6

VOLTAGE REGULATOR

6.1 INTRODUCTION

The function of a voltage regulator is to provide a stable dc voltage for powering other electronic circuits. A voltage regulator should be capable of providing substantial output current. Voltage regulators are classified as:

Series regulator
Switching regulator

Series regulators use a power transistor connected in series between the unregulated dc input and the load. The output voltage is controlled by the continuous voltage drop taking place across the series pass transistor. Since the transistor conducts in the active or linear region, these regulators are also called linear regulators. Linear regulators may have fixed or variable output voltage and could be positive or negative. The schematic, important characteristics, data sheet, short circuit protection, current fold-back, current boosting techniques for linear voltage regulators such as 78 XX, 79 XX series, 723 IC are discussed.

Switching regulators, on the other hand, operate the power transistor as a high frequency *on/off* switch, so that the power transistor does not conduct current continuously. This gives improved efficiency over series regulator. In Sec. 6.4, the principle of switching power supply and its advantages over linear type of voltage regulator are discussed.

6.2 SERIES OP-AMP REGULATOR

A voltage regulator is an electronic circuit that provides a stable dc voltage independent of the load current, temperature and ac line voltage variations. Figure 6.1 shows a regulated power supply using discrete components. The circuit consists of following four parts:

1. Reference voltage circuit
2. Error amplifier
3. Series pass transistor
4. Feedback network.

It can be seen from Fig. 6.1 that the power transistor Q_1 is in series with the unregulated dc voltage V_{in} and the regulated output voltage V_o. So it must absorb the difference between these two voltages whenever any fluctuation in output voltage V_o occurs. The transistor Q_1

is also connected as an emitter follower and therefore provides sufficient current gain to drive the load. The output voltage is sampled by the $R_1 - R_2$ divider and fed back to the (–) input terminal of the op-amp error amplifier. This sampled voltage is compared with the reference voltage V_{ref} (usually obtained by a zener diode). The output V_o' of the error amplifier drives the series transistor Q_1.

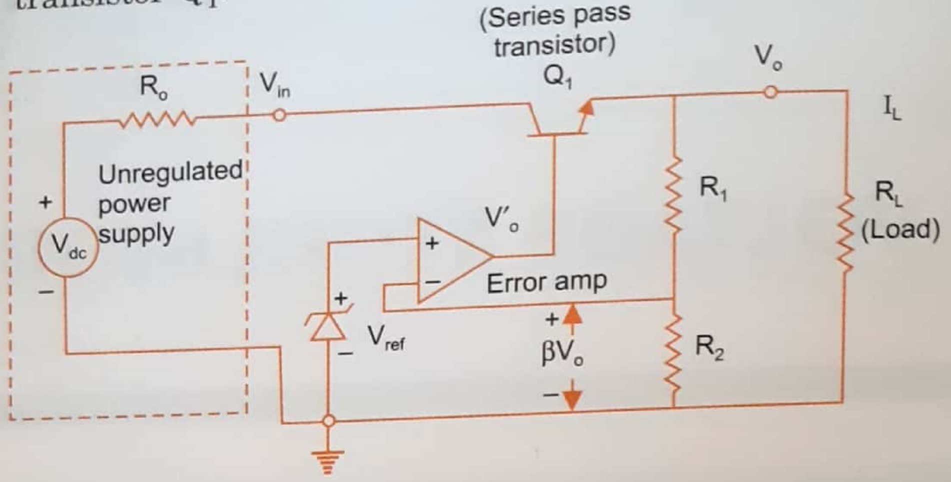


Fig. 6.1 A regulated power supply

If the output voltage increases, say, due to variation in load current, the sampled voltage βV_o also increases where

$$\beta = \frac{R_2}{R_1 + R_2} \tag{6.1}$$

This, in turn, reduces the output voltage V_o' of the diff-amp due to the 180° phase difference provided by the op-amp amplifier. V_o' is applied to the base of Q_1, which is used as an emitter follower. So V_o follows V_o', that is V_o also reduces. Hence the increase in V_o is nullified. Similarly, reduction in output voltage also gets regulated.

6.3 IC VOLTAGE REGULATORS

With the advent of micro-electronics, it is possible to incorporate the complete circuit of Fig. 6.1 on a monolithic silicon chip. This gives low cost, high reliability, reduction in size and excellent performance. Examples of monolithic regulators are 78 XX/79 XX series and 723 general purpose regulators.

6.3.1 Fixed Voltage Series Regulator

78 XX series are three terminal, positive fixed voltage regulators. There are seven output voltage options available such as 5, 6, 8, 12, 15, 18 and 24 V. In 78 XX, the last two numbers (XX) indicate the output voltage. Thus 7815 represents a 15 V regulator. There are also available 79 XX series of fixed output, negative voltage regulators which are complements to the 78 XX series devices. There are two extra voltage options of – 2 V and – 5.2 V available in 79 XX series. These regulators are available in two types of packages.

Metal package (TO – 3 type)
Plastic package (TO – 220 type)

Figure 6.2 shows the standard representation of monolithic voltage regulator. A capacitor C_i (0.33 μF) is usually connected between input terminal and ground to cancel the inductive effects due to long distribution leads. The output capacitor C_o (1 μF) improves the transient response.

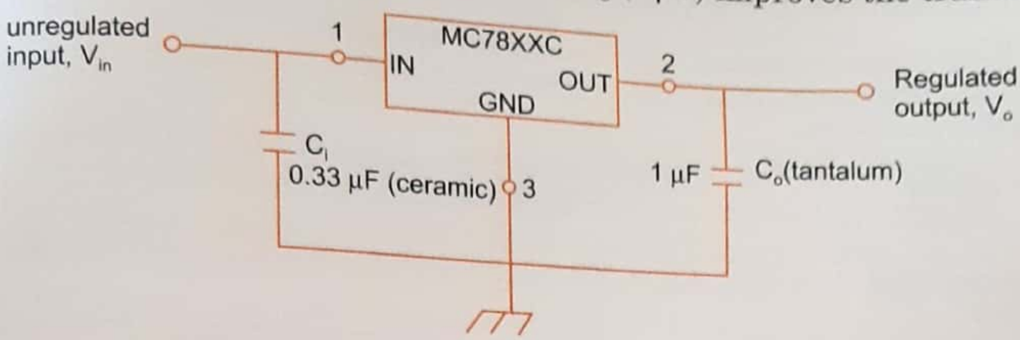


Fig. 6.2 Standard representation of a three terminal positive monolithic regulator

National Semiconductor also produces three terminal voltage regulators in LM series. There are three series available for different operating temperature ranges:

LM	100	series	– 55°C	to	+125°C
LM	200	series	– 25°C	to	+85°C
LM	300	series	0°C	to	+70°C

The popular series are LM 340 positive regulators and LM 320 negative regulators with output ratings comparable to 78 XX/79 XX series.

Characteristics

There are four characteristics of three terminal IC regulators which must be mentioned.

1. V_o : The regulated output voltage is fixed at a value as specified by the manufacturer. There are a number of models available for different output voltages, for example, 78 XX series has output voltage at 5, 6, 8 etc.
2. $|V_{in}| \geq |V_o| + 2$ volts: The unregulated input voltage must be atleast 2 V more than the regulated output voltage. For example, if $V_o = 5$ V, then $V_{in} = 7$ V.
3. $I_{o\,(max)}$: The load current may vary from 0 to rated maximum output current. The IC is usually provided with a heat sink, otherwise it may not provide the rated maximum output current.
4. Thermal shutdown: The IC has a temperature sensor (built-in) which turns off the IC when it becomes too hot (usually 125° C to 150°C). The output current will drop and remains there until the IC has cooled significantly.

Table 6.1 gives the electrical characteristics of 7805 voltage regulator and the connection diagram of packages available. Some of the important performance parameters listed in the data sheet are explained as follows:

Line/Input Regulation

It is defined as the percentage change in the output voltage for a change in the input voltage. It is usually expressed in millivolts or as a percentage of the output voltage. Typical value of line regulation from the data sheet of 7805 is 3 mV.

Table 6.1 Electrical characteristics of 7805 voltage regulator

Absolute Maximum Ratings

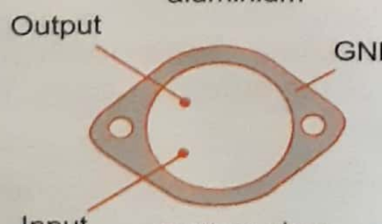
Input Voltage (5 V through 18 V)	35 V
(24 V)	40 V
Internal Power Dissipation	Internally limited
Storage Temperature Range	–65°C to +150°C
Operating Junction Temperature Range	
µA7800	–55°C to +150°C
µA7800C	0°C to +125°C

7805C

Electrical Characteristics V_{IN} = 10 V, I_{OUT} = 500 mA, 0°C ≤ T_j ≤ 125°C, C_{IN} = 0.33 µF, C_{OUT} = 0.1 µF, unless otherwise specified.

