CHAPTER 3

Regulated Power Supplies

3.1 Regulated Power Supplies

The power supplies considered in this chapter are electronically regulated supplies designed for ac and dc inputs and outputs. Included are series-pass dc-output voltage regulators, switching-mode dc-output voltage regulators, dc-output current regulators and ac rms voltage regulators. The purpose of a dc regulator is to maintain a constant ripple-free dc output for changes in input voltage, load impedance, and temperature. The device used as the regulator control can be either in series with the load or in shunt with the load. Shunt regulators are not considered here since their low efficiency limits their practical usage to regulators with low output voltages and fairly constant loads. If the regulating element is to maintain continuous control of the output voltage, then the device must be a transistor. If the regulator is to operate in the switching mode and the primary power source is dc then a transistor is also the best choice for the control element. If the primary power source is ac then either a thyristor or a transistor (a rectifier must precede the transistor) can be used as the switching element.

Series Pass Regulators

The ideal voltage-regulated power supply would have a zero output impedance so that the output voltage would remain constant for any load current requirements. A zero output impedance cannot be achieved although supplies with output impedance levels on the order of milliohms can be constructed. The properties of semiconductor devices place a limit on the maximum current and voltage that can be supplied to a load; these two parameters are dependent on each other and upon the particular circuit used as a regulator. Two simple series-pass voltage regulators are shown in Figures 3-1 and 3-2. Transistor Q1 in each of these circuits is required to buffer the difference between the unregulated input voltage and the required output voltage, thus the collector-emitter voltage rating of the device used for Q1 determines the maximum input and output voltage. The current delivered to the load must pass through Q1. Therefore

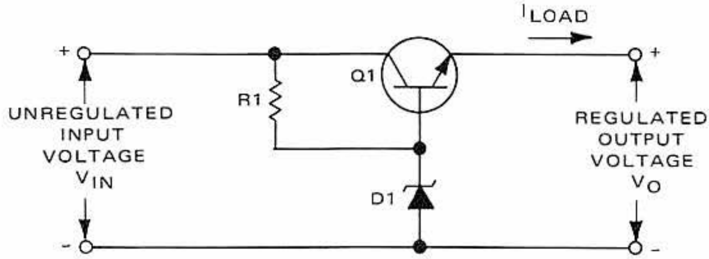

Figure 3-1 – Simple Series-Pass, Fixed-Voltage Regulator

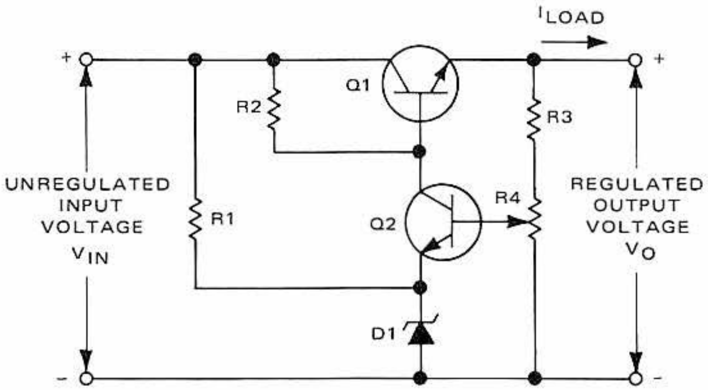

Figure 3-2 – Simple Series-Pass, Variable-Voltage Regulator

the average power dissipated in Q1 is (V_{in} - V_{out}) times I_{LOAD}. If high input voltages and low output voltages and/or large load currents are required, large amounts of power can be dissipated in Q1. Obviously under these conditions, the regulator efficiency will be low. The power rating for the particular heat sinking used, therefore, limits regulating capacity. For limited load variations a resistor may be placed in shunt with Q1, thus shifting some power from Q1 to the resistor. For any input supply voltage and output load combinations, the safe operating area of Q1 must not be exceeded. (See Motorola Applications Note AN415.) The output voltage of the circuit shown in Figure 3-1 is the zener voltage minus the base-emitter voltage of Q1. R1 must provide enough current to the base of Q1 and to D1, to keep the voltage of D1 above its breakover point at all times. If the voltage versus temperature characteristic of D1 is equal and opposite to that of the base-emitter junction of Q1, the output voltage will remain constant with temperature. If a variable output voltage is required, then a circuit similar to that shown in Figure 3-2 can be used. The lowest output voltage attainable is the breakdown voltage of D1 plus the base-emitter voltage of Q2, if R3 is small compared to R4. The highest output voltage is limited by the lowest excursion of the unregulated input plus enough voltage to provide adequate drive to Q1 through R2. R1 provides bias current to D1; having its voltage compared to that at the potentiometer arm through Q2. If the load increases, thereby decreasing the regulator output, Q2 will conduct less and Q1 will conduct more, thus restoring the voltage to the original level.

If the requirements of the regulator are greater than one transistor can handle, then the power section of the regulator may be as shown in Figure 3-3 or 3-4.

Series operation of several transistors can be used to decrease the power dissipation in each unit or to regulate voltages greater than one transistor can withstand. Since the transistors all carry the same current, the voltage must be divided equally to equalize individual power dissipations and to prevent one device from failing due to operation outside its safe area. Resistors connected between the bases of each transistor can be used to equalize the voltages, but the power dissipation in the resistors can be excessive for high output current and for wide fluctuations in output voltage such as expected in series regulator service. Transistors which can withstand 700 V are presently available. If voltages above this are required, then series transistor operation can be used.

The controlled device for the circuit shown in Figure 3-3 is Q2. The maximum voltage across Q2 is the breakdown voltage of zener diode D1 minus the base-emitter voltage of Q1, thus the maximum power dissipated in Q2 is easily controlled. Q1 and shunt resistor R2 must now withstand the remainder of the total series pass voltage. The higher this voltage becomes, the greater is the share of the total current which passes through R2. Therefore, both the power and the safe operating area of the transistors have been reduced. Only two transistors are shown, but more can be placed in series if required.

The circuit shown in Figure 3-4 will deliver load currents greater than that possible with a single device, since the series-pass transistors are placed in parallel. The major problem with this connection is having the current divide equally between Q1 and Q2 in order to equalize power dissipations. To achieve this, either the transistors must be matched or feedback must be used to compensate for individual characteristics. Resistors R1 and R2 provide such feedback at the expense of increased power loss in the resistor; also, more control signal is required. However, a bonus of this connection is that the thermal stability of the regulator is improved. The maximum output-to-input voltage is limited by the collector-emitter voltage rating of the transistors used. Again, only two transistors are shown, but more can be paralleled if required.

Basic limitations of series-pass regulators are maximum current, voltage and power dissipation ratings, and safe operating area of the series control transistor. The design of the particular circuit and the components used control the degree of regulation, output impedance, temperature coefficient and other parameters mentioned.

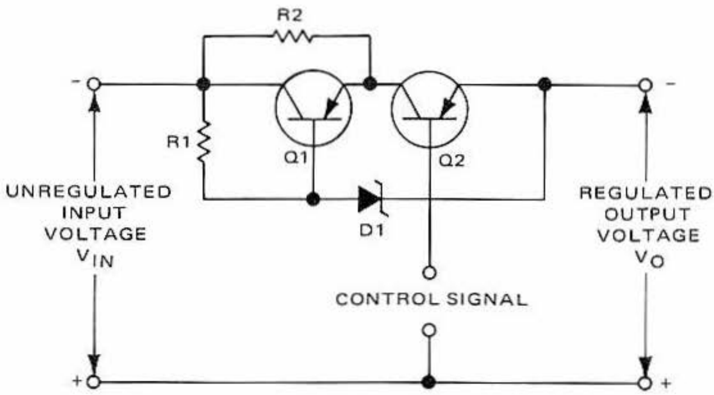

Figure 3-3 – Typical Series-Connected Transistors with Power-Dissipation Resistor

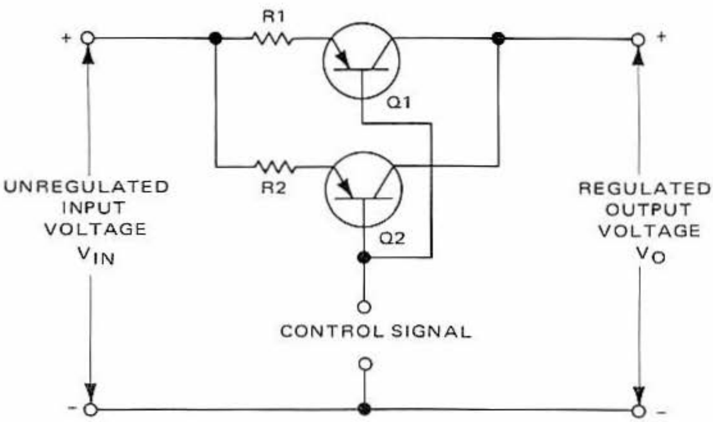

Figure 3-4 – Typical Parallel-Connected Transistors Used in a Regulator

Series-pass regulators can provide extremely good regulation, fast response time, low output impedance and low ripple. Their performance is almost independent of input frequency fluctuations and they have excellent dynamic response by virtue of transient-free output. They also can provide variable output voltage and are readily adaptable to remote voltage sensing, remote programming and current limiting or current regulation.

