Protecting solid state power supplies

It is becoming increasingly important for solid state power supplies to be protected against overload and short circuits. Not just for the protection of the power supply itself, but also — and often more importantly — to prevent damage to the equipment or circuits it powers. This article reviews many of the protection methods which are available.

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The power supply is an important part of any system. It should not only be reliable and efficient in operation, with well regulated and ripple-free output, but should also possess self-protecting features. One of the most desirable features is over-current and short circuit protection. This type of protection can not only protect the power supply, but also (and usually more importantly) prevent costly damage and burnouts in the circuits to which power is supplied. In fact in most cases, overcurrent and the short circuit protection are essential characteristics of any good semiconductor power supply.

In this article, we will assume that the reader knows how to design a regulated power supply and hence will only discuss different techniques used to protect series-regulated power supplies against overcurrent and short circuit. Initially, a very simple series regulator is discussed and gradually other complex foldback types of power supplies are described.

The most common type of semiconductor power supply is the series voltage regulator. This type of regulator has many advantages over the other types and gives superior performance. Normally the load current in its entirety passes through the series pass transistor, which regulates the output voltage within very narrow limits of the designed value, irrespective of current level up to a predetermined maximum. If this current is exceeded, or a short circuit is applied to the output of the power supply, there is always a good chance that the series regulating transistor could be damaged permanently. If this transistor is big enough to withstand the overcurrent, then perhaps the rectifying diodes, or in some extreme cases power transformer might also suffer permanent damage.

A fuse, which is sometimes used for protection, is a relatively slow acting device and the semiconductors in the circuit are invariably damaged before the fuse gets any chance to act. This is because a normal fuse, unless it is semiconductor type, has a much higher thermal time constant than most semiconductors. From this it is quite apparent that protection of power supplies against short circuit and over current is something which has to be built into the design, using semiconductors only, so the protection action is fast enough for damage is prevented.

The output current and voltage characteristics most often found in series regulated DC semiconductor power supplies are shown in Fig. 1.

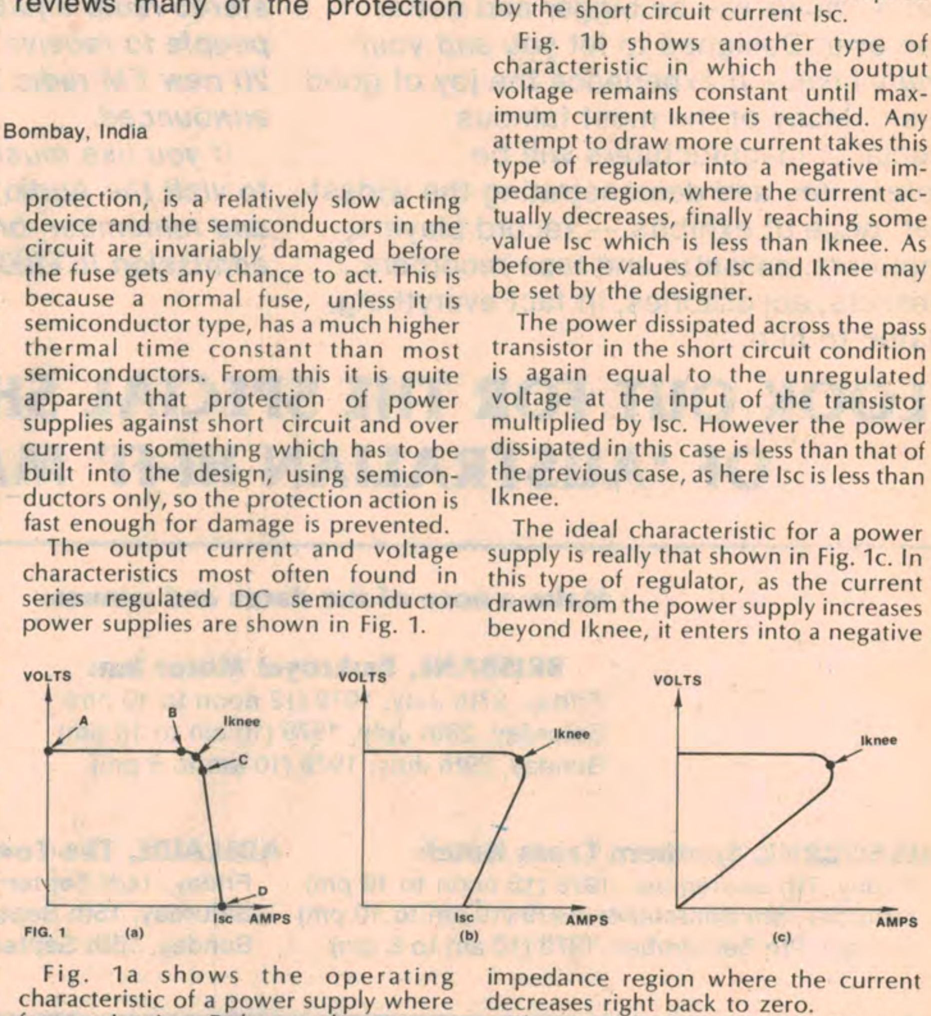

FIG. 1

Fig. 1a shows the operating characteristic of a power supply where from point A to B the supply operates as a constant voltage source. As the current increases from zero to some value Iknee, the output voltage remains constant. Any further increases in current, then causes it to change into a constant current source, and this section is shown by the curve from point C to point D. For the short circuit condition, the output voltage goes to zero and the short circuit current is limited to some value of Isc. The maximum current Iknee and the short circuit current Isc are under the control of the circuit designer.

In the short circuit condition, very high power is dissipated in the series pass transistor. The power dissipated is equal to the unregulated voltage at the input of the series transistor multiplied by the short circuit current Isc.

Fig. 1b shows another type of characteristic in which the output voltage remains constant until maximum current Iknee is reached. Any attempt to draw more current takes this type of regulator into a negative impedance region, where the current actually decreases, finally reaching some value Isc which is less than Iknee. As before the values of Isc and Iknee may be set by the designer.

The power dissipated across the pass transistor in the short circuit condition is again equal to the unregulated voltage at the input of the transistor multiplied by Isc. However the power dissipated in this case is less than that of the previous case, as here Isc is less than Iknee.

The ideal characteristic for a power supply is really that shown in Fig. 1c. In this type of regulator, as the current drawn from the power supply increases beyond Iknee, it enters into a negative impedance region where the current decreases right back to zero.

Thus at short circuit, the regulator actually turns off and supplies either no current, or negligible current to the load. Accordingly the power dissipated across the series transistor is almost nil, a most desirable situation. However, this type of regulator does not restart after removal of a short circuit and either needs a resetting arrangement or special design care to make it self starting.

The most simple type of series regulator circuit is shown in Fig. 2. where the components shown in the dashed block add current limit and

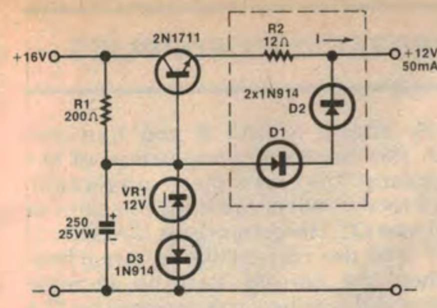

FIG. 2

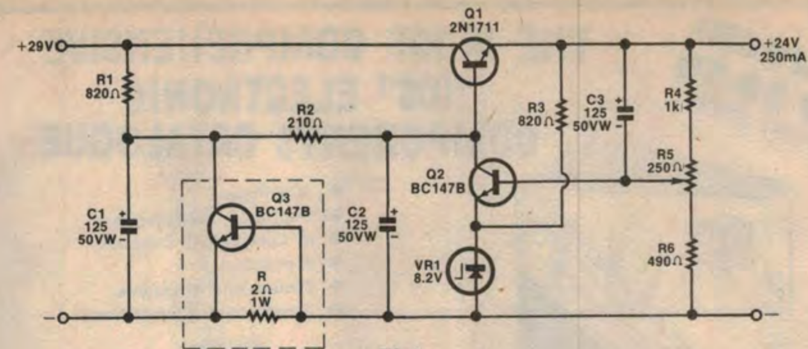

FIG. 3

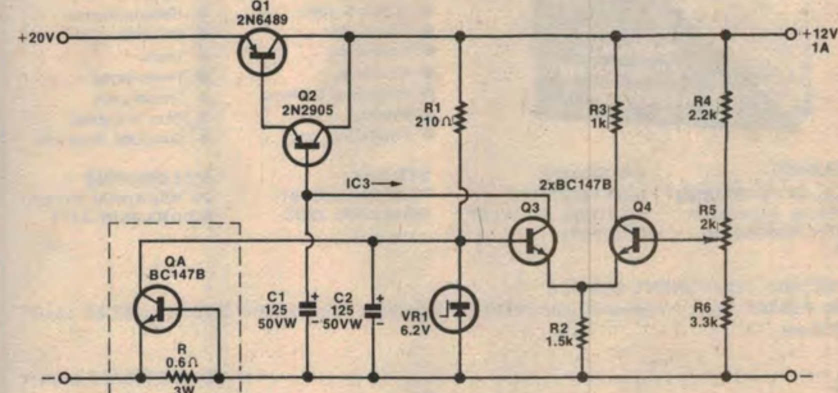

Fig. 4

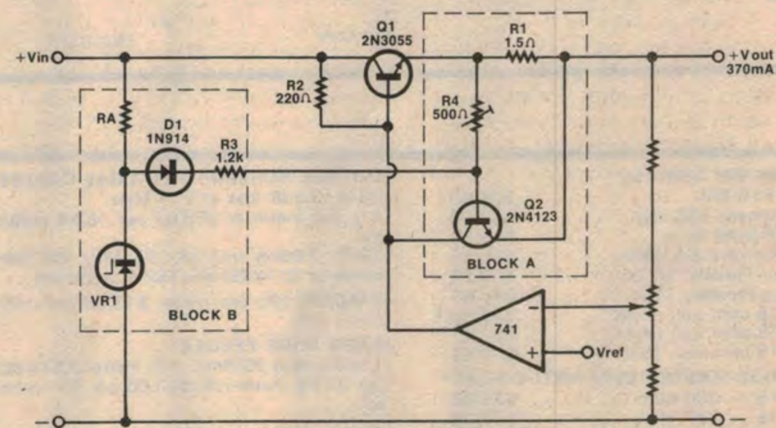

FIG. 5

hence short circuit protection. Without the components in the block, the regulator gives regulated output easily up to 100mA or more.

During normal operation, before the current limit section starts to play its part, transistor Q1 has its base-emitter junction forward biased and this keeps the transistor well inside the active region. The voltage drop across resistor R2 is negligible under these conditions. There is no current flow, or negligible current flow through diodes D1 and D2, so they do not affect operation.

As long as the current I is low and is less than Iknee, the drop across resistor R2 is very small. But when the current I starts to exceed the knee this drop increases and starts to back bias the base-emitter junction of Q1, gradually turning it off. At the same time diodes D1 and D2 start conducting. Here, diode D1 compensates for the drop across the base-emitter junction of the transistor and D2 takes care of the drop across resistor R2.

At total short circuit, the maximum current is approximately given by

$$0.6/R2 + (Vin - 1.2)/R1$$

This supply can remain short circuited indefinitely provided all the components are properly chosen for their power rating. The approximate equation for the maximum current at which regulation will hold good is given by $I = 0.6/R2$. The regulator has the characteristic shown in Fig. 1a.

A simple feedback type of series regulator is shown in Fig. 3, where Q1 is the series regulating transistor and Q2 is an error amplifier that controls the conduction of Q1 to maintain the output voltage constant. As before, the addition of transistor Q3 and resistor R makes this circuit current limiting and short circuit protected. At low output currents, the drop across R is insufficient to forward bias Q3; hence Q3 is cut off and does not affect the normal regulating function. As the output current starts to increase from zero, due to feedback action, the output voltage is maintained constant; however, at a certain value of current, Iknee, the drop across R becomes sufficient to forward bias the base-emitter junction of Q3. As the current further increases, Q3 starts conducting more and more and in doing so, it diverts base current from Q1. This reduces the output voltage and at this point the regulator converts itself from constant voltage mode to constant current mode, to take the characteristics as shown in Fig. 1a.

During a short circuit, high power is dissipated in the series pass transistor Q1 and the current sensing resistor R. Hence this particular circuit, although it protects itself from short circuits, cannot withstand a short circuit condition indefinitely. The approximate value of the short circuit current is given by

$$Isc = 0.6/R.$$

Another feedback type of series regulator, using a PNP series pass transistor, is shown in Fig. 4. Here, as before, current limiting circuit is shown in the dashed block.

Interestingly enough, this particular regulator circuit can and does function to limit the output current without the components shown in the block. And the circuit is also short circuit protected. However, the maximum current Imax given out by the regulator depends on the current gains of transistors Q1 and Q2. Imax is equal to the maximum base current of transistor Q2 times the gains of transistors Q1 and Q2. The base current of Q2 is the same as the collector and emitter currents of Q3. Therefore, the maximum output current of the regulator, in absence of transistor QA is given by

$$Imax = \beta 1 \beta 2 \, (VR1 - 0.6)/R2$$

Under short circuit conditions the action of the regulator in Fig. 4, without transistor QA, is also self-protecting. When a short circuit is applied to the regulator the output voltage is reduced to zero, so there is no bias current through resistor R1 for the zener VR1. As the reference is reduced to zero, the regulator turns off.

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By adding resistor R and transistor QA the current limiting action of the regulator becomes more predictable and totally independent of the gains of Q1 and Q2. Here, transistor QA is in cut off until the current Iknee is reached. When the current starts to increase beyond this critical value, transistor QA conducts and reduces the reference voltage of the regulator. The output voltage thus decreases.

Under short circuit conditions, QA goes fully into conduction to reduce the reference voltage to practically zero. As the reference goes to zero, the output voltage also goes to zero. The regulator operating characteristics are as shown by Fig. 1a. Again, here the approximate value of the short circuit current is given by

$$I_{sc} = 0.6/R$$

This circuit looks as if it is not self starting, because the reference operates from the output voltage. But capacitor CL gives it the self starting feature, by causing initial conduction of Q2 and Q1.

A circuit that uses the popular NPN type of series pass transistor is shown in Fig. 5. In this particular circuit current limiting and short circuit protection are

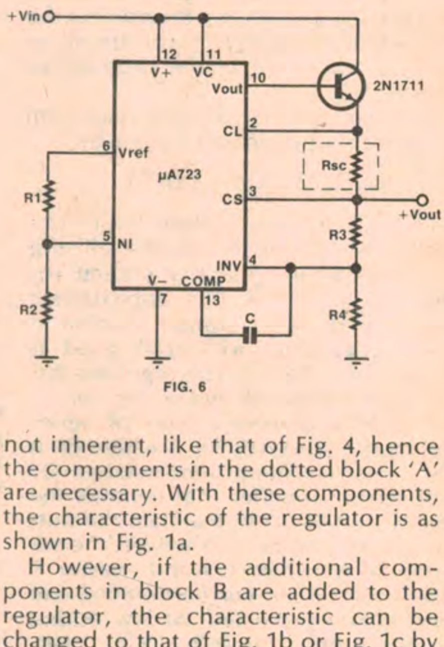

FIG. 6

not inherent, like that of Fig. 4, hence the components in the dotted block 'A' are necessary. With these components, the characteristic of the regulator is as shown in Fig. 1a.

However, if the additional components in block B are added to the regulator, the characteristic can be changed to that of Fig. 1b or Fig. 1c by simply varying resistor value RA. When the value of RA is a maximum the characteristic is as per Fig. 1c, while when RA is a minimum it changes to Fig. 1b. However when RA is maximum the circuit needs resetting and starts only when RA is reduced.

With the availability of voltage regulator ICs such as the popular 723 the design for overcurrent and short circuit protection has become very simple. The recommended circuit for a simple 723 voltage stabilizer is shown in

