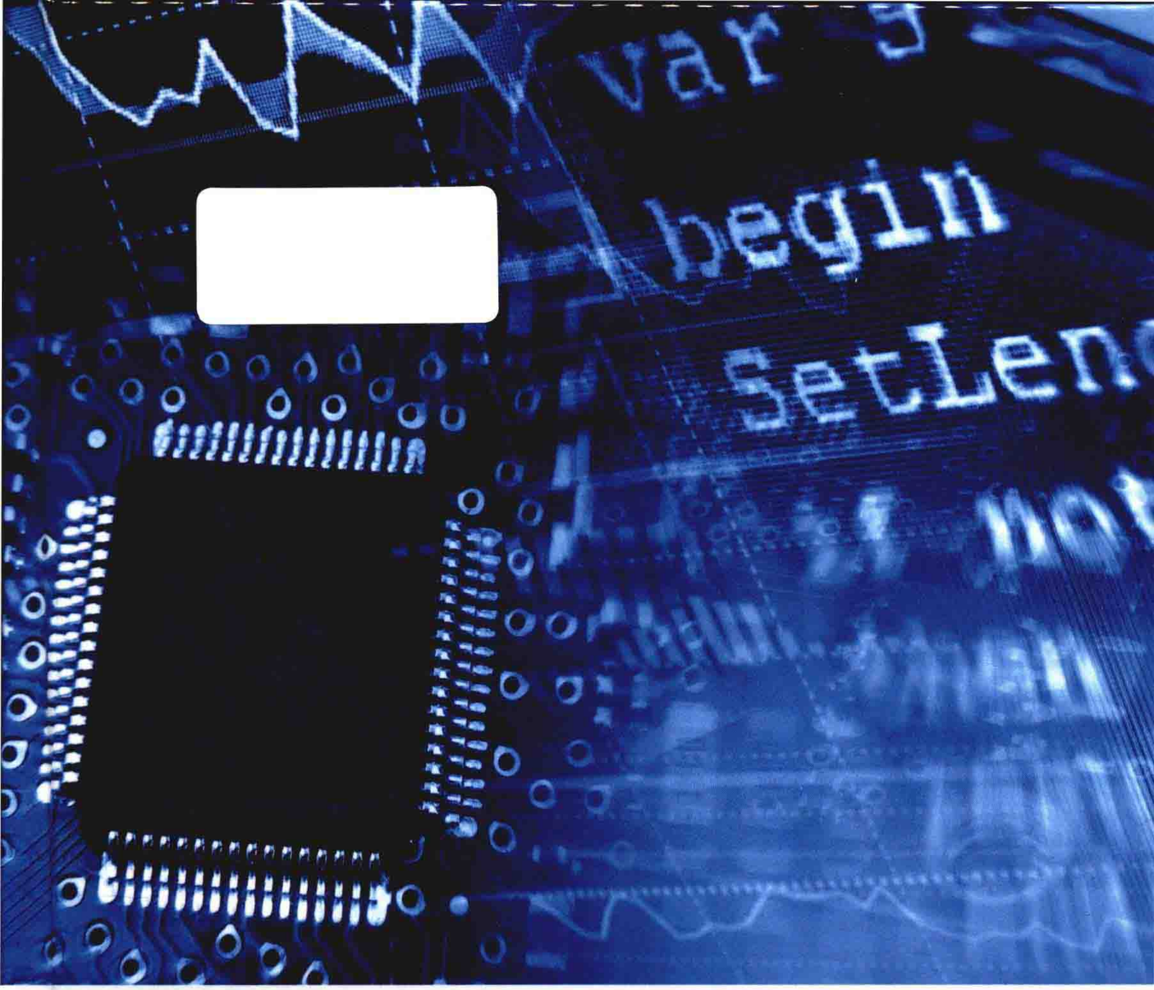

Power Electronics Applied to Industrial Systems and Transports

Nicolas Patin

volume 5

Measurement Circuits, Safeguards and Energy Storage

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Preface

This volume could have been called *"All which was not discussed in the first four books but which should not be overlooked!"*. Indeed, this book completes the four preceding books by addressing topics that, even though not an integral part of the power electronics field, are crucial to designing reliable and efficient converters. The first chapter deals with current, voltage, and temperature measurements. Such measurements are recurring issues in any power electronic converter. Components and sensors are introduced and specified by means of their technology, key characteristics, and conditioning circuits required to process information (whether by analog or digital circuits). The second chapter deals with shielding components used commonly in power electronics as well as in other electronic fields (especially in measuring devices). Indeed, the task at hand here is to study how "fragile" components can be shielded from damage caused by voltage, or intensity, surges that can occur in either faultless or malfunctioning circuits. Standards set for electronic protective setups are also mentioned. Additionally, part of the chapter focuses on explosion-proof equipment (ATEX) and on waterproof ratings of electrical devices (Protection Index concept – IP code). The final chapter deals with electrical energy storing elements commonly used in association with power electronic converters. This chapter addresses capacitors and supercapacitors first, then deals with batteries and accumulators. Part of the chapter focuses on the features of these components, especially monitoring, recharging, and establishing charge equilibrium (supercapacitors or batteries). The concept of accuracy is addressed in the first chapter which deals with measurements. Appendix 1, dedicated to uncertainty calculations, gives further information on how the performance of a measurement chain is characterized. As a final note, a short appendix (Appendix 2) introduces helpful information for converting between metric and imperial units.

Nicolas PATIN
January 2016

Contents

1

Sensors for Power Electronics

1.1. Overview

Regardless of the quantities that have to be measured, the sensors used in power electronics are characterized by generic parameters as well as in any other electronic field:

– precision;

– bandwidth;

– differential input (or single-ended input when the signal is taken relative to ground);

– galvanic insulation.

