, so that it rotates at the corresponding speed. Changing the frequency changes the speed.



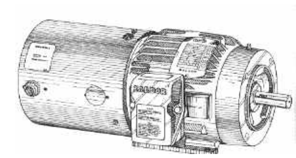
An inverter has an input power supply that converts the AC supply to a constant DC high voltage supply, shown by the diode block on the left and the capacitor. The DC voltage is then chopped into an AC supply for the motor at a variable frequency as required by the user to control the speed of the motor. The chopping circuit uses high voltage transistors controlled by the control/power interface and the microprocessor. It uses Pulse Width Modulation (PWM) to generate an approximation to a sine wave that keeps the motor running smoothly and reduces losses in the windings. Most chopping circuits operate in the higher audible range, which is the high-pitched whine you can often hear when the inverter is operating.

The inverter has a microprocessor that monitors the voltages to the motor and keeps these within safe-levels to protect the motor against overheating and over-voltage stresses. The microprocessor can ramp up the speed slowly at start-up to prevent massive start currents stressing the motor and the mechanical components. It can also implement dynamic braking to slow down the motor more quickly to a stop if required. This is where the motor is turned into a generator that dumps energy into a resistor, generating a braking torque to slow it down more quickly. The inverter can be programmed to control the speed against an input or control signal to keep it constant if needed, by compensating for slip at different loads.

An inverter has the advantage of a widely variable speed range that is continuously variable from some practical minimum, such as 30 rpm up to the rated speed of the motor (1500 rpm for a 4 pole motor). The inverter can be set up to compensate for speed variations at different loads. It can ramp the speed up and down smoothly to prevent mechanical shocks to the drive train. You can use it with a speed control knob that is quick and easy to adjust. When used with a three-phase motor, if you want to reverse the direction for sanding, just press reverse. The inverter will safely slow down to a stop and reverse up to the same speed turning in the other direction. Obviously, on a lathe, you need to make sure that your work will not unscrew from the spindle when operating in reverse!

Attaching an Induction Motor

What an inverter cannot do is give you more low-speed torque than the motor is capable of. The torque is limited by the magnetic fields in the motor that are created by the currents that can flow in the windings, so the inverter is programmed to limit this to safe levels for the motor, to prevent overheating. Fan cooled motors rely on the fan operating at near to rated speed, so if the motor is operating at much below rated speed, cooling is drastically reduced. A fan is a square law device – the airflow increases with the square of the speed, so at low speeds a fan is largely ineffective. Special inverter rated motors are supplied with independent fans to maintain cooling at low speeds (see right where an auxiliary fan can be seen on the left of the motor). So with a standard induction motor, you cannot get large torque outputs at slow speeds just using an inverter. You need some other sort of torque multiplying device.



A mechanical torque-multiplying device is still needed if large torque at slow speeds is required. What is a torque-multiplying device? Examples are a reduction gearbox or a pulley drive with different pulley sizes – a smaller one on the motor shaft, and a larger one on the spindle shaft. The gearbox on your car multiplies the engine torque in low gears for better acceleration. You can see examples of a multiple speed pulley drive on your drill press or lathe. Most lathes fitted with a variable speed drive still retain two or more pulley options, so that you get high torques at low speeds if you need them (such as the VB36 and the Stubby lathes). Those that don't often have a higher minimum speed at reasonable torque outputs to stay within the limitations of the motor such as the Nova DVR (100 rpm). The DVR has a special 1.3 kW motor and controller that are carefully matched for optimum performance. The controller is programmed to keep the range of operating speeds and torques within the safe operating region of the motor, so you know that you cannot overheat the motor. The DVR is designed to give you good low speed torque characteristics that you won't find just by adding an inverter to a three-phase motor alone.

Adding an inverter to an induction motor.

The speed flexibility offered by an inverter is a great asset on a wood turning lathe. You can rapidly change the speed and also make small changes to avoid vibrations that can set up a resonance. Most lathes come with single-phase motors, and these motors are not really suitable for use with an inverter. It can be done, but the inverter needs to be larger and is more expensive that the equivalent three-phase inverter, so the combination of an inverter and a new three-phase motor will be cheaper and better. When I last priced these, a combination one horsepower (0.75kW) inverter and three-phase motor cost between R3000- and R4000-, with the motor coming in at less than a R1000-. If you are converting an existing lathe, you may be able to sell off the single-phase motor to recover some of the cost.

Smaller inverters usually run off a single-phase supply, and there are some that will run off both single and three-phase. If you are converting a single-phase machine, it makes sense to buy the inverter and a new three-phase motor as a matched combination, so that they will be appropriately rated for your application (power, duty cycle and torque characteristics). There are several suppliers and the ones I have contacted offer good technical support. The inverter manuals that I have seen are comprehensive. Inverters are very sophisticated these days, but most of the options can be left at the default settings, and the supplier should help you with any changes needed for your application.

If you have an existing three-phase motor that you wish to connect to an inverter, you need to be more cautious. Modern motors come in “Inverter rated” versions, which is what you should get when you buy a combination as above. The grade of insulation needs to be higher, due to the extra voltage stresses imposed by the high switching frequencies generated when the inverter generates the approximate sine waves.

