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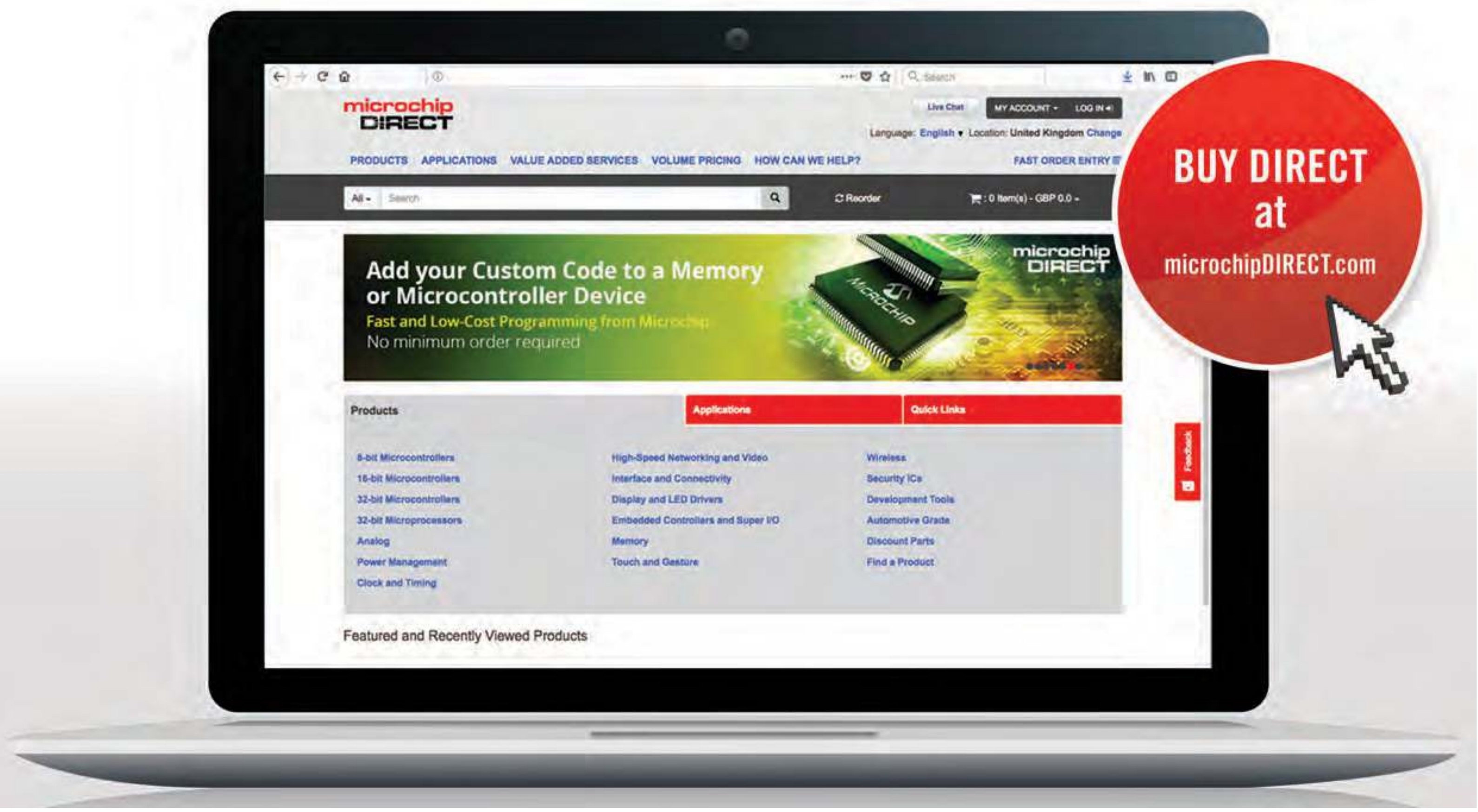

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ISSN 0262 3617
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VOL. 48. No 1 January 2019

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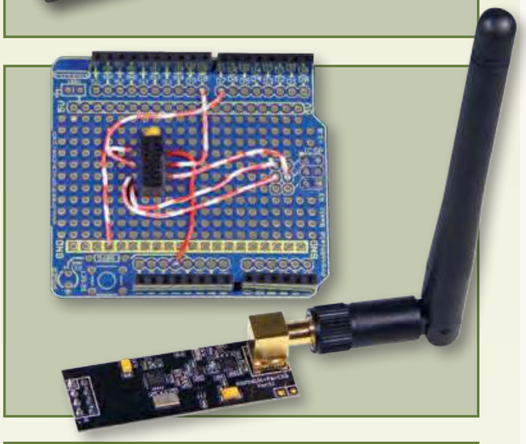

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Practical Electronics

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Projects and circuits
All reasonable precautions are taken to ensure that the advice and data given to readers is reliable. We cannot, however, guarantee it and we cannot accept legal responsibility for it.
A number of projects and circuits published in EPE employ voltages that can be lethal. You should not build, test, modify or renovate any item of mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD adaptor.

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EPE EVERYDAY PRACTICAL ELECTRONICS

Back to the future!

EPE publisher and former editor Mike Kenward explained last month that from this issue *EPE* is changing hands – my company, Electron Publishing has taken over from Mike's Wimborne Publishing. This sounds like a huge move; but in reality the magazine you enjoy each month has the same editor, the same contributors, the same designer, the same number of pages – and the same price.

However, there will be two changes – as highlighted opposite. First and foremost, from the April 2019 issue we are reverting to our original name of *Practical Electronics*. Mike added 'Everyday' when he combined two magazines: *Everyday Electronics* with the original *Practical Electronics*, but everyone I have discussed this with prefers *PE*, so that will be the 'new' title. I spoke to Mike about this change, and he not only approved, but also told me he had been thinking about making the very same change for the last couple of years.

Second – it's time for a design refresh. You will notice some columns in this issue have already started to wear their new uniform, and over the next few months the whole magazine will be smartened up, culminating with a new cover design, also in the April issue.

Thank you

Mike has handed me a wonderful opportunity, and I am very grateful for the trust he has placed in me to look after and continue with his life's work – a popular, successful and widely read magazine. I have worked for Mike and subsequently Stewart and Fay at Wimborne for over 25 years, and I could not have hoped for a better company, publisher and team of colleagues – thank you.

...and more thanks!

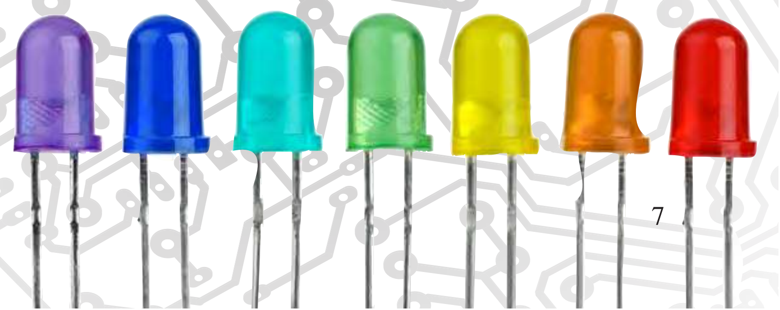
It's become an annual tradition for me to salute our hardworking contributors at the end of the year. So, as before – and in no particular order – a rousing *EPE* 'well done and thank you' for Alan Winstanley, Mike Tooley, Ian Bell, Mark Nelson, Mike O'Keeffe, Mike Hibbett, Lucy Rogers, Julian Edgar and Jake Rothman. Plus, I'd like to offer an extra special 'thank you' to Mike O'Keeffe, who is moving to new pastures after this issue – thank you Mike, for all your hard work and dedication to *PIC n' Mix*. Finally, a very warm 'welcome back' to Mike Hibbett, who is returning to *PIC n' Mix* with an exciting list of projects and ideas, and Clive 'Max' Maxfield returns with his unique take on the world of electronics in *Cool Beans*.

Extra special Christmas present?

If you are lost for ideas when facing the inevitable 'What would you like for Christmas?' interrogation from your nearest and dearest, then why not suggest a subscription to your favourite magazine. It doesn't matter whether you choose paper or online, as a subscriber you can be sure that you won't miss out.

From all of us at *EPE*/*PE*, thank you for you support during 2018, have a very happy Christmas and a fantastic, solder-filled 2019!

Matt Pulzer
Publisher



NEWS

A roundup of the latest news from the world of electronics

A real use for augmented reality – *report by Barry Fox*

Virtual reality (VR) and augmented reality (AR) have been dubbed technical solutions looking for problems to solve – and so far, they've been most useful for gamers with leisure time on their hands. But now, inevitably, more socially useful applications for VR and AR are emerging.

Theatre assistance for deaf members of the audience

Theatre-goers who are deaf or hard of hearing and book seats at the National Theatre (NT) in London can now pre-order – for no extra cost – the loan of Epson's latest Moverio BT-350 Augmented Reality glasses. These will then superimpose an always-on synchronised text transcript of dialogue and sound effects over the live stage view.

National Theatre devlopment

The 'smart caption' system was developed by the NT in partnership with Accenture. It relies on the same captioning information that is already used for a few selected NT performances (up to four per production) to display captions on screens at the side of the stage. Work on the new smart system began in 2014, and after a year of testing the system went live for the NT's productions of *Hadestown* and *War Horse*. Smart captioning will now extend to all new productions in all three of the NT's stages.

I attended a live stage demonstration based on a 15-minute excerpt from the play *Exit the King*, by Eugene Ionesco; and found the glasses light and reasonably comfortable, even when wearing varifocal spectacles. The captioning was bright, clear and easy to centre over the stage view.

The glasses receive the captions by Wi-Fi and work anywhere in the auditorium. A built-in tutorial and menu help wearers adjust caption typeface, colour and positioning to personal taste. Each eye displays the same data.

Stagetext

The caption data is pre-prepared by Stagetext, a UK Arts Council charity that already provides captioning for theatres and arts venues.

Stagetext programmers work from the dialogue script, music score and sound effect cue sheet. Voice-following software then 'listens' to the live sound and controls the data transmission, so that the captions are in sync with the actors' delivery.

The scheme has public funding from the UK's National Lottery and Arts Council. The NT is starting off with 90 pairs of glasses to share between the three stages, but plans to buy more. Battery life is four hours, which is sufficient for most plays. The glasses currently cost around £800 a pair, and the NT's technical director Jonathan Suffolk says he is confident that, 'if someone inadvertently took a pair home we will have their contact details from the pre-booking scheme, so can remind them to return their loan'.

Jonathan Suffolk says the NT is also well aware of the risks of accidental damage and Epson has already made changes, such as modifying the nose pads, based on the NT's feedback.

Open system

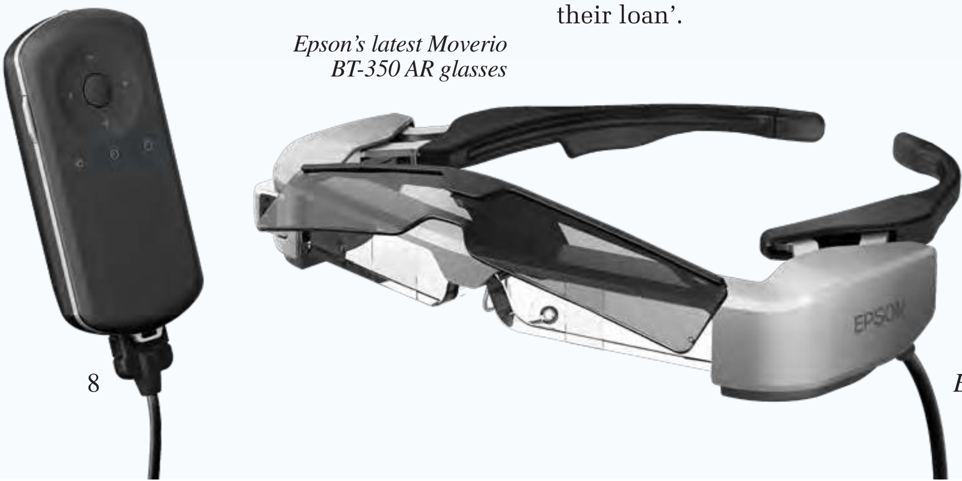
He dismisses concerns that the NT may be taking sides in an AR format war. "We are encouraging competition. If there is big pick-up prices will fall and glasses will improve, for instance become lighter. We are not locked into any one brand of glasses," he says. "It's like a phone App that can be changed to work with any glasses".

Lisa Burger, executive director at the National Theatre, said: "There is much more to explore, for instance translation of foreign language performances. And we are committed to the free, altruistic model."

"We are already moving towards captioning live events and improvisation," says Jonathan Suffolk.

In 2019, the NT and Epson will partner with Leeds Playhouse, as a first step towards making the technology available in theatres across the UK. The service will be available on their 2019 pop-up season productions of *Hamlet*, *Around the World in 80 Days* and *Be My Baby*. The NT will also test the glasses during the UK and Ireland tour of Rufus Norris' production of *Macbeth* in January; at venues including the Bord Gáis Energy Theatre, Dublin; Nottingham Theatre Royal; Hull New Theatre; the Marlowe Theatre, Canterbury; and Glasgow Theatre Royal.

Further details at:
nationaltheatre.org.uk/smartglasses
stagetext.org



Epson's latest Moverio BT-350 AR glasses

5G to launch at sites across the UK

UK mobile network operator and Internet service provider EE has announced it is switching on 5G sites in 16 UK cities in 2019. The first launch cities will be the UK's four capitals – London, Cardiff, Edinburgh and Belfast – plus Birmingham and Manchester.

EE, a division of BT Group, is building 5G in the busiest parts of the six launch cites, including Hyde Park in London, Manchester Arena, Belfast City Airport, the Welsh Assembly, Edinburgh Waverly train station and Birmingham's Bullring.

As well as the six launch sites, during 2019 EE will also be introducing 5G across parts of ten more cities: Glasgow, Newcastle, Liverpool, Leeds, Hull, Sheffield, Nottingham, Leicester, Coventry and Bristol.

EE is aiming to launch with multiple smartphone partners, as well as a 5G home router with external antenna, to showcase the power of 5G for domestic broadband.

5G rollout strategy

The 5G rollout strategy is determined by the number of business and consumer customers the EE network connects in busy places, and the amount of data those customers use. 5G is built on top of the network's existing 4G network, and the first 1,500 sites that EE is upgrading to 5G in 2019 carry 25% of all data across the whole network, but only cover 15% of the UK population.

Rival networks, Vodafone, O2 and Three are also running trials of the advanced network technology.

Security issues

EE's announcement follows the government writing to UK telecommunication and infrastructure firms, warning those building 5G networks to choose carefully when selecting hardware providers. The letter, reported in the *Financial Times*, said a review of hardware used for the UK's national infrastructure started in July 2018 could delay any rollout.

It also explained that the review could enforce limits on the quantity of equipment firms could use from Chinese electronics firm Huawei. (Huawei has been blocked from being used for 5G networks in Australia and the US.)

Super fast and responsive

According to **5g.co.uk**, the main benefits of 5G are that it will be much faster – possibly as much as 100 times faster. Top-end 4G networks, known variously as 4G+, LTE-A or 4.5G, can deliver peak download speeds of 300Mbit/s. By comparison, 5G promises to offer speeds in excess of 1Gb/s (1000Mbit/s), with many estimates placing it closer to 10Gb/s (10000Mbit/s). To place that in context, users will be able to download – not merely stream – a full HD movie in less than 10 seconds on a 5G network. The same task would take closer to 10 minutes on 4G, and might take over a day to download on a 3G network.

It will also have much lower latency, which means users see very little delay or lag when doing things on their phone or other device – basically, the odd millisecond, which is essentially undetectable for a user. That will help not just with existing things such as online gaming, but could also be vital for self-driving cars, where any delay could be catastophic.

5G will also have greater capacity, meaning the networks will be able to cope better with many high-demand applications all at once – from connected cars and IoT (Internet of Things) devices to virtual reality experiences and simultaneous HD video streaming.

AI hardware from Intel

Intel has unveiled its new Neural Compute Stick 2 (NCS2). Designed to build smarter AI algorithms and for prototyping computer vision, NCS2 enables deep neural network testing, tuning and prototyping.

The new system brings computer vision and AI to Internet of Things (IoT) and edge device prototypes. For developers working on a smart camera, a drone, an industrial robot or the next must-have smart home device, the Intel NCS2 offers what's needed to prototype faster and smarter.

What looks like a standard USB thumb drive hides much more inside. The NCS2 is powered by the latest generation of Intel VPU – the Intel Movidius Myriad X VPU. This is the first to feature a neural compute engine – a dedicated hardware neural network inference accelerator delivering additional performance. Combined with the Intel Distribution of the OpenVINO toolkit supporting more networks, the Intel NCS2 offers developers greater prototyping flexibility.

With a laptop and the NCS2, developers can have their AI and computer vision applications up and running in minutes. The Intel NCS 2 runs on a standard USB 3.0 port and requires no additional hardware, enabling users to seamlessly convert and then deploy PC-trained models to a wide range of devices natively and without Internet or cloud connectivity.

Saturnalia special

Techno Talk

Mark Nelson

When in Rome, do as the Romans do, so this month – even if you're not actually reading this in the Eternal City – we're lightening up a bit. The Romans certainly knew how to do this, calling the period from 17 to 23 December their season of Saturnalia, embracing non-stop festivities, public banqueting, private present-giving and lots more, all conducted in a carnival atmosphere. Let's have some fun!

Just about everyone's noticed how the weight of a laptop computer increases over time; what started off quite bearable at 9:0am feels heavier than a millstone by 4:00pm. Or so it seems. What you may not know is that adding data to a hard drive increases its weight. I kid you not; it is demonstrably true that there's a palpable difference in weight between an empty and a full hard disc.

Louis Bloomfield of the University of Virginia explains at Ask-a-Physicist: 'In principle, the data stored on a hard disc will affect its weight. The issue here is energy: since energy and mass are in some respects equivalent, both experience gravitational forces and both have weight. The more energy a hard disc has stored in its surfaces, the more it will weigh.'

Repulsive revelation

Exactly how much heavier depends on how the surfaces are magnetised and on how data is represented by these magnetisation effects. If we assume that the disc is designed so that the tiny permanent magnets on its surface are magnetised in or out of the plane of the disc, then the highest energy of magnetisation will occur when all those tiny magnets are aligned with one another. They will then have a large number of repulsive interactions and few attractive ones. Because the total potential energy stored in the disc is then large, the disc will then weigh slightly more than at other times – but do note the word 'slightly'.

He concludes: 'The weight changes that we're talking about here are so incredibly small that it's unlikely they'll ever be detected, let alone studied in any detail. Nonetheless, it's an interesting question and there are situations in which stored energy is large enough to weigh.'

Defying gravity

If that leaves you in total bewilderment, stand by to be even more discombobulated. Let's get this right: so far, we have established that adding MP3 files (or WAV files if you're a true music lover) increases the mass of a hard drive. But this is despite the fact that music has 'negative mass', even if the tunes are heavy metal music. Put another way, sound floats heavenwards, perhaps to join the 'Music of the Spheres'? Well, in a manner of speaking.

For this insight we must pay due credit to *New Scientist* magazine for enlightening (geddit?) us of this remarkable fact, which has the endorsement of several academics across the US. Angelo Esposito speaks for his colleagues in the Department of Physics at Columbia University, New York, stating: 'Contrary to common belief, sound waves carry gravitational mass (in a standard Newtonian sense, they are affected by gravity), but they are also a source of gravity. In particular, for ordinary equations of state (higher sound speeds at higher pressures), their gravitational mass is negative.' On Instagram Ira Rothstein at the Carnegie Mellon University in Pennsylvania says: 'It's almost like antigravity. The atoms that are moved by the wave are still being pulled down by the Earth, but the sound wave itself is being repelled." Riccardo Penco, a postdoctoral fellow of the University of Pennsylvania, agrees, saying: 'Heavy metal music, given a long enough time, is probably going to start floating in air, so it is probably not that heavy.'

All of this is more theoretical than practical, of course, but Esposito argues the physics are sound (no pun intended, probably). 'Sound waves do carry mass – in particular, gravitational mass. This implies that a sound wave not only is affected by gravity, but also generates a tiny gravitational field,' he asserts. 'It is possible to envision experimental setups where this effect could be detected. One possibility is to employ ultra-cold atomic or molecular gases. In these systems, in fact, not only might one be able to achieve very small sound speeds and enhance the effect, but also use suitable trappings to simulate strong gravitational potentials. Moreover, atomic clocks and quantum gravimeters can currently detect tiny changes in the gravitational acceleration of Earth, so … it is possible to imagine that, in a not too distant future, such techniques will reach the sensitivity necessary to detect the gravitational field associated with seismic waves.'

Green noise?

No, nothing very ecological, but proof that it's surprising what you hear when you listen, as they say on BBC Radio 4. And it was on Radio 4 that I recently heard a discussion of green noise. Of course, every electronicist and audio enthusiast is familiar with the concept of white noise and even pink noise, which according to Wikipedia is the most common signal in biological systems. In pink noise, each octave (halving/doubling in frequency) carries an equal amount of noise energy. This is in contrast with white noise, which has equal intensity per frequency interval.

So far so good, but what is green noise? Well, the sound is just like travelling on a fast train on a hot summer's day with the windows open; a fairly abrasive rushing sound. If curious, listen for yourself at: **https://youtu.be/pqjEqCj_zM0**

To my cloth ears, the radio programme did not explain exactly what green noise is, but Wikipedia is far clearer, even if it concedes that the definition of green noise is imprecise. It amounts to the mid-frequency component of white noise and is a good approximation to speech, making it highly useful for testing audio circuits (and also on-topic for this article). According to Joseph Wisniewski of the Ford Motor Company, 'Green noise … is supposedly the background noise of the world.' It replicates the spectra of natural settings, but without man-made contributions.

Happy Christmas!

Other colours are available, by the way. Have a hue-filed, but noise-free Christmas, Saturnalia, well-earned rest… and a positive New Year!

Net Work

Alan Winstanley

Alan Winstanley ponders the virtues of virtual taxation – goverment attempts to tax the tech giants; avoiding Internet blackmail and saving the planet, one printer ink drop at a time.

When I started work 40-odd years ago, a UK tax return comprised nothing more than a single folded sheet of paper. Nowadays we are blighted with almost unfathomable tax laws: a tax return fills a small manual, unhelpful 'Help' notes fill another one and all kind of tax forms have been migrated online. The tax code is intended to legally extract the maximum tax possible from everybody, but it works the other way as well. Exploiting loopholes in complex tax codes and devising creative and convoluted tax dodges is the province of smart lawyers and accountants whose avoidance schemes enable celebrities, millionaire footballers, wealthy business owners and tech firms like Google, Amazon, eBay and Facebook to minimise their tax liabilities in a supposedly lawful manner.

Corporate tax evasion

There is no law against doing this, and besides, nowhere does it say that everyone should organise their affairs to pay the maximum amount of tax possible. The Internet tech giants are especially gifted at offshoring operations around the world so that they can 'book' a sale in a lower tax jurisdiction or take advantage of other tax loopholes to reduce their corporation tax bills.

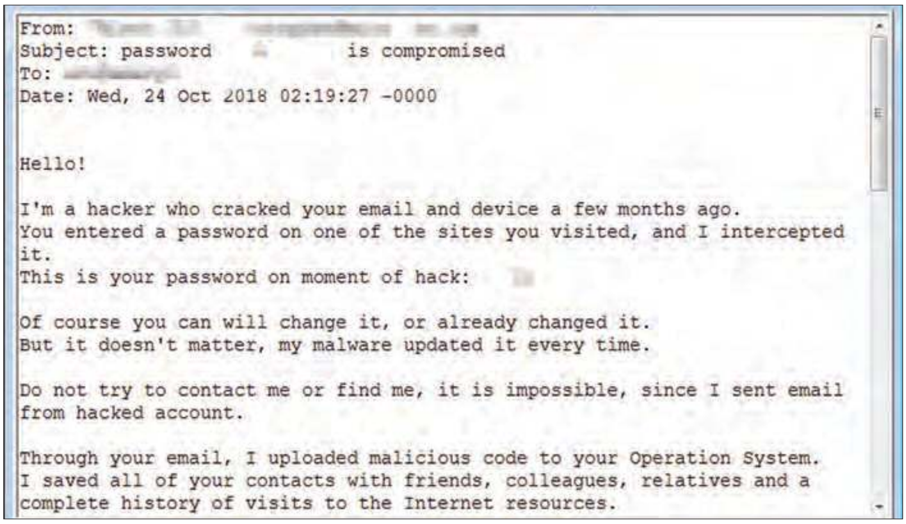
Governments everywhere are scrambling to deal with the impact that the Internet has made on a nation's tax 'take', as huge volumes of trade are transacted in countries like Britain, for example, with little to show for it in the UK Exchequer's creaking coffers. Britain's High Streets are increasingly being hollowed out because shoppers are going online in their droves, but because of the way they 'legally' structure themselves, large online vendors like Amazon and Google stand accused of paying pitifully small levels of tax (9.5% average, says the EU) compared with traditional businesses (23.2%) that struggle with disproportionately high overheads. Hence the empty shops and deserted High Streets.

Back in 2012, Starbucks offered to pay a 'voluntary' extra tax contribution to counter protests about their 'unfair' (but still legal) business arrangements that minimised their tax bills. It has always been the case that tax is compulsory, not voluntary, and the EU is set to overhaul a centuries-old tax code that dates from the era of the quill and bring it into the 21st Century to 'safeguard public finances,' as they put it. The tech industry's answer to criticism and 'unfairness' is always the same rather disingenuous one, namely that they comply with all relevant tax and company laws and they invest in local jobs and premises too. The fractured global tax system has yet to address the imbalance between trade and taxation caused by multi-national corporations operating in the Internet age, but some countries are now biting back in a bid to recoup lost revenue and ensure that trade transacted in their country is taxed there as well.

Taxing the digital economy

The British Government's annual Budget statement in October 2018 trumpeted a new Digital Services Tax (DST). Commentators exclaimed that Britain was 'showing the way' in taxing the big Internet players, but Britain's supposedly home-spun legislation is anything but that: it simply parrots the EU's own stated position which is that, until the global tax system is reformed, a temporary DST on certain Internet-derived revenues will do as a way of raising some immediate cash. The EU's March 2018 report, *Fair Taxation of the Digital Economy* has already highlighted the mismatch between the place where value is generated in a digital economy and where taxes on it are actually paid (or avoided). Keen to avoid building a chaotic *ad hoc* tax system between member states, the EU proposes an interim tax on certain Internet trade that will create immediate revenue until a uniform system can be implemented, and Britain intends to join in the fun as well.

The UK's proposed Digital Services Tax aims to raise £1.5bn ($1.95bn) and would see a 2% levy on 'soft' transactions that currently escape traditional tax mechanisms due to the multi-national basis of their markets. The Treasury points out that the DST would not be a tax on selling online goods themselves, but it *would* tax the revenues created by their marketing mechanisms: auction listing fees, Facebook-sponsored ads targeting UK users, Amazon Marketplace, Airbnb services and Google Adsense, for example. Consultation will be held before the DST is implemented in 2020, after which the DST will tax the wealthiest tech firms – even in non-EU countries – until the global tax system has been reformed by 2025,



```
From:
Subject: password         is compromised
To:
Date: Wed, 24 Oct 2018 02:19:27 -0000

Hello!

I'm a hacker who cracked your email and device a few months ago.
You entered a password on one of the sites you visited, and I intercepted
it.
This is your password on moment of hack:

Of course you can will change it, or already changed it.
But it doesn't matter, my malware updated it every time.

Do not try to contact me or find me, it is impossible, since I sent email
from hacked account.

Through your email, I uploaded malicious code to your Operation System.
I saved all of your contacts with friends, colleagues, relatives and a
complete history of visits to the Internet resources.
```

Fraudsters steal passwords and then try to blackmail victims with baseless threats.

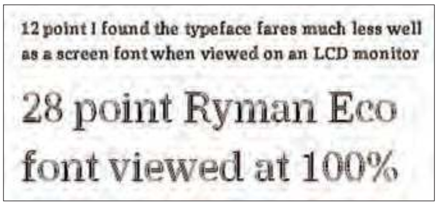
they hope. Apart from Britain, others including Spain, Germany and France are already exploring ways of taxing the Internet giants in line with EU policy.

Black email

One thing the EU is powerless to prevent is the upsurge in ransomware and blackmail emails, such as the particularly nasty one (illustrated) received some weeks ago by the author. While it contained a 'junk' but authentic password used on some trivial websites, the email held no other personal information. It demanded $800 in Bitcoins otherwise it threatened to publish (non-existent) video supposedly captured from my webcam. These sinister threats would undoubtedly upset and alarm some recipients, but readers can be assured that the threats are empty: almost certainly an insecure website was hacked somewhere along the line and some user details were stolen; they may then be posted for sale on the dark side of the web. This generic email only contained that password and fraudsters are trying their luck in blackmailing innocent users. The rule is never to engage with such villains: your money would be gone forever and your name would go on a 'sucker's list' rendering you liable to be targeted by others. For this reason, it's not a bad idea to have a 'junk' password for those 'don't care if it's stolen' unimportant websites and much stronger ones for social media, eBay, Amazon and the like.

Save ink and the planet – print less!

Back in the 1990s, primitive inkjet printers cost a fortune (laser printers cost even more) and black print was derived by combining the colour cartridges to produce, at best, a muddy brown print. Today, mass-produced flimsy five- or six-colour printers are dirt cheap in comparison with their forebears, but of course the cost of OEM ink cartridges remains prohibitively high. At £91 ($118) retail for an XL 47ml five-cartridge refill set, the author's OEM ink cartridges cost nearly £2,000 per litre of ink! Hence the booming market for generic refills or fill-your-own, and there is great pressure to recycle empty cartridges and also reduce the volume of them (plus their packaging) sent to landfill.



Ryman's free 'Eco' font promises to save up to a third in printer ink costs.

To economise on running costs, it's worth first checking your printer settings in software. The author's Epson, for example, defaults to 'standard' quality which uses much more ink and is far too wasteful for quick personal printouts where quality doesn't matter: setting 'draft' as the default instead will save valuable ink and also shorten printing times.

The choice of fonts used in documents can also affect ink consumption, and mindful of the overall ecological damage that printer consumables create, the UK stationery chain Rymans produced an eco-friendly font specially designed to minimise ink usage, which in turn can only help lengthen the working life of a disposable cartridge and save money all round. The Ryman Eco font was specially designed to lay characters down on paper with unprinted fine 'channels' carved within them, and the printer ink is left to run (or bleed) into these ink 'valleys' and render the character more solidly. Ryman claims its Eco typeface uses typically 33% less ink than standard fonts.

Given that Times New Roman and Arial are deeply embedded into many a computer user's regimen, the ornate serif Ryman Eco takes a little getting used to, but print quality is more than acceptable, even in draft mode. Unfortunately, I found the typeface fares much less well as a screen font when viewed on an LCD monitor, as text can be harder to discern. However, if you have copious amounts of heavy documentation or manuals to print, one idea would be to compose them onscreen using traditional and familiar fonts and switch styles to Ryman Eco before printing them. Ryman Eco is worth trying and it can be downloaded free from: **https://rymaneco.co.uk**

An alternative approach is offered by Ecofont, which sells a special Windows virtual printer driver that seamlessly converts fonts into their identical-looking 'ink-saving equivalent' when printing. Ecofonts print using fewer pixels and the human eye can barely notice the difference, they say. They claim up to 50% savings in ink. Home users pay €7 per year per person and business users pay €10 each annually. More details are at: **www.ecofont.com**

What about home photo printing? Many modern inkjet printers are highly capable at printing photographs, but churning out large numbers of photos can become an expensive time-consuming exercise. Some inkjet printers are Internet and cloud-printing aware, which makes it easy to print photos remotely: they may have a dedicated email address, so sending them a JPEG from halfway round the world will result in a photo popping out back at home.

However, with Christmas festivities and holidays in mind, dedicated online photo printing services can work out much cheaper and hassle-free, and websites such as **photobox.com** let you upload and compile your own photo albums and store them for future printing. Presenting a proper album of favourite photos is an excellent Christmas gift idea, and Photobox's postal printing service has proven fast and reliable. Upload photos for printing from a PC, Facebook, Flickr, Instagram, Dropbox or iPhone – but the Android app has been discontinued. Rival Snapfish has both Android and iPhone apps and offers 50 free prints a month for a whole year, see: **www.snapfish.co.uk**. The Touchnote app for Android and iPhone (download from: **www.touchnote.com**) lets you upload a photo for printing and delivering as a traditional postcard, great for when you are on holiday. Other online photo printers are available that will print on a wide range of media, and it's worth searching and trying them out.

Last, but not least, please stay safe online. A very merry Christmas and a happy New Year to all readers – see you next month for more *Net Work*.