This last parameter is particularly important in power electronics in order to:

– maintain existing galvanic insulation of the power electronic converter for the sensor (refer to the Insulated Switching Power Supply section in Volume 3 [PAT 15c]);

– avoid propagating faults/parasitic effects from the power circuit to the control circuit (especially in the case of high power applications with high voltages and strong currents).

The unique characteristics of power electronics are due to the "chopped up" nature of measurable quantities (or at least of certain quantities in the system). This can cause measuring issues in terms of the bandwidth required for sensors that are not all suited to pick signals up presenting steep wavefronts (large $\frac{dV}{dt}$ and/or $\frac{dI}{dt}$). Furthermore, although theoretically the measured quantities do not suffer discontinuities (current through an inductance, voltage across a capacitor), their readings can be affected by other quantities undergoing large fluctuations (current or voltage through a transistor). Those fluctuations are likely to induce parasitic signals via capacitive or inductive coupling in the measuring circuit connectors of a printed circuit board, for example.

Broadly speaking, the routing of a printed circuit board for a power electronic converter requires paying careful attention to the following critical elements:

– power circuit connections;

– measuring circuit connections (to avoid introducing parasitic effects in the readings as much as possible);

– connections of control signals of electronic switches (to avoid oscillations/parasites, therefore, avoid unwanted switch commutations or at the very least avoiding slow commutations leading to additional losses).

In this respect, circuit miniaturization limits inductive coupling in the best way possible (and, to a lesser extent, capacitive coupling). It is always possible, using fine qualitative reasoning, to evaluate whether a given routing "geometry" is adequate or not. This qualitative analysis can even be carried out before performing a quantitative analysis (usually lengthy) requiring expensive and complex equipment (such as retrieval software for parasitic components due to component wiring, and simulation software). In order to conduct this reasoning, it is essential to focus only on the critical connections listed previously, and to neglect non-critical connections (power supply tracks for control circuits, if the latter are properly uncoupled, thanks to capacitors connected as close as possible to their power supply pins).

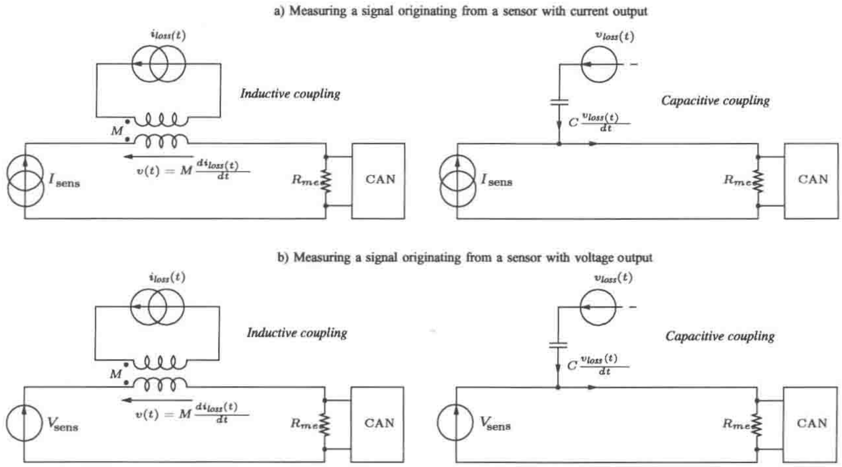

Figure 1.1. *Parasitic coupling schematics (inductive and capacitive) for sensors with current output a) and voltage output b)*

