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Core-as-a-Sensor: Ferrite DC-Resistance-Based Core Temperature Measurement of Magnetics

D. Menzi,
G. Edvaldsson,
J. Huber,
J. Kolar

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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David Menzi, Garðar Eðvaldsson, Jonas E. Huber, Johann W. Kolar
Power Electronic Systems Laboratory
ETH Zurich, Switzerland
menzi@lem.ee.ethz.ch

***Abstract*—Future power electronic systems should feature continuous in-situ monitoring of components to facilitate, e.g., predictive maintenance and lifetime prognostics. Temperatures of magnetic components (i.e., transformers and inductors) are typically measured with thermocouples attached to the core surface. It is known from literature that the electrical conductivity of ferrite, typically used as core material of high-frequency magnetics, is temperature dependent. Hence, this paper proposes a method to observe the magnetic component temperature based on a ferrite core resistivity measurement, advantageously allowing to track the average core temperature (which is typically above the core surface temperature). First, methods for electrically contacting the core surface are discussed and common magnetic materials (MnZn ferrites) are characterized. Possible disturbance factors such as dc and ac magnetic flux occurring during operation of power electronic converters are experimentally found to have little impact on the measured resistivity. Finally, a smart inductor prototype with core-resistivity-based temperature estimation is presented and experimentally verified, and the applicability of the method to high-frequency NiZn and powder cores is indicated.**

***Keywords*—Smart passives, industry 4.0, magnetics, ferrite, conductivity, temperature measurement**

I. Introduction

Health monitoring and lifetime prediction for power electronic converters benefit from real-time and in-situ monitoring of the systems, which enable, e.g., predictive maintenance, improved failure diagnostics, etc. [1]. Whereas there is a trend towards data-driven methods that utilize measurement data anyway collected by the converter's control system, in-situ sensing of component stresses might still remain necessary at least during testing and qualification, e.g., to generate training data. A prominent example is the in-situ monitoring of a semiconductor's on-state voltage [2], [3] or the direct junction temperature measurement with chip-embedded sensors [4]. Similarly, the ESR of electrolytic capacitors can be sensed continuously to obtain information on the capacitors' health status [5]. Also, parasitic effects create opportunities for in-situ sensing: for example, the spectral distribution of the electroluminescence emitted during the conduction of SiC MOSFETs' body diodes encodes temperature and current density information [6] [7]. Alternatively, monitoring the on-state forward-voltage of IGBTs allows to observe the (area-weighted average) junction temperature [8].

The temperature of a magnetic component is typically measured during prototype testing to avoid high steady-state temperatures (accelerating insulation aging) and to prevent