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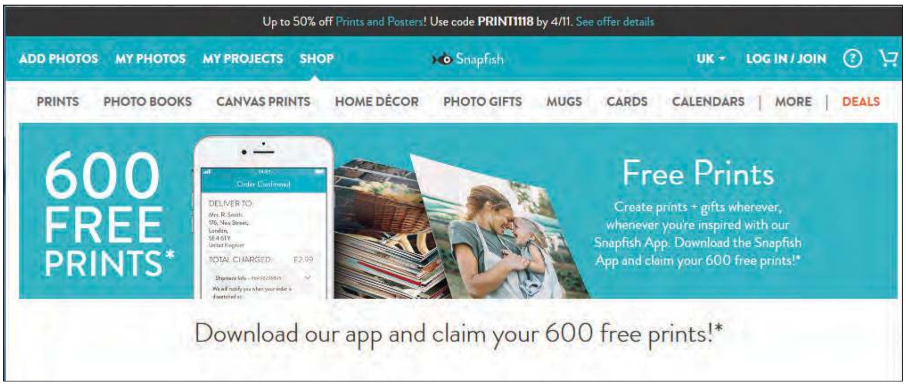
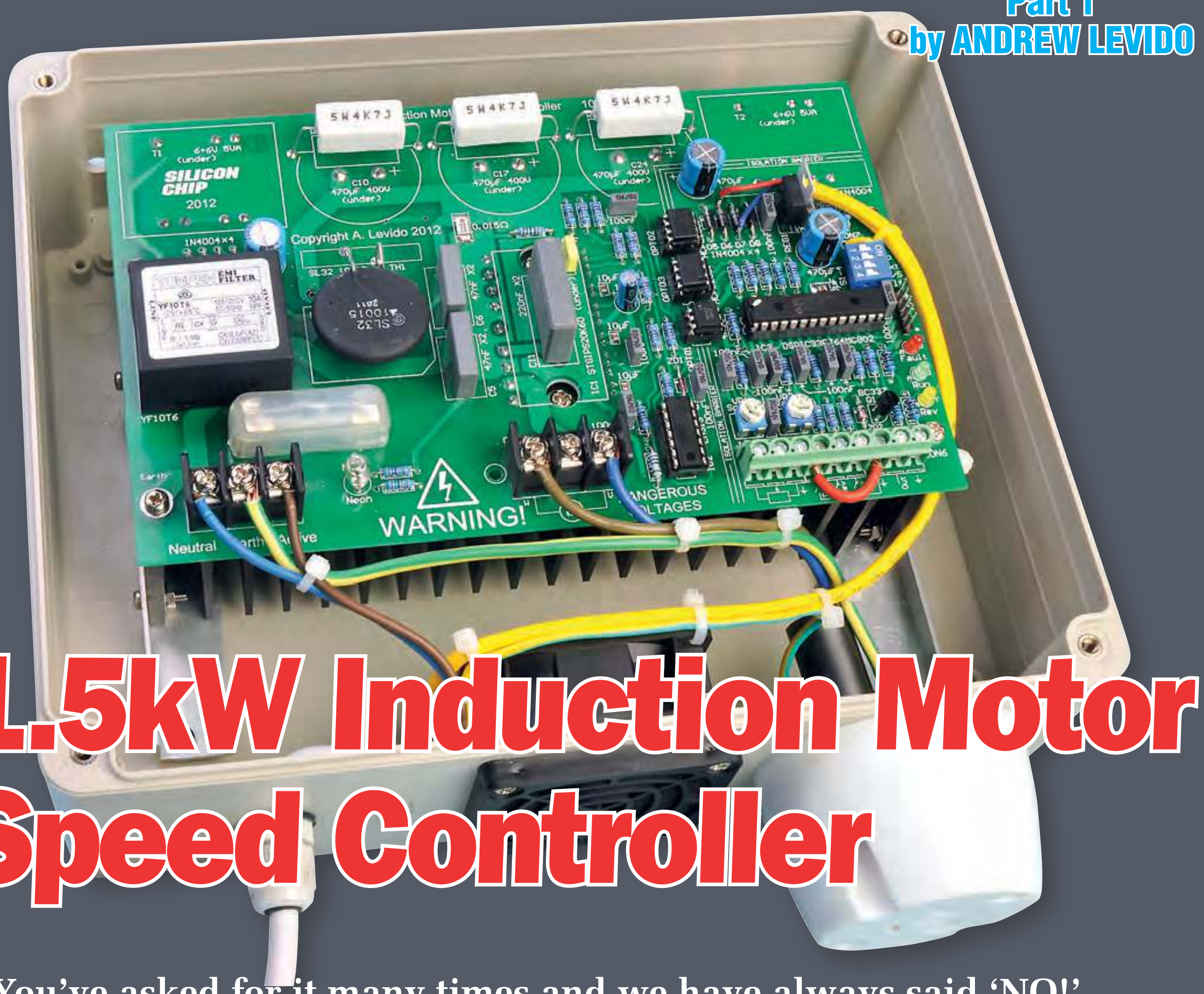


Snapfish is one of several online photo print shops, and offers 50 free prints a month for 12 months for downloading their app.

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.

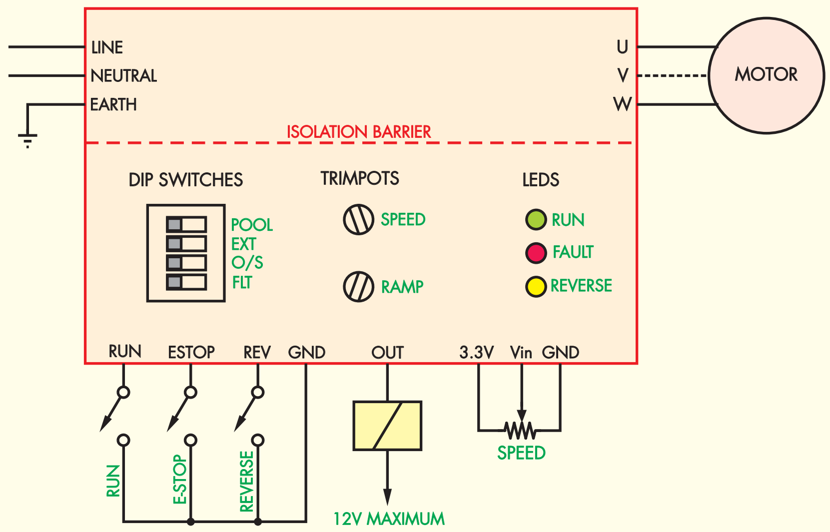


Fig.1: overview of the *Induction Motor Speed Controller*. The mains input power (left) and the motor (right) are connected to the high-voltage section at top, with the earth connection used for EMI suppression. The DIP switches and trimpots allow the unit to be configured, while the LEDs provide feedback.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

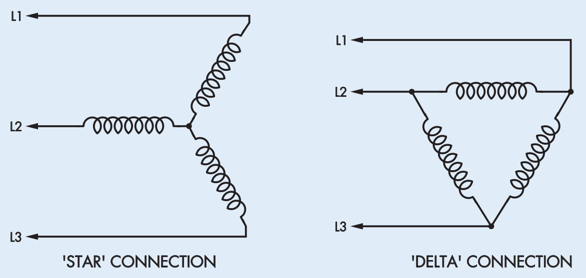


Fig.2: the windings of small 3-phase motors are normally connected in star configuration for use with the 400V RMS 3-phase mains supply. In this case, each winding is driven with the phase-to-neutral voltage of 230V. By changing how the windings are connected (which can usually be done by moving some 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

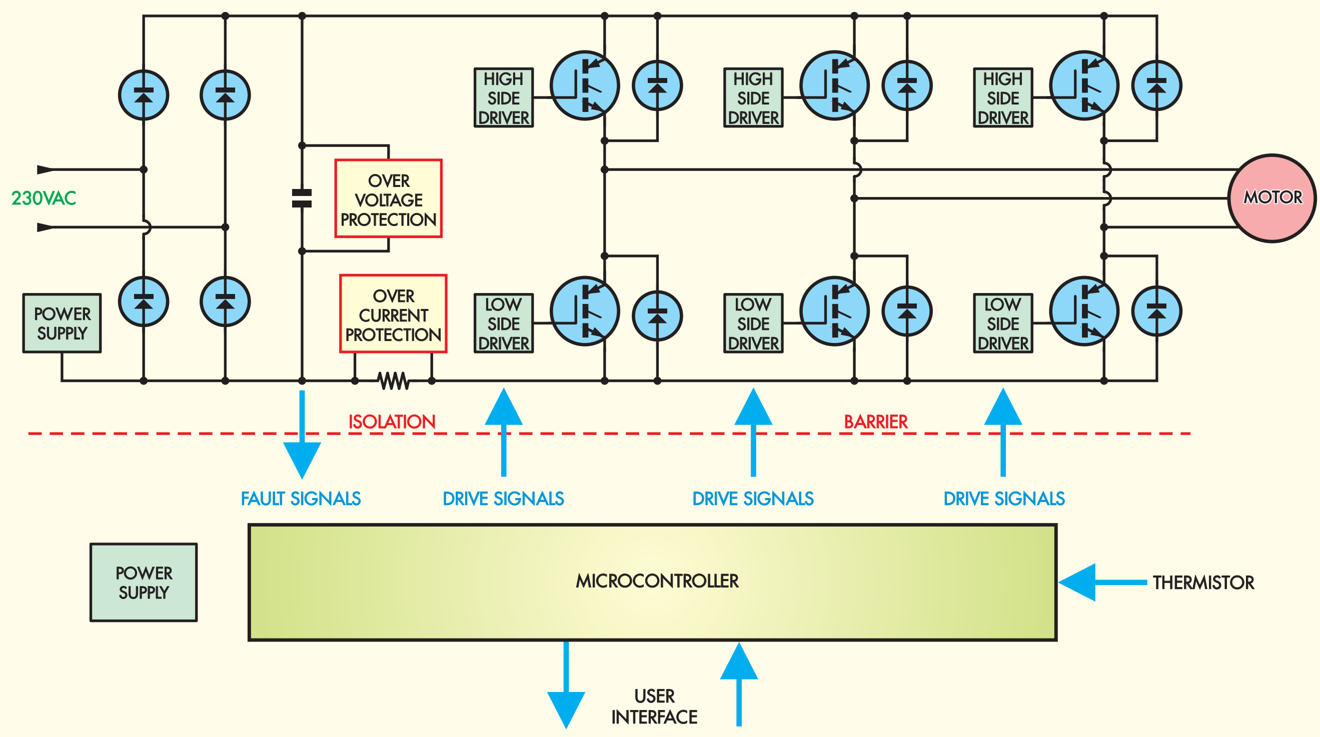


Fig.3: this block diagram shows how the incoming 230VAC mains is rectified and filtered before being applied to the motor by six IGBTs configured as a 3-phase bridge. The capacitor bank voltage can increase during over-run and the over-voltage protection circuit disables the IGBTs before damage can occur. 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 inter-phase voltage of:

$115V \times \sqrt{3} = 200V$ 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

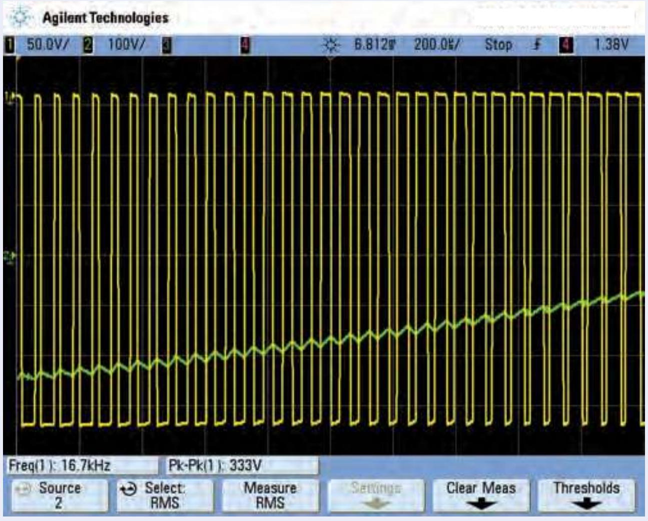
This circuit is directly connected to the 230VAC mains. Therefore, most of the parts and wiring operate at mains potential and there are also sections running at 325-350V DC. Contact with any part of these non-isolated circuit sections could prove FATAL (see Fig.5).

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

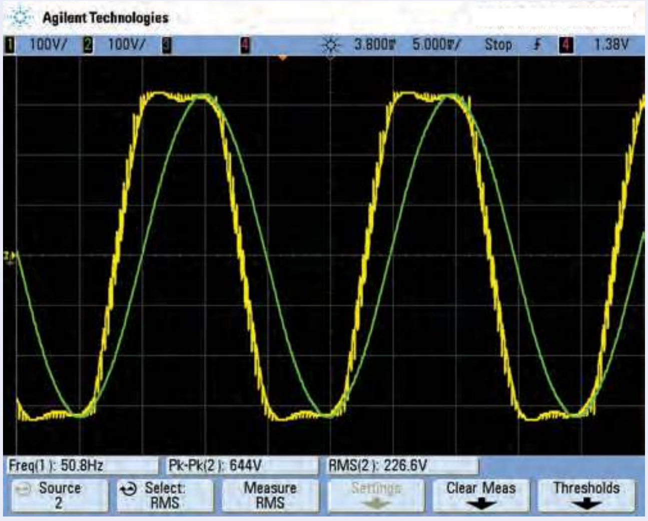
To ensure safety, this circuit MUST NOT be operated unless it is fully enclosed in an appropriate plastic case. Do not connect this device to the mains with the lid of the case removed. DO NOT TOUCH any part of the circuit unless the power cord is unplugged from the mains socket, the on-board neon indicator 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 STGIP3S0C60 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.

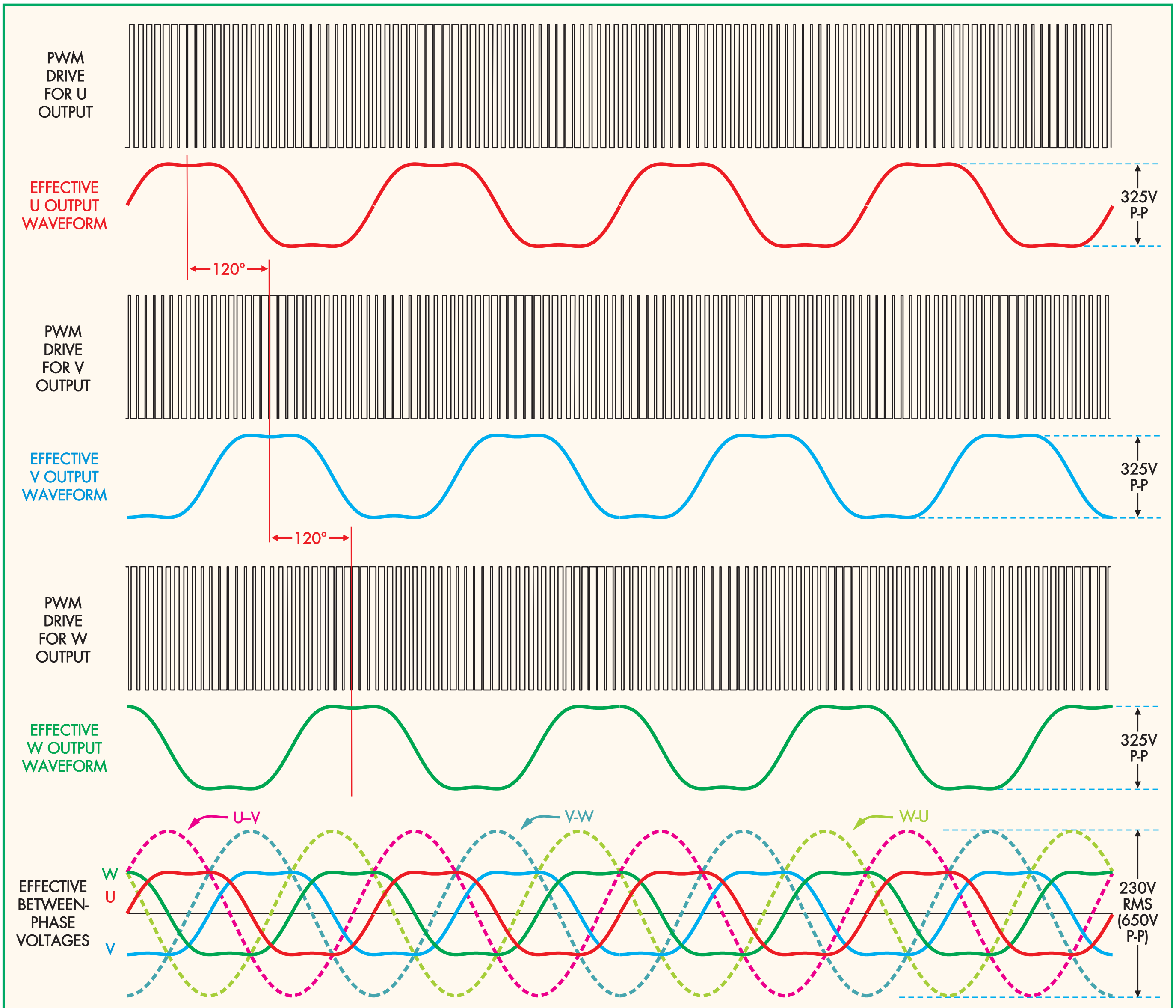


Fig.4: in operation, 16kHz PWM is used to generate identical waveforms with different phases from all three outputs (U, V and W). The motor winding(s) are connected between these outputs and so are driven with the difference between them. When we subtract these wavforms from each other, the result is 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

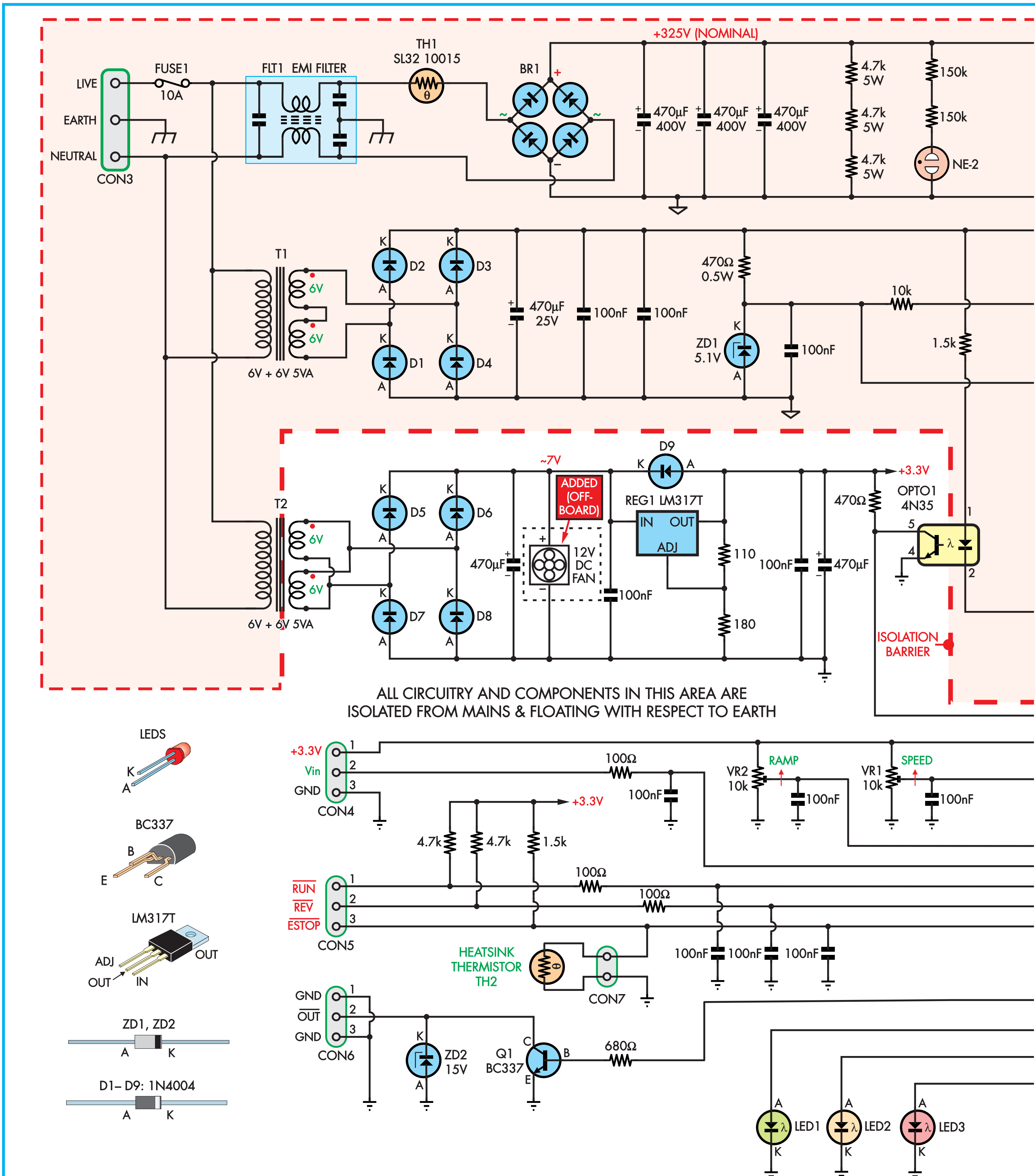
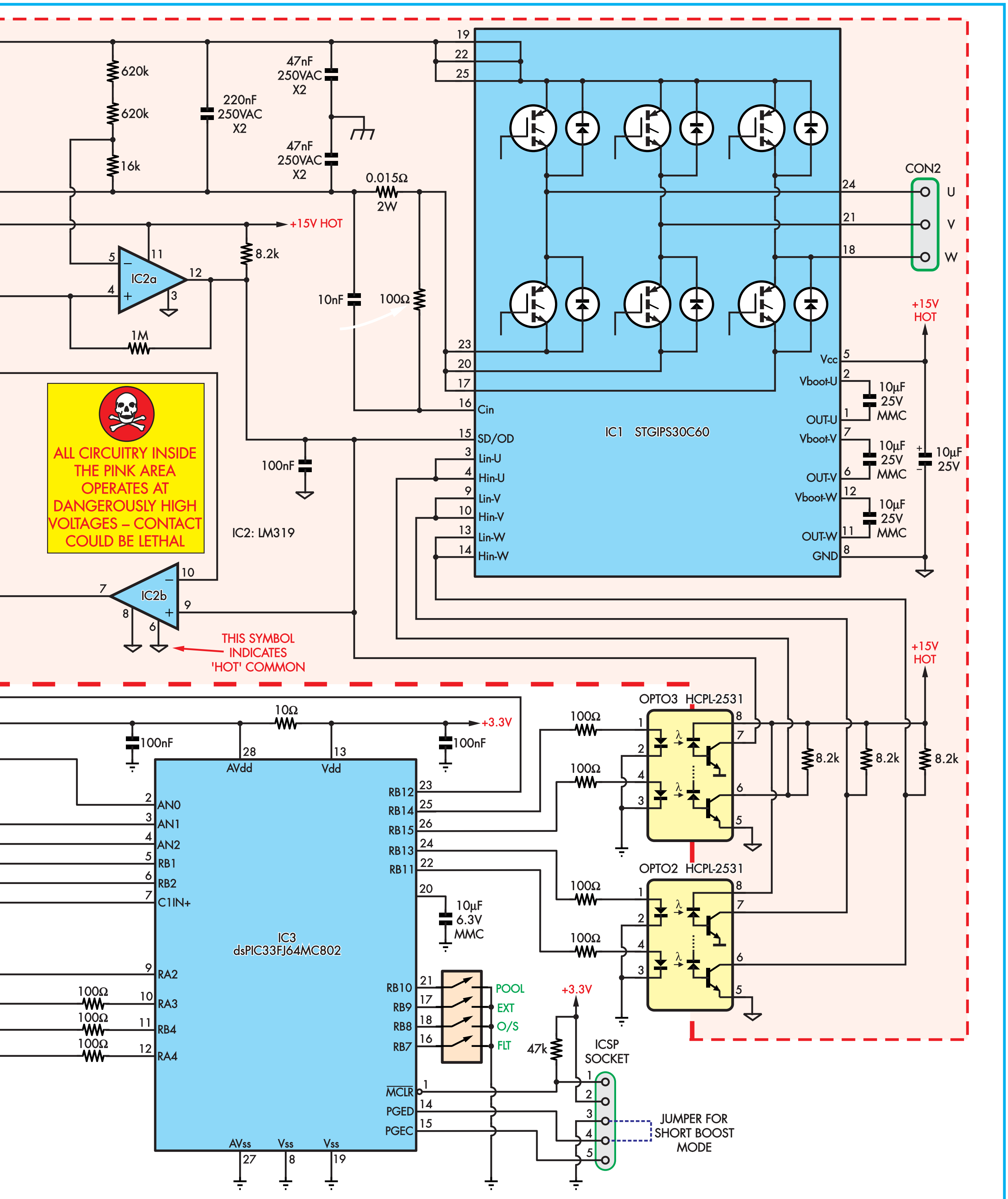


Fig.5: the full circuit diagram of the *1.5kW Induction Motor Speed Controller* PCB. The incoming mains is rectified by BR1 to provide a +325V DC bus. This powers 3-phase IGBT bridge IC1, which switches the voltage to the motor via CON2. A 0.015Ω resistor in its ground path provides current feedback 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 optocoupler 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

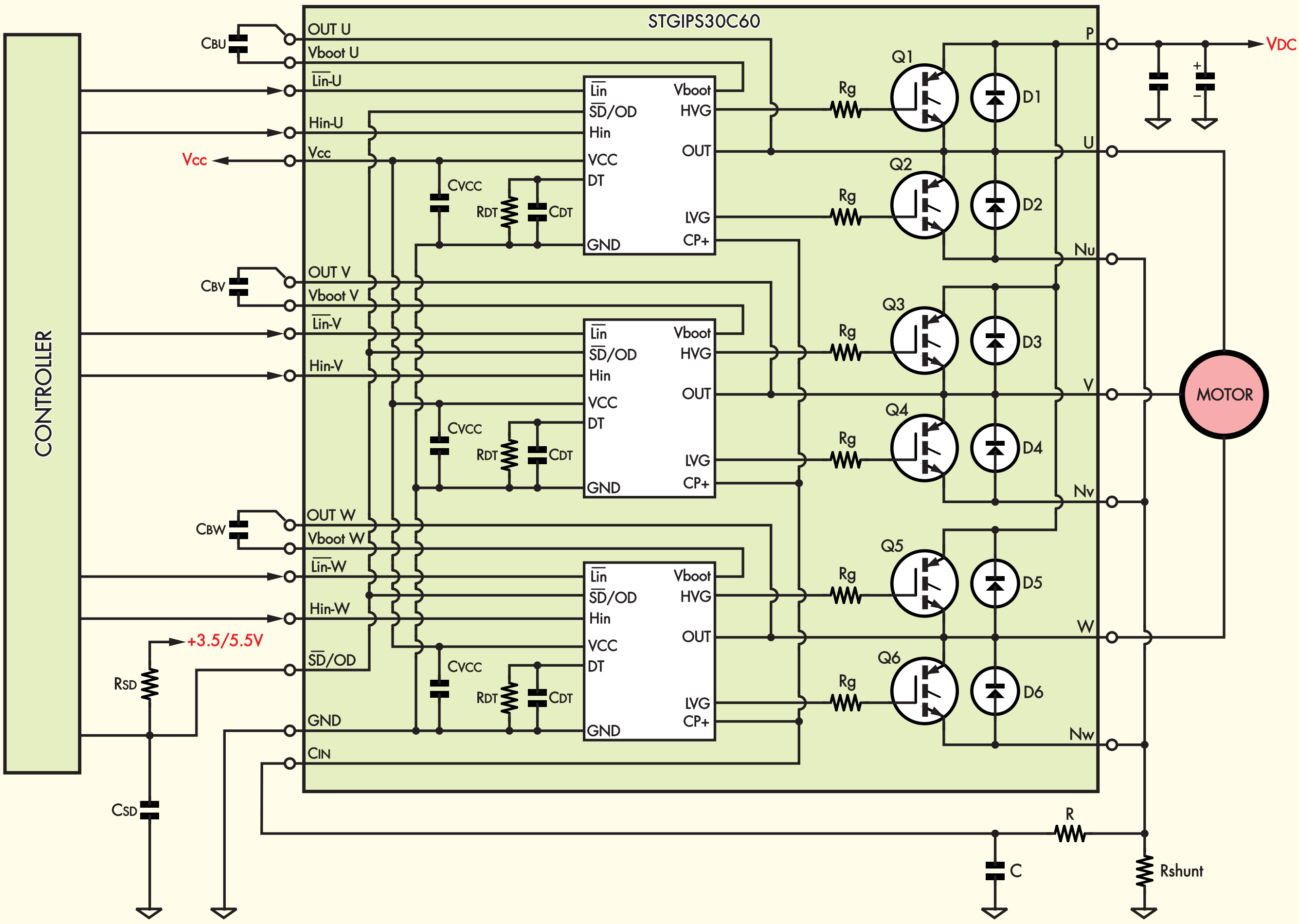


Fig.6: typical application of the STGIP3S0C60 IGBT bridge, redrawn from the data sheet. Each pair of IGBTs has parallel free-wheeling diodes and drives one of the motor terminals. The associated control blocks drive the IGBT gates, generating the high drive voltage for the upper IGBT in each pair (in 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 ($\overline{SD}$/OD) which also acts as a fault output.

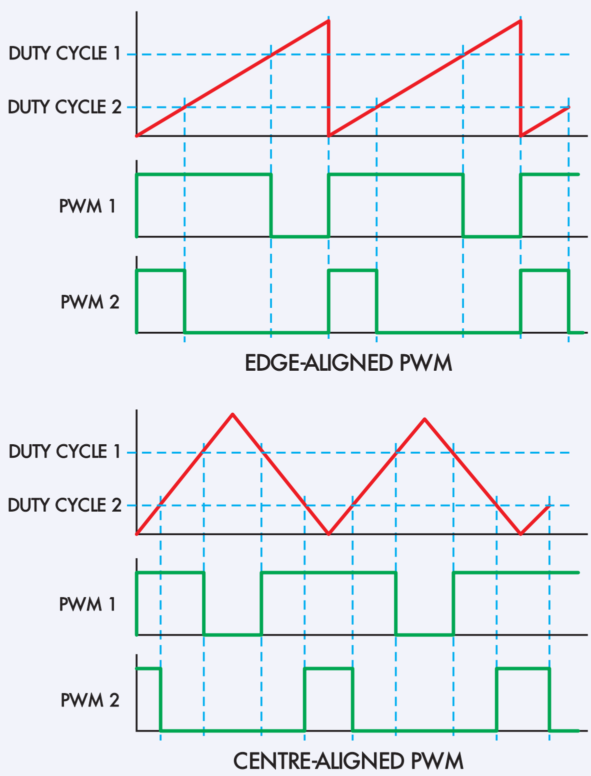


Fig.7: this diagram illustrates the difference between traditional edge-aligned PWM and centre-aligned PWM (also known as dual-ramp PWM).

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

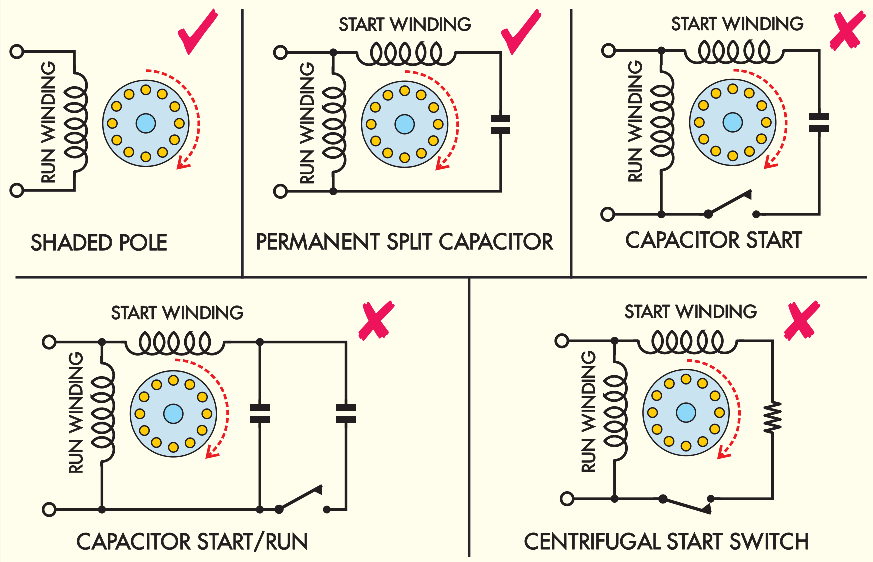
Single-phase induction motors

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.*

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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*.

Win a Microchip dsPIC33CH Curiosity Development Board

Everyday Practical Electronics is offering its readers the chance to win a Microchip dsPIC33CH Curiosity Development Board (DM330028).

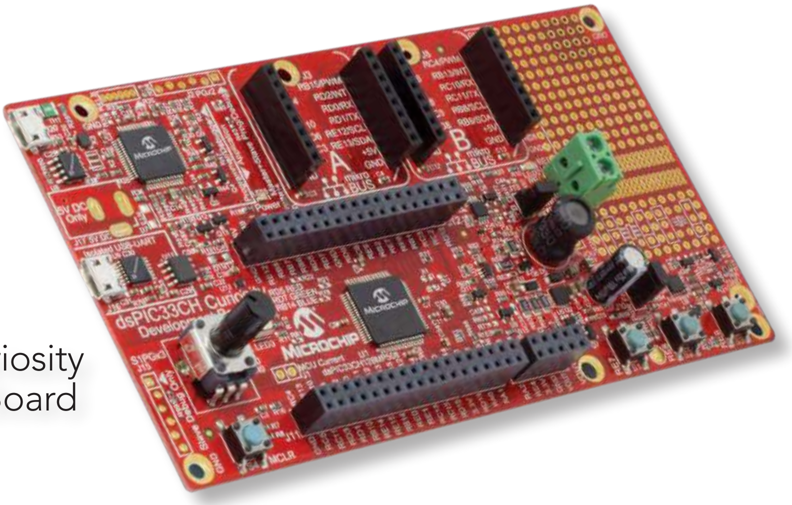
The dsPIC33CH Curiosity Development Board is a cost-effective development and demonstration platform for the dsPIC33CH128MP508 family of dual-core high-performance digital signal controllers. The dsPIC33CH has one core that is designed to function as a master while the other is designed as a slave. The slave core is useful for executing dedicated, time-critical control code, while the master core is busy running the user interface, system monitoring and communications functions, customised for the end application. The dsPIC33CH is designed specifically to facilitate independent code development for each core by separate design teams, and allows seamless integration when they are brought together in one chip.

Worth $28.00 (approx £22.80) each

The board is designed to take full advantage of Microchip's MPLAB X IDE and includes an integrated programmer/debugger. The board requires no additional hardware, making it a perfect starting point to explore the dsPIC33CH dual-core family.

Supported by Microchip's MPLAB development ecosystem, including Microchip's MPLAB Integrated Development Environment and MPLAB Code Configurator, the dsPIC33CH Curiosity Development Board is a cost-effective and flexible platform enabling customers to rapidly create a feature-rich prototype.

The board supports the dsPIC33CH Plug-in Module for motor control platforms, available for Microchip's MCLV-2 and MCHV 2/3 systems. The dsPIC33CH PIM for general-purpose platforms is now also available for the Explorer 16/32 development board.



Microchip dsPIC33CH Curiosity Development Board

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THE ALTRONICS MEGA BOX

Article by
Bao Smith

Make your Arduino projects easier to build and look much more professional with this kit from Altronics. It includes a pre-cut plastic instrument case, 16x2 alphanumeric LCD, four illuminated pushbuttons, two relays, an infrared receiver, rotary encoder and pluggable terminal blocks. This makes building your Arduino Uno or Mega project a breeze.