Moreover, knowing the nature of the quantities carrying the information at the sensor output allows us to determine the output signal coupling vulnerabilities (capacitive or inductive). For example, consider the case of a sensor supplying a *current* reflecting the measured quantity (this is the case for a large number of Hall effect sensors). Then, inducing an EMF on a long track separating the sensor from the data processing circuit will, in this case, have little impact on the measured signal. This is illustrated in Figure 1.1(a). Indeed, let us assume the sensor is an ideal current source and the signal measured at the acquisition circuit (for instance, an analog-to-digital converter – ADC) is obtained by recording the voltage across a resistor placed as close as possible to the ADC. Then under these assumptions, the sensor output impedance is a current source impedance i.e. theoretically infinite impedance (even though only very large in practice), therefore it will not be possible for the EMF induced by inductive coupling on the (possibly long) connecting tracks to inject a parasitic current in the loop. On the other hand, a capacitive coupling with a closed track undergoing strong $\frac{dV}{dt}$ would be able to inject a parasitic $C\frac{dV}{dt}$ type current, therefore affecting the acquisition circuit and, consequently, the readings.

On the contrary, the circuit connecting a sensor delivering a *voltage* (reflecting the measured quantity) to an acquisition circuit (Figure 1.1(b)) will not be vulnerable to capacitive coupling as long as the impedance of this circuit is low (which is the case for a sensor acting like an ideal voltage source). Consequently, if the circuit does not have too high an impedance (especially, a reactance due to track inductance), the $C\frac{dV}{dt}$ type current will be absorbed by the voltage source, and will not have any impact on the voltage measured by the ADC. However, the same circuit will be very vulnerable to inductive coupling. This is because inductive coupling will induce an EMF that will add to the voltage supplied by the sensor, resulting in the voltage perceived by the ADC.

It is important to keep in mind that capacitive and inductive coupling, although different in nature, are often due to bad routing (of the printed circuit board). Common denominators are:

– long parallel tracks carrying chopped up current and/or voltage for the power circuit, on the one hand, and the signal coming from a sensor and leading to an acquisition circuit (analog or digital) on the other;

– "forward" and "return" conductors placed too far apart that create an inductive loop (self-inductance) and introduce a vulnerability to induction from another circuit (mutual inductance).

Although proximity between the power circuit and the measuring circuit cannot be avoided (because of course, the sensor must measure a variable of the power circuit!), the problems listed above should be minimized as much as possible. Firstly, coupling can be minimized by tracing tracks as short as possible on the "power side" and on the "measuring side" and by angling them at 90° with respect to each other. Secondly, in the case of single-ended measurements, minimizing the distance between a "forward" and a "return" conductor can be facilitated by implementing earth planes. Otherwise, for differential measures, the problem can be solved by routing the two tracks in parallel with spacing as small as possible (even more efficient if these tracks are angled at 90° with respect to the power circuitery (or circuit) in order to minimize disturbances).

1.2. Current sensors

Common current sensors can be grouped in three broad families:

– shunts (resistors);

– current transformers;

– Hall effect sensors.

Each of these sensor categories have different performances in terms of accuracy and bandwidth (or more precisely, maximum measurable frequency). However, certain sensor types have the noteworthy ability to measure a direct current; for example shunts, whereas current transformers are grossly incapable of performing such a measurement.

1.2.1. *Current measuring shunts*

1.2.1.1. *Ohm's law and related complications*

Since a shunt operates like a resistor, its operation can simply be described using Ohm's law:

$$v = R.i \tag{1.1}$$

The voltage across the shunt is proportional to the current passing through it. Therefore, knowing the proportionality coefficient R is enough to be able to derive, from the voltage reading, the current circulating through the branch on which the shunt is connected(in series). Unfortunately, even assuming that the voltage was measured perfectly (which is never the case in practice), not knowing the value of R remains an issue. Before discussing this resistance measurement and calibration, let us recall the relation linking resistance R (in Ω) to the physical (resistivity ρ in Ω.m) and geometric (length l and section S in m and m^2) properties of the resistive element considered:

$$R = \rho \cdot \frac{l}{S} \tag{1.2}$$

In practice, a shunt should allow for the current to be measured without disturbing the power circuit excessively, through which the current circulates. In particular, this keeps the converter efficiency from being deteriorated to a greater extent as losses will inevitably be triggered by this component. Additionally, these losses might impact the readings themselves. Indeed, losses lead to heating and heating has an effect on material resistivity as well as on the geometric dimensions of the resistive element (thermal expansion). As a guideline, the resistivity at 300 K of some metals as well as their associated temperature coefficient α are exhibited in Table 1.1. The α coefficient corrects for material resistivity according to the following linear function: