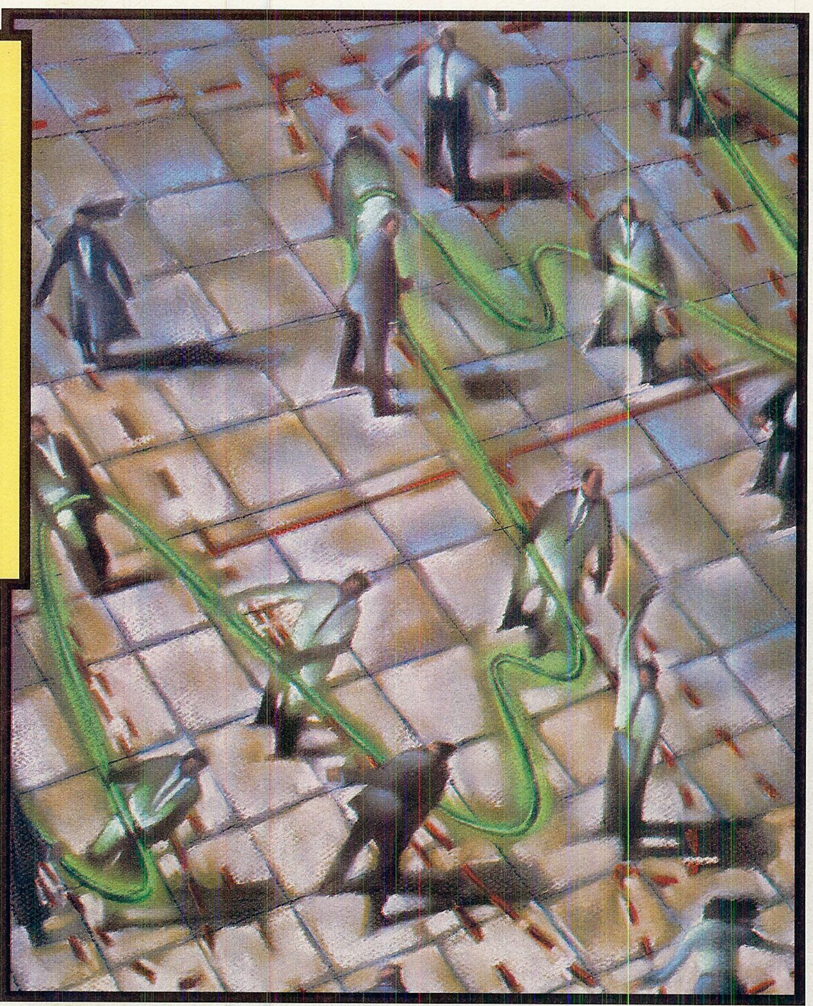
Paul Bennett's three-phase power inverter uses high-frequency switching to avoid the bulky and expensive inductive components associated with non-switching 400Hz inversion.



400Hz inverter

This design is for a three-phase 400Hz inverter for running 200V aircraft equipment from a normal 230V mains supply. High-frequency techniques are used, i.e. there are no 400Hz magnetics or other special components. Each phase is separately regulated and isolated from the mains, output neutral being connected to earth. Maximum output is around 1kVA, about 3A per phase.

Input converter

This design divides into two parts – the mains input converter and the three phase output bridge.

For the input side, a half-bridge forward converter is used, sometimes called an asymmetric half bridge. This provides two outputs, ±200V either side of ground. Only the positive side is sensed for regulation. Acceptable regulation is achieved for the negative output by cross coupling the smoothing inductors.

Mains supply is filtered, rectified and smoothed. A thermistor with a negative temperature coefficient provides inrush limiting. Two igbts are used for the switching transistors, type *IRGP440U* from International Rectifier[1]. These are 500V die-size 4 types but size 3 or above, 500 or 600V ultra-fast types should prove satisfactory. Size 5 mosfets could also be used.

When igbts are used, a reverse diode across the transistor is needed to clamp any reverse voltage transient. The devices are rated for some reverse voltage, but at unrealistically low current for most power-switching applications. A fast turn on diode should be used such as a slow or moderate reverse recovery speed type.

Generally with low voltage output switch mode power supplies, diode reverse recovery can be ignored. The resulting current spike at turn on of the power switches is very short and requires little energy.

As the output circuit impedance level increases with higher output voltages, the diode recovery transient becomes more significant – even with the latest ultra fast types. This can be tolerated, but it causes higher EMI, extra stress in the switch and diode, and fast current sensing problems.

The spike can be reduced by slowing the turn on of the power switch, but this increases losses. The technique I have used is a current snubber. This device slows down the current rise by placing an inductor in series with the switch.

At turn off, some energy is returned to the supply by the *BYW96C* diodes. The igbts now turn on at zero current and the current wave form is very clean.

Another bonus is that during output short circuits, such as with the output capacitors uncharged, the snubber lengthens the pwm duty cycle required. This reduces demands on the current limit speed and propagation delays.

Drive to the igbts is provided by an RM8 size transformer. The driver IC and *IN4148* diode network is effectively the same topology as the power converter. This arrangement ensures proper reset of the RM8 core every cycle under all conditions, including under current limit when the duty cycle may vary rapidly.

The pulse-width modulation IC is the popular voltage mode *SG3525A*, running at around 30kHz and 50% maximum duty cycle. Digital current limiting is employed which terminates the pwm on a pulse by pulse basis.

The *LM319* provides more accurate limiting than the *SG3525A*'s shut-down pin. An RM6 transformer senses current at the collector of the lower igbt. The current limit sets the inverter's maximum overall power output to around 1kW, giving a peak switch current of about 7A.

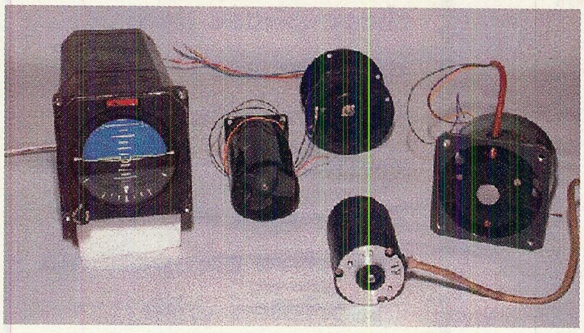
Output bridge

Design of the three-phase output bridge is conventional. It uses closed-loop pwm at 25.6kHz.

Three reference sine waves are generated by the crystal oscillator, counter/divider, eprom and d-to-a converter circuit. All three phases are identical, apart from a 120° and 240°

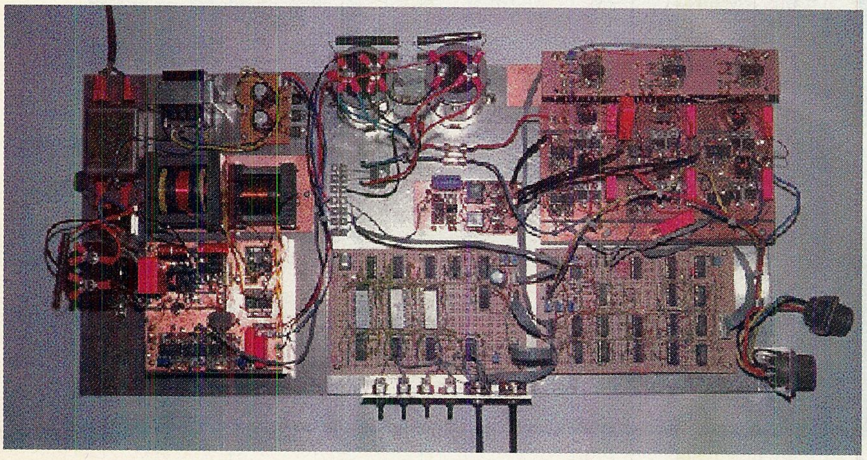
Warning
In addition to live mains, this circuit involves equally lethal dc voltages. Don't forget that high-voltage capacitors can hold lethal charges when the circuit is switched off too.

Packaged inverter



Artificial horizon and motors

Inverter breadboard



phase shifts encoded in the eproms.

The most significant address line is used to swap between two look up tables which swap the codes around for the A and B phases. This reverses the phase rotation.

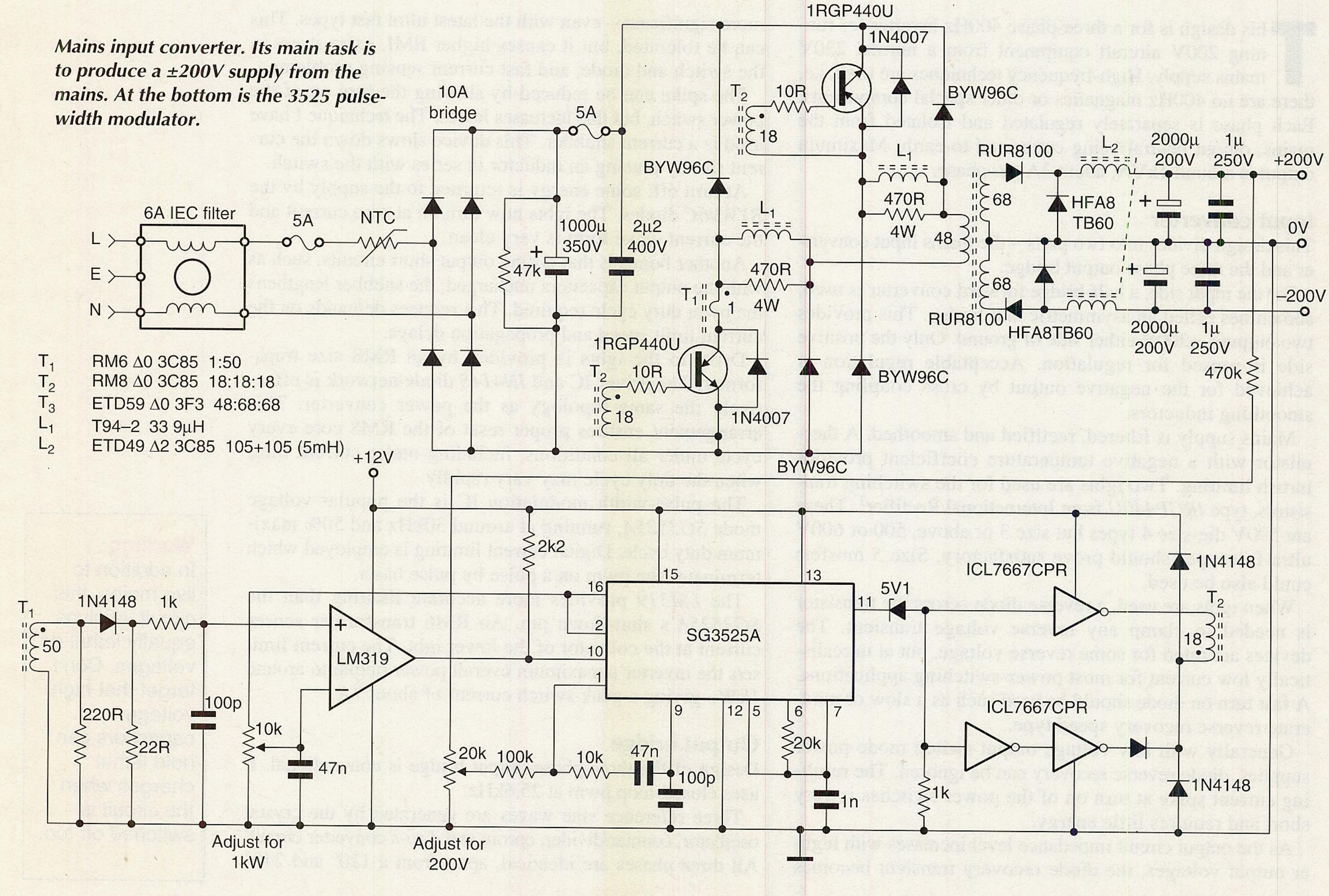
The algorithm used, in floating-point decimal, is:

```
A=INT(128*(1+SIN(2*PI*(X+0.5)/4096)))-0.5)
B=INT(128*(1+SIN(2*PI*(X+1365.83)/4096)))-0.5)
C=INT(128*(1+SIN(2*PI*(X+2731.17)/4096)))-0.5)
```

To check the rounding errors, etc., the resulting sine wave should look perfect with no flat on the peak or trough. The resulting code should contain equal numbers of 0s and 255s and change from 127 to 128 as the address changes from 2047 to 2048 for phase A.

