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Inductor DCR Current Sensing With Temperature Compensation: An Accurate, Lossless Approach For POL Regulators

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The trends in current sensing within buck or boost regulator powertrains are closely aligned with several design goals. One is providing output current limiting including output short-circuit and overload protection. Other goals include implementation of the current-mode control loop, current-sharing between phases in multi-phase converters, and adaptive voltage positioning (AVP) in microprocessor core voltage supplies. Yet another design objective that depends on current sensing is the provision of load current telemetry and monitoring back to a host controller or microprocessor.

While a shunt resistor offers an accurate solution at currents below 10 A, it becomes impractical at higher currents given its size and power dissipation. Leveraging intrinsic circuit elements for lossless current sensing is highly advantageous as it enables high-power density and low-cost circuit implementation. Unfortunately, there are some drawbacks to the existing current-sensing techniques.

In a buck or boost converter, merely sensing the voltage across the low-side MOSFET on-state resistance is inaccurate, given the large initial tolerance (typically ±30%) of this resistance and the inherent, temperature-dependent variation in the MOSFET's resistive elements (silicon die, aluminum and copper connections). Also, sensing is only available when the low-side MOSFET is conducting. No sensing occurs during the on-time of the high-side MOSFET.

In contrast, the tolerance of an inductor dc resistance (DCR) typically is specified at ±8%, and sometimes even lower. In one version of this sensing method that has been widely adopted in dc-dc solutions for point-of-load (POL) applications, a passive filter network is connected in parallel with the inductor (Fig. 1). It also has seen some recent use for input current sensing in single- and multi-phase boost converters [1] for automotive, industrial and audio applications. As indicated in Fig. 1, the circuit configuration for inductor DCR sensing is also compatible with shunt resistor sensing.

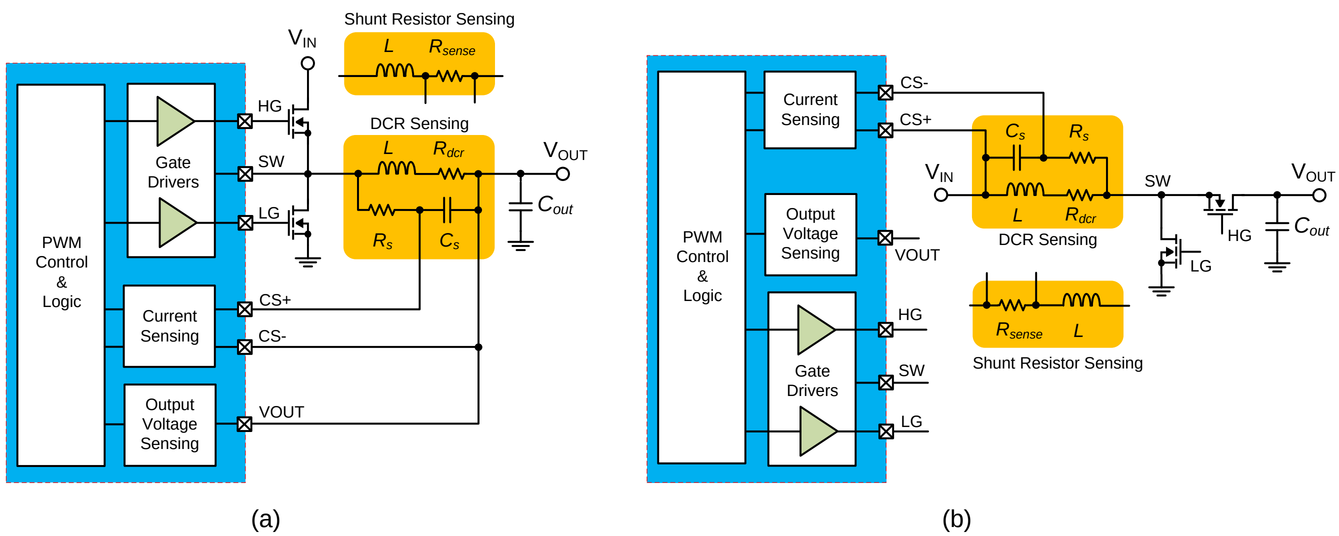

Fig. 1. Inductor DCR current-sensing with synchronous buck (a) and synchronous boost (b) topologies. The DCR is represented as a lumped circuit element. The circuit implementation is also compatible with shunt resistor sensing.

By closely emulating the inductor admittance with a low-pass sense network, you can derive a proportional voltage image of the inductor current. Based on Fig. 1, you can determine the sense capacitor voltage in the Laplace domain:

$$v_C(s) = \frac{1/sC_S}{R_S + 1/sC_S} v_L(s) = R_{DCR} \frac{1 + sL/R_{DCR}}{1 + sR_S C_S} i_L(s) \qquad \text{(Eq. 1)}$$

A flat frequency response is achieved when the inductor time constant matches that of the RC sense network. Time-constant matching and DCR temperature dependence are important constraints that must be addressed to achieve a high level of current-sense accuracy across variations in load and operating temperature.

