TSM1011:
REGULATION LOOPS PRECISION CALCULATION

by Giuseppe SCUDERI

1 PRINCIPLE OF OPERATION

This technical note shows how it is possible to calculate the current and voltage precision in the regulation loop of the TSM1011.

The TSM1011 is a highly integrated solution for SMPS applications requiring CV (Constant Voltage) and CC (Constant Current) mode.

The TSM1011 integrates one voltage reference and two operational amplifiers (with ORed outputs - common collector).

The voltage reference combined with one operational amplifier makes it an ideal voltage controller.

The other operational amplifier, combined with few external resistors and the voltage reference, can be used as a current limiter.

This circuit is designed for use in battery chargers with a constant voltage and a limited output current and in adapters.

It can be used in every type of application requiring 0.5% and 1% voltage reference precision fixed at 2.5 Volts.

Figure 1 : Typical application using TSM1011 inSSMPS
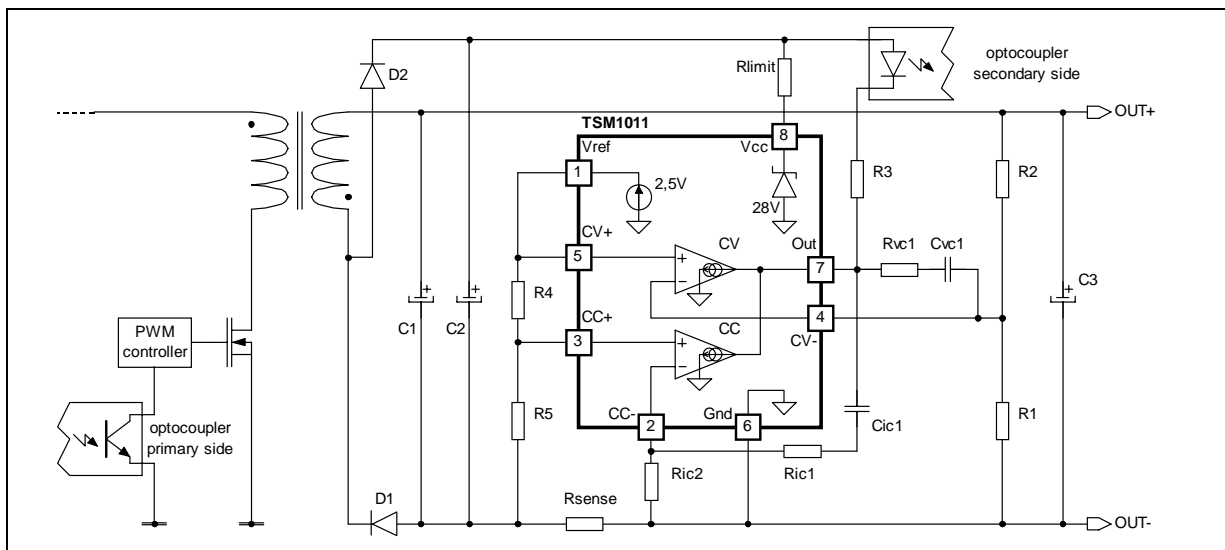
1.1 Voltage Control

The Voltage Control loop is controlled via a first transconductance operational amplifier, the optocoupler which is directly connected to the output and an external resistor bridge connected between the output positive line and the Ground reference.

The middle point is to be connected to the CV- pin of TSM1011, and, if R_2 is the upper resistor, and R_1, the lower resistor of the bridge, the relationship between R_2 and R_1 value should be chosen as written in Equation 1:

Equation 1

$$V_{lim} = f(R_1, R_2, V_{ref})$$

$$V_{lim} = V_{ref} \frac{R_1 + R_2}{R_1}$$

where V_{lim} is the desired maximum output voltage.

When under constant voltage control mode, the output voltage is fixed thanks to the R_1/R_2 resistor bridge. To avoid the discharge of the load, the resistor bridge R_1, R_2, should be highly resistive.

For this type of application a total value of 100kΩ (or more) would be appropriate for the resistors R_1 and R_2 . Note that if the low drop diode should be inserted between the load and the voltage regulation resistor bridge to avoid current flowing from the load through the resistor bridge, this loop should be taken into account in the above calculations by replacing V_{out} by $(V_{out} + V_{drop})$.

1.2 Current Control

The Current Control loop is controlled via the second transconductance operational amplifier, the optocoupler and the sense resistor that is to be placed in series on the output negative line.

