Project 163

0-40 V/5 A laboratory power supply

Part 1.

Here's a laboratory standard power supply featuring truly regulated output from zero to 40 volts capable of delivering a massive 5 A across the whole voltage range, plus current limiting variable from zero to 5 A. Two meters monitor voltage and current and regulator dissipation is reduced by employing an automatic transformer switching circuit.

David Tilbrook

IN APRIL 1976 we published the ETI-131 General Purpose Power Supply. This project could be built in two versions — 0-20 V/2.5 A or 0-40 V/1.25 A. It featured variable current limiting and had pretty close to lab-standard specs. A great many have been built since then and are to be found in development laboratories, service workshops, technical college and university labs and hobbyist's workshops.

Since that time, electronic technology has made considerable strides and the sort of things now being investigated by hobbyists and in electronics labs of all descriptions range much wider than they did when the ETI-131 was in vogue. It came to our notice that a lab-standard supply having 'expanded' specifications was in demand so we set out to investigate what sort of project would best meet that demand.

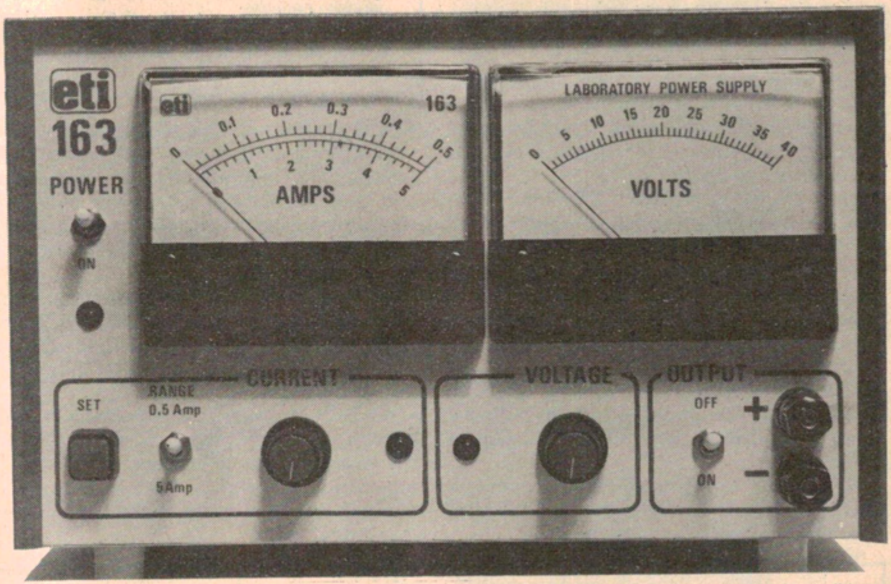
Following considerable discussion with both users and project suppliers, it was apparent that the most generally useful output voltage range would be about 0-40 V or 0-50 V and the required maximum current capability would be in the vicinity of 3-4 A or so. The next thing to do was to define 'lab-standard'.

Defining 'lab-standard'

An 'ideal' power source should provide the following: • a regulated voltage variable from zero to some chosen limit • no extraneous hum or noise on the output and none radiated from the supply • current-limit operation from zero to some chosen limit • simultaneous metering of current and voltage output • protection from short circuits on the output at any output setting.

In addition, handy 'operator features', such as indicators to show voltage and current mode operation, output and current-set switches, are desirable.

What sort of specifications would approach the 'ideal'? With sensitive high gain, dc control, audio or RF circuitry attached to the supply during circuit development or fault locating, you want to be sure that any problem experienced is not caused by some characteristic of the power supply. Hence, hum and noise are an important consideration. ▶

