

Voltage Regulator Types and Working Principles

How Does a Voltage Regulator Work?

A voltage regulator is a circuit that creates and maintains a fixed output voltage, irrespective of changes to the input voltage or load conditions.

Voltage regulators (VRs) keep the voltages from a power supply within a range that is compatible with the other electrical components. While voltage regulators are most commonly used for DC/DC power conversion, some can perform AC/AC or AC/DC power conversion as well. This article will focus on DC/DC voltage regulators.

Types of Voltage Regulators: Linear vs. Switching

There are two main types of voltage regulators: linear and switching. Both types regulate a system's voltage, but linear regulators operate with low efficiency and switching regulators operate with high efficiency. In high-efficiency switching regulators, most of the input power is transferred to the output without dissipation.

Linear Regulators

A linear voltage regulator utilizes an active pass device (such as a BJT or MOSFET), which is controlled by a high-gain operational amplifier. To maintain a constant output voltage, the linear regulator adjusts the pass device resistance by comparing the internal voltage reference to the sampled output voltage, and then driving the error to zero.

Linear regulators are step-down converters, so by definition the output voltage is always below the input voltage. However, these regulators offer a few advantages: they are generally easy to design, dependable, cost-efficient, and offer low noise as well as a low output voltage ripple.

Linear regulators, only require an input and output capacitor to operate (**see Figure 1**). Their simplicity and reliability make them intuitive and simple devices for engineers, and are often highly cost-effective.

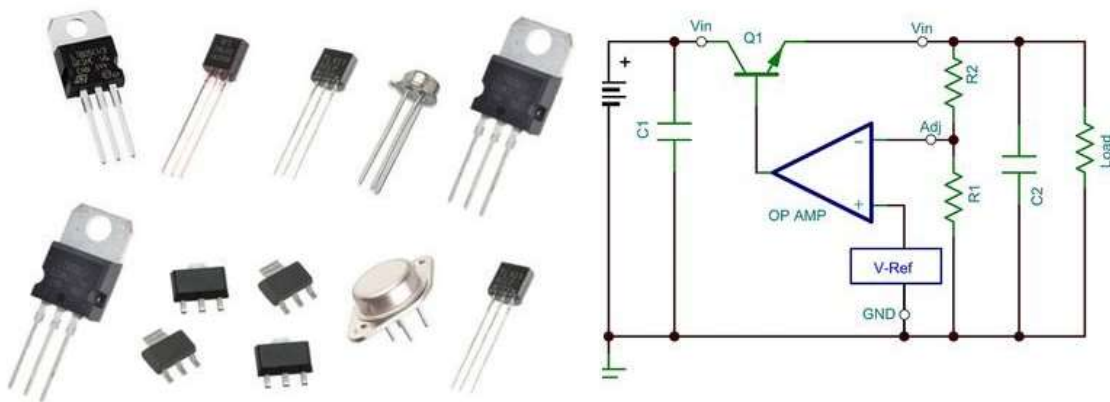


Figure 1: Linear Regulator

Linear voltage regulators can be further classified as either **series** or **shunt** types. Both linear and switching regulators are capable of performing the same function of converting an unregulated input into a regulated output. Linear regulators exhibit efficiency of 20–60%, whereas switching regulators have a much higher efficiency, typically 70–95%. Linear regulators can only be used as a step-down regulator, whereas switching. A zener diode regulator can maintain a fairly constant voltage across a load resistor. It can be used to improve the voltage regulation and reduce the ripple in a power supply. However, the regulation is poor and the efficiency is low because of the non-zero resistance in the zener diode. In some series voltage regulators, overloading causes permanent damage to the pass transistors. The pass transistors must be kept from excessive power dissipation under current overloads or short circuit conditions.

Integrated Circuit Voltage Regulators

The linear series and shunt voltage regulators presented in the previous sections have been developed by various solid-state device manufacturers and are available in integrated circuit (IC) form. Like discrete voltage regulators, linear IC voltage regulators maintain an output voltage at a constant value despite variations in load and input voltage.