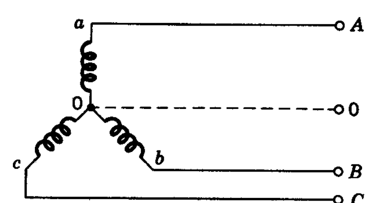
You may wish to add an inverter onto an existing machine that is fitted with a three-phase motor, such as a saw bench to operate on a single-phase supply. These usually operate at a constant speed, so there is little to be concerned about. It might be cheaper to change the motor to a single phase one, unless you have several three-phase machines. These can all be operated from a single inverter, with the appropriate power ratings. You must check the cable lengths, as long cables can induce high voltage spikes in motors driven by inverters (leading to insulation failures) – check with the suppliers.

When you are using an existing three-phase motor, as mentioned above, and you wish to vary the speed, then you need to worry about the operating speed range of the motor, and particularly cooling at low speeds. If you want to operate at low speeds only for light finishing operations on a lathe, you should be OK. That should not stress the motor too much. However, if you plan on roughing out large blanks with heavy cuts at 200 rpm, then you need to be careful. (Large torque requires large currents, which have large I^2R losses, and without the required cooling air at low speeds, the motor will overheat.) If you have a data sheet on the motor, you can often program the inverter to protect the motor. For reliability, you also should consider either a larger motor with a better duty cycle rating and/or a torque-multiplying device, such as a lower pulley ratio.
In other words, for heavy cuts at low speeds, choose a pulley ratio that runs the motor quickly and the work-piece slowly. Then the motor runs fast enough to stay cool, and the work-piece runs slowly enough, but with all the torque you need for heavy cuts.

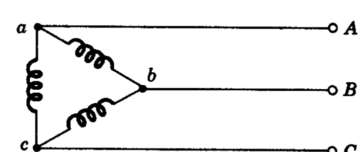
You may also want to add on separate start, stop and speed controls. These can be housed in a separate box located in the most convenient place, and are more robust than the membrane keys on the panels of most inverters. The supplier may be able to sell you some parts and advise you on how to wire them up if the manual is not clear.

All this may sound rather technically daunting, but if you ask around the club, you are bound to find one or two electrical engineers and electricians who are comfortable with this technology, who would be able to help you. Also the suppliers are helpful. When you buy, take along the switchgear and cables you have and ask them to show you how to wire everything up. They may also help you configure the inverter for your application. Before you switch on, get an electrician to check your wiring is correct and safe.

Peter Middleton suggested that I give more information on how induction motors are wired up, so that you know what to look for.



(a)

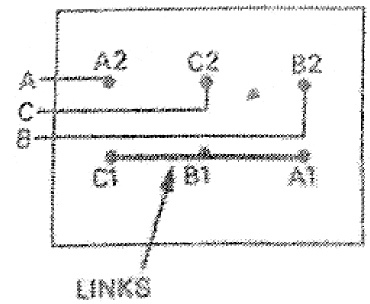


(b)

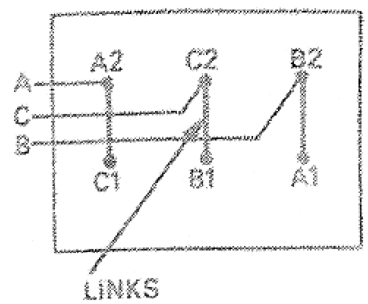
Three phase induction motors can be wired up into two configurations, called star and delta.
Star: The star configuration (a) has the windings connected to one common point at one end, called the neutral point (0), and the other ends are connected to the phases. The phase-to-phase voltage here is commonly 400V, which is used in industrial installations (it was previously 380V which relates to 220V). The voltage across the individual windings is still 230V (The phase to neutral voltage). Due to the phase relationships between the phases, the line-to-line voltage is √3 x phase voltage. If you draw a vector diagram and calculate the voltages between the three phases that are 120° out of phase, you can show this.
Delta: If you look at the diagram (b), you will see that the delta configuration has the three windings arranged in the form of a triangle, hence the delta term. The windings are connected directly across

the phases. For the motors that interest us, the phase-to-phase voltage is 230V. (The new IEC standard is 230V, which harmonizes the mixture of standards previously implemented, which were 220V and 240V.)

Usually, if you have a three-phase induction motor that is wired for 400V as a star configuration, it can be wired for 230V in a delta configuration. Inside the motor terminal box are six terminals for the ends of the three windings, and these can be rewired by changing the jumper strips. There seems to be a standard way of doing this as shown in the diagrams (to BSS822), but it is just as well to be cautious and measure the windings to make sure if no information is given with the motor. The upper diagram shows the links connected for a star configuration. The lower diagram shows the links connected for a delta configuration. You can check this by removing the links and checking continuity to identify the individual windings. For the individual windings A1-A2, B1-B2, and C1-C2 the locations should correspond to the diagrams.



Some motors only have three terminals, and these are often wired internally in a star configuration for 400V, with the neutral buried in the motor. By dismantling, the neutral points can sometimes be brought out, but this should be done with caution: you need to know what you are doing, to get the phasing right.



To summarize, for domestic applications with a 230V single-phase supply, using a 230V inverter, you need to connect the motor for 230V in a Delta configuration (lower diagram). In an industrial application, where you have a three- phase supply, 400V phase-to-phase, the same motor will be wired in a Star configuration.

Bear in mind we are dealing with 230V AC Mains here which is potentially dangerous, so you must know what you are doing and work carefully, to guard against errors. If you are unsure, before you switch on, measure all the current paths to look for shorts and imbalances. Ask a licensed electrician to check the circuit for you. (There is an advert for Stan Lewis in this issue.)