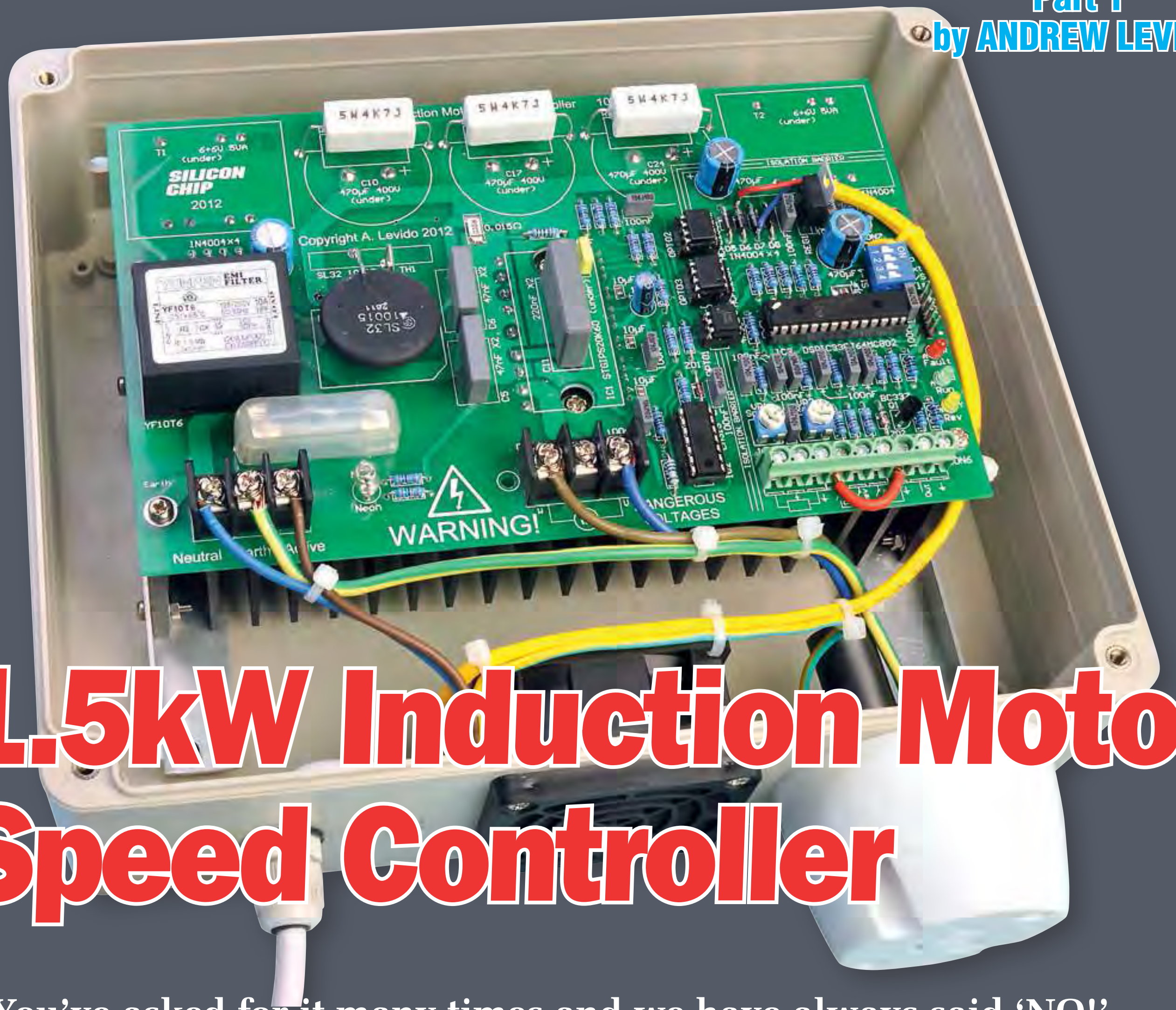
Part 1

by ANDREW LEVIDO



1.5kW Induction Motor Speed Controller

You've asked for it many times and we have always said 'NO!' It's too complex, too difficult, too expensive, whatever. Now we're saying 'YES'. This *Induction Motor Speed Controller* is suitable for motors up to 1.5kW (2HP) and can be used to control speed over a wide range. It will save big dollars with swimming pool pumps and will be great for running machinery at different speeds. Even better, it will control 3-phase motors as well!

WE HAVE PUBLISHED quite a few speed controllers over the years, some suitable for DC motors and others for universal AC motors. Up until now, we have not published a design suitable for the most common type of AC motor – the induction motor.

Controlling the speed of induction motors is not easy; you cannot simply reduce the voltage and hope that it works – for two reasons. First, an induction motor's speed is more or less locked to the 50Hz frequency of the 230VAC mains supply; so reducing the supply voltage doesn't work. Second, induction motors don't like reduced supply voltage; it makes them difficult to start and there is a risk of burnout.

No, the only reliable way of controlling the speed of an induction motor is to vary the drive frequency. As we shall see, it is not enough to simply vary the frequency; as the frequency drops below 50Hz, the applied voltage must be reduced proportionally to avoid magnetic saturation of the core. This makes the electronic circuitry complex and its design is made more difficult by the wide variety of induction motors.

Fortunately, advances in power semiconductors have reached a point where such a project is now viable. But our previous objections still apply. It is complex, relatively expensive and potentially dangerous.

This project is only recommended for experienced constructors. Most of the circuit is at 230VAC mains potential, and worse, it has sections running at 325-350V DC. Furthermore, the circuit can remain potentially lethal even after the 230VAC mains supply has been disconnected.

We envisage a typical application of the speed controller will be in reducing the energy consumption of domestic pool pumps – one of the biggest single contributors to the power bills of pool owners. You should be able to build this unit for a couple of hundred dollars, making it a much more attractive proposition.

That said, we have tried to make this unit fairly versatile. It will drive virtually any modern 3-phase induction motor or any single-phase motor that

Features and specifications

Features

- Controls single-phase or 3-phase induction motors
- Runs from a single-phase 230VAC, 10A power point
- Over-current, over-temperature, under-voltage, over-voltage, short-circuit protection
- EMI (electromagnetic interference) filtering for reduced radio interference
- Inrush current limiting
- Isolated control circuitry for safety
- Adjustable speed ramp up/down
- Pool pump mode
- Tool spin-up mode
- Can run 3-phase motors in either direction
- Optional external speed control pot with run, reverse and emergency stop switches
- Motor run/ramping and reverse indicator LEDs
- Fault indicator LED
- Open-collector output provides either fault or up-to-speed indication

Specifications

Motor power: up to 1.5kW (2 horsepower)
Maximum output voltage (single or 3-phase motor): ~230V RMS
Continuous output current: 8.5A RMS (single-phase), 5A RMS (3-phase)
Short-term overload current: 13A RMS (single-phase), 7.5A RMS (3-phase)
Switching frequency: 16kHz
Quiescent power: 28W
Speed ramp period adjustment: 1-30s to full speed
Continuous input current: up to 8.7A RMS
Speed control range: 1-100% or 1-150% (0.5Hz to 50Hz or 75Hz) in 0.05Hz steps
Efficiency: up to 96%
Speed control signal: 0-3.3V
Up-to-speed/fault output sink: 12V/200mA

This is an improved and updated version of the original *Silicon Chip Induction Motor Speed Controller*. It incorporates a number of improvements which have been made since they published the original design, including PCB design improvements, up-rated parts and revised software.

does not contain a centrifugal switch, rated at up to 1.5kW (2HP).

In this first article, we describe the features of the controller and explain how it works. In the follow-up article next month, we'll detail the construction, testing and installation.