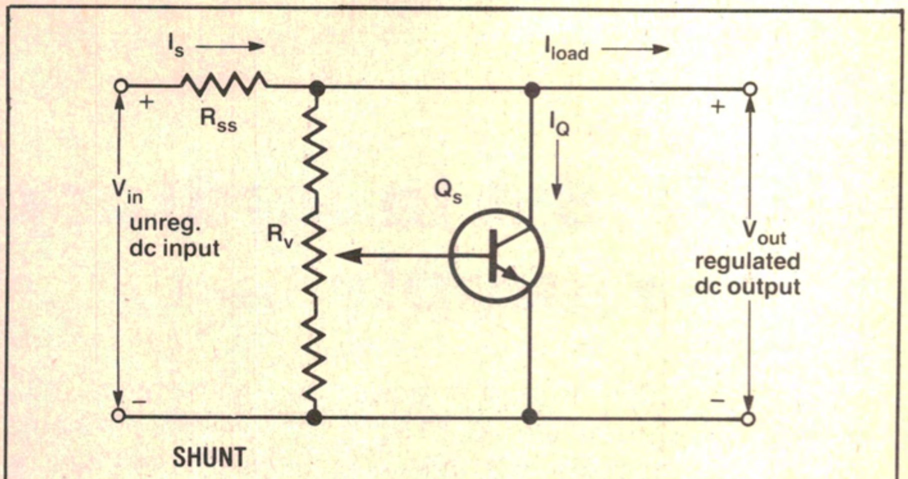


Power and performance. The completed supply looks smart, performs well and is economical to build — at around $150-$160.

SPECIFICATIONS — ETI-163 LAB. SUPPLY TABLE 1

Output voltage	0-40 V, variable
Output current	0-0.5 A, variable limiting 0-5 A, variable limiting
Output regulation	<50 mV at up to 2.5 A <100 mV up to 5 A
Ripple and noise	
voltage mode	<3 mV RMS
current mode	<10 mV RMS
Maximum output power	200 watts
Metering	
Voltage	0-40 V in 1 V divisions
Current	0-0.5 A in 20 mA divisions 0-5 A in 200 mA divisions

- **LED to indicate voltage mode operation**
- **LED to indicate current mode (limiting) operation**
- **Current-set switch provided for setting current limit value**
- **Output switch provided to isolate supply output**
- **Output terminals isolated from chassis**
- **Full output current available right up to 40 V**



The shunt regulator. Fundamental circuit of a shunt regulator. As the load current (I_{load}) increases, the output voltage (V_{out}) tends to fall, reducing base current to Q_s. This, in turn, reduces the collector current (I_Q) of the shunt regulator, Q_s. The voltage drop across R_{ss} then decreases, maintaining the output voltage. As load current decreases, the opposite happens.

If the input voltage (V_{in}) increases, V_{out} tends to rise, increasing the base current to Q_s. This increases I_Q and the voltage drop across R_{ss} increases, maintaining the output voltage. If V_{in} decreases, the opposite happens.

Varying the wiper of R_v varies the collector current of Q_s, thus varying the voltage dropped across R_{ss}, setting the output voltage. Resistor, R_{ss} dissipates considerable power and Q_s dissipates the maximum output power under no load.

A figure under 10 mV is a desirable goal, preferably less than 5 mV. Performance in the current-limit mode should be similar, but is not as critical a parameter.

As supply voltage variations can adversely affect some circuits, regulation of the output voltage over the whole variation range is paramount. It should remain virtually constant despite relatively large mains input voltage excursions and despite large variations in current drawn (up to the maximum). Regulation can be expressed as a percentage (with respect to full output) or as a voltage variation. The latter is preferred as it shows performance over the whole output variation range.

A regulation figure of 0.1% (100 mV in 100 V) is common for low current output supplies (up to 1 A), but 0.5% is more usual for high current supplies. That would be 250 mV for a 50 V supply.

Regulator techniques

There are a number of basic techniques used to provide a regulated supply voltage. Choice depends on the application. The respective methods and their characteristics may be summarised as follows:

- **The shunt regulator.** This design is suitable mainly for low-power supplies — 15 to 20 watts. It has good regulation and is inherently short circuit proof. However, it dissipates the full amount of power it is capable of handling under no-load conditions.