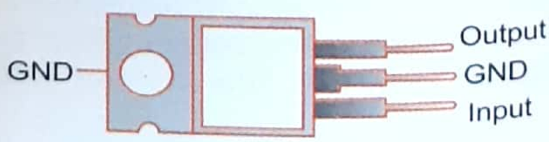
Characteristic	*Condition*		*Min*	*Typ*	*Max*	*Unit*
Output Voltage	T_j = 25°C		4.8	5.0	5.2	V
Line Regulation	T_j = 25°C	7 V ≤ V_{IN} ≤ V		3	100	mV
		8 V ≤ V_{IN} ≤ 12 V		1	50	mV
Load Regulation	T_j = 25°C	5 mA ≤ I_{OUT} ≤ 1.5 A		15	100	mV
		250 mA ≤ I_{OUT} ≤ 750 mA		5	50	mV
Output Voltage	7 V ≤ V_{IN} ≤ 20 V 5 mA ≤ I_{OUT} ≤ 1.0 A P ≤ 15 W		4.75		5.25	V
Quiescent Current	T_j = 25°C			4.2	8.0	mA
Quiescent Current Change	with line	7 V ≤ V_{IN} ≤ 25 V			1.3	mA
	with load	5 mA ≤ I_{OUT} ≤ 1.0 A			0.5	mA
Output Noise Voltage	T_A = 25°C, 10 Hz ≤ 1 ≤ 100 kHz			40		µV
Ripple Rejection	f = 120 Hz, 8 V ≤ V_{IN} ≤ 18 V		62	78		dB
Dropout Voltage	I_{OUT} = 1.0 A, T_j = 25°C			2.0		V
Output Resistance	f = 1 kHz			17		mΩ
Short-Circuit Current	T_j = 25°C. V_{IN} = 35 V			750		mA
Peak Output Current	T_j = 25°C			2.2		A
Average Temperature Coefficient of Output Voltage	I_{OUT} = 5 mA, 0°C ≤ T_j ≤ 125°C			1.1		mV/°C

Metal can package aluminium



Bottom view

Plastic package



Top view

Load Regulation

It is defined as the change in output voltage for a change in load current and is also expressed in millivolts or as a percentage of V_o. Typical value of load regulation for 7805 is 15 mV for 5 mA < I_o < 1.5 A.

Ripple Rejection

The IC regulator not only keeps the output voltage constant but also reduces the amount of ripple voltage. It is usually expressed in dB. Typical value for 7805 is 78 dB.

The Schematic diagram of MC 78 XXC* is shown in Fig. 6.3. The circuit consists of a reference voltage V_{ref}. This circuit basically consists of level shifter with zener diode input and the transistor Q_9 used as emitter follower buffer. The circuit enclosed in the shaded region is a difference amplifier consisting of a current mirror (Q_4, Q_5), and an active load (Q_6, Q_7, Q_8). The combination of R_1R_2 forms the feedback network for sampling the output voltage. The sampled voltage is fed to one of the inputs of the difference amplifier. The Darlington pair Q' Q'' forms series pass element Q_1 of the circuit shown in Fig. 6.1.

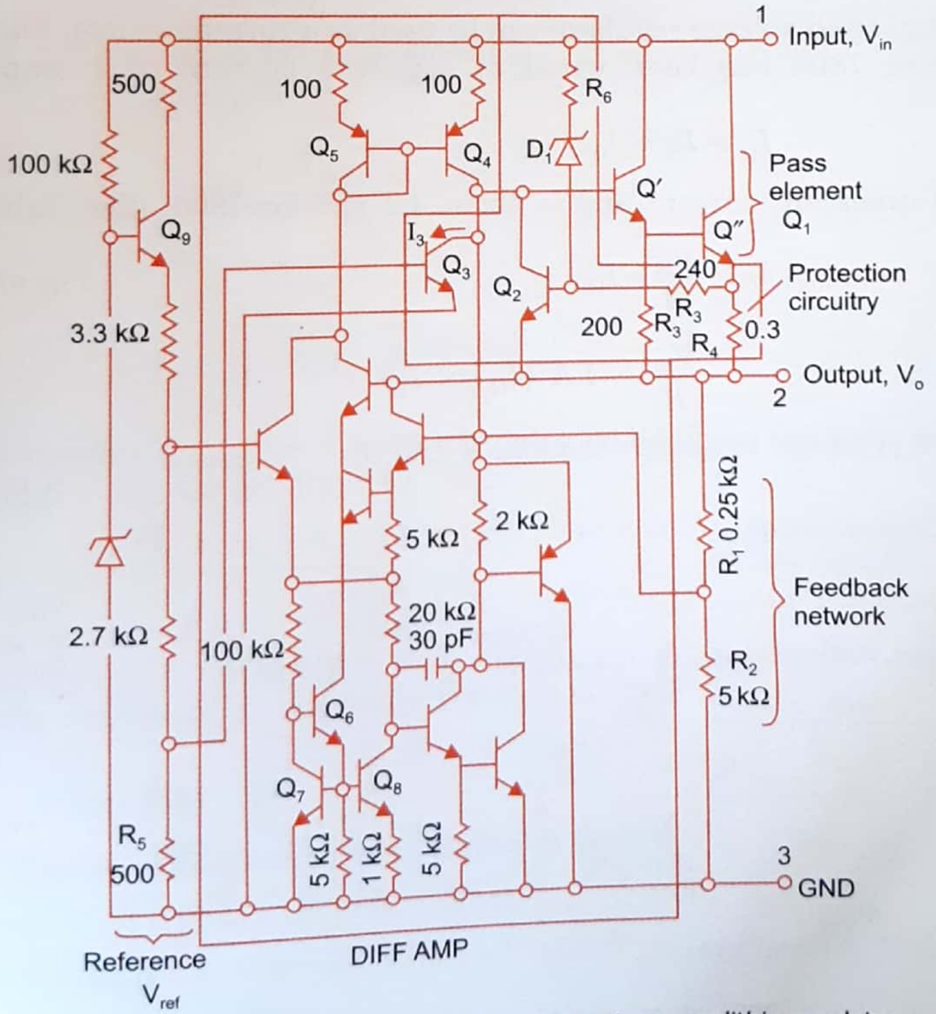


Fig. 6.3 Schematic diagram for MC 7800C series monolithic regulator

*C stands for commercial use.

The monolithic regulator has in-built circuitry enclosed in the solid line to provide:

Over-current protection.

Thermal overload protection.

Current is limited by R_3, R_4 and transistor Q_2. If the output voltage goes low due to overload, the excess voltage appears across the pass element (Q'-Q''), that is, across the collector emitter of Q''. When this voltage is more than the break-down voltage of the zener diode D_1, it starts conducting. This provides sufficient base current to transistor Q_2 and drives it ***on***. Now, because of the collector current of Q_2 when fully ***on***, current flowing to the base of Q' is reduced. This in turn reduces the conduction of Q''. Thus the volt-ampere product of the pass element (Q'-Q'') is limited.

The thermal overload protection is provided by the resistor R_5 and transistor Q_3. The voltage drop across resistor R_5 is directly applied to the base-emitter of Q_3. When the temperature goes high, Q_3 conducts more, thereby reducing the base drive of $Q'Q''$ combination. This provides thermal protection.

Current Source

The three terminal fixed voltage regulator can be used as a current source. Figure 6.4 (a) shows the circuit where 7805 has been wired to supply a current of 1 ampere to a 10 Ω, 10 watt load.

$$I_L = I_R + I_Q \tag{6.2}$$

where I_Q is the quiescent current and is about 4.2 mA for 7805. (See Table 6.1)

$$I_L = \frac{V_R}{R} + I_Q \tag{6.3}$$

Since $I_L = 1$ A, $$\frac{V_R}{R} \simeq 1 \text{ A } (I_Q << I_L) \tag{6.4}$$

Also $V_R = 5$ V (Voltage between terminal 2 and 3)

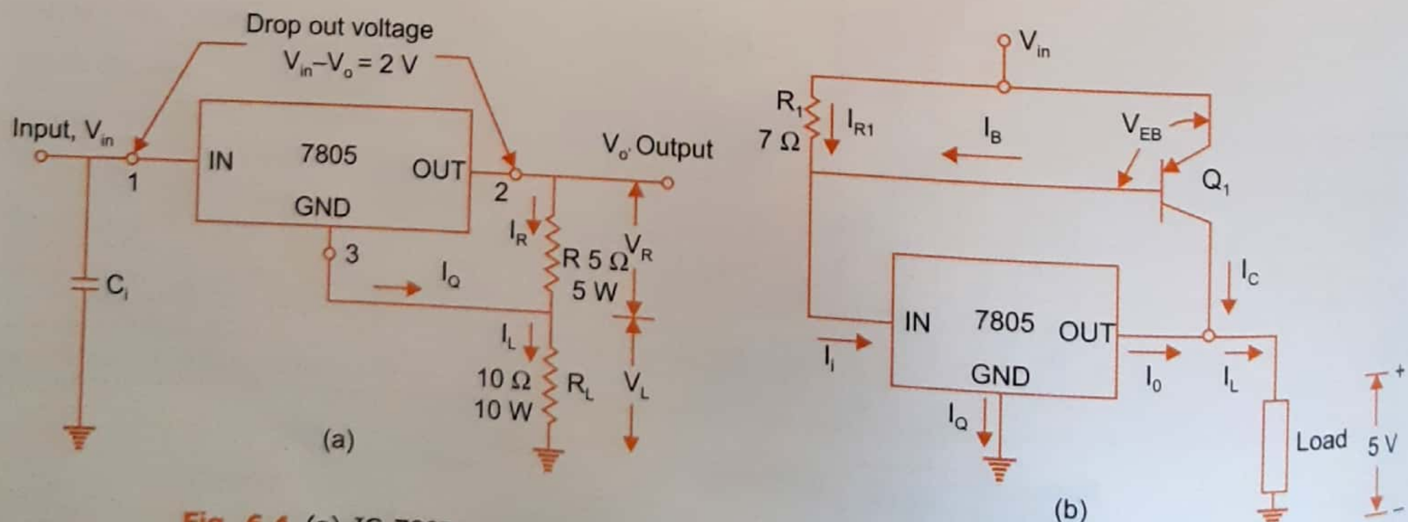


Fig. 6.4 (a) IC 7805 as a current source (b) Boosting a three terminal regulator

So the value of R required is

$$R = 5 \text{ V}/1 \text{ A} = 5\ \Omega \tag{6.5}$$

Thus choose $R = 5\ \Omega$ to deliver 1 A current to a load of 10 Ω.