This article explains the requirements for time-constant matching and DCR temperature compensation as they relate to current sensing in point-of-load regulator applications. Then after a brief look at the conventional, NTC thermistor-based approach to temperature compensation, this article describes an alternative approach that leverages capabilities within newer PWM controllers to perform remote temperature sensing close to the inductor and then provides temperature compensation of the inductor DCR. An implementation of a POL regulator using this DCR current-sensing and temperature-compensation scheme is then presented along with experimental results. The results confirm that this current-sensing method achieves accurate current limiting across the POL's operating temperature range.

Time-Constant Mismatch

Fig. 2 shows the transfer function from inductor current-to-sense capacitor voltage according to Equation 1. The RC pole and inductor DCR zero are represented by x and o symbols, respectively. Based on the relative magnitude of the inductor and sense-network time constants, the high-frequency gain can run higher or lower than at dc. The inductor DCR zero typically is below 1 kHz. Fortunately, waveform phase-shift does not occur at the switching frequency and harmonics thereof.

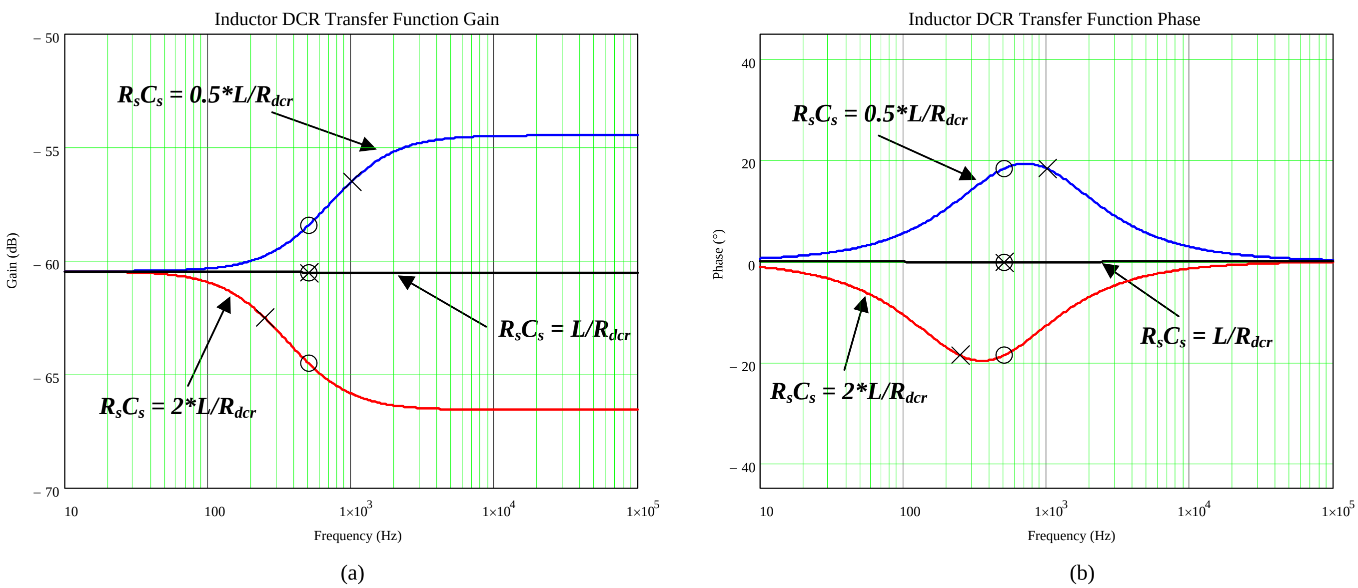

Fig. 2. Inductor current-to-sense capacitor voltage transfer functions, magnitude (a) and phase (b), show the ideal response and effect of mismatched time constants.

Circuit Simulation

The current-sensing circuit performance is explored with the circuit simulation schematic presented in Fig. 3. The circuit operating conditions and key component values provided are taken from a practical POL circuit implementation we will soon cover. Fig. 4 is a time-domain simulation result for a 20-A load step transient response at 10 A/µs showing waveforms for the instantaneous inductor current and the sense capacitor voltage. Here, the inductor and sense-network time constants are set perfectly matched. With a DCR of 1 mΩ, it is easy to see that the best possible representation of the inductor current is attained.