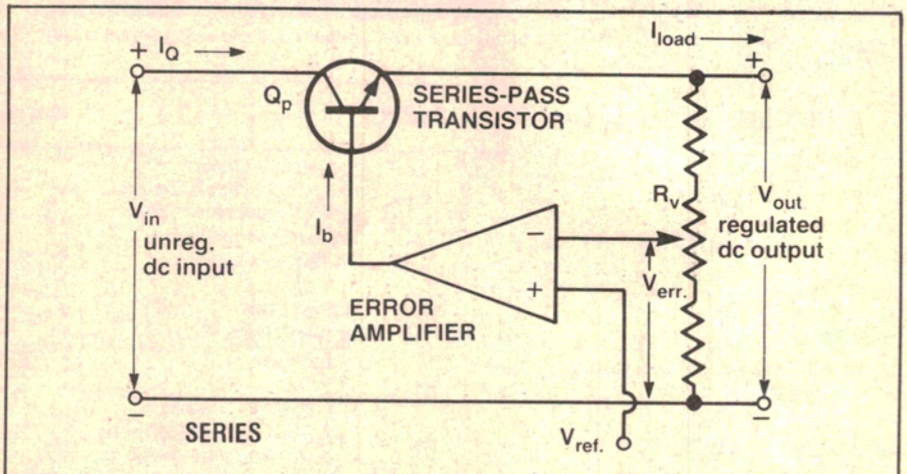
Current-limit operation is not so easy to incorporate, but cost is low.

- **The series regulator.** Probably the most widely used technique. It is suitable for power supplies capable of delivering up to 200 watts.

Regulation, hum and noise performance is good, it's easy to arrange current-limit operation and cost is relatively low.

- **SCR regulator.** This technique is mainly suited for medium to very high power applications. The regulator has low dissipation and good regulation, but output noise and ripple are worse than for the series regulator and radiated switching 'hash' requires extensive shielding.
- **SCR pre-regulator and series regulator.** This combines the best features of the previous two and is best suited to medium to high power applications (say to several hundred watts).

An SCR pre-regulator provides a roughly regulated supply about five volts above the required output voltage, followed by a conventional series regulator. This keeps dissipation in the series regulator low. Cost is relatively high.



The series regulator. Fundamental circuit of a series regulator. As the load current (I_{load}) increases, the output voltage (V_{out}) tends to fall. This causes $V_{err.}$ to fall (the 'error voltage'). The error amplifier is operated as an inverting amplifier and thus, as $V_{err.}$ falls, the base current (I_b) to the series-pass transistor (Q_p) will rise. This causes the collector current (I_Q) of Q_p to rise, maintaining the output voltage. If I_{load} decreases, the opposite occurs.

If the input voltage (V_{in}) rises, the output will tend to rise, as will $V_{err.}$. This will produce a decrease in base current to Q_p, reducing I_Q, thus maintaining the output voltage. If V_{in} falls, the opposite will occur.

Varying the wiper of R_v varies $V_{err.}$, setting the output voltage.

- **Switchmode regulator.** This technique is also used in medium to very high power applications. A series switching element stores energy in an inductor or capacitor, the on-time of the switching element being controlled to provide the required regulated output.

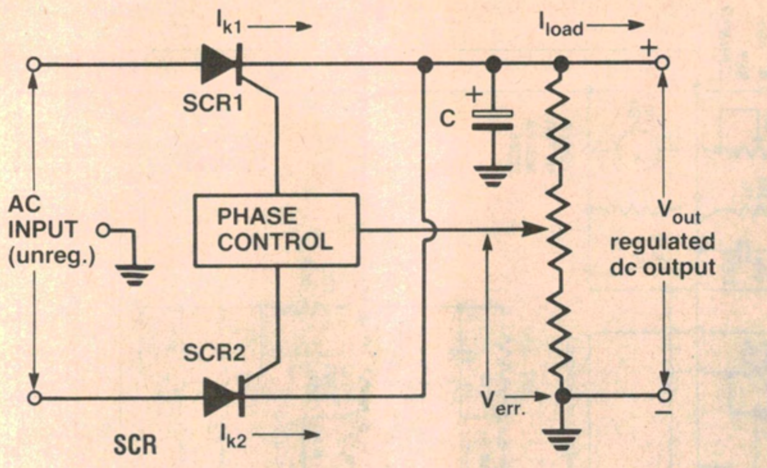
This technique keeps regulator dissipation low and regulation performance is good. With modern ICs purpose-built for the application, cost is about the same as a series regulator. However, noise and ripple on the output can be difficult to suppress and considerable wideband RF energy is radiated by the circuitry, necessitating careful and extensive shielding.