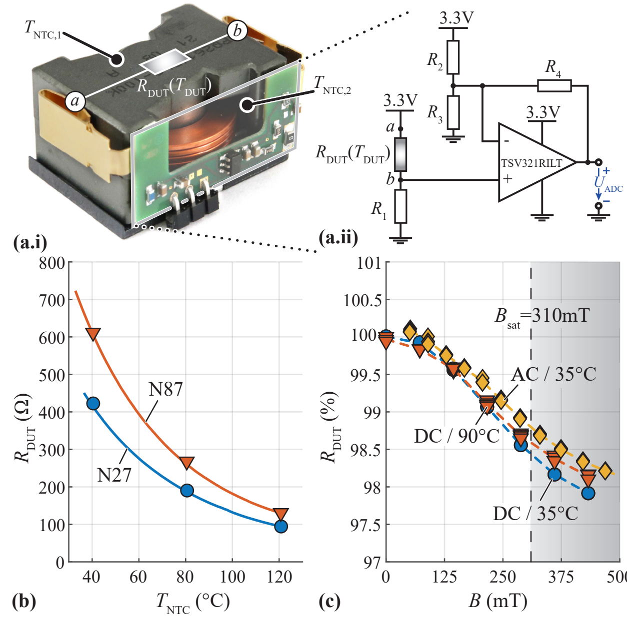

Fig. 1. (a.i) Smart inductor prototype based on a commercially available flat-wire inductor (Bourns PQ2614BLA-100K with $10\,\mu\mathrm{H}$, $30\,\mathrm{A_{rms}}$ rated current, and $17.6\,\mathrm{A_{pk}}$ saturation current). **(a.ii)** Measurement circuitry based on a Wheatstone-bridge with an output voltage $U_{\mathrm{ADC}} \in [0\,\mathrm{V}, 3.3\,\mathrm{V}]$ which is compatible with typical microcontroller Analog Digital Converter (ADC) inputs. **(b)** Impact of the temperature T_{NTC} (sensed with an Negative Temperature Coefficient (NTC) sensor) on the DUT resistance R_{DUT} of an N87 (TDK, B67345B0002X087) and an N27 (TDK, B67345B0002X027) I-core (dimensions: $93\,\mathrm{mm} \times 28\,\mathrm{mm} \times 30\,\mathrm{mm}$). The solid lines and scatter points are determined based on transient cool-down and steady-state measurements, respectively. **(c)** Impact of the magnetic field B on the resistance R_{DUT} (normalized by R_0) of the previously considered N87 I-core for 1) a dc B-field and temperatures $T_{\mathrm{NTC}} = 35\,^\circ\mathrm{C}$ ($R_0 = 684.7\,\Omega$), and $T_{\mathrm{NTC}} = 90\,^\circ\mathrm{C}$ ($R_0 = 221.6\,\Omega$), and 2) an ac B-field (with B representing the peak value of the $50\,\mathrm{Hz}$ sinusoidal B-field excitation) for a temperature $T_{\mathrm{NTC}} = 35\,^\circ\mathrm{C}$.

thermal run-away [9]. A typical measurement method is to accommodate one or several thermocouples or NTC sensors within the winding window or on the core surface which results, however, in a temperature reading below the inner hot-spot temperature.

It is known from literature that MnZn ferrite materials behave like intrinsic semiconductors, with the electrical conductivity increasing with temperature [10]–[15]. Hence, this paper proposes to utilize this parasitic effect and to realize a *smart* inductor (**Fig. 1a**) where the component temperature is observed based on a core resistivity measurement, advantageously allowing to track the average core temperature (which is typically above the core surface temperature).

II. Core-as-a-Sensor Fundamentals

In a first step, two commercially available MnZn materials (TDK N87 and N27) in an I-core geometry are characterized. To enable electrical contacts, copper plates are attached on both sides of the Device Under Test (DUT) with an electrically conductive silver-epoxy glue (MG chemicals 8331 silver epoxy) [13], [14]. A dc voltage U_{DUT} is applied to the DUT and both voltage U_{DUT} and current I_{DUT} are measured with a precision multimeter to calculate the temperature dependent core resistance $R_{\mathrm{DUT}} = U_{\mathrm{DUT}}/I_{\mathrm{DUT}}$. Note that the metal-semiconductor (copper-ferrite) contact results in a Schottky diode-like behavior [16], such that the measured core resistance R_{DUT} is also a function of the measurement voltage U_{DUT} and thus a sufficiently high $U_{\mathrm{DUT}} = 15\,\mathrm{V}$ is employed here.

The DUT is placed in an oven and heated until thermal steady-state at the desired temperature is reached, ensuring a homogeneous temperature distribution within the core (only marginal losses occur in the core due to the measurement current I_{DUT}). This allows to use an NTC surface temperature measurement to obtain the DUT temperature $T_{\mathrm{DUT}} \approx T_{\mathrm{NTC}}$. **Fig. 1b** presents the measured DUT resistance R_{DUT} obtained with steady-state measurements (scatter points); to speed up the measurements, a slow transient cool-down is used to obtain quasi-steady-state measurements (solid lines). The non-linear behavior of R_{DUT} over T_{DUT} relative to a reference temperature $T_0 = 35\,^{\circ}\mathrm{C}$ can be approximated with

$$R_{\mathrm{DUT}}(T_{\mathrm{DUT}}) = R_0 + \alpha(T_{\mathrm{DUT}} - T_0) + \beta(T_{\mathrm{DUT}} - T_0)^2, \quad (1)$$

with parameters $R_0 = 681.5\,\Omega$, $\alpha = -13.23\,\Omega/\mathrm{K}$, $\beta = 0.08\,\Omega/\mathrm{K}^2$ for N87. Solving (1) towards T_{DUT} thus allows to obtain the DUT temperature from the ferrite core resistance.