In general, linear IC voltage regulators are three-terminal devices that provide regulation of a fixed positive voltage, a fixed negative voltage, or an adjustable set voltage. The basic connection of a three-terminal IC voltage regulator to a load is shown in Fig. 23.14. The IC regulator has an unregulated input voltage V_i applied to the input terminals, a regulated voltage V_o at the output, and a ground connected to the third terminal. Depending on the selected IC regulator, the circuit can be operated with load currents ranging from milliamperes to tens of amperes and output power from milliwatts to tens of watts. Note that the internal construction of IC voltage regulators may be somewhat more complex and different from that previously described for discrete voltage regulator circuits. However, the external operation is much the same. In this section, some typical linear IC regulators are presented and their applications are also given.

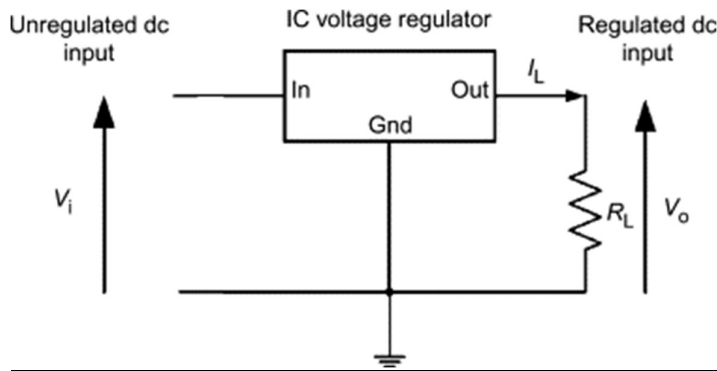


Figure 2 Basic connection of a three-terminal IC voltage regulator.

Fixed Positive and Negative Linear Voltage Regulators

The 78XX series of regulators provide fixed regulated voltages from 5 to 24 V. The last two digits of the IC part number denote the output voltage of the device. For example, a 7824 IC regulator produces a +24 V regulated voltage at the output. The standard configuration of a 78XX fixed positive voltage regulator is shown in Fig. 23.15. The input capacitor C_1 acts as a line filter to prevent

unwanted variations in the input line, and the output capacitor C_2 is used to filter the high-frequency noise that may appear at the output. In order to ensure proper operation, the input voltage of the regulator must be at least 2 V above the output voltage. Table 1 shows the minimum and maximum input voltages of the 78XX series fixed positive voltage regulator.

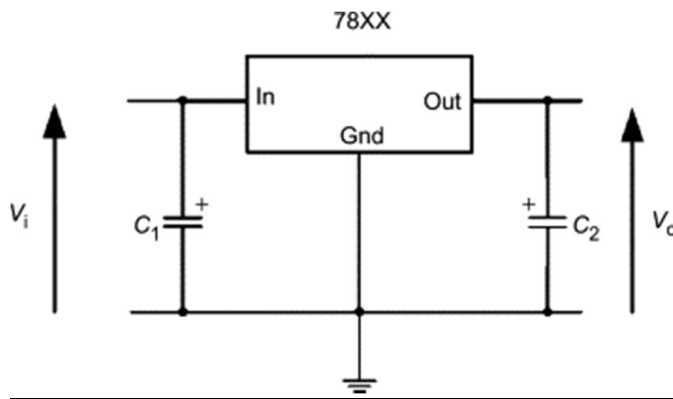


Figure 3 The 78XX series fixed positive voltage regulator.

Type number	Output voltage V_o (V)	Minimum V_i (V)	Maximum V_i (V)
7805	+5	7	20
7806	+6	8	21
7808	+8	10.5	25
7809	+9	11.5	25
7812	+ 12	14.5	27
7815	+15	17.5	30
7818	+18	21	33
7824	+24	27	38

Table 1. Minimum and maximum input voltages for 78XX series regulators

The 79XX series voltage regulator is identical to the 78XX series except that it provides negative regulated voltages instead of positive ones. Figure 4 shows the standard configuration of a 79XX series voltage regulator. A list of 79XX series regulators is provided in Table 2. The regulation of the circuit can be maintained as long as the output voltage is at least 2–3 V greater than the input voltage.

