

Designing Low-Power Circuits (LPCs) using an eFuse for Household and Similar Appliances

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1 Introduction

There has been a rapid increase in the number of electronic equipments being used in households in the recent years. The role of safety is very important in white goods and appliances as they could be unsafe for the users to operate if one or more of their components fail. This is why these products are subjected to severe testing and qualification process to ensure safety and reliability. Standards organizations such as IEC (International Electrotechnical Commission) and UL (Underwriters Laboratories) outline the process in which a product is tested to help mitigate risk, injury or danger.

Companies that develop home and consumer appliances need their products to comply with respective standard for them to be marketed globally. For example, household appliances sold in Europe must pass IEC60335-1, while home appliances sold worldwide must pass UL 60730. The intention of this application note is to help readers understand Low-Power Circuits (LPC) as mentioned in the IEC60335-1 and UL 60730 standards, highlight the advantages of qualifying circuits as LPCs and design Low-Power Points using an eFuse which help qualify circuits as LPCs.

eFuses are integrated power path protection devices that are used to limit circuit currents, voltages to safe levels during fault conditions. eFuses offer many benefits to the system and can include protection features that are often difficult to implement with discrete components.

2 What are Low-Power Circuits (LPCs)

The two standards, IEC60335-1 and UL 60730 have a lot in common including a shared definition of a Low-Power Circuit (LPC). The electronic circuit is a Low-Power Circuit as described below.

“The control is operated at rated voltage or at the upper limit of the rated voltage range and a variable resistor, adjusted to its maximum resistance, is connected between the point to be investigated and the opposite pole of the supply source.

The resistance is then decreased until the power consumed by the resistor reaches a maximum. Any point nearest to the supply and at which the maximum power delivered to this resistor does not exceed 15W at the end of 5 s is called a Low-Power Point. The part of the circuit farther from the supply source than a Low-Power Point is considered to be a Low-Power Circuit.

In addition, each Low-Power Circuit is short-circuited by connecting the Low-Power Point to the pole of the supply source from which the measurements were made.” (Definition of Low-Power Circuits in UL 60730-1, section H.27.1.1 and IEC60335-1 Ed. 5.2, section 19.11.1 and 19.11.2)

Let's try to understand the definition of LPC with the help of an example application circuit as shown in [Figure 1](#).

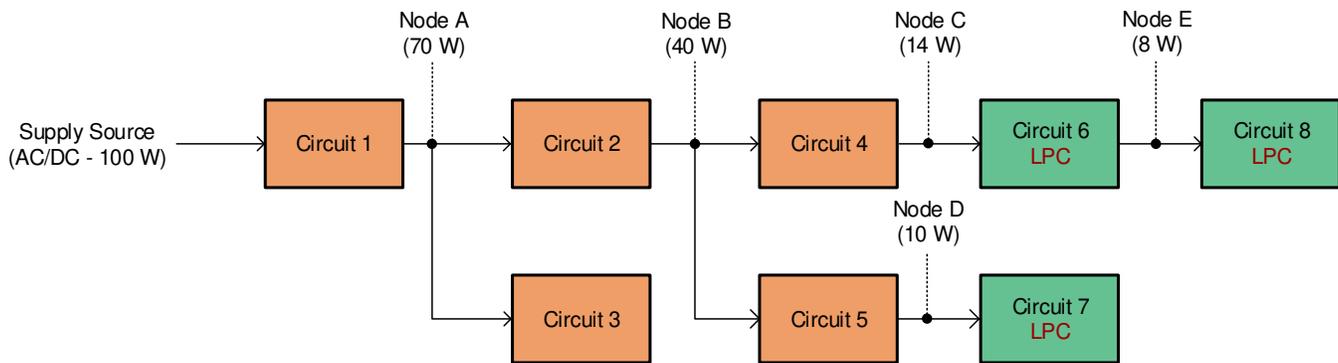


Figure 1. Example Electronic Circuit of an Application

The example electronic circuit of an application has different circuits numbered from 1 to 8 and nodes in between the circuits named as Node A, B, C, D and E. At each node, the maximum power consumption across a variable resistor when it is varied from maximum to minimum value is also specified. One can infer from [Figure 1](#) that,

- Beyond Node B there is no other point in the circuit which consumes power greater than 15 W
- Node C and Node D are points closest to the supply source where the maximum power consumed does not exceed 15 W

Then, Node C and D can be called Low-Power Points. The circuits farther from the supply source than low-power points i.e. Circuit 6, 7 and 8 will be qualified as Low-Power Circuits.

Many of the household appliances have sub-circuits which consume less than 15 W. For example in [Refrigerator](#) the ice maker units, interior lights, control panel and multiple valves typically consume less than 15 W power each. [Figure 2](#) shows an example block diagram of a refrigerator with different sub-circuits which can be considered as a LPCs.

