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Recommendations and Typical Errors in Design of Power Converter PCBs With Shunt Sensors

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ABSTRACT Nowadays the percentage of power electronic devices, which use shunts for sensing of electrical signals, is increasing significantly. This method of measurements is simple, reliable and low-cost, however it requires careful elaboration of schematics and meticulous design of printed circuit boards. The author provides a detailed insight into the design of power converter Printed Circuit Boards (PCBs) with shunt-based sensing circuits and provides recommendations on improvement of signal measurements. He analyses the most popular design mistakes and illustrates their impact on measuring signals, which can be used for mistake localization. This paper demonstrates that the properly designed schematic can be turned into poorly operating PCB and recommends measures to avoid it. The author shares his more than 20-years experience and illustrates his statements with examples from real life. Although this paper is mainly addressed to young engineers, it could also be useful for experienced researchers, who work in neighboring areas and do not gain experience in PCB design.

INDEX TERMS Current measurement, shunts (electrical), printed circuits.

I. INTRODUCTION

With the last trends on green energy and decrease of carbon emissions [1]–[3], the role of electrical systems significantly increases. Therefore, a number of various researches and development projects have been recently started or are planning for investigation in near future. Almost all of them include power converters (rectifiers, inverters, DC/DC, etc.) intended for changing parameters of electrical energy and control of output voltage and/or currents [4]. As a result, the overwhelming majority of power electronic converters involves current measurements in its operation, therefore performance of these devices significantly depends on the sensing quality [5], [6]. In order to measure currents, power converters include sensors, which are based on one of the techniques considered in [7]–[9]. The simplest and most reliable solution is usage of current transformers or sensors based on the Hall effect [10], [11], which are galvanically isolated and typically contain preamplification circuits. As a result, these types of current sensors output signals with good noise characteristics and can be connected directly to analog to digital converters (ADC) of a microcontroller unit (MCU). However, the usage of these current sensors significantly increases the total cost of power converters, especially the cost of converters which sense several currents. On the other hand, the shunt-based current sensors are notably cost effective, however they have the drawback of high noise-to signal ratios, and require careful elaboration of schematics and design of printed circuit boards (PCB) [12]. Taking into account the fact that manufacturers of power converters continuously compete against each other and wage a war on every cent spent on the cost of their devices, shunt-based current sensors have become more and more popular and have been adapted for usage in converters of middle power range [13]. Furthermore, shunt-based current sensors demonstrate a better response at higher frequencies (tens of kHz), therefore they are widely used in power converters operating under these conditions [14].

At the same time, the main disadvantages of shunt sensors are: galvanically connected power and control parts of converters, resistance instability with temperature variation, the presence of thermo-EMF and low voltage drop across shunt resistors (tens of millivolts) [15]. The low-level sensor output signal requires amplification before sending it to ADC [16]. Since amplification circuits are placed at some distance from the sensors, the PCB under design contains circuits with low-level signal, which are extremely sensitive to external factors (noise, inaccurate design, etc.). Therefore, engineers have to carefully design the analog part of shunt-based sensing circuits and follow the recommendations provided in this paper.

Taking into account that the proper design of PCB, which contains digital, low- and high- power analog signals, is a challenging task, the first prototype of the designed board typically contains mistakes. These mistakes must be detected at the next stage of prototype analysis and exploration, and rectified. After that, the next version of the converter prototype is developed and its performance is evaluated. These iterations are repeated until the prototype with desired characteristics is designed and produced. The decrease in the number of iterations can significantly save design time and reduce development cost, therefore it is desired to design PCBs and analyze first prototypes carefully [17]. Furthermore, modern projects on power converters development are closely connected with production lines, which have reservation time for future production of the developing devices. As a result, these projects have tough deadlines, which, if violated, lead to significant losses.

The recommendations on design of mixed-signal boards have been published in many papers and application notes from electronic components manufacturers. At the same time, these recommendations are frequently general and do not consider specific of power converter PCBs with current shunt sensors, or are not applicable to them. As a result, many engineers cannot find the detailed recommendations on design of these PCBs and may not interpret published suggestions properly.

In order to solve this problem, this paper considers the specifics of PCBs with current shunt sensors intended for usage in general purpose power converter operating at frequencies below 100 kHz and controlling currents below 200~300A. The author discusses typical design mistakes, analyses their impact and provides design recommendations for shunt-based sensing circuits. The most frequent mistakes are illustrated with oscillograms of the sensed signals, thus these pictures may be used for rapid problem localization in PCB prototypes. All examples were taken from real life and were results of inaccuracies made by design engineers, which could have been avoided, provided they were more experienced. It is hoped that suggestions provided in this paper, together with detailed illustrations can help engineers in the PCB design and verification stages, decrease the number of redesign iterations and save development time and budgets.