V_{sense} threshold is achieved externally by a resistor bridge tied to the V_{ref} voltage reference.

Its middle point is tied to the positive input of the current control operational amplifier and its foot is to be connected to lower potential point of the sense resistor.

The resistors of the bridge are matched to provide the best precision possible.

Equation 2

$$I_{lim} = f(R_{sense}, R_4, R_5, V_{ref})$$

Equation 3

$$R_{sense}I_{lim} = V_{sense}$$

Equation 4

$$I_{lim} = \frac{1}{R_{sense}}\left(\frac{R_5}{R_4}V_{ref}\right)$$

where I_{lim} is the desired maximum output current, and V_{sense} is the threshold voltage for the current control loop. Note that R_{sense} resistor should be chosen taking into account the maximum dissipation (P_{lim}) through it during full load operation:

Equation 5

$$P_{lim} = V_{sense}I_{lim}$$

For most adapter and battery charger applications, a quarter-watt, or half-watt resistor to make the current sensing function is sufficient.

The current sinking outputs of the two transconductance operational amplifiers are common (to the output of the IC), this makes an ORing function that ensures that whenever the current or the voltage reaches too high values, the optocoupler is activated.

The relation between the controlled current and the controlled output voltage can be described with a square characteristic as shown in the following V/I output power graph *Figure 2*.

Figure 2 : Output voltage versus output current
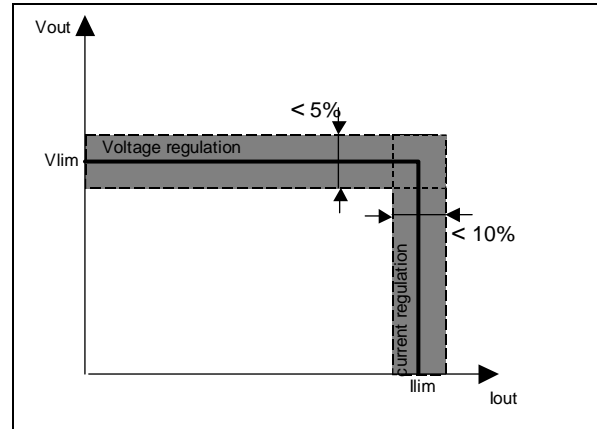
1.3 Start Up and Circuit Conditions

If the TSM1011 V_{cc} is connected to the converter output voltage, then under start-up or short-circuit conditions, the TSM1011 was not provided with a high enough supply voltage. This is due to the fact that the chip has its power supply line in common with the power supply line of the system.

Therefore, the current limitation can only be ensured by the primary PWM module, that should be chosen accordingly.

If the primary current limitation is considered not to be precise enough for the application, then a sufficient supply for the TSM1011 has to be ensured under any condition. It would then be necessary to add some circuitry to supply the chip with a separate power line.

The schematic in *Figure 1* shows how to realize a low-cost power supply for the TSM1011 (with no additional winding). Please pay attention to the fact that in the particular case presented here, this low-cost power supply can reach voltages as high as twice the voltage of the regulated line.

The Absolute Maximum Rating of the TSM1011 supply voltages is 28 Volts.

It is possible to insert R_{limit} resistors in order to limit TSM1011 I_{cc} current in high voltage condition.The current sunk by internal zener diode can be calculated by following formula:

Equation 6

$$I_{vz} = (V_{cc} - V_z)/R_{limit}$$

2 PRECISION CALCULATION

In order to calculate the precision of I_{lim} and V_{lim} in the regulation loop, it is possible to write one relationship that point some parameters out for current and voltage output variation.

As shown in *Figure 3* and *Figure 4* it is possible to make a model of the current and voltage control transconductance operational amplifiers using a voltage source for input offset and an impedance Z_1 with V_1 voltage drop.

Typical precision requirements for battery charging are less than 10% for I_{lim} and less then 5% for V_{lim} see *Figure 2*.

Now, let's go on to the voltage and current loop precision calculation.