Induction motors

Invented in the 1880s by the Croatian-born Serb engineering genius Nikola Tesla, the cheap and reliable induction motor has become the most common type of electric motor in use today. According to Tesla, the concept came to him in a vision while he was walking in a park in Budapest in 1882. The vision was so vivid and detailed that he was able to construct a working prototype completely from memory.

Since we don't all have Tesla's powers of memory and visualisation, a quick refresher on induction motor principles is probably in order. A set of windings in the stator, fed by a 3-phase voltage supply, produces a rotating magnetic field. This field induces (by transformer action) a corresponding current in a set of short-circuited windings in the rotor. These rotor currents create their own magnetic field that interacts with the stator's rotating field to produce torque that turns the rotor and any attached load.

Things are more tricky in the case of single-phase induction motors, since with one winding we can only produce a pulsating field. This can induce current in the rotor but unless the rotor is already turning, there will be no torque. Single-phase induction motors must therefore have a separate start winding.

This start winding is usually connected via a capacitor and/or a centrifugal switch. **Some of these motors are not suitable for use with the speed controller described here. Please refer to the panel later in this article for specific information.**

Shaded pole and permanent split capacitor (PSC) types, which includes most domestic pumps, fans and blowers, should be fine.

The ubiquity of induction motors is a result of their low cost and high reliability. Unlike DC or universal motors, there are no brushes or slip-rings to wear out or be adjusted. The stator is constructed like a standard mains transformer, with a laminated steel core and conductive windings.

In most cases, the rotor 'windings' take the form of aluminium bars cast into slots in the surface of the rotor laminations, running parallel to the shaft. Conducting rings cast at either end of the rotor short these bars, forming a cylindrical cage around the rotor – hence the term 'squirrel cage motor'.

So the rotor is effectively a solid lump of metal, making for an extremely rugged and low-cost motor.

Features

Refer now to Fig.1 for an overview of the *1.5kW Induction Motor Speed Controller*. The input is 230V 50Hz single-phase mains and the output is either a single or 3-phase supply with a frequency variable between 0.5Hz and 50Hz (or 0.5Hz and 75Hz) and a voltage between almost zero and 230V RMS. The output voltage tracks the frequency linearly, except at very low frequencies, when a little extra is applied to help overcome the voltage lost across the stator winding resistance.

The 3-phase output produces 230V RMS, measured between any two of the three outputs. So it doesn't matter which two outputs a single-phase motor is connected to, it will receive 230V regardless.

The output frequency and voltage is controlled either by an on-board trimpot or using an external potentiometer or voltage source. This is selected by a DIP switch labelled 'EXT'.

To start the motor, the Run terminal is pulled to ground, whereupon the motor will ramp smoothly up to the preset speed. If the Run terminal is opened, the motor will ramp back down smoothly to a stop. If the Run terminal is hard wired to ground, the motor will start ramping immediately power is applied.

The rate at which the motor ramps up and down is set by a second on-board trimpot. The ramp is adjustable from 1-30 seconds, for a full ramp from 0.5Hz to 50Hz.

It is important to set this rate sufficiently long, particularly if the load has high inertia. If the acceleration is too fast, the motor will draw very high current and trip the over-current protection. This occurs because the rotor does not have time to 'catch up' with the rotating magnetic field.

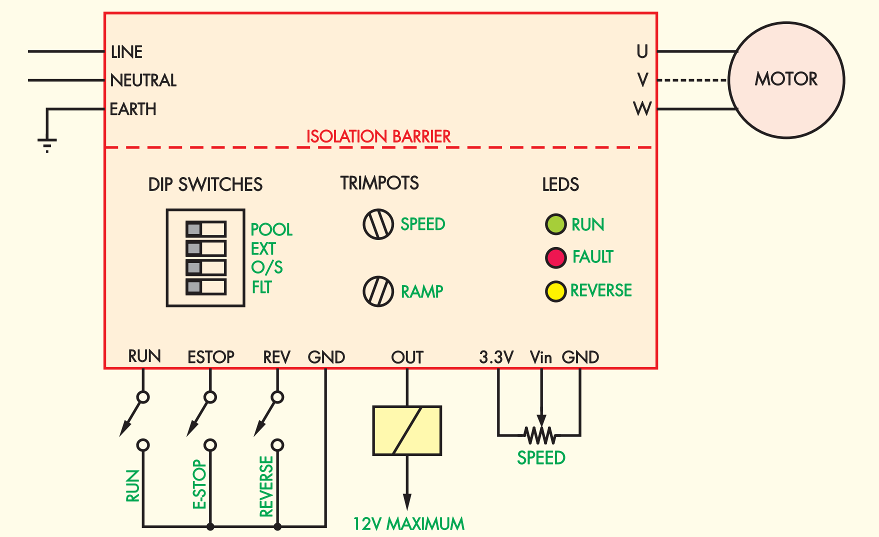


Fig.1: overview of the *Induction Motor Speed Controller*. The mains input power (left) and the motor (right) are connected to the high-voltage section at top, with the earth connection used for EMI suppression. The DIP switches and trimpots allow the unit to be configured, while the LEDs provide feedback. The optional external controls (shown at bottom) may be attached when the application requires them.

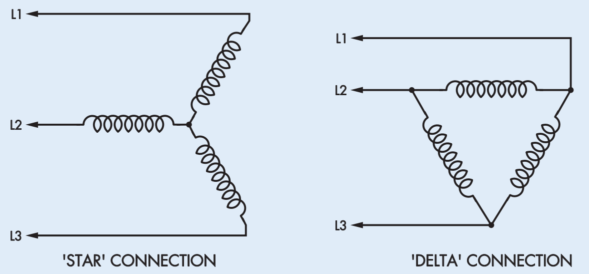


Fig.2: the windings of small 3-phase motors are normally connected in star configuration for use with the 400V RMS 3-phase mains supply. In this case, each winding is driven with the phase-to-neutral voltage of 230V. By changing how the windings are connected (which can usually be done by moving some jumpers), the motor can be changed to delta configuration, with just one winding between each phase. It can then be driven from a 230V RMS 3-phase supply such as the output of this motor controller.

Similarly, decelerating a high inertia load too quickly can cause an over-voltage trip. This can occur if the load overtakes the motor, causing it to regenerate too much energy back into the controller.

A green LED indicates when the motor is running. This flashes while the motor is ramping to or from the set speed and lights solidly when the set speed is reached.

If the Reverse terminal is pulled low, the direction of rotation will change. This only works for 3-phase motors, since the direction of single-phase motors is fixed by the wiring of their start circuit. If the motor is running while this input changes state, the controller will ramp down to zero, wait for a second for the motor to come to a complete stop, then ramp back up again in the opposite direction. A yellow LED lights to indicate the motor is running in reverse.

A single open-collector output (OUT) is provided to drive an external 12V relay or a lamp. This output can be programmed via the 'FLT' DIP switch to pull down, either when the motor reaches the target speed or when a fault event occurs.

The AC motor speed controller also has fault-protection circuits to protect it against over-current, over-voltage and over-heating. An external source may also trigger a fault condition by pulling the ESTOP terminal low.

The over-current protection monitors the current through the output devices and signals a fault if it approaches the device limits. The over-voltage protection detects excessive voltage rise caused by energy being fed back into the motor terminals by regeneration. As you would expect, the over-heating protection is triggered if the heatsink temperature rises to an unacceptable level.

When any of the above faults occur, the output devices switch off and the red LED lights. The fault condition remains latched until the source of the fault is cleared and either the run switch is opened or the power is cycled off and on.

There is also an over-speed option, which is selected using the 'O/S' DIP switch. When this is enabled, the output frequency goes up to 75Hz rather than 50Hz. However, the maximum voltage of 230V is achieved at 50Hz and does not increase further with higher frequency. This allows motors to be run at 50% above their normal speed, but with decreasing power and torque.

Pool pump mode

A common application for this induction motor controller will be to reduce the energy consumption of domestic pool pumps. Most pool pump motors are PSC (permanent split capacitor) types and so are suitable for use with this speed controller.