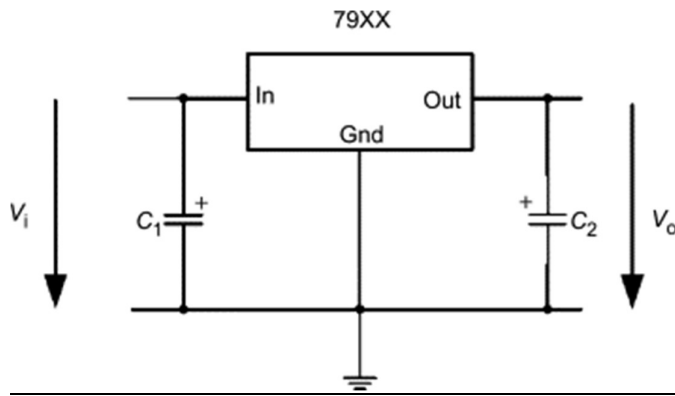


Figure 4 The 79XX series fixed negative voltage regulator.

Table 2. Minimum and maximum input voltages for 79XX series regulators

Type number	Output voltage V_o (V)	Minimum V_i (V)	Maximum V_i (V)
7905	-5	-7	-20
7906	-6	-8	-21
7908	-8	-10.5	-25
7909	-9	-11.5	-25
7912	-12	-14.5	-27
7915	-15	-17.5	-30
7918	-18	-21	-33
7924	-24	-27	-38

Adjustable Positive and Negative Linear Voltage Regulators

The IC voltage regulators are also available in circuit configurations that allow the user to set the output voltage to a desired regulated value. The LM317 adjustable positive voltage regulator, for example, is capable of supplying an output current of more than 1.5 A over an output voltage range of 1.2–37 V. Figure 5 shows how the output voltage of an LM317 can be adjusted by using two external resistors R_1 and R_2 . The capacitors C_1 and C_2 have the same function as those in the fixed linear voltage regulator.

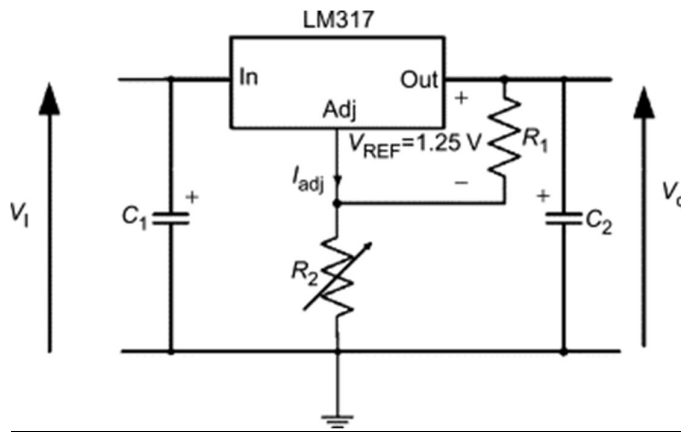


Figure 5 The LM317 adjustable positive voltage regulator.

As indicated in Fig. 5, the LM317 has a constant 1.25 V reference voltage, V_{REF} , across the output and the adjustment terminals. This constant reference voltage produces a constant current through R_1 regardless of the value of R_2 . The output voltage V_o is given by

$$(Eq\ 1) V_o = V_{REF}(1 + R_2/R_1) + I_{adj}R_2$$

Where I_{adj} is a constant current into the adjustment terminal and has a value of approximately 50 μA for the LM317. As can be seen from Eq. (1), with fixed R_1 , V_o can be adjusted by varying R_2 .

The LM337 adjustable voltage regulator is similar to the LM317 except that it provides negative regulated voltages instead of positive ones. Figure 6 shows the standard configuration of a LM337 voltage regulator. The output voltage can be adjusted from -1.2 to -37 V, depending on the external resistors R_1 and R_2 .