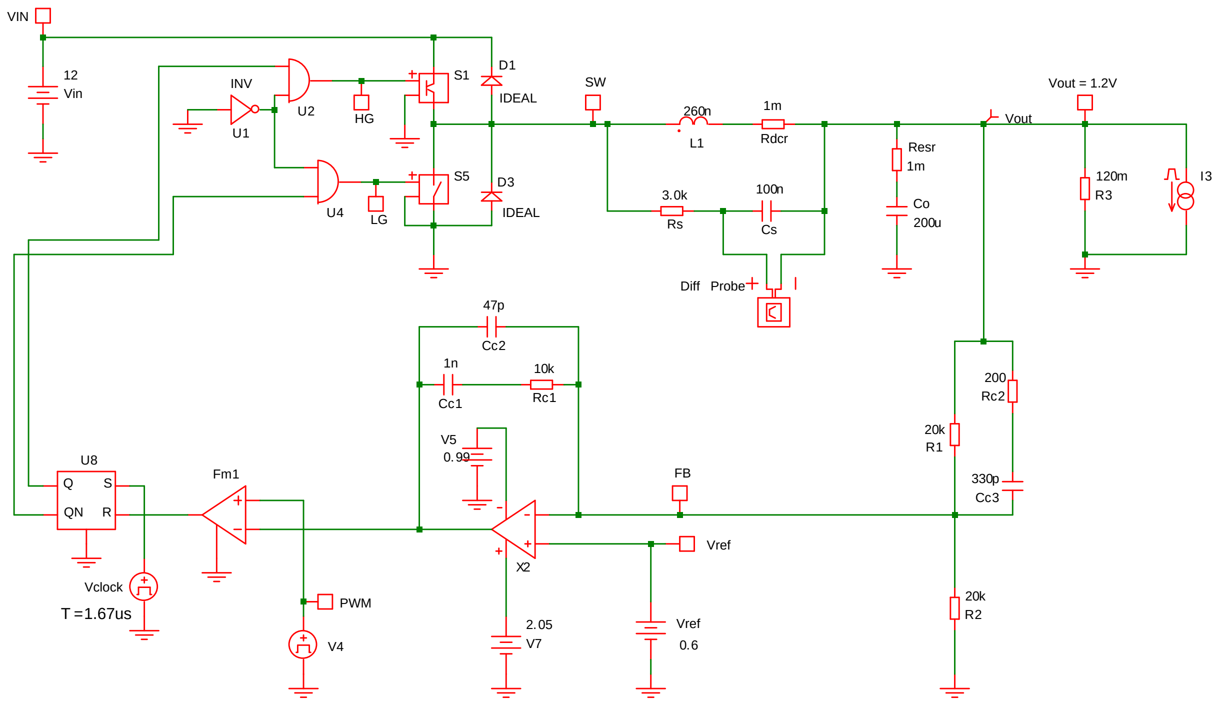

Fig. 3. Schematic for transient analysis simulation of an inductor-DCR current-sensing buck converter.

Fig. 5 shows the sense-capacitor voltages for a 10-A load-on transient with sense resistor, R_S, set to 2, 3 and 4.5 kΩ. These values correspond, respectively, to sense-network RC time constants of 66, 100 and 150% of the inductor time constant. Fig. 6 shows the startup waveforms, again using these sense resistances.

Figs. 5 and 6 indicate that the sense-capacitor voltage on a large-signal basis, respectively, leads or lags the inductor current when 2-kΩ and 4.5-kΩ sense resistances are used (see green and black traces). This observation aligns with the frequency domain plots in Fig. 2 for mismatched time constants. A sense-voltage overshoot or undershoot is evident during the large-signal event, if the sense-network time constant is undersized or oversized, respectively.