The Altronics *Mega Box* kit (Cat K9670; **www.altronics.com.au/p/k9670-inventa-mega-box-for-arduino**) is a clever Arduino prototyping system developed by Altronics.

It comes with a large PCB measuring 197 × 115mm, and the Arduino module and optional shield board plug into this. The PCB then neatly fits into the supplied case with the controls accessible through holes cut into the front.

It's easy to build since all the components are through-hole types. While we describe it as a prototyping system, it's quite possible to build a finished project using it; something that would come in handy everyday.

As well as the extra components mentioned above, which you can use to build your project, the PCB has a 210-pin prototyping area that lets you fit the extra components you need which are not already provided by the *Mega Box* or fitted to the Arduino or shield boards.

All the connections from the main Arduino board and the other hardware in the box are broken out into female headers so that you can easily make connections between them using jumper wires.

The *Mega Box* also has a lot of extra power supply connection points, which you will often find you need. For example, near where the Arduino module is mounted, there are four sets of five sockets giving you additional 3.3V, 5V, GND and V_{IN} connections. Similarly, there are two 14-pin headers near the prototyping area, one giving you access points to the 5V rail and the other GND.

Due to the way the boards are mounted they provide a separate 6-pin in-circuit serial programming (ICSP) connector. Then you have connection points to attach wires for interfacing with other components like the illuminated pushbuttons, relays, LCD, LEDs, rotary encoder and infrared receiver.

Note that to take full advantage of all the features in the *Mega Box*, you really need to use an Arduino Mega to have enough I/O pins. But you can certainly use it with an Uno for some applications, and this is how we tested it.

What can it be used for

When you plug a shield board into an Arduino, you can play around a bit but all you're really left with is a bit of a curiosity. To turn it into something truly useful, you need a user interface for your device, some kind of enclosure and so on. The *Mega Box* gives you all that.

For example, you could build an Arduino Music Player by plugging an MP3 player shield into an Arduino Uno, but to make it truly useful, you'd need to add a keypad and an LCD so you could control it. And while that might work well, all you'd really have is three separate modules connected by flying leads; hardly a 'finished product'.

If you had the *Mega Box*, then you could easily build a finished product and with a lot less hassle.

You may remember our *Arduino-based Digital Inductance and Capacitance Meter* from the June 2018 issue. Guess what – Altronics have actually designed a shield board for that project and it integrates perfectly with the *Mega Box*.

Those are just two examples of what you can do with the *Mega Box*. Given the plethora of Arduino shields, the hardware provided by the *Mega Box* itself and the ability to add extra components in the prototyping area, it's a really flexible system that would be suitable for a lot of different purposes.

Circuit description

The *Mega Box* circuit is shown in Fig.1. Much of this is taken up by the Arduino module, the optional shield and the wiring between them.

The headers where the shield can be plugged in are wired directly to the corresponding pins on the Arduino, which is also plugged into a set of headers. So the shield works as if it's plugged on top of the Arduino board,

even though the two are mounted side-by-side.

A third set of headers, shown next to the ones the Arduino is plugged into, are provided so that it's easy to wire up any free Arduino pins to other parts of the board.

Most of the rest of the circuitry is in separate blocks with headers for the inputs and/or outputs of each block. So to use one of these sub-circuits, all you have to do is run jumper wires between the Arduino headers and the headers for that sub-circuit.

One of the few portions of circuitry already wired to the Arduino itself surrounds LED3, which lights up when the SCK pin is high, indicating that SPI serial communication is in process.

LED3 is driven by NPN transistor Q4, which is in turn driven by pin 13 (the SCK pin on the Arduino Uno) via a 10kΩ current-limiting resistor. A second 10kΩ base pull-down resistor shunts any leakage current to ground.

There's also a reset pushbutton (S5) on the *Mega Box* board because the button on the Arduino itself is inaccessible due to being mounted upside-down. This is simply wired between the Arduino reset pin and ground.

Headers CON3-CON6 provide an easy way to access the 3.3V, 5V and V_{IN} (DC input) supply rails and make ground connections. Each provides five sockets to make connections to one of these rails.

Separate sub-circuit blocks

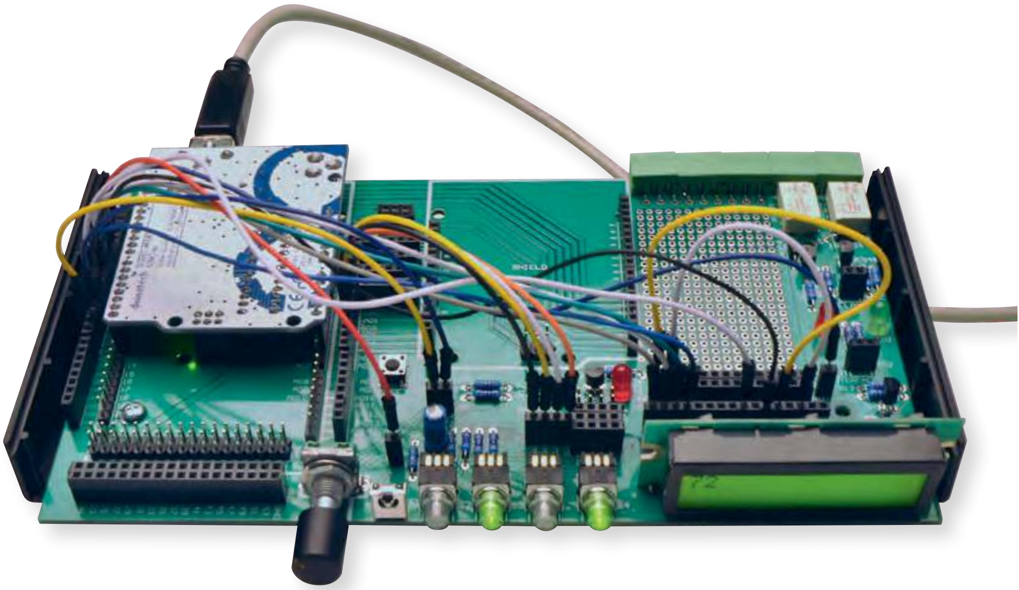
Pushbuttons S1-S4 are illuminated momentary types; the illumination is provided by a built-in LED. Three headers are provided to make connections to these buttons.

One 8-way header (CON2) gives access to the LED anodes via 1kΩ current-limiting resistors; the cathodes are connected to ground. That same 8-way header also gives access to the switch common terminals.

Two additional four-way headers (CON17 and CON18) are provided to connect to the normally open and normally closed contacts, plus there are four jumpers (JP1) to short the normally open contacts to ground.

This makes it easy to sense when a button is pressed since all you need to do is fit the shorting block on the jumper for a button and then wire the same button's common terminal to an Arduino digital pin. Set that pin as a digital input with internal pull-up and the pin will be high normally and is pulled low when the button is pressed.

Two extra general-purpose LEDs, LED1 and LED2, are provided and would be most useful for debugging



The Altronics *Mega Box* connected and running the provided example program. The illuminated pushbuttons are controlled via an IR remote control, and the LCD backlight brightness is adjusted by the rotary encoder, with an integer value displayed on the screen indicating the number of units away from the rest position of the rotary encoder.

purposes since they are mounted inside the case. These are also provided with 1kΩ current-limiting resistors and have their cathodes connected to ground and their anode connections made via a 2-way header (LED interface).

There are also two on-board DPDT relays. One set of contacts for each relay is wired to a 3-way pluggable terminal block at the back of the unit.

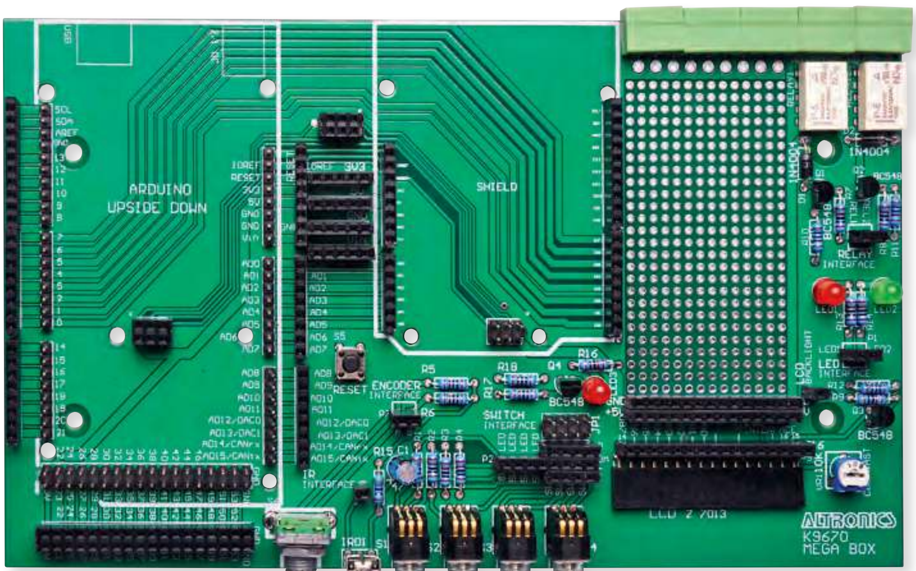
Each relay has a back-EMF quenching diode across its coil and a BC548 transistor to drive that coil, along with 1kΩ base current-limiting resistors and 10kΩ pull-down resistors. A two-way header (Relay interface) allows you to wire these relays up to Arduino pins.

There are also three extra 3-way pluggable terminal blocks at the back of the unit which are wired to solder pads on the board. You could wire these up to extra circuitry fitted to the prototyping area.

An infrared receiver is mounted at the front of the unit and it is powered from the 5V supply, with a 47Ω/47µF RC filter to prevent supply noise from affecting its operation. Its output is available on a 1-pin header (IR interface) and the signal can be decoded using the Arduino IRLib or other library.

There is provision for mounting a 16x2 LCD panel on the front of the unit and its 16 pins are wired directly to a 16-pin female header (CON9). The power supply (+5V and GND) pins are pre-wired for you, along with contrast adjustment trimpot VR1.

Transistor Q3 allows PWM control and dimming of the backlight and it has a 1kΩ base current-limiting resistor



This is what the PCB should look like after all the soldering has been completed. Three of the 3-way screw terminals do not have a matching relay, so you will need to solder wires to the adjacent pins to utilise them. Also, you can see that digital pin 3 of the Arduino main board is mislabelled on the PCB.

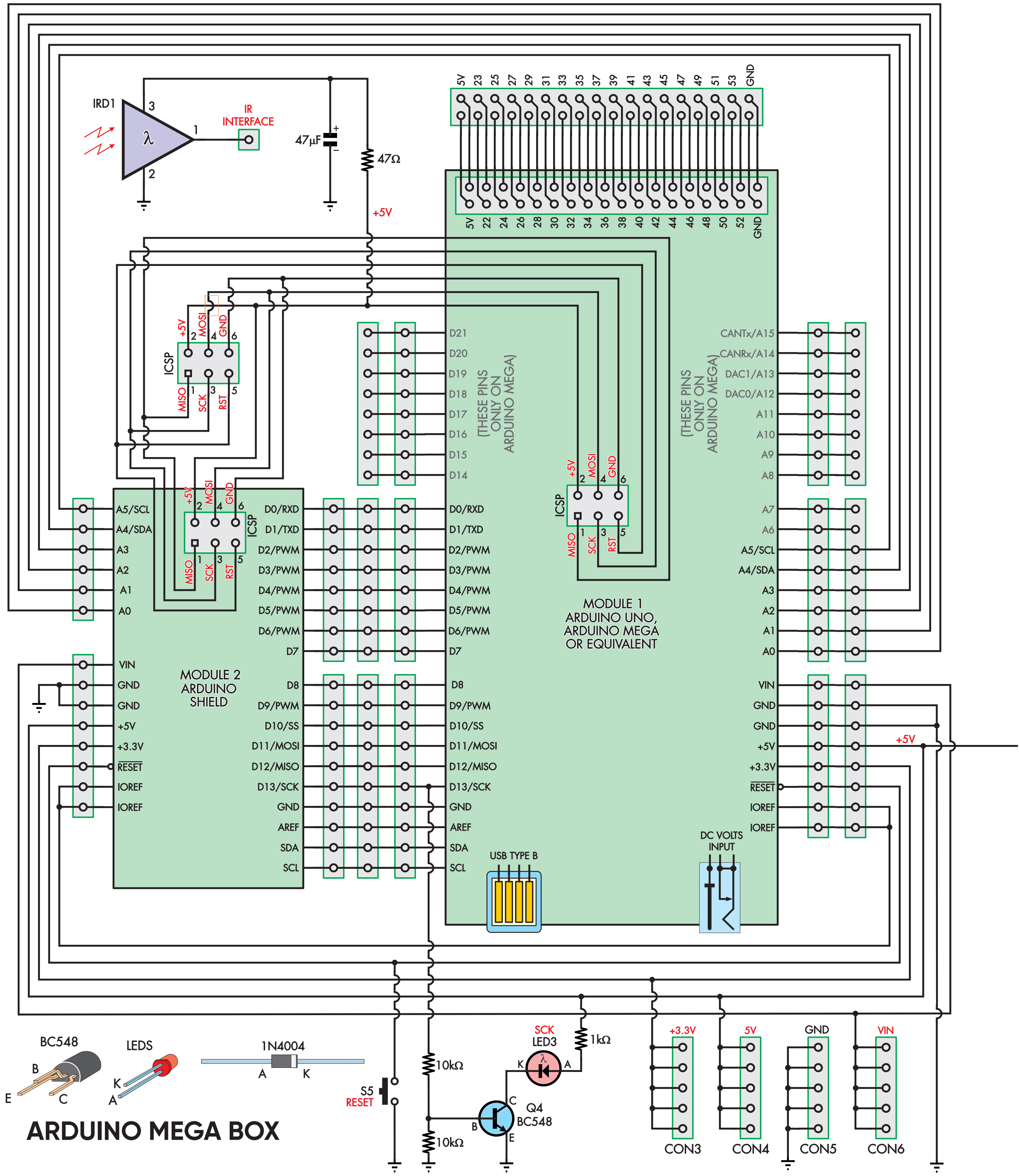


Fig.1: complete circuit diagram for the Arduino *Mega Box*.

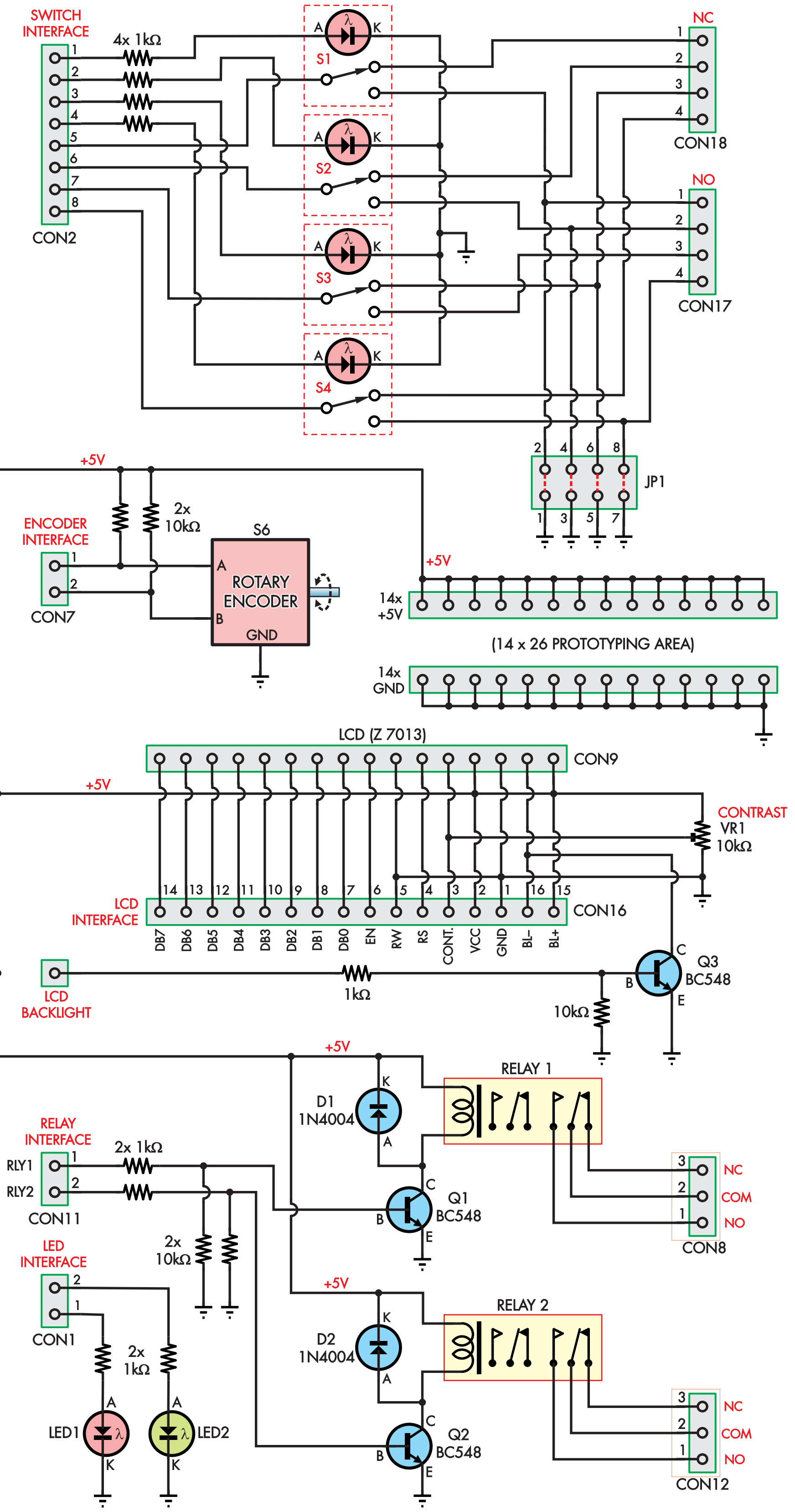
and a 10kΩ resistor to ensure it stays off when not driven.

A 'gray-code' rotary encoder (similar to a potentiometer but with a digital output) is provided for user input and is wired to a 2-way header (Encoder interface) with 10kΩ pull-ups to 5V on its two output terminals.

When rotated in one direction, the binary output at terminals A and B have the following sequence: 00, 01, 11, 10, 00, 01, 11, … while rotation in the other direction gives: 00, 10, 11, 01, 00, 10, 11, … There are various Arduino libraries to help you decode this, including one called (predictably) 'Encoder'.

Construction

The main task when building the *Mega Box* is soldering all the components onto the main PCB. Fig.2 shows the overlay diagram, which indicates where all the components go. Many of them are headers (mostly female, but some male too).



Our sample *Mega Box* didn't come with much in the way of instructions and if yours doesn't either then this article should be a useful guide. You can also refer to our photos to see how the finished board should look.

Start by soldering all the low-profile components first (eg, resistors and diodes) then move on to the relays, semiconductors and capacitor. Some components, such as the diodes, capacitor and relays, need to be fitted the right way around. For the diodes and relays, match up the stripe/line on the component to the one shown in Fig.2 or on the PCB.

For the three LEDs, the cathode (shorter lead) is on the same side as the flat portion of the plastic lens and should be matched up with what is shown in Fig.2 and the PCB silkscreen.

On the single 47µF electrolytic capacitor, the stripe down its side indicates the negative lead while the positive lead will be longer. The longer (positive) lead goes to the pad marked with the '+' symbol.

We found it easier to fit the switches, terminal blocks and infrared sensor before the headers, and left the rotary encoder for last.

Note that the headers supplied may be longer than needed and you will have to cut the female headers to length and snap the male headers apart.

The various different header lengths required are listed in the parts list. The headers supplied are likely to be 40 pins long, so cut these up to form several of the smaller headers. (You may well be left with some spare headers at the end.)

To snap the male headers, grab either side of the location where you want to snap them with two pairs of pliers (or just one pair) and then apply force to bend the header until it snaps. Double-check you will get the right number of pins before snapping.

The female headers are a little more tricky because you need to cut them apart using side cutters. This almost always destroys one pin so you should make the cut in the middle of the pin *past* the end of the last one you want to keep. You can then remove the pin at the cut (if it didn't already fall out) and file any jagged plastic edges smooth.

Three dual-row female headers are required, and while Altronics do provide a long dual-row header to cut apart, doing so is quite tricky; you really need a large pair of side-cutters. Instead you can cut and fit two single-row headers side-by-side.

Soldering the pin headers so they're straight can be tricky. Our tip is to solder one pin, then visually check it is flush and straight and re-melt the joints if it isn't, while applying a small amount of pressure.

Once it's straight, you can solder the other pins. You may also find that it helps to use a small flat piece of wood or similar material to support the header during soldering.

The right-angle female header is used as the socket for the LCD, but do note that you will have to solder a 16-pin male header to the back of the LCD panel to plug into this.

When soldering the rotary encoder, be sure to solder the two support pins on either side to prevent it from being ripped off the board.

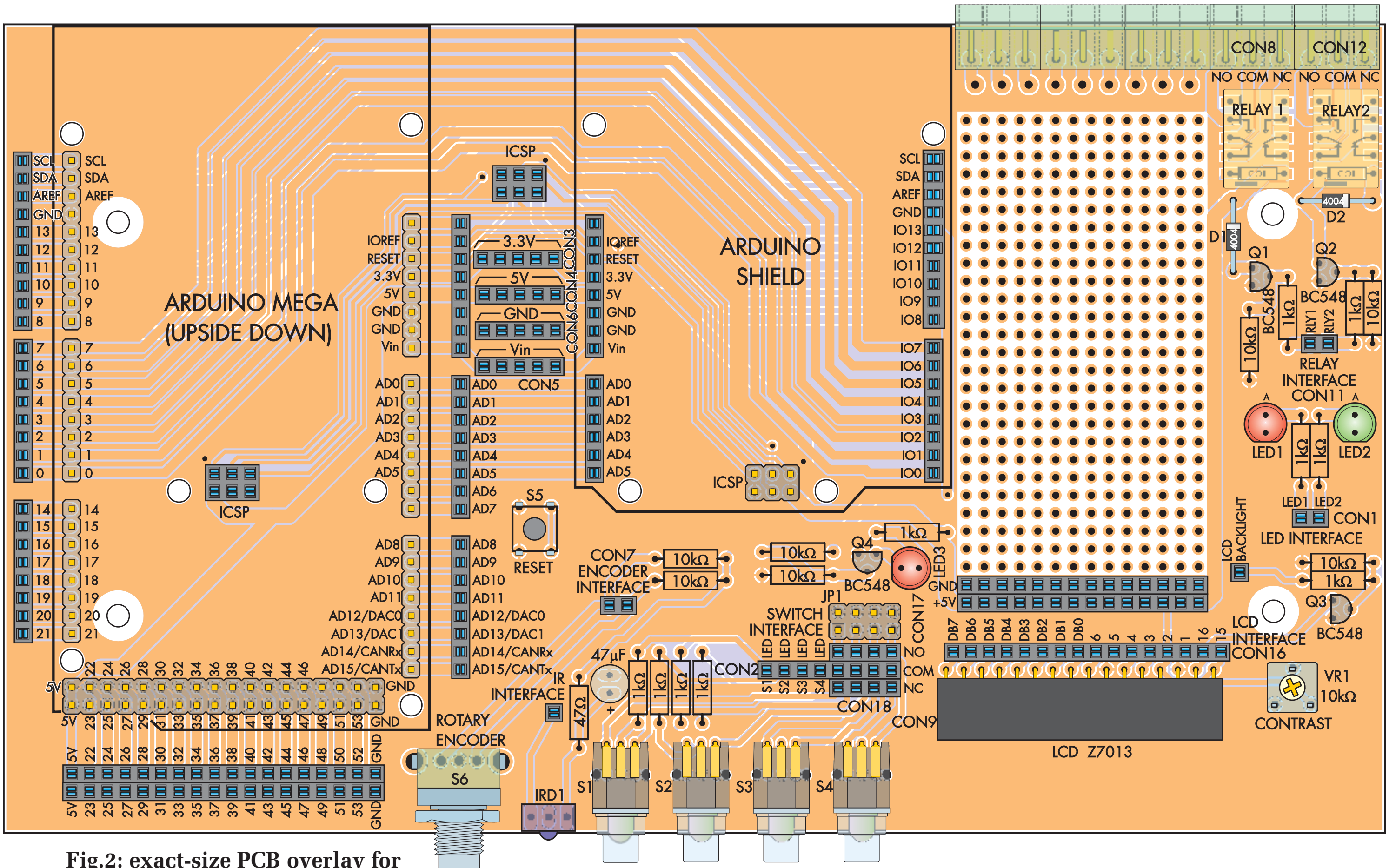


Fig.2: exact-size PCB overlay for the Altronics *Mega Box*, which shows the locations of the various headers and other components.

An example program

Altronics provides a small example program on their website that showcases the LCD screen, rotary encoder, IR sensor and four illuminated pushbutton switches. You can download it from: **http://download.altronics.com.au/files/software_K9670.zip**

This program assumes you're using an Arduino Mega for the pin layout; you can use an Arduino Uno, like we did, but some of the I/O pin numbers will need to be changed. Here are the pin numbers we used with their software to work with the Uno:

- Encoder interface:
  pin A → D2, pin B → D3 (line 35)
- LCD screen:
  RS → D4, E → D5, DB4 → D6,
  DB5 → D7, DB6 → D8, DB7 → D9
- Backlight interface → D10 (line 46)
- IRD1 → D11 (line 53)
- SW1 LED → A3, SW2 LED → A2,
  SW3 LED → A1, SW4 LED → A0
  (lines 60-63)

Before you can compile and upload the software in the Arduino IDE, you will need to install third-party libraries from the following sources:
https://www.pjrc.com/teensy/td_libs_Encoder.html

Parts list

1 double-sided PCB, coded K9670, 196.5 x 115mm (from Altronics kit)
1 quarter-rack plastic instrument case with pre-cut holes
1 16x2 alphanumeric backlit LCD screen (LCD1)
1 infrared receiver (IRD1)
4 right-angle illuminated momentary pushbutton switches (S1-S4)
1 4-pin PCB-mount vertical tactile switch (S5)
1 10kΩ horizontal trimpot (VR1)
2 2A 5V mini DIL DPDT relays (RLY1,RLY2)
5 3-way PCB-mount right-angle pluggable terminal blocks (CON8,CON12)
1 rotary encoder with nut, washer and knob (S6)
1 2x18 pin dual-row female header
1 2x14 pin dual-row female header
2 2x3 pin dual-row female headers
1 16-pin right-angle female header (CON9)
1 16-pin female header (CON16)
2 10-pin female headers
8 8-pin female headers (including CON2)
1 6-pin female header
4 5-pin female headers
2 4-pin female headers
3 2-pin female headers (including CON7)
2 1-pin female headers
1 2x18 pin dual-row male header
1 2x4 pin dual-row male header (JP1)
1 2x3 pin dual-row male header
1 16-pin male header (for LCD1)
1 10-pin male header
5 8-pin male headers
plus mounting screws and rubber pads for the case.

Recommended: Arduino Uno or Mega; set of various male-to-male single jumper wires (try Altronics P1016); universal infrared remote control (eg, Altronics A1012); 4 shorting blocks (for JP1). All not included in the kit.

Semiconductors
4 BC548 NPN transistors (Q1-Q4)
2 5mm red LEDs (LED1,LED3)
1 5mm green LED (LED2)
2 1N4004 1A diodes (D1,D2)

Capacitors
47µF 16V electrolytic

Resistors (all 1/4W, 1% metal film)
7 10kΩ
10 1kΩ

https://www.pjrc.com/teensy/td_libs_IRremote.html

You might run into conflicting names for the IRremote library as the header file shares the same name as the RobotIRremote library.

The easiest way to solve this problem without renaming one of the libraries is to temporarily remove the RobotIRremote library from: **C:\Program Files\Arduino\libraries** (or wherever the Arduino IDE is installed). That's assuming it was already installed. Otherwise, it won't be an issue.

With the libraries loaded, you can upload the program to your Arduino board using a type-B USB cable and then make the various pin connections using male-male flying jumper leads (not included in the kit, but see parts list for a suitable set from Altronics).

It helps to have a variety of lead lengths for tidiness; you will at least need a few that are more than 100mm long, if not 200mm to match the width of the PCB.

To figure out where the wires go, first refer to the list of connections above in reference to changes to the software (which is a complete list) but you can also refer to the photos in this article as a guide.

LCD display

Note that when you run the software you will need to adjust the display's contrast trimpot (VR1) for text to be visible on the LCD. We found that we had to wind the trimpot almost fully anti-clockwise for the text to be visible.

Also, note that their software doesn't adjust the LCD backlight until you turn the rotary encoder. You could connect the backlight control pin directly to 5V so that the backlight runs at full brightness all the time (as long as the unit is powered).

Or you can remedy this by adding the line: **analogWrite(BL, 255);** after line 69, which reads **lcd.begin(16, 2);** This will cause the backlight to start out at its highest brightness (if you haven't wired it directly to 5V, as suggested above).

The data sheet for the LCD screen used in this project is available from: **http://bit.ly/2qHJHMe**

The sample software will detect rotation of the front-panel encoder and display the rotation amount on the screen.

Using a remote control

It will also pick up and display some infrared remote control codes, specifically, RC5 codes 0x001 – 0x004 and 0x801 – 0x804. These correspond to buttons 1-4 on a universal remote set on one of the more common Philips TV codes.

When these buttons are pressed and are generating the correct codes, it will toggle on/off the corresponding LED in one of the four pushbutton switches.

Conclusion

The Altronics *Mega Box* is a very flexible system and can be used with virtually any Arduino shield (apart from a few that are too tall to fit in the case). Altronics supply a range of shields but it can also be used with shields from other sources.

Building the *Mega Box*, available from the Altronics website, is not difficult. It's suitable for anyone, including relative beginners who want to give their Arduino projects a neat and properly finished look.

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nRF24L01+ 2.4GHz Wireless Data Transceiver Modules

This month, we're looking at a number of modules based on the nRF24L01+ chip, a complete wireless data transceiver capable of up to 2Mb/s over modest distances in the 2.4-2.5GHz ISM (industrial/ scientific/medical) band. It has a standard SPI interface, making it easy to use with any microcontroller.

Connecting a couple of Arduino, Micromite or other popular micros via a wireless data link can be done by making use of a pair of low-cost modules, based on Nordic Semiconductor's ultra-low-power nRF24L01+ chip.

There are quite a few of these modules around, most of them costing just a pound or so, with the more expensive units generally giving longer range (often due to a better antenna). (At the time of publication, a typical example is eBay item 143005028113, available for 99p each including postage.) This circuit used an nRF24L01+ module, available with a whip antenna.

All modules based on the nRF24L01+ device operate in the internationally unlicensed 2.4-2.5GHz ISM band and use the same kind of modulation, described below. So they can all communicate with each other.

It's important to realise that the 2.4-2.5GHz band is also used by Bluetooth devices, most Wi-Fi devices and is also subject to various sources of noise like microwave ovens. We have directly observed serious Wi-Fi speed degradation while a microwave oven was operating, so this isn't just a theoretical issue.

Because it's basically a 'free-for-all', this is a noisy band and becoming noisier all the time. Still, there are ways to minimise the risk of interaction and interference, as we'll explain later.

While you may not have heard of Nordic Semiconductor before, many of their chips are found in all kinds of common devices like non-Bluetooth wireless PC peripherals such as keyboards and mice, gaming controllers, sports and fitness sensors, toys and set-top box wireless remote controls.

Based in Trondheim, Norway, Nordic Semiconductor was established in 1983 as a spin-off from the Technical University of Trondheim. It has grown to become a publicly listed global Norwegian company that boasts full ISO 9001:2008 certification.

Inside the nRF24L01+ IC

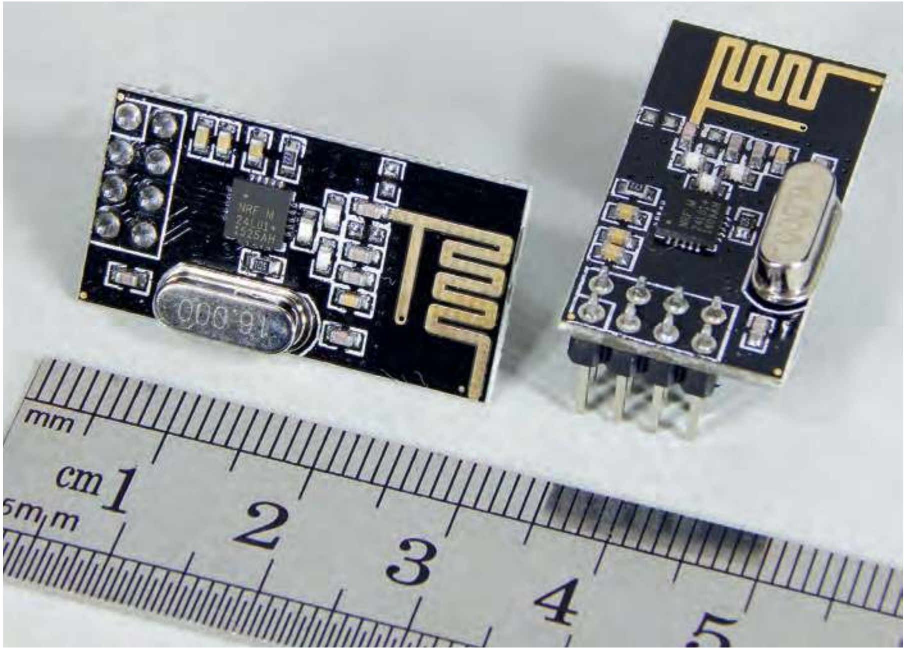
Essentially, the nRF24L01+ is a complete single-chip 2.4GHz wireless data transceiver in a 20-pin QFN (4 x 4mm) package.

Fig.1 shows a block diagram depicting the internal circuitry of the nRF24L01+ chip on the left, while the additional circuitry used to augment performance in the higher-power modules is shown on the right.

First, let's concentrate on the left-hand side. There you see the baseband section which provides a full bi-directional SPI (serial peripheral interface) port plus an embedded 'protocol engine' (using Nordic's 'Enhanced ShockBurst' technology), transmit and receive data FIFO (first-in, first-out registers/memory buffers), a radio control section and an array or 'map' of control and configuration registers

On the right is the RF section, which includes an RF transmitter and receiver plus an RF synthesiser, a power amplifier (PA) and a low-noise amplifier (LNA) for signal reception.

The chip's SPI interface allows it to be controlled by a microcontroller, while the Enhanced ShockBurst baseband engine provides a range of packet data communication protocols from manual up to advanced autonomous operation.



The simplest nRF24L01+ module, with its circuit diagram shown in Fig.2. Variants of this module might instead have a slightly different antenna track or SMA connector for an external antenna,

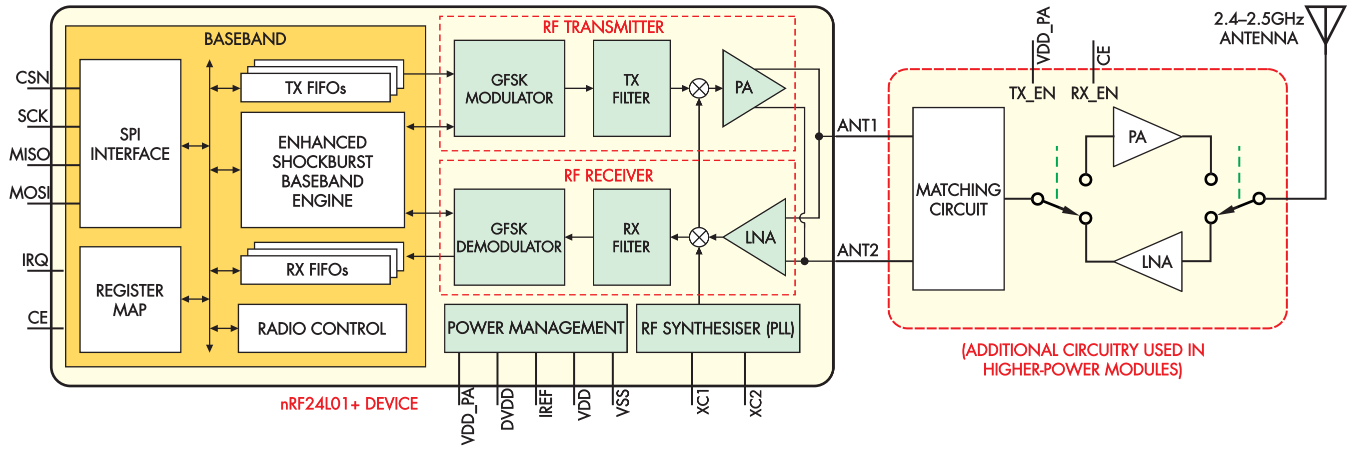


Fig.1: the internal block diagram of the nRF24L01+ IC to the left, with the additional circuitry used for performance improvements in higher-power modules shown at right. The chip also includes a feature called Enhanced ShockBurst, which implements a bidirectional data communication protocol that is primarily used for transferring data between two of Nordic's nRF51 chips (Bluetooth and 2.4GHz) or between an nRF51 and nRF24.

Basically, it handles all of the high-speed link layer operations. The two FIFO buffers ensure a smooth data flow between the RF front end and the microcontroller (via the SPI interface), in both directions, storing data until it can be processed.

The RF sections employ GFSK modulation, which stands for 'Gaussian Frequency-Shift Keying', an enhanced form of frequency-shift keying in which the modulating data is passed through a Gaussian filter to make the transitions smoother, before modulation. This reduces sideband power and cross-channel interference, at the cost of increasing inter-symbol interference, which effectively limits the maximum data rate to about 2Mb/s.

GFSK was the original type of modulation used in Bluetooth and it is still used in BR (basic rate) Bluetooth devices.

The nRF24L01+ can operate at data rates of 250Kb/s, 1Mb/s and 2Mb/s, although the 2Mb/s rate is not compatible with devices based on the earlier nRF24L01 chip.

The transmitter is also programmable in terms of output power, with four options available: 0dBm (1mW), –6dBm, –12dBm or –18dBm (320µW). This makes the chip very suitable for ultra-low-power wireless links.

The RF sections of the chip can be programmed to operate on any of 125 frequency channels between 2.400GHz and 2.525GHz, with the channels spaced 1MHz apart. However, the channels above 2.500GHz are strictly out of the ISM band, leaving only the lower 100 for legal use.

In addition, since Wi-Fi devices use the spectrum between 2.400GHz and 2.484GHz fairly heavily, modules using the nRF24L01+ are best programmed to use upper channels 85-100 to ensure minimum interference and the most reliable operation.

Also note that when the nRF24L01+ is being used at the highest data rate of 2Mb/s, it can only use every second 1MHz channel because the modulation bandwidth is larger than 1MHz.

The selected channel frequency is generated by the RF synthesiser section at lower right in Fig.1, using an external 16MHz crystal connected between pins XC1 and XC2.

Despite its internal complexity and multiple functions, the chip is surprisingly economical in terms of power consumption. Operating from a 3.3V DC supply, the RF transmitter section draws only 11.3mA when set for the highest 0dBm output power, while the receiver section draws only 13.5mA when receiving at the highest 2Mb/s data rate and drops to 12.6mA at 250Kb/s.

So the nRF24L01+ is suitable for all kinds of portable and battery-powered applications, especially since the chip is inexpensive.

Complete modules

Quite a few wireless data transceiver modules based on the nRF24L01+ chip are currently available, falling into two main categories:

- Those using only the chip itself together with a handful of passive components
- Those which provide one or more additional ICs to give higher RF output and additional receiver preamplification, for longer range operation.

The basic types are the cheapest and most popular, but the higher-power types are also quite widely used.

Fig.2 shows the complete circuit for one of the basic modules. This module is quite small, measuring just 15 x 29mm, including both the 8-pin DIL header for SPI and power connections and the zig-zag PCB track antenna.

There are other variations of this basic module, which may have a hook-shaped PCB track antenna instead of the zig-zag pattern. Jaycar have this latter module (Cat XC4508). These have a slightly longer PCB, measuring 15 x 33mm.

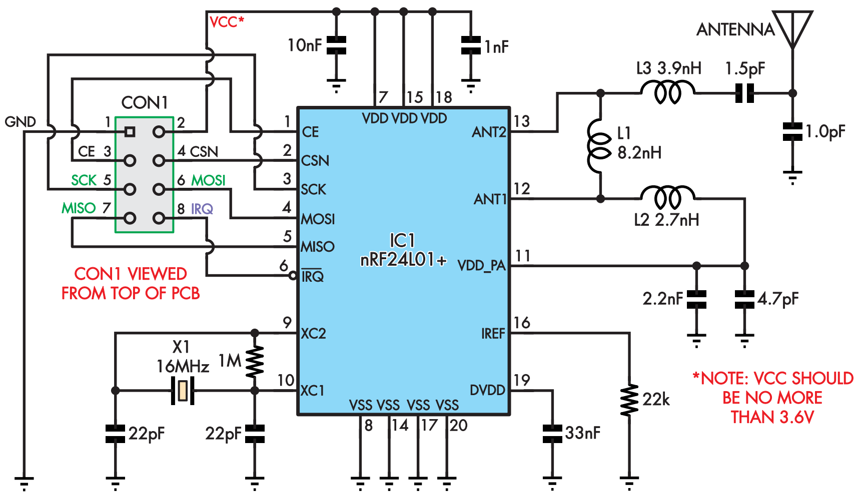


Fig.2: circuit diagram for the NRF24L01+. All connections are made via an 8-pin male header (CON1) which carries power and SPI connections.

One of the fancier nRF24 modules that sports a reverse-SMA socket with whip antenna and three extra SMD ICs to boost RF signals. This module uses a combination of a TI CC2500/CC2530 and SI4432, but not all modules will use the same set.

Yet another variant has an SMA socket for connection to an external antenna (instead of the PCB track antenna) on a smaller PCB measuring 10.6 x 23.8mm.

There's very little in one of these modules apart from the nRF24L01+ chip itself. The 16MHz crystal (X1) is at lower left (in Fig.2), while the 2.4GHz antenna and the passive components used to match the chip to it are at upper right. All of the connections to and from the micro are made via CON1 at upper left. The remaining passive components are mainly for supply bypassing.

Fancier versions

As with the basic versions, there are a number of variations when it comes to the longer-range versions. They all seem to consist of the basic nRF24L01+ transceiver chip coupled to a transmit/receive 'front end' circuit, along the lines of what is shown on the right-hand side of Fig.1. The differences are mainly with regard to the IC or ICs used in the added front end and the antenna arrangements.

Fig.3 shows the circuit for one of these augmented versions. The left-hand side is virtually identical to the basic nRF24L01+ module circuit shown in Fig.2, and so these modules generally use much the same software and I/O connections to the micro.

In this particular module, all of the additional RF matching, filtering, transmit/receive switching, power amplification and input preamplification is done inside IC2 (shown on the right).

This is an RFaxis/Skyworks RFX2401C device, rated to provide 25dB of transmit gain at 2.45GHz plus 12dB of receive gain with a noise figure of 2.5dB. Both features should give a very useful extension of the module's operating range.

Some of the other longer-range modules seem to use a combination of three ICs in place of the RFX2401C. Some use the TI CC2500 and CC2530 chips together with an SI4432, but we haven't been able to find a circuit for these.

Although one of the longer-range modules shown in the above photograph has a reverse-SMA socket for the antenna connection and comes with a matching 'rubber ducky' whip antenna, this is not always the case.

Some modules simply come with copper pads on the end of the PCB to either solder on an SMA connector or else have a short piece of wire soldered directly to the centre pad to act as a DIY whip antenna. Still others have a monopole ceramic chip antenna mounted on the end of the PCB. One of these is also shown in the photos.

One further point: most of the modules, whether basic or enhanced, have a copper ground plane on the underside of the PCB (but not under the antenna) to reduce the level of EMI from and into the nRF24L01+ and its associated circuitry.

A small number of the enhanced units also have a screening can over the whole of the circuitry on the top of the PCB, and these modules have been found to be somewhat better for reliable long-range operation.

Apparently, some users have achieved similar results with the modules which lack an upper screening can by wrapping the electronics part of the module with thin brass or aluminium metal foil.

The foil should be covered on the inside with a thin layer of plastic to make sure it doesn't cause any short circuits, and should ideally also be connected to the module's PCB earth (eg, via pin 1 of CON1).

Just make sure you don't wrap the foil around the end of the module's PCB with the antenna, or you'll seriously *reduce* its range rather than increase it!

Working with an Arduino

Fig.4 shows how to connect any of these modules up to an Arduino or Arduino clone, taking advantage of the fact that most of the connections needed for interfacing to an SPI bus

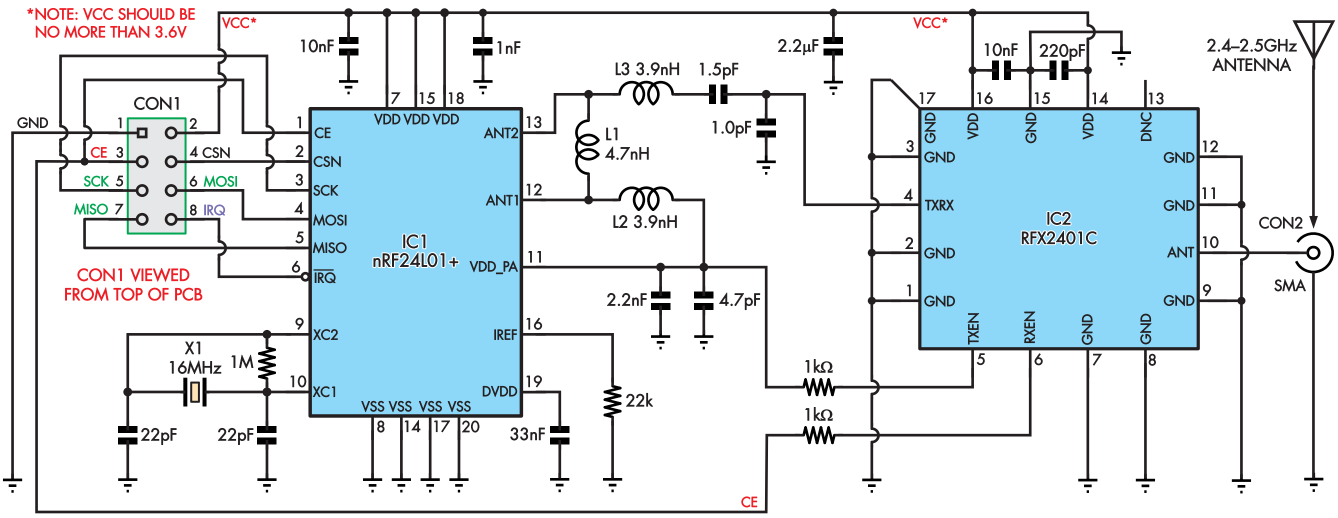
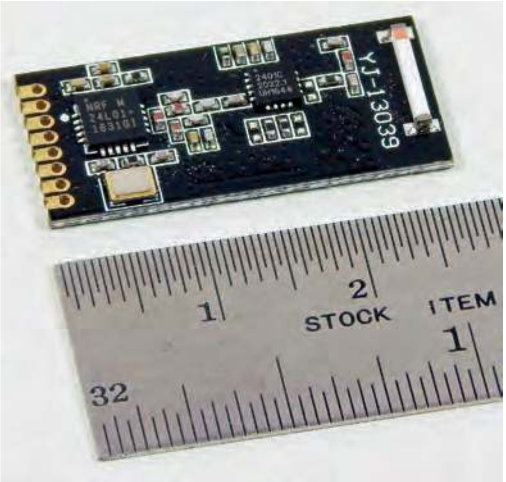
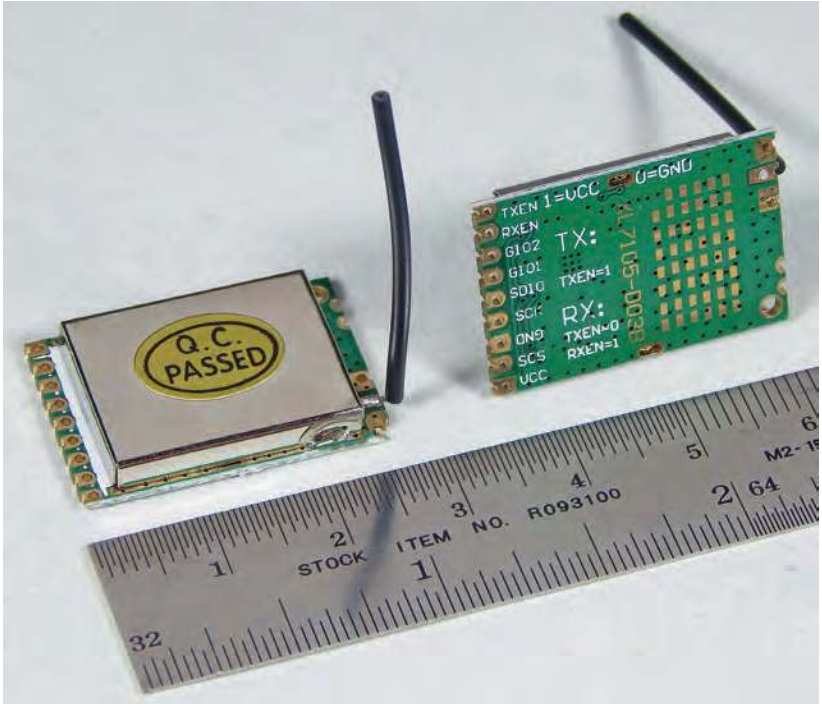


Fig.3: circuit diagram for one of the fancier nRF24L01+ variants (photo at upper right, labelled YJ-13039). While the left half of this circuit may be identical to Fig.2, there is additional circuitry around the RFX2401C (IC2) that sets it apart.



Above: one of the fancier nRF24L01+ based modules featuring a monopole ceramic chip antenna at the end of the PCB. It also has CON1 in the form of a single row of PCB pads.



Right: a different nRF24 module featuring a metal shield around the circuitry to reduce EMI; it also comes with a simple wire antenna.

are made available on the 6-pin ICSP header fitted to most Arduino variants.

The connections to the ICSP header are consistent with many Arduino variants, including Uno, Leonardo and Nano, the Freetronics Eleven and LeoStick and the Duinotech Classic or Nano.

The only connections that are not available via the ICSP header are those for +3.3V, CE and CSN, which need to be connected to the IO7 and IO8 pins respectively. The reason why they need to be connected to those particular pins of the Arduino is that these are expected by the most-popular and easy-to-use Arduino Library for nRF24L01+ based modules – more on that later.

Before we move on to the firmware, in the photos overleaf you'll see a Freetronics ProtoShield wired up to connect an nRF24L01+ based module to an Arduino Uno or its equivalent.

It's fitted with a 4x2 DIL header socket near the centre of the shield to accept the nRF24L01+ module's plug, with short lengths of hookup wire to make the connections between the header socket pins and the appropriate Arduino pins. The 10µF tantalum bypass is fitted very close to the pin 1 end of the header socket, to keep its leads as short as possible.

This little shield cost less than £3, took very little time to make and works well. Having built it, the next step was to install the RF24 Library in the Arduino IDE.

The Arduino RF24 Library

Written by a programmer with the moniker of 'TMRh20', the Library is called 'RF24'. The latest version is available in zipped-up form from **https://github.com/maniacbug/RF24** Click on the green 'Clone or download' button and then 'Download ZIP'.

To help you get started using a couple of nRF24L01+ modules to set up a wireless link between a pair of Arduinos, I have adapted one of the 'Getting Started' sketches provided by TMRh20 to show how to make use of his/her RF24 library. The revised sketch is called **sketch_to_check_nRF24L01_modules.ino**, and is available for download from the *EPE* website.

Having downloaded the RF24 library zip, fire up the Arduino IDE, open up the sketch and then get the IDE to add the RF24 to its list of libraries. This is done by clicking on the 'Sketch' drop-down menu, then clicking on 'Include Library' down near the bottom, and then on 'Add .ZIP Library'.

The IDE will then provide a dialog to let you select the RF24 ZIP library you've downloaded, whereupon it will automatically unpack and install the library.

The sketch has been written so that it can be uploaded to two Arduinos, one at each end of your proposed wireless link. The only thing that needs to be changed is the value of the parameter 'radioNumber', in the first line of

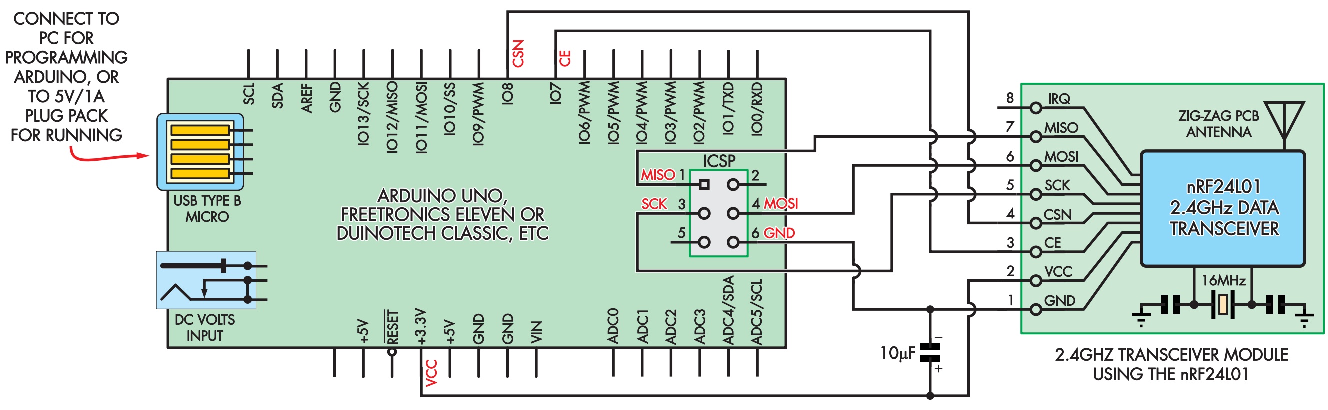
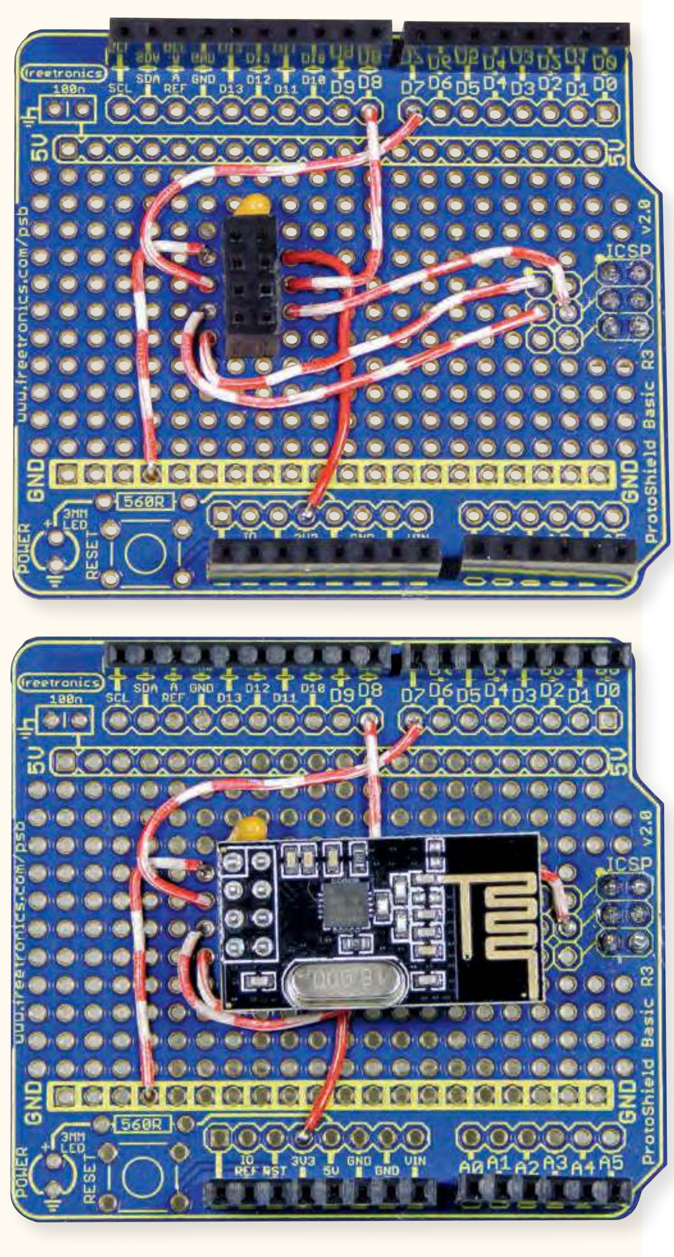


Fig.4: wiring diagram showing how to connect an nRF24-based module to an Arduino board. On the next page there is a photo showing one of these modules hooked up to a Freetronics ProtoShield, which can then be plugged directly into a compatible Arduino board.



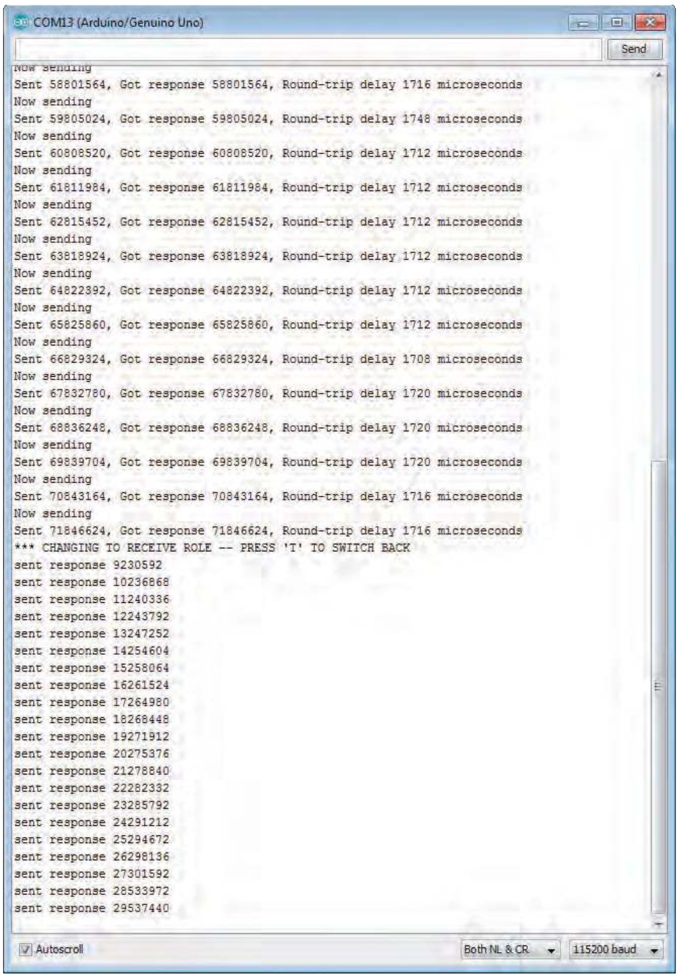


Fig.5 (above): example output from running the Arduino sample program. The upper half of the screen grab shows one of the modules in 'transmit' mode, while the lower half is in 'receive' mode.

Left: you can see the header, 10µF tantalum capacitor and various wires that need to be soldered to the Freetronics ProtoShield that is plugged into an Arduino. The module is then plugged into the 4x2-pin DIL female header.

code after the introductory comments and the five #include lines. As supplied, the line looks like this:

```
bool radioNumber = 0;
```

But for the second Arduino, it should be changed to:

```
bool radioNumber = 1;
```

Then, when you power up both Arduinos (each with an nRF24L01+ module connected), they can communicate with each other. The software is controlled via the Arduino IDE's Serial Monitor utility.

To start one Arduino pinging the other, press the T key on that PC's keyboard, and then the Enter key. That Arduino will then begin sending a number (the time it has been powered up in microseconds) to the other, via the wireless link.

The other should then respond by returning the same number, after a short delay. This should be visible in the Serial Monitor dialog, which should look like the screen grab shown in Fig.5. If you then press the R key, followed by Enter again, the Arduinos should swap roles, with the local one becoming the receiver and the other one becoming the transmitter.

The display in the Serial Monitor dialog should change, as shown halfway down the screen grab, with a series of lines showing when it sends each response back to the other Arduino.

So this sketch shows how a couple of Arduinos can be hooked up via a 2.4GHz wireless link, using a pair of nRF24L01+ based modules.

Doing it with a Micromite

Connecting one of these modules up to a Micromite is done using the connections shown in Fig.6. The MOSI, MISO and SCK lines are connected to pins 21, 22 and 24 of the Micromite as shown. The CE and CSN lines are connected to Micromite pins 17 and 18 respectively in this example. Just like with the Arduinos, it is also a good idea to connect a 10µF tantalum capacitor across pins 1 and 2 of your nRF24L01+ module.

Now, if you're wondering why these SPI connections to the Micromite are a little different from those you've seen in other projects, that's because we're making use of an 'additional' SPI port on the Micromite, provided by means of an embedded C function in Geoff Graham's MMBasic.

This is being used as an alternative to the SPI port already built into MMBasic, to prevent timing conflicts when you're using an *LCD BackPack* version of the Micromite.

The reasoning behind this is that there doesn't seem to be available at present any pre-written Micromite applications or libraries available to control and exchange data with the nRF24L01+ chip – so basically, I've had to write one myself.

This took quite a while, as programming the nRF24L01+ turned out to be surprisingly complex and confusing. I ended up having to get help from Geoff

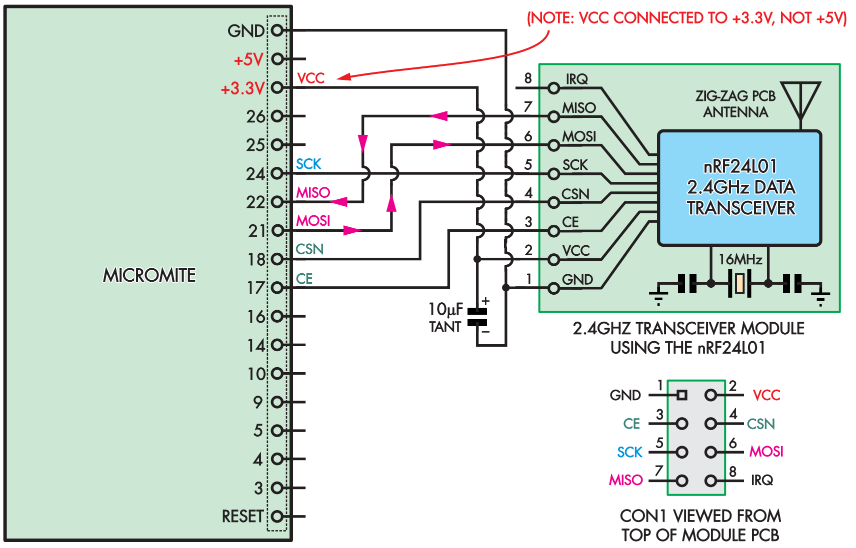


Fig.6: connections required for the NRF24L01+ to a Micromite. The 10µF tantalum capacitor between pins 1 and 2 is optional but recommended.

The sample program running on a Micromite *LCD BackPack*. Unlike the Arduino program, setting which device is the receiver or transmitter is done via the touchscreen, rather than serial input.

Graham, as well as from the support engineers at Nordic Semiconductor.

By the way, if you want to see how complex programming the chip really is, you can download a copy of the 78-page product specification called *nRF24L01+ Product Specification v1.0* for free from Nordic Semiconductor's website (**www.nordicsemi.com/eng/Products/2.4GHz-RF/nRF24L01P**).

Anyway, I finally got the program to work, with two Micromite *LCD BackPacks* exchanging data in both directions without problems. Whew!

You can see the display it provides on the Micromite's LCD screen in the photo above, allowing the Micromite to be configured as either Radio #0 or Radio #1; and for either RECEIVE or TRANSMIT.

This is configured using the LCD touchscreen, but as with the Arduino sketch, the actual data being transmitted or received is printed/displayed on the PC in the MMChat windows for each device.

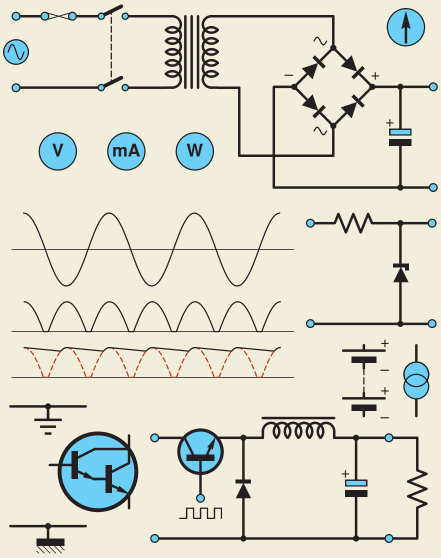
The program is not very fancy, but it should at least provide a good starting place for writing more complex programs of your own.

The program is called **nRF24L01 checkout.bas**, and is available to download from the *EPE* website.

Teach-In 2019

Powering Electronics

Part 2: Transformers and rectifiers



by Mike Tooley

Your project is finished and ready to go, but the job isn't done until you've found an appropriate source of power. This could be as simple as choosing a suitably rated mains adapter or as complex as designing a switched-mode power supply with multiple outputs and battery backup. Our latest series – *Teach-In 2019* – is here to help, and will provide you with insight into all aspects of powering your electronic projects and designs.

In this second part we introduce conventional (linear) power supplies and the three building blocks that work together to produce a constant DC output when supplied from an AC mains source.

Our *Teach-In Practical Project* takes the form of a raw DC supply capable of delivering 18V at 0.5A. This handy module has been designed for use in conjunction with several upcoming projects, including fixed and variable bench power supplies and a high-voltage supply based on switching technology.

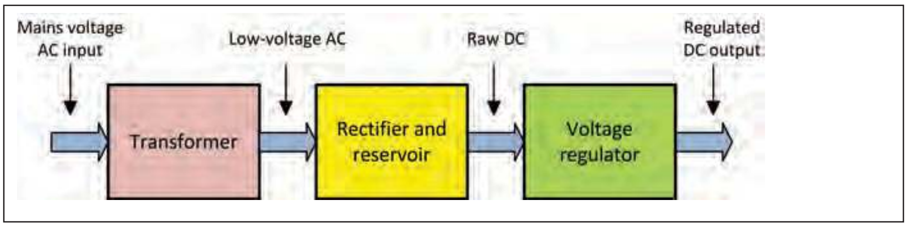


Fig.2.1. Block diagram of a simple linear DC power supply.

This month

As mentioned briefly in Part 1 last month, the problem of converting an alternating (AC) supply to a constant (DC) voltage can be solved using either conventional (linear) techniques or by employing switched-mode technology. In this second part of our *Teach-In 2019* series we will be concentrating on linear circuit techniques, leaving switching technology for later in the series.

AC to DC conversion

The simplified block diagram of a basic linear DC power supply is shown in Fig.2.1. Since the AC mains input is at a relatively high voltage (typically 115V or 230V) a step-down transformer of appropriate turns ratio is used to reduce the incoming voltage to one suitable for conversion to DC. The AC output from the secondary winding of the transformer is then rectified to produce a rough (unsmoothed) DC, which is then smoothed and filtered before being applied to a circuit that regulates the output voltage and maintains it at the desired value. The regulator ensures that the output voltage remains reasonably constant in spite of variations in both load current and incoming mains voltage (see last month). In this part we will concern ourselves with the first three stages of the conversion process – step-down, rectification and smoothing – leaving regulation until next month.