It is known that the presence of a magnetic field B alters the electrical conductivity in a magnetic core [16], [17], hence potentially deteriorating the temperature reading of a ferrite core during converter operation. To assess the impact of the B-field on the resistance R_{DUT} a U-I core configuration was employed with an excitation winding supplied from an ac or dc power supply regulating a winding current I_{B}. In **Fig. 1c**, a dc B-field up to the saturation flux density of $B_{\mathrm{sat}} = 310\,\mathrm{mT}$ applied to the N87 core results in a reduction $< 2\%$ of R_{DUT} corresponding to an overestimation of the temperature by $< 1\,^{\circ}\mathrm{C}$ and $< 2\,^{\circ}\mathrm{C}$ for a DUT temperature of $35\,^{\circ}\mathrm{C}$ and $90\,^{\circ}\mathrm{C}$, respectively. Similarly, the deviation of R_{DUT} remains small for a $50\,\mathrm{Hz}$ sinusoidal B-field excitation. The impact of the B-field frequency was also evaluated at $35\,^{\circ}\mathrm{C}$ (not shown) for a constant sinusoidal B-field with an amplitude of $15\,\mathrm{mT}$ (up to $10\,\mathrm{kHz}$) and $150\,\mathrm{mT}$ (up to $1\,\mathrm{kHz}$) with only a marginal reduction $< 1\,\%$ of R_{DUT}. Hence, the impact of magnetic fields on the dc resistivity of the investigated core materials remains small and has no substantial influence on the temperature measurement results.

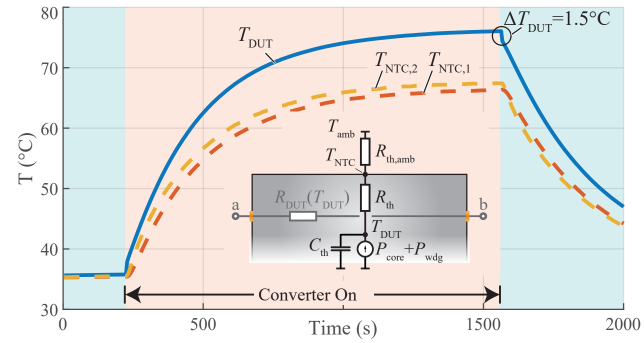

Fig. 2. Experimental verification of the smart inductor in a $1.6\,\mathrm{kW}$ $400\,\mathrm{V}$-to-$200\,\mathrm{V}$ buck dc-dc converter (switching frequency $f_{\mathrm{s}} = 72\,\mathrm{kHz}$, inductor $L = 70\,\mathrm{\mu H}$ (realized by series-connecting a $60\,\mathrm{\mu H}$ power inductor in series with the $10\,\mathrm{\mu H}$ smart inductor DUT, see **Fig. 1a.i**)): In addition to the DUT temperature measured via the proposed method, the surface temperature is also measured with two NTCs as indicated in the simplified thermal equivalent circuit.

III. Prototype and Experimental Verification

Fig. 1a.i presents a smart inductor prototype with a core-resistivity-based temperature measurement. The Wheatstone-bridge circuitry depicted in **Fig. 1a.ii** is used to accurately sense the core resistivity.

Fig. 2c depicts experimental waveforms obtained from operating the smart inductor in a buck dc-dc converter. The core-resistance based temperature reading T_{DUT} is more than $10\,^{\circ}\mathrm{C}$ higher than the surface temperature measurements $T_{\mathrm{NTC,1,2}}$. This clearly highlights the advantage of the proposed measurement method over surface temperature measurements, as the proposed method captures the average core temperature and not only the (lower) surface temperature. The measurements converge once the converter is turned off and thus no further heat is generated in the inductor. Note that at the turn-off instant, the temperature reading drops by $\Delta T_{\mathrm{DUT}} = 1.5\,^{\circ}\mathrm{C}$, which can be attributed to the impact of the B-field occurring during operation (see **Fig. 1b,c**).

IV. Conclusion

Future power electronic systems should feature continuous in-situ monitoring of components to facilitate, e.g., prognostics, real-time observation, and predictive maintenance. This paper proposes a method to observe the magnetic component temperature based on a measurement of the temperature-dependent ferrite core resistivity, advantageously allowing to track the average core temperature which is typically above the core surface temperature. All relevant aspects including contacting methods, material characterization and possible disturbance factors are discussed. Further, a *smart*-inductor prototype with core-resistivity-based temperature estimation is presented and verified experimentally. In closing, it is worth highlighting that the method is also applicable to high-frequency NiZn ferrite and also to iron powder cores; there, however, the high specific resistivity poses an additional challenge for an accurate measurement.

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