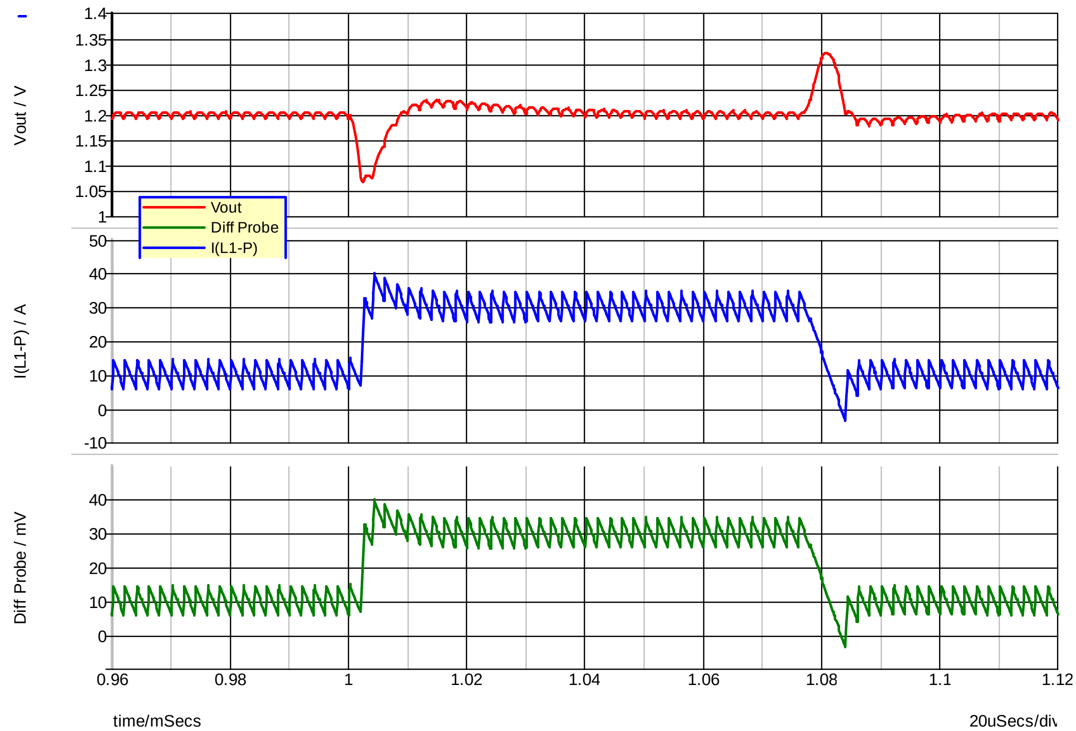

Fig. 4. 20-A load-step response simulation showing output voltage, inductor current and sense capacitor voltage.

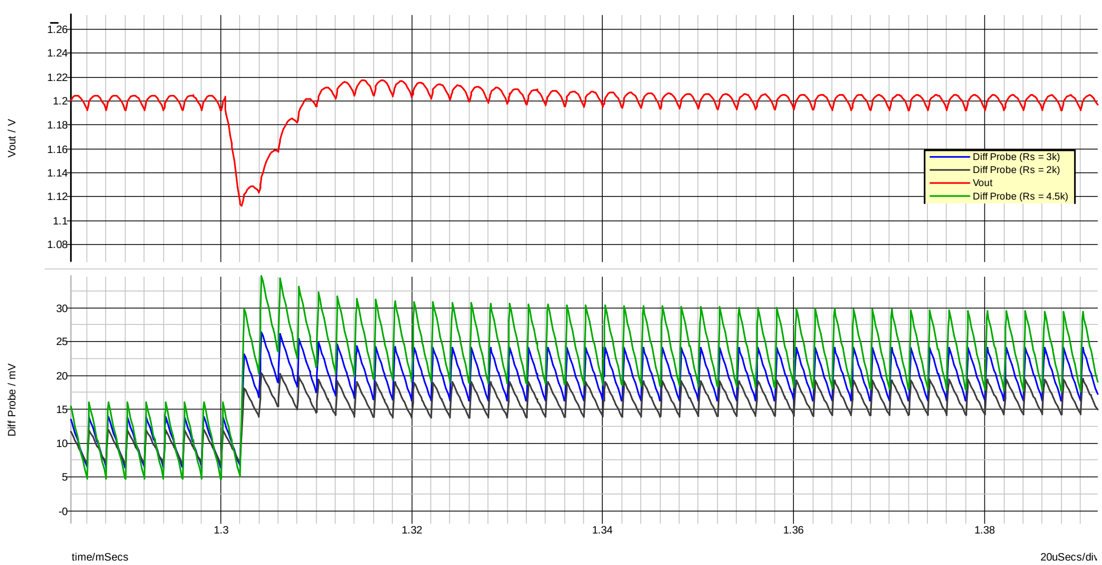

Fig. 5. 10-A load-step response simulation with sense network filter resistance set to 2 kΩ, 3 kΩ and 4.5 kΩ.

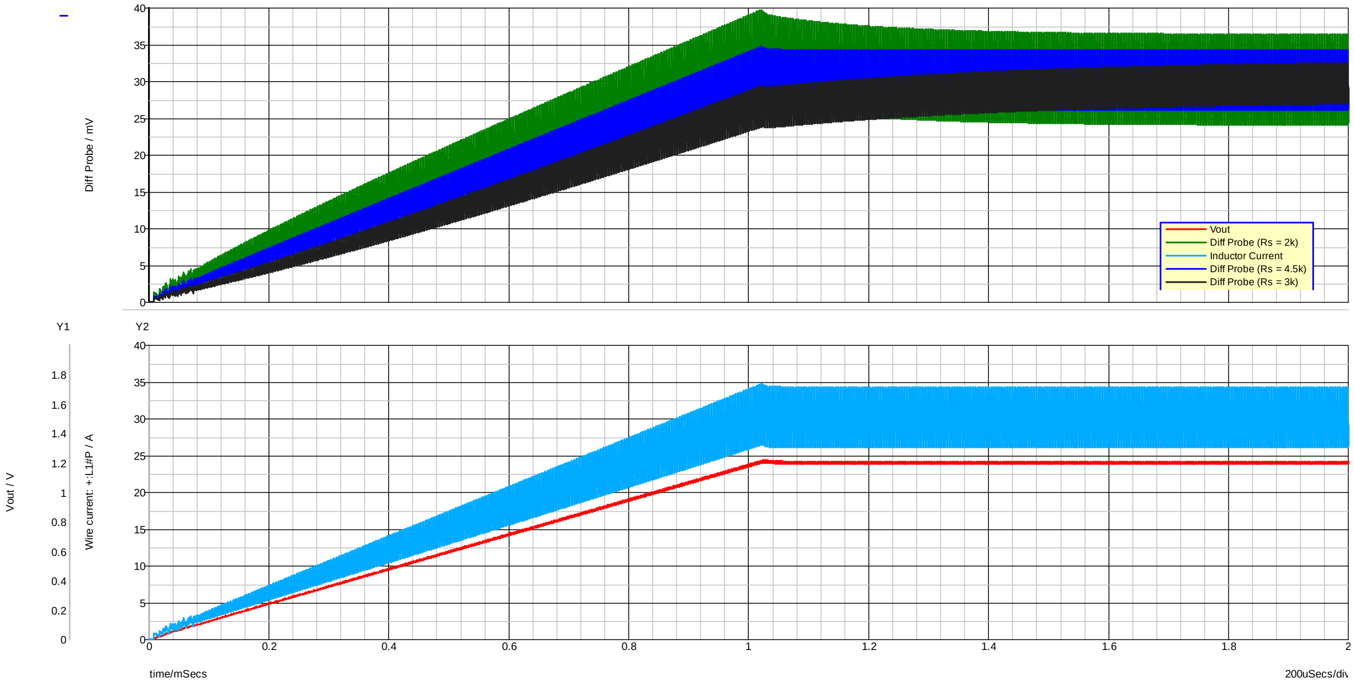

Fig. 6. Output soft-start simulations with a 30-A resistive load and a sense-network filter resistance of 2 kΩ, 3 kΩ and 4.5 kΩ.

The sense-voltage-signal dc levels in Figs. 5 and 6 converge in steady-state, based on the sense-network time constant (typically 0.2 ms to 1 ms).

DCR Temperature Coefficient

The resistance-versus-temperature characteristic of the inductor DCR is essentially linear and given by:

$$R_{DCR}(\mathrm{T}) = R_{DCR\_25°\mathrm{C}} + \alpha(\mathrm{T} - 25°\mathrm{C}) \qquad \text{(Eq. 2)}$$

where α is the temperature coefficient (TC) of resistance of the copper winding, 3930 ppm/°C. Thus, the sensed variable is quite sensitive to temperature variations where, for example, an increase in winding temperature from 25°C to 100°C causes a 30% increase in DCR.

Some inductor vendors use a manganin copper alloy. Manganin is a commonly used name for an alloy of typically 86% copper, 12% manganese and 2% nickel. It provides the advantage of having virtually zero temperature coefficient (TC) of resistance. However, the range of available inductors is very limited, and the decrease in winding conductivity relative to copper can exact a larger package size.

The classic way to compensate for temperature is to use a negative temperature coefficient (NTC) thermistor network. Two resistors, one in series and one in parallel with the NTC, are required to linearize the resistance function with temperature. Unfortunately, the NTC solution is somewhat large and expensive, particularly in multi-phase applications where the network is replicated in each phase. Moreover, the available current-sense signal amplitude is attenuated by the NTC network, compromising the signal-to-noise ratio (SNR) and making the solution untenable when using ultra-low DCR (< 1 mΩ) inductors.

PWM Controller DC-DC Application

Realizing that remote diode temperature-sensing techniques normally found in dedicated temperature-sensor ICs are synergistic with inductor DCR current sensing, one way to provide a simple and inexpensive solution to implement overcurrent protection is using a voltage-mode controller such as the LM27403 from TI. A current-limit threshold that is largely independent of temperature is particularly advantageous with ferrite inductors that typically have sharp saturation characteristics. Remote diode temperature sensing becomes very appealing in such applications as the temperature sensor is positioned close to the inductor. PTC or NTC thermistor components are not required. The circuit schematic is shown in Fig. 7.