Switching Regulators

Switching regulators have the distinct advantage over series-pass regulators (especially at high power outputs) of low power dissipation in the main control device. Since the series control element is either saturated or off, it has a low forward voltage drop when conducting load current, and only leakage current flowing when it is not conducting. Thus, transistor power dissipation is small, and this results in high regulating efficiencies. Either transistors or thyristors can be used as the controlled element if appropriate drive circuits are employed. The basic factors limiting the regulator voltage and current are the voltage and current specifications of the controlled power element. The drive requirements and operating characteristics of transistors naturally make them ideal for application in dc input and dc output regulators while the natural application of thyristors is in ac input regulators. Transistor circuits have the advantages of simple circuits, no commutation problems, no dv/dt nor di/dt problems, low saturation voltages, and fast switching speeds with consequent high frequency operation. Thyristor circuits are capable of handling high voltages (to 1500 volts) and high currents (to 400 amperes), require low average driving power at low frequencies and have no safe operating area problems. Switching regulators must be followed by adequate filtering and/or regulation to keep output ripple low. For this reason, switching regulators provide excellent, efficient preregulation to reduce the voltage across and the average power dissipation of series pass regulators.

The important switching transistor parameters are switching speed, pulse safe operating area, high-temperature collector-leakage current, dc gain, $V_{CE(sat)}$ and $V_{BE(sat)}$. The predominate power dissipated in the transistor is that which occurs during the switching time. This power loss is a function of the frequency since the higher the frequency, the higher the proportion of the total period the switching interval becomes. The load line during the transition time determines the safe operating area required of the transistor.

If the circuit elements will force the transistor to exceed its safe operating area, then protection must be provided for reliable operation. The transistor can be protected by connecting a capacitor or zener diode between the collector and emitter terminals of the transistor. If a zener diode is used, it should have a breakdown voltage greater than the supply voltage but less than the collector-emitter sustaining voltage. If a capacitor is used, its capacitance must not be too high as it may cause excessive charging currents and slow the transistor switching response. Another protective method is to use a free-wheeling diode as shown in Figure 3-5 by D1. For some cases a capacitor can be used in place of the diode, but again it is subject to the conditions above. The voltage requirement resulting from full input voltage being sustained by the switching transistor limits present regulators to about 400 volts at 4 amperes. A typical transistor switching regulator circuit is shown in Figure 3-5. The circuit is connected so that the Schmitt trigger turns Q2 on when the voltage at the arm of R3 falls below the Schmitt triggering voltage. This turns Q1 on and increases the output voltage, and thus the voltage at the arm of R3. When this voltage exceeds the Schmitt triggering voltage, then Q2 and thus Q1 are turned off. While Q1 is off, free-wheeling diode D1 conducts so that current in inductor L1 is preserved. This increases the effectiveness of the filter and prevents excess voltage on Q1. The frequency of operation is a function of the filtering capability of L1 and C1 and the load. The output ripple is a function of the feedback factor from R3 and R2 to the triggering level of the Schmitt trigger.

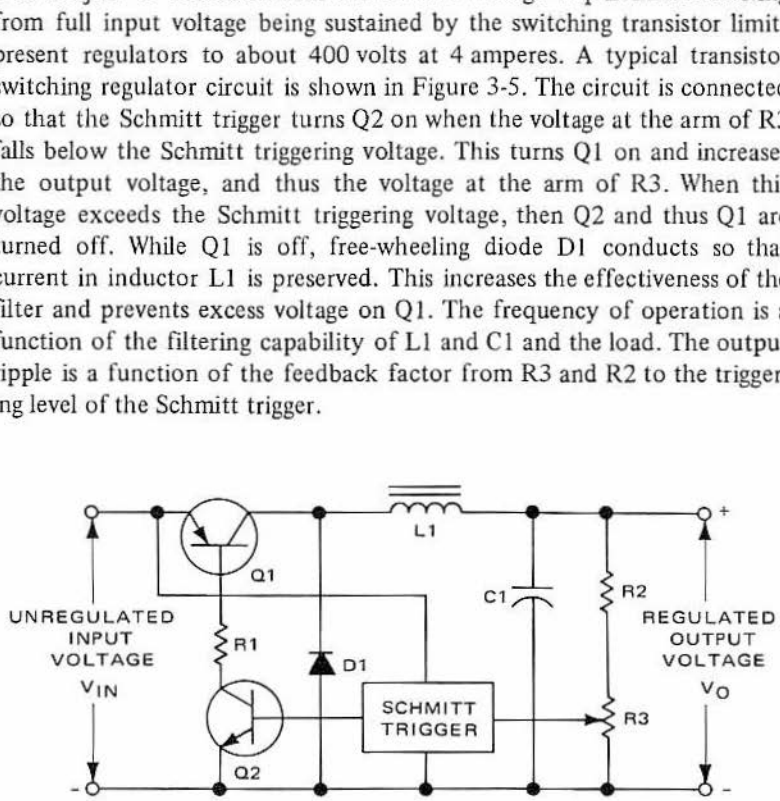

Figure 3-5 – DC-Input Switching Voltage Regulator

Silicon controlled rectifiers are useful as the main control element in phase-controlled regulators. Regulation is achieved through phase control by adjusting the portion of the half sine wave during which conduction occurs. Because this is a fraction of the 60 Hz sine wave, extensive filtering is required to achieve low output ripple. Phase control is highly efficient since the SCRs are either on or off and have a low power dissipation in either condition. Also, low average power is required to drive the SCRs.

SCR regulators are most useful for high current supplies in which the high current would impose severe requirements upon transistors, and for phase-controlled preregulators for series-pass voltage regulators. The SCR turns off every time the current through it goes to zero and is held there for a few microseconds. Therefore a circuit which is sensitive to the line voltage must be used to turn on the SCRs every half cycle (for full-wave control). The function of this circuit is to compute the required conduction angle for each half cycle of input voltage so the output voltage remains constant for any combination of changes in input voltage, output voltage and output current. Since this firing control circuit functions each half cycle, it provides correction for sudden changes in line voltage or load current by altering the timing of the trigger pulse which occurs during the next half cycle of supply voltage. It is desirable to operate the SCR into an inductor to limit the inrush current when the SCR is turned on, since this improves reliability and suppresses electromagnetic interference (EMI). Generally the filter will reduce the EMI on the load; however, a high frequency capacitor across the regulator output may be desirable to bypass any high frequency switching effects on the SCR.

A typical SCR regulating circuit with ac input and dc output is shown in Figure 3-6. SCRs Q3 and Q4 are connected in a bridge to deliver energy to the filter each half cycle of input voltage. Inductor L1 limits the input surge current when either SCR is turned on. A portion of the output voltage (as determined by R4 and R5) is compared to the zener voltage of D6; the difference controls the conduction of Q1, which sets the charging rate of C1 and thus the firing point of Q2 each half cycle. T1 couples the firing pulse from Q2 to the SCRs. D3 and D4 in conjunction with D1 and D2 form a full wave bridge which synchronizes the operation of the firing control circuit to the line. Which SCR comes on is determined by the polarity of the line voltage.

Phase-controlled operation of SCRs is not limited to dc output regulators; it can be used to regulate the rms value of an ac output voltage. A problem is encountered in the method of detecting the rms voltage delivered to the load. This value is difficult to measure due to the irregular waveshapes generally encountered. An irregular waveshape forces some form of integrator to be used to obtain a usable feedback signal. This restricts the response time of the regulator to several cycles of input voltage, limiting its usefulness in compensating for over-voltage and increased load current requirements. Since the line voltage has a uniform waveshape, its rms value is easily detectable and can be used to provide a control signal to regulate the output voltage. However, this does not provide any feedback thereby restricting its usefulness to a narrow range of input voltages.

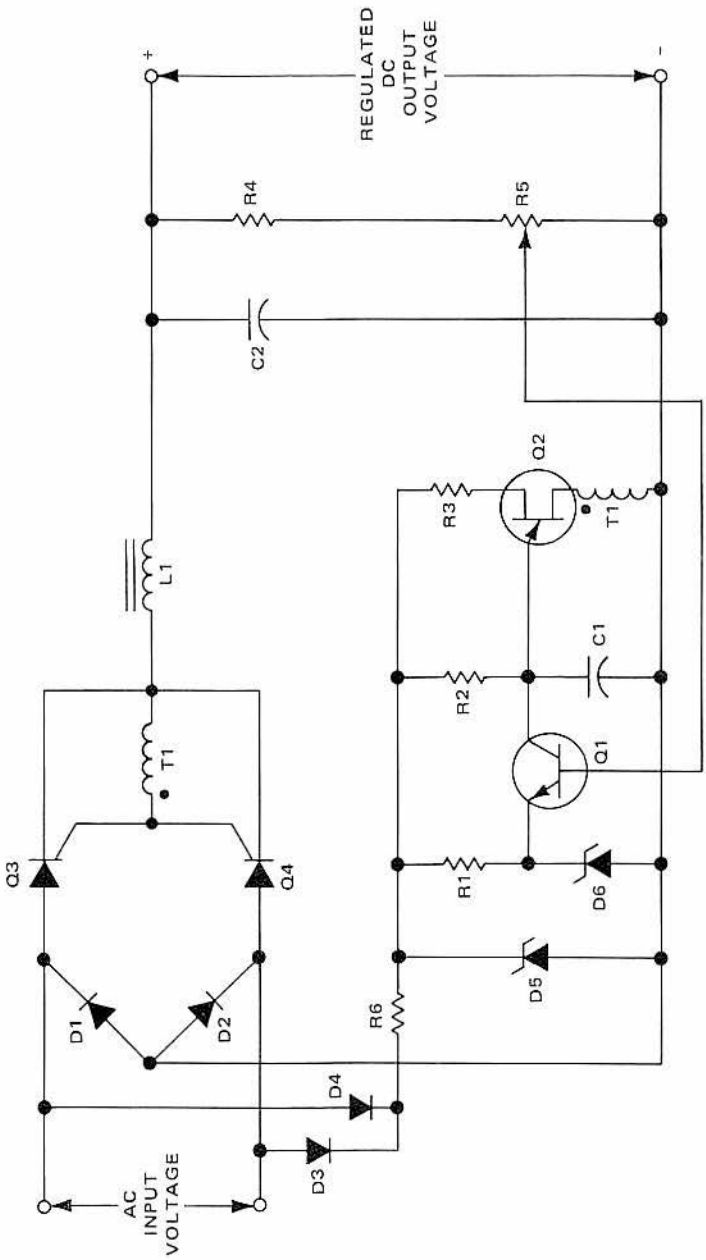

Figure 3-6 — Phase-Controlled DC Voltage Regulator

Current Regulators

The dual of a *voltage* regulated power supply is one that regulates the output *current*. The ideal current source would have an infinite internal impedance and if open-circuited, would produce an infinite voltage. Practically, the devices used as the regulator elements limit the maximum current and voltage that can be delivered to the load. In many instances current regulators are coupled with voltage regulators to limit the maximum current to a load and thus protect the regulator components and the load. Current is regulated indirectly by regulating the voltage developed by the load current across a resistor in series with the load.