2.1 Current Loop Precision Calculation

2.1.1 Theoretical Calculation

Let's show some different steps in order to calculate the current precision loop

According to the *Figure 3* it is simple to verify that:

Equation 7

$$V_{R5} = \left(V_{ref} + V_{sense}\right)\frac{R_5}{R_5 + R_4}$$

For the virtual ground at the input of the current amplifier:

Equation 8

$$Ve_+ - Ve_- = -V_{io} + V_{R5} - V_{sense} - V_1 = 0$$

Equation 9

$$V_{sense} = V_{R5} - V_{io} - V_1$$

Equation 10

$$V_1 = \frac{I_{out}}{G_m}$$

Substituting *Equation 9* in *Equation 7*

Equation 11

$$\frac{V_{ref} + V_{sense}}{R_4 + R_5} = \frac{V_{sense} + V_{io} + V_1}{R_5}$$

where

Equation 12

$$V_{sense} = \frac{R_5 V_{ref} - \left(R_4 + R_5\right)\left(V_{io} + V_1\right)}{R_4}$$

Equation 13

$$V_{sense} = R_{sense} I_{lim}$$

Substituting *Equation 12* in *Equation 13*

Equation 14

$$I_{lim} = \frac{1}{R_{sense}}\left[\frac{R_5}{R_4}V_{ref} - \left(1 + \frac{R_5}{R_4}\right)\left(V_{io} + V_1\right)\right]$$

ΔI_{lim}^{tot} is the sum of the following:

Equation 15

$$\Delta I_{lim}^{tot} = \Delta I_{lim}^{Vref} + \Delta I_{lim}^{Vio} + \Delta I_{lim}^{R5} + \Delta I_{lim}^{R4} + \Delta I_{lim}^{Rsense} + \Delta I_{lim}^{Iout}$$

where

Equation 16

$$I_{lim}^{Vref} = \frac{\Delta I_{lim}}{\Delta V_{ref}} = \frac{R_5}{R_{sense}R_4}$$

Equation 17

$$I_{lim}^{Vio} = \frac{\Delta I_{lim}}{\Delta V_{io}} = -\frac{R_5 + R_4}{R_{sense}R_4}$$

Equation 18

$$I_{lim}^{R5} = \frac{\Delta I_{lim}}{\Delta R_5} = \frac{V_{ref} - \left(V_{io} + V_1\right)}{R_{sense}R_4}$$

Equation 19

$$I_{lim}^{R4} = \frac{\Delta I_{lim}}{\Delta R_4} = -\frac{R_5}{R_{sense}R_4^2}\left[V_{ref} - \left(V_{io} + V_1\right)\right]$$

Equation 20

$$I_{lim}^{Rsense} = \frac{\Delta I_{lim}}{\Delta R_{sense}} = -\frac{1}{R_{sense}^2 R_4}\left[R_5 V_{ref} - \left(R_4 + R_5\right)\left(V_{io} + V_1\right)\right]$$

Equation 21

$$I_{lim}^{Iout} = \frac{\Delta I_{lim}}{\Delta I_{out}} = -\frac{1}{R_{sense}G_m}\left(1 + \frac{R_5}{R_4}\right)$$

Substituting *Equation 16* and *Equation 21* in *Equation 15* and considering the absolute value of these terms:

Equation 22

$$\begin{aligned}
\Delta I_{lim}^{tot} = &\left(\frac{R_5}{R_4 R_{sense}}\right)\Delta V_{ref} \\
&+ \left(\frac{R_4 + R_5}{R_4 R_{sense}}\right)\Delta V_{io} + \\
&+ \frac{1}{R_{sense}}\left[\frac{V_{ref} - \left(V_{io} + V_1\right)}{R_4}\right]\Delta R_5 + \\
&+ \frac{R_5}{R_{sense}R_4^2}\left[V_{ref} - \left(V_{io} + V_1\right)\right]\Delta R_4 + \\
&+ \frac{1}{R_{sense}^2}\left(\frac{R_5}{R_4}V_{ref} - \frac{\left(R_4 + R_5\right)\left(V_{io} + V_1\right)}{R_4}\right)\Delta R_{sense} + \\
&+ \frac{1}{R_{sense}G_m}\left(1 + \frac{R_5}{R_4}\right)\Delta I_{out}
\end{aligned}$$

Equation 22 is important in order to calculate ΔI_{lim}^{tot} and shows the many parameters that characterize current variation.

It can be observed that V_{io}=4mV, V_{ref}=2.5V and V_1<5mV, so the term $V_{io}+V_1$ can be neglected with respect to V_{ref}.

