Calculation of Series Reference Voltage Error

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The reference voltage is a specially designed device used to maintain a constant output voltage. It is classified into series voltage reference and shunt voltage reference based on different designs. The series voltage reference plays a crucial role in precise measurements in many data converter applications due to its high accuracy and low temperature drift characteristics. This article will mainly introduce the error categories and error calculation of the series reference voltage, providing a reference for evaluating the reference voltage in data converters or other applications.

1. Series Voltage Reference Errors Include Several Types, as outlined below:

a) Initial Accuracy

The variation in the output voltage measured at a given temperature (typically 25°C), is expressed as a percentage. The initial accuracy error for an individual device is generally fixed and can be eliminated through calibration.

b) Temperature Drift

The change in output voltage due to temperature variations (normalized to the output voltage at 25°C), is expressed in ppm/°C.

Most manufacturers define the temperature drift formula for series voltage reference as follows:

$$\text{Temperature Drift} = \left(\frac{V_{out,\,max} - V_{out,\,min}}{V_{out}}\right) / (T_{max} - T_{min}) \times 10^6 (\text{ppm/°C})$$

Where: $V_{out,max}$ and $V_{out,min}$ are the maximum and minimum output voltages within the specified temperature range, T_{max} and T_{min} are the highest and lowest temperatures, and V_{out} is the output voltage at 25°C.

c) Thermal Hysteresis

The change in output voltage is caused by a specified temperature cycle, expressed in ppm.

$$\text{Thermal Hysteresis} = \left(\frac{V_{pre} - V_{post}}{V_{out}}\right) \times 10^6 (\text{ppm})$$

Where: V_{pre} is the output voltage before the temperature cycle, V_{post} is the output voltage after the temperature cycle, and V_{out} is the nominal output voltage.

d) Noise

Noise typically includes low-frequency and high-frequency noise. Low-frequency noise refers to the peak-to-peak voltage within a bandwidth of 0.1 Hz to 10 Hz, expressed in uVpp or uVpp/V. High-frequency noise refers to higher than 10 Hz.

e) Line Regulation

The change in output voltage due to variations in input voltage, is expressed in ppm/V.

f) Load Regulation

The change in output voltage due to variations in load current, is expressed in ppm/mA.

g) LTD

The change in output voltage over time (e.g., 1000 hours, 2000 hours, or other durations), is expressed in ppm.

2. Calculation of Total Error for Series Voltage Reference

Line regulation error is related to the power supply of the voltage reference. This article assumes that the reference voltage is powered by a linear regulator (LDO) with an assumed input voltage variation of 0.1 V.

Load regulation error is related to the model of the data converter (ADC/DAC) and the output rate. This article assumes that the output load current of the reference voltage is 0.5 mA.

Long-term stability error is related to specific usage scenarios. It is crucial for applications requiring long-term continuous operation. This article disregards the calculation of long-term stability error.

Taking the TPR5025 high-precision series voltage reference from 3PEAK as an example, assuming an operating temperature range of −20 to 60°C, the calculations for various errors are as follows:

Initial Accuracy Error：

$$Error|_{Accuracy} = 0.05\% = 500ppm$$

Temperature Drift Error：

$$Error|_{Temp} = 5ppm/°C \times (60°C - (-20°C)) = 400ppm$$

Thermal Hysteresis Error：

$$Error|_{Hysteresis} = (99 + 29)ppm = 128ppm$$

Noise Error：

$$Error|_{Noise} = 3\mu Vpp/V = 3ppm$$

Line Regulation Error：

$$Error|_{Line} = 20ppm/V \times 0.1V = 2ppm$$

Load Regulation Error：

$$Error|_{Load} = 20ppm/mA \times 0.5mA = 10ppm$$

The various errors in the voltage reference are generally uncorrelated. Therefore, this article uses the Root Sum Square (RSS) method, which provides a more realistic estimation of the total error. The RSS error can be calculated as:

$$Error_{RSS} = \sqrt{Error_{Accuracy}^2 + Error_{Temp}^2 + Error_{Hysteresis}^2 + Error_{Noise}^2 + Error_{Line}^2 + Error_{Load}^2} = 653ppm$$

Calibration can further reduce inaccuracies for voltage reference errors. Typically, single-temperature point calibration (often room temperature calibration, referred to as single-point calibration) or multi-temperature point calibration (multi-point calibration) methods are employed.

With single-point temperature calibration, the initial accuracy error can be eliminated. If the device undergoes a full temperature cycle across the entire temperature range before single-point calibration, it can further reduce the thermal hysteresis error, assuming a 70% reduction in thermal hysteresis error. In this case, the RSS error is:

$$Error_{RSS\_Single\_Cal} = \sqrt{Error_{Temp}^2 + (Error_{Hysteresis} \times 0.3)^2 + Error_{Noise}^2 + Error_{Line}^2 + Error_{Load}^2} = 402ppm$$

For multi-point temperature calibration, the temperature drift error can be further reduced. The more temperature points used, the greater the reduction in error. Assuming a 90% reduction in error with this method, the RSS error is:

$$Error_{RSS\_Multi\_Cal} = \sqrt{(Error_{Temp} \times 0.1)^2 + (Error_{Hysteresis} \times 0.3)^2 + Error_{Noise}^2 + Error_{Line}^2 + Error_{Load}^2} = 56ppm$$

3PEAK has introduced multiple series of series voltage reference, each with a 2.5-V output. The summary of error calculations for each series product under the same conditions and assumptions is presented in the table below:

Error	TPR3525	TPR3325	TPR3125	TPR5025	TPR7025
Initial Accuracy /ppm	2000	1500	500	500	500
Temperature Drift (−20~60℃) /ppm	4000	2400	800	400	240
Thermal Hysteresis/ppm	80	80	128	128	27
Noise/ppm	20	20	3	3	1
Line Regulation/ppm	7	7	2	2	0.5
Load Regulation/ppm	15	15	10	10	10
RSS/ppm	4473	2831	952	653	555
Single-point Calibration RSS/ppm	4000	2400	801	402	240
Multi-point Calibration RSS/ppm	402	243	89	56	27

In many scenarios, series voltage reference are used in conjunction with data converters (ADC/DAC). The ppm values corresponding to 1LSB for different resolutions of data converters (ADC/DAC) are shown in the table below:

Bits	10	12	14	16
LSB(ppm)	977	244	61	15

For data converters using external series voltage reference, the error of the series voltage reference must be significantly smaller than 1LSB to avoid impacting its performance. In practical applications, the series voltage reference error can be calculated based on design requirements to assess compliance.