The reference signal is compared to a sample of the output by an *LF347* op-amp. This modifies the reference to the pwm generator to remove any distortion in the output. I chose the compensation to give a good compromise between stability and transient response.

Mains input converter. Its main task is to produce a ±200V supply from the mains. At the bottom is the 3525 pulse-width modulator.



An *LM319* compares the modified reference to a 25.6kHz triangle wave derived from the crystal. Basic pwm is then modified by the monostables to give two outputs including some dead time to avoid cross conduction in the bridge.

The modified reference is not bounded to the triangular wave so the pwm could saturate positive or negative. This is undesirable as the bridge current is sensed with transformers which cannot pass dc.

To prevent total saturation addition pulses are added to the pwm by the NAND gates. Current limiting is achieved by terminating each pwm pulse on detection of over current at each switch. The 74HC74 bistable device is set by an over-current turning off both pwm drives. It is then reset twice each cycle at 51.2kHz.

As with the input converter igbts are used, type *IRGBC20U*. Other ultra-fast igbts, size 2 or 3, 500 or 600V, should prove suitable or size 4 mosfets.

Recovery problems

Diode recovery is potentially a bigger problem in pwm inverters, where the duty cycle swings close to 0 or 100%.

The snubber used in the input converter cannot be used as there is insufficient time for it to properly reset. Instead, after much experimentation, I simply limited the turn on speed by inserting a 100Ω gate resistor. A *1N4148* diode across this resistor makes sure that turn off is still as fast as possible.

Electromagnetic interference is not a significant problem as the converter is referenced to true ground. Gate drives are provided by high-speed opto couplers and buffer ICs. This means that four floating gate drive supplies are needed, provided by a simple dc-to-dc converter.

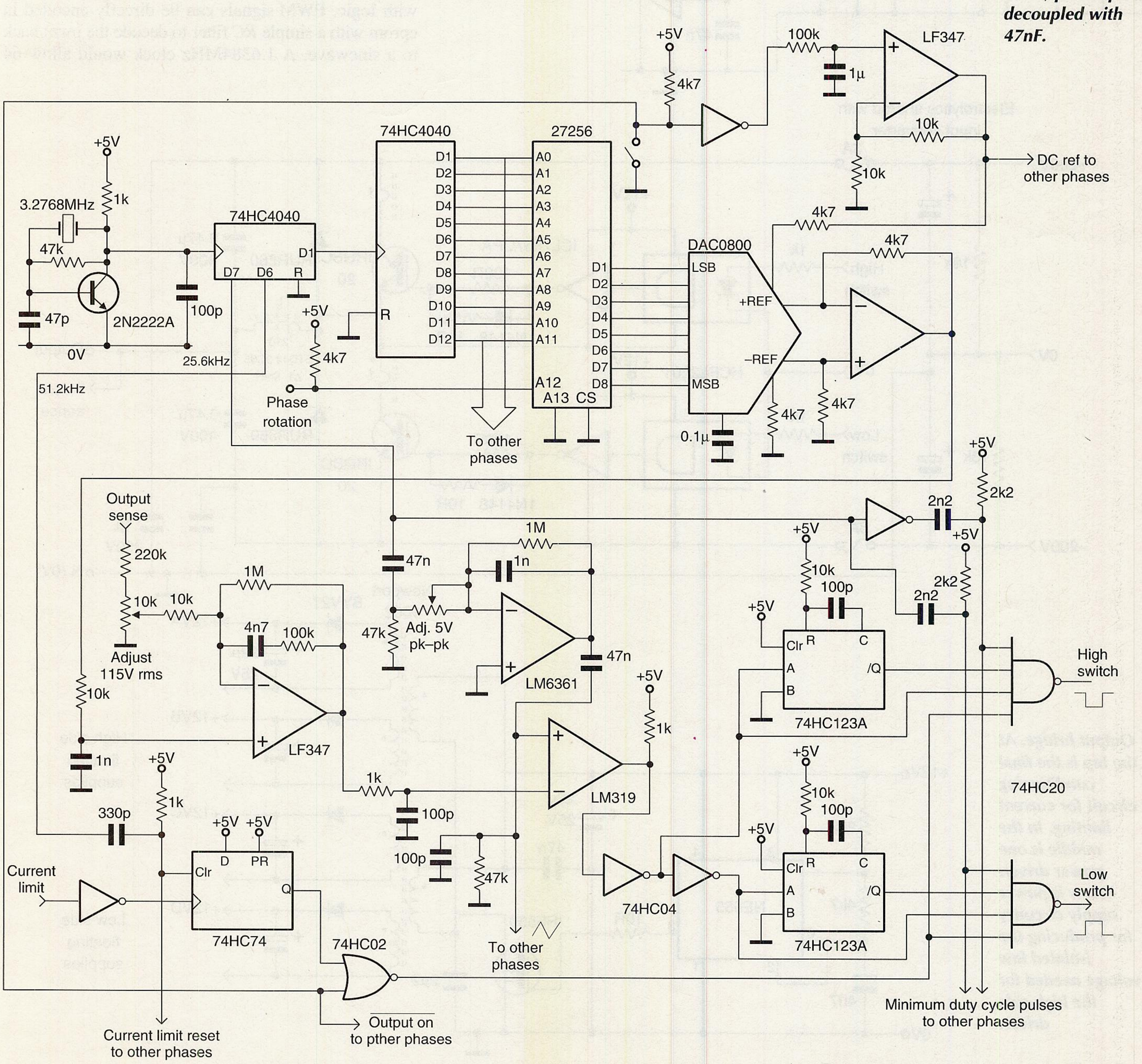
The low side switches use a common supply. Current sensing is by six RM6 size transformers. Each transistor is individually sensed so that all combinations of phase-to-phase and phase-to-neutral faults are protected against.

A single potentiometer sets the current-limit comparator references. This determines the overall kVA rating of the inverter and is set to approximately 5A for 3A rms output.

Output filtering

The output filter inductor and capacitor have to be chosen carefully and an exacting compromise is required.

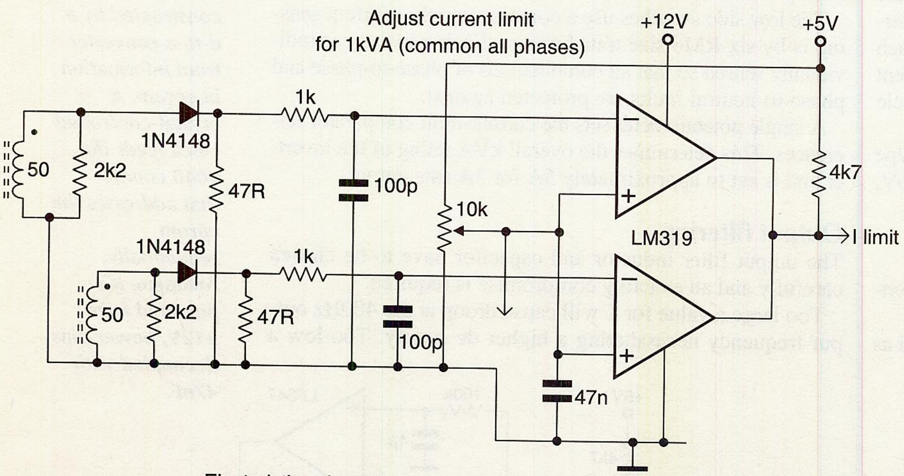
Too large a value for *L* will cause droop at the 400Hz output frequency necessitating a higher dc supply. Too low a



One phase of the intermediate driver circuitry. Sine-waves are constructed by a d-to-a converter from information in eprom. A crystal-controlled clock feeds the 4040 counter that addresses the eprom sequentially. Analogue ICs powered from ±12V, power pins decoupled with 47nF.

value will increase the peak transistor current and associated losses and output 25.6kHz ripple. Too high a value for *C* will increase circulating current inside the bridge legs, and again if the value is too low, 25.6kHz ripple will increase.

Further constraints are placed on *L* by available core sizes and materials. The values chosen just allow 115V output with 400V dc bus and give around 1.5V rms 25.6kHz ripple.



The complete inverter was spread out on an aluminium sheet ground plane then repackaged in a custom-made box.

A 12V 100ft^3/min fan was used for cooling with the ±12V and +5V supplies derived from *78/79* series regulators and a 12VA 50Hz transformer. Both converters have fuses between the converters and electrolytic capacitors.

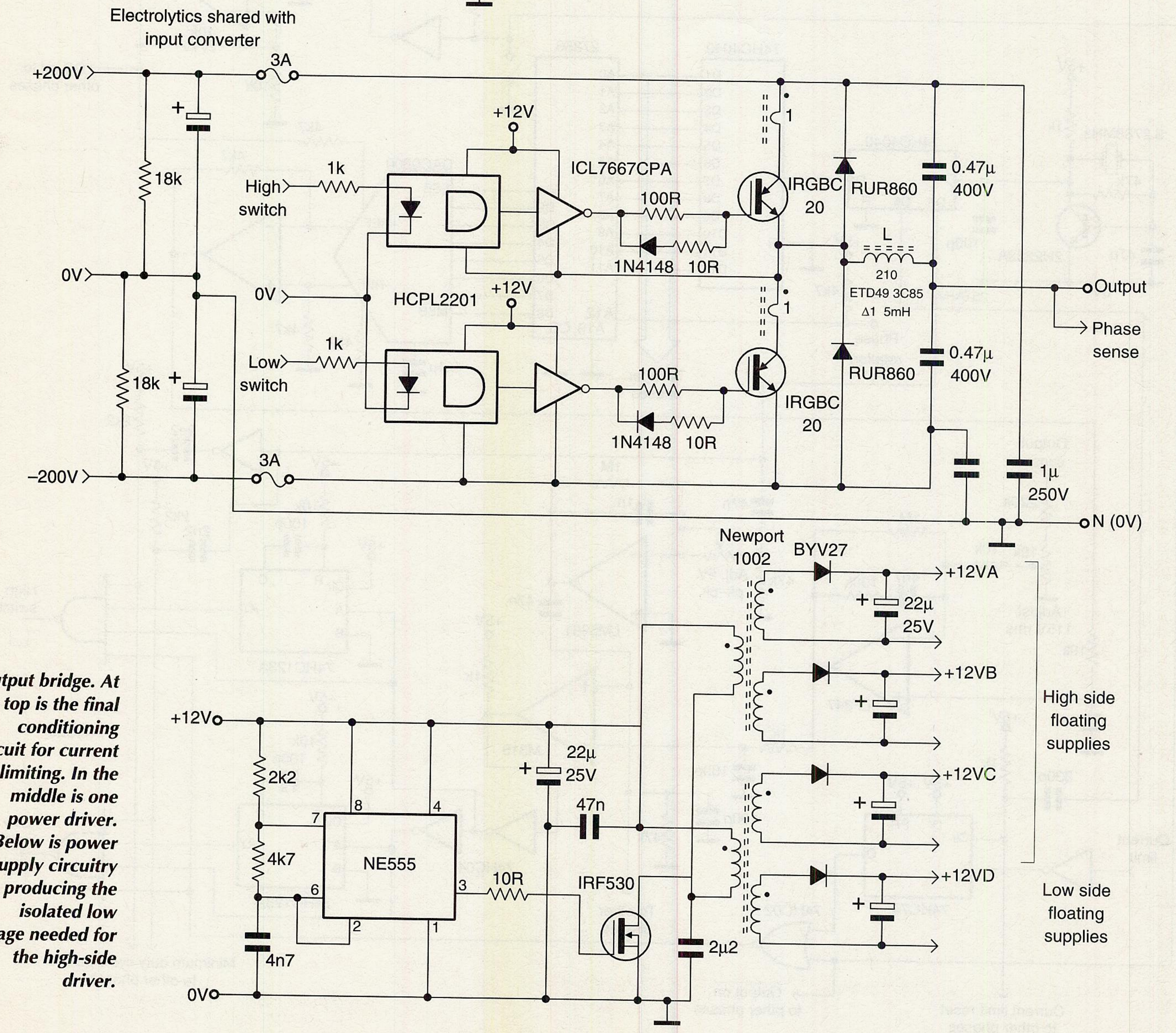
It is surprising how many commercial power switching designs have inadequate fusing. Without it, all manner of expensive blow-outs can occur.

Five neons indicate, mains present, intermediate dc voltage present and output phases on. The output was tested using various 400Hz loads, small fans and blowers, an artificial horizon and array of 115V 100W lamps.

Simplifications and enhancements

Various simplifications and enhancements appear possible. Numerous possibilities exist for the sine wave references, with perhaps reduced precision. One technique is to have a six-pole filter extract the fundamental from the 400Hz square wave.

Three 120°-spaced square waves are easy to generate with logic. PWM signals can be directly encoded in eprom with a simple *RC* filter to decode the pwm back to a sinewave. A 1.6384MHz clock would allow 64



Output bridge. At the top is the final conditioning circuit for current limiting. In the middle is one power driver. Below is power supply circuitry for producing the isolated low voltage needed for the high-side driver.

samples per 400Hz cycle with 65 levels. All six drive signals for the bridge could be encoded in eprom. This would reduce the component count significantly but would not allow closed loop waveform or voltage regulation. Only the overall output could be regulated by regulating the dc input.

Recently Micro Linear[2] has brought out a sine-wave reference generator IC series, the ML2037/8/9, and a simple three-phase pwm driver IC including sine reference, the *ML4423*. The former works well and is very flexible with regard to clock and output frequencies. Synchronising three at120° may be tricky or anologue means will be needed for the other phases. The *ML4423* proved less satisfactory with various stability and output purity problems. It is intended for low cost driving of three phase motors. Linfinity[3] has brought out an audio pwm controller for class D amplifiers.This is designed to drive two full bridges for stereo, and features closed loop and current limiting. Fully independent operation of each phase may be a problem but these should match the precision of the eproms with far fewer components.

My prototype included a little extra circuitry to offer 50Hz, variable frequency, variable amplitude and linear voltage-to-frequency operation for motor driving. Slightly more logic or different clock frequency could give 60Hz.

The output control loop may benefit from refinement for difficult loads. The system may even benefit from open-loop operation in some circumstances.

Various ICs are available for high side driving bridges. These would eliminate the need for the dc-to-dc converter and opto couplers. These may not be able to cope with the split rails about ground though. The *HCPL3120* and *HCPL3150* igbt opto-coupled gate drivers from Hewlett Packard[4] are simpler and cheaper than the *HCPL2201* and *ICL7667CPA* employed here.

The input converter needs little regulation, so a power-factor correction scheme could be added. This would do away with the electrolytic and surge suppressor. But it would also result in much higher peak currents in the input converter.

If the inverter only needs to run at one output frequency, say 400Hz, then a transformer could be used at the output. This could be wired delta/star fashion to produce a neutral and provide isolation. The three phase bridge could then work directly from rectified mains or the usual boost power-factor correction circuit.

Only one current sense per phase would be needed. The disadvantage would be getting hold of a suitable transformer.

Thanks to Chris Clarke for programming the eproms and to Graeme Penhorwood for taking the photographs. ■

References

1. International Rectifier, Hurst Green, Oxted, Surrey RH8 9BB, tel. 01883 713215.
2. Micro Linear, 2092 Concourse, Drive San Jose, CA 95131. Tel. 408 433-5200. Distributed in the UK by Ambar Components Ltd, tel. 01844 261144.
3 Linfinity Microelectronics, 11861 Western Ave, Garden Grove, CA.92841, tel +1 714 898 8121
4. Hewlett Packard Ltd, Amen Corner, Cain Road, Bracknell, Berkshire, RG12 1HN, tel. 01344 360000. Distributed in the UK by Farnell Electronic Components, tel. 0113 263 6311.