Running a pool pump at around 70% of rated speed can result in significant energy (and cost) savings with little or no impact on the effectiveness of the filtration. Various commercial products are available to do this job, but this unit should cost less to build and has some other advantages such as less radio frequency interference.

Pool pumps ideally require a short period of running at full speed when first switched on, so that the pump seals warm up and the full flow of water can push out any air which may have accumulated in the system. We have designed the *Induction Motor Speed Controller* with a special pool pump mode that first ramps the motor up to full speed and holds it there for 30 seconds, before ramping down to the preset level.

Right at the point of starting, the motor receives a little extra voltage to help overcome the stiction that can occur when the pump seals are cold. During the 30-second hold time, the green LED remains on but flickers quickly.

Machine tools

We have also added a 'tool spin-up' mode which is very similar to pool pump mode except that the time spent at full speed is reduced to about half a second. This mode is useful for driving lathes at low speed as it gives enough voltage initially to overcome stiction and then ramps down to the desired operating speed once the motor is spinning.

3-phase motors

You may be wondering how a controller with 230VAC input and output can drive 3-phase induction motors, since these are normally rated for a 400VAC supply (415VAC with 240VAC mains).

Fortunately, most 3-phase induction motors rated up to about 2.2kW actually have 230V windings. These are normally wired in 'star' configuration

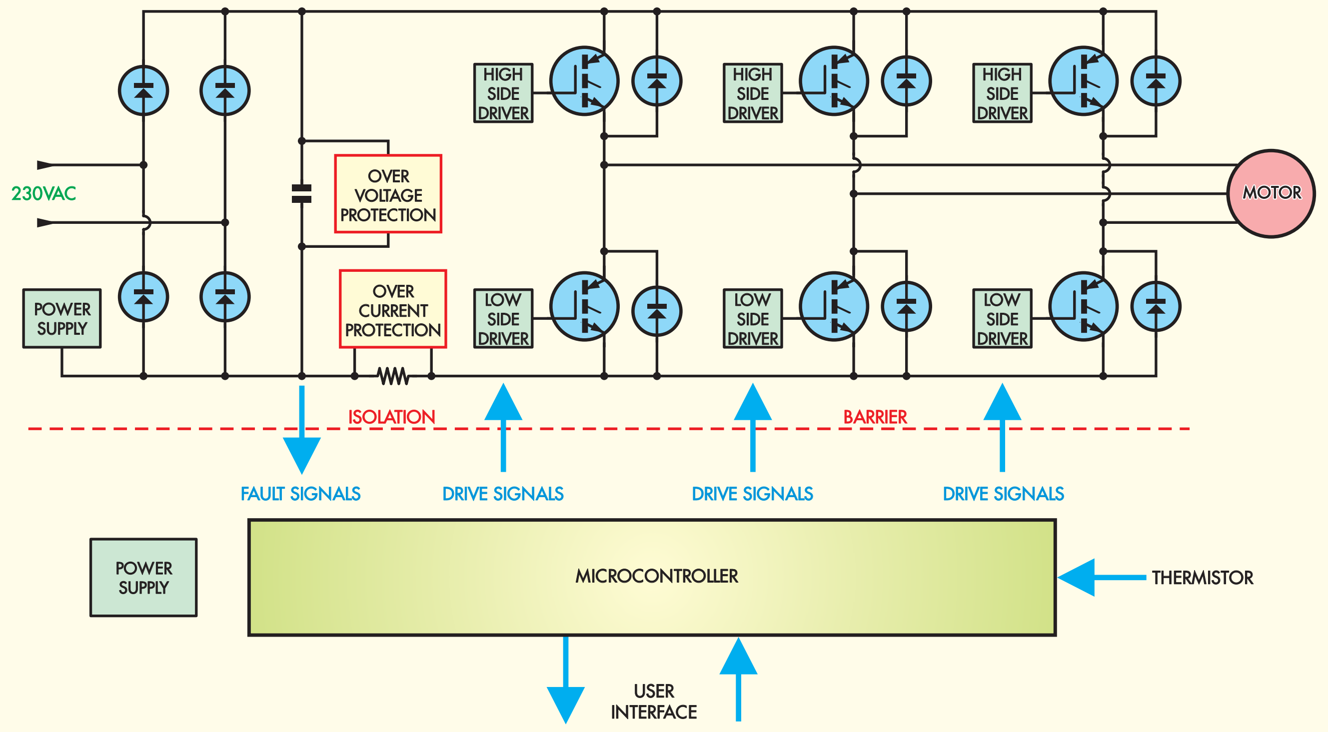


Fig.3: this block diagram shows how the incoming 230VAC mains is rectified and filtered before being applied to the motor by six IGBTs configured as a 3-phase bridge. The capacitor bank voltage can increase during over-run and the over-voltage protection circuit disables the IGBTs before damage can occur. The over-current protection prevents damage in case of overload or a shorted output, while a thermistor shuts it all down if the heatsink gets too hot. The micro is isolated from the high-voltage circuitry by opto-couplers.

(Fig.2), with two windings between consecutive phases for 400V operation. With a balanced load, the star junction voltage is near neutral potential, and so each winding is driven with the phase-to-neutral voltage, 230V RMS.

Alternatively, these motors can be run in 'delta' configuration, with one winding between consecutive phases, for operation with single-phase input 3-phase inverters such as this one.

The wiring change to reconfigure a motor from star to delta is made by repositioning a set of jumpers inside the motor's terminal box. The jumpers come with the motor and there is usually a diagram of their configuration on the motor rating plate or on the inside of the terminal box cover.

With the speed controller's DC 'bus' at a nominal 325V, each phase voltage is limited to 325V peak-to-peak, or 115V RMS if we generate a pure sinewave. This would give us an interphase voltage of:

115V × √3 = 200V RMS.

However, it is possible to generate the required 230V RMS sinewave between the three phases by deliberately making each phase output non-sinusoidal. We do this by adding the third harmonic, as shown in Fig.4. The resultant 'squashed' sinewaves from each output give pure phase-to-phase sinewaves with voltages of 650V peak-to-peak or 230V RMS.

How it works

Fig.3 is a block diagram of the *AC Speed Controller* showing the basic building blocks. The mains is rectified and filtered to provide the DC bus of about 325V. This feeds a 3-phase bridge of six IGBTs (insulated-gate bipolar transistors) which pulse-width modulate the DC bus to synthesise sinusoidal phase-to-phase voltages. The switching frequency is 16kHz and the inductance of the motor filters this waveform to produce a motor current that is almost purely sinusoidal.

The modulation applied to each output is actually a mixture of two sinewaves, one at the desired frequency and one with a lower amplitude at three times that frequency (ie, its third

WARNING: DANGEROUS VOLTAGES

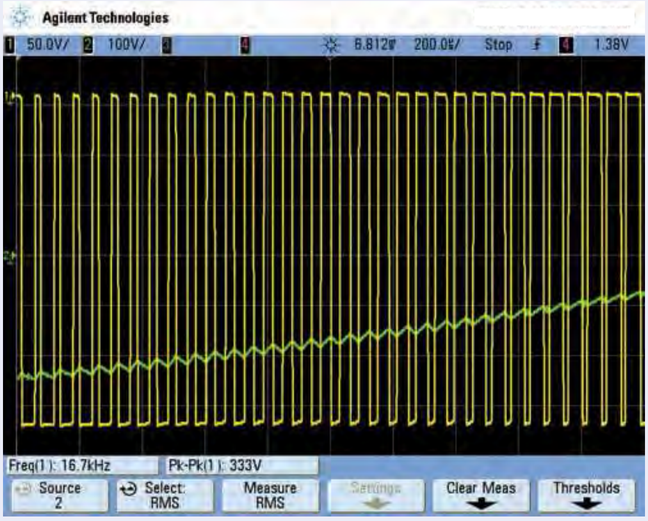
This circuit is directly connected to the 230VAC mains. Therefore, most of the parts and wiring operate at mains potential and there are also sections running at 325-350V DC. Contact with any part of these non-isolated circuit sections could prove FATAL (see Fig.5).

Note also that the circuit can remain potentially lethal even after the 230VAC mains supply has been disconnected!

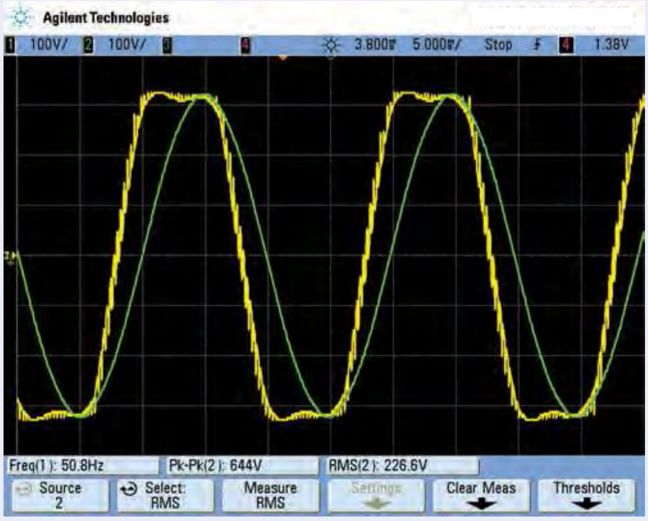
To ensure safety, this circuit MUST NOT be operated unless it is fully enclosed in an appropriate plastic case. Do not connect this device to the mains with the lid of the case removed. DO NOT TOUCH any part of the circuit unless the power cord is unplugged from the mains socket, the on-board neon indicator has extinguished and at least three minutes have elapsed since power was removed (and the voltage across the 470μF 400V capacitors has been checked with a multimeter – see text).

This is not a project for the inexperienced. Do not attempt to build it unless you understand what you are doing and are experienced working with high-voltage circuits.

Scope output waveforms at full speed



Scope1 (200µs/div)



Scope2 (5ms/div)

These two scope grabs show the output waveforms with the *Motor Speed Controller* set at full speed (ie, 50Hz). The yellow traces show the voltage at one of the outputs, while the green trace shows the voltage between it and another output, ie, the inter-phase voltage. The inter-phase voltage is measured using an RC low-pass filter (8.2kΩ/33nF).

Scope1 has a faster time base and only shows a portion of the sinewave along with the PWM pulses. Its peak-to-peak amplitude of 333V corresponds with the DC bus voltage; our mains voltage was around 233V at the time this was captured.

Scope2 uses a time base which is too slow to show the individual 16kHz PWM pulses, so the scope shows the average voltage instead, with some switching pulses still visible. Compare this waveform to the theoretical shape shown in Fig.4 and you will find that they are quite similar.

The inter-phase sinewave peak-to-peak voltage (644V) is nearly double the peak-to-peak voltage of the PWM waveform (333V), as we expect. The measured RMS voltage of 226.6V is very close to what we would expect (227.7V RMS).

The actual sinewave frequency is slightly above 50Hz, due to the microcontroller's internal RC oscillator tolerance of ±2% (-40 to 85°C), giving a frequency range of 49-51Hz for full speed.

harmonic). The waveform generated by each pair of IGBTs is identical but displaced from the others by 120°. The phase sequence can be swapped by the microcontroller to reverse the direction of the motor's rotation.

The third harmonic is unaffected by this displacement as 3 × 120° = 360°. Since the windings are connected between output pairs, it cancels out and the voltage across each winding varies in a purely sinusoidal fashion. The third harmonic component exists only to allow us to increase the modulation to provide 230V RMS without clipping the peaks (see Fig.4).

For a 1.5kW single-phase induction motor, the normal full-load current is over 8A RMS. Allowing for a 50% margin and taking into account the peak current, the output switches must therefore be capable of switching about 18A. This presents a formidable design challenge. We need output devices capable of switching at 16kHz, rated for 600V and nearly 20A continuously. The diodes across the switches must be similarly rated.

The low-side IGBT drivers are referenced to the negative line of the DC bus, but the high-side drivers must float on their respective output line and these are switching up and down at high speed. In addition, we need to monitor the DC current and voltage in order to protect the controller from fault conditions.

Fortunately, these days it's possible to buy a power module combining six 600V 30A IGBTs, six matching freewheel diodes, all the necessary drivers and level-shifting circuitry plus the overcurrent protection circuit, all for about £12. As a bonus, the whole lot is encapsulated in an isolated-base package that measures a very compact 20mm × 45mm × 5mm.

The device we chose (the STGIP-3S0C60 from ST Microelectronics) requires a 15V DC supply referenced to the negative side of the DC bus. The microcontroller and the rest of the circuitry must be optically isolated from the high-voltage circuitry and are therefore powered by a separate isolated power supply.

Circuit description

Now take a look at the full circuit diagram, Fig.5. As shown, the mains input passes through a protective fuse and EMI (electromagnetic interference) filter (FLT1) before being rectified and filtered in the classical manner.

NTC thermistor TH1 is wired in series with the rectifier to limit the inrush current when the DC bus capacitors are discharged. This thermistor has a resistance of about 10Ω when cold, limiting the peak current to 35A. As the thermistor begins to conduct, it heats up and its resistance drops dramatically. When conducting 8A, its resistance is around 100mΩ.

The EMI filter is included to help minimise the conduction of noise back onto the mains. EMI is a major issue for drives of this kind because the very fast switching of very high voltages generates a lot of electrical noise. Thanks to this filter and the other precautions taken with this design, the radio interference produced by this circuit is significantly lower than that of commercial equivalents we have tested.

The DC bus is filtered by three 470µF 400V electrolytic capacitors. **These capacitors store an enormous amount of energy and they could remain charged to lethal levels for many minutes after the power is removed.** We have added a series string of three 4.7kΩ power resistors across the bus to discharge it. Even so, it takes a minute or so for the bus to discharge to a safe level.