For constant output current, the voltage across the resistor must be constant. If the power dissipated in the resistor is sufficient to change the resistance, then current is changed also. The sensitivity of the circuit depends on the gain of the circuits and the size of the resistor. Thus the working voltage can be increased for higher sensitivity at the cost of increased power dissipation, or the gain of the comparison amplifier can be increased with a result of a poorer signal-to-noise ratio. A compromise must be made for any given regulation range.

The circuit shown in Figure 3-7 demonstrates a method of current limiting. Q1, R1, and D1 form a simple voltage regulator. The output current is sensed by R2, which develops a voltage which controls Q2. As the output current increases, Q2 turns on harder and robs base current from Q1. The level to which the output current is limited is equal to the forward base-emitter voltage of Q2 divided by the value of R2.

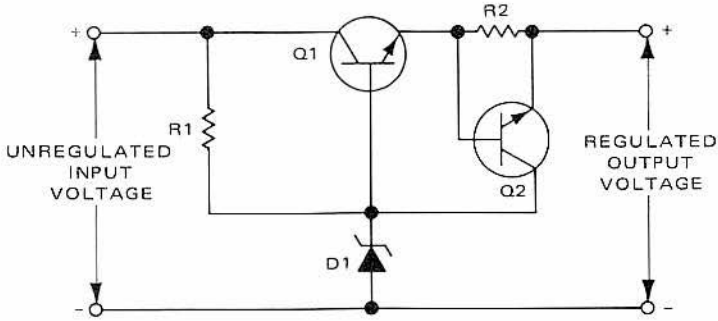

Figure 3-7 – Current-Limited Voltage Regulator

Figure 3-8 shows the circuit of a simple current regulator. Zener diode D1 and resistor R2 set a voltage across R1 equal to the zener voltage minus the base-emitter voltage of Q1. The level at which the output current is regulated is the voltage across R1 divided by the value of R1. Obviously the input voltage must be greater than the zener voltage for regulation to occur.

For low level current regulation, a current-regulating diode can be used as shown in Figure 3-9. This device will maintain a fairly constant load current for an input voltage variation from the knee to the maximum power point. This device is the dual of the zener diode in that it is a regulator for current rather than voltage.

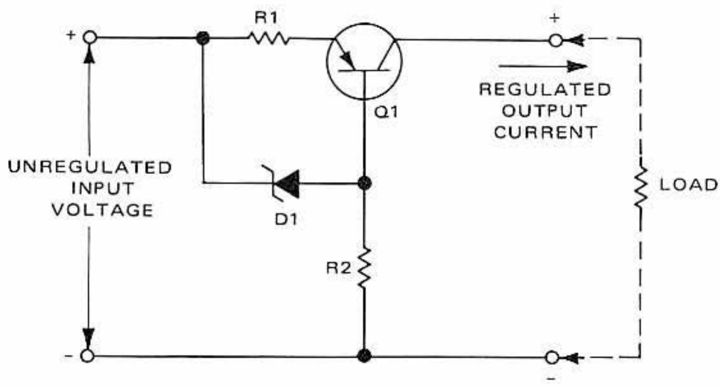

Figure 3-8 – Simple Current Regulator

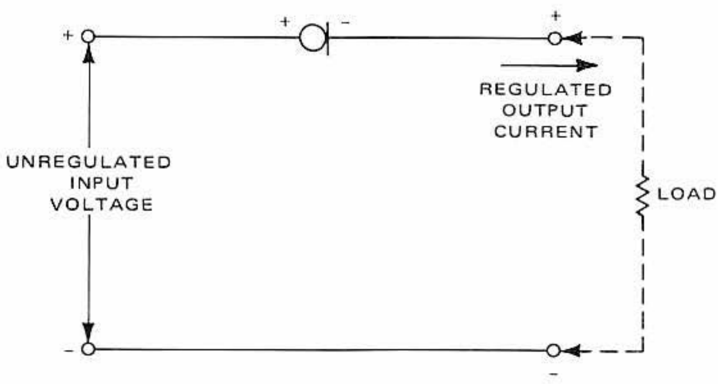

Figure 3-9 – Current Regulator Using Current-Limiting Diode

3.2 11-32 V Output Regulated Power Supply With Overcurrent Protection

The circuit shown in Figure 3-10 is a regulated power supply with overcurrent protection and an output of 11-32 Vdc. The maximum output current with the specified circuit components is 700 mA. The diode bridge of D1 through D4 provides full-wave rectification of the 25 volt secondary of T1. Capacitor C1 is used to reduce the ripple of the rectified current thereby holding a positive voltage on the collectors of Q1 and Q2. Resistor R1 and capacitor C2 further reduce the ripple in order to maintain a pure dc voltage as a collector supply for Q3 and Q4, and for driving the base of Q1. Series-pass transistor Q2 regulates the output voltage. The resistive divider, R4, R5, and R6, is a sensing network. The voltage at the arm of potentiometer R5 is applied to the base of Q4, which compares the voltage to that of zener diode D5. The difference between the two voltages determines the degree of conduction of Q4. If the output voltage increases, then the base voltage of Q4 increases, turning it on more. This reduces the base current of Q1, which in turn reduces the conduction of Q2, thereby lowering the output voltage. If the output voltage drops, Q4 begins to turn off, which turns Q1 and Q2 on, thereby increasing the output voltage. In essence, the circuit is a feedback amplifier which tries to maintain the output voltage at a constant level independent of load condition.

The output voltage is determined by the potentiometer setting according to the following formula:

$$V_{out} = \frac{(V_{D5} + V_{BE}\,Q4)\ (R4 + R5 + R6)}{R6 + R5\ (\text{Setting})}$$

If R5 is set at the low end (A), the output is maximum and is given by

$$V_{out(max)} = \frac{(10.7)\,(24.2\text{k}\Omega)}{8.2\text{k}\Omega} = 31.7 \text{ volts.}$$

The minimum output voltage occurs when the arm of R5 is set to the high side (B), or

$$V_{out(min)} = \frac{(10.7)\,(24.2\text{k}\Omega)}{23.2\text{k}\Omega} = 11.2 \text{ V.}$$

The regulation is a function of the potentiometer setting since this determines the amount of feedback. The closer the base of Q4 is to the positive output the more feedback and the better the regulation will be.

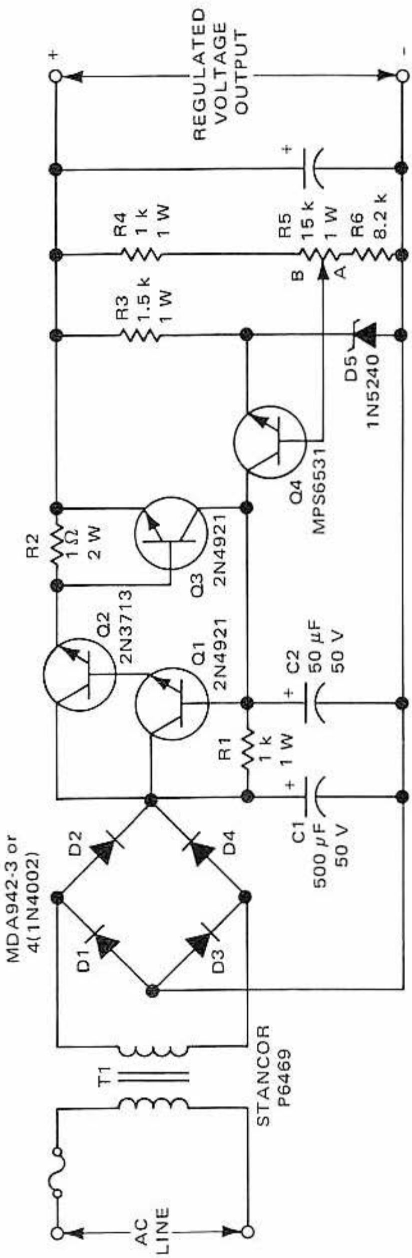

Figure 3-10 – Variable 11-32 Vdc Voltage-Regulated Power Supply with Overcurrent Protection

The overcurrent protection is provided by R2 and Q3. Since R2 is in series with the output, the voltage across it is proportional to the output current. This voltage is used to drive Q3 so that the larger the output current becomes, the more Q3 turns on. When Q3 comes on, base drive is removed from Q1 which turns off power regulator Q2 thus limiting the output current. The values were chosen to limit the maximum current to approximately 700 mA. The curves shown in Figure 3-11 show the effectiveness of the current limiter.

The load regulation obtained for several output voltages is shown in Figure 3-12. The overcurrent circuit actually degrades the performance of

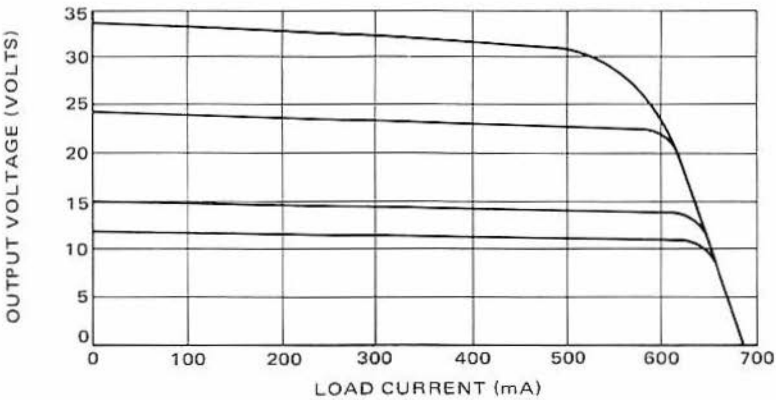

Figure 3-11 – Voltage Output versus Load Current for Regulator of Figure 3-10

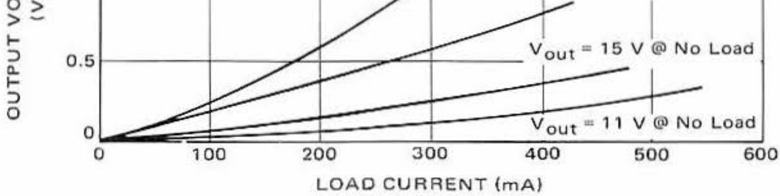

Figure 3-12 – Regulation versus Load Current for Regulator of Figure 3-10

the regulator circuit, particularly at the higher current levels, since it decreases the base drive of Q1.

The power stage of Q1 and Q2 was selected to have a high gain at −55°C in order to maximixe the control the voltage regulator and current regulator exerts on the power stage. At maximum output voltage and at low temperatures, Q1 requires a base current of about 1 mA. R1 was selected to deliver approximately 2.5 mA. This sets the minimum voltage regulator current in Q4 at 1.5 mA, when the current regulator is not working. When the current regulator, Q3, comes on, it must handle this current. For the opposite condition at high temperatures and low output voltages, R1 provides about 25 mA maximum current. The drive requirement for the power stage is not critical here, but Q3 and Q4 must be able to handle this current for effective control.

The maximum temperature at which the circuit will operate is set by the heat sinking of Q1 and Q2. If these transistors are mounted directly to a heat sink and a good silicone grease is used, then the worst-case temperature rise above the temperature of the heat sink for Q2 is 25°C, while that for Q1 is about 20°C. Since the maximum operating temperature of Q1 is 150°C, this means the heat sink temperature must be kept below 130°C.

3.3 24 Vdc Switching Voltage Regulator

The blocking-oscillator voltage regulator shown in Figure 3-13 produces an output of 24 volts ±1% for currents from 100 mA to 2 amperes. The power switching transistor(Q1) is controlled by the feedback winding of T1 and transistors Q2 and Q4. Initially Q4 turns on, which turns on Q2 and this turns on Q1. This supplies energy to the output pi filter consisting of C3, C4, and L1. The output voltage is fed back to one side of the differential voltage comparator consisting of Q3 and Q4. This voltage is compared to that of zener diode D1, the difference controlling the conduction of Q4, and thus of Q2 and Q1, thereby completing the feedback loop. Q2 was selected to be a high speed switch to work in conjunction with the high-gain voltage-comparator transistors to minimize loading the supply and thus maximize the efficiency. Reverse bias is provided to Q1 by C1 and R2. This helps turn Q1 off once it has started to go off due to T1 becoming saturated and thus reversing the base drive voltage. The fall time of the collector current for Q1 is approximately 1/2 microsecond. Diode D3 is a free-wheeling diode which allows current to continue through the load when Q1 is off. D3 must be a fast-recovery diode to minimize the reverse current through it, which occurs while it is turning off when Q1 is again turned on. This increases the efficiency of the

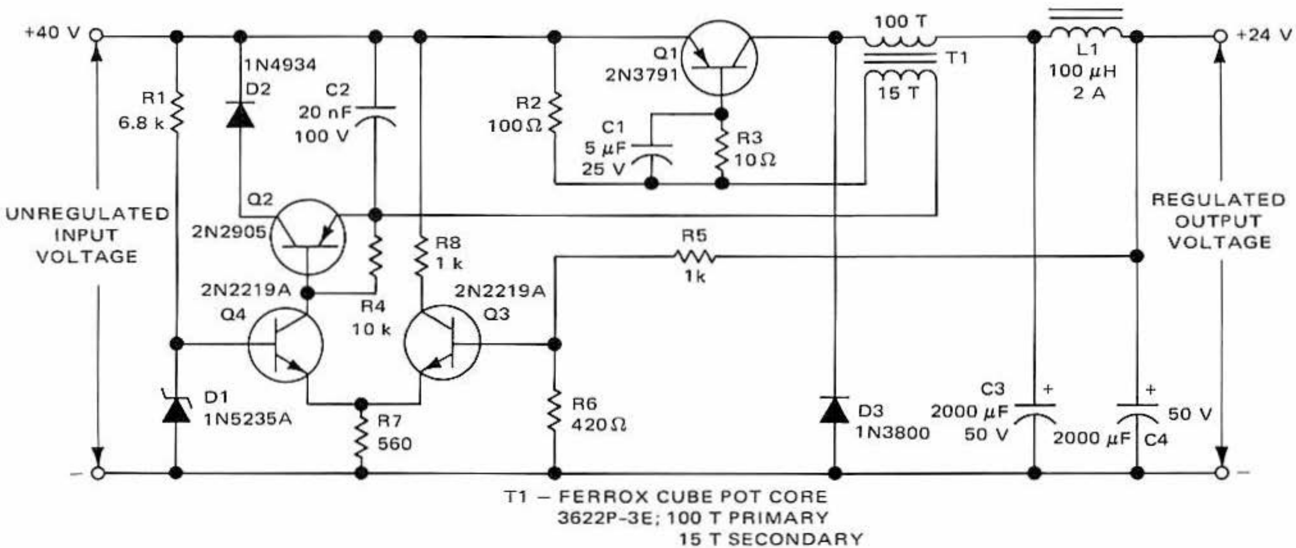

Figure 3-13 — 24 Vdc Switching Voltage Regulator circuit since load current is maintained by C3 and L1 in addition to C4, when Q1 is both on and off. The maximum voltage that Q1 must withstand is the supply voltage plus the forward voltage drop of D3. As the output voltage is decreased, the feedback voltage available from T1 is increased; this can cause the peak current through Q1 to increase for a given supply voltage. This increased drive to Q1 can be reduced by allowing Q2 to come out of saturation where the high drive conditions exist. If changes are made in the circuit values, then these conditions as well as the load-line stress on all transistors must be considered for reliable operation.

The maximum frequency of the blocking oscillator is limited by the transformer used; it is 6 kHz for this circuit at the higher input voltages. The peak collector current of Q1 is 5 to 7 A depending on the input voltage and transistor gain. The safe operating area of Q1 must be able to withstand this stress. For high efficiency the switching time and the saturation voltage should be minimized. A 2N3791 was selected for Q1, since its switching time is less than 500 μs, $V_{CE(sat)}$ is about 1 V, and it is fairly inexpensive.

The performance curves of Figure 3-14 show that the 24 volt output is regulated within ±1% for a load current range of 100 mA to 2 A and for supply voltage changes of ±10%. The efficiency as shown in Figure 3-15 is approximately 85% for currents in excess of 1 ampere at the nominal input voltage (40 volts) and for a 10% supply voltage change at 2 amperes of load current. Additional gain in the voltage sensor may improve the