Figure 3 : Simplified model for current precision calculation
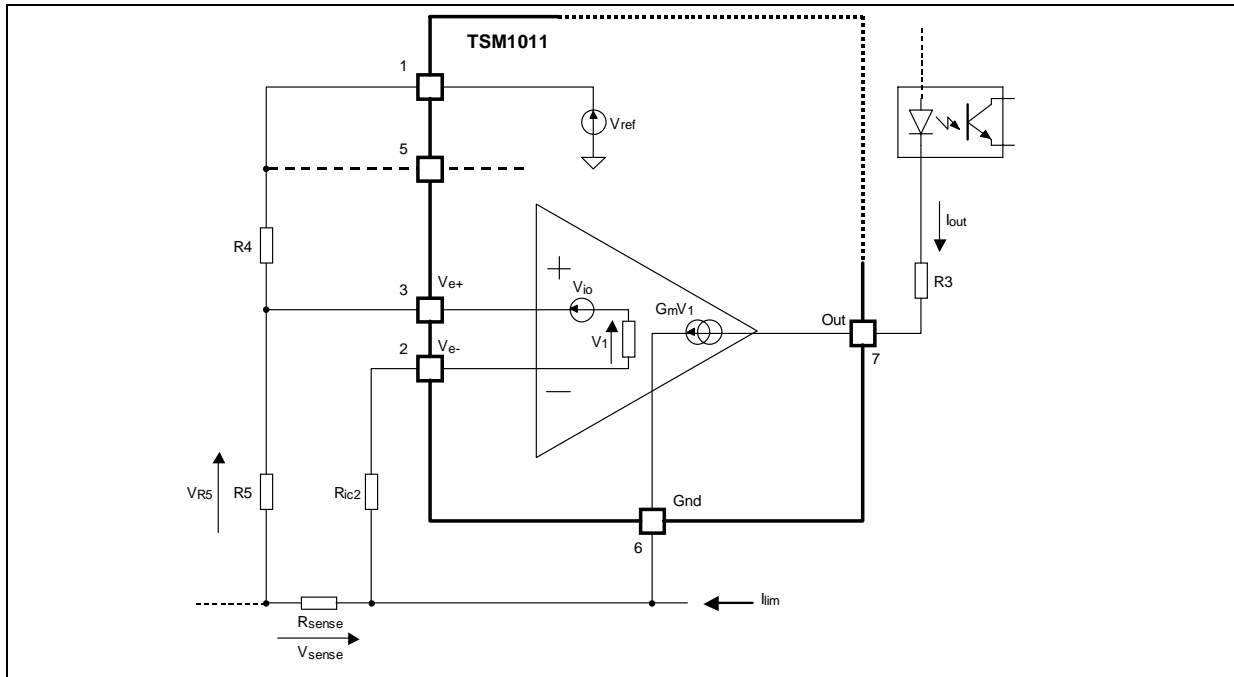
2.1.2 Practical Example

In order to simplify the comprehension of ΔI_{lim}^{tot} formula, let's take a practical example that uses absolute and relative tolerances typical for TSM011 applications.

Consider for example:

see Footnote1)

$$\frac{\Delta V_{ref}}{V_{ref}} = \pm 0.5\%$$

$$\frac{\Delta R_5}{R_5} = \pm 1\%$$

$$\frac{\Delta R_4}{R_4} = \pm 1\%$$

$$\frac{\Delta R_{sense}}{R_{sense}} = \pm 1\%$$

see *Footnote 1*

$$\Delta V_{io} = \pm 2mV$$

Let's assume that I_{out} will vary between 0 and 5mA, therefore:

$$\Delta I_{out} = \pm 2.5mA$$

I_{lim} = 3A

G_m = 3.5mA/mV - R_4 = 174kΩ

R_5 = 10kΩ - R_{sense} = 0.047Ω

Rewriting *Equation 22*

Equation 23

$$\Delta I_{lim}^{tot} = \left(\frac{R_5 V_{ref}}{R_4 R_{sense}} \right) \frac{\Delta V_{ref}}{V_{ref}} +$$

$$+ \left(\frac{R_4 + R_5}{R_4 R_{sense}} \right) \Delta V_{io} +$$

$$+ \left(\frac{V_{ref} R_5}{R_{sense} R_4} \right) \frac{\Delta R_5}{R_5} +$$

$$+ \left(\frac{R_5 V_{ref}}{R_{sense} R_4} \right) \frac{\Delta R_4}{R_4} +$$

$$+ \left(\frac{R_5 V_{ref}}{R_4 R_{sense}} \right) \frac{\Delta R_{sense}}{R_{sense}}$$

$$+ \frac{1}{R_{sense} G_m} \left(1 + \frac{R_5}{R_4} \right) \Delta I_{out}$$

it is possible to obtain a good current variation

$$\frac{\Delta I_{lim}^{tot}}{I_{lim}} = \pm 5.3\%$$

Footnote 1   using TSM1011"A" version

2.2 Voltage Loop Precision Calculation

2.2.1 Theoretical Calculation

Let's show some different steps in order to calculate the voltage precision loop.