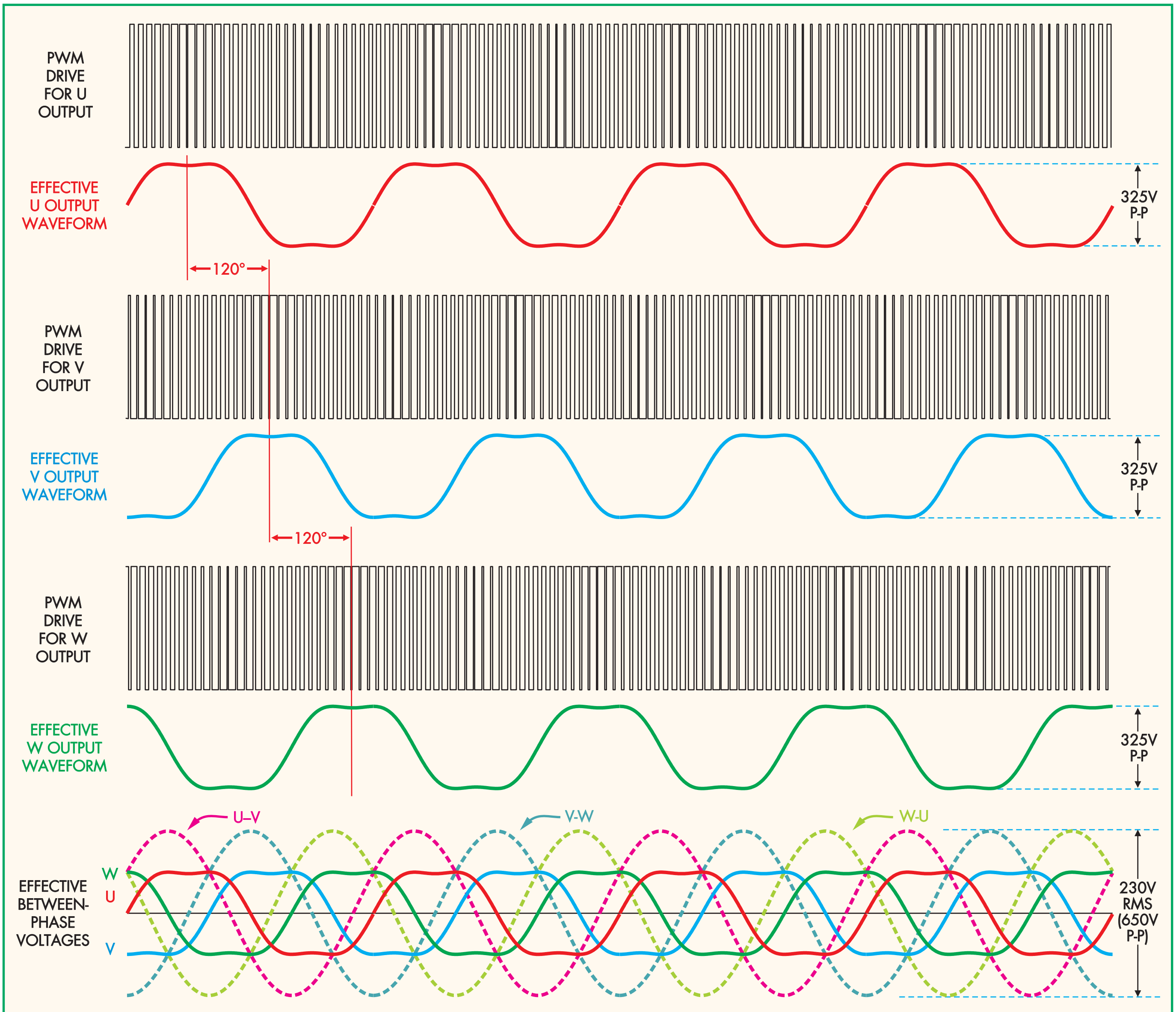


Fig.4: in operation, 16kHz PWM is used to generate identical waveforms with different phases from all three outputs (U, V and W). The motor winding(s) are connected between these outputs and so are driven with the difference between them. When we subtract these wavforms from each other, the result is three 230V RMS sinewaves, also 120° out of phase. To reverse the motor, the controller simply swaps the phase of two of the outputs.

As a further protection, a neon lamp is wired across the bus to indicate the presence of dangerous voltages. You should not attempt to work on this circuit even when the power is removed unless the neon is out. Even then, you must check with a multimeter!

Incidentally, two 150kΩ resistors are used in series with the neon because one standard 0.25W resistor does not have sufficient voltage rating.

The 220nF X2 capacitor across the bus provides a low-impedance path for differential-mode noise, while the two 47nF X2 capacitors serve a similar function for common-mode noise. These are also part of the EMI suppression, as well as providing a high-frequency bypass for the DC bus.

The DC bus current is monitored by a low-inductance surface-mount 0.015Ω 2W shunt resistor. The voltage across this resistor is filtered by a 100Ω resistor and 10nF capacitor before being fed into pin 16 of the power module, IC1. When this input reaches +0.54V (corresponding to about 36A), it immediately shuts down the IGBTs and signals an over-current fault.

IC1 requires a 15V supply (+15V_{HOT}) referenced to the negative leg of the DC bus. The 10µF capacitor between pins 5 and 8 of IC1 decouples this supply, right at the point it enters IC1.

Three 10µF capacitors are required for the high-side driver bootstrap power supplies. These capacitors are charged from the +15V_{HOT} rail via diodes inside IC1 each time the low-side IGBTs turn on. They provide a high-side power rail floating on each of the output terminals. We selected low-cost surface-mount ceramic types in 0805 packages for these capacitors because they need to have a very low value of impedance.

Each of the six output switches can be controlled independently, but the STGIP3S0C60 allows for the high and low-side inputs to be connected, so that only three control lines are required. When these signals change state, an internal dead-time circuit inside IC1 ensures that the upper and lower IGBTs never conduct at the same time.

The three inputs are driven from the microcontroller via high-speed HCPL-2531 optocouplers (OPTO2 and OPTO3) and associated 8.2kΩ pull-up resistors. High-speed optocouplers with well-matched turn-on and turn-off times are necessary as the switching pulses become very narrow when the duty cycle of the modulation approaches 0 or 100%.

Pin 15 of the power module (IC1) is both an input and output. If an over-current or other fault is detected within IC1, it pulls this pin low. It also