Design features of this supply

I settled on an output voltage range of 0-40 V as this seemed to cover the great majority of supply requirements for circuit testing, development and fault locating. A maximum output current of 5 A was settled on for similar reasons. This results in an output rating of 200 watts, hence choice of an appropriate regulator technique was of paramount importance.

Two techniques were obvious contenders — series regulator and switchmode regulator. Previous experience with switchmode regulators made me wary that I could use one in a 'lab-standard' supply. The ETI-142 0-30 V/15 A supply (Feb. '79) employed a switchmode pre-regulator and a series regulator. Despite elaborate precautions, noise from the switchmode pre-regulator made it impossible to use this supply in the vicinity of, let alone connected to, sensitive circuitry. Pity, but a fact of life.

The inherent attractiveness of high efficiency — low dissipation is generally outweighed in this application. The necessity of elaborate screening and filtering brings problems of its own for constructors and increases costs.



The SCR regulator. Fundamental circuit of an SCR regulator. As the load current (I_{load}) increases, the output voltage (V_{out}) tends to decrease causing the 'error voltage' ($V_{err.}$) to drop. The phase control circuit then advances the triggering of the SCRs so that I_{k1} and I_{k2} and the average rectified voltage increases, maintaining the output voltage. If load current decreases, the opposite occurs.

If the ac input voltage rises, V_{out} tends to rise, causing $V_{err.}$ to rise also. The phase control circuit then retards the triggering of the SCRs, reducing the average rectified voltage, and maintaining V_{out}. The opposite happens if the ac input falls.

Varying the potentiometer varies $V_{err.}$, setting the output voltage.

I looked at the series regulator — and how to reduce the dissipation. For a 40 V output, dc input to the regulator would have to be around 50 V. At 5 A output into a short circuit, worst case dissipation would be around 250 watts! That requires *big* transistors and *lots* of heatsink.

As pre-regulators increased the cost and the noise problems, I had to find another way to reduce regulator dissipation and I hit on the idea of switching the transformer secondary.

Using several cheap ICs as comparators and a couple of relays, I could switch the rectifier across different transformer taps as the regulator output voltage was varied.

However, this technique had the drawback that a 'special' transformer would be required. If I could choose the output taps so that they were at generally 'useful' voltages, the transformer stood a good chance of becoming a 'stock' item. With this in mind, I chose the secondary taps to be 12 V, 24 V and 36 V.

The prototype transformer was wound up for us by Permatran of Melbourne. It is rated at 250 VA.

Astute readers will notice that basically, only two output taps are really required as the 12 V output could be selected by switching between the 24 and 36 volt terminations. However, using relay switching, it is possible under some circumstances to short part of the secondary with consequent disastrous results. The 'switching' tree employed avoids this possibility.

A separate low voltage and current dc supply is necessary to power the op-amps in the regulator and to provide a 5 V reference. In the prototype, I used a small 12 V/150 mA transformer — a stock item from most electronics suppliers — but a 15 V/200 mA winding may be available on the transformers obtained by suppliers of this project.

Worst case regulator dissipation for this supply is around 120 watts, a much more manageable figure than 250 watts. It occurs when the output current is 5 A at a voltage setting near 25 volts. At maximum dissipation, the heatsinks stabilise at a temperature of around 65°C.