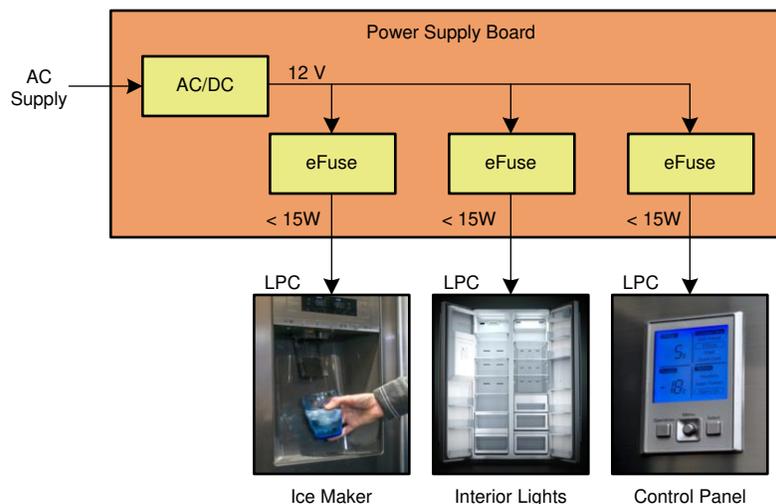


Figure 2. Example Block Diagram of Sub-circuits of a Refrigerator

3 Benefits of using Low-Power Circuits

The electronic circuits have to pass severe tests to qualify for standards such as UL 60730 and IEC60335-1. There are exemptions to Low-Power Circuits from various tests in these standards as listed below,

- Fault Condition tests which include open and short tests to various components (stated in IEC 60335-1 Ed. 5.2; section, 19.11.2 a) – g))
- Glow Wire Test of IEC 60695-2-11 for appliances that are operated while attended (stated in IEC

60335-1 Ed. 5.2; section, 30.2.2, Note 5)

- Glow Wire Test for appliances that are operated while unattended (stated in IEC 60335-1 Ed. 5.2; section, 30.2.3.2)
- Needle Flame Test (NFT) on printed circuit boards (stated in IEC 60335-1 Ed. 5.2; section, 30.2.3.2)

Exceptions from these tests mean that the boards and systems on LPCs are qualified faster and resulting in the more important time to market.

UL 94 which is a 'Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances' determines the plastic material's tendency to either extinguish or spread the flame once the specimen has been ignited. A Low Power Circuit reduces the potential of a fire in the system thus the flame retardance rating of the plastic enclosures housing the Printed Circuit Boards and wiring can be lessened. The cost of plastic decreases as the flame retardance rating is reduced because the weight of the plastic decreases due to less flame retardants required per kilogram of plastic.

Designers can design one board with circuits which can be qualified as LPCs that power all other loads. By doing so, only the AC/DC power source board is subject to Open, Short, Glow Wire and Needle Flame Tests. LPCs also increase design portability as proven LPC designs can be migrated in to new product designs. Thus qualifying circuits as LPCs have several benefits which result in saving cost and time for the end product.