Fig.2.2 shows how a simple DC power supply could be realised using a handful of common electronic components. Here, a step-down transformer feeds a rectifier arrangement (often based on

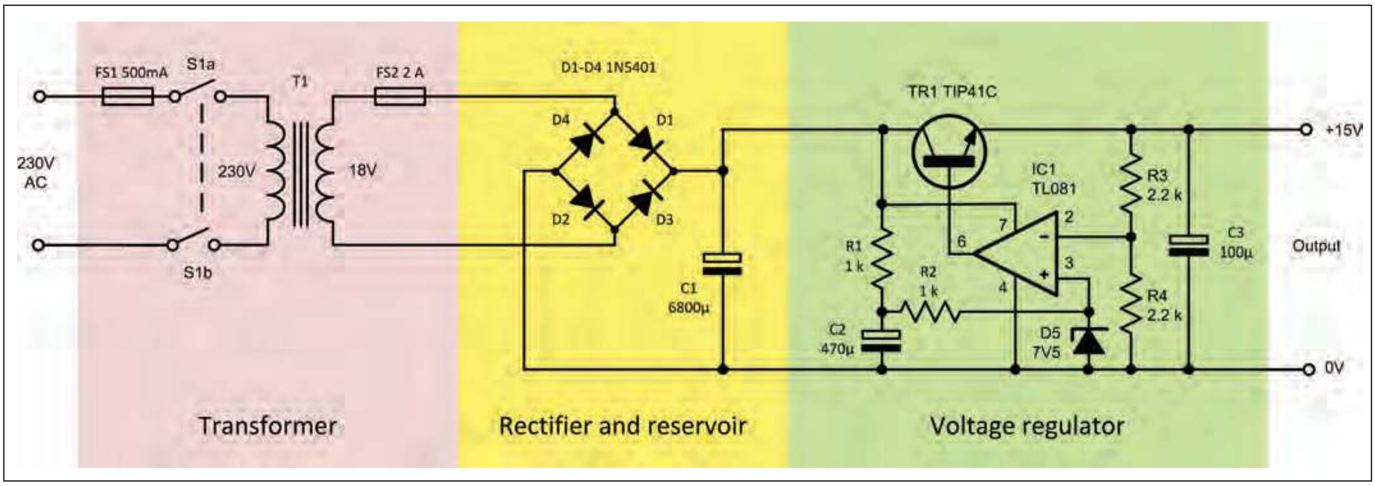


Fig.2.2. Basic building blocks of a simple linear DC power supply.

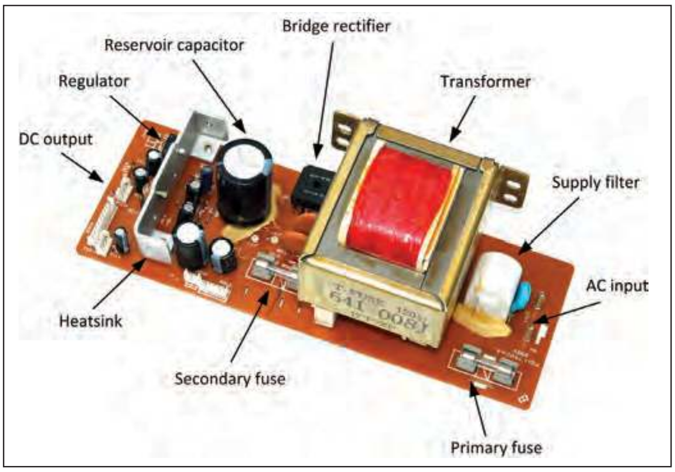


Fig.2.3. Typical electronic low-voltage DC supply based on linear technology.

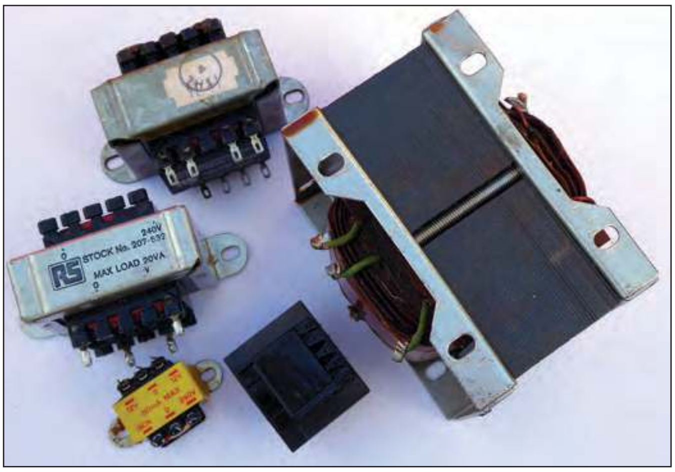


Fig.2.4. A selection of mains transformers with ratings ranging from 1.2VA to 100VA.

the diode bridge arrangement shown) with its output fed to a high-value reservoir capacitor. This capacitor is constantly topped-up by the rectifier arrangement and retains a considerable amount of charge so that the load current is sustained when the rectifier is in its non-conducting state. The reservoir is followed by a voltage regulator, which holds the output voltage constant at the required value, automatically compensating for variations in AC input voltage and load demand. The typical physical layout of a linear power supply is shown in Fig.2.3. Note the space occupied by the transformer; it also contributes significantly to the cost and weight of the unit.

Transformers

Transformers are available in a wide variety of styles, windings and voltage/current ratings. The simplest form of transformer has just one primary winding (nominally rated for either 110V or 220V) and a single suitably rated secondary winding. The secondary winding will usually be specified in terms of on-load voltage (eg, 12V or 15V) and rated current (eg, 1A, 4A…). The overall power rating of a transformer is usually quoted in volt-ampere (VA). Where more than one secondary winding is available, this is the total rated load for all secondary windings.

The VA rating takes into account the fact that a load might not be purely resistive, but it is safe to approximate a transformer's VA rating to the product of on-load voltage and rated load current. For example, a component rated at 15V 12VA will supply 15V at a 0.8A (15/12) into a resistive load. At this point, it is important to be aware that a transformer's off-load secondary voltage can be significantly greater than its on-load voltage. This is particularly the case with smaller power transformers.

A selection of mains transformers, with ratings ranging from 1.2VA to 100VA is shown in Fig.2.4. These transformers are designed for operation at 50 or 60Hz and use a conventional laminated steel core made from thin E- and I-shaped sections, as shown in Fig.2.5. Transformers suitable for a wide range of applications are available from several of our advertisers and numerous on-line sources. In addition, transformers can be self-wound using a kit of parts like that shown in Fig.2.6. A kit-constructed transformer is shown in Fig.2.7. The primary winding is supplied ready wound (two 115V windings) on a bobbin (see Fig.2.6) and the secondary winding is self-wound with a number (N_{SEC}) of turns that can be calculated using the formula:

$$N_{SEC} = TPV \times V_{SEC,\ rated}$$

Where TPV is the quoted 'turns-per-volt' rating of the transformer. Note that it is wise to allow for some losses in the transformer and, in practice, about 4% extra turns is advisable. Thus, as a rule of thumb:

$$N_{SEC} = 1.04 \times TPV \times V_{SEC,\ rated}$$

Fig.2.7. Completed 50VA transformer. The secondary winding is rated at 25V, 2A and used 18 SWG enamelled copper wire.

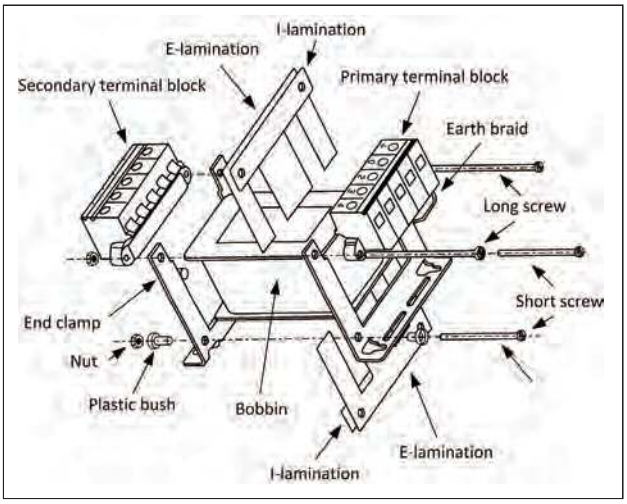


Fig.2.5. Exploded view of a conventional steel-cored power transformer.

Fig.2.6. Parts kit for a 50VA transformer.

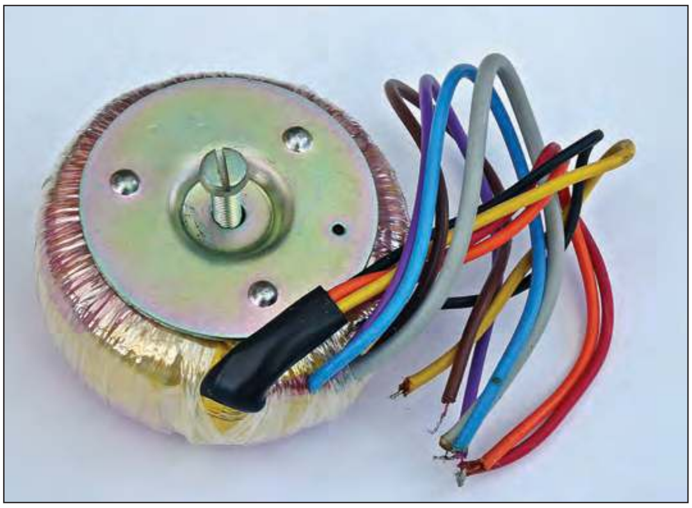


***Fig.2.9.** A compact 30VA toroidal core transformer with dual 115V primary windings and dual 12V secondary windings. Each secondary is rated for a load of 1.25A.*

For example, if the secondary winding is to have a rated voltage ($V_{SEC,\ rated}$) on-load of 20V and the transformer has a TPV rating of 2.5 the required number of turns will be given by:

$$N_{SEC} = 1.04 \times 2.5 \times 20 = 130 \text{ turns}$$

If you intend to wind your own transformers it is important to ensure that the enamelled copper wire has a gauge/diameter that is adequately rated to support the full-load secondary current (see Table 2.1).

Table 2.1 Wire rating

Rated secondary current (A)	SWG	Approx. wire diameter (mm)
0.5	24	0.6
0.8	22	0.7
1.3	20	0.9
2.3	18	1.2
4	16	1.6
6.5	14	2.1

Primary and secondary winding configurations

Many transformers have two identical primary windings, each designed for 115V operation. The primary windings should be connected in parallel for 115V operation or in series for operation from a 230V supply. Note that, in both cases, the windings must be connected in the correct phase relationship. Similarly, dual secondary windings can be connected in series or parallel. Here again, the correct phase relationship is essential. Fig.2.8 shows the range of possibilities for a typical transformer with dual primary and secondary windings. (The dots indicate a winding's phase.)

Toroidal transformers

Although they are the most common, not all transformers take the form of those shown in Fig.2.6 and 2.7. You will also come across 'toroidal' (the mathematical term for doughnut shaped) transformers, as shown in Fig.2.9. Their geometry gives them some advantages that make them particularly suitable for low-noise circuits, and they are often found in good quality audio designs. The example shown has two groups of four colour-coded cables; revealing its dual primary / dual secondary construction.

Rectifiers

Half-wave rectifiers

Thanks to their unidirectional properties, semiconductor diodes are ideal for converting alternating current (AC) to direct current (DC). In this application they are referred to as 'rectifiers'. The simplest form of rectifier circuit makes use of a single diode. Since current flows only during one half of their incoming AC cycle, the circuit is known as a 'half-wave rectifier'.

In the half-wave rectifier shown in Fig.2.10, the incoming mains supply (nominally 115V or 230V) is applied to the primary of the step-down transformer, T1. The secondary voltage is applied to the rectifier diode (D1), which will only allow the current to flow in the direction shown – from the anode to the cathode of D1. During each positive-going half-cycle of the secondary voltage, Dl will become forward biased (conducting), effectively behaving like a closed switch. Conversely, during the negative half-cycle of secondary voltage, D1 will be

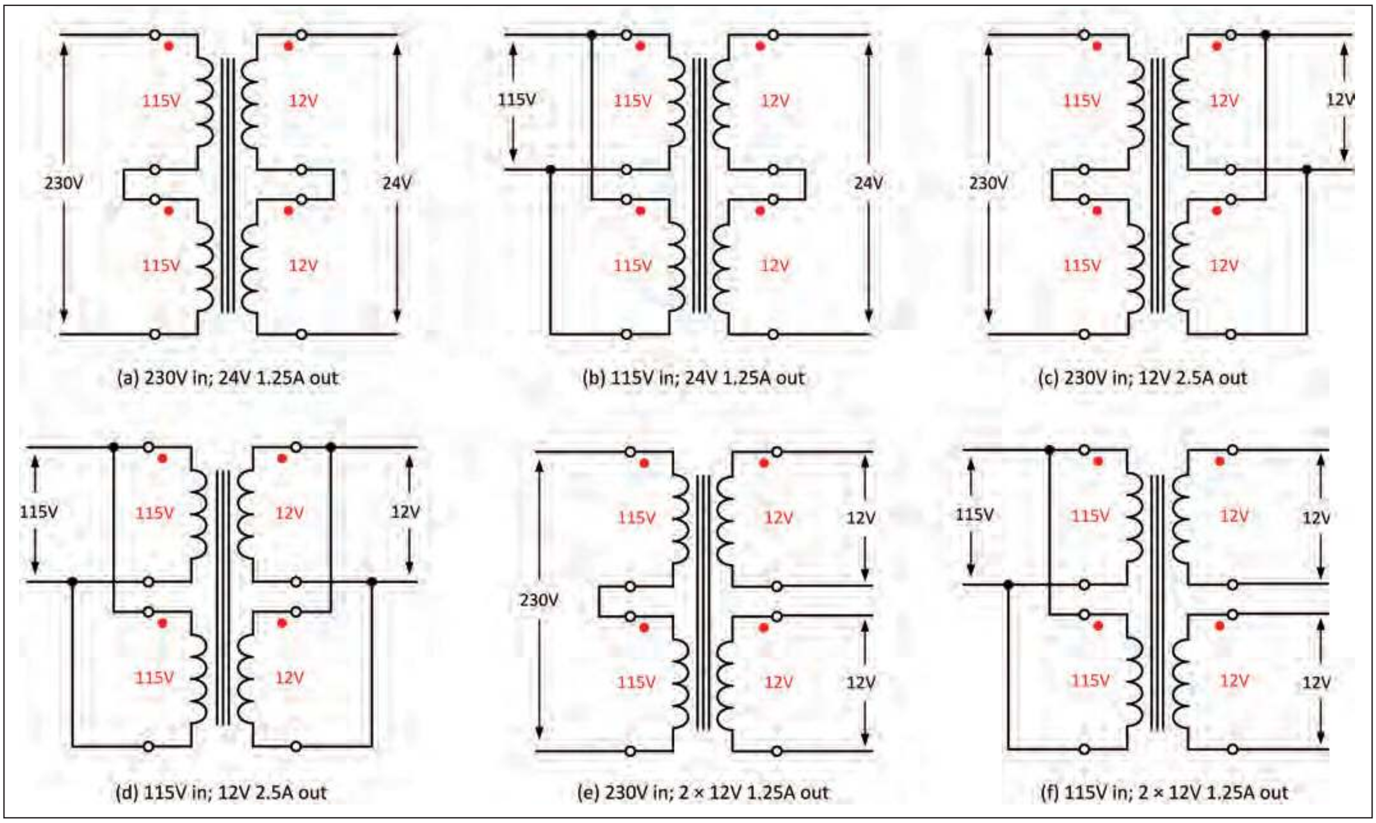


***Fig.2.8.** Various winding configurations for a transformer with dual primary and secondary windings.*

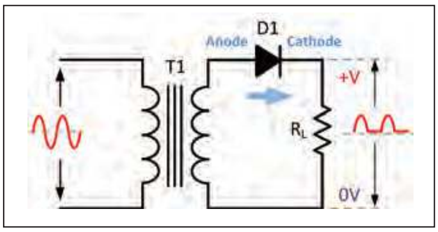


Fig.2.10. A simplified half-wave rectifier circuit.

reverse biased and will act like an open switch, as shown in Fig.2.11.

The switching action of Dl results in a pulsating output voltage that is developed across the load, R_L. If the mains supply is at 50 Hz, the pulses of voltage developed across R_L will also be at 50Hz, even if only half the AC cycle is present. Note that, during the positive half-cycle, the diode will drop the 0.6V to 0.7V forward threshold voltage normally associated with silicon diodes. With power rectifiers carrying high current this forward voltage drop can be as much as around 1.1V and this must be allowed for in the overall thermal and efficiency design of large power supplies.

During the negative half-cycle the peak AC voltage will appear across Dl. This can be a vitally important consideration when selecting a diode for a particular application. Assuming that the secondary of T1 provides $12V_{RMS}$, the peak voltage output from the transformer's secondary winding will be given by:

$$V_{pk} = 1.414 \times V_{RMS}$$
$$= 1.414 \times 12V = 16.97V$$

The peak voltage applied to Dl will thus be approximately 17V. The negative half-cycles are blocked by Dl and thus only the positive half-cycles will appear across R_L, Note, however, that the actual peak voltage across R_L will be the 17V positive peak from the secondary of T1, *minus* the 0.7V forward threshold voltage dropped by Dl. In other words, the positive half-cycle pulses with a peak amplitude of 16.3V will appear across R_L.

Note that, when designing high-voltage supplies it is essential to choose rectifier diodes that can withstand the high peak reverse voltages. For example, a peak inverse voltage (PIV) rating of at least 600V will be required when designing a rectifier that can cope with a 240V AC supply. We will be looking at this again when we describe switched-mode power supplies (SMPS) later in this series.

Reservoir capacitor

Adding a capacitor (C1) significantly improves the circuit of Fig.2.10. It acts as a reservoir, storing charge and releasing it when the diode is in its non-conducting state. This helps to ensure that the output voltage remains near the peak voltage, even when the diode is not conducting.

The improved circuit is shown in Fig.2.12. Once again, let's assume that the secondary voltage supplied by T1 is 12V. When the primary voltage is first applied to T1, the first positive half-cycle output from the secondary will charge C1 to the peak value seen across R_L, As before, C1 will charge to 16.3V at the peak of the positive half-cycle. Because C1 is in parallel with the load, the voltage across R_L will be the same as that across C1.

The time required for C1 to charge to the maximum (peak) level is determined by the charging circuit time constant (the series resistance multiplied by the capacitance value). In this circuit, the series resistance comprises the secondary winding resistance together with the forward resistance of the diode and the (minimal) resistance of the wiring and connections. Hence C1 will charge very rapidly as soon as Dl starts to conduct.

The time required for C1 to discharge is, in contrast, very much greater. The discharge time constant is determined by the capacitance value and the load resistance, R_L. In practice, R_L is very much larger than the resistance of the secondary circuit and hence C1 takes an appreciable time to discharge. During this time, Dl will be reverse biased and will thus be held in its non-conducting state. As a consequence, the only discharge path for C1 is through R_L, and the circuit of Fig.2.12 is thus able to maintain a reasonably constant output voltage across R_L, Even so, C1 will discharge by a small amount during the negative half-cycle periods from the transformer secondary.

In Fig.2.12 the small variation in DC output voltage is referred to as 'ripple'. This comprises a small AC component (at the supply frequency) superimposed on the output. Since ripple is undesirable we must take additional precautions to reduce it. One obvious method of reducing the amplitude of the ripple is to simply increase the discharge time constant. This can be achieved either by increasing the value of C1 or by increasing the resistance of the load. Unfortunately, the latter isn't usually an option because we don't usually have the ability to change R_L. Instead, we would need to increase the value of C1 and use very large capacitor values (often in the range 1,000µF to 10,000µF).

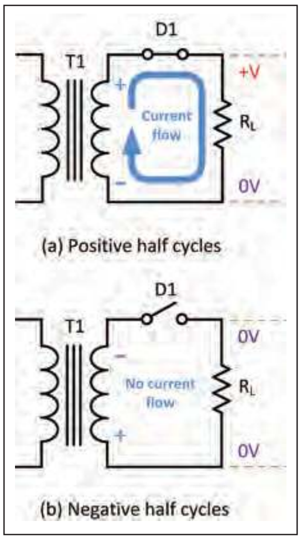


Fig.2.11. Current flow in half-wave rectifier circuit.

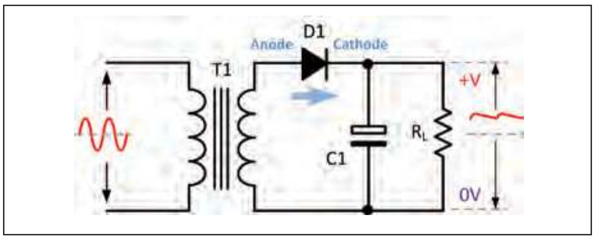


Fig.2.12. An improved half-wave rectifier circuit.

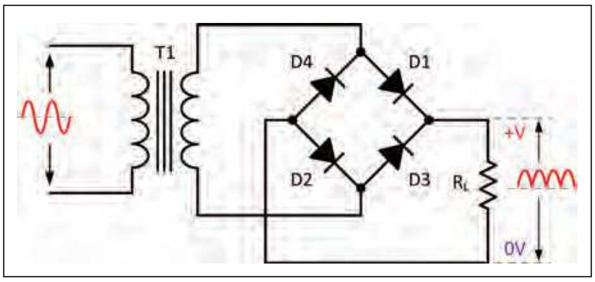


Fig.2.13. A simplified full-wave rectifier circuit.

Full-wave rectifiers

Because conduction takes place only on alternate half-cycles, the half-wave rectifier is relatively inefficient. A better rectifier arrangement would make use of both positive *and* negative half-cycles. These 'full-wave rectifier' circuits offer a considerable improvement over their half-wave counterparts. They are not only more efficient but are significantly less demanding in terms of the reservoir and smoothing components. There are two basic forms of full-wave rectifier, called 'bi-phase' type and 'bridge rectifier' type. For now, we will restrict our explanation to the latter as it is more common and also more efficient.

In the four-diode bridge rectifier shown in Fig.2.13, opposite pairs of diode conduct on alternate half-cycles. As before, mains voltage (115V or 230V) is applied to the primary of the step-down transformer (T1). Once again, we will assume that the secondary winding provides 12V RMS (approximately 17 V peak). On positive half-cycles, D1 and D2 conduct, while on negative half-cycles D3 and D4 conduct. This is illustrated in Fig.2.14, where the diodes are replaced with switches. Note how the full-wave circuit supplies current to the load in the *same direction* during *successive* half-cycles.

The switching action of the two diodes results in a pulsating output voltage being developed across the load, R_L. If the secondary winding produces 17V peak, the output voltage delivered to the load will be approximately 15.6V (ie, 17 V less the *two* forward-voltage drops attributable to the opposite pair diodes).

As with the half-wave rectifier, the switching action of the two diodes results in a pulsating output voltage being developed across R_L. However, unlike the half-wave circuit the pulses of voltage developed across the load will occur at a frequency that is double that of the supply (100Hz for a 50Hz supply, or 120Hz for a 60Hz supply). This doubling

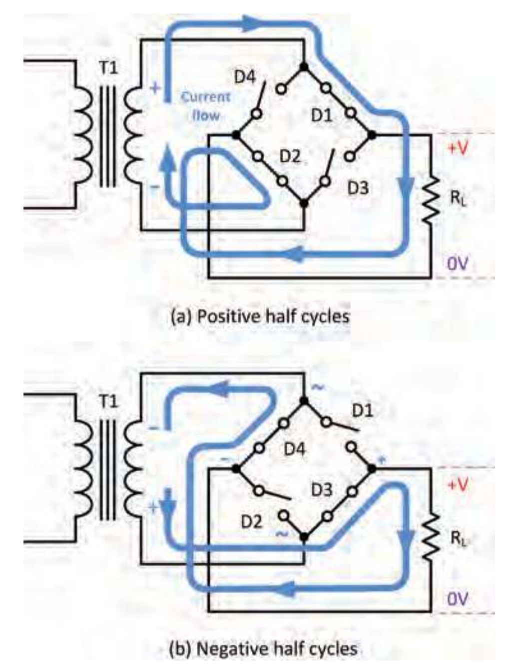


Fig.2.14. Current flow in the full-wave rectifier circuit.

of the ripple frequency allows us to use smaller values of reservoir/smoothing capacitor to obtain the same degree of ripple reduction (recall that the reactance of a capacitor is inversely proportional to the frequency of the current flowing through it).

Fig.2.15 shows how a reservoir capacitor can be added to maintain the output voltage when the pairs of diodes are non-conducting. This component operates in exactly the same way as for the bi-phase circuit; ie, it charges to approximately 15.6V at the peak of the positive half-cycle and holds the voltage at this level when the diodes are in their non-conducting states. Once charged, the reservoir capacitor discharges into the load in exactly the same way as for the improved half-wave rectifier shown in Fig.2.12.

Practical project: 18V, 0.5A raw DC supply

This month's *Practical Project* is a building block for use in conjunction with future projects. It comprises a mains-powered DC supply capable of delivering an unregulated 18V DC at currents up to 0.5A.

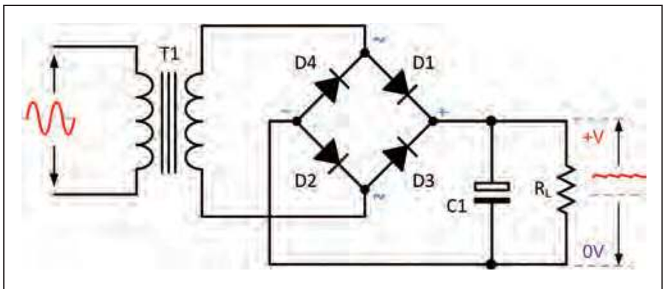


Fig.2.15. An improved full-wave rectifier circuit.

Safety – an important note!

The 18V 0.5A raw DC supply uses mains voltage electricity and great care must be taken to avoid contact with the mains supply during testing and use. It is also important to check the track layout and wiring very carefully, ensuring that all track breaks are in place and that no shorts or solder splashes are present.

When it's time to connect the unit to the AC mains supply it is essential to avoid contact with the mains wiring and primary connections to T1. Failure to observe this precaution can result in a very real risk of serious electric shock.

If you've not worked with mains-powered electronic equipment, do seek the advice of a more experienced person who can double check your work and ensure that it is safe before you connect it to the mains supply.

The circuit of our 18V, 0.5A raw DC supply is shown in Fig.2.18. This follows several of the design concepts introduced earlier. For example, the PCB mounting transformer (T1) uses dual primary and secondary windings (and can thus be configured for 115V operation as well as 230V operation – see Fig.2.8). The circuit (shown in Fig.2.18) and layout (shown in Fig.2.19) is configured for 230V operation, but can be easily changed for 115V operation, if required.

An encapsulated bridge rectifier (BR1) is used instead of four individual rectifier diodes. This component should be rated at 200V, 2.5A. The reservoir capacitor (C1) has a value of 4,700µF and must have a working voltage of 35V, or more. A simple diode power indicator (D1 and R1) provides confirmation of the output. If desired, D1 can be mounted off-board as a front-panel indicator. Basic protection is provided by a glass quick-blow 250mA 5 × 20mm fuse in the line connection to the AC mains supply.

You will need

Perforated copper stripboard (24 strips each with 37 holes)
- 1 3-way PCB screw terminal connector (ST1)
- 1 2-way PCB screw terminal connector (ST2)
- 1 2.2kΩ resistor (R1)
- 1 4700µF 35V capacitor (C1)
- 1 SKB 2/02L5A (200V, 2.5A) bridge rectifier
- 1 red LED
- 1 12VA PCB-mounting open-frame transformer (see text)
- 4 stand-off pillars and mounting screws

Construction

The layout of the 18V, 0.5A raw DC supply is shown in Fig.2.19. There are 34 track breaks and nine links. Note that there should be no connection between the primary side and secondary side of T1 and we have incorporated 18 track breaks on the lower side of the stripboard (K4 to K21) to ensure that this is the case.

The pin connections for the semiconductor devices are shown in Fig.2.20. Note that it is important to ensure that the bridge rectifier (BR1) is inserted into the stripboard with the correct polarity (as shown in Fig.2.20). The 5 × 20mm mains fuse (F1) is fitted into a PCB mounting fuse holder which should be fitted with an insulated cover in order to prevent inadvertent contact.

All mains-powered circuits must be safely mounted in a suitable enclosure (a small ABS box or a properly earthed metal case – get help and advice if you

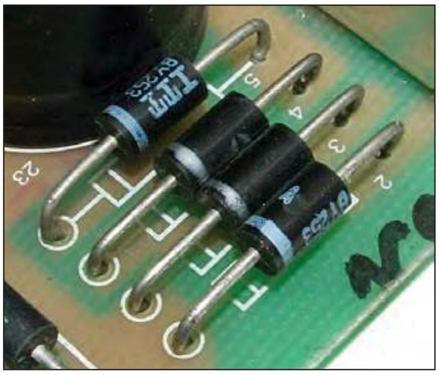


Fig.2.16. Example of a bridge rectifier based on four BY253 diodes. The diodes have a maximum forward current rating of 3A and a maximum reverse repetitive voltage of 600V.

Fig.2.17. Four large electrolytic capacitors connected in parallel are used as a reservoir in conjunction with the diode bridge shown in Fig.2.16. Each capacitor is rated at 220uF, 450V.

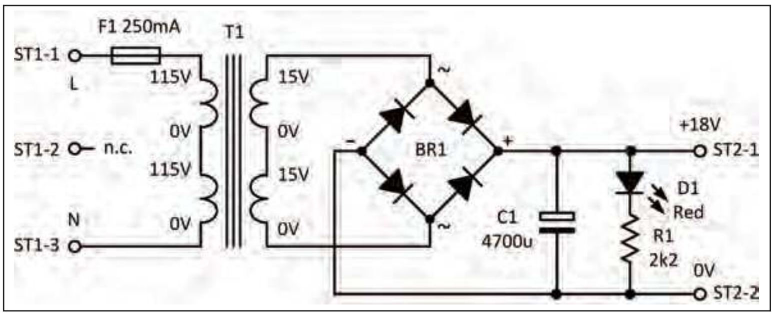


Fig.2.18. Circuit of the 18V 0.5A raw DC supply.

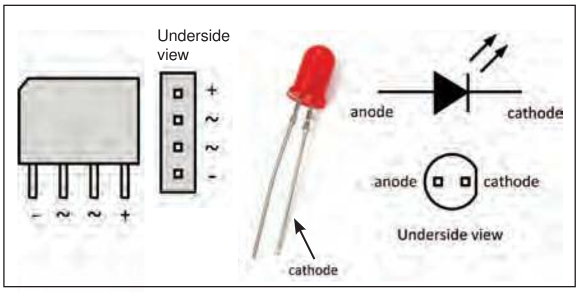


Fig.2.20. Semiconductor pin connections for the 18V, 0.5A raw DC supply: (left) BR1 and (right) LED.

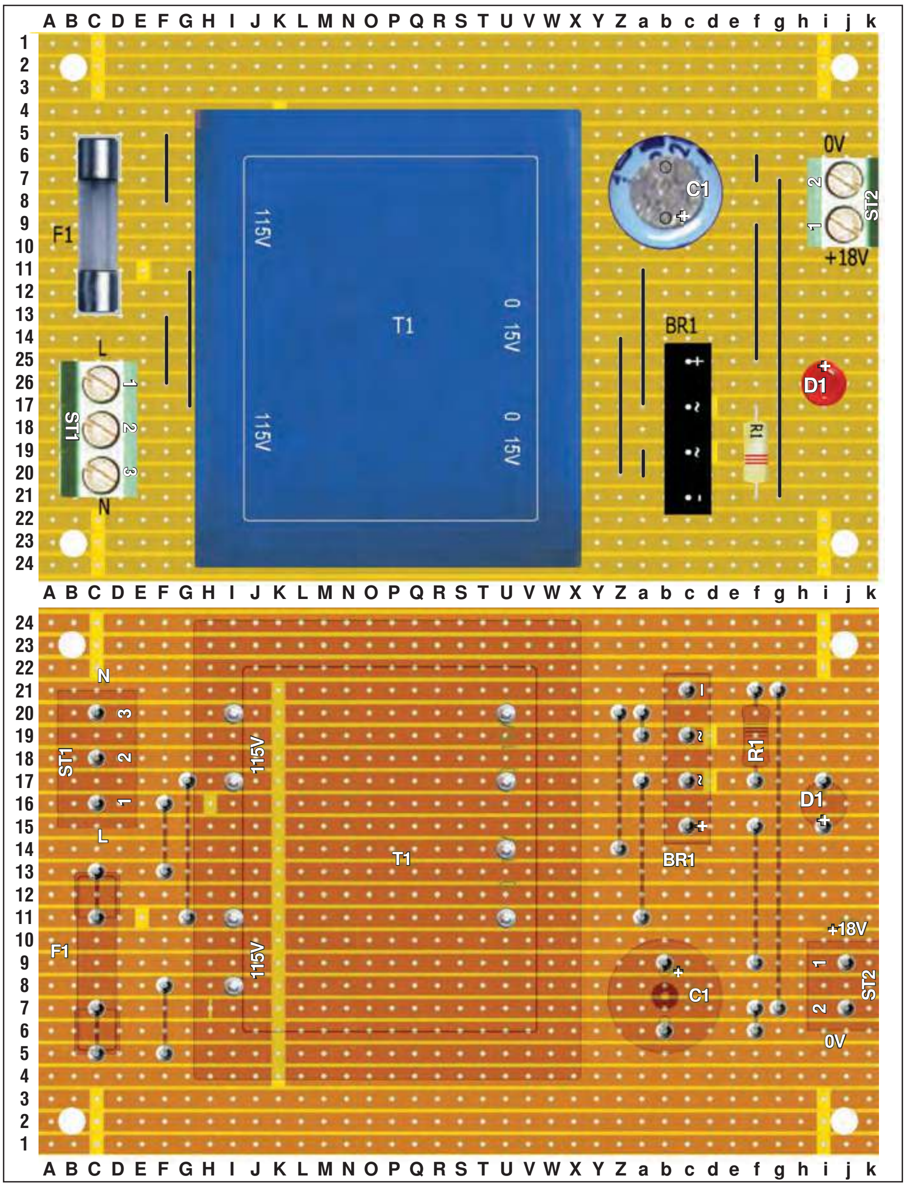


Fig.2.19. Stripboard layout of the 18V 0.5A raw DC supply: (top) component side, (below) copper track view (cut tracks marked in yellow)

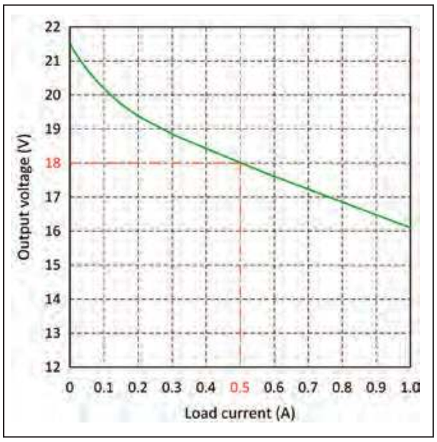


Fig.2.22. Load regulation curve for the 18V 0.5A raw DC supply.

have not done this before). Builders might want to add further modules (such as the variable regulator featured in next month's *Practical Project*) so it might be wise to allow some extra space within any enclosure to allow for future expansion.