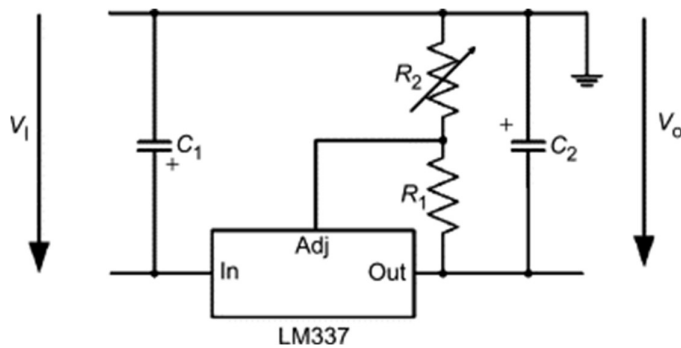


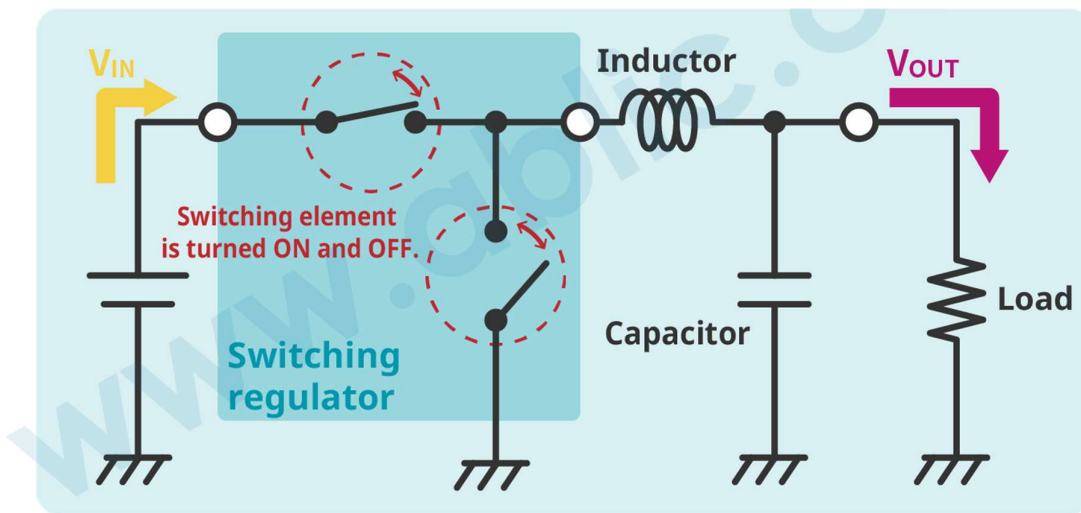
Figure 6 The LM317 adjustable negative voltage regulator

Switching Regulators

A switching regulator circuit is generally more complicated to design than a linear regulator, and requires selecting external component values, tuning control loops for stability, and careful layout design.

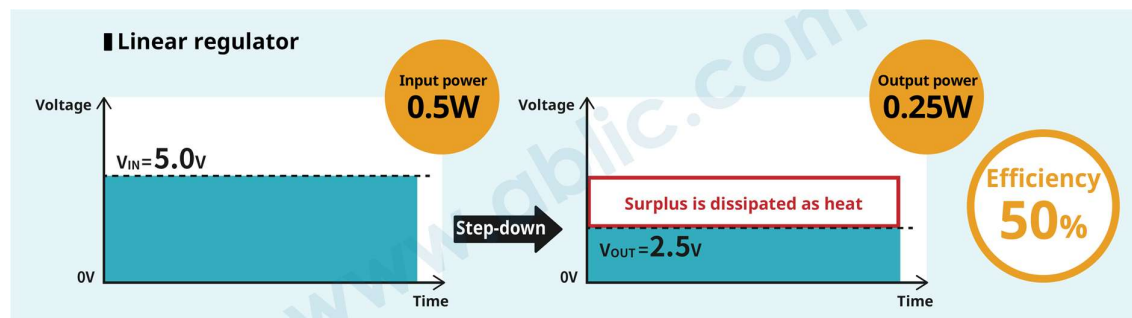
Switching regulators can be step-down converters, step-up converters, or a combination of the two, which makes them more versatile than a linear regulator.