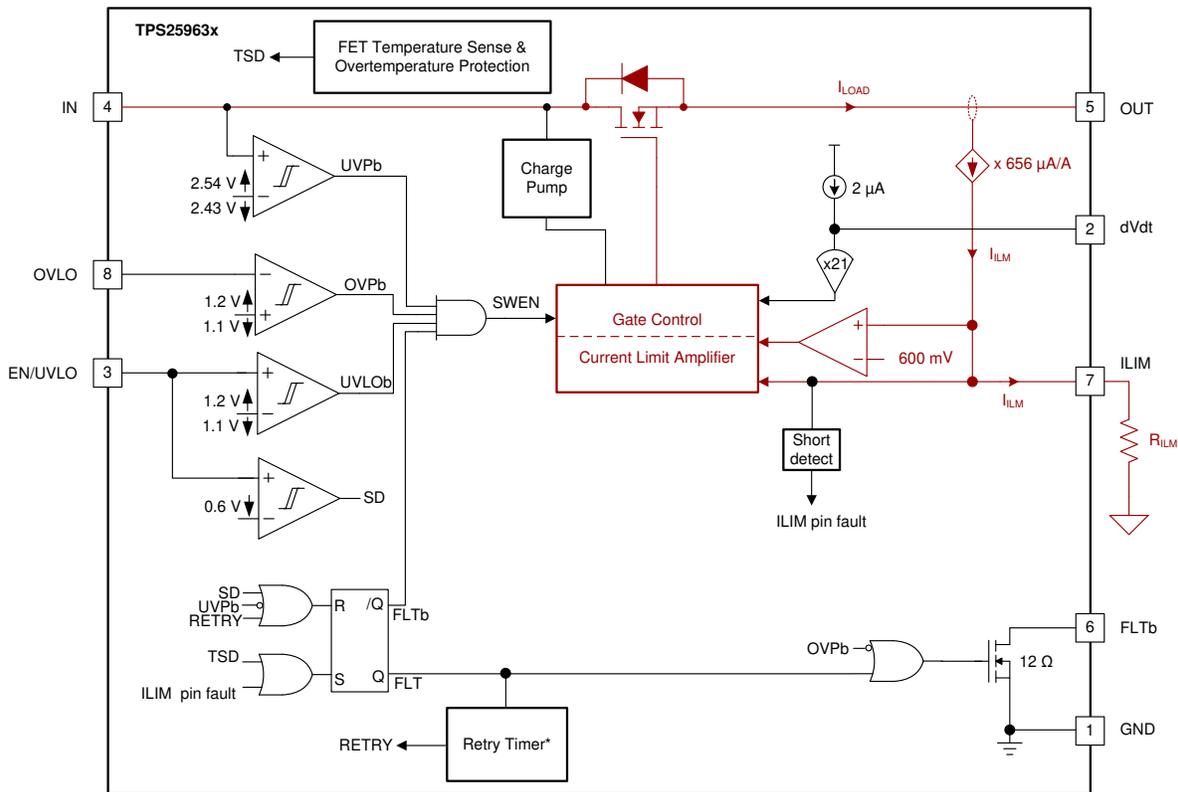
4 Design of Low-Power Circuits using TPS2596

The TPS2596 is an eFuse with precision current limit which can operate for 2.7 V to 19 V supply voltage and has features including inrush current limiting, output current monitoring, overvoltage clamp and programmable undervoltage. This device can be used to realize robust defense against overloads, short circuits, voltage surges, and excessive inrush current using very few external components. Before going into the implementation of power limiting using TPS2596, let us first understand how the current limit circuit of TPS2596 works.

As shown in [Figure 3](#), current flowing in the internal FET is monitored and a proportional current (I_{ILM}) is mirrored into the external R_{ILM} resistor. The scaling factor for the proportional current is 656 $\mu A/A$. The voltage at the ILIM pin which is the product of R_{ILM} and I_{ILM} is continuously compared with a reference voltage of 600 mV. When the voltage at ILIM pin increases beyond 600 mV, it is considered as an overload event and the gate signal to the internal FET of TPS2596 is controlled to limit the current flowing in the FET such that the voltage at ILIM pin is equal to 600 mV.

The resistance R_{ILM} sets the current limit value. [Equation 1](#) can be used to find the R_{ILM} for a desired current limit.

$$R_{ILM}(\Omega) = \frac{903}{I_{LIM}(A) - 0.0112} \quad (1)$$



* Only for Auto-Retry Variant (TPS259631)

Figure 3. TPS25963x Block Diagram with Current Limit Circuit Highlighted

TPS2596 provides an adjustable current limit setting for a current range of 0.125 A to 2 A with a maximum current limit accuracy of $\pm 10.4\%$ across temperature. The current limit accuracy at 1 A current limit setting is $\pm 5.5\%$. TPS2596 also protects upstream power supplies and itself during a short circuit event at the output. If the current exceeds $1.5 \times I_{LIM}$, the device engages a fast current clamping circuit to regulate down the current faster than the nominal overcurrent response time (t_{LIM}). The device does not completely turn off the power FET to ensure uninterrupted power in the event of transient overcurrents or supply transients. The device stops limiting the current once the load current falls below the programmed I_{LIM} threshold. The output voltage drops in the current limiting state, resulting in increased power dissipation in the internal FET and might lead to thermal shutdown if the condition persists for an extended period of time.

4.1 Design LPC for tightly regulated input voltages

For a node to be qualified as a Low-Power Point, the maximum power available at the node should not exceed 15 W. To obtain a maximum power limit of less than 15 W, the current limit of TPS2596 can be set such that the product of current limit (I_{LIM}) and maximum input voltage ($V_{IN(MAX)}$) is less than the required power limit setting of 15 W. This will reduce the power available at lower input voltages as the current limit is independent of input voltage. The reduction in input power available at minimum input voltage can be significant for unregulated power supplies which can have wide variation in input voltage.

$$P_{IN(MAX)} = I_{LIM} \times V_{IN(MAX)} \quad (2)$$

In an eFuse, output current is always equal to input current but output voltage (V_{OUT}) is not always equal to input voltage. During overload conditions TPS2596 will be limiting the load current to the set current limit value and the output voltage can drop below input voltage depending on the load resistance (R_{LOAD}). When the device is operating in current limit, the output voltage is equal to minimum of input voltage and product of current limit and load resistance as shown in Equation 3. As output voltage varies with load resistance, output power also varies proportionally as shown in Equation 4.