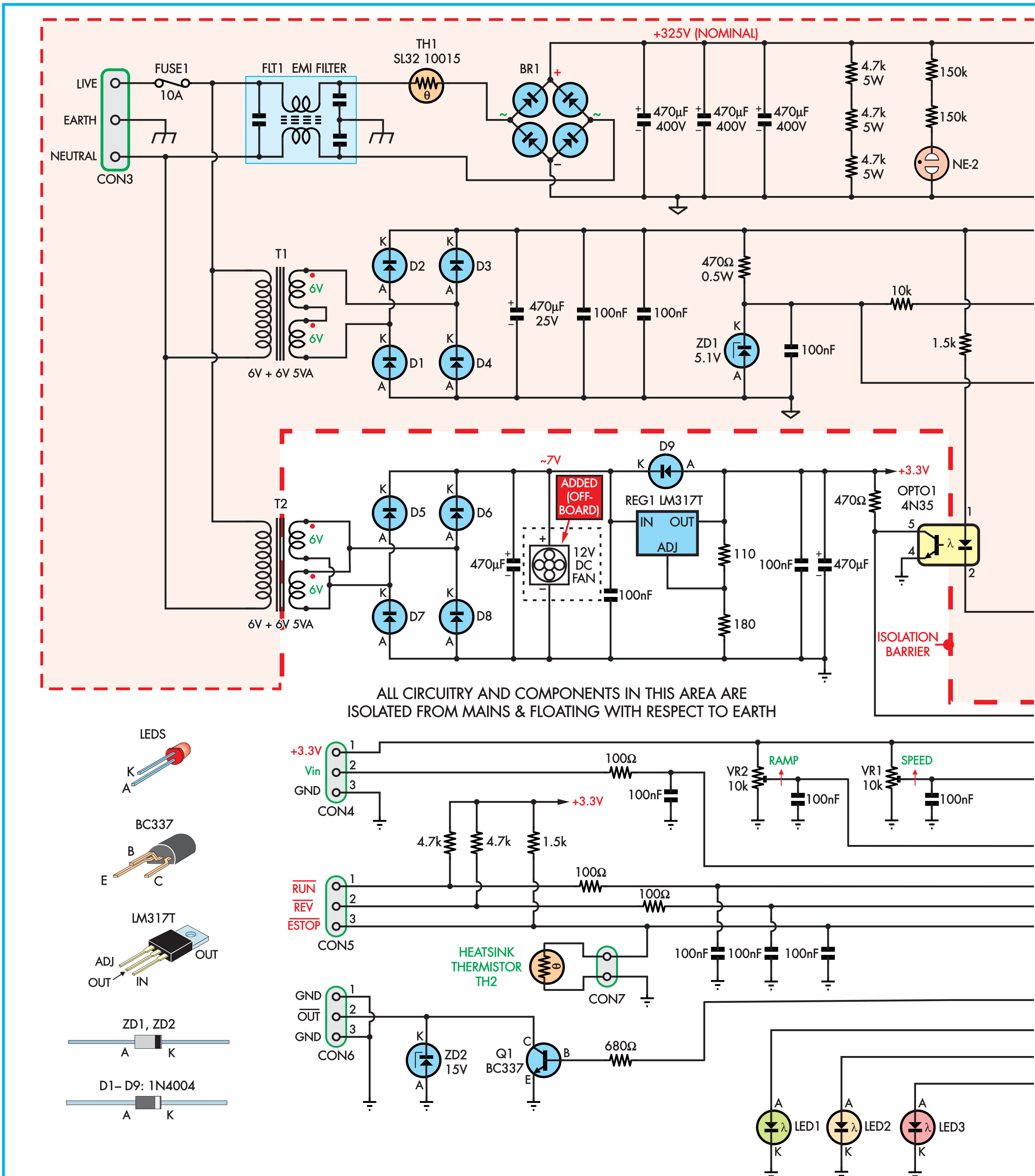
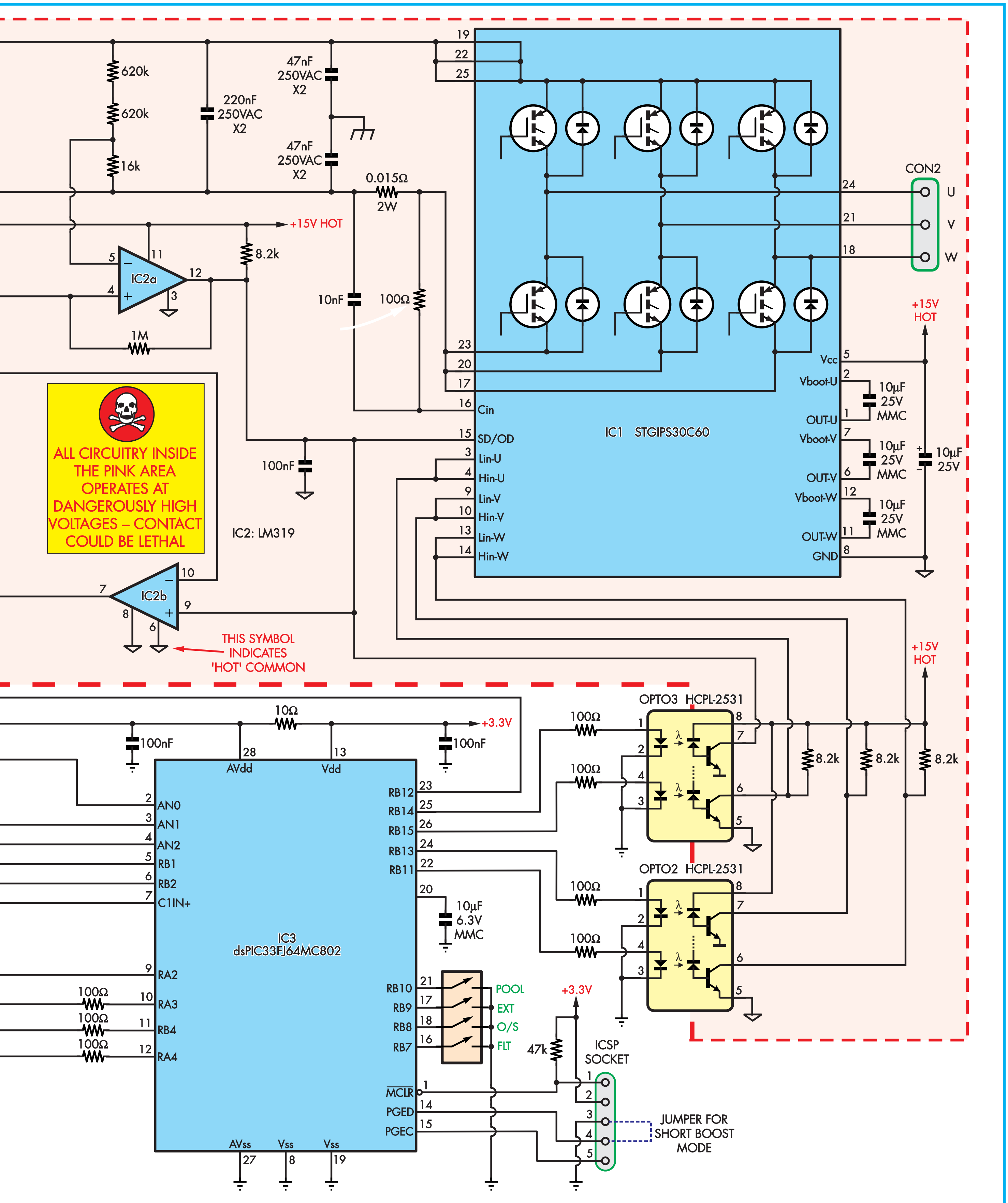


Fig.5: the full circuit diagram of the *1.5kW Induction Motor Speed Controller* PCB. The incoming mains is rectified by BR1 to provide a +325V DC bus. This powers 3-phase IGBT bridge IC1, which switches the voltage to the motor via CON2. A 0.015Ω resistor in its ground path provides current feedback to Cin (pin 16) for over-current and short-circuit protection. PIC microcontroller IC3 controls the 3-phase bridge via optocouplers OPTO2 and OPTO3.

monitors the voltage on this pin and shuts down the power stages if it is driven low externally. Thus, the micro can pull this line down to shut off the IGBT bridge. In our case, pin 15 can be pulled low by the open-collector output of comparator IC2a (LM319). This comparator compares the DC bus voltage (via a voltage divider) with a 5.1V reference derived from zener ZD1 and associated components. If the DC voltage exceeds 400V, a fault is triggered. The 10kΩ and 1MΩ resistors provide some useful hysteresis for this comparator.

Pin 15 can also be pulled low by the microcontroller via one half of the high-speed optocoupler pair OPTO3.



1.5kW Induction Motor Speed Controller

The other half of the LM319 dual comparator, IC2b, is used to monitor the voltage at pin 15 of IC1 and signals the microcontroller via 4N35 opto-coupler OPTO1 if it falls below +5.1V. This tells the microcontroller that one or other of the protection circuits described above has been activated and that the IGBTs have been switched off.

The $+15V_{HOT}$ supply is derived via a conventional rectifier (D1-D4) and filter capacitors from the 12VAC produced by transformer T1. This supply is effectively at 230VAC mains potential, so a second isolated supply is required for the control circuitry. Transformer T2 and the associated rectifier (D5-D8) and 470µF filter capacitor provide about

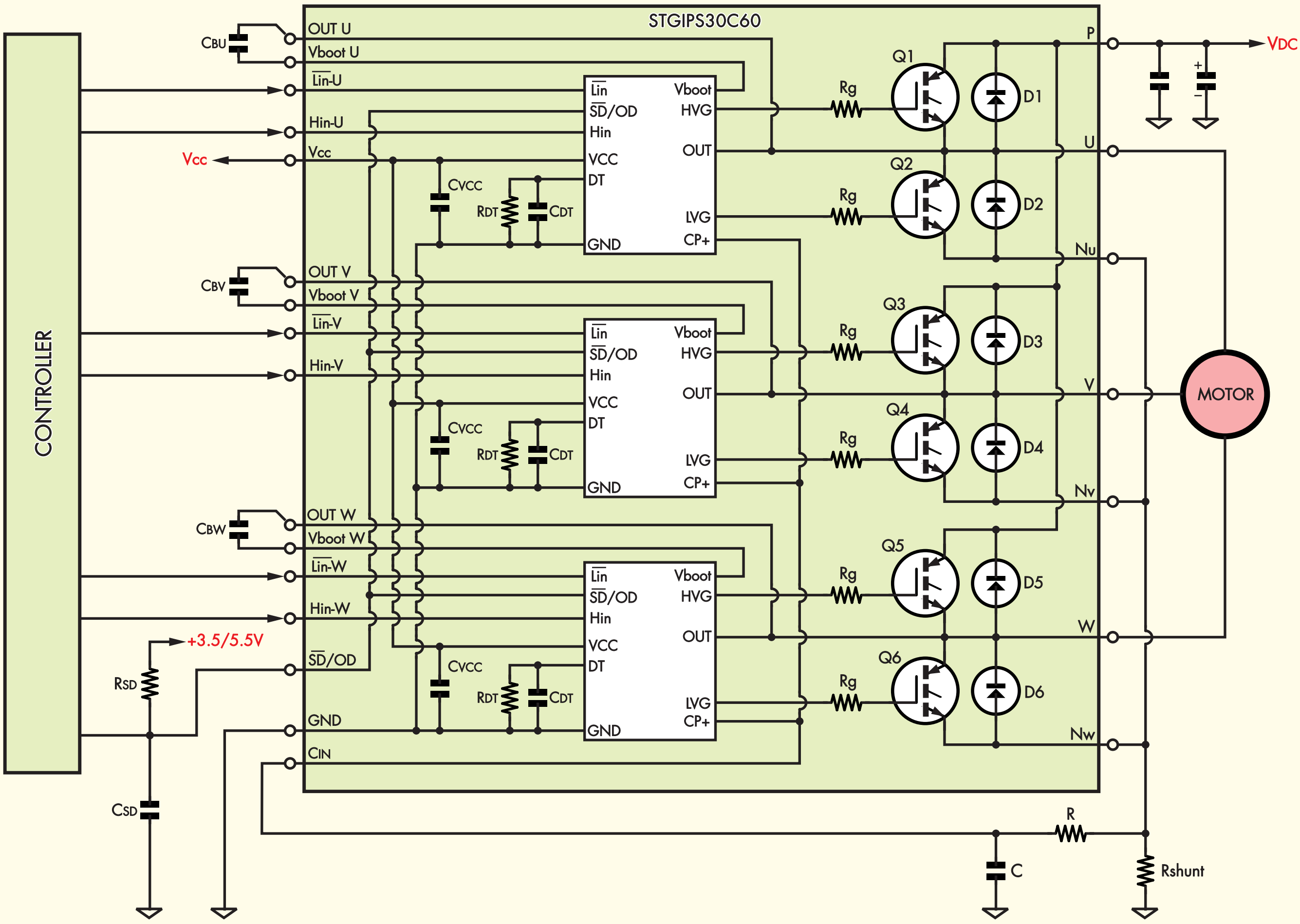


Fig.6: typical application of the STGIP3S0C60 IGBT bridge, redrawn from the data sheet. Each pair of IGBTs has parallel free-wheeling diodes and drives one of the motor terminals. The associated control blocks drive the IGBT gates, generating the high drive voltage for the upper IGBT in each pair (in combination with external boost capacitors) and providing dead time during switching to prevent cross-conduction. The module also features over-current protection via the C_{IN} input and has a shut-down input (SD/OD) which also acts as a fault output.

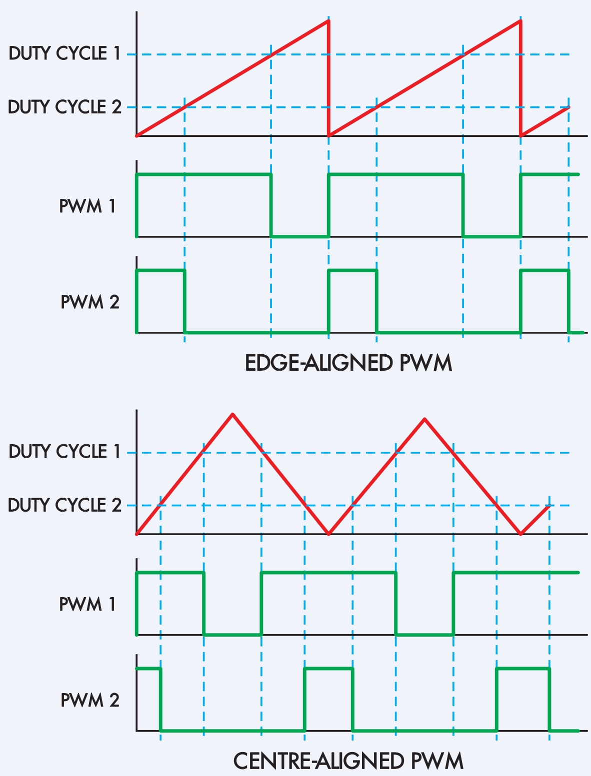


Fig.7: this diagram illustrates the difference between traditional edge-aligned PWM and centre-aligned PWM (also known as dual-ramp PWM).

With centre-aligned PWM, the leading edge of each pulse moves as the duty cycle changes. This is an advantage because if all outputs switch high at the same time, as with edge-aligned PWM, the total current pulse is larger and so more EMI is generated.

+8V DC to LM317T linear regulator REG1 which in turn drops this to the +3.3V required by the microcontroller.

Microcontroller

The microcontroller (IC3) is a Microchip dsPIC33FJ64MC802. This is a 16-bit device with 64k bytes of Flash and 16k bytes of RAM. The letters MC in the part number indicate that it is optimised for motor control applications – more on this later. The micro requires all the usual supply bypass capacitors. The 10µF capacitor connected to pin 20 is the bypass for the 2.5V CPU core power supply. This has to be a low impedance type and mounted close to the device pins. We used a surface-mount ceramic chip capacitor here.

The analogue parts of the micro are powered from the AVdd pin, so this is connected to a low-noise 3.3V supply filtered by a 10Ω resistor and 100nF capacitor. This low-noise 3.3V rail also feeds trimpots VR1 and VR2.

Pins 2, 3 and 4 on IC3 are connected to the microcontroller's ADC and read the internal speed, ramp rate (trimpots VR1 and VR2) and external speed

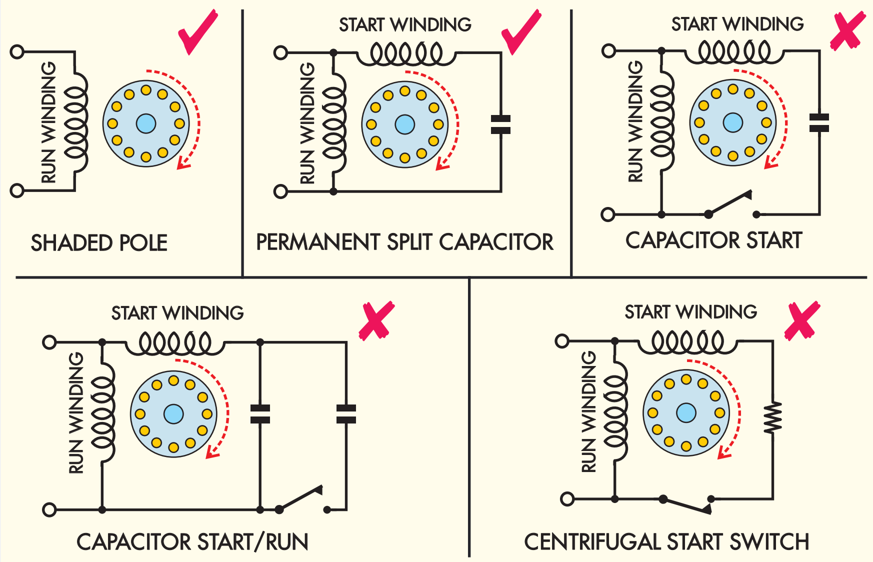
Single-phase induction motors

With a 3-phase supply, achieving a rotating magnetic field is simple since three windings can be positioned around the stator so that the resulting field 'drags' the rotor around. Swap any two of the phases and the field will rotate in the opposite direction.

