Cuk Converter

Georg Gerads

The operating principle of the Cuk Converter avoids the need for particularly exotic components. That means we can right away take the plunge with a 'heavy-duty' dc converter, which is ideal for use with fluctuating energy sources such as solar systems.

Personal Download for Prica, Ognjen | copyright Elektor

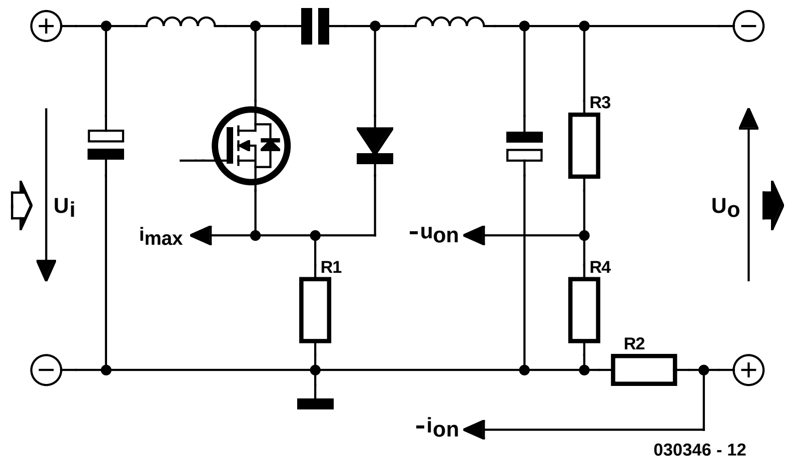


Figure 1. The input current, output current and output voltage can be measured as shown here.

Cuk Converter specifications

Type	Secondary-side switched-mode
Topology	CuK
Input voltage	20–45 VDC 18–35 VAC
Output voltage	0–100 V
Output current	0–5 A
Power	500 W
Continuous power	U_{in} = 35 V 500 W U_{in} = 30 V 400 W U_{in} = 25 V 300 W
Efficiency	> 85 %

The Cuk Converter[1] topology yields a theoretically infinite variety of currents and voltages. Consequently, all relevant parameters must be monitored, and conditions that could destroy the semiconductor devices used in the circuit must be avoided. The important parameters are the input current, the output voltage and the output current. **Figure 1** shows how these quantities are measured. The voltage across the source resistor of the switching transistor (R1) is used to limit the input current i_i and set the short-circuit protection level. The output voltage U_o is regulated by monitoring the voltage U_{on} obtained using voltage divider R3/R4, and the output current i_o is measured by simply inserting a sense resistor (R2) in the output lead.

Measurement circuitry power supply

U_{on} and i_{on} are negative with respect to ground, so the circuit requires a bipolar power supply. If the Cuk Converter is operated from a transformer, the negative supply voltage can easily be generated using the capacitor charge-transfer arrangement shown in **Figure 2**. Besides the bridge rectifier and smoothing capacitor, this requires two additional diodes and capacitors. Of course, the negative supply can only power a light load, but that's all we need here.

If the circuit is operated from a battery, the negative auxiliary voltage can be generated by using a simple charge pump to periodically transfer charge to and from a capacitor , as shown in **Figure 3**. In this case, the switch actually consists of an astable multivibrator followed by a power stage. The printed circuit board for the Cuk Converter is designed to accommodate both options and the unnecessary components can simply be omitted.

A control transformer with a secondary voltage of 24 VAC and a 500-VA power rating is a good choice for the power supply. Suitable types are readily available and quite inexpensive. Without a load, such a transformer will provide a voltage of around 35 V after rectification. This is also the upper limit for the input voltage of the two fixed voltage regulators.

Naturally, even higher secondary voltages can also be used. This improves the efficiency of the circuit, since the power stage can by operated with a smaller duty cycle and lower current levels. However, in this case you must do something to reduce the voltage at the regulator inputs, such as inserting Zener diodes in series with the input leads. These Zener diodes must be able to dissipate a rather hefty amount of power.

Bridge rectifier B1 also has to be able to dissipate a relatively large amount of power (as much as 15 W). The total thermal resistance to ambient for the high-power devices and heat sink should not exceed 1 K/W. It is recommended to fit the components to a heat sink, but if this is not possible, a small fan should be used.

Power section

The power section of the Cuk Converter (see **Figure 4**) corresponds to the block diagram in nearly all respects. Some of the components are present in duplicate or triplicate, in order to handle the rather high currents. The circuit's high-power switching element is formed by two power MOSFETs made by Ixys, a California-based semiconductor manufacturer (see www.ixys.com/deurope.html for distribution information). The type IXFK90N30 transistor can be used with drain–source voltages up to 300 V and currents up to 90 A (at 25 °C), and it has an integrated source–drain diode with a recovery time less than 250 ns. The 'on' resistance of the drain–source channel is specified as 33 mΩ in the data sheet. In principle, it is also possible to use IBGTs rated at 25 A (at 150 mΩ and 1.8 V).

Diodes D1 and D2 are DSEP60-06A epitaxial soft-recovery diodes from the same manufacturer. They have a specified reverse blocking voltage of 600 V and a forward current rating of 60–70 A. Although this type of diode switches extremely fast (with a recovery time of only 35 ns), it avoids the severe current spikes generated by fast-recovery diodes. If you wish to use a different type, ensure that it has a recovery time of less than 50 ns and a

[1] *For good measure we should mention that 'CuKonverter' is a trademark of the TESLACo company. Cuk is pronounced /chook/.*

Personal Download for Prica, Ognjen | copyright Elektor

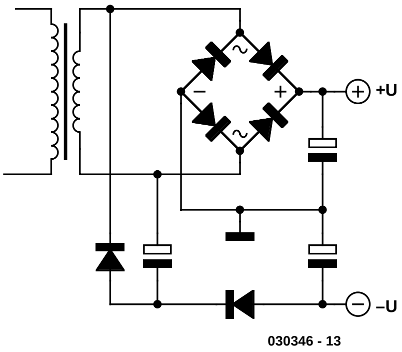


Figure 2. The negative auxiliary voltage can be generated by a capacitive charge-transfer circuit…

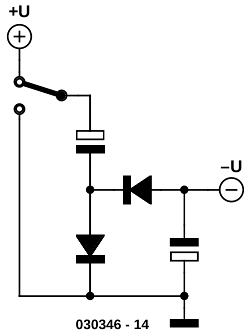


Figure 3. … or by using a simple charge pump.

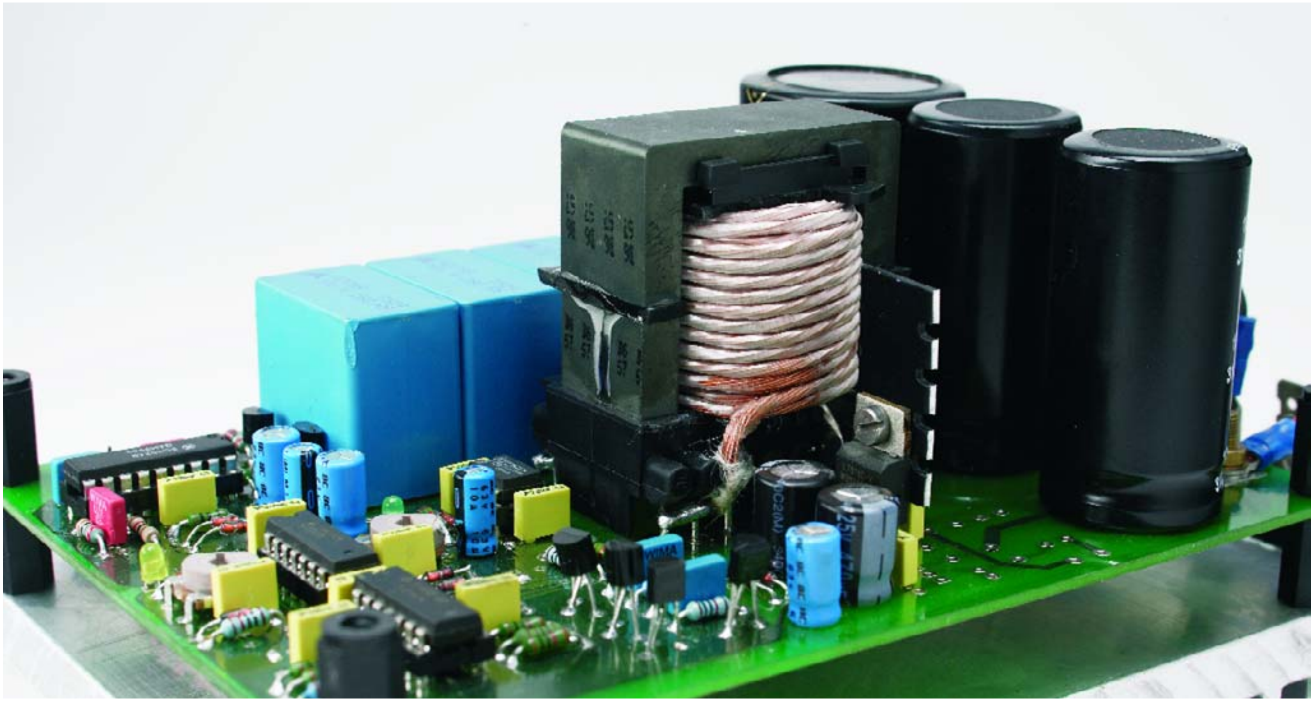
forward current rating of at least 30 A. The transistors and diodes must have a specified maximum breakdown voltage of 300 V or more.
The capacitive coupling is provided by four MKT capacitors connected in parallel. 10 µF at 250 V is not exactly a standard catalogue item, but it is certainly available (Vishay 373 series; available from RS Components, Bürklin and Spoerle).

Inductor

Unlike most comparable high-power switched-mode regulators, the design of the inductor is not critical with the Cuk Converter, since it conducts a continuous current instead of being switched. The Epcos type E42/21/20 core, which is made from N27 core material, is quite suitable, readily available and a real bargain at less than 7 pounds (including mounting hardware). The core accessories include a plastic coil former and a sheet-metal clamp for securing the core. In our lab prototype, the job was handled by an LCC type E-45220A core. Spacers cut from 1.5-mm PCB material create a gap with a width of 1.5 mm, which in the case of an E-section core corresponds to an air gap of 3 mm in the magnetic path. Type ETD49 and E47/20/16 cores are also suitable, but the base of the coil former for these types doesn't match the circuit board layout.
Regardless of which type of core is used, 32 turns of 1-mm diameter RF litz (multi-stranded) wire must be wound on the former for each winding, with the wires for the two coils simply being wound in parallel.
Solid enamelled copper wire can also be used, but the insulation breakdown voltage of enamelled copper wire is not all that high. Consequently, the primary winding should be wound first, followed by the secondary, and paper strips must be placed between the layers of the windings.
In either case, pay particular attention to the direction of the windings, since otherwise things will go bang.

Control loops

For monitoring the currents and voltages in the power section and driving the switching transistors, we use a type 3526 IC, which is available from several manufacturers (including TI and ST). Although this is a special-purpose IC, it is a well-proven industry standard and thus fairly well known. Detailed information for this IC is available from the manufacturer's data sheet, so here the block diagram of this pulse-width modulator IC (**Figure 5**) is sufficient for understanding how it works. The 3526 is a PWM controller for push-pull converters, so the drive signals at its outputs (OUT A and OUT B) are pulse-width modulated according to the value of the control variable. The output signals have a maximum duty cycle of 50 % less the dead time, with a phase offset of 180 degrees. Diodes D10 and D11 combine the two output signals. This yields a PWM signal with a duty cycle ranging from 0 to 100 %, less two dead-time intervals.



Personal Download for Prica, Ognjen | copyright Elektor

The internal output drivers obtain their operating voltage via VC (pin 14). As can be seen, R27 limits the current through these transistors to prevent them from becoming excessively saturated, so they won't generate undesirable current spikes during switching transients (both transistors 'on'). The internal transistors don't require a lot of current, since they only have to provide the base currents for a pair of external driver transistors (T3 and T4), which in turn drive the power MOSFETs (T1 and T2).

The period of the oscillator is set to just under 20 µs (equivalent to 50 kHz) by C17 and R28, while R29 sets the dead time to 6 µs. The internal PWM latch is clocked by the oscillator, but it is also affected by the error amplifier (+ERR on pin 1) and the current sense inputs (+CS and –CS). The –ERR input is connected to COMP, so the error amplifier acts as a voltage follower. That's all we need here, since external opamps (IC1 and IC2) are used to amplify and condition the two measured variables U_{on}

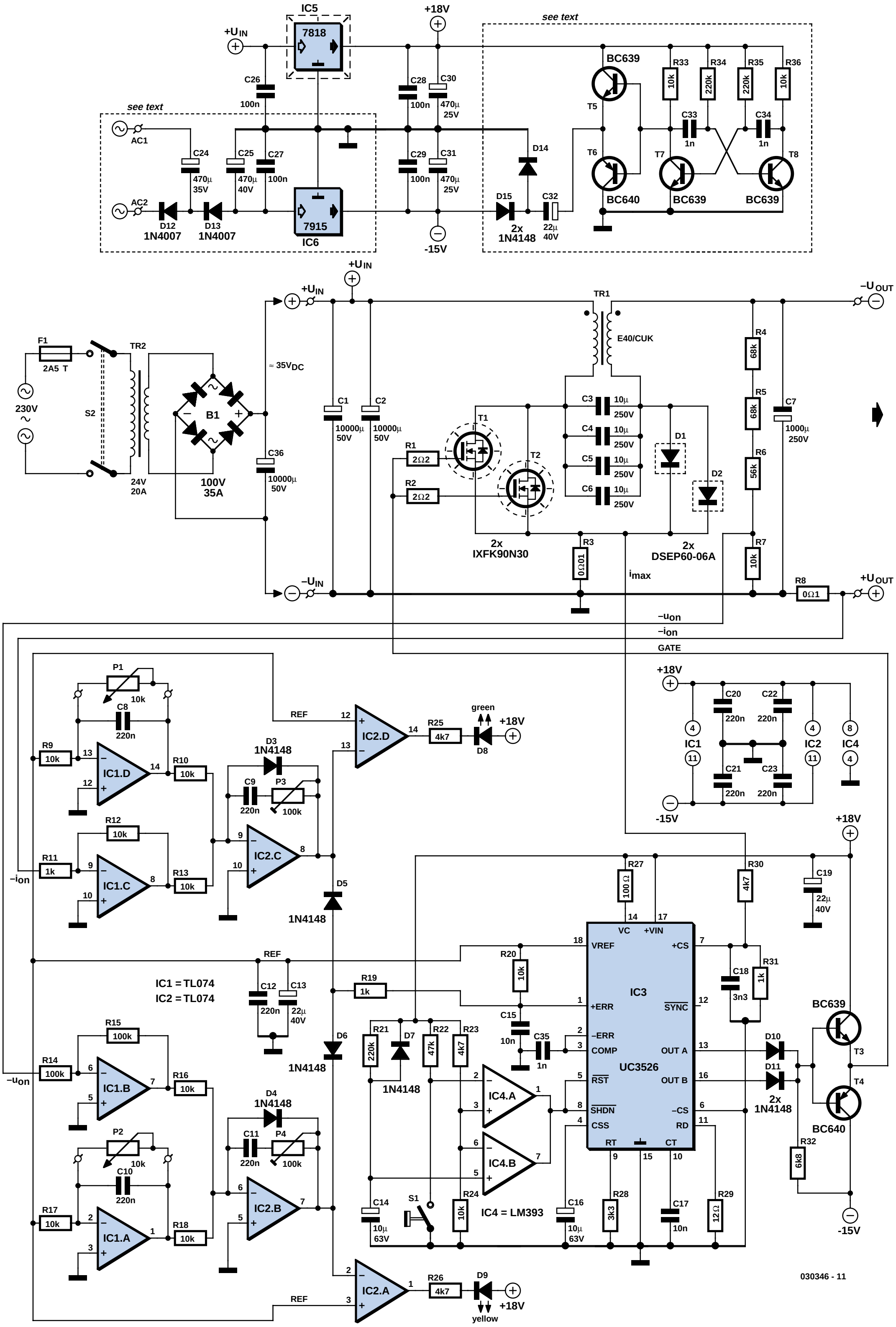


Figure 4. The complete, detailed circuit diagram of the Cuk Converter.

Personal Download for Prica, Ognjen | copyright Elektor

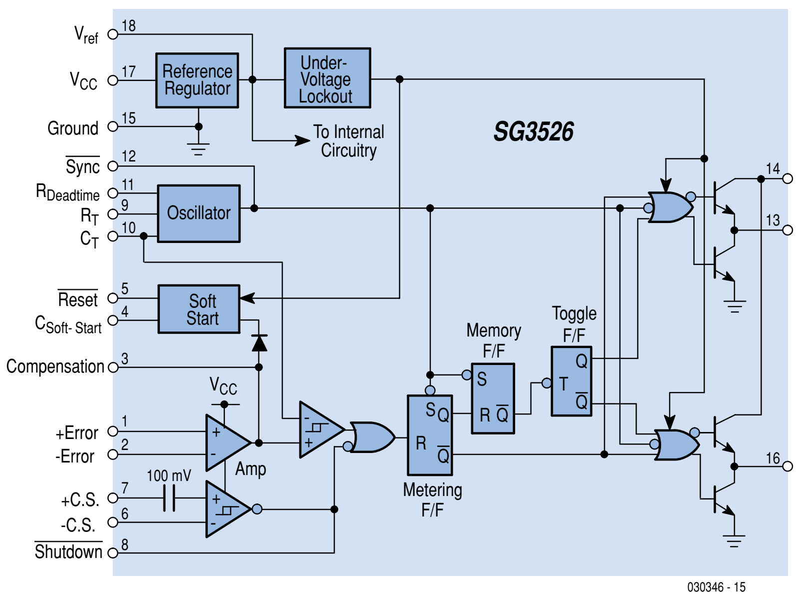


Figure 5. Internal configuration of the 3526.

and I_{on} to suit the requirements of the 3526. This isn't all that simple, since the measured quantities are negative with respect to ground and must be inverted before they can be used by the PWM controller IC.

The reference voltage output VREF (pin 18), which provides exactly +5 V, is used for the signal conditioning circuitry. Opamps IC1d and IC1a invert the reference voltage and allow set-point values in the range of 0 to –5 V to be set by adjusting P1 and P2. The measured quantities, which represent the actual values, are amplified by a factor of –10 by IC1c (for the output current) and IC1b (for the output voltage) and summed with the set-point voltages. Sense resistor R8 and voltage divider R4–R7 are dimensioned such that the voltage at the output of IC1b or IC1c is +5 V for an output current of 5 A or an output voltage of 100 V, respectively.

Each circuit has a control amplifier (IC2b or IC2c) at its output, and the output voltage of the control amplifier is regulated such that the sum of the negative set-point value and the positive actual value is exactly zero. The two signals are ORed via D5 and D6, which causes the lower of the two voltages to reach the input to the error amplifier inside the 3526 and thus determine the duty cycle of the PWM modulator.

The 3526 input is connected via R20 to +5 V, which corresponds to the maximum duty cycle. The lowest voltage on the control amplifier outputs thus always dominates the control loop. The duty cycle always adjusts to meet the demands of whichever control ampli-

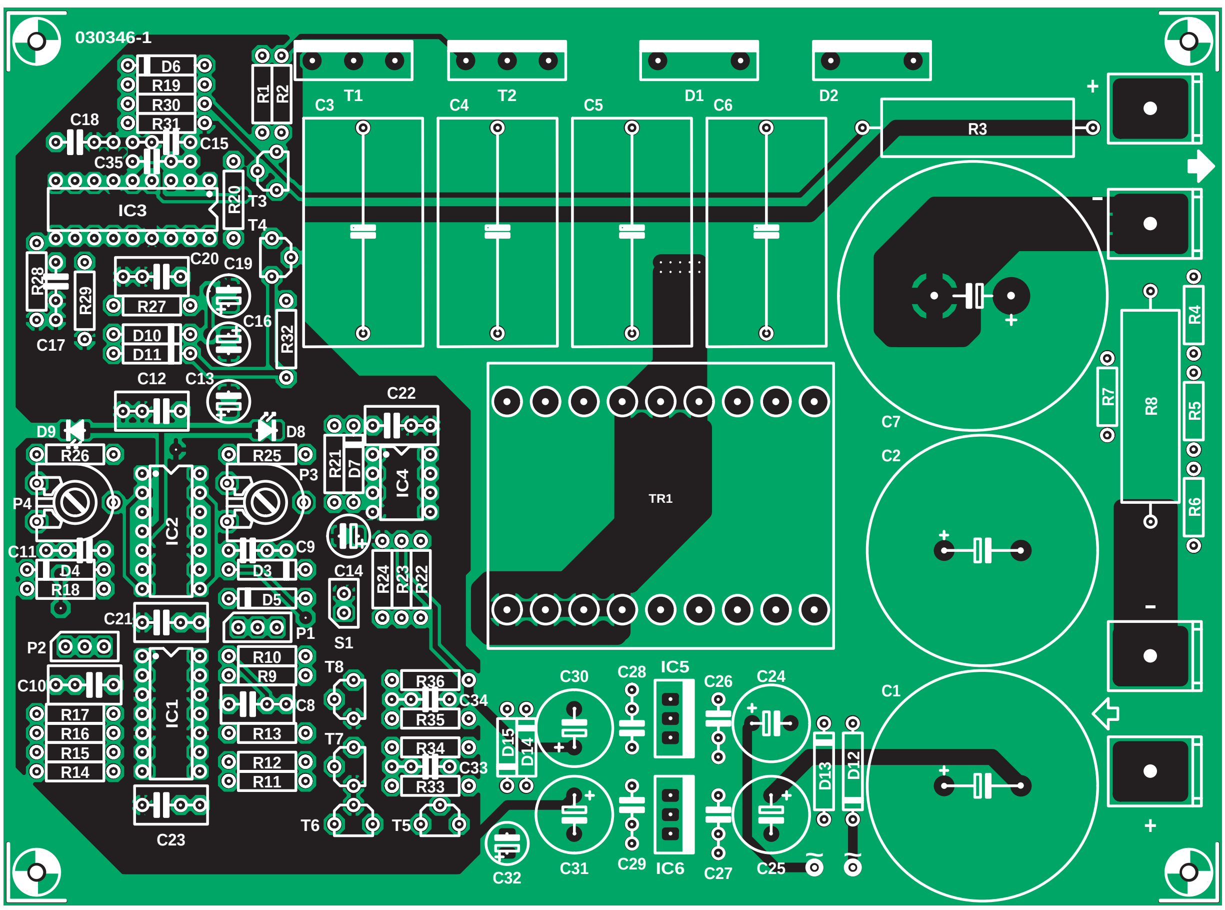


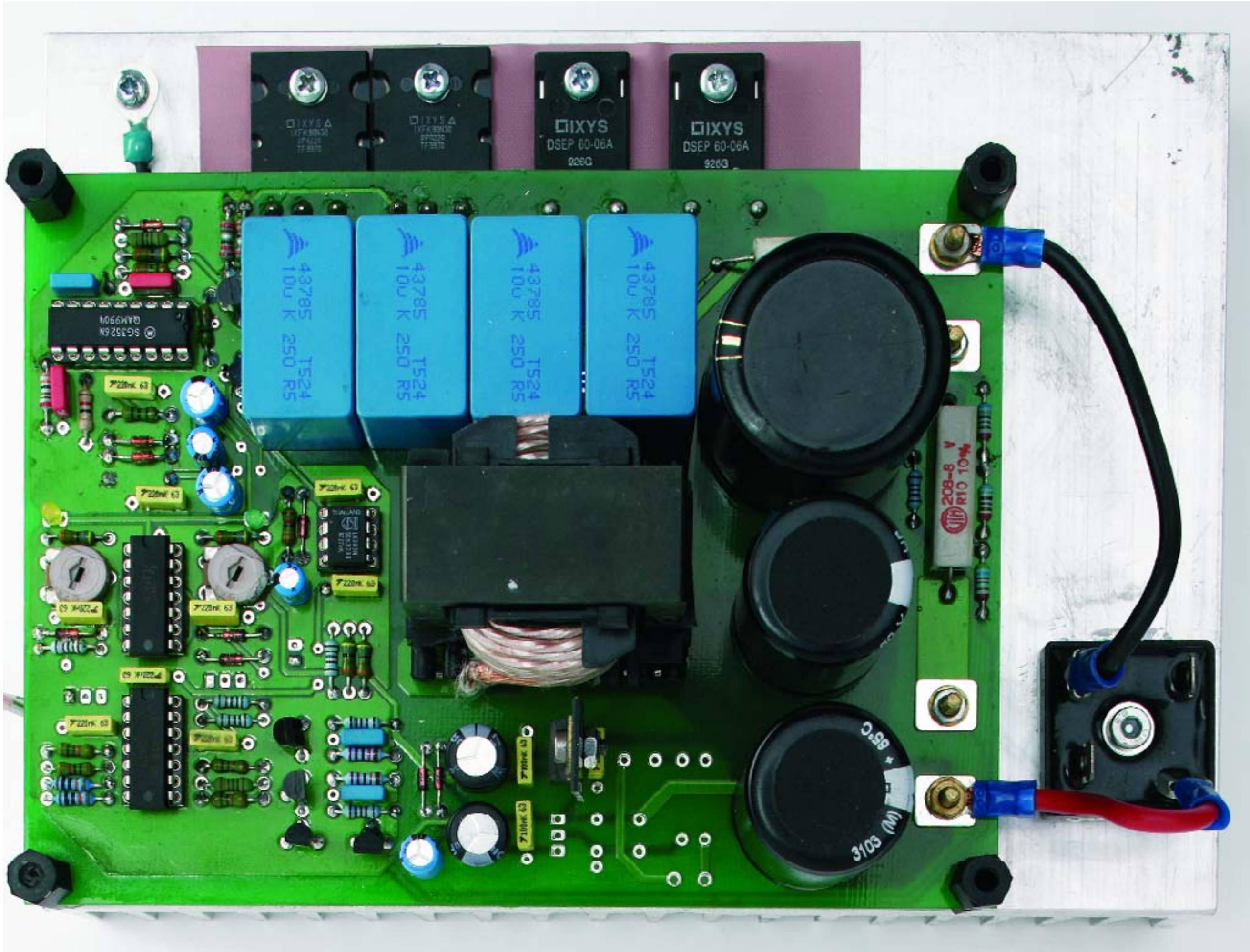
Figure 6. A double-sided layout is used for the printed circuit board.

Personal Download for Prica, Ognjen | copyright Elektor

fier is effectively 'in the loop'.
The two remaining opamps (IC2a and IC2d) are used as comparators to visually indicate when the upper voltage limit or upper current limit is reached. They allow the user to see whether the circuit is operating under voltage control or current control.
The measured quantity for the input current (i_{max}) is easier to handle. Here the 3526 provides an internal Schmitt-trigger comparator with a 100-mV fixed reference voltage. If the measured voltage reaches this value (after being divided by R30/R31 and smoothed somewhat by C18), the comparator triggers a shutdown. The PWM modulator will not start up again until the measured voltage drops below 80 mV.
Finally, a soft-start function is implemented using R21, C14 and IC4b, and manual reset capability is provided by R22, S1 and IC4a. The outputs of the these two comparators are ORed together and connected to the Reset and Shutdown inputs of the 3526. Connecting theses two pins together causes the IC to execute a soft start after each overcurrent event.
A thermostatic switch (normally open) can be connected in parallel with S1 to monitor the temperature of the heat sink. A PTC thermistor could be used for the same purpose. Thermistors have extremely steep characteristic curves. For a type with a rated temperature of 60 °C, the resistance rises from a few ohms to the megaohm range when the temperature increases from 50 °C to 70 °C. This means that any type with a rated temperature of 50–70 °C is suitable, such as the B59901-D60-A40 or any other type with a '50', '60' or '70' in the middle of the type number.
The 3526 has internal undervoltage protection and overtemperature protection, which also trigger a shutdown.

Construction and alignment

A printed circuit board for a DC voltage converter in this power range requires a carefully designed layout (**Figure 6**), which usually has to be double-sided due to the necessary ground-plane area. The measurement amplifiers, control circuitry and power circuitry are clearly separated from each other, and 'sensitive' connections are keep a short as possible and as broad as necessary. The large ground planes protect the measurement and control circuitry against undesirable electronic interference.
Before starting to fit the components to the board, place inductor TR1 aside, since it will only be fitted during the alignment process. You should fit feedback capacitors C9 and C11 for IC2c and IC2b, but immediately short them out by connecting short wire bridges across them (on the component side).
Next you have to decide whether the negative auxiliary voltage should be generated by the transformer or the on-board charge pump. Fit the corresponding components, as well as all of the control electronics. Potentiometers P1 and P2 are connected using pin headers, wired such that they have minimum resistance when adjusted fully counter-clockwise. The LEDs can later be relocated to the front panel using pin headers as well. The ICs can be fitted in sockets. Pay attention to the correct orientation of the numerous diodes, the ICs and the small electrolytic capacitors. Fitting the components for the power section, including the AMP screw terminals for the input



Personal Download for Prica, Ognjen | copyright Elektor

COMPONENTS LIST

Resistors:
R1,R2 = 2Ω2
R3 = 0Ω01 3W horizontal
R4,R5 = 68kΩ
R6 = 56kΩ
R7,R9,R10,R12,R13,R16,R17,R18,R20, R24,R33,R36 = 10kΩ
R8 = 0Ω1 3W horizontal
R11,R19,R31 = 1kΩ
R14,R15 = 100kΩ
R21,R34,R35 = 220kΩ
R22 = 47kΩ
R23,R25,R26,R30 = 4kΩ7
R27 = 100Ω
R28 = 3kΩ3
R29 = 12Ω
R32 = 6kΩ8
P1,P2 = 10kΩ mono potentiometer
P3,P4 = 100kΩ preset

Capacitors:
C1,C2 = 10,000µF, 50V radial, ∅ 30mm, lead pitch 10mm
C3-C6 = 10µF, 250V MKT, 18x31.5mm, lead pitch 27.5mm (Vishay 373)
C7 = 1000µF 250V radial
C8-C12,C20-C23 = 220nF
C13,C19,C32 = 22µF 40V radial
C14,C16 = 10µF 63 V radial
C15,C17 = 10nF
C18 = 3nF3
C26,C28,C29 = 100nF
C30,C31 = 470µF 25V radial
C33,C34,C35 = 1nF

Semiconductors:
D1,D2 = DSEP60-06A (Ixys)
D3-D7,D10,D11,D14,D15 = 1N4148
D8 = LED, green, low current
D9 = LED, yellow, low current
IC1,IC2 = TL074
IC3 = UC3526 (TI) or SG3526 (ST)
IC4 = LM393
IC5 = 7818 with clip-on heatsink
T1,T2 = IXFK90N30 (Ixys)
T3,T5,T7,T8 = BC639
T4,T6 = BC640

Miscellaneous:
S1 = pushbutton and/or thermal fuse or PTC
TR1 = E42/21/20 core with coil former and mounting clamp (standard stock item from RS Electronics)
1m 1mm^2 RF litz wire, or 1mm^2 enamelled copper wire
Heatsink <1K/W (<0.35K/W when thermal fuse not triggered)
PCB, order code **030346-1** (from The PCB Shop)

Leave open:
C24 = 470µF, 35V radial
C25 = 470µF, 40V radial
C27 = 100nF
D12,D14 = 1N4007
IC6 = 7915

Not on PCB:
B1 = bridge rectifier 100V piv, 35A (secure to heatsink)
C36 = 10,000µF, 50V radial (additional ripple reduction at direct voltages below 35V)
TR2 = mains transformer, 24V, 20A
F1 = Fuse, 2.5AT (slow) with fuse holder
S2 = double pole mains on/off switch for Tr2

and output voltages, should not present any problems. Bend the leads of the power semiconductors so they can later be attached to the heat sink.

At this stage, it is already possible to perform initial testing and alignment after a thorough visual examination. Connect a laboratory power supply (35 V, with the current limiting set to several tens of milliampères) to the input terminals, and connect the two potentiometers to the pin headers. Now adjust the gain of the current control amplifier (using P3) and the voltage control amplifier (using P4) such that the voltage measured at pin 1 of the 3526 can be continuously adjusted from 0 V to 5 V using P1 or P2, respectively. After this, turn P2 fully clockwise and P1 fully counter-clockwise. Using an oscilloscope, check that the MOSFETs are being properly driven with a PWM signal having a frequency of approximately 40 kHz (as measured on R1 and R2). The duty cycle of this signal can be adjusted over the range of 0–90 % by rotating the current-limit potentiometer (P1).

The control amplifiers cannot presently regulate the loop, since capacitors C9 and C11 are shorted out and the loop is open because the inductor has not yet been fitted. As a result, the duty cycle can be directly adjusted using the potentiometers. Only something that can be controlled can also regulate a controller.

Now it's time to fit the inductor and attach the fully assembled board to the heat sink in 'piggy-back' fashion, as shown in the title photo for this article, using eight previously drilled and tapped holes in the heat sink. As the drain and cathode voltages of the power semiconductors are present on their cooling tabs, these components must of course be properly insulated from the heat sink using the standard methods.

This is a good time to fit the assembled module into a suitable enclosure along with its power supply, and then wire everything together except the mains transformer. Instead of using the transformer, you should first operate the circuit from a laboratory power supply with current limiting. Restricting the power reduces the risk of destroying any components if there is an assembly error.

The wiring and connectors used for the input and output must be able to handle the amount of power drawn or supplied by the Cuk Converter. Don't forget to turn P1 fully counter-clockwise and P2 fully clockwise (100-V setting)!

Now we come to the serious work. Connect a hefty power resistor, an incandescent lamp or a halogen floodlight to the output to provide an output load, and connect a voltmeter to the output of IC1d. The output of IC2b will remain 'stuck' and cannot affect anything. Now slowly increase the load current from 0 to the maximum value by adjusting P1.

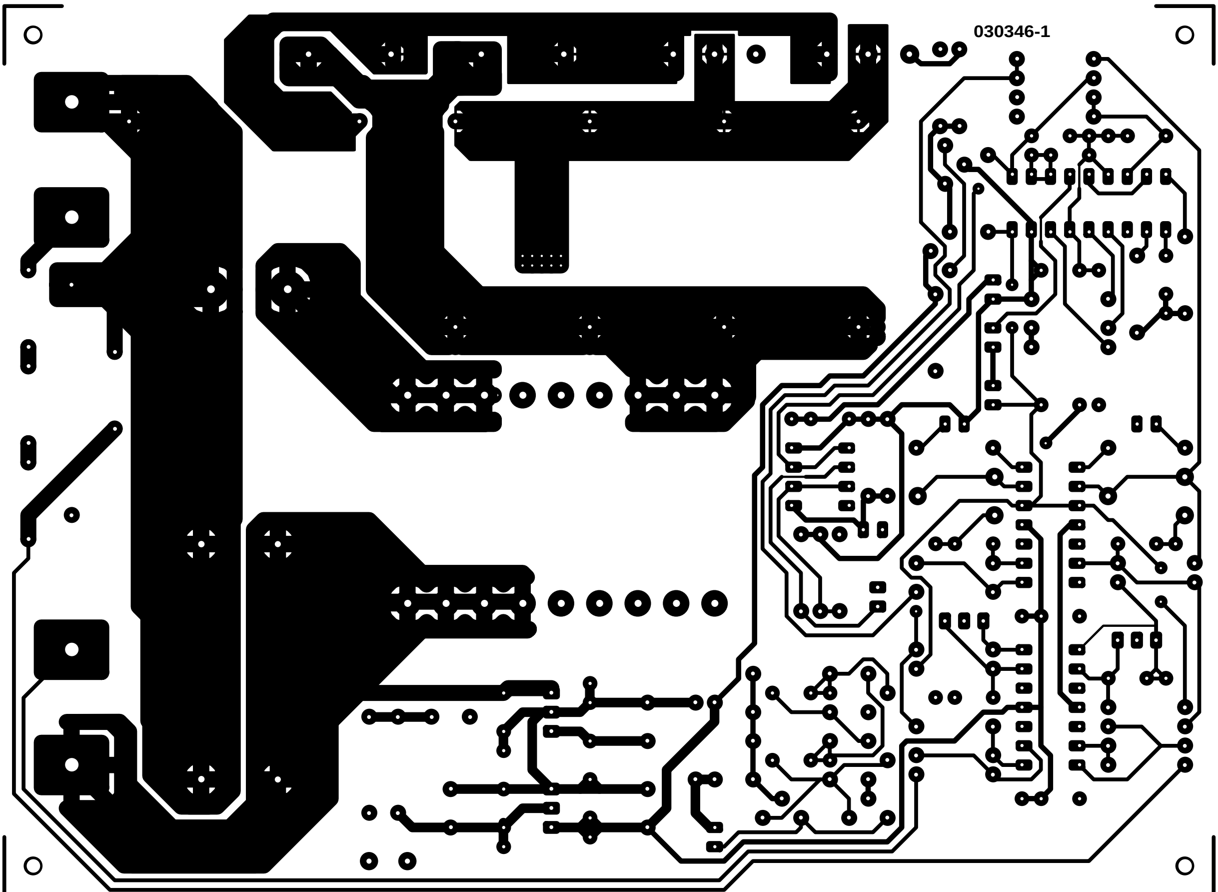
Next, perform the above procedure the other way around: first rotate P1 fully clockwise (5-A setting), and then use the voltage control (P2) to slowly increase the output voltage to its maximum value of 100 V. Naturally, a current of 5 A can only be achieved if the load resistance is not more than 20 Ω (100 V ÷ 5 A), and 100 V can only be achieved if the load resistance is 20 Ω or more.

However, you're not finished yet, since only part of the circuit's control function is operating. Adjust both potentiometers to their minimum settings, and then cut away both wire bridges to enable operation with the full closed-loop control characteristic. Now slowly increase the setting of P1 again. If the inductor starts to make squealing noises, slightly reduce the gain of the control amplifier by adjusting P3 (the maximum current will still be 5 A). Finally, repeat this procedure for the voltage control stage.

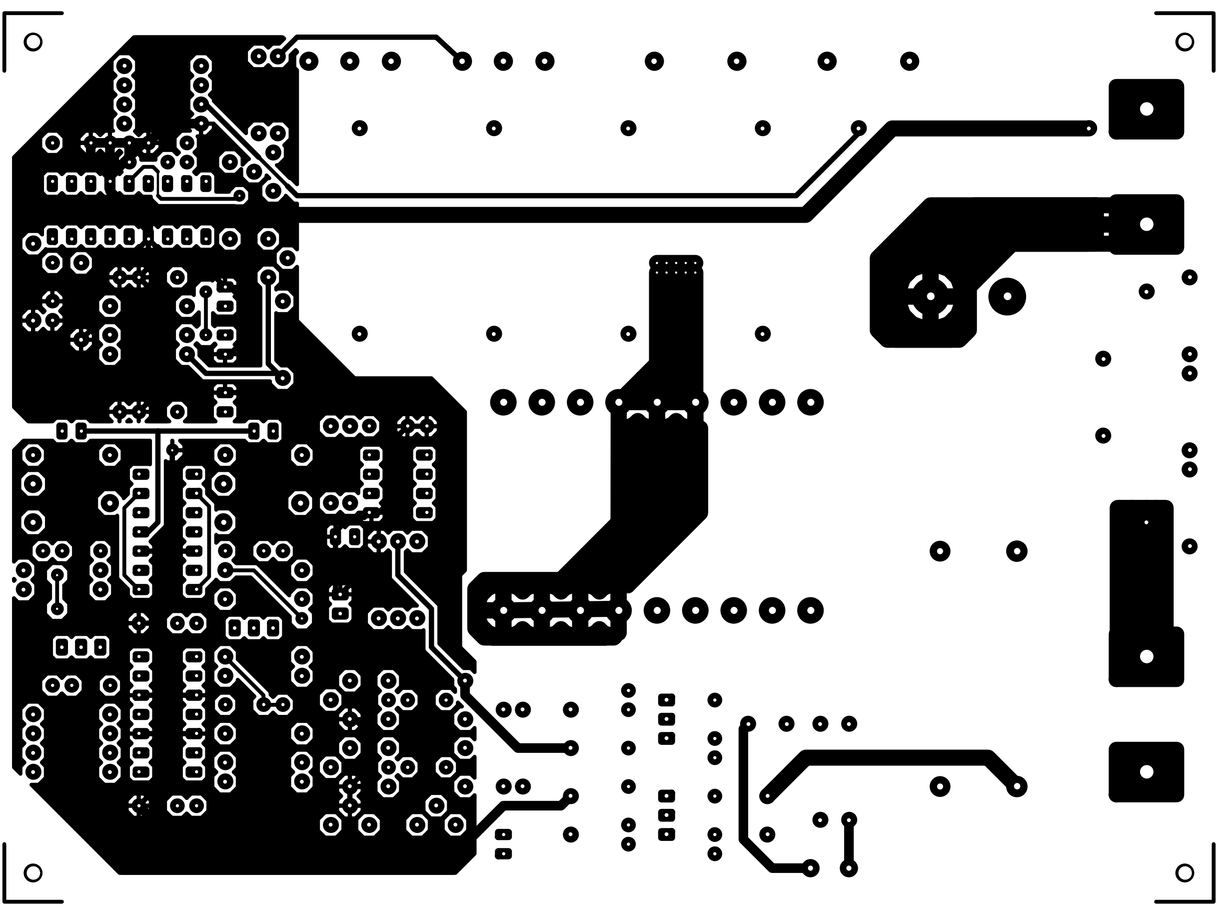
Warning. The circuit generates dangerous voltages. No part must be touched when the circuit is in operation and all relevant electrical safety precautions should be observed.

(030346-2)

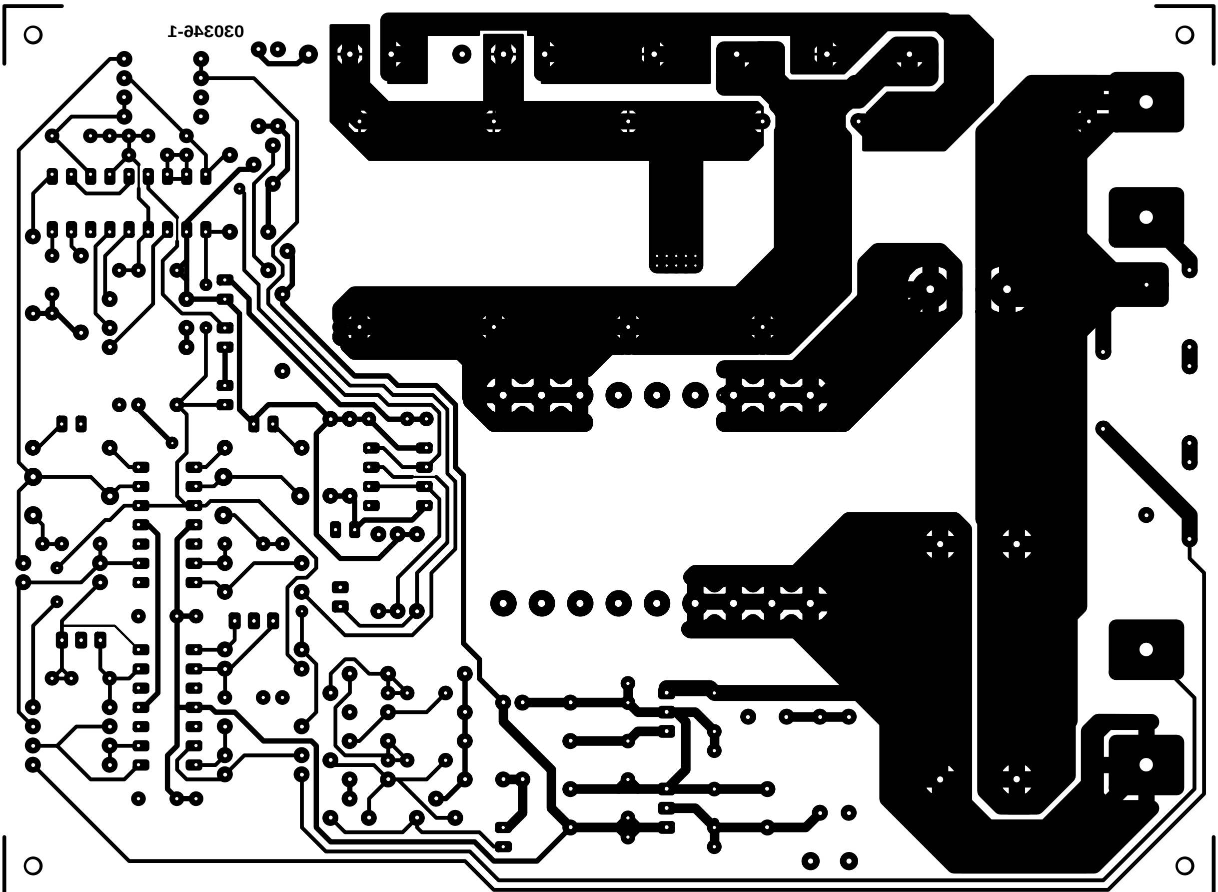
Personal Download for Prica, Ognjen | copyright Elektor



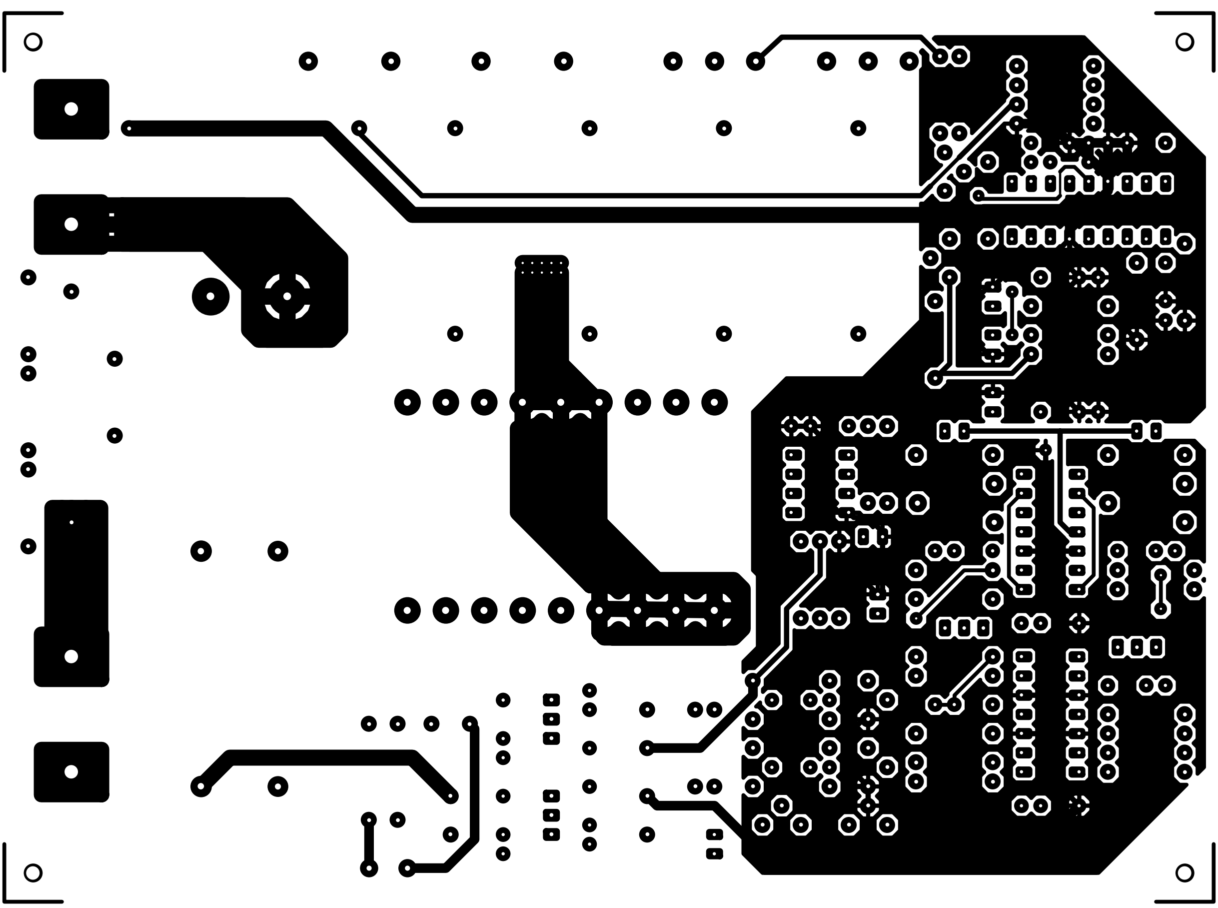
Personal Download for Prica, Ognjen



non reflected



Personal Download for Prica, Ognjen



reflected