$$V_{OUT} = \text{MIN}(V_{IN}, I_{LIM} \times R_{LOAD}) \quad (3)$$

$$P_{OUT} = I_{LIM} \times \text{MIN}(V_{IN}, I_{LIM} \times R_{LOAD}) \tag{4}$$

For example, consider a regulated power supply at the input which can deliver 12 V nominal voltage with a tolerance of 10 %. As the maximum input voltage of power supply is 13.2 V the current limit can be set to 1.0 A so as to limit the power to less than 15 W considering current limit accuracy of $\pm 5.5\%$. Now, calculate R_{LIM} from Equation 1 and choose the closest available standard resistor. $R_{LIM} = 909$ ohms is the closest standard resistance value and it sets the current limit at 1.005 A typical.

Figure 4 shows variation of the maximum power limited at the input for the input voltage range of 10.8 V to 13.2 V. The variation of output power with load resistance for different input voltages is shown in Figure 5. As load resistance reduces, the output voltage drops below input voltage and hence the power at output is less than power available at input. As input power reduces proportionally with reduction in input voltage, this method is not suitable for wide varying input voltages.

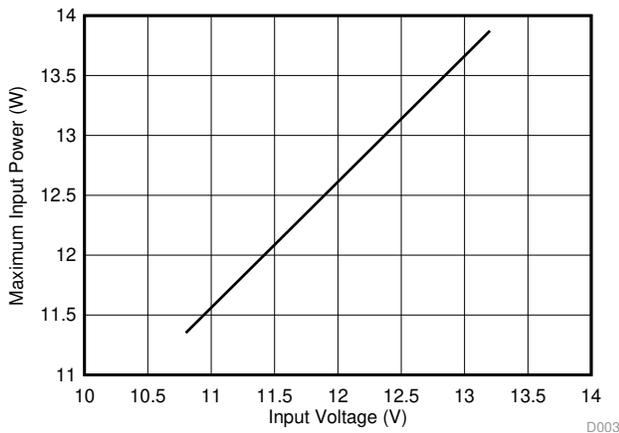


Figure 4. Maximum Input Power Limit vs Input Voltage

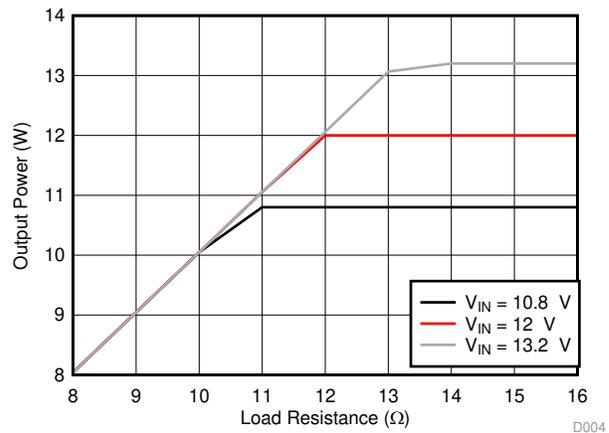


Figure 5. Output Power vs Load Resistance

TPS2596 provides a simple and cost effective way to limit the power delivered to the downstream load. The key parameter to be considered is the current limit accuracy which determines how high one can set the nominal current limit without exceeding the 15 W power limit on the upper end. On the lower end, it determines the maximum power the load can draw in normal conditions without hitting the current limit. TPS2596 provides a current limit accuracy of $\pm 5.5\%$ at 1 A current limit setting, which allows the load to use nearly 90 % out of the 15 W limit under normal operating conditions. In contrast, an alternative current limiting solution with wider current limit tolerance, say $\pm 25\%$ would leave only 50 % out of 15 W for the load circuit to operate under normal conditions. This places severe constraints on the load circuit design and/or capabilities.

By proper selection of current limit value the power at both input and output of TPS2596 can be limited to less than 15 W. The short circuit protection feature of TPS2596 is very useful when Low-Power Points are tested by shorting them to the return path. Taking this into consideration, the output of TPS2596 can be chosen as a Low-Power Point and all the circuits downstream can be qualified as Low-Power Circuits.