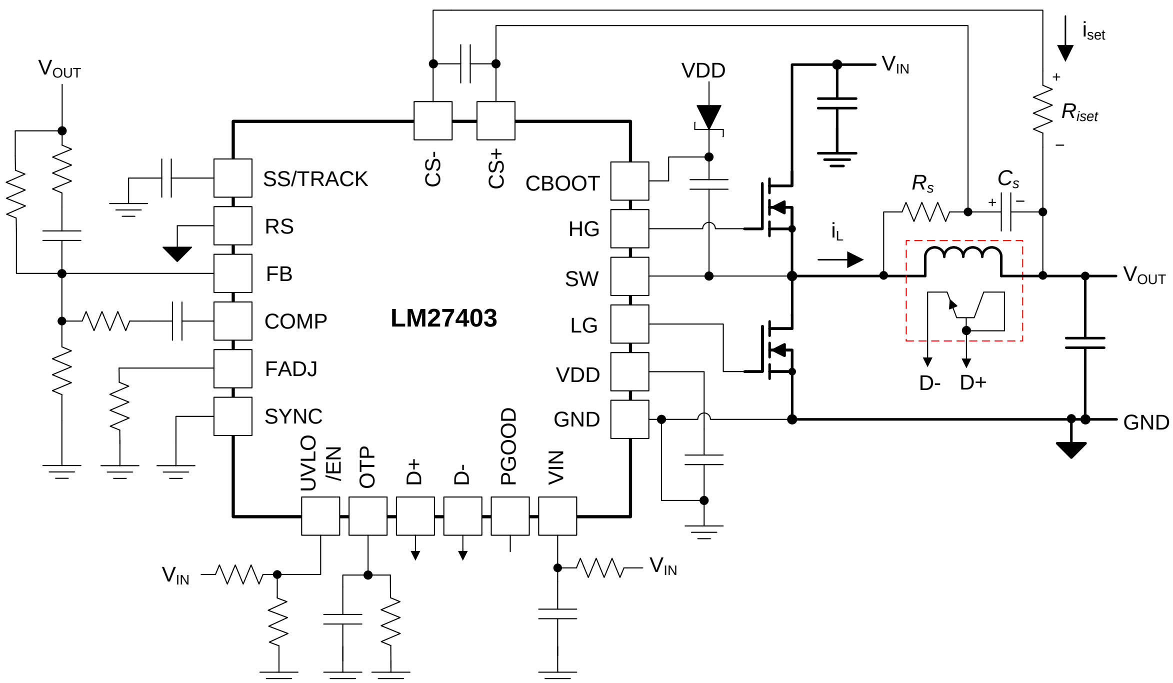

Fig. 7. A PWM controller implementation based on the LM27403 synchronous buck controller provides inductor DCR current sensing-based overcurrent protection and remote thermal diode temperature sensing.

A 2N3904-type NPN transistor with well-defined ideality factor (η = 1.004) is configured so that its base-emitter voltage is sampled once every 64 switching cycles given low and high injected currents of 10 μA and 100 μA, respectively. The measured difference in base-emitter voltage is used to deduce temperature using this equation:

$$\Delta V_{\mathrm{BE}} = \frac{\eta k\mathrm{T}}{q} \ln\left(\frac{I_{HIGH}}{I_{LOW}}\right) \quad \text{(Eq. 3)}$$

where I_{LOW} and I_{HIGH} are the low and high injected diode currents, respectively. The other parameters in Equation 3 are well-known diode parameters.

A current sourced from the controller's CS pin proportional to sensed temperature creates an offset voltage on resistor R_{iset} to determine the current-limit setpoint. This current scales with measured temperature affecting a concomitant change in current-limit threshold voltage. The current-limit setpoint, thus, is thermally compensated from a dc basis. The ac ripple component of inductor current translated to the sense-capacitor voltage will see some amplitude disparity apropos of the time-constant mismatch. The degree to which this affects the current-limit setpoint (if peak current limit is required) is not substantial, if the inductor ripple current amplitude is less than one-third of the maximum dc output current, as typically recommended.

A current-limit comparator in the controller is used to detect a current-limit event; the controller shuts down after five consecutive overcurrent events. The measured temperature is also used to implement board-level overtemperature protection (OTP). The OT setpoint is configured using a resistor from the LM27403 OTP pin to ground.

Implementation Details And Experimental Results

A high-density 600-kHz 30-A POL implementation with single-sided PCB is shown in Fig. 8. The power stage comprises a CSD87350Q5D NexFET Power Block (co-packaged high-side and low-side power MOSFETs [2]), a 300-nH ferrite inductor with sub-milliohm DCR, and ceramic input and output filter capacitors. The design uses the PWM controller to provide inductor DCR-based overcurrent protection through continuous DCR current sensing. A transistor in a small SOT-523 package is used to sense temperature.