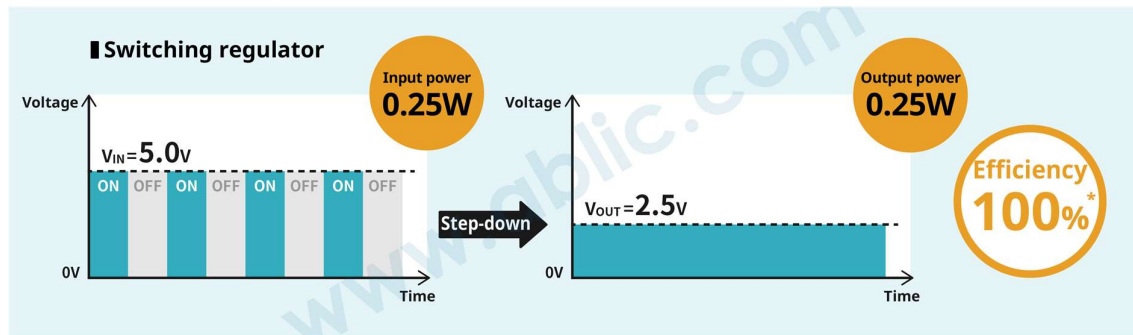
Advantages of switching regulators include that they are highly efficient, have better thermal performance, and can support higher current and wider V_{IN} / V_{OUT} applications. They can achieve greater than 95% efficiency depending on the application requirements. Unlike linear regulators, a switching power supply system may require additional external components, such as inductors, capacitors, FETs, or feedback resistors. A switching regulator that offers high reliability and efficient power regulation.



*A type of switching regulator that requires an external coil

Figure 7: Switching Regulator





Noise

The switching element ON/OFF operations in a switching regulator cause sudden changes in voltage and current, and parasitic components that generate ringing, all of which introduce noise in the output voltage.

Using an appropriate board layout is effective in mitigating noise. For instance, optimizing the placement of capacitor and inductor and/or wiring. For more information on the mechanism of how noise (ringing) is generated and how it is controlled

Table 3. Comparing switching regulator and linear regulator characteristics

	Switching regulator	Linear regulator
Output voltage conversion system	Step-down, step-up, step-up/down, invert	Step-down only; V_{OUT} must be less than V_{IN}
Efficiency	High (negligible heat generation)	Comparatively low (high heat generation) Low when the difference between input and output voltage is large
Output current	Large (high efficiency means high current)	Small
Noise	Large	Small
Output ripple	Present	None
Required external components	Many C_{IN} , C_{OUT} , L, (SBD)	Few C_{IN} , C_{OUT}

Limitations of Voltage Regulators

One of the main disadvantages for linear regulators is that they can be inefficient, as they dissipate large amounts of power in certain use cases. The voltage drop of a linear regulator is comparable to a voltage drop across a resistor. For instance, with a 5V input voltage and a 3V output voltage, there is a 2V drop between the terminals, and the efficiency is limited to $3V/5V$ (60%). This means linear regulators are best suited for applications with lower V_{IN} / V_{OUT} differentials.

It is important to consider the estimated power dissipation of a linear regulator in application, since using larger input voltages results in high power dissipation that can overheat and damage components.

Another limitation of linear voltage regulators is that they are only capable of buck (step-down) conversion, in contrast to switching regulators, which also offer boost (step-up) and buck-boost conversion.

Switching regulators are highly efficient, but some disadvantages include that they are generally less cost-effective than linear regulators, larger in size, more complex, and can create more noise if their external components are not carefully selected. Noise can be very important for a given application, as noise can affect circuit operation and performance, as well as EMI performance.

