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Optimizing Thermistor Placement For Accurate Power-Plane Current Sensing

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The use of copper power planes or traces as current sensors does not require adding any components in the current path and thereby presents an attractive option for power monitoring. The impact of tolerances associated with their geometric (width and thickness) variations can be minimized with calibration. [1] However, because copper trace and plane impedances are temperature dependent, such sensors also have thermal drifts that need to be considered.

The temperature-dependency concern can be addressed with a zigzag trace placed in close proximity to the power plane [2] and using its resistance as an accurate equivalent plane temperature sensor. If a PCB does not have space available for accommodating such a trace, a small surface-mount (SM) thermistor, acting as a pin-point temperature sensor, can be used instead. Such a thermistor can sense the power plane temperature with an accuracy that is sufficient for all practical purposes.

When power plane resistance is affected only by ambient air temperature and PCB components or when plane self-heating impacts are negligible, the plane has a uniform temperature distribution, and a temperature sensor (thermistor) can be placed in any convenient location on the plane. However, when the power plane has noticeable temperature variation across it, random sensor placement would cause considerable errors since the thermistor would sense the plane temperature inaccurately. This article explores a simple procedure to determine the optimum sensor location on the PCB, providing minimal temperature sensing error.

The Thermal Compensation Concept

The concept underlying thermal compensation of the power-plane (PP) current sensor is illustrated in Fig. 1. Power-plane current I generates a voltage drop between sense points A and B. Current sense amplifier U1 and transistor Q1 generate a voltage drop across the zigzag trace R2 (points A and C) always equal to the voltage drop between sense points (across R1) caused by the current flowing through the power plane. Therefore, the sensed current signal referenced to ground can be described by the equation:

$$V_{sense} = \frac{R_1 \cdot I \cdot R_{sense}}{R_2}$$

Since the zigzag trace has the same thermal coefficient as the power plane and is positioned adjacent to it their temperatures are equal, so the current sense signal V_{sense} becomes temperature independent. In cases when there is insufficient board space the zigzag trace can be replaced with a pin-point sensor. A SM thermistor can be used as such pin-point sensor (its connections are shown in Fig. 1 with blue dashed lines).

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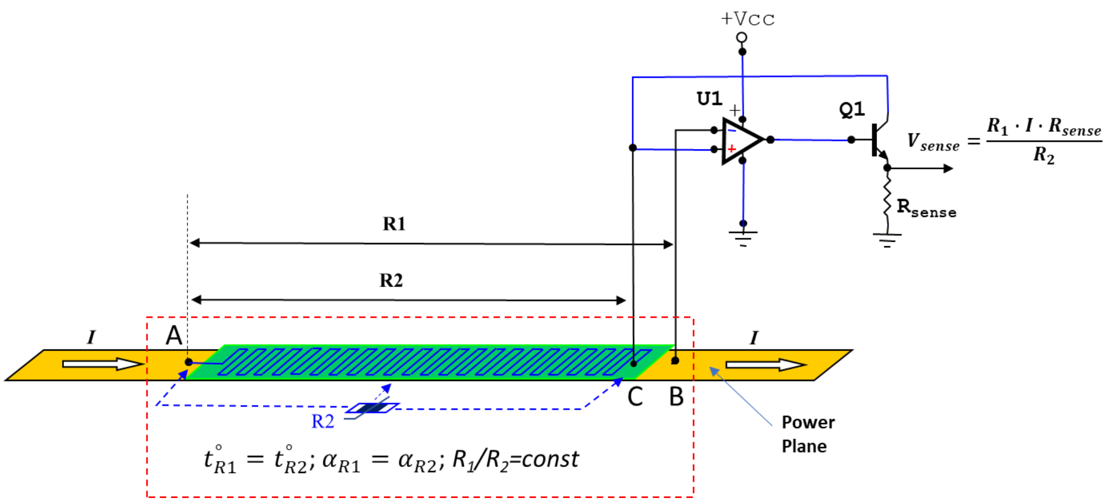

Fig. 1. Nonintrusive power-plane current monitoring concept. If thermal coefficients of the power-plane sensor (R1) and temperature drift compensating element R2 (zigzag trace or a thermistor) are equal and operate at the same temperature, the sensed signal V_{sense} becomes temperature independent.