II. CURRENT SHUNTS

What is a shunt? According to the Merriam-Webster dictionary, it is a conductor joining two points in an electrical circuit so as to form a parallel or alternative path through which a portion of the current may pass (as used for regulating the amount passing in the main circuit) [18]. The origin of the term is in the verb "to shunt" meaning to turn away or follow a different path. This term corresponded to the usage, because the earliest shunts were meter shunts, used as external accessories to ammeters, allowing one meter to be used for a variety of current levels, depending upon which shunt was chosen [19]. However, nowadays the term "shunt" was expanded to various 2- or 4-terminal measuring resistors of high current capacity, and this paper also uses the term "shunt" in the latest meaning.

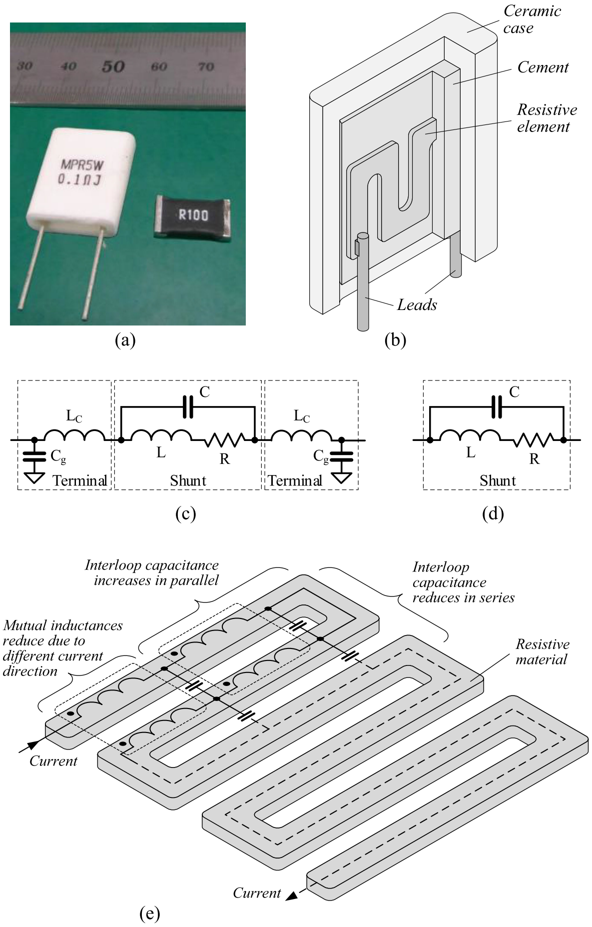

FIGURE 1. Typical structure of current shunts. a) Shunt pictures; b) Shunt construction; c) Shunt equivalent circuit; d) Simplified shunt equivalent circuit; e) Shunt model.

A. SHUNT MODEL

Modern makers of passive components propose variety of shunt resistors of different constructions. The most popular among them are ceramic (left) and power metal strip (right) shunts depicted in Fig. 1(a). As it clearly seen, they differ in size and construction, which is caused by different capability to dissipate power. Ceramic shunts can withstand higher temperatures and can dissipate more energy, thus they are typically used in devices of higher power.

The construction of power metal strip shunt is based on the strip made of resistive material with relatively stable characteristics. It is relatively simple and can be found in [20], thus it will not be considered here. Construction of ceramic shunt resistor is more complicated and demonstrated in Fig. 1(b). Its core consists of resistive element made of special metal alloy with joined lead terminals. This core is put inside the ceramic case and fixed with a cement with low thermal expansion coefficient, which provides lower mechanical stress at heating.

The detailed model of a shunt resistor is demonstrated in Fig. 1(c), where R is value of shunt resistance; L and C are its parasitic inductance and capacitance, respectively; L_C is external connection inductance; C_g is external capacitance to ground [20]. This model includes inductance and capacitance of shunt terminals and connections, which are relatively small, and can be ignored for applications operating below MHz region. As a result, the shunt model can be simplified as demonstrated in Fig. 1(d) [21].

It should be noted that shunt inductance and capacitance are parasitic parameters, therefore shunts are designed to decrease them as much as possible. In order to do it, the resistive element typically has serpentine shape, Fig. 1(e) with even number of elements. As it clearly seen, currents in the neighboring conductors flow in opposite directions, which decreases mutual inductance. Simultaneously, this geometry increases interloop capacitance, which is undesired. In order to decrease interloop capacitance, the length of parallel conductors should also be decreased and their number enlarged. As a result, the number of parallel conductors and their number is a tradeoff between values of parasitic inductance and capacitance.