Switching Regulator Topologies: Step-Down, Step-Up, Linear, LDO, and Adjustable

There are various topologies for linear and switching regulators. Linear regulators often rely on low-dropout (LDO) topologies. For switching regulators, there are three common topologies: step-down converters, step-up converters, and buck-boost converters. Each topology is described below:

LDO Regulators

One popular topology for linear regulators is a low-dropout (LDO) regulator. Linear regulators typically require the input voltage to be at least 2V above the output voltage. However, an LDO regulator is designed to operate with a very small voltage difference between input and output terminals, sometimes as low as 100mV.

Step-Down and Step-Up Converters

Step-down converters (also called buck converters) take a larger input voltage and produce a lower output voltage. Conversely, step-up converters (also called boost converters) take a lower input voltage and produce a higher output voltage.

Buck-Boost Converters

A buck-boost converter is a single-stage converter that combines the functions of a buck and a boost converter to regulate the output over a wide range of input voltages that can be greater or less than the output voltage.

Voltage Regulator Control

The four fundamental components of a linear regulator are a pass transistor, error amplifier, voltage reference, and resistor feedback network. One of the inputs to the error amplifier is set by two

resistors (R_1 and R_2) to monitor a percentage of the output voltage. The other input is a stable voltage reference (V_{REF}). If the sampled output voltage changes relative to V_{REF} , the error amplifier changes the pass transistor's resistance to maintain a constant output voltage (V_{OUT}).

Linear regulators typically only require an external input and output capacitor to operate, making them easy to implement.

On the other hand, a switching regulator requires more components to create the circuit. The power stage switches between V_{IN} and ground to create charge packets to deliver to the output. Similar to a linear regulator, there is an operational amplifier that samples the DC output voltage from the feedback network and compares it to an internal voltage reference. Then the error signal is amplified, compensated, and filtered. This signal is used to modulate the PWM duty cycle to pull the output back into regulation. For example, if the load current increases rapidly and causes an output voltage droop, the control loop increases the PWM duty cycle to supply more charge to the load and bring the rail back into regulation.

Linear and Switching Regulator Applications

Linear regulators are often used in applications that are cost-sensitive, noise-sensitive, low-current, or space constrained. Some examples include consumer electronics such as headphones, wearables, and Internet-of-Things (IoT) devices. For instance, applications such as a hearing aid could use a linear regulator because they don't have a switching element that could create unwanted noise and interfere with the device's performance.

Moreover, if designers are mainly interested in creating a low-cost application, they need not be as concerned with power dissipation, and can rely on a linear regulator.

Switching regulators are beneficial for more general applications, and are especially useful in applications that need efficiency and performance, such as consumer, industrial, enterprise, and automotive applications. For example, if the application requires a large step-down solution, a switching regulator is better suited, since a linear regulator could create high power dissipation that would damage other electrical components.

What are the Basic Parameters for a Voltage Regulator IC?

Some of the basic parameters to consider when using a voltage regulator are the input voltage, output voltage, and output current. These parameters are used to determine which VR topology is compatible with a user's IC.

Other parameters — including quiescent current, switching frequency, thermal resistance, and feedback voltage — may be relevant depending on the application.

Quiescent current is important when efficiency during light-load or standby modes is a priority. When considering switching frequency as a parameter, maximizing the switching frequency leads to smaller system solutions.

Additionally, thermal resistance is critical to remove heat from the device and dissipate it across the system. If the controller includes an internal MOSFET, then all losses (conductive and dynamic) are dissipated in the package and must be considered when calculating the maximum temperature of the IC.

Feedback voltage is another important parameter to examine because it determines the lowest output voltage that the voltage regulator can support. It is standard to look at the voltage reference parameters. This limits the lower output voltage, the accuracy of which impacts the accuracy of the output voltage regulation.

How to Pick the Right Voltage Regulator

To select the proper voltage regulator, the designer must first understand their key parameters such as V_{IN} , V_{OUT} , I_{OUT} , system priorities (e.g. efficiency, performance, cost), and any additional key features, such as power good (PG) indication or enable control.

Once the designer has defined these requirements, use a parametric search table to find the best device to meet the desired requirements. The parametric search table is a valuable tool for designers, as it offers different features and packages available to meet the required parameters for your application.