Boosting IC Regulator Output Current

It is possible to boost the output current of a three terminal regulator simply by connecting an external pass transistor in parallel with the regulator as shown in Fig. 6.4 (b).

Let us now see how the circuit works. For low load currents, the voltage drop across R_1 is insufficient (<0.7 V) to turn on transistor Q_1 and the regulator itself is able to supply the load current. However, as I_L increases, the voltage drop across R_1 increases. When this voltage drop is approximately 0.7 V, the transistor Q_1 turns on. It can be easily seen that if I_L = 100 mA, the voltage drop across R_1 is equal to 7 Ω × 100 mA = 0.7 V. Thus, if I_L increases more than 100 mA, the transistor Q_1 turns on and supplies the extra current required. Since $V_{EB\,(ON)}$ remains fairly constant, the excess current comes from Q_1's base after amplification by β. The regulator adjusts I_B so that

$$I_L = I_c + I_o \tag{6.6}$$

and

$$I_c = \beta I_B \tag{6.7}$$

For the regulator,

$$I_o = I_i - I_Q$$

$$\simeq I_i \text{ (as } I_Q \text{ is small)} \tag{6.8}$$

Also

$$I_B = I_i - I_{R_1}$$

$$\simeq I_o - \frac{V_{EB\,(ON)}}{R_1} \tag{6.9}$$

Simplifying, we get

$$I_L = (\beta + 1)\, I_o - \beta \frac{V_{EB\,(ON)}}{R_1} \tag{6.10}$$

The maximum current $I_{o\,(max)}$ for a 7805 regulator is 1 A from the data sheet. Assuming $V_{EB\,(ON)}$ = 1 V and β = 15, we get from Eq. (6.10)

$$I_L = 16 \times 1 - 15 \times (1/7) = 13.8 \text{ A} \tag{6.11}$$

Example 6.1

In Fig. 6.4 (b), let $V_{EB\,(ON)}$ = 1 V and β = 15. Calculate the output current coming from 7805 and I_c coming from transistor Q_1 for loads 100 Ω, 5 Ω, 1 Ω.

Solution

Load = 100 Ω

For 7805, the output voltage across the load will be 5 V.

$$I_L = 5\text{V}/100\,\Omega = 0.05 \text{ A} = 50 \text{ mA}$$

The voltage across R_1 is 7 Ω × 50 mA = 350 mV which is less than 0.7 V. Hence Q_1 is *off*.

So,

$$I_L = I_o = I_i = 50 \text{ mA}$$

and

$$I_c = 0.$$

Load = 5 Ω

$$I_L = 5 \text{ V}/5\,\Omega = 1 \text{ A}$$

Assume that the entire current comes through regulator and that Q_1 is ***off***. Now the voltage drop across R_1 is equal to $7\ \Omega \times 1\ \text{A} = 7\ \text{V}$. Thus our assumption is wrong and Q_1 is ***on***. Putting the values in Eq. (6.10), it can be found that

$$I_o = 196\ \text{mA}$$

$$I_c = 904\ \text{mA}$$

Load = 1 Ω

$$I_L = 5\ \text{V}/1\ \Omega = 5\ \text{A}$$

Here also Q_1 is ***on***. Solving Eq. (6.10) for I_o, we get

$$I_o = 446\ \text{mA}$$

So, $$I_c = 4.55\ \text{A}$$

Fixed Regulator used as Adjustable Regulator

In the laboratory, one may need variable regulated voltages or a voltage that is not available as standard fixed voltage regulator. This can be achieved by using a fixed three terminal regulator as shown in Fig. 6.5. Note that the ground (GND) terminal of the fixed three terminal regulator is floating. The output voltage

$$V_o = V_R + V_{pot} = V_R + (I_Q + I_{R1})\ R_2 = V_R + I_Q R_2 + \frac{V_R}{R_1} R_2$$

or, $$V_o = (1 + R_2/R_1)\ V_R + R_2 I_Q \tag{6.12}$$

where V_R is the regulated voltage difference between the OUT and GND terminals. The effect of I_Q is minimized by choosing R_2 small enough to minimize the term $I_Q R_2$. The minimum output voltage is the value of the fixed voltage available from the regulator. The LM117, 217, 317 positive regulators and LM137, 237, 337 negative regulators have been specially designed to be used for obtaining adjustable output voltages. It is possible to adjust output voltage from 1.2 V to 40 V and current upto 1.5 A.

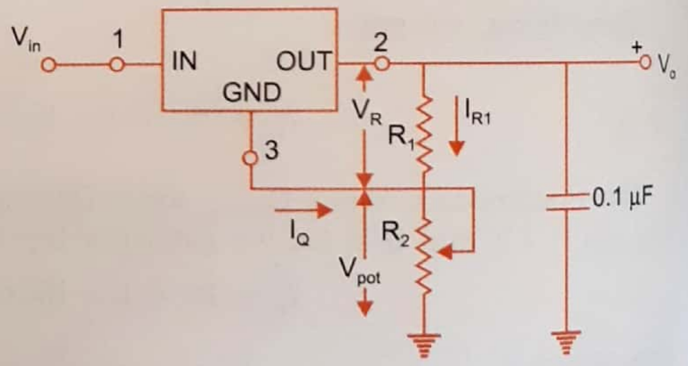


Fig. 6.5 Adjustable regulator

Example 6.2

Specify suitable component values to get $V_o = 7.5\ \text{V}$ in the circuit of Fig. 6.5 using a 7805 regulator.

Solution

From the data sheet of 7805, $I_Q = 4.2\ \text{mA}$. Say, we choose $I_{R_1} = 25\ \text{mA}$.

As $$V_R = 5\ \text{V for 7805},$$

$$R_1 = 5\ \text{V}/25\ \text{mA} = 200\ \Omega$$

We have to choose R_2 so as to develop a voltage of 2.5 V across it. So,

$$R_2 = 2.5\ \text{V}/(I_{R_1} + I_Q) = 2.5/(4.2 + 25) = 85.6\ \Omega$$

Choose $$R_2 = 85\ \Omega$$

Dual Voltage Supply

Many discrete and IC circuits (such as op-amp) require bipolar (dual or ±V) supplies. This can be easily done with two three-terminal regulators. Figure 6.6 shows a bipolar ±15 V supply that can give 1 A from both (+) and (–) terminals. LM 340–15 is a +15V regulator with load current capability upto 1.5 A. The LM 320–15 is a –15 V regulator. It may be noted that the pin configuration of LM 340 and LM 320 is different. The diodes D_1 and D_2 in the circuit protect the regulator against short circuit occurring at its input terminals. Diodes D_3 and D_4 provide protection against the situation when both the regulators may not turn on simultaneously. If there is a load between the two outputs, the faster one will try to reverse the polarity of the other and cause it to latch up unless it is properly clamped. This clamping function is done by the diodes. Once the regulator start operating properly, both diodes will be reverse biased and will no longer have any effect on the circuit.