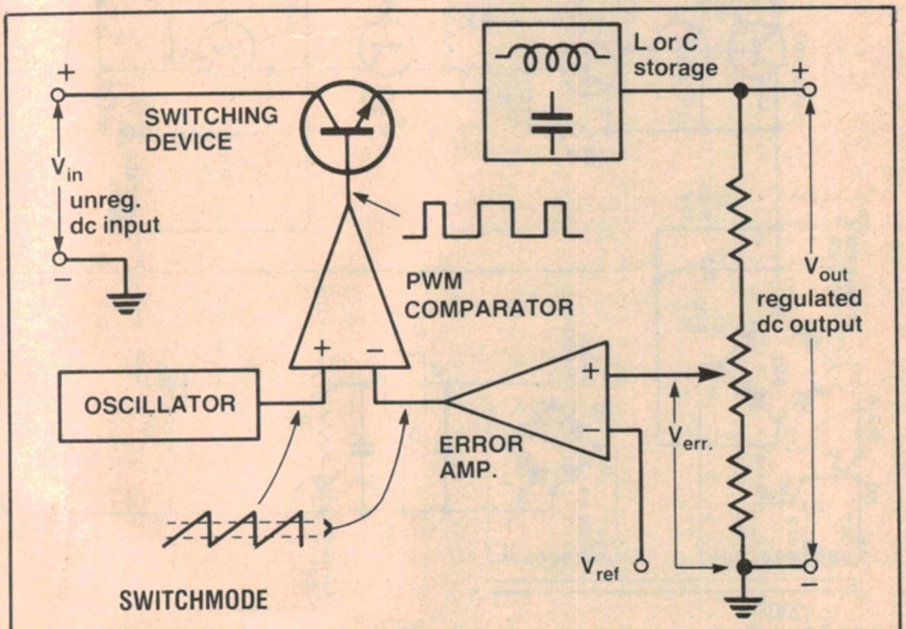
The regulator circuit is similar to the ETI-131 and employs two CA3130s for the voltage-mode and current-mode error amplifiers. A pair of MJ15003 high power NPN transistors connected in parallel are used for the series-pass element.

Another pair of CA3130s are used as comparators for the transformer secondary relay switching circuitry. These were chosen because their output can go right down to 0 V, ensuring the relay driver transistors turn off. The transformer taps are switched as the output voltage passes through about 12 V and about 25 V (these are adjustable over a few volts range). About a volt of hysteresis is added to the switching points so that the relays won't chatter when the output control is set on the switching point.

Separate meters are provided for indicating output voltage and current. There are two current-limit ranges — zero to 0.5 A and zero to 5 A. The point at which the supply switches from constant-voltage to current-limited (constant-current) output is fully variable across the two ranges.

A current-set pushbutton, which shorts the output terminals, is provided on the front panel and two LEDs indicate in which mode the supply is operating. A switch in series with the output allows you to isolate the supply from the load, without having to disconnect the supply or turn it off if you want the supply removed.

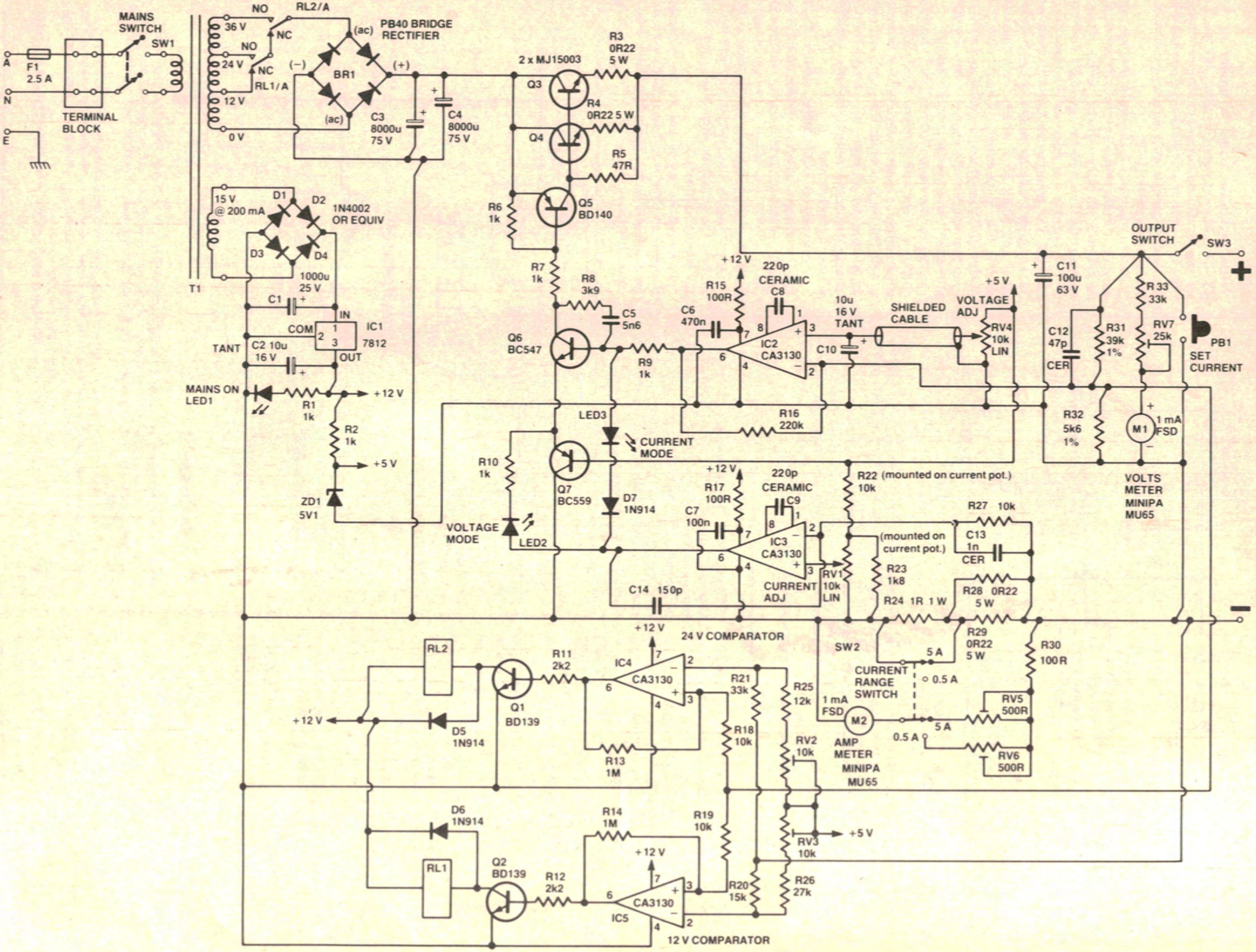
Performance turns out to be generally better than what was discussed as desirable for a lab-standard supply. See Table 1 for a complete run-down. ▶



The switchmode regulator. Fundamental circuit of a switchmode regulator. The output of a sawtooth oscillator and the output level of the 'error amplifier' are compared by the 'pwm comparator' which drives a switching device. The switching device turns on and off, storing energy from the unregulated input in a capacitor or inductor.

As the load current increases, the output voltage (V_{out}) will tend to fall as will the error voltage ($V_{err.}$). The output of the pwm comparator will turn on for a longer period for each cycle of the sawtooth. The switching device then conducts for a longer period, storing more energy in the L or C, maintaining the output voltage. As the output current decreases, the opposite occurs.

As the switching device is either hard on or fully off, it dissipates little power. Varying the potentiometer varies $V_{err.}$, setting the output voltage.


MAINS SWITCH
SW1
A
F1
2.5 A
N
E
TERMINAL BLOCK
NO
36 V
NC
RL2/A
NO
24 V
NC
RL1/A
12 V
0 V
PB40 BRIDGE RECTIFIER
(ac)
(−)
(+)
BR1
(ac)
C3
8000u
75 V
C4
8000u
75 V
2 x MJ15003
Q3
R3
0R22
5 W
R4
0R22 5 W
Q4
R5
47R
R6
1k
Q5
BD140
15 V
@ 200 mA
D1
D2
1N4002
OR EQUIV
D3
D4
T1
1000u
25 V
C1
IN
IC1
7812
COM
1
2
3
TANT
C2 10u
16 V
OUT
MAINS ON
LED1
R1
1k
+12 V
R2
1k
+5 V
ZD1
5V1
R7
1k
R8
3k9
C5
5n6
Q6
BC547
R9
1k
LED3
CURRENT MODE
R10
1k
Q7
BC559
D7
1N914
VOLTAGE MODE
LED2
+12 V
R15
100R
220p
CERAMIC
C8
C6
470n
IC2
CA3130
10u
16 V
TANT
C10
SHIELDED CABLE
VOLTAGE ADJ
+5 V
RV4
10k
LIN
R16
220k
C11
100u
63 V
C12
47p
CER
R31
39k
1%
R32
5k6
1%
R 33
33k
RV7
25k
PB1
SET CURRENT
OUTPUT SWITCH
SW3
+
M1
1 mA
FSD
VOLTS METER
MINIPA
MU65
+12 V
R17
100R
220p
CERAMIC
C9
C7
100n
IC3
CA3130
R22 (mounted on current pot.)
10k
R27 10k
(mounted on current pot.)
C13
1n
CER
R23
1k8
RV1
10k
LIN
CURRENT ADJ
C14 150p
R24 1R 1 W
R28 0R22
5 W
R29
0R22
5 W
R30
100 R
−
+12 V
24 V COMPARATOR
RL2
R11
2k2
IC4
CA3130
Q1
BD139
+12 V
D5
1N914
R13
1M
R21
33k
R18
10k
R25
12k
SW2
CURRENT RANGE SWITCH
5 A
0.5 A
1 mA
FSD
M2
AMP METER
MINIPA
MU65
RV5
500R
5 A
0.5 A
RV6
500R
RV2
10k
D6
1N914
R14
1M
R19
10k
+5 V
RV3
10k
RL1
Q2
BD139
R12
2k2
+12 V
IC5
CA3130
R20
15k
R26
27k
12 V COMPARATOR

HOW IT WORKS — ETI-163

The power supply employs a series regulator circuit with current limiting operation added. The 36 V secondary of the power transformer has taps which are switched in automatically by relays as the output voltage is adjusted so that power dissipation in the series-pass transistors is minimised.

An auxilliary 15 V secondary (or an auxilliary transformer) provides a supply for the reference voltage, the relays, relay drive circuitry and voltage and current feedback op-amps (IC2 and IC3).

The main power transformer (T1) secondary of 36 volts is rated to deliver 5 A and is tapped at 12 and 24 volts. The appropriate tapping is selected by the contacts of relays RL1 and RL2.

These relays are controlled by Q1 and Q2, which are driven by a pair of comparators formed by IC4 and IC5 and associated resistors — R13, 14, 18 and 19. These resistors give the comparators some hysteresis which ensures that the relays do not chatter when the output voltage is set exactly equal to one of the trip voltages.

Resistors R21, 25, 20 and 26 and the two preset pots RV2 and RV3 form adjustable potential dividers, driven from the +5 V reference line. These potential dividers set the trip voltages for the two comparators. The presets allow the actual trip voltage to be adjusted over a small range.

Relay RL1 will trip when the voltage is around 12 V, while RL2 will trip when it is around 25 V. In this way the series-pass transistors, Q3 and Q4, are supplied with enough voltage to ensure good regulation but not excess voltage which would cause unneccessary power dissipation.

The main voltage regulator error amplifier is formed by IC2, a CA3130 FET-input op-amp. This compares the voltage on its non-inverting input (pin 3) with that on its inverting input (pin 2) which measures the output voltage via the potential divider formed by R31 and R32. The non-inverting input is connected to the wiper of RV4 which allows the reference voltage at this point to be varied from 0 to 5 V.

The output of IC2 is connected via resistor R9 to the base of Q6 which, in conjunction with Q5, provides the necessary current to drive the bases of the parallelled series-pass transistors, Q3 and Q4.