Testing

Once assembly is complete it is well worth carrying out a careful visual inspection of the circuit board; checking, in particular the mains supply connections to ST1 and the primary side of the mains transformer (T1). As an additional check, it is well worth using a multimeter on the resistance range to check that there is absolutely no continuity between the mains input and DC output connectors. The measured resistance should be extremely high (typically greater than 100MΩ). If the resistance is less than this it is essential to check the component layout and wiring.

Next, switch the multimeter to an appropriate DC voltage range and connect the test leads to the +18V (red test lead) and 0V (black test lead) terminals on ST1. Connect a mains lead fitted with a fused mains plug to ST1 then plug in and switch the supply on. D1 should immediately become illuminated and the output voltage should be measured in the range +17V to +19V. If this is not the case, switch the supply off at the mains, disconnect and carefully check the stripboard wiring.

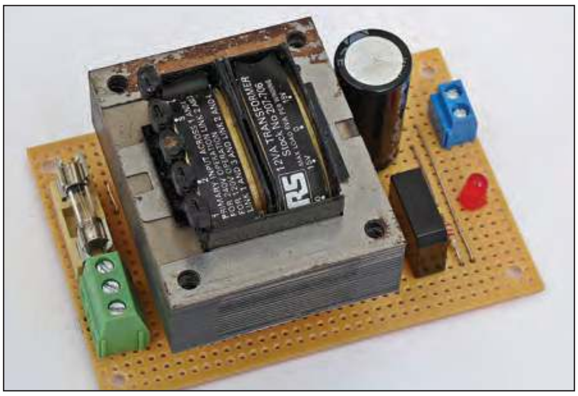


Fig.2.21. Finished 18V 0.5A raw DC supply.

Next month

In next month's *Teach-In 2019* we will explore the world of linear voltage regulators using both discrete and integrated circuit technology and a combination of both. We will also include two *Practical Projects*. The first of these is a range of simple 1A fixed-voltage supply modules while the second features the construction of a handy low-cost bench power supply which is ideal for testing your projects with an output that's fully adjustable from 1.5V to 13.5V and a current-limited output of 600mA.

PIC n' Mix

Mike O'Keeffe

Our periodic column for PIC programming enlightenment

PICMeter Part 4 – Displaying measurements

THIS month, the *PICMeter* series is concuding with work on the functionality of the display. This is my last article for the magazine – I'm taking a long sabbatical and handing over the reigns to other authors. I feel honoured to have been part of the team for the last three years and especially to have taken over the column (twice!) from Mike Hibbett. I hope you found the articles both useful and inspiring.

To finish up the *PICMeter* there's a few small things we need to cover. We now have a circuit that can measure voltage and current, the fundamental features of any multimeter. We built the circuit and explained some of the background theory, including SPI and I²C interfaces, digital potentiometers, and rail-to-rail operational amplifiers. To see our measurements, it's necessary to place the values on the display. The advantage of having the colour screen specified is that we can make the display show a number of useful colour-based features.

Drawing rectangles and squares

The easiest shape to draw on a display is the rectangle, which of course includes the square. Using a function called `LCD_DrawRectangle(xstart,ystart,xend,yend)` we can draw a four-sided shape starting at the *x*,*y* coordinates `xstart` and `ystart` and finishing at the opposite corner at `xend` and `yend`. Remember all that coordinate geometry back in school? Well, it was really all about preparing you to draw rectangles on LCD displays! Fig.1a shows *x* and *y* axes with a rectangle. To know where to put the rectangle on a display, we need to know the rectangle's corner coordinates. (Note that *x*1,*y*1 is the bottom left corner, these are the start points; while *x*2,*y*2 are the end points in the top right corner.)

```
void LCD_DrawRectangle(unsigned short x1,
unsigned short y1, unsigned short x2, unsigned
short y2) {
    LCD_DrawLine(x1,y1,x2,y1);
    LCD_DrawLine(x1,y1,x1,y2);
    LCD_DrawLine(x1,y2,x2,y2);
    LCD_DrawLine(x2,y1,x2,y2);
}
```

The code above shows the innards of the function `LCD_DrawRectangle()`. While the code here looks fairly straightforward, it leverages a much more complicated function – `LCD_DrawLine()` – which handles the SPI interface and the manual drawing of each pixel to the display. Each function adds another layer of complication.

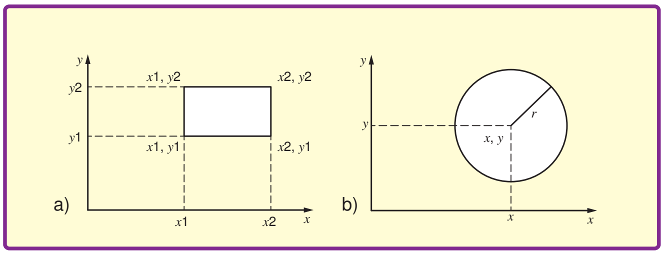


Fig.1. In the x-y plane: a) The key parameters of a rectangle, and b) The key parameters of a circle

`LCD_DrawRectangle()` draws a rectangle by using the function `LCD_DrawLine()` to draw four lines. `LCD_DrawLine()` uses another function (not seen here) called `LCD_DrawPoint()` which draws the line, one pixel at a time.

Back to the coordinate geometry, the first `LCD_Drawline()` draws a line from point *x*1,*y*1 to *x*2,*y*1, which is the bottom line in Fig.1. The second line drawn is from point *x*1,*y*1 to *x*1,*y*2, which is the left-hand vertical line. The third line draws a line from *x*1,*y*2 to *x*2,*y*2, which is the line on top. Finally, the last line to be drawn starts at *x*2,*y*1 and finishes at *x*2,*y*2; the vertical line on the right-hand side.

Circles

Looking back at the rectangle function, we can see it wasn't quite as straightforward as you might first think. The top layer function of numerous sub-functions made the higher-level code easier to use and masked the underlying complexity. Drawing a circle is a little more complicated. Fortunately, the function `Draw_Circle(x,y,r)` takes all the hassle out of handling each pixel individually. The coordinates *x*,*y* are the centre of the circle and r represents the radius of the circle – see Fig.1b. If this was on paper, we would place a drawing pin at point *x*,*y*, attach a piece of string of length *r* with a pen at the end and simply trace the circle around *x*,*y*. In code, it is not so straightforward. We need to be able to calculate the position of each displayed pixel, so that it looks like a circle.

```
void Draw_Circle(unsigned short x0,unsigned
short y0,unsigned char r) {
    int a,b;
    int di;
    a=0;    b=r;
    di= 3-(r<<1);

    while (a<=b) {
        LCD_DrawPoint(x0-b,y0-a);
        LCD_DrawPoint(x0+b,y0-a);
        LCD_DrawPoint(x0-a,y0+b);
        LCD_DrawPoint(x0-b,y0-a);
        LCD_DrawPoint(x0-a,y0-b);
        LCD_DrawPoint(x0+b,y0+a);
        LCD_DrawPoint(x0+a,y0-b);
        LCD_DrawPoint(x0+a,y0+b);
        LCD_DrawPoint(x0-b,y0+a);
        a++;

        if (di<0) {
            di += 4*a+6;
        } else {
            di+=10+4*(a-b);
            b--;
        }
        LCD_DrawPoint(x0+a,y0+b);
    }
}
```

The code above shows the internal workings of the function `Draw_Circle()`. It is quite complex. The equation used in

this case is called 'Bresenham's circle algorithm', which is derived from the midpoint circle algorithm. This works by breaking the circle into eight pieces called octants and draws them all at the same time in a counterclockwise order. This algorithm is essential in rasterising (converting to pixels or dots) a circle on a digital display.

The first three lines of the code are the local variables to be used (`a,b,di`). Our display uses a matrix of square pixels, so there needs to be some error correction in drawing the circle. The next line handles this by calculating `di` as the 'delta value' to compensate for this problem. << is the left shift operand, a shorthand of multiplying by two. A while loop then rotates around 360 degrees, drawing the relevant points to the display using `LCD_DrawPoint()`. An `if else` statement uses the delta value `di` to compensate for the change in in the *x* coordinate as the code orbits the circle.

Enumeration, switch and case

Looking back at our embedded code, we can do some cleaning up and make things more user friendly. Say for example we want a function that takes a variable that makes the function perform different tasks. `printString()` is one such function that we can use to print a new value for current, voltage or power to the display based on the values we pass to it.

First thing to look at is the `enum` keyword, which sets up a list of named constants called the enumerator list. We could set up a number of variables and assign individual values so that the function `printString()` knows what to do with them.

```
current = 1;
voltage = 2;
power = 3;
```

The above code shows how this would be done normally. Each value is stated with their relevant value. As long as the value for each is unique, the value itself is irrelevant.

```
enum {
    current = 0,
    voltage,
    power
};
```

The code here shows the use of `enum`. The compiler assigns a value to each variable in the list automatically. Only the variable current is equal to 0, whereas the variables voltage and power are assigned sequentially based on the first. The use of `enum` allows for improved readability, better debugging and lower maintenance. There's no need to assign a specific value to these anymore, which allows the compiler to optimise these values.

Next we look at switch and case. The switch statement allows a variable to be tested against a number of variables. This is a much-preferred method of comparing values for different behaviours compared to the popular nested `if else` loops.

```
if (valueType == current) {
    printCurrentValue();
} else if (valueType == voltage) {
    printVoltageValue();
} else if (valueType == power) {
    printPowerValue();
}
```

The code here shows the normal `if else` statements trying to capture what action to take based on the value stored in `valueType`. While it doesn't look too bad, `if else` statements can become unwieldy and very quickly difficult to manage.

```
switch (valueType){
    case current: {
        printCurrentValue();
        break;
    }
    case voltage: {
        printVoltageValue();
        break;
    }
    case power: {
        printPowerValue();
        break;
}
}
```

The `switch` statement above starts off the keyword switch followed by the variable it is comparing against. Below this we have multiple case variables that are tested against the switch keyword. Looking at this piece of code, it is much easier to read the three cases are current, voltage and power. Each case must end with the `break;` command to make sure the running code exits the `switch` statement and doesn't try to execute other `case` statements.

In each of the functions above – `printCurrentValue()`, `printVoltageValue()`, `printPowerValue()` – we show the measured current/voltage/power on the display by building up the string first, using the following line:

```
sprintf(sbuf, "Current Measurement:  %2.4f
mA", showValue);
```

The function `sprintf()` is used to concatenate a series of words to be displayed, and stores them in `sbuf`. While this was covered previously, note the `%2.4f` and the variable `showValue` at the end of the command. If the variable name `showValue` was seen between the inverted commas, it would print the word 'showValue' to the display, instead of the value stored in the variable. The `%f` is a format specifier, a place holder in the sentence for the variable. The compiler recognises the `%f` specifier and replaces it with the value in `showValue`, thus showing the value on the display. Different specifiers are used for different variable types; for example:

```
%c – char single character
%d – int signed integer
%f – float or double signed decimal
%u – int unsigned decimal
%x – int unsigned hex value
```

This list shows some of the commonly used format specifiers. These are typically used when adding a stored value to a string. While the PIC itself stores these values as binary in registers, they can be displayed differently on the screen. For example, the decimal value 65, as a character (`%c`) will be interpreted as an ASCII character, and in this case the letter 'A' will be displayed. As an integer (`%d` or `%u`), the decimal value '65' will be displayed. As a float (%f), this could be displayed as '65.00'. With a hexadecimal specifier (`%x`), 65 would be displayed as 0x41.

The `2.4` used in `%2.4f` tells the compiler that the variable is of type float and has two digits to the left of the decimal point and four digits to the right of the decimal point; for example, 12.1234.

Fig.3 shows the *PICmeter* display using some of the basic shapes and colours discussed this month. There are two rows of sixteen yellow circles on top and bottom of the display. With a radius of 5, the circles look more like diamonds. This is down to the pixelation of the display. These are drawn with the `Draw_Circle(230,10,5)` function we discussed above.

```
POINT_COLOR = RED;
LCD_DrawRectangle(151,29,221,289);
POINT_COLOR = YELLOW;
LCD_DrawRectangle(150,30,220,290);
```

The piece of code above draws a red rectangle and then overlays the first rectangle with a yellow rectangle offset by a single pixel. Notice the slight difference in the *x*,*y* coordinates. Before each shape is drawn, the colour needs to be set by assigning a value to `POINT_COLOR`.

```
#define WHITE         0xFFFF
#define BLACK         0x0000
#define BLUE          0x001F
#define RED           0xF800
#define GREEN         0x07E0
#define YELLOW        0xFFE0
#define GRAY          0x8430
#define LIGHTBLUE     0x7D7C
#define LIGHTGREEN    0x841F
#define LGRAYBLUE     0xA651
```

While, the display is capable of up to 65k different colours, it is quite difficult to distinguish between most of them. The above list of defined values shows some commonly used colours that can be used.

Fonts

We are limited to just the 5x7 font, which is stored in a look up table in the **PIC24F-Graphic-Font.h** header file. This table stores a series of values, which detail how to draw each value on the display, pixel by pixel. The font table covers the numbers 0-9, lowercase letters a-z, uppercase letters A-Z, and a number of special characters (!"£$%^&*:@~<>?,./\|). While there are plenty of other fonts available for this display, they would need to be modified for use with the PIC.

Taking it further

I hope this short series inspires you to take the project further and add extra functionality. The PIC24F16KM202 was specifically chosen for its CTMU, the charge time measurement unit, which allows the user to measure the value of external capacitors and inductors. The 2.2-inch TFT display has an optional four pins, which are used for attaching an SD card slot underneath the display. This allows the user to store images on an SD Card to be shown on the display. It could be very nice to display all sorts of slow moving animations or static images. And don't forget all the code for this project can be downloaded from the *EPE* website.

Thank you!

It's been an absolute pleasure writing the *PIC n' Mix* articles for *EPE*. I will miss working with the team to come up with new and exciting projects exploring the world of Microchip's PIC microcontrollers. I will also miss the endless puns around PICs! And so, in the immortal words of Douglas Adams, 'So long, and thanks for all the fish'.

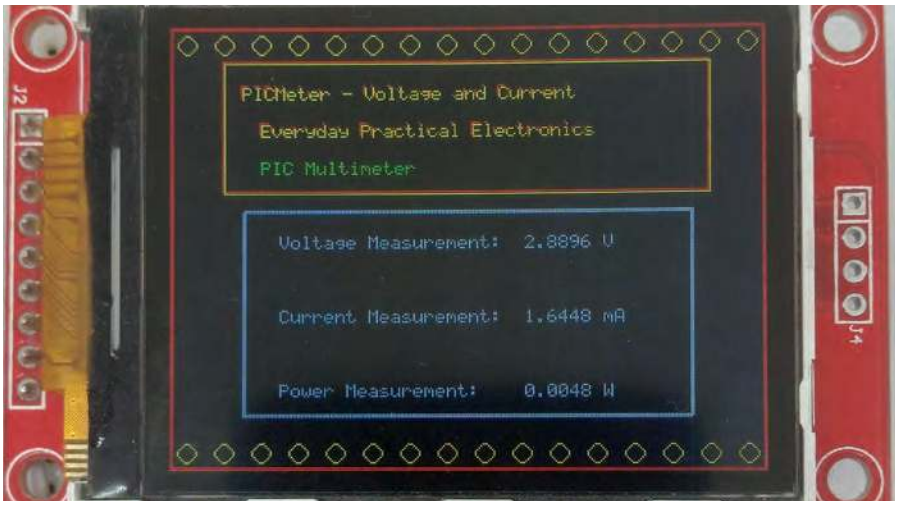


Fig.3. Finished PICmeter display showing voltage, current and power.

Not all of Mike's technology tinkering and discussions make it to print. You can follow the rest of it on Twitter at: *@MikePOKeeffe*

You'll also find him on *EEWeb* forums as '*mikepokeeffe*' and from his blog at *mikepokeeffe.blogspot.com*

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Introduction to Circuit Simulation with LTspice – Part 4

THIS IS THE FOURTH AND FINAL part of our introduction to SPICE analogue circuit simulation using LTspice simulation software from Analog Devices (see: **www.bit.ly/2nsvKzT**). This series was motivated by the fact that LTspice simulations are often used to illustrate *Circuit Surgery* articles and we recently decided to make the files available on the *EPE* website. At one time, circuit simulation was only available to professional engineers, but for many years now tools such as LTspice have been available as free downloads and can be used by anyone with a suitable computer. Simulation can help when designing circuits and can be useful tool for learning about electronics.

So far, we have looked at running transient analysis to see the waveforms in a circuit as a function of time; and AC analysis to enable us to plot circuit characteristics such as gain and phase shift as a function of frequency. To do this, we have used simple *RC* and *LC* circuits as examples. This month, we'll look at another couple of analysis types, briefly discuss the 'solvers' on which some of SPICE's operation is based and look at example circuits using semiconductor devices, discussing the models used to define their behaviour.

The LTspice schematic in Fig.1 comprises a diode connected across a 10V supply via a 1kΩ resistor. With the diode and supply oriented as shown, and the supply set to 10V, the diode is forward biased. Using the usual rule of thumb, we might expect about 0.7V across the diode, implying about 9.3V across the resistor and hence a current of about 9.3mA through the circuit. This calculation of DC currents and voltages in a circuit is related to a SPICE DC operating point analysis. Specifically this involves finding the DC voltages and currents with capacitors treated as open circuits and inductors as short circuits.

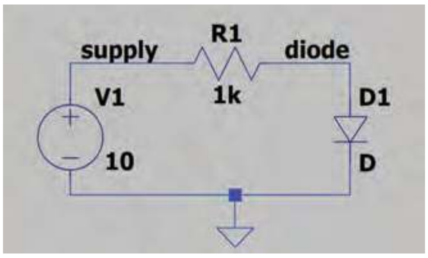

Fig.1. LTspice circuit: diode and resistor.

Solvers and convergence

SPICE simulators do not solve circuits (to find the operating point) using algebraic manipulation of equations, as one might try on paper. In fact, a simple algebraic approach only works for linear circuits (eg, resistors). The non-linear nature of the circuit in Fig.1 means that simple algebraic approaches cannot be used to solve the circuit (find the voltage across the diode and resistor, and the current through them). The diode is described as 'non-linear' because its current-voltage relationship is not a straight line when plotted on a graph. For manual calculation, the well-known approach to solving the circuit in Fig.1 is to use a graphical technique. To do this, the diode characteristics and the resistor's 'load line' are plotted on the same graph. The point where these lines intersect is the DC operating point.

SPICE does not draw graphs to solve circuits, it uses numerical analysis methods to try to home in on the correct values using a step-by-step (iterative) approach. Put crudely, this involves taking a guess at the answer, analysing the situation implied by the guessed values and using these results to try to improve the next guess. The mathematical basis of these approaches go back a long way, including to Sir Isaac Newton. In honour of this, one of the key circuit solving techniques used by LTspice (and SPICE in general) is called the Newton-Raphson method.

The guess, analyse, improve-guess iterative process should get closer and closer to the correct solution – this is called convergence. If things are proceeding well, the longer the solver runs the more accurate the answer should be. Simulators monitor the convergence of the solution and use some criteria to decide when the solution is close enough to stop, so as not to waste unnecessary computational time and effort. For example, the simulator might check how close the current answer is to being valid in circuit theory terms. At every node in the circuit all currents into that node must sum to zero (Kirchhoff's current law). If this condition is getting closer to being exactly correct with each interaction then convergence is occurring and the simulator stops the calculation when its accuracy criteria have been met.

The numerical techniques used by SPICE simulators are not guaranteed to find a solution for non-linear circuits, so you may occasionally get an error message from LTspice saying there has been a convergence failure. Fortunately this is quite rare – if the basic Newton-Raphson technique fails LTspice has a few tricks up its sleeve, which may allow it to achieve convergence. It will try all these approaches before giving up. Advanced users can also control the solver operation by setting various parameters and options. If convergence failure occurs the problem may be re-solved by giving the simulator a hint about the solution. In effect, you manually supply the initial guess to the iterative solver using your knowledge of how the circuit works. If the solver starts close to the correct answer it is more likely to converge on the solution. This is done using the `.nodeset` SPICE directive.

DC operating point for a diode

To try the operating point analysis, start LTspice and either draw and save the circuit in Fig.1, or download and open the schematic file from the *EPE* website. V1 is configured as a DC voltage source with voltage of 10V. To set this up, add the voltage source , right click it and set DC Value(V) to 10. You do not need the advanced settings, but if you do open this then only the DC Value section is set up – other sections are blank or 'none'. To run the operating point calculation do `Simulate > Edit Simulation Cmd` from the main menu and select the DC op pnt tab. There are no settings or parameters to enter (see Fig.2).

Click OK and then click on the schematic background to add the `.op` simulation command. Run the simulation (`Simulate > Run`, or the `Run` button). The result will be a window opening containing text listing the voltages and currents in the circuit, as shown below.

Simulation files

The LTSpice files discussed in this month's *Circuit Surgery* are available for download from the *EPE* website.

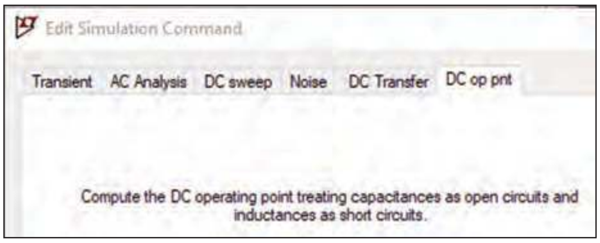

Fig.2. Selecting the DC operating point command.

```
--- Operating Point ---

V(diode):  0.712763    voltage
V(supply): 10          voltage
I(D1):     0.00928724  device_current
I(R1):     0.00928724  device_current
I(V1):     -0.00928724 device_current
```

We see that he results confirm our expectations discussed earlier – the diode voltage is about 0.7V and the current in the circuit is about 9.3 mA.

Current directions

You will notice that current in the voltage source is negative. This is a result of SPICE using the passive sign convention (PSC). The PSC is based on the power dissipated by a passive component (eg, a resistor) being defined as positive, so that the power associated with a source (eg, battery) is negative – it is putting power into the circuit, so the dissipation is negative. For this to hold, the current directions must be defined such that positive current enters the positive voltage terminal of a source. In this circuit, current is flowing out of V1's positive terminal, so the sign is negative.

Another possible source of confusion with current signs and directions occurs with components such as resistors. Close the operating point results window, look at the netlist with `View > Netlist` and note the line concerning R1, for example: `R1 supply diode 1k`

Now edit the schematic to change the orientation of the resistor. To do this, click on the Move button (the hand with separated fingers) then click on the resistor. It will come free of the schematic and move with the mouse – hit the Ctrl and E keys at the same time to flip the direction of the resistor (or use the Mirror button) and place it back in the circuit in the same place. The schematic will not look any different (use `View > Fit` if it has wandered around). However, if you look at the netlist again you will see the order of the two wires connected to the resistor has changed, for example: `R1 diode supply 1k`

Now run the simulation again and you will see that the sign of the current in the resistor has changed:

`I(R1): -0.00928724 device_current`

The current in the resistor is defined as flowing from the first node to the second (in the netlist line), so flipping the order of these connections by mirroring the resistor on the schematic changes the sign of the current in the resistor.

DC sweep

The next analysis type we will look at is DC sweep. This allows us to change a voltage or current source (more than one if required) over a defined range of voltages and plot the circuit values against the varied source voltage or current. Sticking with diodes, we could use this analysis to plot a diode's current against voltage characteristic curve. This is equivalent to working in a lab, using a variable DC voltage source, setting various voltages, measuring the current and plotting a graph of current against voltage. Alternatively, one could use a semiconductor curve tracer designed for this purpose. For a silicon diode we would expect to see the well-known exponential forward-biased characteristic, with the diode current reaching substantial levels for forward voltages above 0.6 to 0.7V. With a reverse voltage applied we expect to see very low currents until the breakdown voltage is reached.

To illustrate some further points we will plot the characteristics of two diodes – one of which is a Zener. The LTspice schematic in Fig.3 is the starting point for this example. Save and close any files you already have open and then either draw and save, or download, the schematic in Fig.3. To place the Zener use the Component button (logic gate symbol) and scroll across to choose Zener. The voltage source is set to DC 0V because the voltages used in the simulation will be controlled by the DC sweep analysis.

This circuit may look strange because you might expect to see a resistor in series with a diode or Zener (as in Fig.1); however, this circuit is about characterising the diode, so the voltage is applied directly across it. If you did this in a lab you would have to be very careful to set current limits or make sure you did not apply a voltage large enough to cause damage. However, SPICE will happily simulate components with currents, voltages and power levels beyond the limits of typical real devices. Although you can define voltage and current ratings in LTspice and this information is displayed on the schematic to help with reality checking, it does not change the simulation.

To set up the DC sweep, edit the simulation command and select the DC sweep tab (see Fig.4). Set the parameters for the '1st Source', as shown in Fig.4. This will cause the voltage source V1 to be stepped through voltages from –4.8V to +0.8V in 10mV steps. This voltage range would be suitable for plotting characteristics of a silicon diode or a 4.7V Zener. Click OK and click on the schematic to add the simulation command (`.dc V1 -4.8 0.8 10m`). Run the simulation and add the traces for I(D1) and I(D2) to the plot.

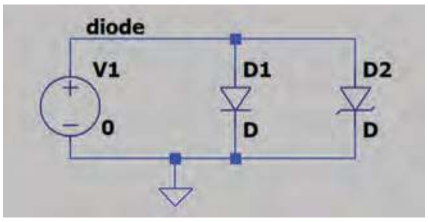

Fig.3. Circuit for DC sweep analysis example.

The results are shown in Fig.5. You can only see one curve on the graph because the two diodes have exactly the same characteristics and so the two curves overlap. We see no evidence of any Zener breakdown for D2. This is perhaps not surprising given that we have not specified a breakdown voltage for D2, but it is sometimes a source of confusion that simply putting a Zener symbol on an LTspice schematic is not sufficient to get a Zener diode in your circuit. To proceed further we need to understand how SPICE deals with semiconductor components.

SPICE models

For components such as resistors and capacitors there are a limited number of parameters which can be specified to control how that component behaves in a simulation. For a basic resistor it is just the resistance and temperature coefficients. For a basic capacitor there are up to five parasitic values (eg, series resistance and inductance) in addition to its capacitance value. These limited number of parameters are specified (in the netlist) if required each time the component is used. For semiconductors the number of parameters may be much larger (over 60 for a MOSFET) and it is not convenient to

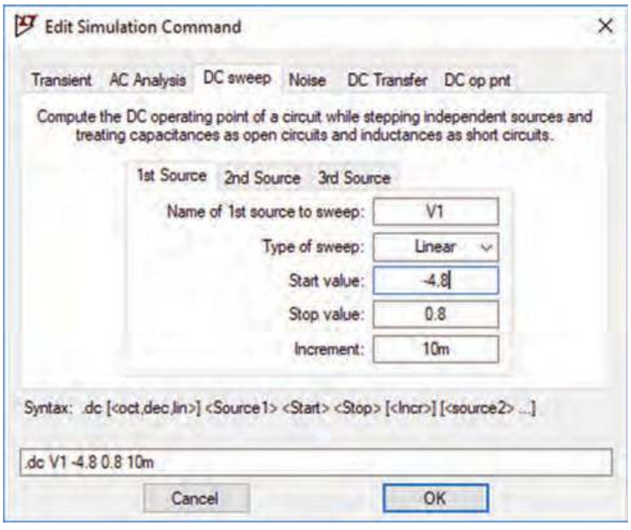

Fig.4. Setting up the DC sweep analysis.

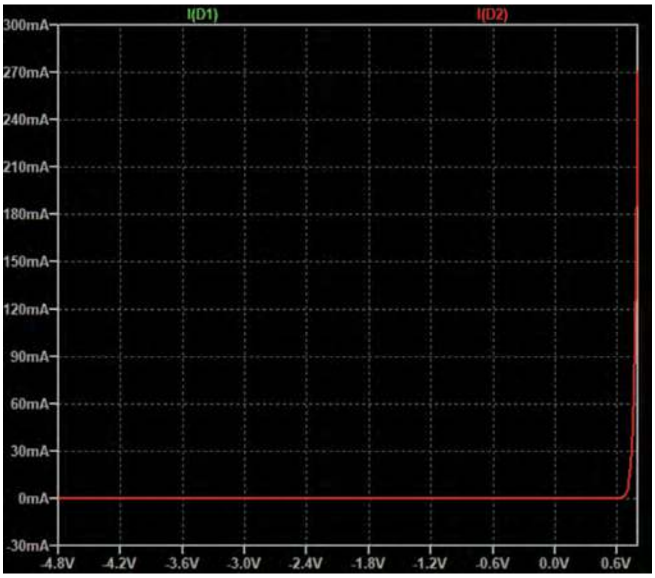

Fig.5. Diode characteristics from DC Sweep analysis.

specify them individually each time a component is used. Instead, a list of parameters values (referred to as a model) is given a name (the model name) and that model name is specified for each component to which it applies.

The 'D' next to the diodes in Fig.3 is the model name – it is referring to LTspice's default diode model. Reverse breakdown voltage (the Zener voltage) is one of the parameters in the diode model, but its default value is infinite, so the D2 in Fig.3 will not show any Zener behaviour at any voltage, despite the symbol.

Although it is used to refer to the list of parameter values, the term 'SPICE model' fundamentally means the mathematical representation of a component that is used by SPICE to perform the calculations required to simulate circuits using that component. There is more than one approach to modelling components. One way is to take the known physics of the device and implement all the equations, which derive from this physics in the simulator. Another approach is to use mathematical techniques that can create relationships (eg, between current and voltage) which are close to the behaviour of those component, but which are not based directly on the physics – these are referred to as curve fitting models. Physics models have the advantage of being based on reality, but are typically more complex than curve fitting, and take more computing power to simulate. Physics models require the physics to be understood and all parameters associated with the equations need to be measured (for a real device). For curve fitting a representative sample of devices can be subject to extensive measurements using curve tracers to obtain the necessary data.

LTspice has two types of model available for diodes; one is curve-fit-based and the other is physics based. In its simplest form the first of these models represents the diode as a piecewise linear resistor. Specifically, this diode has three resistances values, one for the off region, one for forward condition and one for reverse breakdown. The simplest form of the model switches resistance values abruptly at two voltage thresholds (forward conduction and reverse breakdown). Additional parameters allow a non-linear curve fit to smooth the transitions. The physics-based model is the standard Berkeley SPICE diode model with some extensions provided by LTspice. This has 35 parameters, including capacitances and temperature coefficients of some parameters. Unless you have studied semiconductor and diode physics in some depth, many of these parameters will be unfamiliar. However, they include the reverse breakdown voltage, which is relevant to our discussion of Zeners. The full list of parameters for both models, and further information, can be found by searching for 'Diode' in the LTspice help.

Using SPICE Models – example

We can edit the schematic in Fig.3 to set up models for the two diodes, rather than just using the defaults. To set up a device model we specify the model parameters, which are set using the `.model` SPICE directive. To apply the model to a particular component we set the component's model name to match the relevant `.model` statement. To add a `.model` statement to a schematic click on the spice directive button (`.op`) and type the `.model` statement

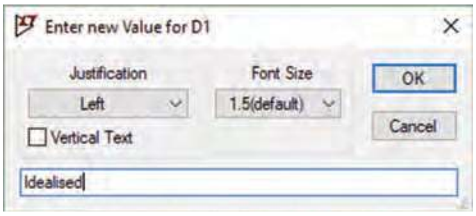

Fig.7. Setting the model name for diode D1.

into the text box. Click OK and then click on the schematic to place the directive text.

Save the schematic in Fig.3 as a new file and use the SPICE directive button to add the following two model statements (for example, see Fig.6):

```
.model Idealised D(Ron=2
 Roff=1Meg Vfwd=.7)
.model Zener1 D(Is=1e-14
 rs=0.5 bv=4.7 ibv=2m)
```

Also right click on the 'D' next to the two diodes and change the 'value' for D1 to `Idealised` and `Zener1` for D2 (for example, see Fig.7). These are the model names that are used to identify the model statements shown above. The resulting schematic should be similar to Fig.8 – alternatively download the schematic file. The syntax of the `.model` statement is:

```
.model <modname>
 <type>[(<parameter list>)]
```

In this example, both models are of type D – for diode. LTspice had 16 model types which cover various semiconductors – diodes, bipolar transistors, JFETS, MOFETS, MESFETS and IGBTs. There are also models for switches and transmission lines. The model names (`modname`) in the example are `Idealised` and `Zener1`. These names are just identifiers, they do not convey any other information to the simulator. The choices of parameters specified in the parameter list determines which version of a given model type is used. As stated above, LTspice had two diode models. In the example the `Idealised` model uses the basic curve-fit piecewise linear model and `Zener1` uses the Berkeley diode model.

The `Idealised` model for D1 sets the voltage at which the diode conducts (forward threshold voltage, parameter `Vfwd`) to 0.7V. The on resistance

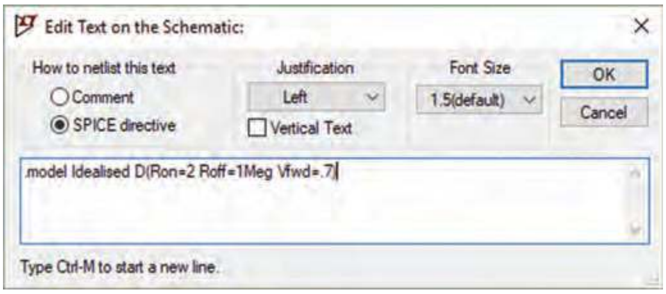

Fig.6. Entering the .model statement.

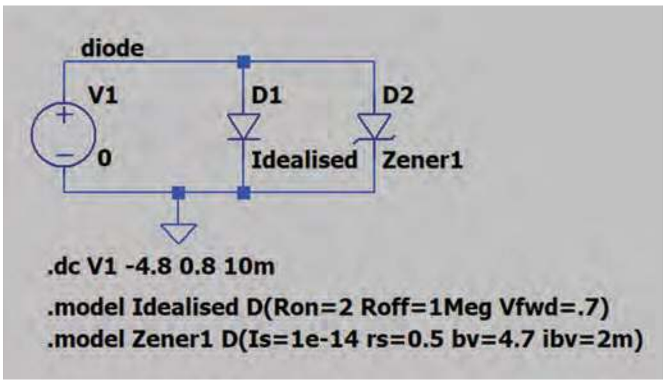

Fig.8. Schematic for investigating use of diode models.

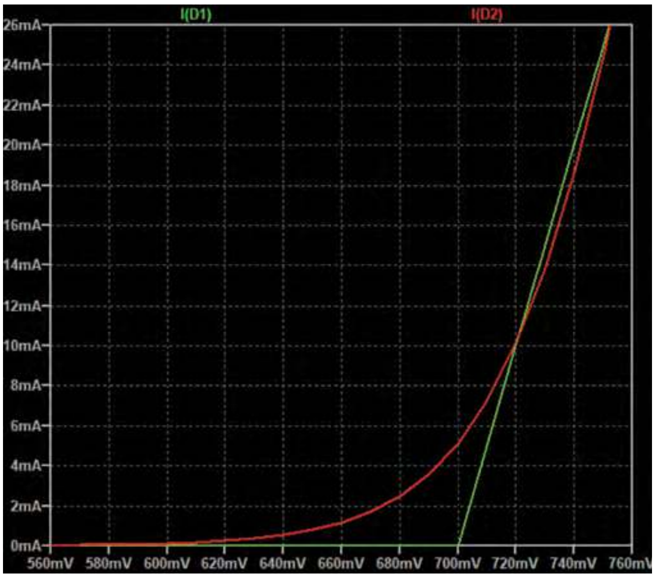

Fig.9. The forward characteristics of the two diodes in Fig.8.

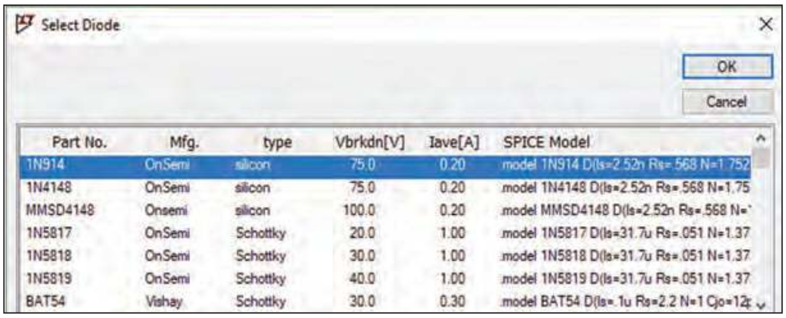

Fig.11. Selecting a diode.

(parameter Ron), applicable at voltages above the threshold is 2Ω. Below the threshold the diode had a resistance of 1MΩ (parameter Roff). The reverse breakdown voltage (parameter Vrev) is not set by this .model statement so it will retain its default value of infinity.

The Zener1 model for D2 sets a couple of basic diode parameters, including the saturation current I_S (parameter Is) and the ohmic resistance of the diode (parameter Rs). The saturation current is a term in the Shockley diode equation relating current (I_D) to diode voltage V_D, that is $I_D \approx I_S\exp(V_D/nV_T)$ where V_T is the thermal voltage and n is the diode's emission coefficient (default value 1). The value set in the example is in fact equal to the default, but it was included to emphasise the link to the physics and to facilitate changing it to explore the effect this has.

To configure a reverse breakdown with the Berkeley model (so we get Zener behaviour to match the symbol) both the voltage (parameter BV) and current at the breakdown voltage (parameter Ibv) need to be set. The example model sets the breakdown voltage to 4.7V and the current at this voltage to 2mA.

Simulating with the Diode Models

With the schematic configured as in Fig.3, run the DC sweep analysis again, and add the I(D1) and I(D2) traces if the plot is not already configured to do this. The results, unlike Fig.5, should enable you to see that there is some difference between the diodes now, but to see the details it is necessary to zoom in on the relevant sections of the plots. This can be achieved by clicking and dragging the zoom marquee or by entering the axis range settings, as discussed in *Part 2*.

Fig.9 shows the forward characteristics. Here it can be seen that the model used for D1 consists of two straight lines (hence the name 'piecewise linear' for this approach to modelling). The diode switches resistance at exactly 0.7V. The results for D2 shows the well-know exponential characteristic of a diode and is more realistic than the model for D1.

Fig.10 shows the reverse characteristic for a range of voltages around 4.7V, where we configured the reverse breakdown to occur. The curve passes through 2mA at –4.7V, the current at breakdown we configured in the model.

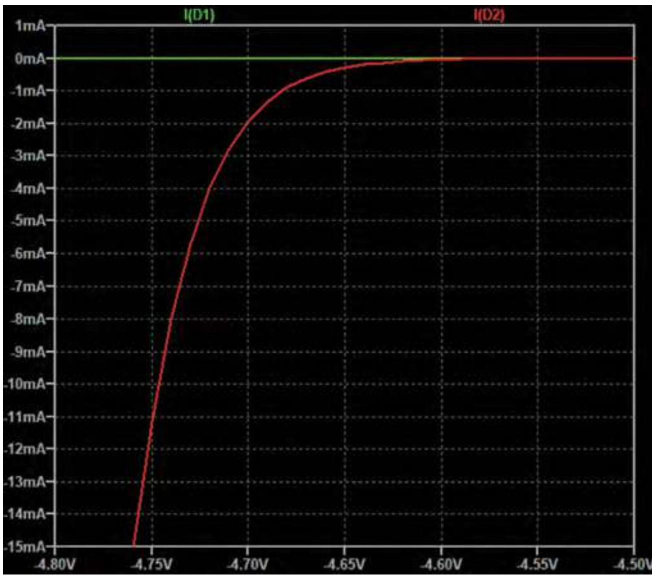

Fig.10. The reverse breakdown characteristics of D2 in Fig.8.

Models for commercial devices

You may be thinking that is seems like hard work to set up device models. Indeed, this may be the case if you start from scratch; however, the manufacturers of components such as diodes often provide SPICE models for their devices, and there are a reasonable number already provided in LTspice. To try these models, save the schematic and then save as a new file, right click on the diode and click the Pick New Diode button in the dialog.

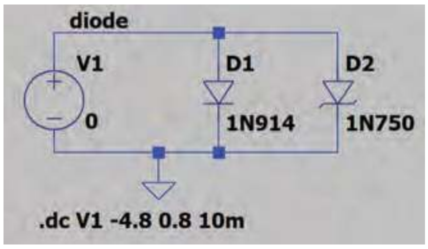

Fig.12. Schematic with two commercial diodes.

This will open a list of diode part numbers from various manufacturers, with their SPICE model statements. Select the diode you want (in this example, 1N914 for D1 and 1N750 for D2) and click OK. The resulting schematic is shown in Fig.12 (also downloadable). The .model statements from earlier can be deleted if you want. Run the simulation, add the I(D1) and I(D2) traces. You will see that D2 is behaving as a 4.7V Zener, because that is what the 1N750 is, but this is controlled by the model, not the symbol.

The diode models which are listed when you pick a diode can be found in a text file installed with LTspice. Typically (on a Windows PC) it will be in: **[User]\Documents\LTspiceXVII\lib\cmp\standard.dio**. Models or other types of device are found in the same folder. These models can be copied and modified if required. One example of why you might want to do this would be to change the gain value of a transistor in an amplifier you had designed – to see what effect this had on circuit performance. Of course, you have to be careful to set meaningful values if you play with model parameters.

If a device is not listed when you 'Pick New' it may be available from the manufacture's website, in which case, if the parameters used are compatible with the models used by LTspice, it can be added to the relevant file in the component models folder. Some models (eg, for didoes) from manufactures are more complex than just a .model statement – these use subcircuits, which we have not discussed here. Similar approaches are used for other devices such as op amps, which are not in the list of devices covered by .model model types. This is just one example of various aspects of LTspice which we have not yet discussed, so we may return to the topic or include background on using LTspice to support other articles.

Designing PCBs with EagleCAD – Part 1

In this series of articles we are going to explore using EagleCAD printed circuit board (PCB) design software to discover how easy and rewarding it can be to design a circuit board and have it manufactured by a professional PCB manufacturer.

For many of us, the process of constructing an electronics design can take one of a number of different routes; pushing components into a breadboard, using hook-up wires to connect pre-built circuits (such as Arduino and Grove shields) or soldering components directly into stripboard. Magazine articles often describe one or more of these techniques, while the bigger construction articles simplify things by offering a professionally manufactured PCB for purchase.

In earlier days, construction techniques were even more varied – building designs based on valve tubes required point-to-point wiring that was more of a three-dimensional mechanical assembly process than today's flat electronics layout, and often required exquisitely drawn diagrams showing the positioning of components within a chassis. Heathkit, for example, a company that produced complex self-assembly projects, created assembly instruction manuals that were something of a work of art, and a joy to follow.

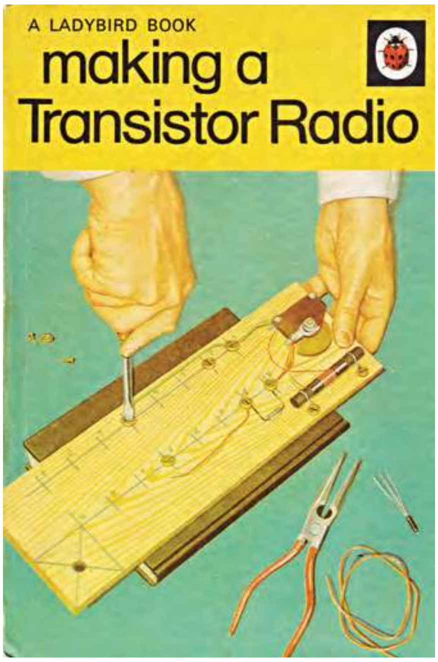

Fig.1. Circuit assembly, old-school style from the 1970s.

Breadboard – old school

The author's first circuit board was a single-transistor radio constructed on a sheet of plywood using wood screws and metals screw-cups to hold the component leads in place and form connections. It wasn't pretty, and it often didn't work. The design of that radio was detailed in a Ladybird book, the cover of which is shown in Fig.1. Building that circuit was physically hard! The 21st century is more generous thankfully, and projects that are published now are easily assembled on low-cost prototyping boards and come with simple yet clear assembly and troubleshooting instructions.

Modern, user-friendly breadboard

When you are designing a circuit, the breadboard technique, as shown in Fig.2, offers the fastest assembly route, assuming all your components are available in 'through-hole' style with stiff wire legs that can be pressed into a hole on a 0.1-inch spacing. Most leaded ICs, transistors and passive components will fit – and some that cannot (such as power connectors) can be modified with some short hook-up wires to fit. This construction technique is idea for proving a circuit design works, and even for making initial measurements such as current consumption. There are some limitations, however, with the main one being that the inevitable long cable lengths connecting the components will limit the maximum frequency that the circuit can operate at. In Fig.2 for example, the communication speed to the LCD had to be lowered due to signal distortions on the long wire connections. The design worked, but the LCD could be refreshed at a higher speed if the design was implemented on a PCB with shorter tracks.

One bonus of using breadboard construction is that as components are pushed into spring contacts in the board rather than soldered, the components are re-usable, and design changes (mistakes) are easily and quickly rectified.

Veroboard – or 'stripboard' to give its generic term – is a more physically robust solution for wiring up circuits. Designs will be more compact, and with shorter wires connecting the components, they can run at much higher frequencies. The drawbacks are that assembly is significantly longer (the design shown in Fig.3 took the author several evenings to construct) and mistakes can be costly. Components can rarely be re-used, unless socketed. Stripboard designs can still suffer from signal delays due to capacitance on the traces, and this can impact high-speed digital communication between components, such as when driving LCD displays over an SPI bus. Complex designs can be difficult to re-produce, especially if there are a large number of point-to-point wires required.

Why build a PCB?

All the techniques mentioned above share one thing in common; they are cheap, only require simple-to-use tools and so offer a great entry into the hobby. These techniques are taught in technical colleges as the foundation for a career in electronics, so why bother transitioning to a PCB, with all the costs involved? And what are those costs?

In the old days, most designs did not gain much benefit from a printed circuit board – they were created with

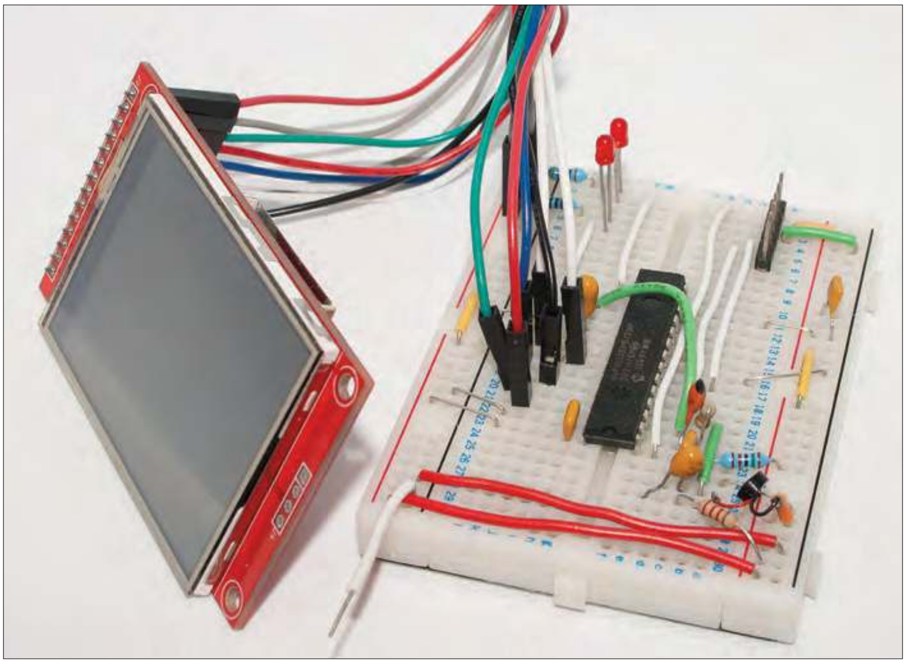

Fig.2. Breadboard assembly – neat, but very fragile.

point to point wiring in mind (especially in the case of valve designs) or simply ran at such low frequencies that a Veroboard-style layout was perfectly acceptable. High quality audio amplifier designs have always demanded a well-designed PCB to achieve superior results, but it's only recently that digital designs with high speed signals have become popular, forcing the need to transition to a PCB. Even a small colour LCD display driven by an SPI bus from a microcontroller can run at 10MHz or 20MHz, and this requires short connections with minimal track-to-track capacitance – a prototype board with long, high capacitance traces will just not work. The noise and capacitance on these traces will limit the speed at which they can run down to less than 1MHz in many cases.

There is also the aspect of enjoying learning a new set of skills and creating something that feels 'professional' – and if you get hooked on that mind set you will probably want to start further expanding your skills to create professional-looking enclosures. (That will be the subject of another series of articles!)

Designing a PCB also opens the opportunity to move from wire-ended components to surface mount. This is a whole new area for many hobbyists, and can be tricky, especially as it is difficult to create surface-mount designs without a PCB designed in a computer-aided drawing (CAD) program (although it is possible – we will discuss this in a later article.) Creating a design using surface-mount components opens up new skill areas to explore. Some interesting components may only be available in surface mount (notice how the Veroboard layout in Fig.3 has two DIY surface mount boards added,) and, by using surface-mount components you can make your designs physically smaller. Many components are available in both through-hole and surface mount varieties, allowing you to design your circuit on breadboard, and then move to surface mount for the final version without modification. SMD-electronics is also a fascinating new skill to acquire. Designing small computing devices is one of my passions, so expect to see user-friendly designs and techniques based around SMD components covered in future articles.

Designing a PCB makes it easier to build a project to fit into an off-the-shelf enclosure, as the board dimensions and holes can be specified to match mounting posts within the chosen enclosure. Battery holders are available with through-hole leads for soldering directly to a PCB, further simplifying assembly. PCB designs are the easiest to assemble, which means you can share the design with others without requiring complex assembly instructions.

DIY verses professional boards

Making PCBs at home has been possible for many years and is still a perfectly reasonable path to take. It's even possible to create a design without the use of a specialised CAD program – the board shown in Fig.4 was drawn with a permanent marker pen directly onto a sheet of copper-clad board, then etched in ferric chloride. This technique is only suitable for simple designs with large components. More complex designs are possible by printing designs onto transparent film, then exposing a photo-resist coated board under UV light, similar to photographic image processing. This is easily achievable in a home lab but requires more equipment and messy, toxic chemicals. It can also be a bit hit-and-miss. In this series of articles, we are going to be focusing on the process of having board designs manufactured professionally, explaining how you navigate the requirements of communicating your design to a manufacturer, which are complex and can be off-putting, but well worth the effort. Professionally manufactured boards can have some advanced processes applied to them. Fig.5 shows a recent design created by the author. This board was delivered in five days after placing the order, for a very reasonable cost. If you could tolerate waiting ten days, ten of these boards would cost £20. Less than £10 if you can wait a month for delivery. Despite that low cost, the design included text printing on the top and bottom layers, and complex milling out of unusual shapes and holes.

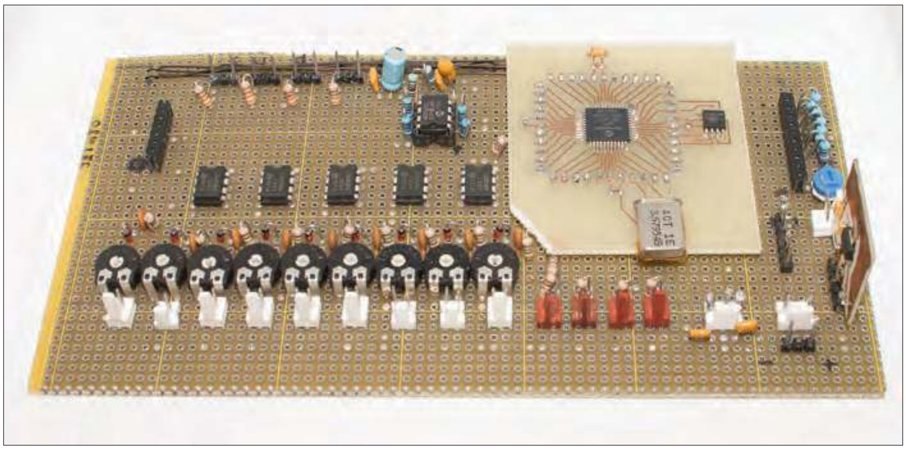

Fig.3. Veroboard assembly with some home-made PCBs for SMDs. This type of assembly is very time consuming.

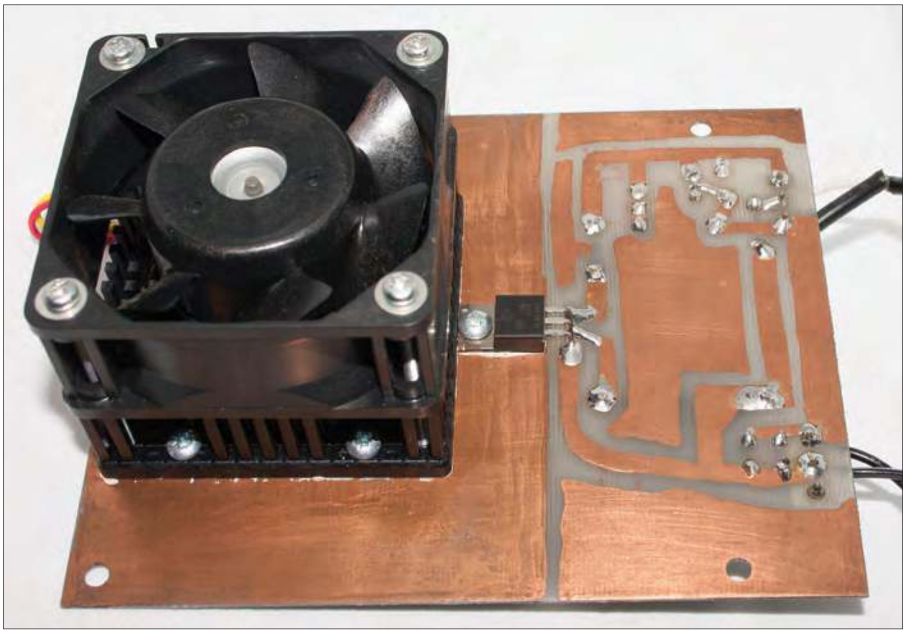

Fig.4. Not all PCBs have to be created with CAD. This design was hand drawn directly onto copper, then etched.

Working with PCB manufacturers

Up until around 5 to 10 years ago, purchasing professionally manufactured PCBs was an expensive and slow process. It typically required you to have a business account to be able to place an order – and you certainly could not expect assistance. Over the years prices have tumbled, and manufacturers around the world are able to ship to anywhere and are happy to do so. It is now possible with at least a dozen PCB suppliers to get an instant, automated quote on-line, pay with a credit card or PayPal and expect your boards to be delivered within 5 to 10 days. As you would expect, there is a higher charge for fast turn-around and fast courier delivery services, but this is an option that you can choose. If you are prepared to wait a month for your boards to arrive by boat from China, then a handful of custom PCBs will almost certainly be so cheap that they represent a small percentage of the overall build cost.

The quality of PCBs from different manufacturers has always been very good, especially for the simpler designs that hobbyists require. Standards for PCB manufacture were established in the 1980s and the equipment used to create PCBs is relatively simple to maintain and run. We will name a number of suppliers whom we consider reputable and safe to deal with on-line, important when you are handing over credit card details.

Placing an order for a PCB with a manufacturer is straightforward, fairly consistent across vendors and can be done without having to speak to someone. On-line, you simply input the width/height of your board, state how many copper layers it uses (typically two) and assuming you accept the defaults for the remaining dozen or so process parameters (we will talk about these in later article, but they are typically acceptable) you will receive a quote. A number of prices will be offered depending on how many boards you want and how quickly you want the boards returned to you. Once you have selected your order details, you will be asked to upload your PCB design file. Now, you have to wait a few hours while a process engineer checks your order details and validates the design meets their process requirements. More often than not there is a small design error that will require a change, but once you make those changes you will be quickly prompted to pay. Once you have paid, the clock starts ticking on the manufacturing of your design.

Many manufacturers provide detailed tracking information of your order on-line so you can see how it is progressing, and will provide a shipping tracking reference if you have chosen a fast courier delivery service. This provides a day-by-day progress report on your board, as you eagerly await its arrival.

You may have noticed that we have glossed over some important points: what files do they want, what are these options for PCB manufacture, and exactly what is it that you are purchasing? It's these points that put people off from starting out with professional PCB manufacture, and we will address these questions over the coming articles. Let's start by answering the question: 'Exactly what are you purchasing?'

PCB construction

For most non-specialist PCBs, the base material on which the various layers are added to is a glass fibre material called 'FR4'. This base comes in a variety of thickness, with 1.6mm being the most common. You can choose a thicker or thinner base material (the author likes 0.4mm thickness when constructing tiny wearable devices) but expect the price to go up – 1.6mm is the standard, most widely used, and therefore the cheapest.

Then, there is the question of how many conductive layers will you use? Two layers – top and bottom – is the most common; as you progress with your designs you can expect to move to four-layer designs, if you are keen to make very small PCBs. Two-layer designs are the most common, and will be the cheapest.

A commercialy made PCB is not just two layers of copper on an FR4 base. On top of the copper layer is a surface finish – copper oxidises quickly, and so during the manufacturing process you have the option to specify how the copper tracks will be coated. The default is 'hot-air surface levelling' (HASL), a process where the board is immersed in what is essentially molten solder, and then sujected to a strong burst of air to remove excess solder and which leave the surface fairly flat. This is the cheapest process but a better option is 'electroless nickel immersion gold' (ENIG), which deposits a microscopic layer of nickel and gold (not much!) which is very flat, and ideal for use with very fine pitch components. It's not required for simple through-hole or home-constructor-friendly surface-mount components, so we recommend you stick with the cheapest option, until your designs become more complex.

Next up, a thin solder resistant layer is selectively deposited across the board, covering all areas that will not needed to be soldered. This is applied in a printing-like process. The layer offers a degree of electrical insulation, protecting against solder bridges between tracks. It's also an oxidation barrier, prolonging the working life of the board.

Finally, a silkscreen print layer is applied. This layer is used to provide component references, product names, and even company logos, as seen in Fig.5.

All of these layers are completely under your control; you can place copper traces, solder resist and silk screen where ever you want. The CAD program you use to design your PCB will automate some of this for you, but you are free to make changes. Whether you add a corporate image to the silkscreen layer, or just plain text will not impact your costs. So feel free to be imaginative. You can even select the colour of your solder resist and silkscreen layers, often at no increased cost. Do bear in mind that these can only be a single colour; PCB manufacturers cannot do full-colour printing. The order page will list your options.

Finally, you can also specify drill holes of various sizes and even milling out features in the PCB, at no additional cost. You can create circular PCBs with holes inside them, whatever you require. You are not limited to rectangular profiles.

All of these details – the copper traces of your circuit; the drill holes for connectors, mounting points and through-hole components; the detail of the solder resist and silk screen layers; and the milling operations – these are all specified in the design file you send to the manufacturer. This is a set of output files from your CAD program, and that's the subject that we will start to explore in the next article – how to create your design in a CAD program. The learning curve may be steep, but the results are worth it, now the cost of manufacturing boards has fallen so low.

We look forward to you joining us on this adventure!

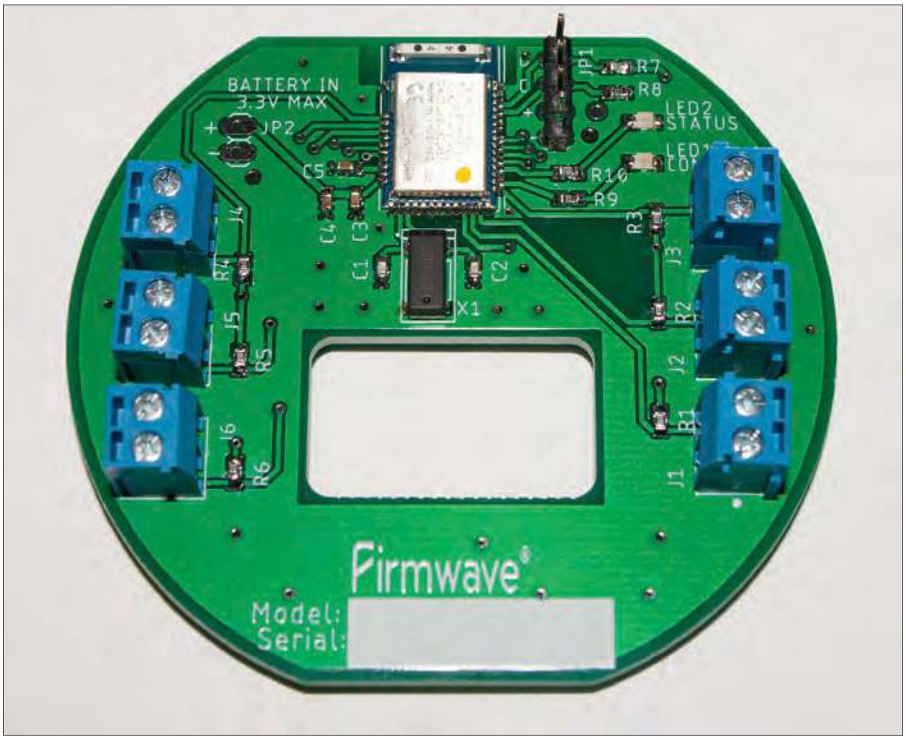

Fig.5. A recent design by the author. Designed in a day, the boards were manufactured and delivered within five days, at modest cost.

Max's Cool Beans

By Max the Magnificent

I don't know about you, but I can't imagine life without having a hobby project to work on in my spare time. In fact, I typically have several projects on-the-go simultaneously. I'll get a surge of enthusiasm and work on one for a few weeks, then something will distract me and… SQUIRREL!

As a result, some of my projects can take years to reach completion. In the case of my *Inamorata Prognostication Engine*, for example, I commenced work on it more than a decade ago. I've only now reached the stage where all the bits and pieces have come together, but it's been worthwhile – it is really starting to look very tasty, as you can see in my YouTube video (**https://bit.ly/2qkI5HX**).

A shocking experience

Sad to relate, but over time I started to get a little blasé with regard to electrostatic discharge (ESD). This eventually resulted in me blowing up the LEDs in the *Prognostication Engine's* furnace. I'd only just powered this up for the first time. I wandered into the next bay to invite a friend to come and look, and then strolled back into my own bay, all the time building up an electrostatic charge, which I promptly discharged into my furnace. 'Oh dear,' I said (or words to that effect).

I'm now fanatical when it comes to ESD protection. The *Prognostication Engine's* meter cases are grounded to the brass front panels, which are in turn grounded to the power supply. All of the internal wiring is shielded, and copper mesh greets your eyes wherever you look.

Hot glue used to be my friend

As you will see in the aforementioned video, the *Prognostication Engine's* upper control panel boasts five motorised potentiometers, each of which is surrounded by a ring of LEDs: 16-element NeoPixel rings from Adafruit (**https://bit.ly/2oL6R3m**).

It proved to be tricky to align these rings while attaching them, so I ended up holding them in place with two pieces of cut-down wooden hobby sticks – one at the front of the panel and the other

Fig.1. NeoPixel ring waiting to be attached.

at the back with the ring sandwiched in the middle – all secured by a nut and bolt (see Fig.1). Having everything 'finger tight' allowed me to power-up the ring and tweak its position and rotation until its NeoPixels were perfectly aligned with the holes in the panel.

Initially, I was planning on using a few dabs of hot glue to attach the rings to the front panel, but this was not to be. It turns out that hot glue doesn't stick to brass panels. I'm not sure why – it may be that the brass acts as a heat sink and the glue cools down too fast – but the reason doesn't matter. Not stuck is not stuck, whatever the excuse. The solution was to use double-sided VHB (very high-bond) adhesive tape with an acrylic foam core (**https://amzn.to/2yJ8wLY**). We stick this to the brass panel and then use hot glue to attach the ring to the tape (Fig.1 shows the tape attached to the panel; its red protective covering is removed before deploying the hot glue).

Oh no, my LED is dead!

So, wearing my trusty ESD wrist strap, which is grounded along with my ESD pad upon which everything rests, I powered-up my rings to make sure all the LEDs worked. Next, I turned them off and attached them to the panel, as illustrated in Fig.1. Then I powered them up again and tweaked them until they were positioned as required.

In the past, I've powered things down before applying the hot glue, but – for some reason – I neglected to do so on this occasion. I hot-glued the first ring and then took a look at the front of the panel. Eeek! Its first LED was extinguished, while all the others continued to glow. I cycled the power, but now none of the LEDs lit up. Since the NeoPixels are daisy-chained together, this is symptomatic of the first LED being dead, but what could have caused its demise?

A bit of a conundrum

My first thought was that hot glue might be conductive in its molten state, but I tested a blob with my trusty multimeter and saw 'infinite' resistance. I also probed the tip of the hot glue gun, only to discover that it's electrically isolated from the rest of the world, including the gun's power supply.

I talked about this problem with some of my chums. Rick Curl in Birmingham, Alabama, USA, noted that his company had experienced problems with LEDs. As Rick told me, 'It finally dawned on me that those labels on the LED packages that say, 'bake if the humidity is above 40%' might be there for a reason. From what I understand, moisture can seep into newer LED plastic packages. When they are heated the moisture can turn to steam, which damages the chips.' Rick says once they started storing their LEDs in a toaster oven at 100°F, all their problems went away.

Who knows? But…

At the end of the day, I have no idea what exactly caused this mishap to occur. My own theory is that having the NeoPixels lit up while applying the molten glue thermally overloaded the chip. All I know is, from that time onwards, I always power-down my LEDs before slathering them with hot glue, and – touch wood – I haven't experienced this problem since.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is editor-in-chief at **EEWeb.com** – the go-to site for users of electronic design tools and askers of electronic questions.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

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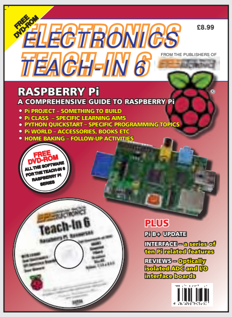

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By Jake Rothman

GULP amplifier-speaker combo – Part 2

Last month, I introduced my ideas for a combo practice/studio/synth amplifier and speaker. Now we'll turn to the circuit details and construction.

Discrete circuit

The block diagram and general architecture of the amplifier circuit is shown in Fig.12. The complete circuit, shown in Fig.13, uses all standard components and can be scaled to provide for different power outputs, load impedances and supply voltages. The output stage is interesting in that it has a voltage gain of 3.7 set by the feedback network R11 to R14. This is necessary to ensure the voltage amplifier stage transistor (TR4) can fully saturate the output transistors. In Hi-Fi amplifiers, voltage gain in the output stage is regarded as a bad idea because it increases distortion. The lower drive voltage requirement of the output stage of my design also allows a reduced maximum voltage swing from the driver. This allows the voltage drop from the current sink and decoupling network (C9 and R20) to be accommodated. This reduces distortion and

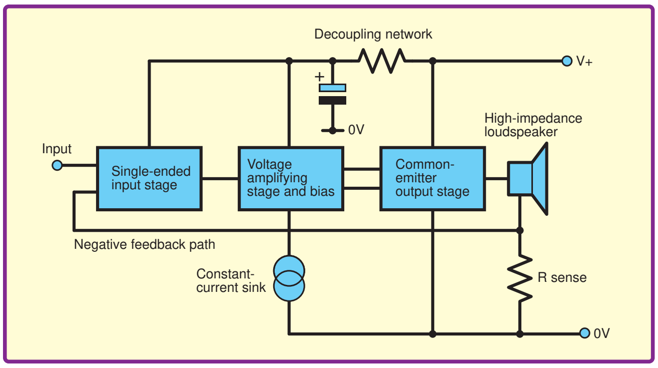

Fig.12. The General Ultra-Low-Power (GULP) amplifer's block diagram, showing the current-sensing topology.