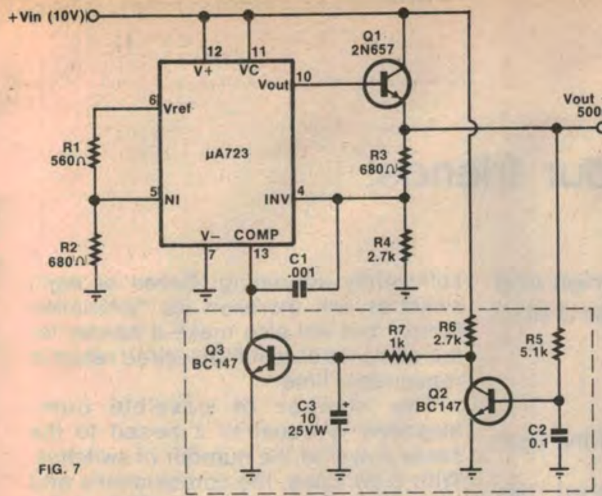

FIG. 7

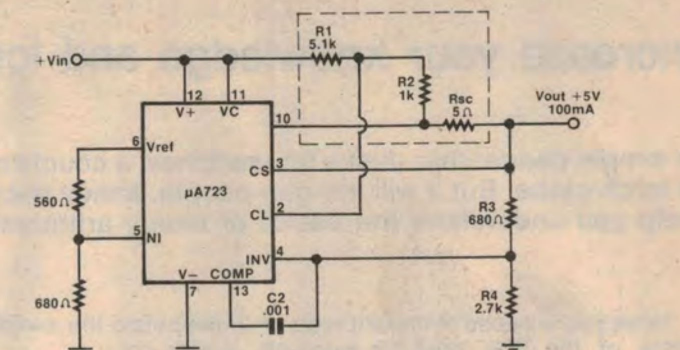

FIG. 8

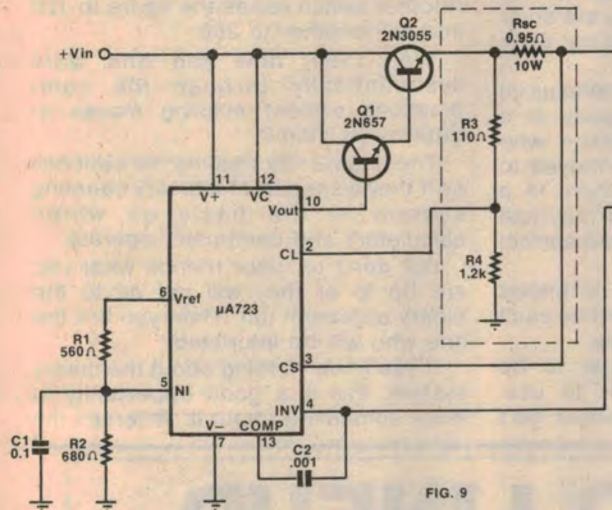

FIG. 9

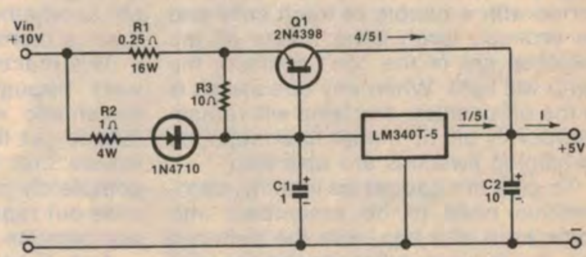

FIG. 10

Fig. 6, where R4 is to be removed for output voltages from 2 to 7 volts. Here resistor Rsc is used for current limiting action and the equation is given as Isc = Vsense/Rsc. For higher current outputs additional external transistors are required.

The circuit shown in the dashed area of Fig. 7 is useful for short circuit protection, although it does not give overcurrent protection. Under normal conditions, transistor Q2 is 'ON' and Q3 is 'OFF'. When the output is shorted, Q2 turns off and in turn switches Q3 on. Thus the base drive for series transistor Q1 is cut off by the IC, to reduce the output current to zero.

Initially, when the power is turned on, the collector of Q2 gets the supply slightly before the base of the same transistor. This could prevent the regulator from turning on, as Q3 would prevent base drive to Q1. This is prevented by the use of the delay network formed by R7 and C3.

As an alternative to standard current limiting techniques foldback current limiting, as shown in Fig. 1b, is an advantage in any power supply situation where the allowable output device power dissipation under short circuit conditions is restricted due to device and/or heatsink limitations. This is especially true for high current regulators. A minimum parts method for doing this with a 723 regulator is shown in the dashed block of Fig. 8. Here three resistors provide the positive feedback necessary for foldback action. This technique introduces positive feedback by the increased current flow through the R1-R2 leg under short circuit conditions. Short circuiting the output causes the circuit to latch up. Reset is achieved by turning the power supply off and then on again to restore normal operation, after the short is removed.

Another method of providing foldback current limiting is shown in Fig. 9, in which the base of the current limit transistor in the 723 is fed from potential divider R3-R4 as shown in the dashed block. With this circuit there is a restriction on obtaining very low short circuit currents, whereas the previous circuit is designed to give approximately zero short circuit current. However this circuit has automatic restart and no resetting is necessary.

The foldback circuit will severely limit the knee current if the difference between Vin and Vout is small. This problem is accentuated by the relatively large value of Rsc, which develops a considerable voltage drop at Iknee and worsens the load regulation. The voltage drop in Rsc is in addition to the minimum voltage drop normally allowed between Vin and Vout. Since R3 and R4 both must be positive it can be proved that the minimum ratio of Isc to Iknee is

$$\frac{I_{sc}}{I_{knee}} \geq \frac{V_s}{V_{out} + V_s}$$

where

Vout = regulated output voltage

Vs = turn-on voltage for the current limit transistor (0.6V)

One last circuit that should be considered is shown in Fig. 10, where a three-terminal LM340T-5 IC regulator is used. This IC regulator chip by itself gives a fixed output of +5V with maximum output current of 1.8 amp. It has built-in over current and short circuit protection.

The current from the chip may be increased by adding the circuitry shown. Here the ratio of R2 to R1 gives the approximate current ratio of transistor current to IC current. In this case it is 4amp to 1amp. Under short circuit condition maximum current through the circuit is 9 amps, out of which 1.8 amps comes from the IC and 7.2 amps come from the current boosting transistor.

The full current limiting and protection capabilities of the regulator IC are retained in this circuit at the higher current levels, because the IC's input current constitutes the current drive for the base of Q1. Hence when the IC throttles itself back under overload conditions, it also throttles back Q1.