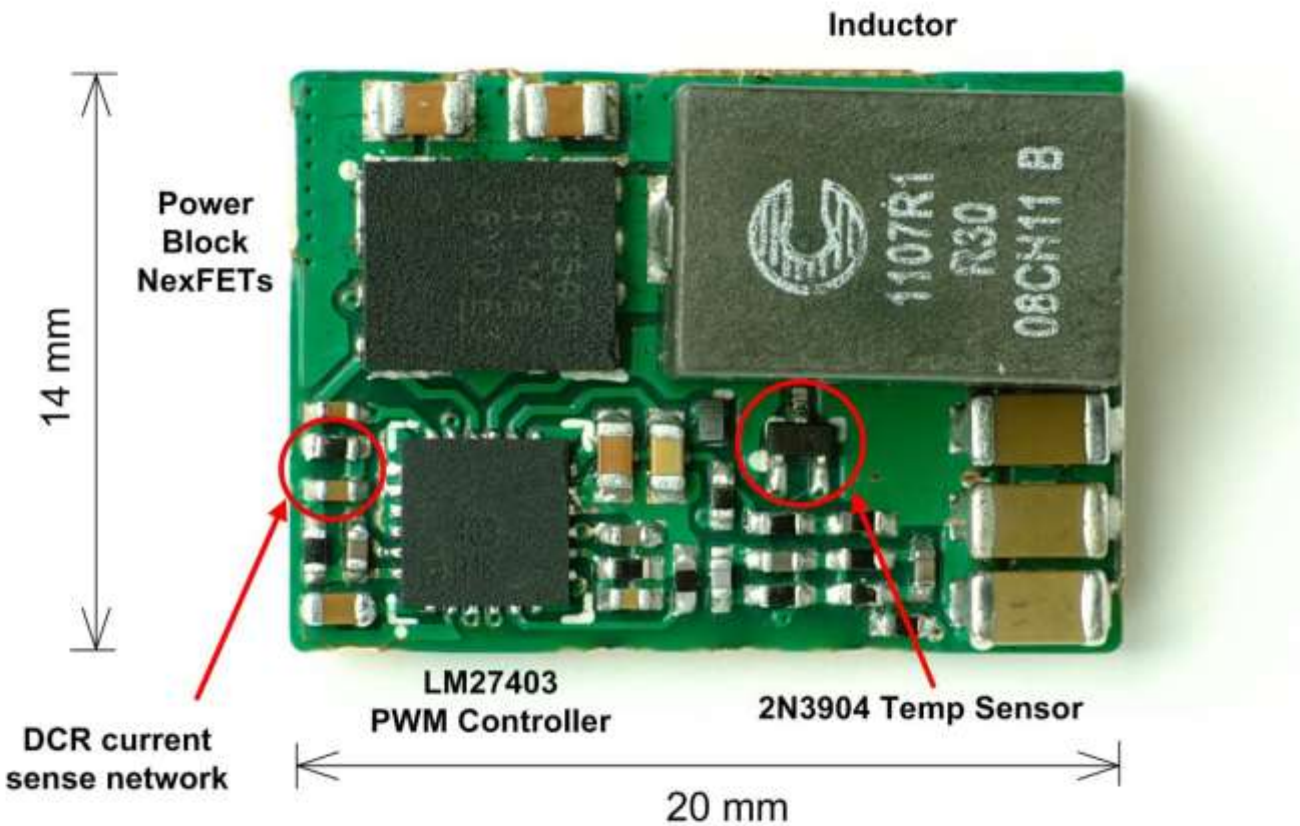

Fig. 8. This 20-mm x 14-mm x 6.6-mm dc-dc module features temperature-compensated inductor DCR-based current limiting.

Traces from the DCR network sense capacitor and thermal diode are routed as differential pairs. The respective traces are kept close together to minimize noise pickup. The signal traces are routed away from the inductor, particularly with ferrite cores (with wide air gap and large fringing/leakage flux field) or with vertical-mount-type inductors where the terminations typically are not close together and significant fringing fields can occur.

The temperature-sensor BJT is located adjacent to the inductor on the same side of the PCB (Fig. 8). Close thermal coupling to the inductor is imperative to correctly compensate for the DCR temperature coefficient. A 1-nF ceramic capacitor close to the transistor is adequate for differential filtering. A 100-pF close to the LM27403 D+ and D- pins is used in noisy environments, but usually is not necessary.

The waveforms in Fig. 9 show the temperature sensor BJT base-emitter voltage waveform at -40°C, 25°C and 125°C. Fig. 10 shows the measured overcurrent-protection setpoint as a function of ambient temperature.