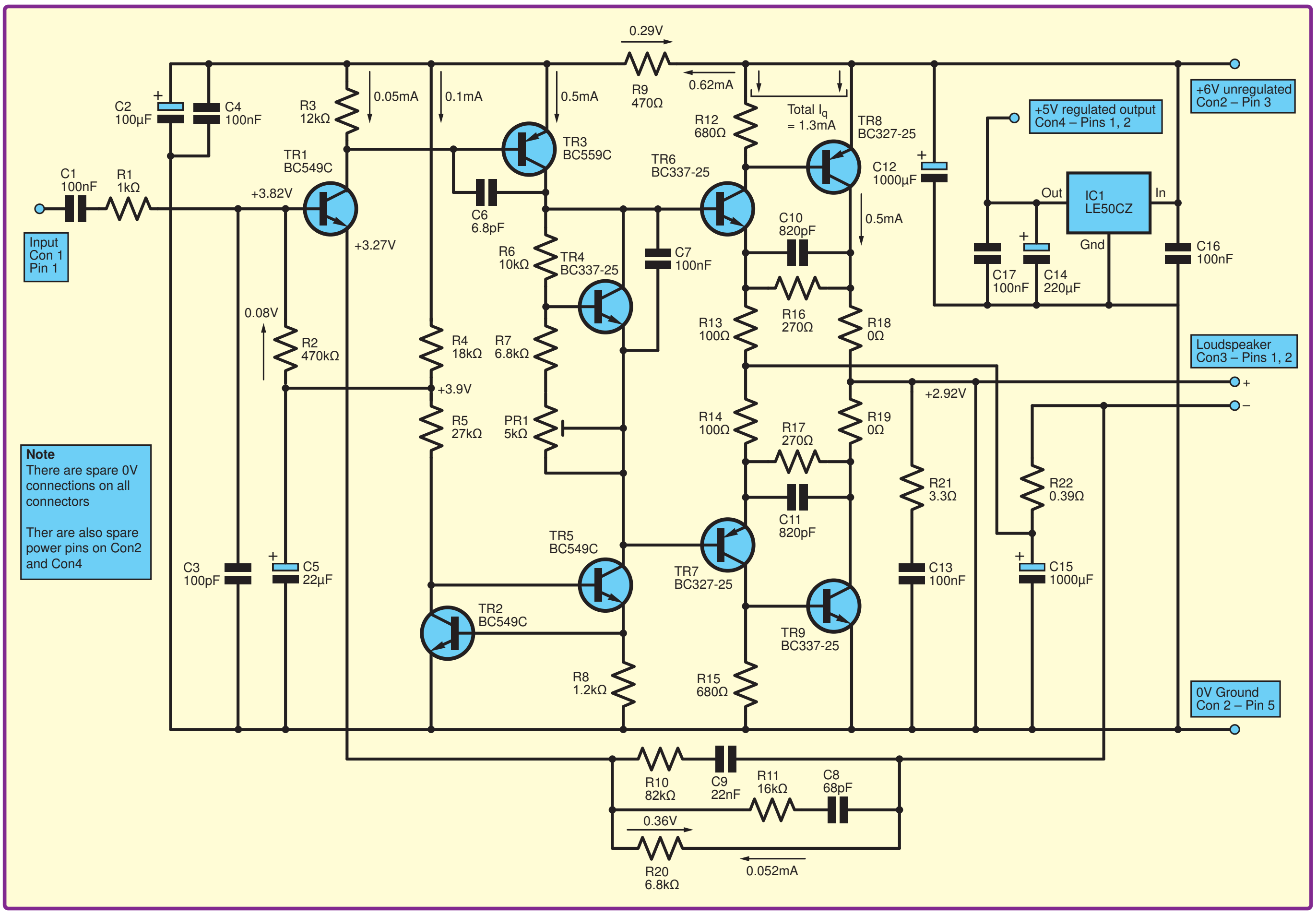

Fig.13. The GULP discrete amplifier circuit. High parts count, but cheap and easy to modify. The circuit operates with an almost rail-to-rail output swing, only limited by the saturation voltage (V_{sat}) of the output transistors.

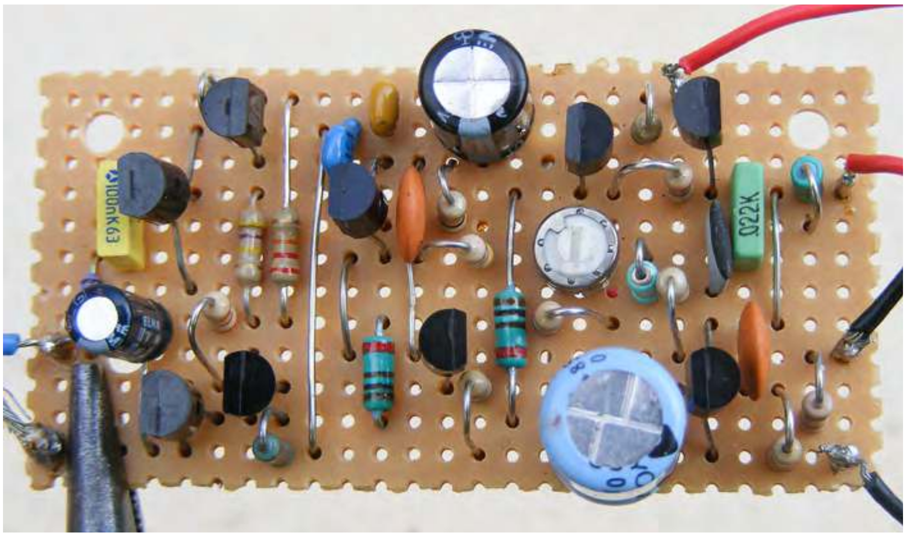

Fig.14. I used to build this design on Veroboard and developed a very compact layout.

enhances stability, a feature normally not available on chip amplifiers.

The loudspeaker DC blocking capacitor (C15) does two other jobs. It doubles as the lower-arm feedback capacitor of the output stage feedback network, and also avoids one in the gain-determining overall feedback network (as regular readers know, I abhor electrolytic capacitors, so this gets rid of two).

Unusually, no emitter resistors are used here with the output transistors (TR7 and TR9). Not using these resistors maximises output, which will be about 5.5V peak-to-peak with 6V on the rail. (In this design, the output swings to within two saturation voltages ($2V_{sat} \approx 0.5$V) of the power rail.) Thermal runaway is unlikely to occur with the low supply voltage used. Into an 8Ω speaker, around 300mW should be obtained, although the amp will draw about 80mA at this level. Unless the batteries are fresh this could cause a pitch droop as notes are played. The solution is to turn the volume down or use a higher impedance speaker to reduce the power and current draw. The driver stage uses a constant current sink (TR3) to prevent supply variations upsetting the critical I_q bias set by V_{be} multiplier TR5. To save power, the DC bias chain (R4 and R5) current also biases the constant current source via TR2. The current sink is the two-transistor feedback type, which can be run at lower currents than the usual single-transistor variety. There is only one input transistor (TR1), rather than the normal long-tailed pair, which has higher distortion and is not suitable for dual-rail systems because of DC offset. This arises as a result of its emitter current flowing through feedback network R16. Here this is of no consequence, R5 or R4 can simply be adjusted to get symmetrical clipping.

The feedback network incorporates a bit of bass boost from R18 and C6, and also current feedback via R17 from sense resistor R22 to reduce speaker damping. There is a loss of efficiency from this resistor, but it is made up by the reduced mechanical resistance from cone motion damping. It is well worth fiddling with these components to optimise them for a particular loudspeaker. This is where electronics moves from physics to art.

There are the usual high frequency stabilisation capacitors: C2 providing input high-frequency filtering; C11 providing phase-lead compensation; C10 is the V_{be} bypass; C6 sets the dominant pole and finally C5 is part of the Zobel network. There are a lot of components for a low-power amp, but they all cost peanuts.

Transistor choices

For low-current amplifiers, using transistors with high H_{fe} of around 400 minimises power consumption because the current in the various stages can be reduced to an absolute minimum. Hence, for TR1 and TR4 I have specified C grade components (the highest H_{fe} group). The driver and output transistors are specified as

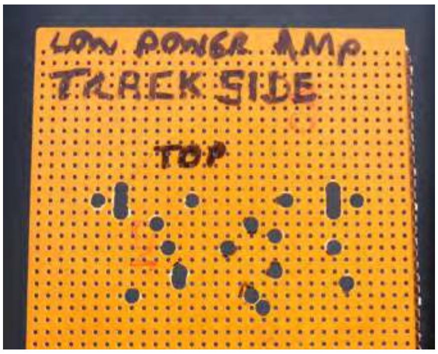

Fig.15. To drill the track breaks accurately when making multiple Veroboard layouts it is worth making a template.

'-25' grade (ie, BC337-25), which have higher gain than an ordinary BC-337. If you can get the '-40' grade (ie, BC337-40), so much the better. If you want to spend more than 5p on the output transistors, you could go for some of the 'Super E line' range of ZTX transistors and you might get 0.2V more output swing. If you want to scale up to a few watts, then you could use small power transistors at the output (TR8 and TR9), such as the BD135 and BD136, with heatsinks, and a 4Ω speaker. You would then have to go mains powered or switch to a big rechargeable battery.

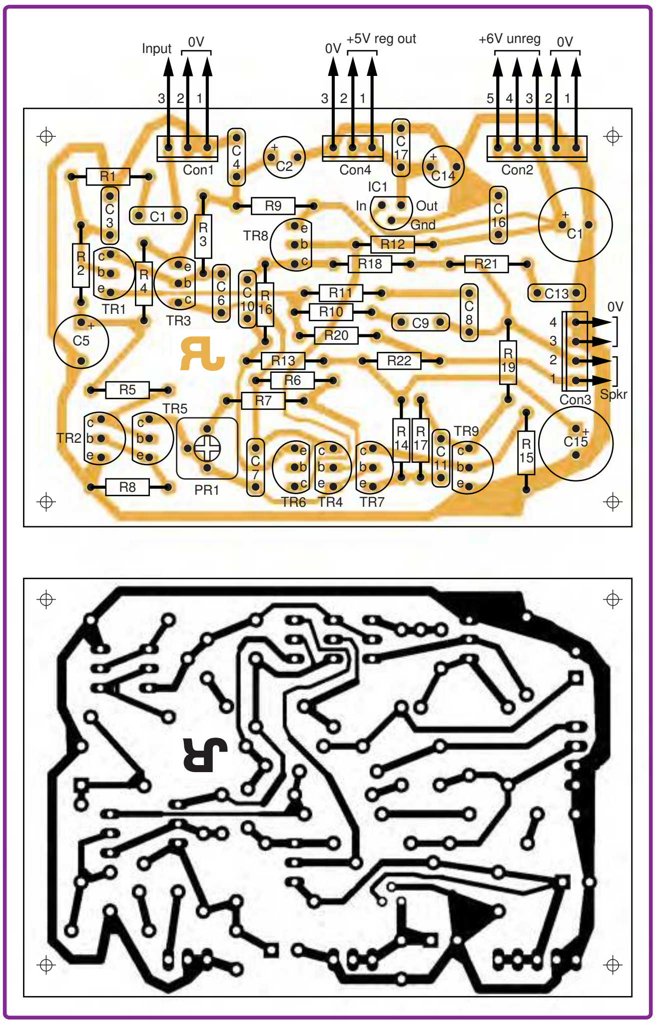

Fig.16. GULP discrete amplifier circuit PCB layout.

Fig.17. Completed GULP discrete amplifier circuit PCB.

Construction

The original Veroboard version of the circuit is shown in Fig.14 – I'm only showing you it because I was rather proud of it! (I even made a template for drilling the track breaks, as shown in Fig.15.) If you opt for Veroboard construction, remember to use 60/40 leaded solder, since the modern Euro stuff won't wet the untinned copper strips. (It is possible to buy tinned stripboard from Rapid and Tayda.) Clearly though, the best approach is to use a PCB (Fig.16) where it's possible to do things that are too fiddly on Veroboard. An example is the thermal linking of the driver transistors TR6 and TR7 with the I_q-controlling transistor TR4. This will keep the I_q low as the amp warms up. I went overboard and did the winding trick with tinned copper wire to bind them together. I was surprised to find the PCB ended up bigger than the Veroboard. If I had gone double-sided with the PCB it would have been a lot smaller, but I wanted to keep PCB construction DIY friendly. The final PCB assembly is shown in Fig.17.

Extra bits and mods

It seemed sensible to put the voltage regulator for the synth on the PCB since that is where the highest currents are. I would have liked to put on some extra sockets such as aux line in, headphones and 2.1mm power in. However, I decided a separate board for these would be a better idea, because it would be useful for other things – I'll design one soon. I would also like to add USB power in, but since it only supplies 5V there will not be enough headroom for the voltage regulator. It should be possible to use a 4.5V regulator such as the LE45CD-TR and tweak the synthesiser VCO and keyboard circuits to operate at this voltage, or you could simply use a boost regulator. This will also be necessary if rechargeable cells are used, which are only 1.2V each; a common configuration of four of these would only provide 4.8V.

There is provision for some extra components on the PCB which aren't used for this design, but will be necessary for larger, slower output transistors, such as the BD436 and BD437. First, you could add emitter resistors (R18 and R19), which are currently zero-ohm links, but may be needed if I_q is increased for higher power. These should be around 0.22Ω to 0.47Ω. Also, the compensation capacitors – C6 around TR4 and the feedback capacitors C8, C10 and C11 – may need to be increased. It's worth checking for high frequency oscillations with a scope, especially near clipping with some particular loudspeakers. It's best to do this at fairly low frequencies of around a few 100Hz. Using high impedance speakers of say 32Ω, 50Ω or even 80Ω and a PP3 9V battery, it is possible to get the I_q down to about 1mA and peaks to around 15mA. This was employed in some ultra-long-battery-life BBC Radio 4 longwave receivers I designed for use in bathrooms and bedrooms.

That's it, a fun and thoroughly useful combo that won't break the bank or damage your hearing!

Components

Semiconductors

IC1 LE50CZ low drop-out 5V positive regulator

TR1, TR2, TR5 BC549C high-gain NPN

TR3 BC559C high-gain PNP

TR4, TR6, TR9 BC337-25 medium-power NPN

TR8 and TR7 BC327-25 medium-power PNP

Fig.18. Rear view of the recommended new driver – Celestion Eight 15 driver.

Fig.19. Celestion Eight 15 driver – the lightweight ribbed cone is clearly apparent.

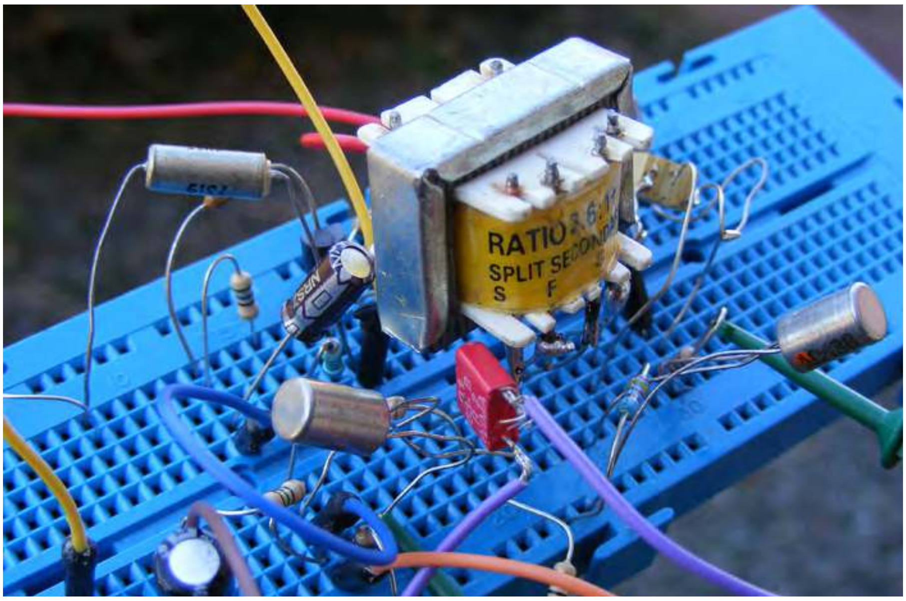

Fig.20. I did try building a breadboard of the germanium amplifier out of historical interest. The distortion was clearly audible and the £5 phase-splitter transformer limited the bass response to –6dB at 150Hz. Good for a radio with minimal parts count).

PCB
The design for the PCB is available for download from the *EPE* website.

Resistors
All 0.25W 5% carbon film CR25

R1 1kΩ	R2 470kΩ
R3 12kΩ	R4 18kΩ
R5 27kΩ	R6 10kΩ
R7, 20 6.8kΩ	R8 1.2kΩ
R9 470Ω	R10 82kΩ
R11 16kΩ	R12, R15 680Ω
R13, R14 100Ω	R16, R17 270Ω

R18, R19 zero-ohm links
R21 3.3Ω
R22 0.1Ω to 1.8Ω proportional to speaker impedance used. From 4Ω to 50/80Ω: 0.22Ω for 8Ω, 0.39Ω for 15Ω, 1.8Ω for 50Ω

Preset potentiometer
PR1 5kΩ TO5 trimmer

Capacitors
All 5mm lead spacing

C1 100nF polyester
C2 100µF
C3 100pF ceramic disc
C4, C7, C13, C16, C17 100nF ceramic disc
C5 22µF
C6 6.8pF ceramic disc
C10, C11 820pF ceramic disc
C12, C15 1000µF 6.3V
C14 220µF 6.3V.

Connectors
All Molex-style 0.1-inch PCB headers and housings

Con1, Con4	3-way
Con3	4-way
Con2	5-way

Loudspeaker
Light, paper cone design with paper corrugations around edge. Choose low-power, high-sensitivity 8Ω to 50Ω impedance depending on power required. 5-inch to 8-inch size (old radio speakers can be ideal). The Celestion Eight 15 is a good choice, available from: **www.Lean-Business.co.uk**

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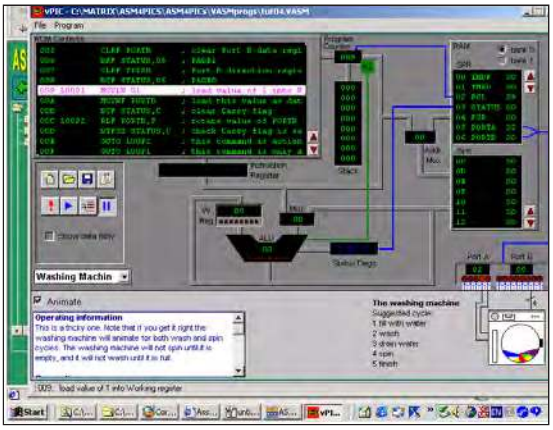
- Tests, exercises and projects covering a wide range of PICmicro MCU applications
- Includes MPLAB assembler
- Visual representation of a PICmicro showing architecture and functions
- Expert system for code entry helps first time users
- Shows data flow and fetch execute cycle and has challenges (washing machine, lift, crossroads etc.)
- Imports MPASM files.



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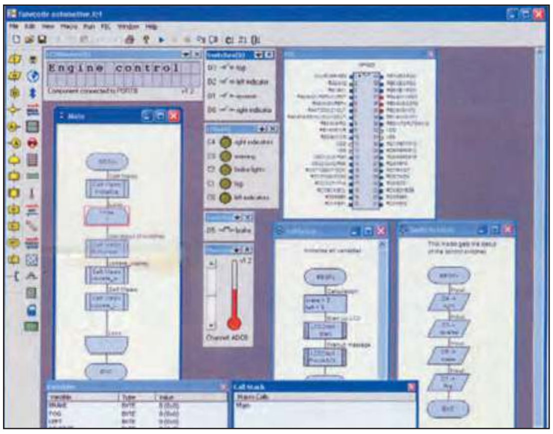

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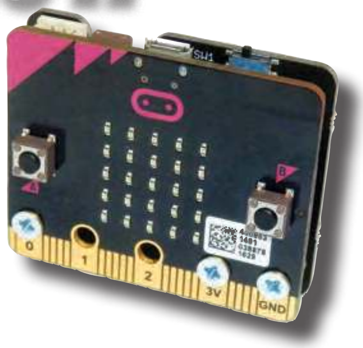

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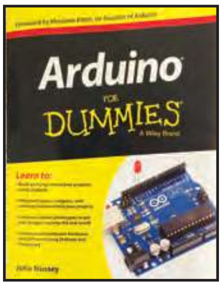
Teach-In 2016
Exploring the Arduino



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John Nussey

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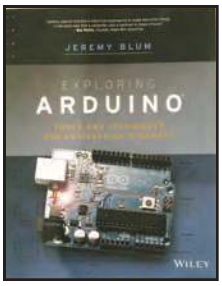

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Jeremy Blum

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Exploring Arduino shows how to use the world's most popular microcontroller to create cool, practical, artistic and educational projects. Through lessons in electrical engineering, programming and human-computer interaction this book walks you through specific, increasingly complex projects, all the while providing best practices that you can apply to your own projects once you've mastered these. You'll acquire valuable skills – and have a whole lot of fun.

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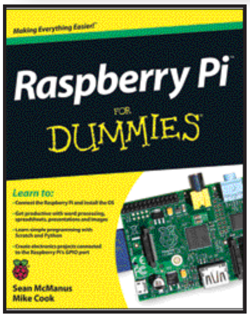

RASPBERRY Pi FOR DUMMIES
Sean McManus and Mike Cook

Write games, compose and play music, even explore electronics – it's easy as Pi! The Raspberry Pi offers a plateful of opportunities, and this great resource guides you step-by-step, from downloading, copying, and installing the software to learning about Linux and finding cool new programs for work, photo editing, and music. You'll discover how to write your own Raspberry Pi programs, create fun games, and much more! Open this book and find: What you can do with Python; Ways to use the Raspberry Pi as a productivity tool; How to surf the web and manage files; Secrets of Sonic Pi music programming; A guide to creating animations and arcade games; Fun electronic games you can build; How to build a 3D maze in Minecraft; How to play music and videos on your Raspberry Pi.

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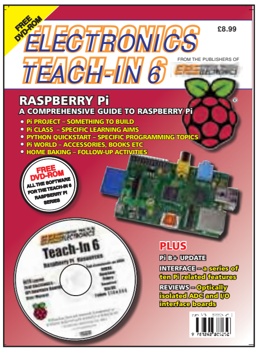
ELECTRONICS TEACH-IN 6



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Mike & Richard Tooley

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Anyone considering what to do with their Pi, or maybe they have an idea for a project but don't know how to turn it into reality, will find Teach-In 6 invaluable. It covers: Programming, Hardware, Communications, Pi Projects, Pi Class, Python Quickstart, Pi World, Home Baking etc.

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Mike & Richard Tooley

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The Arduino offers a remarkably effective platform for developing a huge variety of projects; from operating a set of Christmas tree lights to remotely controlling a robotic vehicle through wireless or the Internet. Teach-In 8 is based around a series of practical projects with plenty of information to customise each project.

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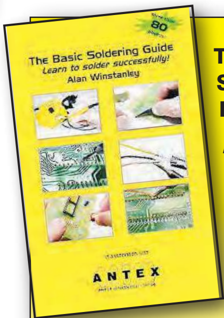

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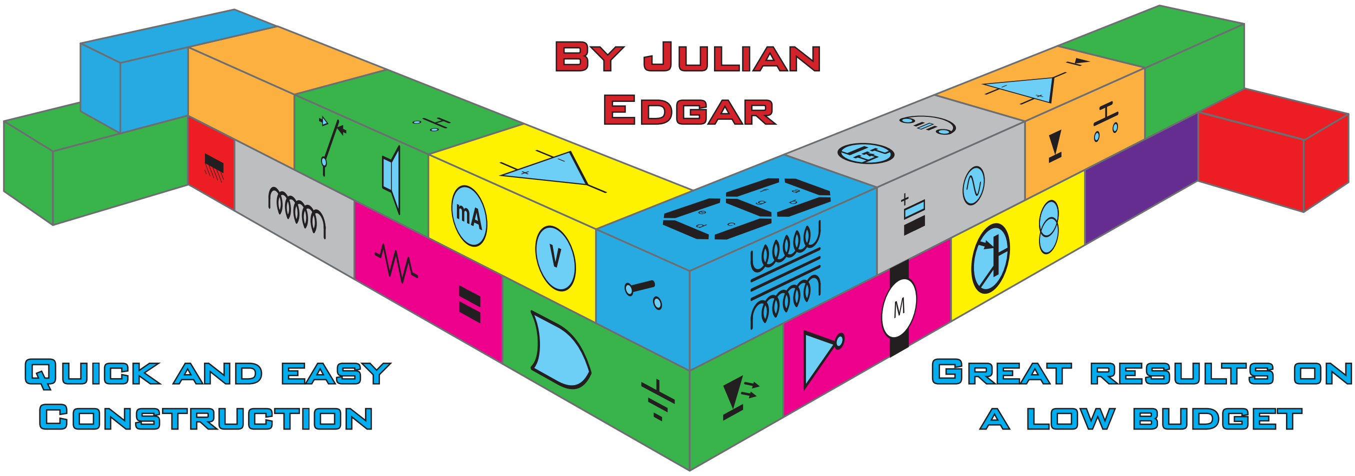
Electronic Building Blocks



By Julian Edgar

Quick and easy construction

Great results on a low budget

DC Motor Speed Controller

Large complex projects are fun, but they take time and can be expensive. Sometimes you just want a quick result at low cost. That's where this series of *Electronic Building Blocks* fits in. We use 'cheap as chips' components bought online to get you where you want to be... FAST! They represent the best value we can find in today's electronics marketplace!

On paper, this *DC Motor Speed Controller* really looks the goods. An ability to work from 6-60V at a current of up to 30A, the panel-mount controller also has a pre-wired speed adjustment pot and a latching press-button on/off switch. Even better, the large LED display shows output duty cycle, from 0-100 per cent. At under £7 delivered, what's not to like?

Well, I am here to tell you that in fact there are a few things wrong with that! But if you take those shortcomings into account, it's still a potentially very useful bit of kit.

Good news...

First the good news. The controller requires a panel cut-out of 90 × 55mm and uses a display that's about 15mm high. Duty cycle is shown to the whole number (eg, 54%) although, oddly enough, the display not only has a % symbol printed on it but also 'rpm' – the latter is erroneous and can be ignored.

Connections are easy – just power and ground, and the output to the motor. The screw terminals are of just the normal type (ie that 30A current rating is starting to look a bit sick!) and the pot and switch are on flying leads about 170mm long. The light aluminium case is used as a heatsink for the output devices.

This motor speed controller comes in a panel-mount display, complete with on/off pushbutton switch and speed control potentiometer and knob.

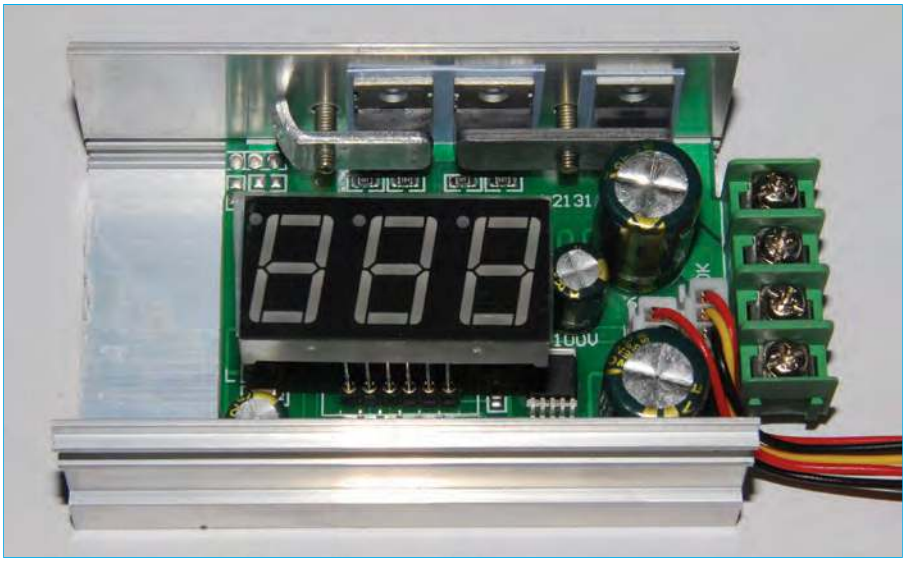
The device – with a measured PWM output frequency of 15.4kHz – controls the speed of a DC motor well. Turn the knob clockwise and the motor gets faster; anticlockwise and the motor can be slowed smoothly to a stop.

...but!

Now, the not-so-good news. There is no speed regulation built in and so as the motor load changes, so does motor speed. Also, rather oddly, the displayed duty cycle is not accurate. Set the output to (say) 60% and a direct multimeter measurement reveals an actual value of 50%. But then change the input voltage to the controller and the error also changes – so error varies with input voltage!

Something too good to ignore!

The next time that you're building a piece of mains-powered equipment, rather than including a pilot light, why not use this AC voltmeter instead? It fits into a 22mm diameter hole and projects rearwards from the panel by 37mm. The front lens is 30mm in diameter. The 7mm high-output red LEDs are bright and clear, and the meter reads from AC 20-500V. The sample unit was within 1V of a recently calibrated multimeter. Cost? Depending on if it's on special, just £2-3, including delivery. This one came from **www.banggood.com** – ID 1225545, or search under 'Machifit AD16-22V 22mm Digital AC Voltmeter AC 20-500V Voltage Meter Gauge Digital Display Indicator'; blue, yellow and green versions are also available.



The output devices use the module's thin aluminium case as the heat-sink. Maximum real-world useable output power is about 120W. It's best suited to low current, higher voltage DC motors like those used in hand engravers and similar.

Now, what about that current rating? Running the controller at 24V and drawing 7A (ie, a power level of about 170W), the thin aluminium case becomes hot – too hot. However, dropping the current draw to 5A results in a case temperature that would be sustainable. (You could easily add extra heatsinking, but that rather misses the point of buying a complete controller in the first place!) Based on this testing, I'd suggest about 120W is the maximum power the controller should be rated at.

So where does that leave us? If you want to control a high-current DC motor at higher voltages, forget it. But that still leaves some effective uses for the unit. The controller is ideal for manually controlling the speed of a 12V DC fan, or of a high-speed 24V or 36V DC motor being used in a tool like a hand engraver. Just don't expect to provide 30A at high voltages!

To find it, search **www.banggood.com** under 'DC 6-60V 30A Speed PWM Controller Adjustable Motor Controller with Digital Display', or Banggood ID 1289892. Alternatively, use eBay – item 382624788666, or search for 'DC6-60V 12V 24V 36V 48V 30A PWM DC Motor Speed Controller.

Next month

In February 2019's *Electronic Building Blocks* we'll look at a really versatile and useful *DC Panel Meter*. Not only can it read DC voltages up to 75V, it can also measure current up to 10A.

PCB SERVICE

CHECK US OUT ON THE WEB

Basic printed circuit boards for most recent *EPE* constructional projects are available from the *PCB Service*, see list. These are fabricated in glass fibre, and are drilled and roller tinned, but all holes are a standard size. They are not silk-screened, nor do they have solder resist. Double-sided boards are **NOT plated through hole** and will require 'vias' and some components soldering to both sides. **NOTE: PCBs from the July 2013 issue with eight digit codes** have silk screen overlays and, where applicable, are double-sided, plated through-hole, with solder masks, they are similar to the photos in the relevent project articles.

All prices include VAT and postage and packing. Add £2 per board for airmail outside of Europe. Remittances should be sent to **The PCB Service, Everyday Practical Electronics, 113 Lynwood Drive, Merley, Wimborne, Dorset BH21 1UU. Tel: 01202 880299; Fax 01202 843233; Email: fay.kearn@wimborne.co.uk. On-line Shop: www.epemag.com**. Cheques should be crossed and made payable to *Everyday Practical Electronics* **(Payment in £ sterling only)**.

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Next Month

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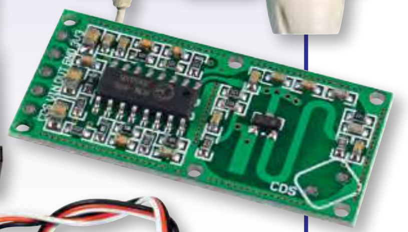


1.5kW Induction Motor Speed Controller – Part 2

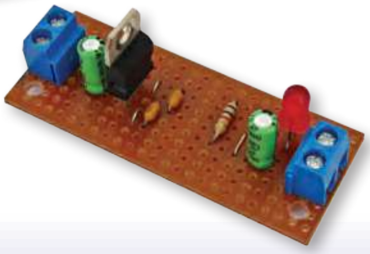
We've described the features of the *1.5kW Induction Motor Speed Controller* and explained in detail how it works. Next month, we describe its construction and testing and give some guidelines for use.

Arduino Mega Box Music Player

Combine an Arduino MP3 player shield with the Altronics Mega Box, along with our software, to make a neat little music or audio player with endless possibilities.

Low-cost Electronic Modules – Part 13

Next month, we look at two low-cost modules from Elecrow. One is a motion sensor which uses microwave Doppler radar technology rather than passive IR sensing. The other module is designed to sense the soil moisture level in a garden or pot plant. Both modules can be easily interfaced with an Arduino or Micromite device.



Teach-In 2019 – Part 3

In the February issue, we'll explore linear voltage regulators, including two *Practical Projects*. The first is a simple 1A fixed-voltage supply module; the second features a handy low-cost bench power supply, which is ideal for testing your projects with an output that's fully adjustable from 1.5V to 13.5V and a current-limited supply of 600mA.

PLUS!

All your favourite regular columns from *Audio Out* and *Circuit Surgery* to *Electronic Building Blocks*, *PIC n' Mix* and *Net Work*.

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Published on approximately the first Thursday of each month by Electron Publishing Ltd., 1 Buckingham Road, Brighton, East Sussex, BN1 3RA. Printed in England by Acorn Web Offset Ltd., Normanton, WF6 1TW. Distributed by Seymour, 86 Newman St., London W1T 3EX. Subscriptions INLAND: £25.00 (6 months); £47.00 (12 months); £89.00 (2 years). EUROPE: airmail service, £30.00 (6 months); £56.00 (12 months); £107.00 (2 years). REST OF THE WORLD: airmail service, £37.00 (6 months); £70.00 (12 months); £135.00 (2 years). Payments payable to "Everyday Practical Electronics", Subs Dept, Email: fay.kearn@wimborne.co.uk.

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