According to Figure 4 it is simple to verify that:

Equation 24

$$V_{lim} = \left(1 + \frac{R_2}{R_1}\right)(V_{ref} - V_{io} - V_1)$$

where   Equation 25

$$V_1 = \frac{I_{out}}{G_m}$$

$\Delta V_{lim}{}^{tot}$ is the sum of:

Equation 26

$$\Delta V_{lim}^{tot} = \Delta V_{lim}^{Vref} + \Delta V_{lim}^{Vio} + \Delta V_{lim}^{R2} + \Delta I_{lim}^{R1} + \Delta I_{lim}^{Iout}$$

where   Equation 27

$$V_{lim}^{Vref} = \frac{\Delta V_{lim}}{\Delta V_{ref}} = 1 + \frac{R_2}{R_1}$$

Equation 28

$$V_{lim}^{Vio} = \frac{\Delta V_{lim}}{\Delta V_{io}} = -\left(1 + \frac{R_2}{R_1}\right)$$

Equation 29

$$V_{lim}^{Iout} = \frac{\Delta V_{lim}}{\Delta I_{io}} = -\frac{1}{G_m}\left(1 + \frac{R_2}{R_1}\right)$$

Equation 30

$$V_{lim}^{R2} = \frac{\Delta V_{lim}}{\Delta R_2} = \frac{1}{R_1}(V_{ref} - V_{io} - V_1)$$

Equation 31

$$V_{lim}^{R1} = \frac{\Delta V_{lim}}{\Delta R_1} = -\frac{R_2}{R_1^2}(V_{ref} - V_{io} - V_1)$$

Substituting *Equation 27* and *Equation 31* in *Equation 26* and considering the absolute value of terms:

Equation 32

$$V_{lim}^{tot} = \left(1 + \frac{R_2}{R_1}\right)\Delta V_{ref} +$$
$$+ \left(1 + \frac{R_2}{R_1}\right)\Delta V_{io} +$$
$$+ \frac{1}{G_m}\left(1 + \frac{R_2}{R_1}\right)\Delta I_{out} +$$
$$+ \frac{1}{R_1}(V_{ref} - V_{io} - V_1)\Delta R_2 +$$
$$+ \frac{R_2}{R_1^2}(V_{ref} - V_{io} - V_1)\Delta R_1$$

Equation 32 is more important in order to calculate $\Delta V_{lim}{}^{tot}$ and shows many parameters that characterize voltage variation.

It can be observed that V_{io}=4mV, V_{ref}=2.5V and V_1<5mV, so the term $V_{io}+V_1$ can be neglected with respect to V_{ref}.

2.2.2 Practical Example

In order to better understand the formula, let's take a practical example that uses absolute and relative tolerances typical for TSM011 applications.

Let's consider for example:

see *Footnote 1*

$$\frac{\Delta V_{ref}}{V_{ref}} = \pm 0.5\%$$

$$\frac{\Delta R_1}{R_1} = \pm 1\%$$

$$\frac{\Delta R_2}{R_2} = \pm 1\%$$

$$\Delta V_{io} = \pm 2mV$$

Assume that I_{out} will vary between 0 and 5 mA, therefore:

$$\Delta I_{out} = \pm 2.5mA$$

V_{lim} = 18V
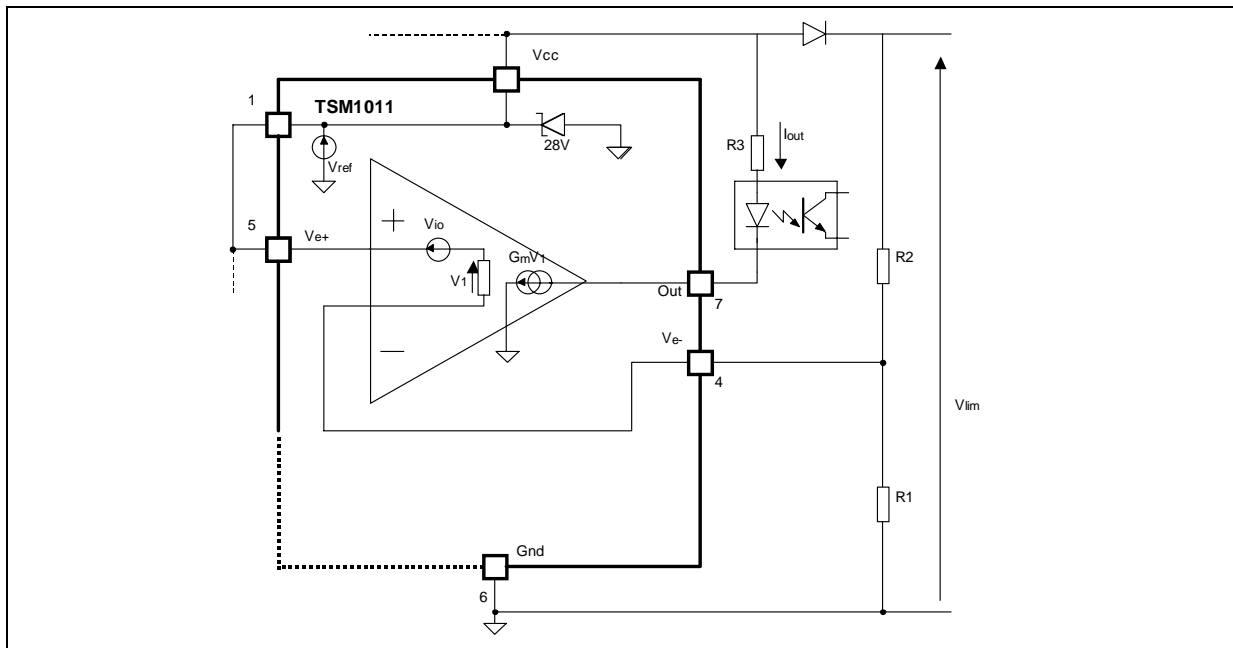
G_m = 3.5mA/mV

R_1 = 30kΩ - R_2 = 186kΩ

rewriting *Equation 32*

Equation 33

$$V_{lim}^{tot} = V_{ref}\left(1 + \frac{R_2}{R_1}\right)\frac{\Delta V_{ref}}{V_{ref}} +$$
$$+ \left(1 + \frac{R_2}{R_1}\right)\Delta V_{io} +$$
$$+ \frac{1}{G_m}\left(1 + \frac{R_2}{R_1}\right)\Delta I_{out} +$$
$$+ \frac{R_2}{R_1}V_{ref}\frac{\Delta R_2}{R_2}$$
$$+ \frac{R_2}{R_1}V_{ref}\frac{\Delta R_1}{R_1}$$

it is possible to obtain a good current variation

$$\frac{\Delta V_{lim}^{tot}}{V_{lim}} = \pm 2.3\%$$

Figure 4 : Simplify model for voltage precision calculation

3 CONCLUSION

This application note relative to the TSM1011 shows how very simple it is to calculate a current and voltage variation in order to discern how many parameters characterize the precision of regulation loop.

In accordance with market needs, current and voltage precision in the TSM1011 is extremely accurate. This allows a broaden application range for our products as compared with those of competitors. At this moment the current and voltage variation precision requested by market is:

$$\frac{\Delta I_{lim}^{tot}}{I_{lim}} = \pm 10\%$$

$$\frac{\Delta V_{lim}^{tot}}{V_{lim}} = \pm 5\%$$

The TSM1011 ("A" version) shows excellent performance in typical adapter and battery charger applications.

The results achieved in the above two practical examples for current and voltage precision are:

$$\frac{\Delta I_{lim}^{tot}}{I_{lim}} = \pm 5.5\%$$

$$\frac{\Delta V_{lim}^{tot}}{V_{lim}} = \pm 2.3\%$$

These results confirm the optimum performances and give clear explanation of the external parameters that affect accuracy and precision for the TSM1011

Attached to this application note is an Excel file showing the general schematic of the TSM1011 and which allows the possibility of varying values I_{lim} and V_{lim} according to the parameter variations that characterize the application.

It is possible, moreover, to change the resistor accuracy in order to avoid high-cost components when the application requires a lower precision.