The RC network R8-C5 serves to provide negative feedback around Q6 and helps to ensure stability by reducing the gain of the circuit at high frequencies.

The tantalum capacitor C10 serves to filter the reference voltage. This is important since the error amplifier uses this voltage to establish the output voltage. Any ripple at the non-inverting input of IC2 will be amplified and appear at the output of the power supply. Capacitor C12 serves a similar purpose as C5 and controls the high frequency phase shift in the negative feedback loop to prevent oscillation. C8 provides compensation for IC2.

The current-limit error amplifier is formed by IC3 and associated components — C14, C9, R17 and C7. Resistor R17 and capacitor C7 simply form a low pass filter to ensure a reasonably clean supply to the op-amp. C9 compensates the op-amp and C14 provides feedback to decrease overall gain of the feedback loop at high frequencies, thereby ensuring stability when the supply is operating in the current-limit mode.

The non-inverting input to IC3 is connected to an adjustable voltage reference formed by RV1, R22 and R23. The inverting input is connected via R27 to the negative output terminal of the supply.

This op-amp is, in effect, measuring the voltage drop across the series resistance of R24, R28 and R29. This voltage is proportional to the current drawn from the supply. The amount of series resistance is switchable by the current range switch, SW2.

In the 5 A range, R24 is shorted by the switch providing a series resistance of 0.11 ohms. If for example, a 5 A current limit was desired, the current adjust pot. (RV1) would be adjusted, after depressing the current-set pushbutton (PB1) to give 5 A, and this would result in a 0.55 V reference voltage appearing at pin 3 of IC3. This op-amp then compares the reference voltage to the voltage developed across the series resistance.

IC3 will provide the appropriate output to bring its two inputs to the same voltage and, since 5 A will cause a 0.55 V drop across the series resistance, the load current will be limited to 5 A.

This assumes that the output voltage has been set high enough to force more than the desired current through the load. If this is not the case, it is impossible for the current error amp. to correct what it sees as a gross error in the current. The reference voltage at pin 3 of IC3 will be greater than the voltage at pin 2 so that the output of the op-amp is forced hard against its positive supply rail, i.e: around 12 V. This forward biases LED2, which indicates that the supply is in voltage mode. i.e: the output is controlled by the voltage pot.

If, however, the reference voltage has been set high enough so that the current flowing in the load approaches that set by the current limit potentiometer, then the current error amp takes over control of the feedback loop and maintains the output so that only the required current flows in the load.

The voltage error amp (IC2) is then incapable of correcting the output voltage and its output swings hard against its positive supply rail (12 V) in an attempt to do so. This forward biases LED3 which indicates that the supply is in current mode. i.e: the output is controlled by the current adjust pot., RV1.

The voltage meter, M1, is a straightforward milliameter arranged to measure voltage via series dropping resistors R33 and the preset RV7 — the latter being for the purpose of calibration.

The current meter, M2, is effectively a voltmeter, measuring the voltage developed across the series resistance in the negative output line of the supply. Independent presets RV5 and RV6 are provided to allow calibration of the two output current ranges.

A bridge rectifier (BR1) and two 8000u/75 V capacitors (C3, C4) provide the main supply for the regulator.

The voltage and current error amplifiers must be supplied with a 12 V rail obtained independently of the main tapped secondary winding of the transformer. This can be supplied from an auxilliary winding on the main transformer or from a second small transformer. It should be rated, at a minimum, to deliver 12 V at 150 mA, but a rating of 15 V at 200 mA provides a greater margin.

Diodes D1 to D4 rectify this supply, C1 providing smoothing. This is then regulated by IC1 to 12 V. A 5V1 zener diode connected across this supply provides the 5 V reference used by the reference inputs of the voltage and current error op-amps, IC2 and IC3.

The 'mains on' LED indicator, LED1, is powered from the +12 V rail by the series dropping resistor, R1. The output switch, SW1 permits 'turning off' the supply output without turning off the mains. ●

Next month The interesting bits come next month — putting it together, setting it up and using it. Don't miss the next exciting episode! . . . .