4.2 Design LPC for wide varying input voltages

Most of the home appliances like Refrigerator and Dish washer include an isolated AC/DC power supply to provide clean and regulated DC power for electronic circuits such as microcontrollers, sensors, LED lights, wireless modules etc. Generally, isolated AC/DC converters have multiple secondary windings to generate various voltages such as 12 V, 5 V and 3.3 V in order to power different downstream IC's. The output voltage of the winding whose feedback is taken back to the controller is tightly regulated while the remaining windings are unregulated. As a result of poor cross-regulation, the voltage on unregulated windings can vary due to load change on the regulated winding. Figure 6 shows a dual-output flyback converter using secondary-side regulation with isolated outputs of 5 V and 12 V. The 5 V rail can be regulated within $\pm 1\%$ whereas due to cross regulation the 12 V rail can vary upto $\pm 15\%$. TIDA-010058 is a reference design with similar circuit and is suited for use in isolated offline systems requiring low standby power, high efficiency, and low BOM cost.

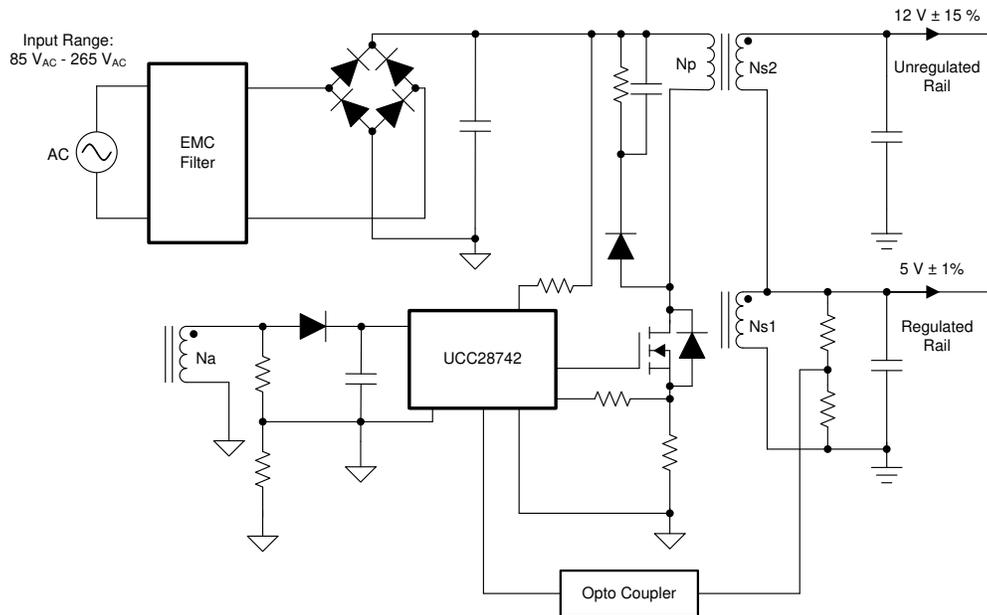


Figure 6. High-Level Block Diagram of an Isolated AC/DC Power Supply

In conditions where the input voltage can have wide variation, TPS2596 along with a few discrete can be used to achieve power limiting and there by qualifying the downstream circuits as LPCs.

4.2.1 Power limiting circuit for wide varying input voltages

The current limit function of TPS2596 is independent of input voltage and therefore the input power varies proportionally with input voltage. The input power can be limited by making current limit inversely proportional to input voltage. This can be achieved by injecting a current proportional to the input voltage into R_{ILIM} as shown in the Figure 7. As input voltage increases, the current injected into R_{ILIM} increases and forces the voltage at ILIM pin to reach 600 mV where the TPS2596 control regulates the gate of the internal FET to limit the current flowing in the FET.