However, with a single-phase supply, there is only one winding and this can only produce a pulsating field. There is no torque on the rotor when it is stationary, so it cannot start without some impulse to get it going. Once moving, the torque builds up and there is no further problem. Of course, the motor will rotate equally well in either direction, depending on the sense of this initial kick. You can't change the direction of these motors electrically, like you can with 3-phase types.

There are quite a few different schemes used to give this initial kick-start. Manufacturers have not adopted a common set of terms to describe their various approaches, so the whole topic is potentially confusing.

Below, we have summarised a few of the more common starting mechanisms, with their characteristics and applications.



Shaded pole ✔

A shorted turn on the corner of the stator poles distorts the magnetic field to create a weak starting torque. Shaded pole motors are inefficient due to the shorted turn and so are usually limited to low-power motors such as found in small domestic fans and blowers. These motors can be used with a speed controller such as the one described here, but generally that would be an expensive solution for a low-power device.

Permanent split capacitor (PSC) ✔

A start winding in series with a capacitor produces a second, weaker field slightly out of phase with the main field. The capacitor and start winding are connected permanently so they are designed to draw a relatively modest current and are rated for continuous operation.

PSC motors have low starting torque and are very reliable since there is no centrifugal switch. Typically used for fans and centrifugal (pool and spa) pumps up to about 2kW, these are suitable for use with a speed controller.

Capacitor start ✘

These are similar to the PSC motor in that a capacitor and start winding create a phase-shifted field for starting. The capacitor is larger and the start winding designed to draw significantly more current and therefore provides a much higher starting torque.

The start winding and capacitor are not necessarily rated for continuous operation and waste a lot of energy so must be switched out by a centrifugal switch, typically when the motor reaches about 70% of full speed.

They are used for conveyors, large fans, pumps and geared applications requiring high starting torque. Capacitor start motors are not suitable for variable speed use because at lower speeds the centrifugal switch will close and the start winding and/or capacitor may burn out.

Capacitor start/run ✘

These are the 'big guns' of single-phase motors and are found in machine tools, compressors, brick saws, cement mixers and a thousand other uses. They have a large start capacitor that is switched out by a centrifugal switch and a smaller run capacitor that is permanently connected to the start winding. They have very high starting torque and good overload performance.

Unfortunately, for the same reason as the capacitor start motors, they cannot be used with variable speed drives. A 3-phase motor is recommended in these applications if speed control is desirable.

Centrifugal start switch ✘

Commonly used on small bench grinders and column drills, these motors arrange a phase-shifted field with a resistive winding. Again, the start winding is only rated for short, intermittent operation (due to its high resistance) and will burn out if operated frequently or continuously.

NOTE: *in spite of the above warnings, some readers may want to try using the Induction Motor Speed Controller with motors using a centrifugal switch to energise the start winding.* ***The main danger is that the start winding may be burnt out if it is energised for too long, due to it being energised at prolonged low speeds.*** *There is also a risk that the over-current protection in the Speed Controller will simply prevent normal operation.*

potentiometer setting (from CON4) respectively. The 100nF capacitors on these inputs provide a little filtering.

The RUN and REV (reverse) terminals at CON5 are connected to digital inputs on the micro via simple RC filters. These are active-low inputs with 4.7kΩ resistors to pull the lines high when the terminals are open.

Heatsink temperature

An NTC (negative temperature coefficient) thermistor connected to CON7 monitors the heatsink temperature. At room temperature, the thermistor has a resistance of about 10kΩ and together with the 1.5kΩ resistor, forms a voltage divider, presenting about +3.0V at pin 7 of IC1. This input is configured as an analogue comparator, with a programmable threshold voltage.

As the temperature of the heatsink rises, the resistance of the thermistor drops and the voltage on pin 7 falls. If the voltage falls below +1.4V, corresponding to a heatsink temperature of about 85°C, an over-temperature fault is triggered. This fault can be triggered externally by pulling the ESTOP terminal (at CON5) low, effectively shorting the thermistor.

Since start-up is hard on the IGBTs, an additional temperature check is made before the motor is spun up. If the heatsink temperature is above about 65°C, the unit waits for it to drop before starting the motor. This protects the unit from damage in case multiple rapid start/stop cycles occur. During normal use, this additional protection should not activate.

NPN transistor Q1 drives an external load (perhaps a relay or lamp) connected to the OUT terminal. ZD2 provides some protection for Q1 in case the load is slightly inductive. Highly inductive loads, such as relay coils, should have a clamp diode connected directly across them. The load should be limited to 200mA at a maximum of 12V.

The three indicator LEDs are driven directly from the micro via current-limiting resistors, as are the LEDs in the HCPL-2531 optocouplers.

The 4-way DIP switch is connected directly to the microcontroller. Internal pull-ups on these inputs eliminate the need for external resistors. An ICSP header is also provided, allowing in-circuit reprogramming should this be necessary.

Pulse-width modulation

The dsPIC33FJ64MC802 microcontroller contains a peripheral especially adapted for motor control PWM applications. It allows the generation of various types of PWM waveforms with up to 16-bit resolution. The pulse width registers are double-buffered so the pulse width can be updated asynchronously, without any risk of glitches in the output. This is critical for the safe and smooth operation of the controller.

We have elected to use a 16kHz switching frequency, which gives us a good balance between quiet motor operation and switching losses in the output devices. We also selected centre-aligned PWM modulation instead of the more common edge-aligned PWM because this gives much better harmonic performance.

In edge-aligned PWM (see Fig.7), the outputs are all set high when a counter rolls over to zero. When the counter value reaches one of the duty cycle thresholds, the appropriate output goes low. This creates PWM with the rising edges of each channel aligned.

In centre-aligned PWM, the counter counts up for the first half of the PWM period and down for the second half. The relevant outputs are set high when the counter counts down through the duty-cycle threshold and high when it counts up through the threshold. Each resulting individual PWM waveform is identical to the edge-aligned case but none of the edges are aligned.

Generating sinusoidal PWM

To generate quasi-sinusoidal (or 'squashed' sinewave) PWM, we have to change the duty cycle for each phase smoothly, allowing for variable frequency and amplitude, and having regard for the relative phases of the three outputs.

We start with a look-up table containing 512 16-bit samples of the desired output waveform (a mixture of two sinewaves with different amplitudes); the values in this table range between –1 and +1. By stepping a pointer through this table at the appropriate rate and multiplying the looked-up value by the required amplitude we can calculate the duty cycle needed to produce variable voltage, variable frequency PWM.

We maintain three pointers into the table, initialised at the beginning, one third and two-thirds through the table respectively. They are all incremented by the same amount so they maintain this phase relationship as they move through the table, producing three waveforms displaced by 120°.

With a 16kHz modulation rate, we have only 62.5 microseconds to increment the three pointers, look up the sine values, multiply each by the amplitude, then scale and offset the three results to calculate the duty cycle values. This is a reasonably tight time frame, so this part of the firmware was written in assembly language and hand-optimised for speed.

But by how much should we increment the look-up table pointers? If we incremented the pointers by one each 62.5 microseconds, one cycle would take 62.5µs × 512 = 32ms, giving 31.25Hz. Clearly we must somehow increment the pointers by a fractional amount, ranging from nearly zero to 2.4, with a few digits resolution.

The solution was to create a 32-bit accumulator for each pointer, and to use bits 17 through 25 as the 9-bit pointer into the table. Now incrementing the accumulator at 62.5µs would produce an output frequency of 0.000238Hz! So for 1Hz output, we increment the accumulators by roughly 4200 and for 50Hz, about 210,000. We don't need this kind of frequency resolution, so the firmware limits the range from 0.5 to 50Hz (or 75Hz) and the resolution to 0.05Hz.

The control routine of the firmware is a fairly straightforward state machine that controls the frequency and voltage set points for the PWM generation part, according to the state of the various inputs.

Coming next month

Next month, we will provide full details of the construction, testing and installation for the *1.5kW Induction Motor Speed Controller*.