B. PARAMETERS AND DESIGN CONSIDERATION

To describe a particular current shunt a number of its parameters have to be defined. The most significant of them, which have to be considered at the stage of design, are:

- Rated resistance,
- Tolerance,
- Maximum dissipated power,
- Voltage drop,
- 2- or 4-terminals,
- Maximum temperature coefficient of resistance,
- Maximum reactance,
- Dimensions,
- Weight.

The rated resistance defines current sensor gain and must be selected in order to properly convert current through the shunt into output voltage. This means that the maximum operational current must not cause voltage drop across the shunt, which exceeds the maximum measurable voltage. If the value of resistance is selected incorrectly, some current ranges could be unmeasurable and control algorithms may fail. After value selection, the tolerance of the shunt resistor must be identified. This parameter is defined by control system precision requirements to measurement circuits. In turn, these requirements are determined by demands to performance of the device under design. The overwhelming majority of commercial power electronics are equipped with a 1% tolerant shunt, which is a compromise between cost and precision.

The next important shunt characteristic is maximum dissipated power. Since shunt resistors conduct high currents, a significant amount of power, which is proportional to squared current, is dissipated there. In order to exclude shunt overheating, its power rating should be higher than the maximum possible dissipated power. Furthermore, environmental conditions and cooling of shunts significantly impact the amount of heat which can be dissipated, and must therefore also be considered. Besides that, the shunts with lower current ratings are cheaper, which must be taken into account, especially for low-cost applications. In order to improve power dissipation, the sensors are frequently designed as several shunts connected in parallel, thus lower rating parts can be used.

One more parameter, which has to be checked at the stage of design, is voltage drop across the shunt. This drop decreases the voltage applied to the object under control and total efficiency of the system. Therefore, it should be verified, that the voltage drop is acceptable and does not impact system performance significantly.

When selecting a shunt for current sensing, the number of its terminals has to be defined. Typically, shunts are produced with 2- and 4 terminals, also known as the Kelvin connection. The 4 terminal solution is used with higher currents and lower shunt values (<0.5 mΩ), where the contact and the lead resistances are comparable with the shunt resistance [22]. Since additional contacts are connected directly to the resistive element, this topology excludes undesirable parasitic resistances.

One more important parameter, which impacts the operation of shunt-based sensing circuits, is the temperature coefficient of resistance (TCR), which characterizes the shunt resistance variation with the change of its temperature. This coefficient depends on the material of shunt and can be either positive or negative. The TCR depends on the temperature non-linearly, however it is typically approximated with straight lines. For example, one of the most popular shunt materials manganin, has the TCR of 10 ppm/°C in the range of 0~25°C and -5 ppm/°C in the range of 25~60°C. This feature must be taken into account for applications, which are intended for work in a wide temperature range.

All the shunts have a reactance caused by the parasitic inductances and capacitances of the shunt and its connections. In low value resistors (below 10 Ω), the inductive reactance usually outweighs the capacitive reactance, while higher values are more likely to be capacitive [19]. This parasitic reactance increases voltage drop at non-DC currents and creates a phase shift between voltage and current. This voltage drop is insignificant for sinusoidal currents under megahertz ranges, however it can impact signals with significant current derivative. Furthermore, this parasitic inductance may lengthen transients, increase minimal PWM pulse lengths and decrease the operational range of power systems.

The weight and dimensions of shunts are typically not important for lower current applications, however it can impact the design process of higher current power converters and must be considered.

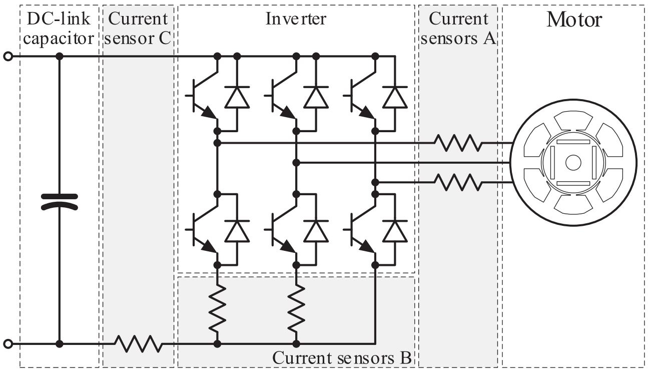

FIGURE 2. Typical points to sense currents. A) inverter output lines; B) Inverter bottom legs; C) DC-link.