Theoretical Cases—Problem Statement

Let's consider a trapezoidal power plane geometry, which is typical for a CPU voltage regulator (VR)-to-CPU power delivery path. It is illustrated in Fig. 2 for both the uniform and variable power-plane temperature distribution cases.

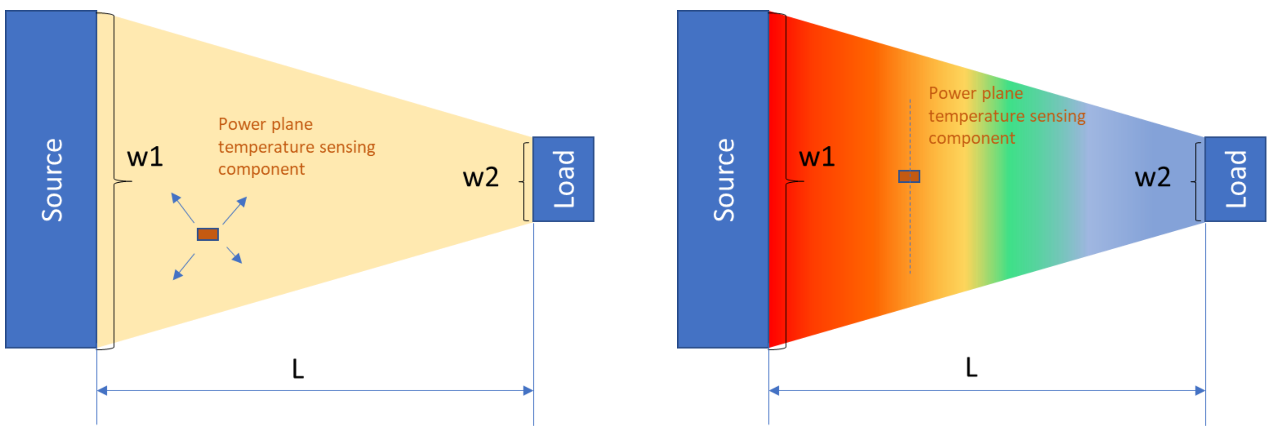

Fig. 2. With uniform power plane temperature distribution (a) the temperature sensor can be placed anywhere in the power delivery conductor geometrical profile. In the variable temperature case (b) the sensor position needs to be optimized for most accurate temperature sensing.

Uniform Power-Plane Temperature

Expressing the power-plane width as a linear function of path length (distance) x, as measured from the source end:

$$w(x) = \frac{w_1 - (w_1 - w_2) \cdot x}{L}$$

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where L is the plane length, w_1 and w_2 are plane widths at the source and load sides respectively, we can write an equation for power plane resistance R_{pp} for the uniform temperature distribution case (Fig. 2a):

$$R_{pp(\Delta t^\circ=const)} = \int_0^L \frac{\rho \cdot dx}{Th \cdot w(x)} = \int_0^L \frac{\rho \cdot dx}{Th \cdot \left[w_2 + \frac{w_1 - w_2}{L} x\right]} = \frac{\rho \cdot L \cdot \ln(w_1/w_2)}{Th \cdot (w_1 - w_2)} \quad (1)$$

where *Th* is the copper thickness and *ρ* is copper resistivity at a measured temperature, which can be defined as:

$$\rho = \rho_o \cdot (1 + \alpha \cdot \Delta t^\circ) \quad (2)$$

where ρ_0 is the copper resistivity at room temperature, α is the thermal resistivity coefficient and $\Delta t°$ is the plane temperature rise.

Variable Power-Plane Temperature

For the case of a nonuniform temperature distribution let's assume, for example, that the temperature rise across the plane varies linearly from $\Delta t_1°$ to $\Delta t_2°$, as illustrated in Fig. 2b. Based on this assumption we can write equations for temperature rise and resistivity as functions of distance from the source end x as follows:

$$\Delta t^\circ(x) = \Delta t_1{}^\circ - \frac{(\Delta t_1{}^\circ - \Delta t_2{}^\circ) \cdot x}{L} \quad (3)$$

$$\rho(x) = \rho_o \left[1 + \alpha\left(\Delta t_1{}^\circ - \frac{(\Delta t_1{}^\circ - \Delta t_2{}^\circ) \cdot x}{L}\right)\right] \quad (4)$$

where $\Delta t_1°$ and $\Delta t_2°$ are the temperature rises at the source and load end, respectively. Then, similar to the uniform temperature case, we obtain an expression for power-plane resistance for the variable temperature case:

$$R_{pp(\Delta t^\circ=f(x))} = \frac{\rho_o \cdot [1 + \alpha(\Delta t_2{}^\circ)] \cdot L \cdot \ln(w_1/w_2)}{Th \cdot (w_1 - w_2)} + \frac{\rho_o \cdot [\alpha(\Delta t_1{}^\circ - \Delta t_2{}^\circ)]}{Th \cdot L} \cdot \left[\frac{w_1 - w_2 + w_2 \ln(w_1/w_2)}{\left(\frac{w_1 - w_2}{L}\right)^2}\right] \quad (5)$$

To determine the exact position of the sensor we need to find the point on the plane at which the temperature would match the uniform case having the same resistance. Substituting equation (2) into (1), then equating the obtained expression to (5) we will get the equation for equivalent temperature rise $\Delta t_{eq}°$ as a function of temperature rises $\Delta t_1°$, $\Delta t_2°$ and power plane geometry (L, w_1, w_2).

Knowing the temperature distribution across the plane described by equation (3), we can then find the optimal sensor location. A linear temperature distribution, as well as uniform-, or any other analytically described function represent only theoretical cases. The analytical expression for the optimal sensor location x_{opt} with such a distribution is quite cumbersome and will be omitted here. However, a few numerical solutions for x_{opt} obtained with this expression for L = 10 cm are provided in the table below for illustration purposes.

The numbers in the table demonstrate that with the same power-plane length, the optimal position of the sensor depends on the plane geometry and temperature gradient across it. With the given power-plane geometry and variable temperature distribution, the optimal sensor location remains the same (cases 1 and 4). This means that the sensor location determined for only one, for example, highest temperature rise case, would also be valid for other, lower temperature rise, cases.

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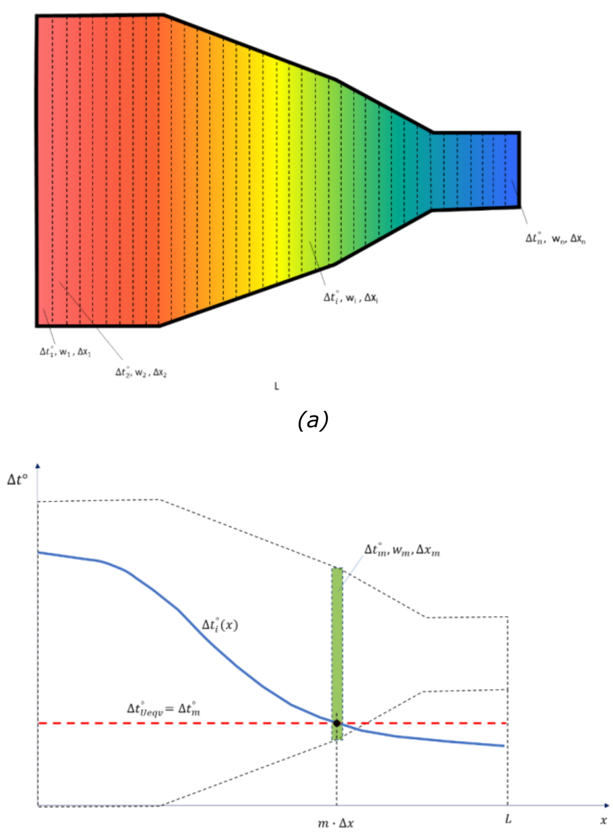
Table. Optimal sensor location x_{opt} calculated for various temperature rises and plane widths.

$\Delta t_1°$ (°C)	$\Delta t_1°$ (°C)	w_1 (mm)	w_2 (mm)	x_{opt} (cm)
100	20	50	30	4.57
50	20	50	10	3.71
100	20	30	50	5.42
21	15	50	30	4.57

A Practical (Arbitrary) Case

For arbitrary power-plane geometry and temperature distribution the power-plane shape and thermal profile need to be given prior to determination of the sensor position. This information can be usually obtained in the initial layout development stage through thermal simulation. Having these data, the approach used for trapezoidal power-plane shape and analytically defined distribution can also be applied for an arbitrary power-plane shape and temperature distribution case. Only, in the latter case, instead of integration of analytical functions, numerical summation of the resistances of small zones with uniform temperatures can be used. This case is illustrated in Fig. 3.



(a)

(b)

Fig. 3. With an arbitrary power-plane shape and temperature profile, the power plane can be divided into multiple rectangular narrow zones with uniform temperature rise $\Delta t_i°$ within one zone (a). Equating total power-plane resistances in the arbitrary and uniform cases yields the equivalent temperature rise required in the uniform case. A zone with the temperature rise $\Delta t_m°$ equal to the equivalent uniform temperature rise Δt_{Ueqv} (red dashed line) represents the area for optimal pin-point sensor location (b).

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In Fig. 3 the power plane with arbitrary shape and temperature profile is divided into multiple narrow rectangular shape zones each of them having its own width w_i, length Δx_i and temperature rise $\Delta t_i°$. Each zone resistance at a given temperature rise $\Delta t_i°$ is described by the equation:

$$R_i = \frac{\rho_o \cdot (1 + \alpha \Delta t_i°) \cdot \Delta x_i}{w_i \cdot Th} \tag{6}$$

Since all zones are "connected" in series, total power-plane resistance can be computed as a sum of all the zone resistances:

$$R_{PP} = \sum_{i=1}^{n} R_i \tag{7}$$

For a uniform temperature profile each of the zones has the same temperature rise $\Delta t_U°$, so the resistance of each zone is

$$R_{Ui} = \frac{\rho_o \cdot (1 + \alpha \cdot \Delta t_U°) \cdot \Delta x_i}{w_i \cdot Th} \tag{8}$$

Similarly, the power-plane resistance can be calculated as a sum of the zone resistances:

$$R_{PP} = \sum_{i=1}^{n} R_{Ui} \tag{9}$$

Substituting equation (6) into (7) and (8) into (9) and then equating the two resulting expressions, which represent the power-plane resistances in the arbitrary and uniform cases, we get the following equation:

$$(1 + \alpha \cdot \Delta t_{Ueqv}°) = \frac{\sum_{i=1}^{n} \frac{\rho_o \cdot (1 + \alpha \cdot \Delta t_i°) \cdot \Delta x_i}{w_i \cdot Th}}{\rho_o \cdot \sum_{i=1}^{n} \frac{\Delta x_i}{w_i \cdot Th}}$$

Solving this equation for Δt_{Ueqv}, after simplification we get a formula for equivalent uniform temperature rise:

$$\Delta t_{Ueqv}° = \left[\frac{\sum_{i=1}^{n} \frac{(1+\alpha \cdot \Delta t_i°) \cdot \Delta x_i}{w_i}}{\sum_{i=1}^{n} \frac{\Delta x_i}{w_i}} - 1 \right] / \alpha \tag{10}$$

Equation (10) determines equivalent uniform temperature rise providing the same power-plane resistance as the arbitrary case with a given $\Delta t_i°(x)$ distribution. As it can be seen from this equation, $\Delta t_{Ueqv}°$ depends only on the power-plane geometry (w_i, Δx_i) and thermal profile ($\Delta t_i°$). This expression can be further simplified if Δx_i is constant for all zones.

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The power-plane zone "m", in which $\Delta t_{Ueqv}°$ = $\Delta t_m°$, represents the optimal sensor position area, providing minimal error. For the Δx_i = constant case, the optimum distance to the sensor l would be defined as $m\Delta x_i$. This is illustrated in Fig. 3b.

Experimental Results

For the experimental baseboard (motherboard) the power-plane thermal profile was extracted from a thermal simulation conducted by a thermal engineer, and the sensing thermistor was placed in the zone determined using the procedure described above. The sensor type used in the experiment was KOA's LP731J thermistor, which has a nominal value of 100 Ω and a TCR of 4000 x 10^{-6}/K.

The goal of this thermal compensation verification experiment was to study how power-plane self-heating at the fastest rate (with no active cooling) would affect the current measurement error. To achieve this goal the power plane is set to conduct maximum projected current (250 A) continuously. According to simulation results, this configuration is supposed to cause a 35°C temperature rise in the sensor zone "m".

At the initial (room) temperature (t_0 = 23°C) the output voltage in the current monitoring network was measured to be V_{sense} = 0.8538 V. Once high current was applied, the current sensing circuit output voltage (V_{sense}) and power-plane temperature readings in the sensor zone were taken every second until the steady-state temperature was reached.

The results of the experiment are shown in Fig. 4. The actual temperature rise in the sensor zone exceeded simulation results by 2.5°C—likely due to different (convection) cooling conditions in the experiment. The uncompensated voltage drift error for the measured temperature rise ($\Delta t_m°$ = 37.5°C) should be +15%. Actual voltage deviations over this ideal case were measured to be within +0.2%/-3.8% limits, which means that the power-plane resistance drift is overcompensated over most of the temperature range. The initial overshoot (positive error) can be attributed to the heat propagation from the power plane to the sensor (sensor latency).

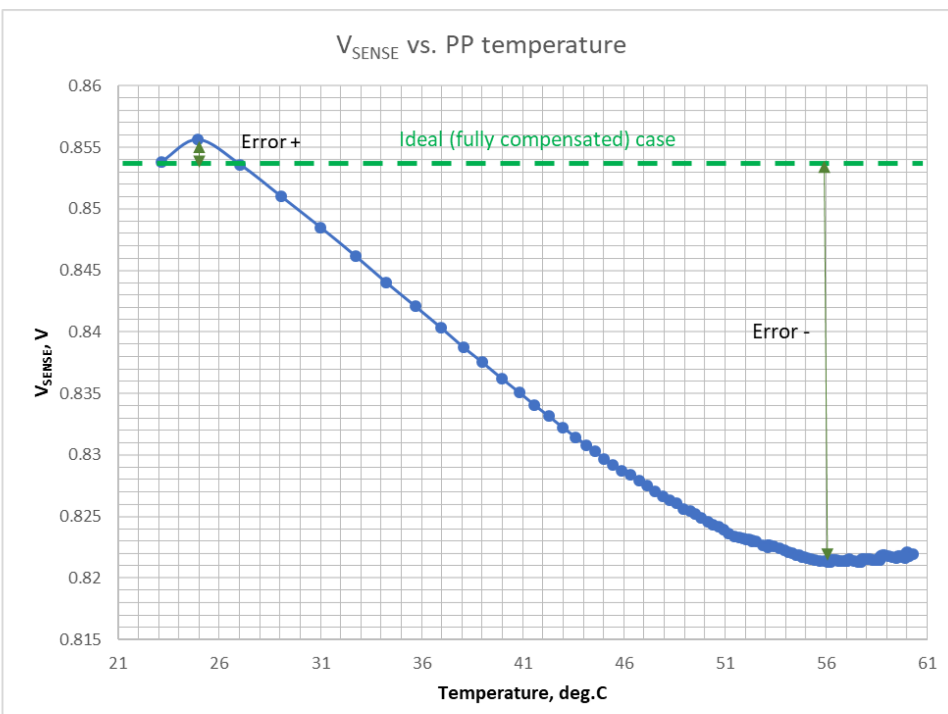

Fig. 4. Change in sensed-current signal level V_{sense} as a function of power-plane temperature. The ideal (fully compensated) case is shown for reference with the green dashed line.

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The experimental results show that to achieve a lower error under the given cooling conditions, the thermistor needs to be moved to the cooler temperature zone in the power-plane temperature profile. Based on the measurement results and considering a possibility of balancing positive and negative errors with a dc offset, the CPU current monitoring error with the selected location will not exceed ±2.2% at the maximum current level, which may be considered acceptable for many practical applications.

Conclusions And Future Work

In this article, a simple method of accurate compensation for power-plane thermal drift has been introduced. The method has been successfully used to determine an optimal location of the pin-point surface-mount temperature sensor so as to provide minimal sensing error with arbitrary power-plane shape and temperature distribution. Experimental results obtained with this method validated the theoretical prediction for the optimal sensor location.

Next steps may include development of a program for automatic generation of the sensor position based on the thermal profile data and power plane geometry.

References

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About The Author

Viktor Vogman currently works at Power Conversion Consulting as an analog design engineer, specializing in the design of various power test tools for ac and dc power delivery applications. Prior to this, he spent over 20 years at Intel, focused on hardware engineering and power delivery architectures. Viktor obtained an MS degree in Radio Communication, Television and Multimedia Technology and a PhD in Power Electronics from the Saint Petersburg University of Telecommunications, Russia. Vogman holds over 50 U.S. and foreign patents and has authored over 20 articles on various aspects of power delivery and analog design.

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