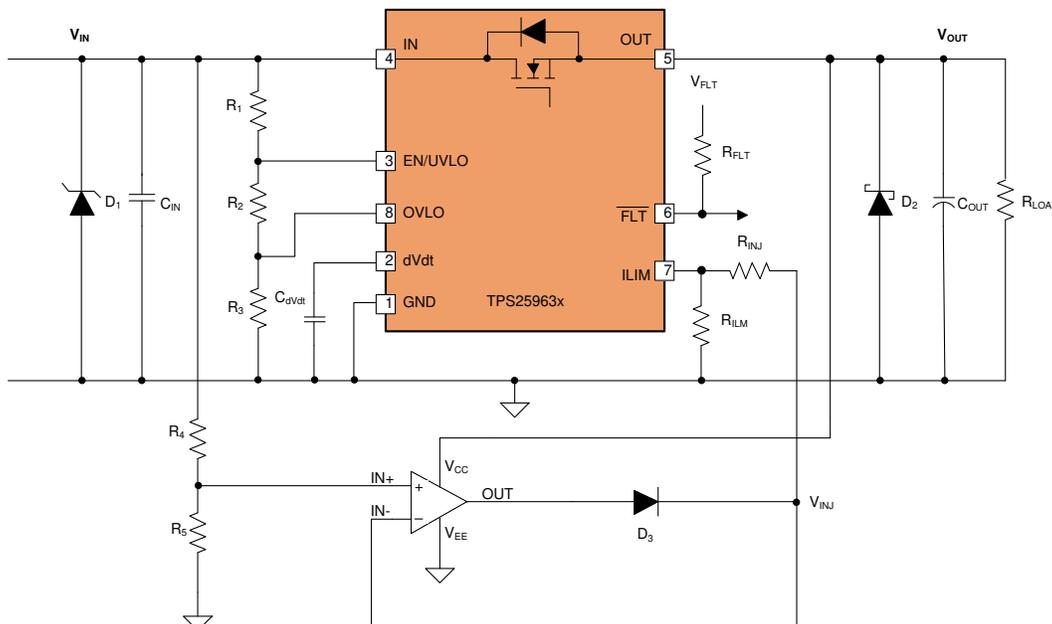


Figure 7. Application Schematic to Limit Power with Increase in Input Voltage

Input voltage is stepped down using a resistor divider and then buffered using an op-amp to generate a voltage, V_{INJ} as shown in [Figure 7](#). Diode D_3 is used to block current flowing from ILIM pin into the Op-amp when voltage at ILIM pin is greater than V_{INJ} . The diode is placed in the feedback path to compensate for the voltage drop and its variation with temperature. The current injected into R_{ILM} due to V_{INJ} is limited by R_{INJ} . Resistors R_4 , R_5 and R_{INJ} set the new current limit value where R_4 and R_5 can be selected so as to set the V_{IN} point from which current needs to be injected into R_{ILM} so that the current limit starts to decrease with increase in input voltage. R_{INJ} can be calculated to obtain the optimal current to be injected to limit power to an acceptable level for entire input voltage range. [Equation 5](#) is the new current limit equation with current proportional to input voltage injected into R_{ILM} .

$$I_{LIM(INJ)} = k \left(\frac{V_{REF}}{R_{ILM}} - \frac{(z \cdot V_{IN}) - V_{REF}}{R_{INJ}} \right) + 0.0112$$

where

- $I_{LIM(INJ)}$ = Current limit value with current proportional to input voltage injected into R_{ILM}
 - $k = 1505$, inverse of scaling factor
 - $z = R_5 / (R_5 + R_4)$
 - $V_{REF} = 0.6$ V, Internal comparator threshold
 - R_{ILM} = Current limit resistor in Ω
 - R_{INJ} = Current Injection resistor in Ω
 - V_{IN} = Input Voltage in V
- (5)

The supply voltage for the op-amp is taken from the output of the efuse to avoid current injection into R_{ILM} during startup. An op-amp which can be powered from the output and has offset voltage low enough to keep the error negligible at an op-amp output voltage of 600 mV can be selected. The bandwidth of the op-amp may not be very important consideration here as the input voltage is generally not expected to vary fast.

4.2.2 Design Example

To understand the procedure to choose values of R_4 , R_5 and R_{INJ} , let us design a circuit to limit the power to 15 W for a 12 V nominal input voltage which can vary from 9 V to 14 V.

- Step1: Select R_4 and R_5 such that V_{INJ} is equal to 600 mV for input voltage from which you want to inject current into R_{ILM} . Consider reducing current limit from lowest input voltages as this will help to limit the power to less than 15 W for the entire input range. Selecting $R_5 = 6.65$ kohms and $R_4 = 93.1$ kohms would result in $V_{INJ} = 600$ mV at 9 V of input voltage.
- Step2: Use [Equation 1](#) to calculate R_{ILM} to obtain 15 W at lowest V_{IN} . Current limit set at 1.5 A would limit the power to close to but less than 15 W at 9 V input considering a current limit accuracy of 7.5 %. Using a standard resistor of 604 ohms sets the current limit to 1.5 A.
- Step3: Using [Equation 5](#), select R_{INJ} such that $I_{LIM(INJ)} \times V_{IN}$ is less than 15 W for the entire input voltage range. Product of two lines (V_{IN} and $I_{LIM(INJ)}$) which have opposite slopes results in an inverted parabola. Hence, the power limit can be expected to peak at some point in the V_{IN} range. Selecting a lower value of R_{INJ} injects more current into R_{ILM} and reduces I_{LIM} significantly at higher input voltages. Similarly, a higher value of R_{INJ} injects less current into R_{ILM} and it can so happen that the reduction in I_{LIM} is not good enough to keep the power limit to less than 15 W for the entire input voltage range. $R_{INJ} = 1000$ ohms gives the right balance of current injected to maintain the power limit to less than 15 W for the entire range of input voltage and also does not drop the current limit too much at higher input voltages.