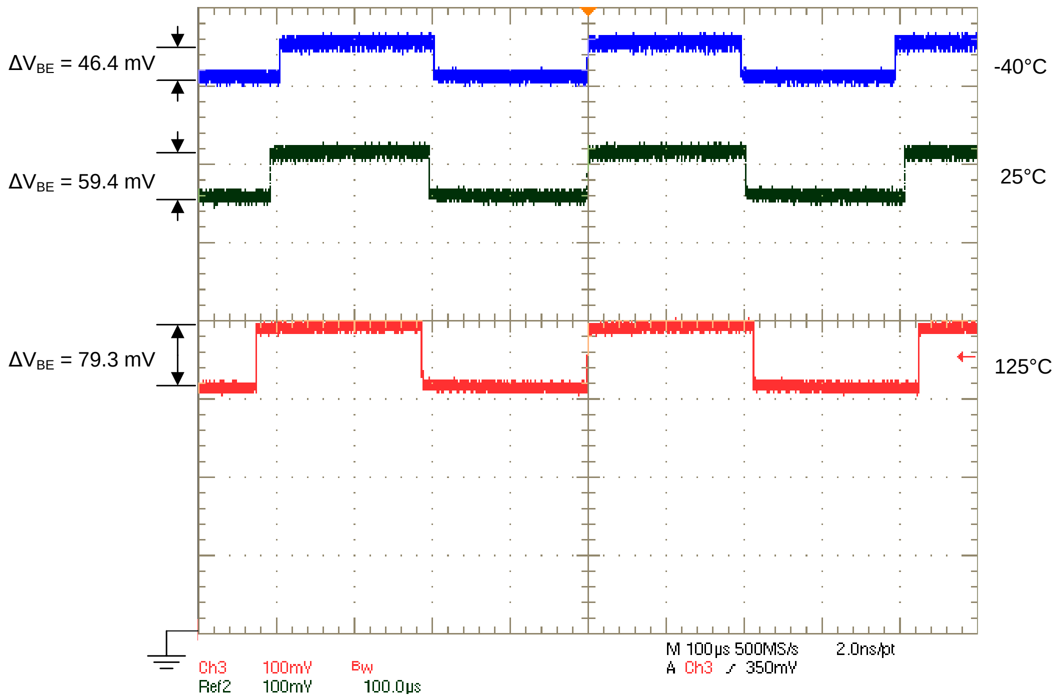

Fig. 9. Measured voltage of remote BJT at -40°C, 25°C and 125°C.

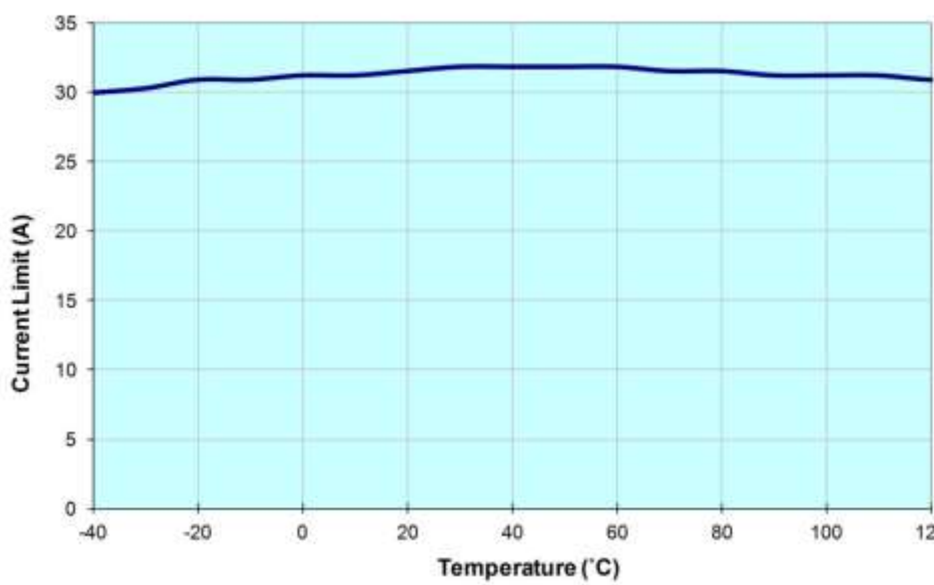

Fig. 10. Measured overcurrent-protection setpoint over full operating temperature range.

Summary

DCR current sensing, particularly when used with temperature compensation, is an excellent way to leverage parasitic circuit elements (i.e. the inductor's resistance) to attain lossless current sensing in both buck and boost regulator designs. High-efficiency, low-cost circuit implementations are readily attained with optimal component choice and high-density PCB layout.

References

1. "Wide Input Synchronous Boost Controller with Multiple Phase Capability," SNVS954D, Texas Instruments, May 2013: www.ti.com/lm5122-ca.

2. "Synchronous Buck Controller with Temperature Compensated, Inductor-DCR-Based Overcurrent Protection and Programmable Thermal Shutdown," SNVS896, Texas Instruments, August 2013: www.ti.com/lm27403-ca.

3. For more information about NexFET Power Block MOSFET technology, see www.ti.com/nexfet-ca.

Further Reading

Texas Instruments WEBENCH Designer Tools and Ecosystem: http://www.ti.com/webench-ca.

About The Author

Timothy Hegarty is a principal applications engineer in the Power Products Business Unit at the Texas Instruments design center in Tucson, Arizona. He received the bachelor's and master's degrees in electrical engineering from University College Cork, Ireland in 1995 and 1997, respectively. Prior to joining Texas Instruments, he worked for National Semiconductor and Artesyn Technologies. His areas of interest are wide input voltage range isolated and nonisolated converters, resonant converters, renewable energy systems, and system-level simulation of same. He is a member of the IEEE Power Electronics Society.

For further reading on current sensing, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category and select "Test and Measurement" in the Design Area category.