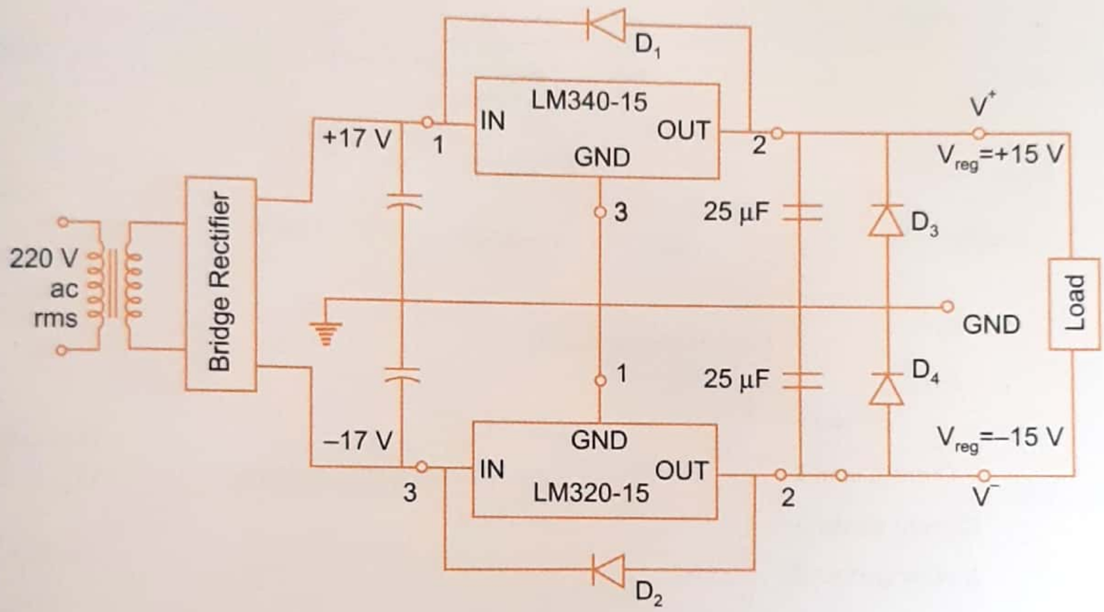


Fig. 6.6 A dual voltage (±15 V) supply

An op-amp draws less than 5 mA current, so a 100 mA supply can be used to drive a circuit consisting of 20 op-amps. LM 325H is a dual tracking ± 15V supply and is available in a 10-pin metal-can package and can furnish current upto 100 mA.

6.4 723 GENERAL PURPOSE REGULATOR

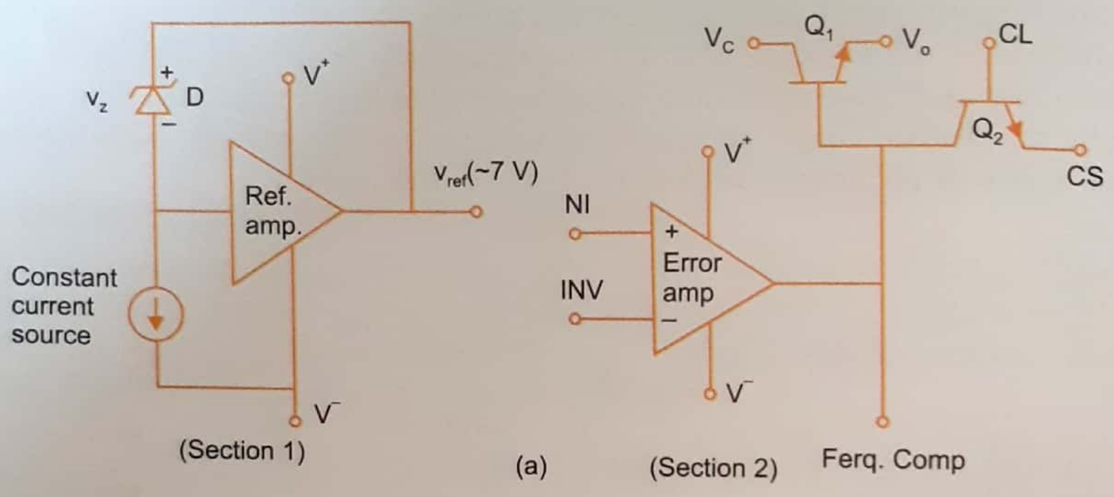
The three terminal regulators discussed earlier have the following limitations:

1. No short circuit protection
2. Output voltage (positive or negative) is fixed.

These limitations have been overcome in the 723 general purpose regulator, which can be adjusted over a wide range of both positive or negative regulated voltage. This IC is inherently low current device, but can be boosted to provide 5 amps or more current by connecting external components. The limitation of 723 is that it has no in-built thermal protection. It also has no short circuit current limits.

Figure 6.7 (a) shows the functional block diagram of a 723 regulator IC. It has two separate sections. The zener diode, a constant current source and reference amplifier produce a fixed voltage of about 7 volts at the terminal V_{ref}. The constant current source forces the zener to operate at a fixed point so that the zener outputs a fixed voltage.

The other section of the IC consists of an error amplifier, a series pass transistor Q_1 and a current limit transistor Q_2. The error amplifier compares a sample of the output voltage applied at the INV input terminal to the reference voltage V_{ref} applied at the NI input terminal. The error signal controls the conduction of Q_1. These two sections are not internally connected but the various points are brought out on the IC package. 723 regulated IC is available in a 14-pin dual-in-line package or 10-pin metal-can as shown in Fig. 6.7 (b). The important features and electrical characteristics are given in Table 6.2.



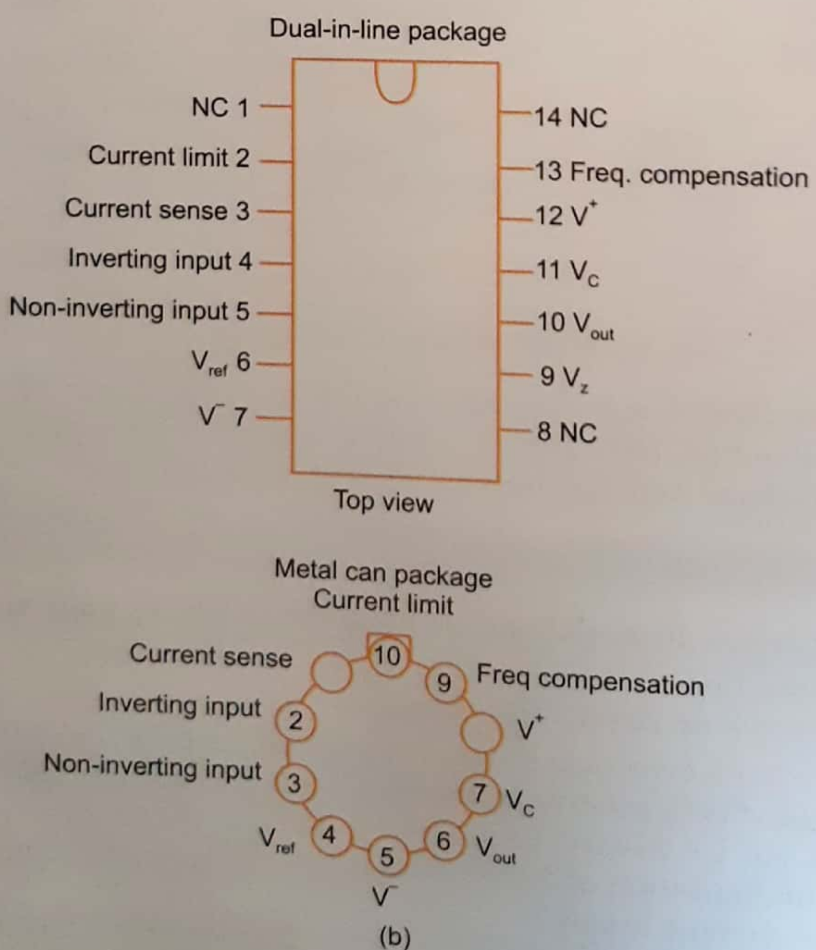


Fig. 6.7 (a) Functional block diagram of 723 regulator
(b) Pin diagram for 14-pin DIP and 10-pin metal-can

Table 6.2 723 IC regulator electrical characteristics

23 Voltage Regulator
nportant Features:
*Input voltage 40 V max
*Output voltage adjustable from 2 V to 37 V
*150 mA output current without external pass transistor
*Output currents in excess of 10 A possible by adding external transistors
*Can be used as either a linear or a switching regulator

rameter	Conditions	LM723			LM723C			Units
		Min	Typ	Max	Min	Typ	Max	
ne Regulation	V_{IN} = 12 V to V_{IN} = 15 V		.01	0.1		.01	0.1	% V_o
	$-55°C \le T_A \le +125°C$			0.3				% V_o
	$0°C \le T_A \le +70°C$						0.3	% V_o
	V_{IN} = 12 V to V_{IN} = 40 V		.02	0.2		0.1	0.5	% V_o
ad Regulation	I_L = 1 mA to I_L = 50 mA		.03	0.15		.03	0.2	% V_o
	$-55°C \le T_A \le +125°C$			0.6				% V_o
	$0°C \le T_A \le +70°C$						0.6	% V_o
ple Rejection	f = 50 Hz to 10 kHz, C_{REF} = 0		74			74		dB
	f = 50 Hz to 10 kHz, C_{REF} = 5 µF	86			86			dB
erage Temperature efficient of Output ltage	$-55°C \le T_A \le +125°C$		.002	.015				%/°C
	$0°C \le T_A \le +70°C$					.003	.015	%/°C
ort Circuit Current nit	R_{SC} = 10 Ω, V_{OUT} = 0		65			65		mA
ference Voltage		6.95	7.15	7.35	6.80	7.15	7.50	V
tput Noise Voltage	BW = 100 Hz to 10 kHz, C_{REF} = 0		20			20		µV_{rms}
	BW = 100 Hz to 10 kHz, C_{REF} = 5 µF	2.5			2.5			µV_{rms}
ng Term Stability			0.1			0.1		%/1000 hrs
ndby Current Drain	I_L = 0, V_{in} = 30 V		1.3	3.5		1.3	4.0	mA
ut Voltage Range		9.5		40	9.5		40	V
tput Voltage Range		2.0		37	2.0		37	V
ut Output Voltage Differential		3.0		38	3.0		38	V

A simple positive low-voltage (2 V to 7 V) regulator can be made using 723 as shown in e schematic of Fig. 6.8 (a). In order to understand the circuit operation, consider the tailed circuit of Fig. 6.8 (b). The voltage at the NI terminal of the error amplifier due to R_2 divider is,

$$V_{NI} = V_{ref}\frac{R_2}{R_1 + R_2} \tag{6.13}$$

Chapter 6

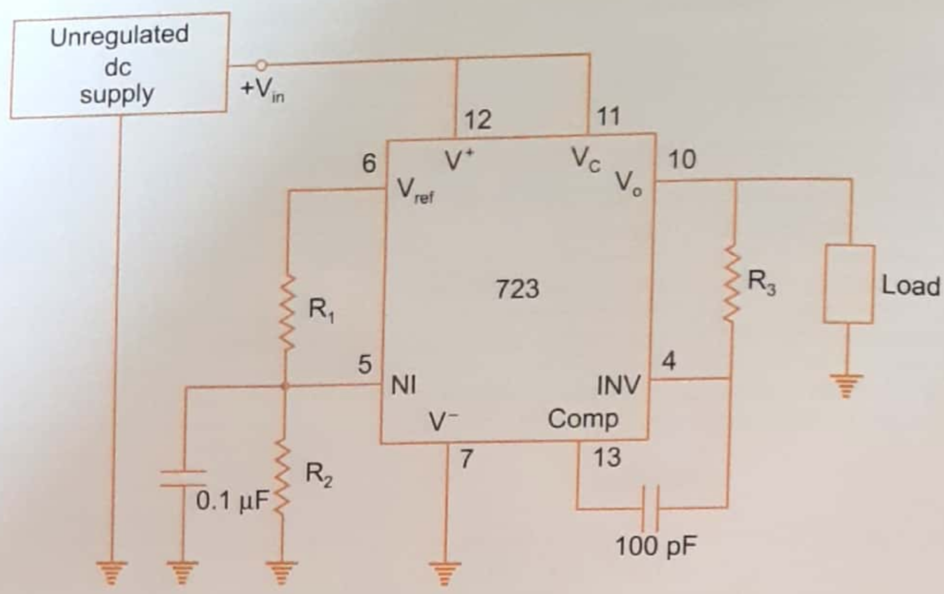


Fig. 6.8 (a) A low voltage regulator using 723 IC

The difference between V_{NI} and the output voltage V_o which is directly fed back to the INV terminal is amplified by the error amplifier. The output of the error amplifier drives the pass transistor Q_1 so as to minimize the difference between the NI and INV inputs of error amplifier. Since Q_1 is operating as an emitter follower

$$V_o = V_{ref} \frac{R_2}{R_1 + R_2} \tag{6.14}$$

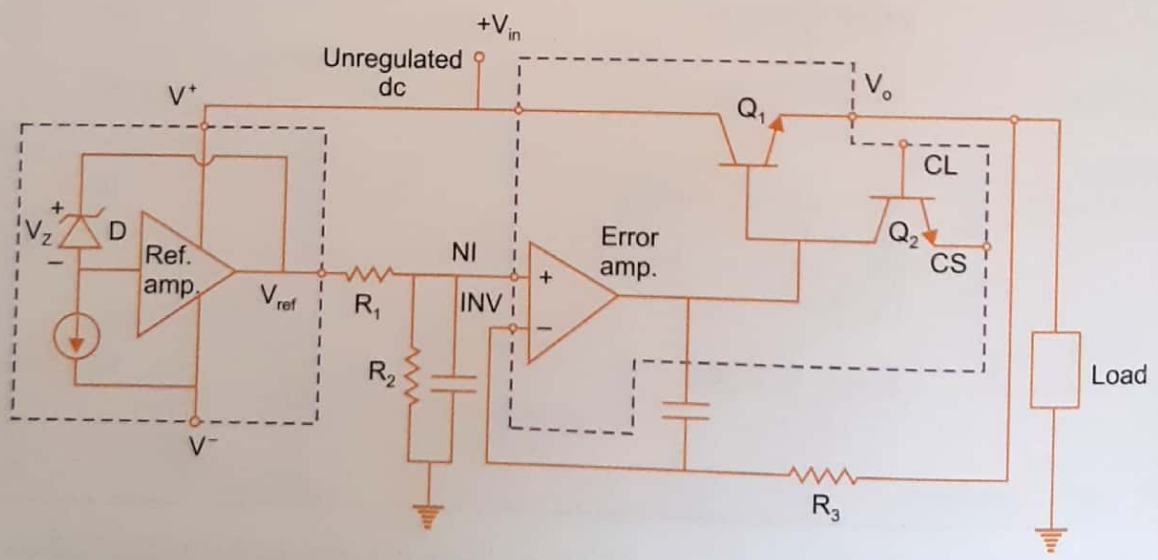


Fig. 6.8 (b) Functional diagram for a low voltage regulator

$V_{ref} \simeq 7$ V, $V_o = V_{NI} = 7R_2/(R_1 + R_2)$, $V^+ = +V_{cc}$, $R_3 = R_1 || R_2$ (minimum drift), $V^- =$ GND

If the output voltage becomes low, the voltage at the INV terminal of error amplifier also goes down. This makes the output of the error amp to become more positive, thereby driving transistor Q_1 more into conduction. This reduces the voltage across Q_1 and drives more current into the load causing voltage across load to increase. So the initial drop in the load voltage has been compensated. Similarly, any increase in load voltage, or changes in the input voltage get regulated.

The reference voltage is typically 7.15 V. So the output voltage V_o is

$$V_o = 7.15 \times \frac{R_2}{R_1 + R_2} \tag{6.15}$$

which will always be less than 7.15 V. So in the circuit of Fig. 6.8 (a) is used as low voltage (<7 V) 723 regulator.

If it is desired to produce regulated output voltage greater than 7 V, then the circuit of Fig. 6.8 (c) can be used. The NI terminal is connected directly to V_{ref} through R_3. So the voltage at the NI terminal is V_{ref}. The error amplifier operates as a non-inverting amplifier with a voltage gain of

$$A_v = 1 + \frac{R_1}{R_2} \tag{6.16}$$

So the output voltage for the circuit is

$$V_o = 7.15\left(1 + \frac{R_1}{R_2}\right) \tag{6.17}$$

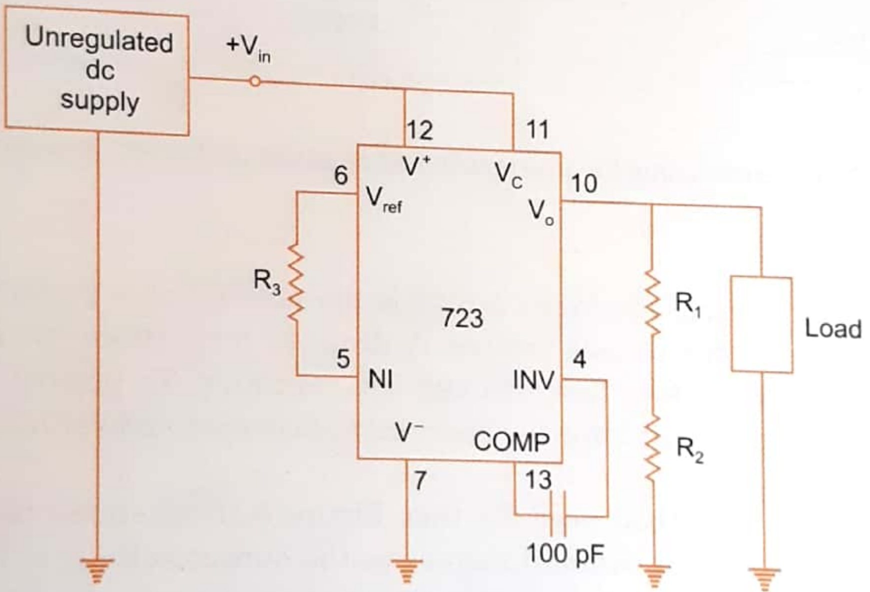


Fig. 6.8 (c) Basic high voltage 723 regulator
$V_{ref} = 7$ V, $V_o = 7(1 + R_1/R_2)$, $R_3 = R_1 R_2$, $V^+ = +V_{CC}$, $V^- =$ GND

Current Limit Protection

The circuits of Fig. 6.8 have no protection. If the load demands more current *e.g.*, under short circuit conditions, the IC tries to provide it at a constant output voltage getting hotter all the time. This may ultimately burn the IC.

The IC is, therefore, provided with a current limit facility. Current limiting refers to the ability of a regulator to prevent the load current from increasing above a present value. The characteristic curve of a current limited power supply is shown in Fig. 6.9 (a). The output voltage remains constant for load current below I_{limit}. As current approaches to the limit, the output voltage drops. The current limit I_{limit} is set by connecting an external resistor R_{sc} between the terminals *CL* and *CS* terminals as shown in Fig. 6.9 (b). The *CL* terminal is also connected to the output terminal V_o and *CS* terminal to the load.

The load current produces a small voltage drop V_{sense} across R_{sc}. This voltage V_{sense} is applied directly across the base emitter junction of Q_2. When this voltage is approximately 0.5 volt, transistor Q_2 begins to turn ON. Now a part of the current from error amplifier goes to the collector of Q_2, thereby decreasing the base current of Q_1. This in turn, reduces the emitter current of Q_1. So any increase in the load current will get nullified. Similarly, if the load current decreases, V_{BE} of Q_2 drops, repeating the cycle in such a manner that the load current is held constant to produce a voltage across R_{sc} sufficient to turn ON Q_2. This voltage is typically 0.5 V.

So,
$$I_{limit} = \frac{V_{sense}}{R_{sc}} \approx \frac{0.5\text{ V}}{R_{sc}} \tag{6.18}$$

This method of current limiting is also referred to as current sensing technique.

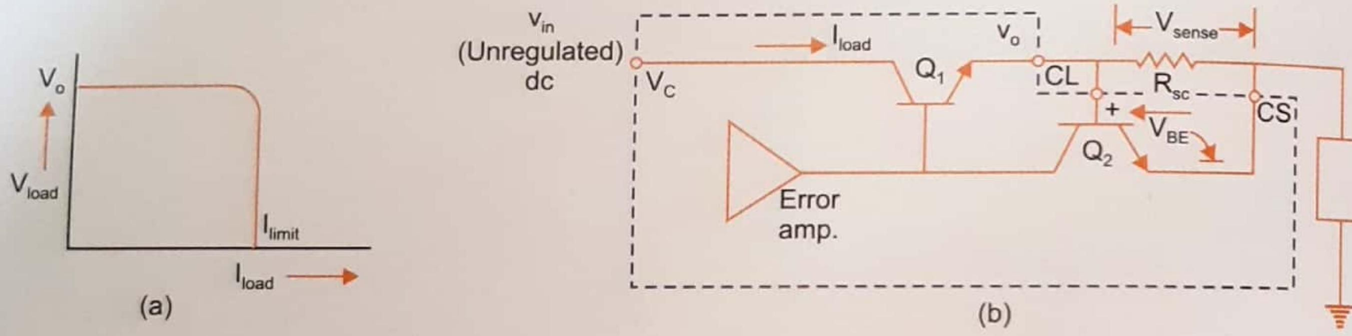


Fig. 6.9 (a) Characteristic curve for a current limited regulator (b) Current limit protection circuit

Current Foldback

In current limiting technique, the load current is maintained at a present value and when overload condition occurs, the output voltage V_o drops to zero. However, if the load is short circuited, maximum current does flow through the regulator. To protect the regulator, one must devise a method which will limit the short circuit current and yet allow higher currents to the load.

Current foldback is the method used for this. Figure 6.10 (a) shows the current foldback characteristic curve. As current demand increases, the output voltage is held constant till a present current level (I_{knee}) is reached. If the current demand exceeds this level, both output voltage and output current decrease. The circuit in Fig. 6.10 (b) shows the method of applying current foldback. In order to understand the operation of the circuit, consider the circuit of Fig. 6.10 (c). The voltage at terminal CL is divided by $R_3 - R_4$ network. The current limit transistor Q_2 conducts only when the drop across the resistance R_{sc} is large enough to produce a base-emitter voltage of Q_2 to be at least 0.5 V. As Q_2 starts conducting, transistor Q_1 begins to turn off and the current I_L decreases. This reduces the voltage V_1 at the emitter of Q_1 and also the output voltage V_o. The voltage at the base of Q_2 (CL) will be $V_1R_4/(R_3 + R_4)$. Thus the voltage at the CL terminal drops by a smaller amount compared to the drop in voltage at CS terminal. This increases V_{BE} of Q_2 thereby increasing the conduction of Q_2, which in turn reduces the conduction of Q_1. That is, the current I_L further reduces. This process continues till $V_o = 0$ V and V_1 is just large enough to keep 0.5 V between CL and CS terminal. This point is I_{sc} and has been reduced by lowering both I_L and V_o.

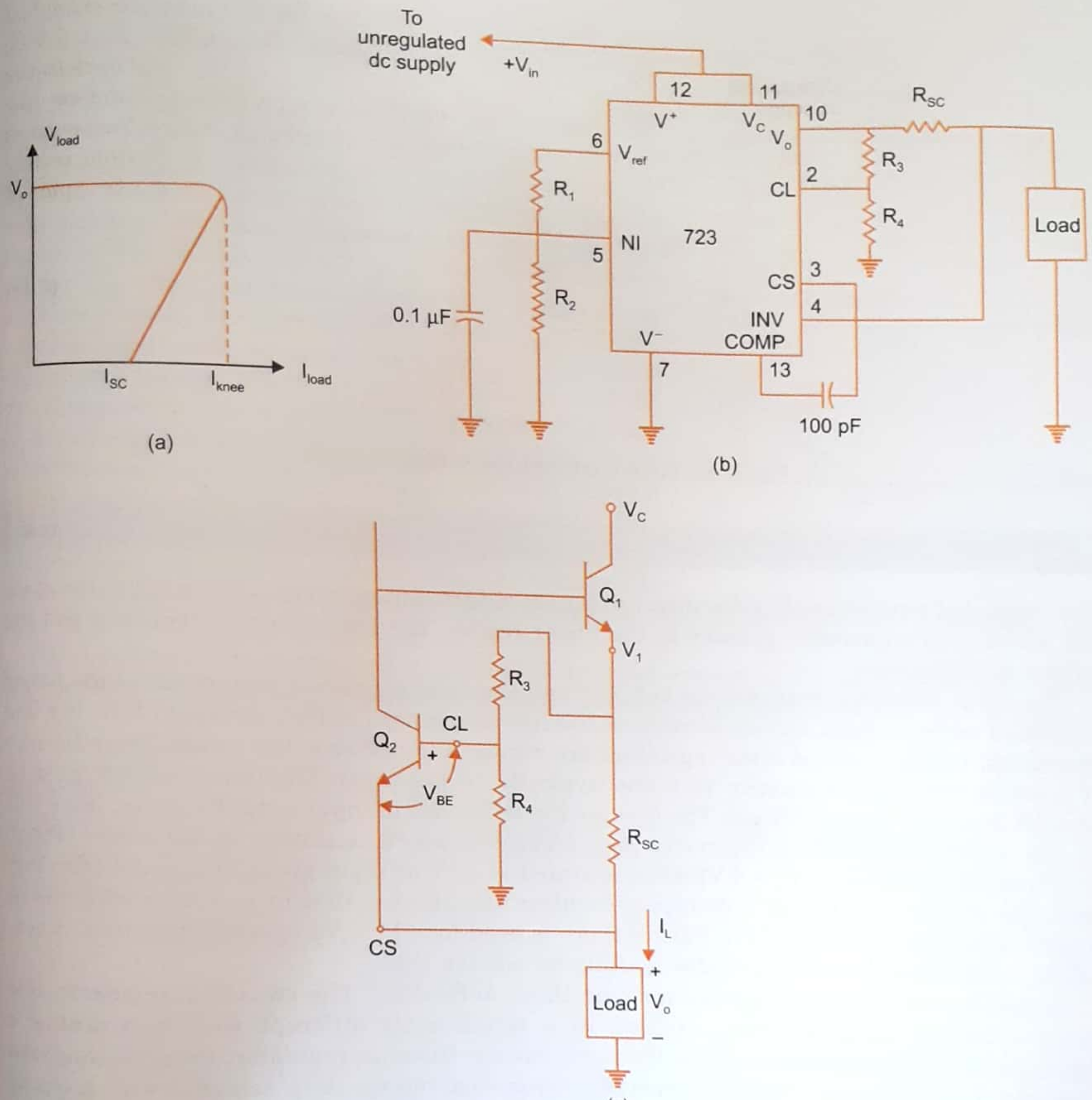


Fig. 6.10 (a) Current foldback characteristic curve (b) A low voltage regulator using current foldback (c) Current foldback (partial schematic)

Current Boosting

The maximum current that 723 IC regulator can provide is 140 mA. For many applications, this is not sufficient. It is possible to boost the current level simply by adding a boost transistor Q_1 to the voltage regulator as shown in Fig. 6.11. The collector current of the pass transistor Q_1 comes from the unregulated dc supply. The output current from V_o terminal drives the base of the pass transistor Q_1. This base current gets multiplied by the beta of the pass transistor, so that 723 has to provide only the base current. So,

$$I_{load} = \beta_{\text{pass transistor}} \times I_{o\,(723)} \tag{6.19}$$

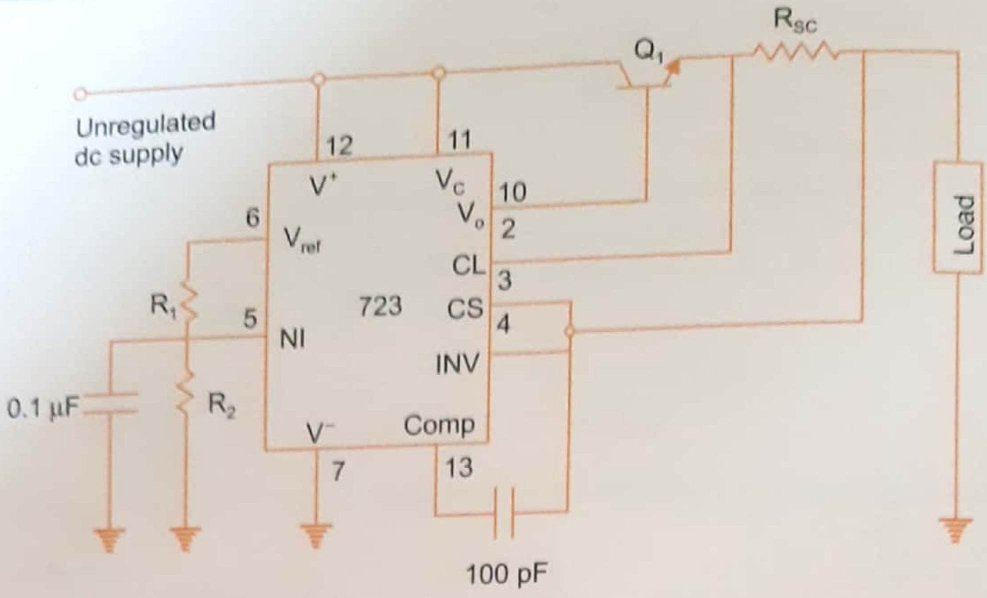


Fig. 6.11 Current boosted low voltage regulator

6.5 SWITCHING REGULATOR

The regulated power supplies discussed so far are referred to as linear voltage regulator, since the series pass transistor operates in the linear region. The linear voltage regulator has the following limitations.

The input stepdown transformer is bulky and the most expensive component of the linear regulated power supply mainly because of low line frequency (50 Hz). Because of the low line frequency, large values of filter capacitors are required to decrease the ripple. The efficiency of a series regulator is usually very low (typically 50 per cent). The input voltage must be greater than the output voltage. The greater the difference in input-output voltage, more will be the power dissipated in the series pass transistor which is always in the active region. A TTL system regulator ($V_o = 5$ V) when operated at 10 V dc input gives 50 per cent efficiency and only 25 per cent for 20 V dc input. Another limitation is that in a system with one dc supply voltage (such as +5 V for TTL) if there is need for ±15 V for op-amp operation, it may not be economically and practically feasible to achieve this.

Switched mode power supplies overcome these difficulties. The switching regulator, also called switched mode regulator operate in a significantly different way from that of a conventional series regulator circuit discussed earlier. In series regulator, the pass transistor is operated in its linear region to provide a controlled voltage drop across it with a steady dc current flow. Whereas, in the case of switched-mode regulator, the pass transistor is used as a "controlled switch" and is operated at either cutoff or saturated state. Hence the power transmitted across the pass device is in discrete pulses rather than as a steady current flow. Greater efficiency is achieved since the pass device is operated as a low impedance switch. When the pass device is at cutoff, there is no current and dissipates no power. Again when the pass device is in saturation, a negligible voltage drop appears across it and thus dissipates only a small amount of average power, providing maximum current to the load. In either case, the power wasted in the pass device is very little and almost all the power is transmitted to the load. Thus efficiency in switched mode power supply is remarkably high–in the range of 70–90%.

Switched mode regulators rely on pulse width modulation to control the average value of the output voltage. The average value of a repetitive pulse waveform depends on the area under the waveform. If the duty cycle is varied as shown in Fig. 6.12, the average value of the voltage changes proportionally.

A switching power supply is shown in Fig. 6.13. The bridge rectifier and capacitor filters are connected directly to the ac line to give unregulated dc input. The thermistor R_t limits the high initial capacitor charge current. The reference regulator is a series pass regulator of the type shown in Fig. 6.1. Its output is a regulated reference voltage V_{ref} which serves as a power supply voltage for all other circuits. The current drawn from V_{ref} is usually very small (~10 mA), so the power loss in the series pass regulator does not affect the overall efficiency of the switched mode power supply (SMPS). Transistors Q_1 and Q_2 are alternately switched ***off*** and ***on*** at 20 kHz. These transistors are either fully ***on*** ($V_{CE\ sat}$ ~ 0.2 V) or cut-off, so they dissipate very little power. These transistors drive the primary of the main transformer. The secondary is centre-tapped and full wave rectification is achieved by diodes D_1 and D_2. This unidirectional square wave is next filtered through a two stage LC filter to produce output voltage V_o.

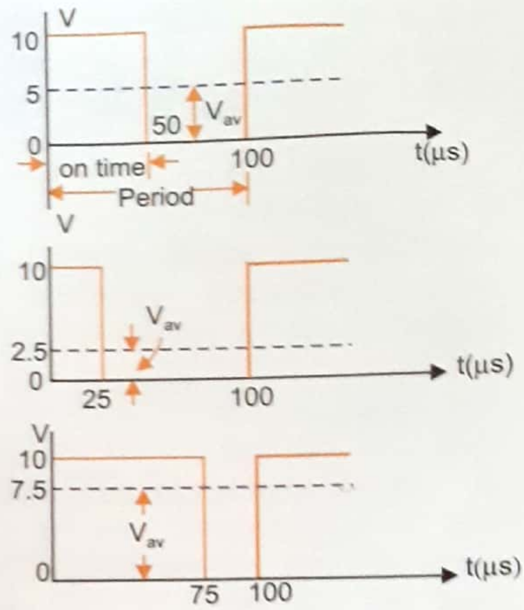


Fig. 6.12 Pulse width modulation and average value

The regulation of V_o is achieved by the feedback circuit consisting of a pulse-width modulator and steering logic circuit. The output voltage V_o is sampled by a R_1R_2 divider and a fraction

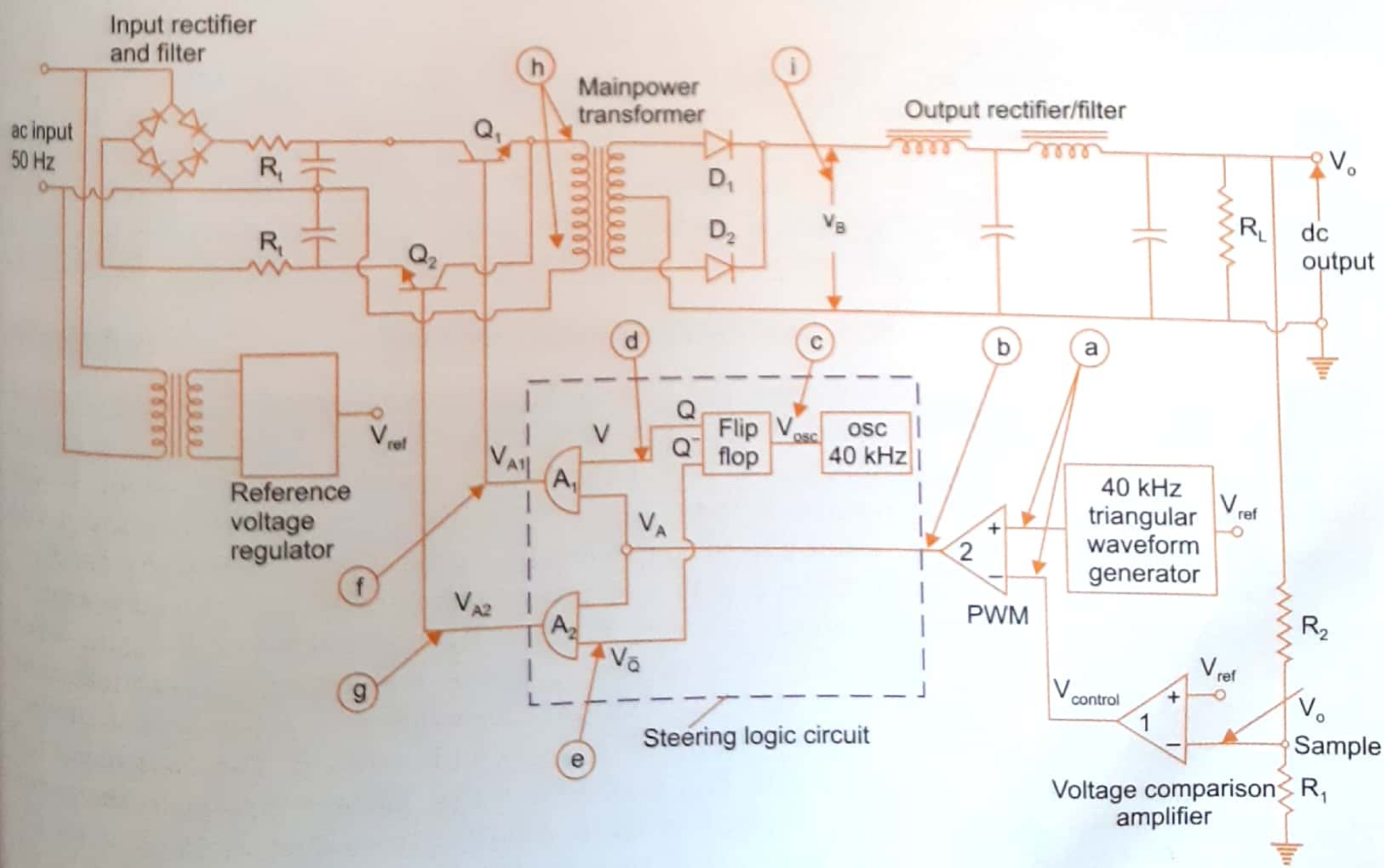


Fig. 6.13 A switched mode power supply

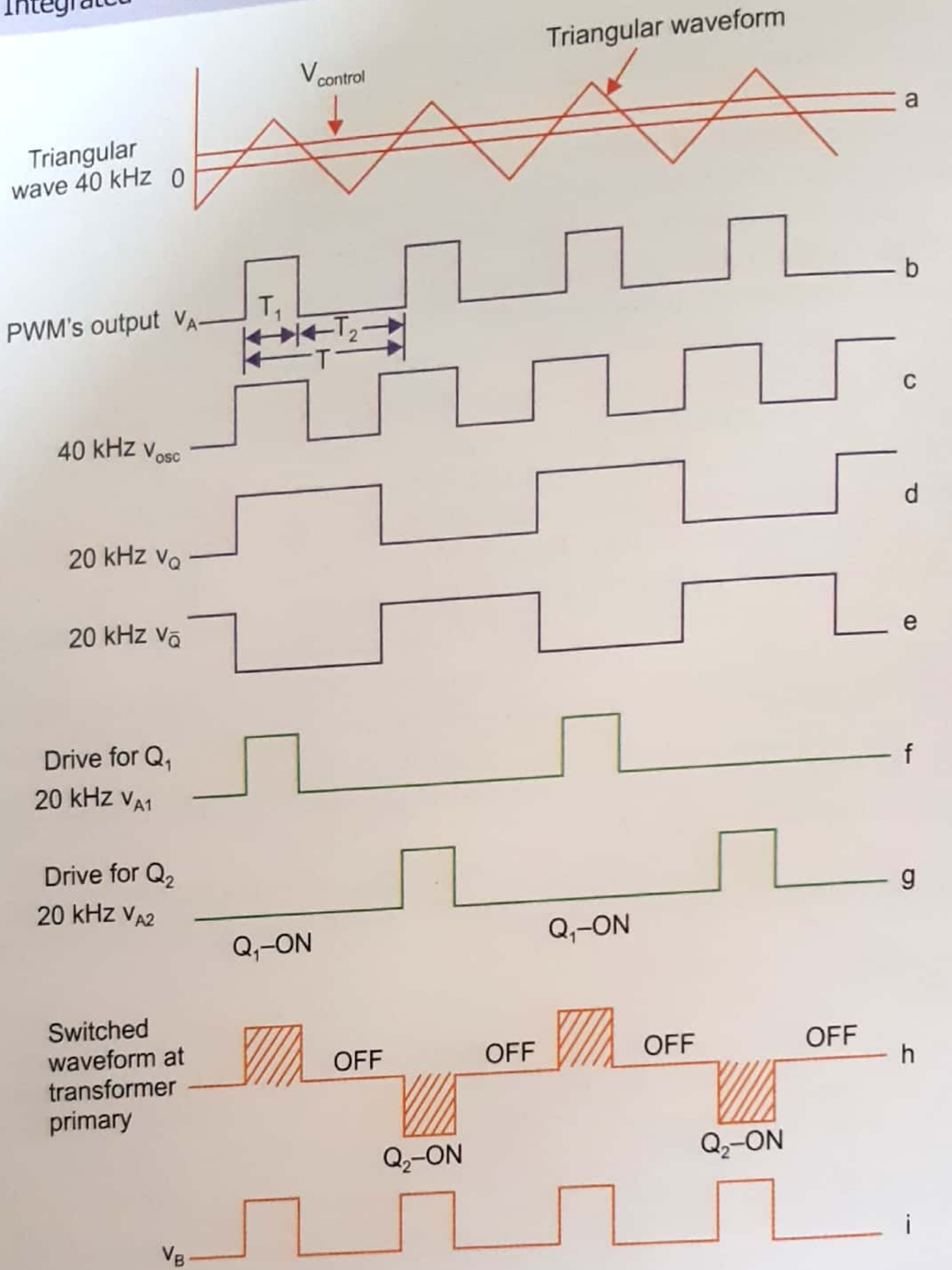


Fig. 6.14 Switching power supply waveforms

$R_1/(R_1+R_2)$ is compared with a fixed reference voltage V_{ref} in comparator 1. The output of this voltage comparison amplifier is called $V_{control}$ and is shown in Fig. 6.14 (a). $V_{control}$ is applied to the (–) input terminal of comparator 2 and a triangular waveform of frequency 40 kHz (also shown in Fig. 6.14 (a)) is applied at the (+) input terminal. It may be noted that a high frequency triangular waveform is being used to reduce the ripple. The comparator 2 functions as a pulse width modulator and its output is a square wave v_A (Fig. 6.14 (b)) of period $T(f = 40$ kHz). The duty cycle of the square wave is $T_1/(T_1 + T_2)$ and varies with $V_{control}$ which in turn varies with the variation of v_o. The output v_A drives a steering logic circuit shown in the dashed block. It consists of a 40 kHz oscillator cascaded with a flip-flop to produce two complementary outputs v_Q and $v_{\bar{Q}}$ shown in Fig. 6.14 (d) and (e). The output v_{A1} and v_{A2} of AND gates A_1 and A_2 are shown in Fig. 6.10 (f) and (g). These waveforms are applied at the base of transistor Q_1 and Q_2. Depending upon whether transistor Q_1 or Q_2 is *on*, the waveform at the input of the transformer will be a square wave as shown in Fig. 6.14 (h). The rectified output v_B is shown in Fig. 6.14 (i).

An inspection of Fig. 6.13 shows that the output current passes through the power switch consisting of transistors Q_1 and Q_2, inductor having low resistance and the load. Hence using a switch with low losses (transistor with small $V_{CE\,(sat)}$ and high switching speed) and a filter with high quality factor, the conversion efficiency can easily exceed 90%.

If there is a rise in dc output voltage V_o, the voltage control $V_{control}$ of the comparator 1 also rises. This changes the intersection of the $V_{control}$ with the triangular waveform and in this case decreases the time period T_1 in the waveform of Fig. 6.14 (b). This in turn decreases the pulse width of the waveform driving the main power transformer. Reduction in pulse width lowers the average value of the dc output V_o. Thus the initial rise in the dc output voltage V_o has been nullified.

So far we have discussed the operation of the SMPS. Now we shall be able to justify why SMPS has better efficiency than linear regulated power supply. We have noted that very high frequency signals (about 40 kHz or more) are being applied. The transistors Q_1 and Q_2 are acting as the switches and become alternately ***on*** and ***off*** at a frequency of 20 kHz (Fig. 6.14 (a)). Again the transistor Q_1 or Q_2 is ***on*** for very small duration and consumes negligibly small power since $V_{CE\,(sat)}$ (0.2 V) is small. It may also be noted that the high operating frequency used for the switching transistors allows the use of smaller transformers, capacitors and inductors. This allows a decrease in size and cost.

There are some limitations and precautions to be taken with switching power supplies. Since the rectifier is tied directly to the ac line voltage, the rectifiers, capacitors and switching transistors must be able to withstand the peak line voltage (310 V for 220 V ac rms line). The resistor R_t must be provided to prevent the uncharged capacitors from shorting out the line when initially turned on. A switched mode power supply is more complex and requires external components like inductors and transformers. It is slow in responding to transient load changes compared to the conventional series regulator. One should be careful about the electromagnetic and radio-frequency interference while using switched mode power supply.

As can be seen, the switching regulator system is quite a complex one. However, with modern microelectronics, quite a few packages are available. The Motorola MC 3420/3520 is a pulse width modulator IC chip. The Silicon General SG 1524 produces an IC package containing reference regulator, pulse width modulator (consisting of saw tooth oscillator and comparator), comparator 1, transistors Q_1 and Q_2, the steering flip-flop and two AND gates.

SUMMARY

1. A regulated power supply provides a dc voltage independent of the load current, temperature and ac line voltage variations.
2. A regulated power supply has four parts: reference voltage circuit, error amplifier, a series-pass transistor and a feed back network.
3. There are several IC regulators available. 78 XX/79 XX series are three terminal positive and negative fixed voltage regulators.
4. The IC regulators combine the reference voltage source, error op-amp, pass transistor with short circuit current limiting and thermal overload protection.
5. The 723 regulator can give adjustable output voltage in a wide range. It provides short circuit protection and current foldback using external components. The basic regulator can be current boosted with an external pass transistor.
6. The switching power supply allows a decrease in size and cost. The pass transistors