With the above calculated values of R_4 , R_5 and R_{INJ} , the current limit varies with input voltage as shown in [Figure 8](#). The current limit value starts decreasing from 9 V input voltage as designed.

[Figure 9](#) shows the variation of maximum input power with input voltage for TPS2596 with and without external current injection circuit. The input power is limited to less than 15 W when current proportional to input voltage is injected into R_{ILM} .

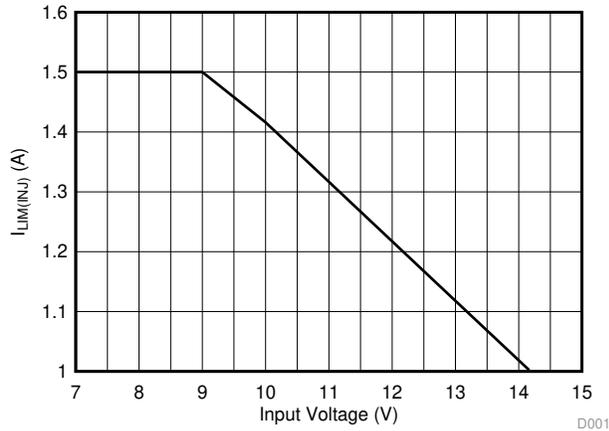


Figure 8. Current Limit with Current Injection Circuit vs Input Voltage

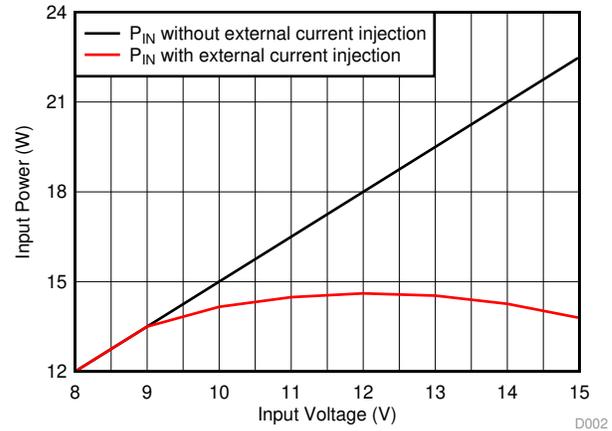


Figure 9. Maximum Input Power with Current Injection Circuit vs Input Voltage

The variation of output power with load resistance for different input voltages can be expected as shown in [Figure 10](#). The output power varies with load resistance but is always less than input power.

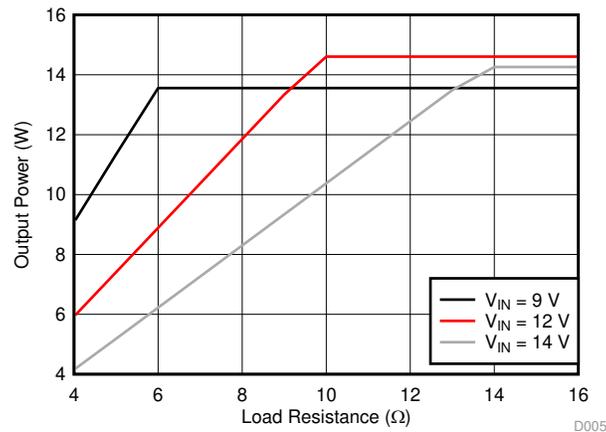


Figure 10. Output Power with Current Injection Circuit vs Load Resistance

The circuit in [Figure 7](#) is tested on bench with a load resistance of 5 ohms and input voltage varying from 9 V to 14 V. [Figure 11](#) and [Figure 12](#) are captured before the device reaches Thermal Shutdown Threshold and turn OFF. [Figure 11](#) shows how current limit varies with increase in input voltage to maintain the input power less than 15W.