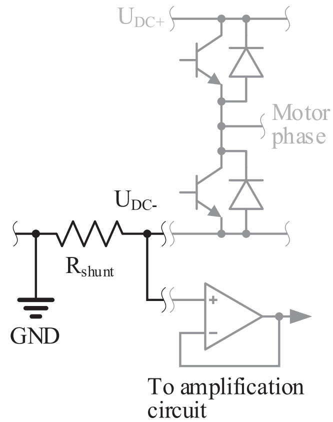

FIGURE 3. Typical schematic of the shunt sensor placed in the negative rail of DC-link.

C. SENSING PROBLEMS

It was explained earlier, that heat dissipation and voltage drop are one of the most important shunt parameters, therefore, in order to decrease these, the value of the shunt is selected as low as possible. As a result, the current sensor operates in the narrow range, e.g., the voltage drop corresponding to the current varying from zero to the rated value is 0∼0.5 V [23]. The digitalization of this low-voltage signal with a built-in ADCs of microcontrollers, which are typically 10- or 12-bit, results in high discretization errors, therefore the signals from the shunts are typically preamplified and only after that, are sent to the ADC [24]. As a result, the PCB contains circuits with low-voltage analog signals, which are sensitive to external disturbances. In order to minimize their negative impact, the low-voltage analog circuits should be as short as possible, and it is recommended to place preamplifiers close to the shunts. Unfortunately, it is impossible in many projects, where the preamplifiers are built into an MCU or share opamp package with other circuits. As a result, the PCB under design contains long low-voltage analog circuits, which are sensitive to disturbances. In order to decrease the noise to signal ratio in these circuits and provide sensed signal to the ADC with acceptable error, the schematic and its implementation in PCB have to be carefully elaborated.

III. TYPICAL SHUNT SCHEMATICS

In order to measure currents in power converters, the shunt sensors can be placed in various points, however the most common solutions are illustrated by Fig. 2: A) output lines (e.g., motor phases) [25]–[28], B) bottom legs of switchers (e.g., between bottom inverter switches and ground) [29], [30] and C) negative rail of DC-link (between ground and negative terminal of inverter) [31], [32]. Solution “A” uses shunt sensors, which are not connected to ground, therefore it needs additional voltage isolation, separate power supplies, etc., which significantly increases the total cost [33]. This solution is typically used in higher cost applications, which contain shunts integrated in power modules [34] or shunts used together with ΔΣ modulators. These modulators are located close to shunts, therefore the length of the low-voltage analog signal is insignificant. In turn, ΔΣ modulators output a bitstream, which passes through the isolation barrier and is then processed by ΔΣ demodulator, before sending to the microcontroller unit (MCU) [35]–[37]. Solutions like this provide more precision measurements, however they significantly increase total cost.

Solutions “B” and “C” use current shunts, which are connected to ground, therefore they can be used without voltage isolation, which makes them popular, especially for low-cost applications [38]–[40]. A good example of the shunt sensor placed in the negative rail of DC-link is demonstrated in Fig. 3. This example was taken from the project discussed in [41], where motor currents were measured using single shunt in the DC-link and current reconstruction technique.

The schematic shown in Fig. 3 uses voltage repeater as the first step of two-stepped preamplification, however signal from the shunt may be processed in other ways [42]–[44]. The collection of the most popular current sensing circuits with explanations of their advantages and drawbacks is provided in [45], which can be used for the selection of the appropriate schematic for the exact PCB. It should be also noted that for loads like electrical motor, current through the shunt may flow in both directions, even for solution “C”, where the shunt is placed in the negative rail of DC-link, therefore the preamplification circuit must shift the sensed signal.

One of the best schematics, which can amplify shunt signal and shift it, is demonstrated in Fig. 4. This schematic is quite popular in general purpose and low-cost applications, because it combines simplicity with cost effectiveness and uses only one operational amplifier. The drawback of this circuit is complexity of its parameter calculations, because its transfer function is:

$$U_{ADC} = \frac{R_1 R_3 (R_4 + R_5)}{(R_1 R_2 + R_1 R_3 + R_2 R_3)} U_{ref} + \frac{R_2 R_3 (R_4 + R_5)}{(R_1 R_2 + R_1 R_3 + R_2 R_3) R_4} I_{shunt} R_{shunt} \quad (1)$$

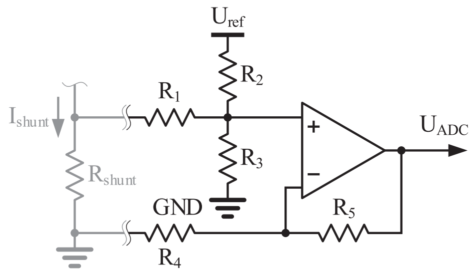

FIGURE 4. Example of amplification circuit with signal shift.

where R_{shunt} and I_{shunt} are values of shunt and current through shunt, respectively; U_{ref} is reference voltage (typically supply voltage of ADC); $R_1 \sim R_5$ values of the corresponding resistors.