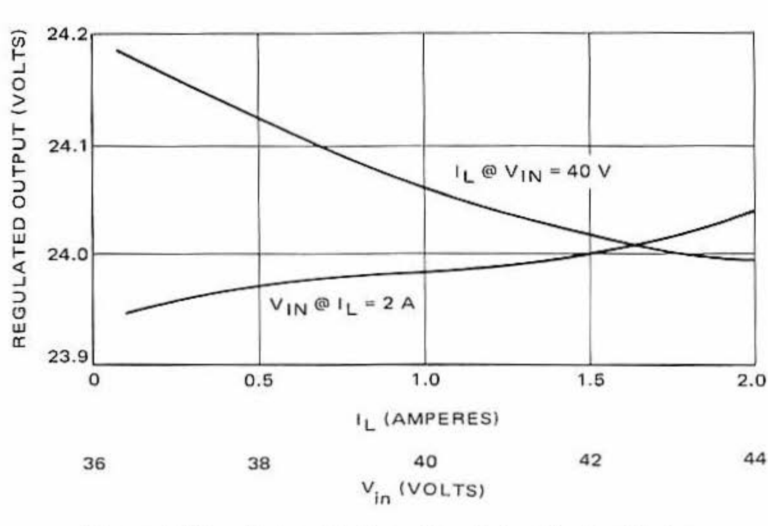

Figure 3-14 – Output Voltage Regulation for Switching Regulator of Figure 3-13

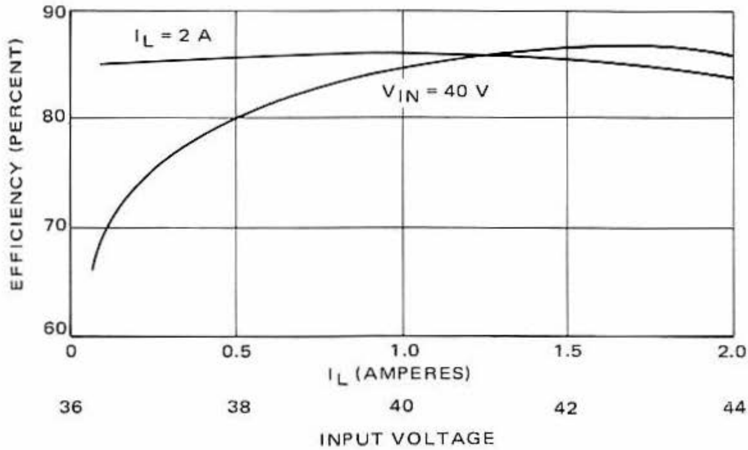

Figure 3-15 – Efficiency for Switching Voltage Regulator of Figure 3-13

regulation, and a lower dc resistance in the transformer should increase the efficiency. If any changes are made, enough current must be supplied to the base of Q1 to start the circuit oscillating.

3.4 20 Vdc Switching Voltage Regulator With Inverted Output

The inverted-output switching regulator shown in Figure 3-16 provides a 20 volt output that is regulated to within ±1% over a load current range of 50 mA to 1 amperes. The basic circuit of the power section is a blocking oscillator formed by Q1 and T1; its drive is obtained by feedback from the output. Initially Q1 is turned on from current through Q3, R4, the base-emitter junction of Q2, T1, and R1. As collector current is drawn through the primary of T1, more base drive is provided by the secondary through Q2, thus turning Q1 on more and driving it into saturation. When T1 saturates, its secondary voltage reverses and removes base drive from Q1; this begins to turn Q1 off. The energy stored in C1 helps to turn Q1 off. While Q1 is off, the output pi filter is charged through D1 from the energy stored in T1. For this reason the voltage at the filter output is greater than that at the positive input terminal. Thus the output voltage is inverted from the input. Resistors R1, R2 and capacitor C1 provide reverse bias to Q1 while Q1 is off. This is necessary in order to overcome the forward bias current from Q3 through R4, the emitter-base of Q2 and the feedback winding of T1. During the time the collector

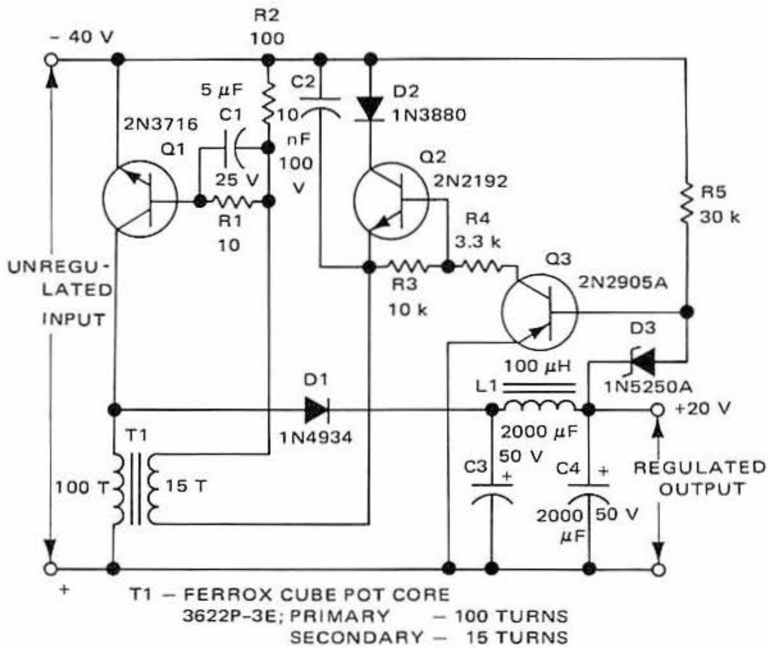

Figure 3-16 – Switching Voltage Regulator with Inverted 20 Vdc Output

current of Q1 is falling (approximately 0.5 microsecond), capacitor C2 provides a low impedance path for turn-off bias from the feedback winding.

The minimum transistor off time depends upon the decay time of the current from the transformer primary to the output filter. The current must decay to a low level before the feedback circuit will turn Q1 on.

For a given input and output voltage, and peak transistor current, the primary inductance of T1 determines the maximum frequency of the blocking oscillator. For a given filter, the higher the frequency, the lower the output ripple voltage will be. Therefore, high frequency of operation and low inductance is desirable. However, high frequencies result in high transistor power dissipation and high core losses in transformers. These factors must be considered in the design. Transformer design set the operating frequency of this circuit at 6 kHz with a peak collector current in Q1 of 5 to 7 amperes depending on transistor gain and input voltage levels. The collector-to-emitter voltage of Q1 is the sum of the supply voltage and the output voltage, so Q1 must be capable of withstanding this stress level.

In addition to this, for maximum efficiency Q1 must have a low saturation voltage and fast switching times. A 2N3716 is used as it is inexpensive and satisfies these requirements. A 2N2192 was chosen for Q2 since it is a high gain, high current switch; this is necessary since it must handle the base current of Q1, which could be about 500 mA. To minimize loading of the supply and maximize efficiency, Q3 should be a high

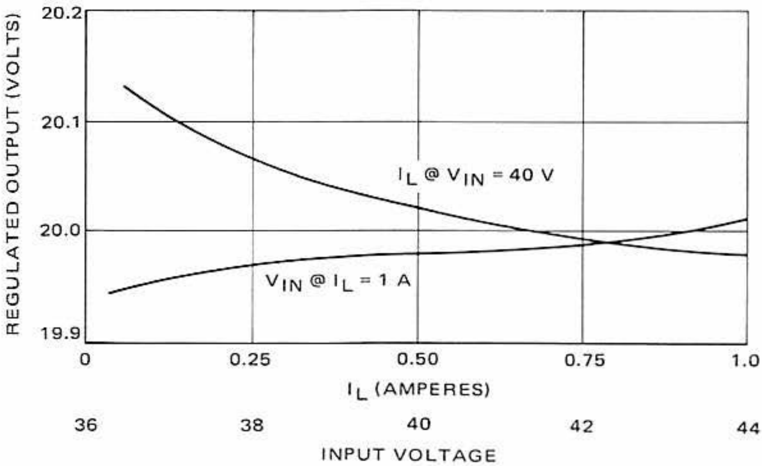

Figure 3-17 – Output Voltage Regulation for Inverted Output Switching Regulator of Figure 3-16

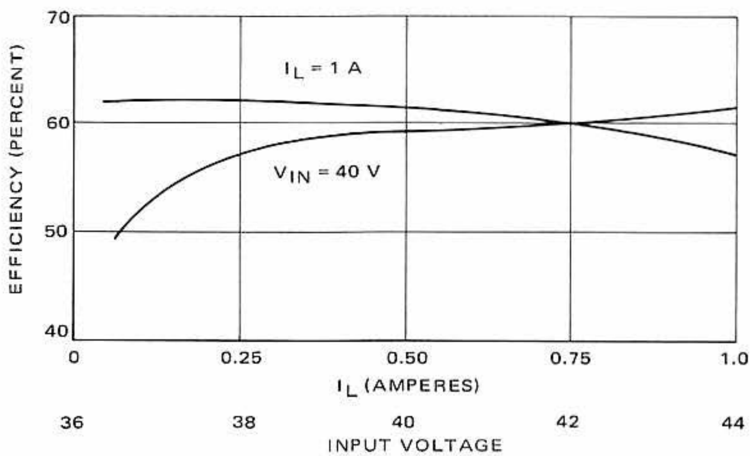

Figure 3-18 – Efficiency for Inverted Output Switching Regulator of Figure 3-16

gain, high speed switch. This requirement is satisfied through the use of a 2N2905A.

The performance curves of Figure 3-17 show the regulation is ±1% for a ±10% input voltage change at output currents up to 1 ampere. The efficiency of the circuit versus both input voltage and load current is shown in Figure 3-18. Additional gain in the voltage sensing circuit will improve the regulation. However, if any changes are made, enough current must be supplied to the base of Q1 to start the circuit oscillating. The efficiency may be improved by using a transformer with a lower dc resistance.

3.5 Pulse-Width-Modulated 38 Vdc, 5 A Switching Pre-Regulator

The pulse-width-modulated 38 Vdc, 5 ampere switching voltage regulator whose circuit is shown in Figure 3-19 utilizes the voltage sensing property of a Schmitt trigger to control the output voltage of the regulator. The Schmitt trigger is formed by transistors Q3 and Q4; Q4 is the voltage sensor and Q3 is used to provide drive for the Darlington series switch, Q1 and Q2. To start the circuit oscillating, zener diode D4 receives enough current to bias it above its knee through resistor R10. Diode D5 is used to block the load from robbing current from D4. After oscillation begins, D5 becomes forward biased and current is supplied through R9. The resistive divider, R11, R14, and R12, is used to set the dc voltage level at the output. Since the switching regulator is basically an ac circuit in that Q4 responds to changes in the output voltage, C3 is used to provde an ac bypass around the divider so that the output voltage ripple is fed to the base of Q4 with little attenuation. The level at which Q4 is turned on is governed by the difference between the voltage at the arm of R14 and the voltage across R5. The voltage on R5 is set by the zener voltage of D4, the divider consisting of R8, R7, R6, the base-emitter junction of Q3, and the small drop across R4. When the output voltage increases and the upper trigger level of the Schmitt is exceeded, Q4 turns on, which removes base drive from Q3, turning it, Q2 and Q1 off, thus removing output drive. These devices remain in this condition until the output voltage decreases and the base voltage of Q4 falls below the lower trigger level, which turns Q4 off, permitting Q3 to turn on. This provides base drive to Q2 and Q1 through R3, thus turning Q1 on. Since Q1 cannot be saturated, because of the Darlington connection, resistor R13 is used to reduce the voltage across Q1 and thereby its power dissipation. This minimizes the requirements of the heat sink for Q1. While Q1 is on, energy is stored in L1 and C2, and the output voltage is increased. When Q1 is off, free-wheeling

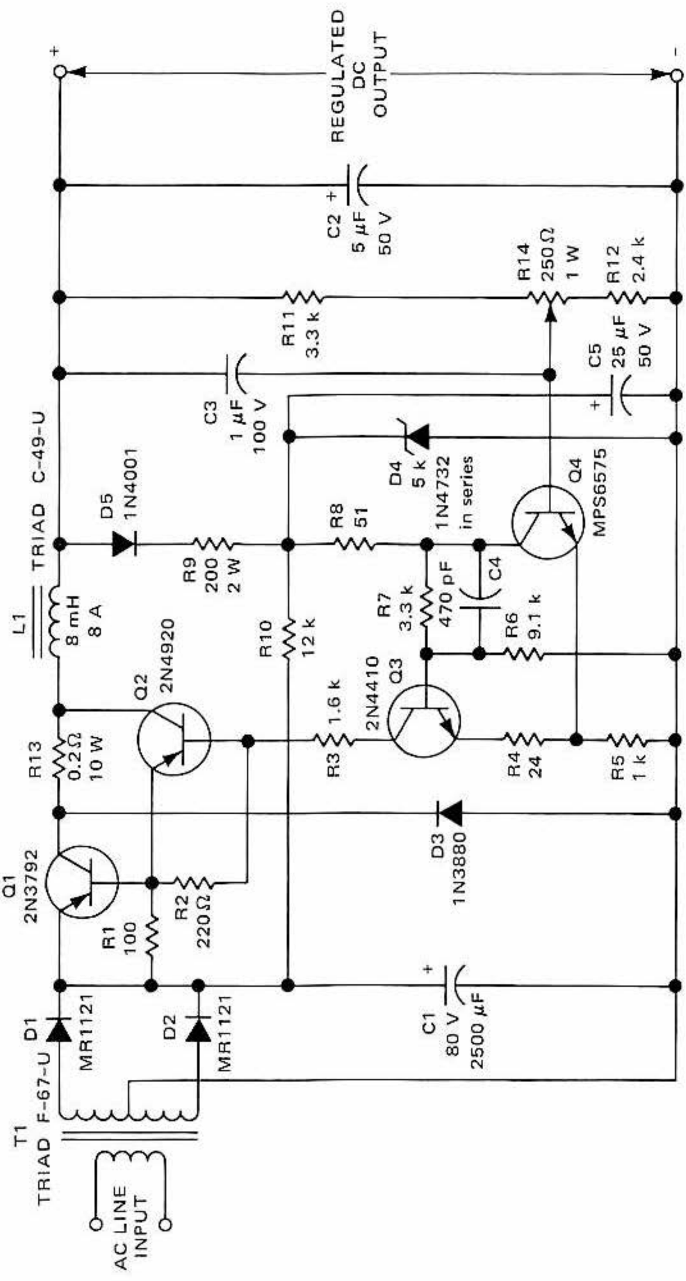

Figure 3-19 — Pulse-Width-Modulated Switching Preregulator diode D3 conducts, permitting load current to continue through L1. This current is provided by the energy stored in L1 and C2. Use of the free-wheeling diode accomplishes two things: (1) it increases the efficiency of the regulator by providing a path for L1 to discharge its energy into the load and (2) it helps to keep Q1 in its safe operating area since voltage spikes on the collector are eliminated. There is still the possibility of exceeding safe operating area, however, since D3 is on when Q1 comes on. This means that Q1 will be subjected to a momentary short circuit until D3 turns off. The use of a fast-recovery diode for D3 minimizes this

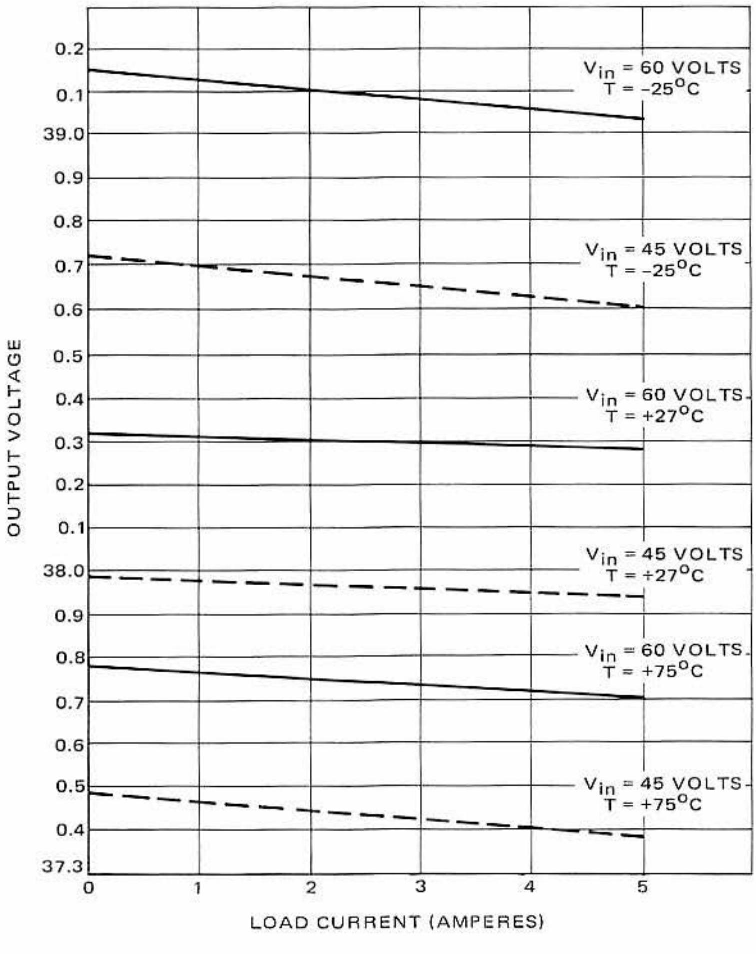

Figure 3-20 – Voltage Regulation of Preregulator of Figure 3-19

problem since turn-off times for the device chosen is less than 200 nanoseconds.

The frequency at which the circuit operates is governed by the filtering capability of L1 and C2 and the hysteresis of the Schmitt trigger. It is found that the frequency is also dependent on the resistive and inductive parameters of the capacitor used for C2. Because of this, some trimming may be required to achieve the desired operating frequency. Once the frequency is set it will remain almost constant from no load to full load. The electrolytic capacitor used for C2 in the test circuit gave an operating frequency of approximately 16.5 kHz.

The circuit was designed to deliver 5 amperes at 38 volts. The regulating characteristics are shown in Figure 3-20; from no load to full load the output voltage dropped about 150 millivolts. The output ripple voltage remained almost constant over this range at approximately 270 mV peak to peak, and the frequency varied from about 19 kHz with 60 V input to about 10 kHz with 45 V input.

3.6 Current Regulators

The circuits shown in Figure 3-21 through 3-24 can be used to regulate the current in a load connected as shown on the schematics. The circuits of Figures 3-21 through 3-23 are three-terminal current regulators and the only difference between these three circuits is the biasing arrangement for the control transistor. Figure 3-24 shows a two-terminal current regulator.

For the circuit shown in Figure 3-21, diodes D1 and D2 set the base potential of Q1. The base-emitter voltage of Q1 is approximately equal to the voltage drop across D1, so the voltage across R2 is the voltage drop of diode D2. The current level at which the regulator will regulate, therefore, is the voltage drop of D2 (0.7 volt) divided by the value of R2. R2 is 10 ohms in this circuit for a regulated current level of 70 mA. The regulation is somewhat dependent on the value of R1 since this controls the biasing current level in D1 and D2. If R1 is too large the diode is working on the knee of the curve and the circuit operation will be very dependent upon the supply voltage. If R1 is too small, excessive power is dissipated in the circuit elements. The value shown for R1 works adequately as can be seen by the results shown in Figure 3-25 and 3-26.

For the circuit shown in Figure 3-22, the voltage drop of D1 compensates for the base-emitter voltage of Q1; thus the current regulated is equal to the breakdown voltage of zener diode D2 divided by the value of R2. To obtain the 70 mA desired, a 5.6 volt zener is selected and R2 is

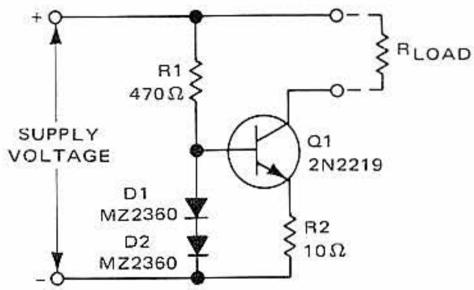

Figure 3-21 – 70 mAdc Current Regulator

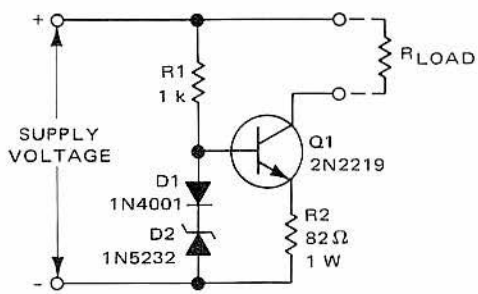

Figure 3-22 – 70 mAdc Current Regulator

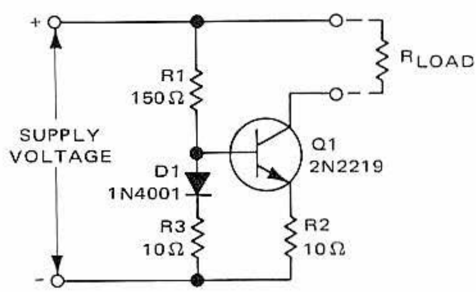

Figure 3-23 – 70 mAdc Current Regulator

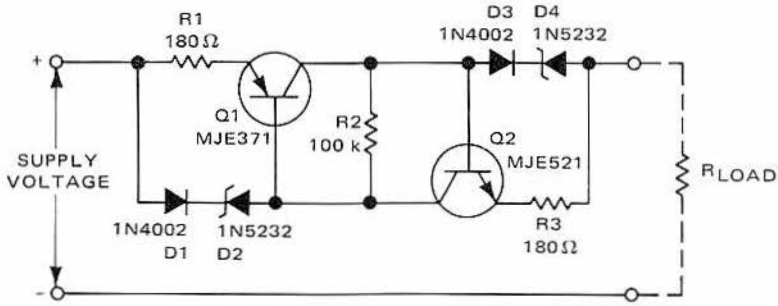

Figure 3-24 — Two-Terminal 70 mAdc Current Regulator

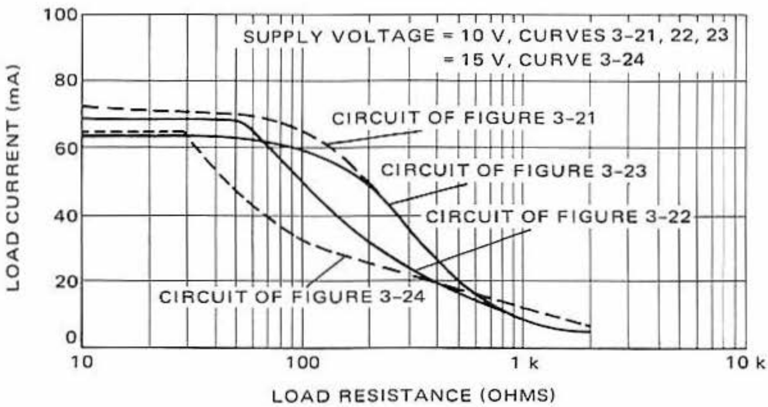

Figure 3-25 — Current-Regulator Load Current versus Load Resistance

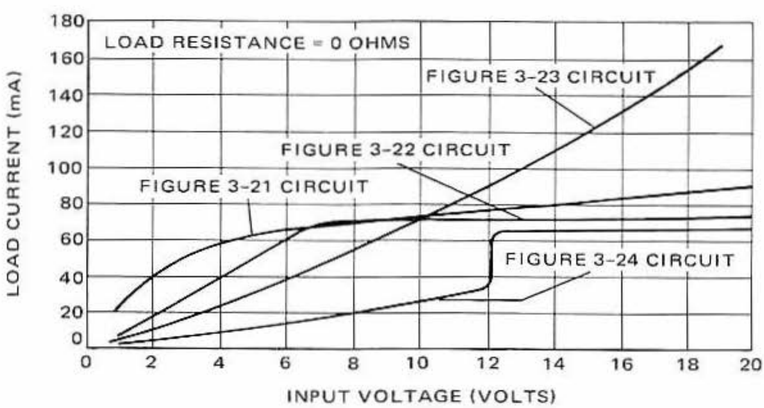

Figure 3-26 — Current-Regulator Load Current versus Input Voltage

set at 82 ohms. The value of R1 for this circuit is not as critical as it was for the circuit in Figure 3-21, since the zener breakdown voltage of D2 is less sensitive to current changes than the forward voltage of the diodes in Figure 3-21, and the current through Q1 is established primarily by the voltage across D2. The 5.6 volt zener diode (D2) was selected since its temperature coefficient is approximately zero. The variation of the base-emitter voltage of Q1 with temperature is compensated by the temperature variation of D1 so that the circuit should exhibit good regulation with temperature. The curves of Figures 3-25 and 3-26 show the results obtained with this circuit for variations in load and input voltage. Figure 3-26 shows that the output current is regulated if the supply voltage is above the knee of the combined curves of D1 and D2.

The circuit shown in Figure 3-23 provides very good current regulation if the supply voltage remains constant and the load is varied. Diode D1 provides compensation for the base-emitter voltage of Q1 and the voltage across R2 equals that across R3. The level at which the current will be regulated is therefore, the voltage across R2 divided by the resistance of R2. If R2 is equal to R3, and R1 is large compared to R2 and R3, the current through R1 is equal to the regulated output current. The load and input-voltage regulation obtained with this circuit is shown in Figures 3-25 and 3-26. This circuit regulates the output current up to the point where the load resistance becomes too large, thereby forcing Q1 into saturation. This prevents further regulation of the load current.

If a three-terminal current regulator cannot be used, then the two terminal regulator shown in Figure 3-24 may be useful. For this circuit to regulate, the supply voltage must be greater than the sum of the voltage drops of D1, D2, D3, and D4. For the components shown, this voltage is 12.5 volts. The level at which the current will be regulated is this voltage divided by the resistance of R1 or R3 since R1 is equal to R3. The curve shown in Figure 3-25 shows the regulation for a supply voltage of 15 volts. The regulation can be increased to higher load resistances if the supply voltage is raised. The maximum load resistance at which regulation can be maintained is shown by the following equation.

$$R_{max} = \frac{V_{supply} - (V_{D1} + V_{D2} + V_{D3} + V_{D4})}{I_{Regulated}}$$

The curve shown in Figure 3-26 demonstrates that the supply voltage must be above the sum of the diode voltage drops for effective regulation. As the regulated current level is increased, the forward-voltage drops of D1 and D3 increase slightly. This circuit has been operated at a regulated current level of 700 mA; for this, the supply voltage must be above 13.5 volts.

3.7 100 V rms Voltage Regulator

The circuit shown in Figure 3-27 will regulate the rms output voltage across the load (which is a projection lamp) to 100 volts ± 2% for an input voltage between 105 and 250 volts ac. This is accomplished by sensing the light output of L1 indirectly and applying this feedback signal to the firing circuit (Q1 and Q2) which controls the conduction angle of triac Q3. The load is a 150 watt projection lamp which has a reflector mirror included inside the glass envelope. If the light output of the lamp were sensed directly by the photocell, it would respond to the 60-Hz variation of the supply voltage unless additional filter components were used. Therefore, another approach was used to generate the feedback signal. The reflector inside the lamp's envelope glows red due to the heat of the filament. Since the reflector has a relatively large mass it cannot respond to the supply frequency, and its light output provides a form of integration. This light is then used as a feedback signal. To eliminate 60 Hz modulation of the photocell, it is mounted at one end of a black tube with the other end of the tube directed at the back side of the reflector in the lamp. The lamp is energized through triac Q3, whose conduction angle is set by the firing circuit for unijunction transistor Q2. This circuit is synchronized with the line through the full-wave bridge rectifier. The voltage to the circuit is limited by zener diode D5. Phase control of the supply voltage is set by the charging rate of capacitor C1. Q2 will fire when the voltage on C1

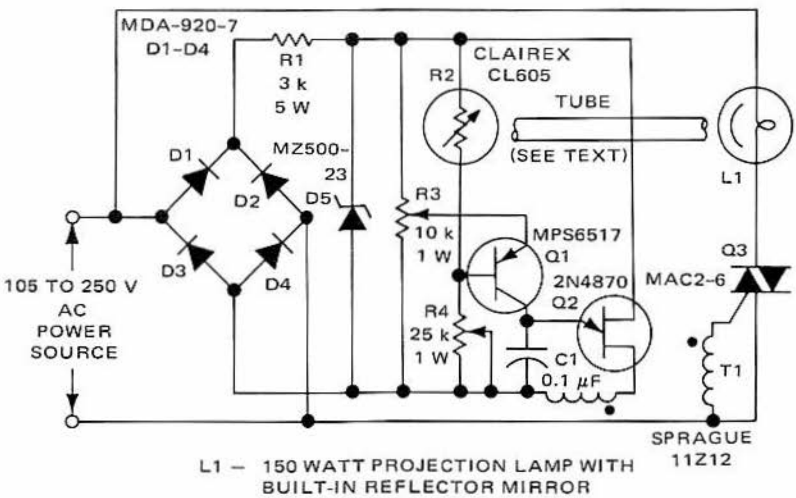

Figure 3-27 – 100 Vrms Voltage Regulator

reaches approximately 0.65 times the zener voltage. The charging rate of C1 is set by the conduction of Q1, which is controlled by the resistance of photocell R2. Potentiometers R3 and R4 are used to set the lamp voltage to 100 volts when the line voltage is 105 volts and 250 volts, respectively. This assures that the lamp voltage will be within the desired tolerance over the operating range of input voltage. Some interaction will occur between R3 and R4 and the adjustment of each potentiometer may have to be made several times. Since this is an rms voltage regulator, a true rms meter must be used to adjust the load voltage.

If the excursion of the supply voltage is not large, then a circuit without feedback such as shown in Figure 3-28 may be used. This circuit regulates the input voltage to the step-up transformer T2 at 90 volts, thereby maintaining the load voltage at 120 volts ±2%. Q2 and Q3 are both pulsed at the same time by Q1 through T1, but the only one that turns on is the one that is forward biased by the supply voltage. The circuit which controls the phase of Q1 is synchronized to the line voltage through full-wave bridge D1 to D4. The voltage to the charging circuit of capacitor C1 is regulated by zener diode D5. The charging circuit is a ramp-and-pedestal combination and the voltage on C1 is as shown in Figure 3-29. R2 and R5 have low values compared to R6 so that C1 can

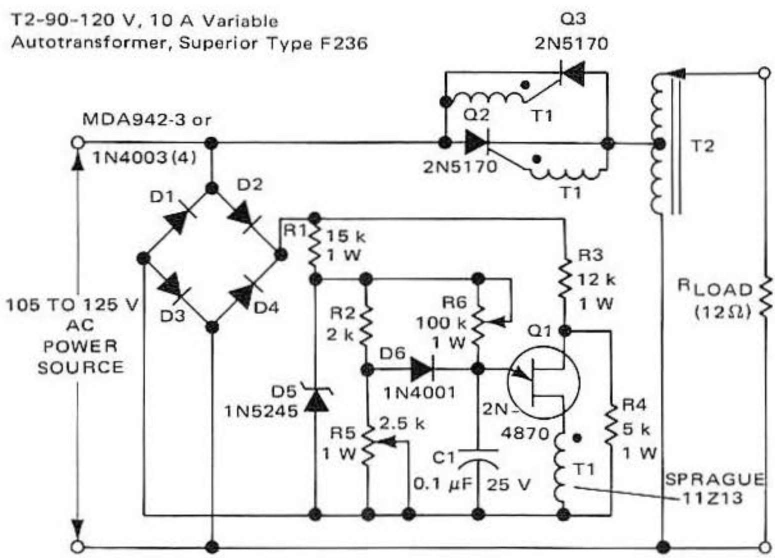

Figure 3-28 — 105 to 125 Vac Voltage Regulator

charge quickly to the level set by R5. Diode D6 then becomes reverse biased, and C1 continues to charge through R6, but at a slower rate, until the breakover voltage of Q1 is reached. Since the interbase voltage of Q1 is proportional to the line voltage, the value to which C1 charges is variable. When the supply voltage is low, R5 is adjusted to provide 120 volts to the load. When the supply voltage is high, R6 is adjusted to provide 120 volts to the load. R5 is set so the firing point of Q1 is close to the voltage at which D6 becomes reverse biased. R6 then adjusts the ramp to delay the firing point as the line voltage is increased. R5 and R6 interact, so the adjustment will have to be made several times. As in the previous circuit, a true rms meter must be used for this adjustment.

The operation of this circuit depends upon the waveshape of the supply voltage. Therefore, the ac power source must provide a low-distortion sine wave to assure good rms voltage regulation at the output. Since there is no feedback in this circuit the regulation at the load depends upon the regulation of transformer T2. As the load is changed some adjustment of R5 and R6 may be required to maintain voltage regulation at the load. This circuit was used to regulate a 10 ampere load and provided a load voltage change of only 2 volts for a line voltage change from 105 to 125 volts using an adjustable transformer for T2.

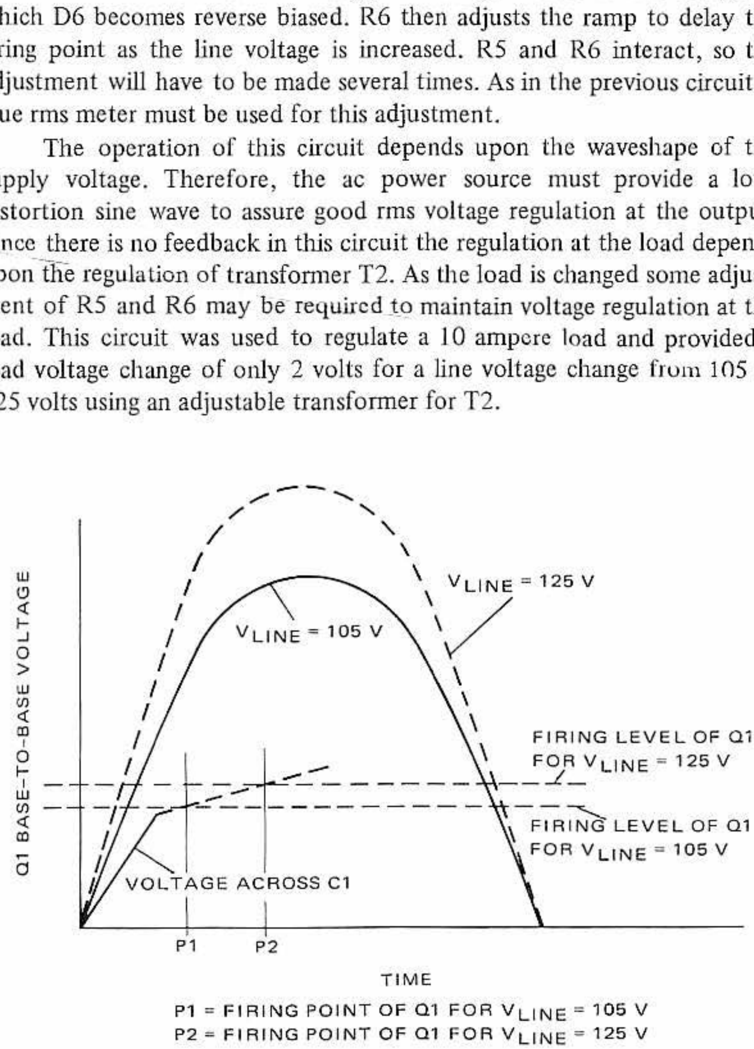

Figure 3-29 – Firing-Point Change of Q1 for Line-Voltage Change

3.8 Short-Circuit Protection for Series-Pass Regulator

Power supplies with series-pass regulators can be adequately protected against damage due to short-circuited loads through the simple addition of a few inexpensive components. The circuit shown in Figure 3-30 not only protects the regulator against a shorted output but incorporates an automatic reset circuit that restores normal operation when the short is removed.

The series-pass portion of the circuit is conventional in operation and is designed to present very low impedance to the load.

The part of the circuit which provides protection against short circuits is shaded in Figure 3-30. It operates as follows: When a short circuit occurs across the output the whole supply voltage appears across D2, R2, and the emitter-base junction of Q2. Since the input supply voltage is greater than the breakdown voltage (V_Z) of zener diode D2, the diode breaks down and supplies base drive to Q2. As Q2 approaches saturation, it robs the series-pass transistor (Q1) of base drive and cuts it off. Capacitor C1, which is charged up to the output voltage before a short appears across the load, aids in turning on transistor Q2 by discharging through the base of Q2 when the output is shorted. Although capacitor C1 discharges to a very low voltage when the regulator is in the short circuited mode, transistor Q2 remains saturated due to the base drive provided through D2 and R2.

The automatic reset incorporated in this circuit operates in the following manner: When the short is removed, the voltage across the output begins to rise due to the current supplied through Q2. Since the

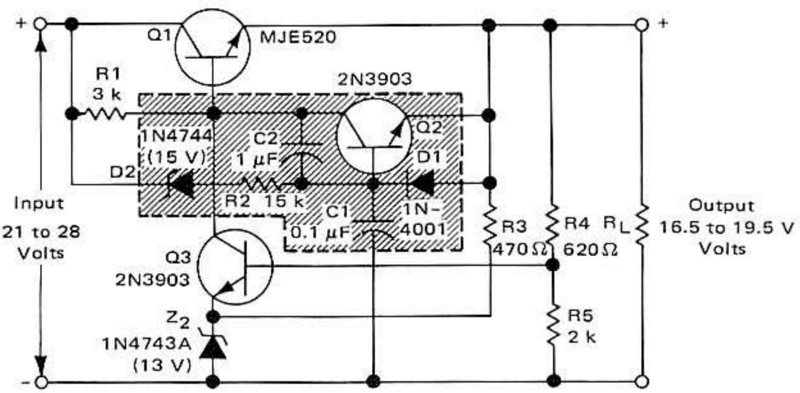

Figure 3-30 – Circuit Protection for Series-Pass Voltage Regulator

voltage differential across the series-pass transistor (Q1) determines the base drive of Q2, and this voltage has decreased due to the rise of voltage across the output, Q2 begins to turn off, allowing Q1 to turn on.

When the voltage across the output exceeds the voltage across C1, this capacitor begins to charge through D1. The voltage thus dropped across D1 back-biases the emitter-base diode of Q2, turning this transistor off. When Q2 turns off, normal base current is supplied to the base of Q1 and the circuit resumes normal operation. Capacitor C2 enhances the ac stability of Q2 and may not be necessary in all circuits.

Under normal series-pass operating conditions, the protective circuit is biased off and does not affect the circuit performance in any way.

The protective circuit is limited in speed only by the storage and fall time of the series-pass transistor (Q1), and operates in approximately one millisecond.

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