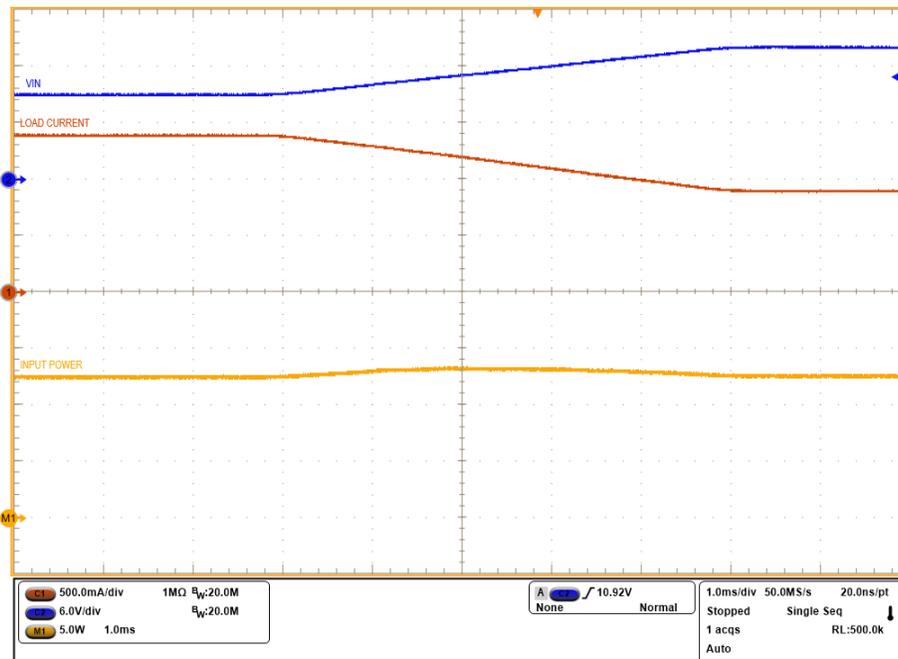


Figure 11. Test Result: Input Power Variation with Input Voltage with Current Injection Circuit

Figure 12 shows the variation of output voltage with increase in input voltage and output power which is simply and product of output voltage and load resistance.

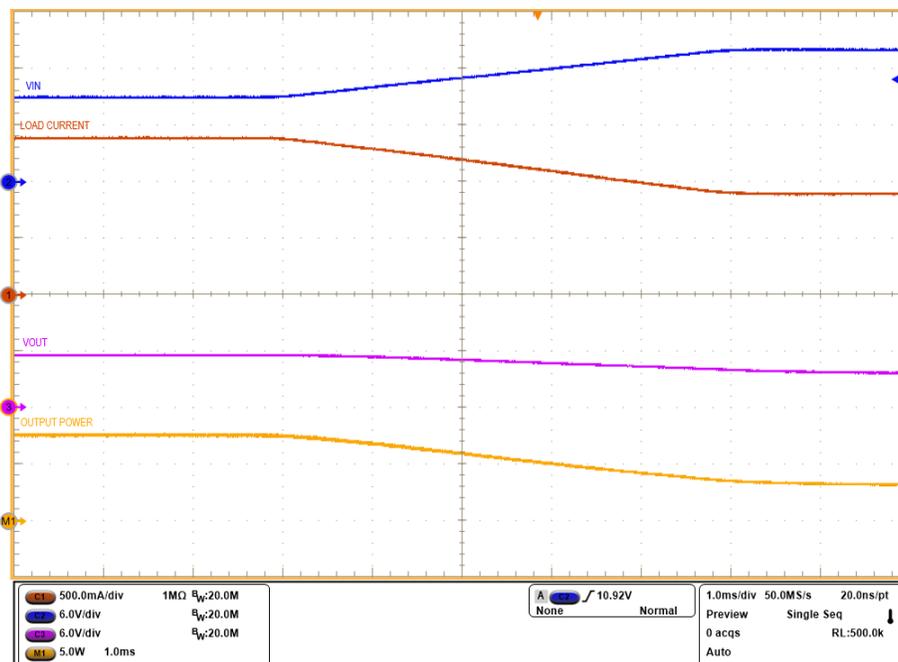


Figure 12. Test Result: Output Power Variation with Input Voltage with Current Injection Circuit

TPS2596 along with few discrete components as shown in Figure 7 can be used to obtain a power limit of less than 15 W at input and output of TPS2596. The short circuit protection feature of TPS2596 enables us to consider output of TPS2596 as a Low-Power Point.

5 Conclusion

- Low-Power Circuits are exempted from various tests in the process of qualifying electronic circuits for standards such as UL 60730 and IEC60335- 1 there by reducing cost and time to market for the end application
- Tight current limit accuracy of TPS2596 helps in realizing Low-Power Point at its output for tightly regulated power supplies without much drop in power available at minimum input voltage. This allows the load to draw more current at minimum input voltage without hitting the current limit.
- For wide varying input voltages, TPS2596 along with few discrete components allow us to realize Low-Power Point by limiting the power at its input to less than 15 W for the entire voltage range without significant degradation of current limit at higher input voltages.

6 References

1. IEC 60335-1 Ed. 5.2, [Household and similar electrical appliances - Safety - Part 1: General requirements](#)
2. UL 60730-1, [Automatic Electrical Controls for Household and Similar Use - Part 1: General Requirements](#)
3. Texas Instruments, [TPS2596 Datasheet](#) (SLVSET8)
4. Texas Instruments, [Basics of eFuses Application Report](#) (SLVA862)
5. Texas Instruments, [TIDA-010058](#)

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