Linear Regulator IC Series

Basics of Linear Regulators

No.15020EAY17

A linear regulator, also referred to as a "three-terminal regulator" or "dropper," is a power supply long known to many designers owning to its simple circuitry and ease of use. Although some linear regulators consisted of discrete devices in the past, progress with ICs has made the configuration more simple, convenient and miniaturized, besides workable with various power supply applications. Recently, high efficiency has been a must requirement for electronic equipment, and equipment that requires large output current has mainly used a switching power supply, yet linear regulators are in strong demand virtually everywhere thanks to their simple structure, space-savings and, above all, low noise characteristics. This application note gives an overview of linear regulators.

Operating Principle

A linear regulator basically consists of input, output and ground pins. With variable output types, a feedback pin that returns the output voltage is added to the above configuration (Figure 1).

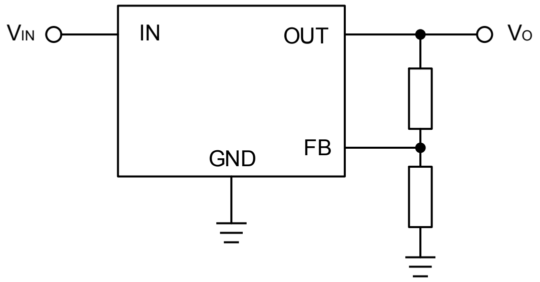

Figure 1 Basic Configuration of Linear Regulator

Figure 2 shows an outline of the internal circuitry of a linear regulator. Basically, it consists of an error amplifier (operational amplifier for detecting errors), reference-voltage source and output transistor. Although a Pch MOSFET is used for the output transistor in this figure, Nch MOSFETs, and bipolar PNP and NPN transistors are also available.

Linear regulator operations are completely analog owing to a feedback loop circuit, one of the basic control circuits using an operational amplifier. Even if input or load changes and output voltage starts changing, the error amplifier continuously compares the feedback voltage to the reference voltage in the regulator output and adjusts the power transistor so that the difference will be zero and Vo will remain constant. This is referred to as stabilization (regulation) by feedback loop control.

More specifically, as voltage of the error amplifier's non-inversed terminal tries to stay the same as V_{REF} as mentioned above, current flowing to R_2 is constant. Since current flowing to R_1 and R_2 is calculated by (V_{REF} / R_2), Vo becomes the calculated current × (R_1+R_2). This conforms exactly to Ohm's law, and is expressed with Formula (1) below.

$$V_O = \frac{V_{REF}}{R_2} \times (R_1 + R_2) = \frac{R_1 + R_2}{R_2} \times V_{REF}\ [V] \quad (1)$$

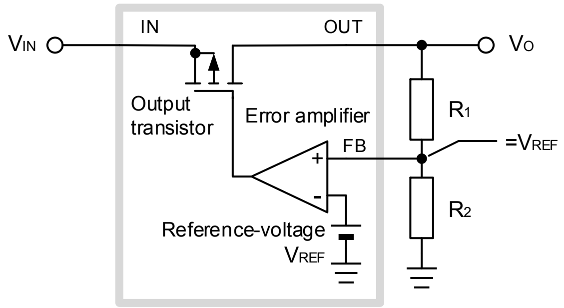

Figure 2 Internal Circuit Outline

Classification

You may have heard names such as "series regulators," "three-terminal regulators," "droppers" and "LDOs." All of these refer to a linear regulator. Apart from these common names, linear regulators can be classified into several groups by function and system.

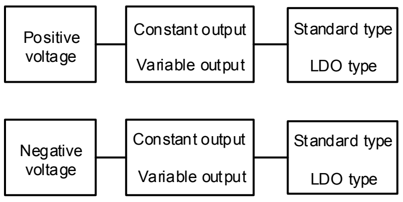

Figure 3 Systematization of Linear Regulators

In the top tier, linear regulators can be roughly classified by positive voltage and negative voltage. However, the negative voltage group does not offer much variation. In the second tier, these two group classified further into constant output and variable output types. The constant type, as represented by the standard models of the 78xx (positive) and 79xx (negative), has a three-terminal (input, output and ground) configuration. Since a resistor for setting purposes is built into the IC, the feedback pin does not need to be mounted externally. The variable type, in the case of the ground reference type as shown in Figure 1, has a four-terminal configuration with an externally mounted feedback pin. The variable type includes a floating operation type without a ground pin, such as 317 (positive), 1117 (positive) and 337 (negative), all of which have a three-terminal configuration.

Beyond their classification into constant/variable types, linear regulators are classified into standard and LDO types. An LDO, short for Low-Dropout, offers improved dropout voltage (minimum voltage difference between input and output that ensures stable operation) below 1V, while that of the standard type has about 3V. This type became popular when ICs of 3.3V power supply were first released on the market. At a time when the conversion from 12V to 5V was a major specification, 3V dropout voltage provided by the standard type presented no problems. However, once the need for 3.3V power supplies arose, the conventional type could not generate 3.3V from 5V. The LDO was developed to solve this problem.

Although all of the aforementioned linear regulators are of the built-in output transistor type, there are other types of ICs called "linear regulator controllers" that have an externally attached output transistor to handle large current.

There is yet another classification by manufacturing process characteristics. Generally, most of the bipolar process linear regulators feature a withstand voltage as high as 35V or 50V and a consumption current of several mA, which is rather high. Although CMOS types featuring a high withstand voltage of 20V have recently been commercialized, most of them assume an input voltage of 5V or less. However, their consumption current has been dramatically reduced to several tens of μA.

ROHM uses a Bi-CDMOS process that features characteristics of both bipolar and CMOS manufacturing processes, and commercializes LDO ICs that offer a withstand voltage of 50V and a consumption current of several μA.

As far as the package is concerned, those having low thermal resistance are used because heat radiation is important for a linear regulator. In through-hole applications, the TO220 family with heatsink is used, while surface mounted applications use a package with a heat radiation pad exposed on the rear.

Model : Manufacturing process
BAxxxx : Bipolar
BUxxxx : CMOS
BDxxxx : Bi-CDMOS

Figure 4 ROHM Models and Manufacturing Processes


TO220FP-3 TO220FP-5 HRP5
TO252-3 HTSOP-J8 SSON004X1010

Figure 5 Packages

Circuit Configuration and Features

The circuitry of a linear regulator basically configured as a feedback loop circuit like that shown in Figure 6. Dropout voltage varies depending on the type of output transistor.

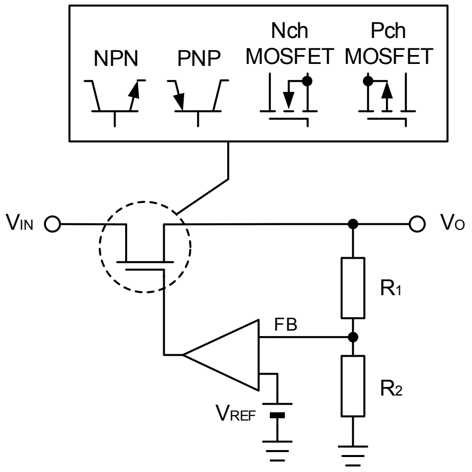

Figure 6 Basic Circuit and Output Transistor

The circuit configuration is roughly classified by the differences between the standard type and the LDO type of linear regulator. The LDO types are further classified into three groups. Although few types of LDOs using a bipolar NPN transistor exist, they allow large current operation. While some large current types have a 10A specification, their dropout voltage is as small as 1V or lower than 2V, which is still high voltage among LDOs. LDOs using a bipolar PNP transistor are the mainstream of current bipolar family LDOs. Initially, there were problems with rush current at startup and current capacity. However, these problems are being solved day by day. MOSFETs were added as an output transistor to low power consumption in consideration of battery-driven applications for lower output voltage (Figure 7).

Control transistor	Dropout voltage
NPN standard type	Around 3V
NPN LDO	1V to 2V
PNP LDO	≤ 0.5V
MOSFET LDO	≤ 0.5V

Figure 7 Output Voltage and Dropout Voltage

Merits and Demerits

The biggest merit of the linear regulator is the ease to use. As it can be activated by mounting capacitors on each the input and output, it can be considered for all practical purposes to be "design-free." Heat radiation design may be more troublesome than circuitry design. The linear regulator is also free from switching noise caused by switching power supplies, and its ripple removing characteristics and low voltage noise are beneficial. This is why the linear regulator tends to be a preferable choice among applications that dislike noise, such as AV, communication, medical and measurement applications.

Although the linear regulator eliminates the need for design, there is something else to consider. Recently, ceramic condensers of large capacity and low ESR, and electrolytic capacitors featuring low impedance have been commercialized. If these components are used with ICs where ceramic capacitors are not indicated for output, abnormal oscillation is likely to occur. With the ICs developed in the previous generation, error amplifier phase compensation was designed on the condition that conventional high ESR capacitor is connected to the output because a low ESR capacitor had not yet been developed. By connecting a low ESR capacitor in this configuration, a phase delay occurs and the amplifier oscillates. Since the latest ICs are designed in consideration of a low ESR output capacitor, a wide range of capacitor types is available.

One particular demerit of the linear regulator is the enormous amount of heat generation under certain conditions because power loss increases as the voltage difference between the input and output increases, and then most of the loss transforms into heat. To use a linear regulator at several watts or more, it is always required to solve heat problems. Due to this shortcoming, the issue often arises that the increase in temperature exceeds the maximum rating of the IC chip junction temperature and current up to the IC maximum output current value is not serviceable. Also, the linear regulator allows "buck" operation only. Although this is also true for negative voltage models, the theory is often confusing, so let us explain it here following. Negative voltage linear regulators, e.g., a -5V input type, cannot output even lower voltages of -12V. As the electrical potential drops from -5V to -12V, it seems to buck. However, voltage increases from -5V to -12V in the negative direction, or, in other words, voltage is boosted in the negative direction. Therefore, an operation that inputs -12V and outputs -5V is allowed (Figure 8).

Merits	Demerits
- Easy to design - Fewer components are used. - Space-saving (In the case of low heat radiation) - Low noise - Inexpensive	- Efficiency deteriorates when the voltage difference between input and output is large. - Low efficiency＝High heat generation - High heat radiation requires large surface mounting area. - Only the buck operation is allowed.

Figure 8 Merits and Demerits

Efficiency and Heat Calculation

This section explains the efficiency and heat calculation of linear regulators. As described above, this is an essential consideration when using a linear regulator.

Efficiency

Efficiency is defined as the ratio of converted output power to input power, and normally indicated as a percentage. The definition is also applied to switching regulators. Formulas (2) and (3) below show calculations for efficiency η. I_{CC} included in input current I_{IN} is the consumption current of the IC itself. However, as this is a small value, it can be ignored if the load current is large. In this case, since input current and output current can be assumed to be the same, efficiency is calculated by simply dividing the output voltage by the input voltage as shown in Formula (4).

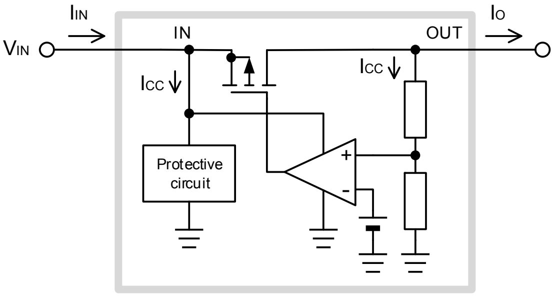

Figure 9 Current Path

$$\eta = \frac{P_O}{P_{IN}} \times 100 \quad [\%] \qquad (2)$$

$$= \frac{V_O \times I_O}{V_{IN} \times I_{IN}} \times 100 \quad [\%] \qquad (3)$$

$$\text{where,} \quad I_{IN} = I_O + I_{CC}$$

$$\cong \frac{V_O}{V_{IN}} \times 100 \quad [\%] \qquad (4)$$

$$\text{where,} \quad I_{CC} \ll I_O$$

For example, the efficiency of converting 5V to 3.3V is calculated to be 66%. Since the efficiency of recent switching regulators is 80% to 90% or more, an efficiency rating of 66% is low.

Now, let us change the input voltage from 5V to 3.8V. Then, efficiency under the above condition is calculated to be 86.8%. To sum things up, a linear regulator yields high efficiency on par with a switching regulator, if the voltage difference between input and output is small. As shown in Figure 10, when V_{IN} gets closer to the dropout voltage $V_{DROPOUT}$, power loss decreases and efficiency increases.

Under such conditions, the contribution factor of an LDO becomes much higher. In this case, since the voltage difference between input and output is 0.5V, the applicable type of linear regulator is an LDO whose dropout voltage is below 0.5V. Standard linear regulators cannot meet this condition. If you have to use a standard type, an input voltage of 6.3V or more is required for a dropout voltage of 3V. This does not meet the initial condition of 5V input and accordingly erodes efficiency down to 52%. On the other hand, to generate 5V from 12V, efficiency and power loss remain the same regardless of the type of linear regulator, standard or LDO.

Linear regulator efficiency depends on the voltage difference between the input and output. Dropout voltage is related to efficiency in terms of the extent of decrease in the voltage difference between the input and output. However, since there is no term for the dropout voltage in the formula, it is not directly related to efficiency.

