Application Note ANP2

Thermal Considerations for Linear Regulators

Introduction

A low-dropout (LDO) linear regulator is a very simple and economical means of designing a regulated power supply. It offers several advantages over a switching type DC to DC converter such as low noise, no EMI, small component count / PCB area, ease-of-use and lower system cost. On selecting a linear regulator for a particular application one must consider several factors. These factors include input voltage, output voltage, output current, dropout voltage and package type. For the most part the input voltage, output voltage, output current and dropout voltage rating are easily determined by reviewing the product's data sheet. Dropout voltage is defined as the minimum input to output voltage differential for maintaining output regulation. For example, if a linear regulator has a dropout voltage of 300mV then the input voltage must be greater than its output voltage by 300mV to ensure proper regulation. The last major consideration for linear regulator designs is selecting the proper package. Determining the proper package type is critical for proper performance. This is where some designers have problems because the smallest available package may not be the most suitable choice for a given application. This application note will address thermal considerations for linear regulator designs to help the designer with selecting the correct package for their power supply design.

The Linear Regulator basic design consists of a series pass element that is controlled by an Error Amplifier using a Feedback network and Reference Voltage (V_{REF}). Generally, Linear Regulators contain a thermal shutdown and over current protection circuitry. Some Linear Regulators also contain specialty features such as an enable input, error flag output and control voltage feature. A basic fixed output linear regulator block diagram is shown in figure 1.

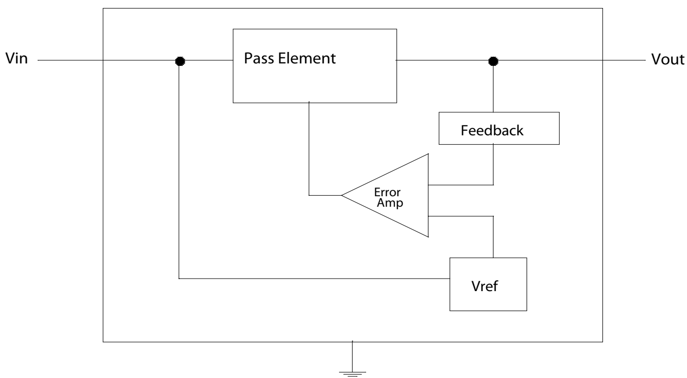

Figure 1. Block Diagram of a basic linear regulator

Note: Thermal calculations discussed in this application note can be quickly iterated with the Linear Regulator Heat Sink Calculator on the web at: www.sipex.com//files/ApplicationNotes/ThermalCalculator.xls

Power Dissipation

Looking at figure 1 we see that the series pass element is connected between V_{IN} and V_{OUT} and is the "work horse" for all linear regulators. When the linear regulator is on and regulating a certain amount of energy or power is dissipated in the device. The power dissipated is the product of input - output voltage difference and output load current. Most of this energy is converted to heat and this is why selecting the proper package is critical for a working design. The bulk of the input current is passed to the output but a very small amount of biasing current also flows out the GND pin and is returned to the input supply. This small amount of return current is called GROUND Current and is specified in all linear regulator data sheets. The typical value of ground current for a high current output device is insignificant when compared to output current and therefore it could be ignored when considering thermal properties. In order to successfully manage this heat / temperature rise we need to calculate the power dissipation. The power dissipation (P_D) can be calculated using the equation:

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$$P_D = [(V_{IN} - V_{OUT})\, I_{OUT}] + (V_{IN} * I_{GND}) \quad (1)$$

Where: P_D = Power Dissipation in watts - W

V_{IN} = Input Voltage applied to regulator

V_{OUT} = Regulator Output Voltage

I_{OUT} = Output Current

I_{GND} = Regulator ground current (biasing current)

$$V_{IN} - V_{OUT} = V_{LDO} \quad (2)$$

As noted above, the ground current is so small that it can be ignored for high output current applications. This will result in a more simplified equation for power dissipation:

$$P_D = (V_{IN} - V_{OUT}) * I_{OUT} \quad (3)$$

When using equation (3) you must use the maximum input voltage and minimum output voltage for maximum V_{LDO}. For example, to calculate P_D for a linear regulator design with a 5.0V +/-5% input and 3.3V +/-1% output at 1A constant load the values would be as follows:

Example 1.

P_D = (5.25V – 3.267V) * 1A

= 1.98W

This result is the amount of power dissipated in the linear regulator. Now we must look at the temperature rise associated with this amount of power while operating in a given ambient temperature. First we must understand the maximum junction temperature of the linear regulator. All of the linear regulators that are offered by Sipex have an absolute maximum junction temperature of 150°C. Operating the device at this temperature will result in performance degradation and reliability issues and thus should be avoided. Hence, the linear regulator has a built in thermal protection feature that will protect against this type of operating condition if accidentally exposed and it is thermal shutdown. Thermal shutdown when activated will force the device to turn off if the die temperature exceeds a certain limit. So how hot will our linear regulator design get under a constant output load current? Using equation (4) we can calculate temperature rise (T_{RISE}) once we know the power dissipation (P_D).

$$T_{RISE} = P_D * \theta_{JA} \qquad (4)$$

Where: P_D = Power Dissipation in watts - W

θ_{JA} = Thermal Resistance - Theta ja (junction to ambient) – ˚C/W

Thermal Resistance

θ_{JA} is the thermal resistance of a given package and it describes how effective the package can dissipate heat. Lower values of θ_{JA} means the package can dissipate heat more effectively. The θ_{JA} rating will be lower for a larger package (TO-263) as compared to a smaller package (SOT-23). θ_{JA} ratings for all of Sipex packages are based on the part being mounted on a 4 layer PCB with JEDEC standards JESD51-1 through JESD51-7 where applicable. A device that has a θ_{JA} of 100 ^oC/W will exhibit a temperature rise of 100 ^oC for a power dissipation of 1W. Using our calculated P_D from Example 1 of 1.98W and using a package having a θ_{JA} of 100 ^oC/W means that the junction temperature (T_J) will rise as follows, using equation (4):

Example 2

$$1.98W * 100^oC/W = 198\ ^oC$$

A design having this amount of power and using a package with this amount of thermal resistance obviously would not work. 198 ^oC far exceeds the junction temperature maximum specification and thermal shutdown would be activated. Moreover, this temperature rise does not take into account the ambient temperature. At this point in the design changes are required in order to have proper operation. Several options are available for minimizing temperature rise such as adding a heat sink, using a cooling fan or perhaps selecting a different package with a much lower θ_{JA} or improving the thermal resistance by increasing copper plane area attached to tab. Heat sink and "air flow" are topics outside the scope of this application note. Another option would be to lower the V_{LDO}. This can be achieved by using a lower voltage for V_{IN} thus reducing V_{LDO} and P_D. It is always best to minimize power dissipation by using a input voltage slightly above dropout voltage to reduce P_D. If reducing V_{LDO} is not possible then lowering the thermal resistance would be the best option. Reducing θ_{JA} is a matter of selecting a larger or different package that offers a better (lower) thermal resistance. The reality of this example is that the power dissipation is extremely high and major changes would be required. If no changes can be made by either lowering θ_{JA} or power dissipation than perhaps the only alternative is to consider using a switching type DC to DC converter. Additionally, you can find several linear regulator products offering a High input voltage range along with a relatively high output current rating. However, this does not mean that a linear regulator offering high V_{IN}, low output voltage and high output current will operate properly at these extreme boundaries due to the large amount of power dissipation and thermal limitations caused by high V_{LDO} for large output currents.

For a linear regulator application one must consider the maximum allowable power dissipation ($P_{D\ (MAX)}$) for a given ambient temperature. Maximum Power Dissipation is a function of the maximum junction temperature, $T_{J\ (MAX)}$, the junction-to-ambient thermal resistance, θ_{JA}, and the ambient temperature, T_A. The maximum allowable power dissipation at any ambient temperature can be calculated using equation (5):

$$P_{D\ (MAX)} = (T_{J\ (MAX)} - T_A) / \theta_{JA} \qquad (5)$$

Where

$T_{J\ (MAX)}$ = Maximum junction temperature as per data sheet (usually 125 °C)

T_A = Ambient temperature

θ_{JA} = Thermal Resistance - Theta ja (junction to ambient) – °C/W

For example, using a package with a θ_{JA} of 100 °C/W we can find the maximum power dissipation allowable for our design when using a linear regulator with a 125°C temperature range and operating in an ambient temperature of 85 °C.

Example 3 using equation (5)

(125 °C -85 °C) / 100 °C/W = 0.4W or 400mW

As you can see we are only allowed to have a maximum power dissipation of 400mW for the given parameters. However, reducing the operating ambient temperature range or lowering the thermal resistance will increase the allowable power dissipation.

Rearranging equation (5) is useful for finding what value of θ_{JA} is necessary for a linear regulator design.

$$\theta_{JA} = (T_{J\ (MAX)} - T_A) / P_D \qquad (6)$$

Design Example

Now that we have a better understanding of thermal properties relating to a linear regulator let's show a design example. The first thing for our design is to list the requirements of our power supply.

V_{IN} = 5.0V +/-5%

V_{OUT} = 3.3V +/-1%

Output Current = 350mA

Product operating temperature is 0 °C to +70 °C.

Small Package size with low component count

Go to www.sipex.com and click on "Low Drop-out" tab in the product's field for a complete listing of LDO devices being offered by Sipex. Scan the I_{OUT} field for meeting the output current requirement of 350mA and review the product's data sheet to ensure device will meet other operating parameters per requirement.

For this design we will use the SPX3819. It offers an output current of 500mA with an input voltage range of 16V along with a Dropout voltage of 340mV and an accuracy of 1%. The SPX3819 comes in three different small packages: 5 pin SOT-23, 8 pin NSOIC and 8 pin DFN. Our V_{IN} to V_{OUT} differential (VLDO) is well above the dropout voltage for this part. The SPX3819 is offered in a fixed 3.3V output and uses only 1 small capacitor for input voltage and 1 small capacitor for output. The SPX3819 also has available a Bypass pin that can be used to reduce the output noise. However, this bypass pin can be left floating if noise is not a major concern. The total component count is 3 thus satisfying requirements for low component count and small space. The SPX3819 input and output capacitors can use surface mount ceramic capacitors that further reduces system cost. Another feature offered with the SPX3819 is the ability to turn the device off with the enable pin. This feature can be useful for battery powered portable designs for increasing battery life when 3.3V is not needed. If your application does not need an enable input simply connect EN to V_{IN}. The SPX3819 has temperature range of -40°C to +125°C. Looking back at all of our initial requirements we see that the SPX3819 fully satisfies all requirements. Now we need to determine which package to use in our design for proper operation. Based on what has been presented here in this application note, we can now select the proper package to meet thermal requirements.

Since we know our constant output current is 350mA we can review the SPX3819 data sheet to find the ground current rating to use in our power dissipation equation. Figure 2 is the graph for ground current vs. output load current graph from the SPX3819 data sheet.

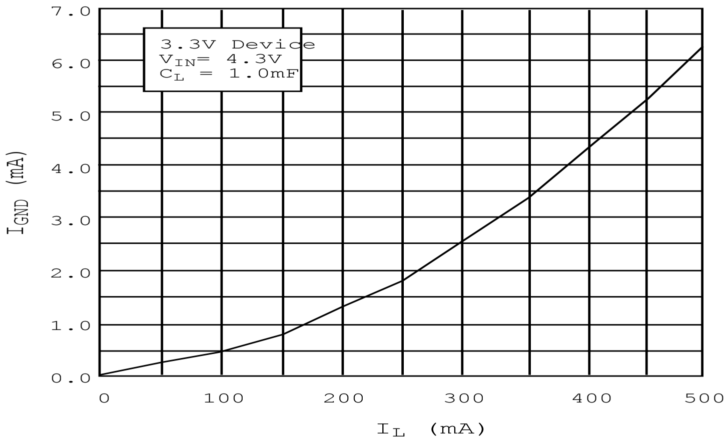

Figure 2 SPX3819 Ground Current VS. Load Current

For a 350mA output current the ground current will be approximately 3.5mA

The power dissipation is then as follows:

P_D = [(Vin – Vout) Iout] + (Vin * I_{GND}) (1)

P_D = [(5.25V – 3.267V) x 350mA] + (5.25V x 3.5mA)

= 0.69 + 0.018

= 0.70W

As stated previously, the power dissipation due to ground current can usually be ignored for it is much smaller than P_D.

Once we know the power dissipation we can quickly determine the required θ_{JA} using equation (6). Since our product is being offered for a maximum ambient temperature of +70 ˚C we will use this value in our equation. Additionally, the SPX3819 has a recommended operating junction temperature range ($T_{J\,(MAX)}$) of 125 ˚C.

$\theta_{JA} = (T_{J\,(MAX)} - T_A) / P_D$ (6)

θ_{JA} = (125 ˚C - 70 ˚C) / 0.70W

θ_{JA} = 78.5 ˚C/W

The package we select for this design must have a thermal resistance (θ_{JA}) lower than 78.5 ˚C/W. The SPX3819 is offered in three different packages with the following thermal resistance.

SOT-23 θ_{JA} = 220 ˚C/W

S0-8 θ_{JA} = 128.4 ˚C/W

DFN-8 θ_{JA} = 59 ˚C/W

We can use the DFN-8 package for our design for its thermal resistance is acceptable. The DFN package offers a very small solution with enhanced thermal properties. The enhanced thermal properties are possible due to its exposed bottom pad that decreases the thermal resistance while still allowing for a small size. Connect this exposed pad to the GND plane and also GND pin of the device.

The next action we must take is to find the amount of temperature rise we can expect using this package. This can be calculated using the temperature rise (T_{RISE}) equation (4) from earlier.

$$T_{RISE} = P_D * \theta_{JA} \qquad (4)$$

$$T_{RISE} = 0.70W \times 59\,^{\circ}C/W = 41.3\,^{\circ}C$$

Now that we have calculated the amount of temperature rise using this package with our power dissipation we want to know how hot the LDO will get at our maximum operating ambient temperature of 70 ˚C. This can be found by adding the ambient temperature and T_{RISE} to give us the junction temperature (T_J) at any given ambient temperature (T_A).

$$T_J \text{ at any given ambient} = T_{RISE} + T_A \quad (6)$$

$$T_J \ @ \ T_A\ 70\,^{\circ}C = 41.3\,^{\circ}C + 70\,^{\circ}C = 111.3\,^{\circ}C.$$

This temperature is well below the SPX3819 maximum junction temperature of 125˚C and we can be assured that thermal shutdown will not be activated. Using the SPX3819 in a DFN package has satisfied all of our design requirements.

Layout Considerations

Place Input and Output capacitors as close as possible to the device. The linear regulator output should also be located as close as possible to load destination. Connect GND pin, Package Tab and exposed pad (if applicable) directly to large GND plane. For packages offering a thermal tab verify tab is connected to GND internally for connection to GND plane. Some package tabs are internally connected to V_{OUT}, consult data sheet for tab connection. Increasing GND plane area reduces thermal resistance. By not using a large ground plane thermal resistance will increase thus lowering the maximum power dissipation. Connect V_{IN} and V_{OUT} traces using a large as possible plane to increase heat-sinking ability and to minimize trace resistance. Having trace resistance for V_{IN} and or V_{OUT} will cause an I/R drop resulting in less than expected voltage at destination. This is particularly true for large input / output currents. Avoid locating linear regulator solution next to other heat generating devices for it will cause the total temperature rise to increase and it could risk activating thermal shutdown.

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