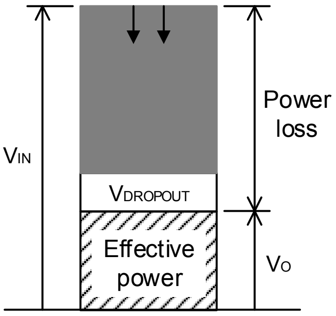

Figure 10 Relationship between I/O Voltage and Power Loss

Heat Calculation

Heat calculation requires information on power loss, the package thermal characteristic parameter and temperature at the center of the package top surface. Power loss is calculated in the same manner as efficiency; put simply, it is calculated by multiplying the voltage difference between the input and output by the input current (Formula [6]). The thermal characteristic parameter is described in the datasheet. If not, it must be obtained from the manufacturer. Temperature at the center of the package top surface can be precisely measured as long as the thermocouple is securely fixed to the center of the package top surface.

Basically, use the thermal characteristic parameter ψ_{JT} from the junction (tip) to the center of the package top surface. Depending on the IC, thermal resistance θ_{JA} may be provided between the junction (chip) and the ambience (Figure 11).

The calculation logic is as follows: Calculate heat generation from the IC chip based on the power loss and thermal characteristics parameter as shown in Formula (5) and add the temperature at the center of the package top surface to the calculated result to obtain the chip temperature. Then, confirm whether the calculated Tj (junction temperature) exceeds Tjmax (maximum junction temperature). If Tj exceeds Tjmax, change one of the conditions. This means that linear regulator operation is subject to restriction because of the input/output voltage, output current and ambient temperature; not all models can be used in accordance with IC specifications.

$$T_J = P \times \psi_{JT} + T_T \quad [℃] \tag{5}$$

$$P = (V_{IN} - V_O) \times I_{IN} \quad [W] \tag{6}$$

P: Power loss $[W]$
ψ_{JT}: Thermal characteristic parameter
T_T: Temperature at the center of the package top surface $[℃]$

It is also possible to simply calculate the chip temperature using thermal resistance θ_{JA}. In this case, information on ambient temperature is required. For example, an ambient temperature of 70°C assumed by the equipment rating will be acceptable. However, if the given condition is rather severe, measurement may be required.

As a calculation theory, calculate heat generated from the IC chip based on the power loss and thermal resistance, as in Formula (7), and add the ambient temperature to the above result to obtain the chip temperature.

$$T_J = P \times \theta_{JA} + T_A \quad [℃] \tag{7}$$

$$P = (V_{IN} - V_O) \times I_{IN} \quad [W] \tag{8}$$

P: Power loss $[W]$
θ_{JA}: Thermal resistance
T_A: Ambient temperature $[℃]$

Generally, there are few examples in which input voltage and output voltage can be changed because temperature exceeds the rated value. For one solution, it may be possible to reduce the load current (output current). To do this, you should select a power receiving device of low power consumption. Alternatively, it is possible to decrease ambient temperature, that is, by changing natural convection type air conditioning to fan cooling, by improving the cooling capability if a fan is already provided or by improving convection. Another solution is to attach a heatsink to the linear regulator and lower thermal resistance to reduce heat generation. However, this will impose significant issues in terms of the cost and size of the heatsink. From a different perspective, a cascade connection of linear regulators or the insertion of a resistor into the IC input section to distribute heat generation is also possible. From the viewpoint of reducing heat generation by enhancing power supply efficiency, use of a switching regulator should be considered.

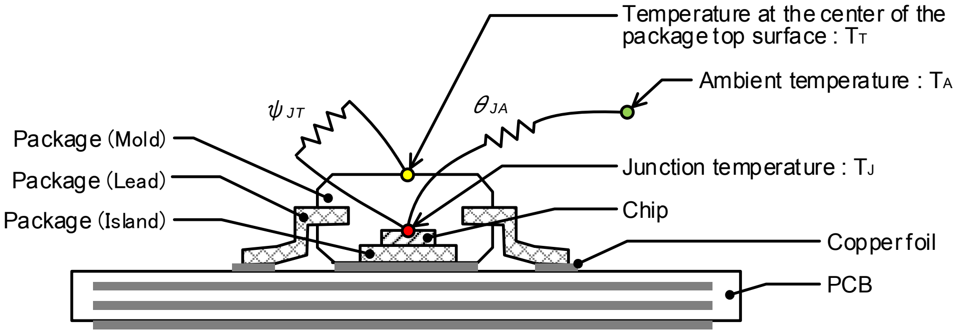

Figure 11 Definitions of Thermal Characteristic Parameter ψ_{JT} and Thermal Resistance θ_{JA}

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