Equation (1) can be significantly simplified by setting $R_1 = R_4$, $R_2 = R_3$ and demanding the voltage shift to be half of the U_{ref}. In this case, the transfer function simplifies to:

$$U_{ADC} = 0.5 \cdot U_{ref} + \frac{R_2}{2R_1} I_{shunt} R_{shunt} \tag{2}$$

which is significantly easier for calculation and tuning.

IV. RECOMMENDATIONS TO DESIGN OF SENSING CIRCUITS WITH SHUNTS

As mentioned above, some common recommendations on design of power supply filters, ground planes, bypass and decoupling capacitors, can be easily found in literature such as [46]–[48] and adapted to power converter PCBs, therefore this paper focuses on the specifics of power converter PCBs.

Before further discussion, a typical power converter PCB has to be considered. It is a two layered board with an amount of surface mounted parts of about 80∼90%. The hole-through mounting is typically used for heavy parts (transformers, inductors) or components with significant power dissipation (power modules, shunts). The overwhelming majority of these PCBs comprises digital parts (microcontrollers, digital circuits, etc.), power parts (power modules, filters, etc.), secondary power supplies (switched mode power supplies (SMPS), voltage regulators, etc.) and analog circuits (sensing circuits, control and encoder interfaces, etc.) as shown in Fig. 5.

Most microcontrollers operate at +5 V and have internal ADCs to process analog signals in the same voltage range. The power part typically includes switching devices like inverters, which modulate output voltage at high frequencies (5∼20 kHz) and commutate significant load currents. The modulated signals are typically rectangular and contains higher harmonics, thus, circuits of the power part radiate electromagnetic noise, which energy is proportional to the current. This electromagnetic radiation (EMR) may distort analog signals, therefore its impact should be minimized. The secondary power supplies typically include several SMPSs, which are used to provide various voltage levels to microcontroller, power modules and operational amplifiers. The SMPSs

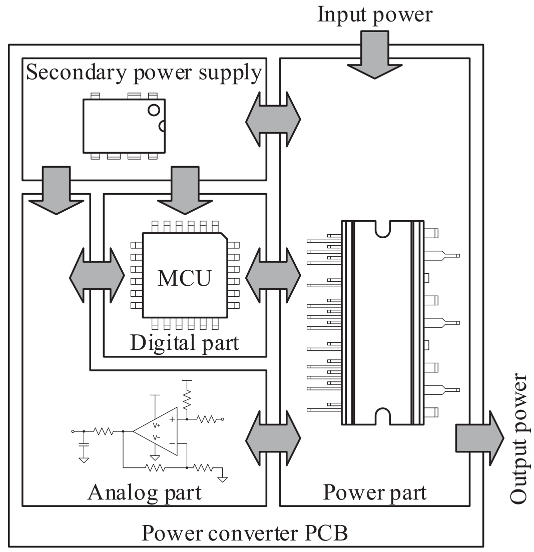

FIGURE 5. Typical architecture of power converter PCB.

modulate input voltage and commutate current at higher frequencies than the power part (20∼200 kHz), however the value of the commutated current is significantly lower. Nevertheless, this EMR also impacts the analog signals, and have to be considered at the stage of design. The analog part of power converter PCBs typically includes sensing circuits and interfaces with external encoders and control signals. All of these have to be designed carefully, however specific attention has to be paid to shunt-based current sensing circuits, which have the lowest signal to noise ratio among them.

The main design rules with explanations are listed below. It should be noted that from the schematic point of view some PCBs could be similar, however the exact design can improve or worsen its sensitivity to noises. It happens, because schematic neglects parts' non-idealities and does not consider parasitic inductances, capacitances and resistances, which impact circuit operation, especially in transients.

A. USE SEPARATE GROUNDS

The analog ground must be separated from the digital and power grounds and contact them only in one point. Analog and digital grounds are typically connected near the ADC, while analog and power grounds are connected near the shunt. This design prevents the flow of significant currents from the digital and power circuits through the analog ground, which can create significant voltage drop and degrade the quality of analog signals [49], [50].

B. CONTROL THE RETURN PATH OF SHUNT SIGNALS

As mentioned above, the voltage drop across the shunt is quite low, therefore it should be carefully checked that there are no additional voltage drops across the current path from shunt [51]. In order to do this, two dedicated lines from the shunt to the amplification circuit should be created. From a schematic point of view, one of these lines is analog ground, however

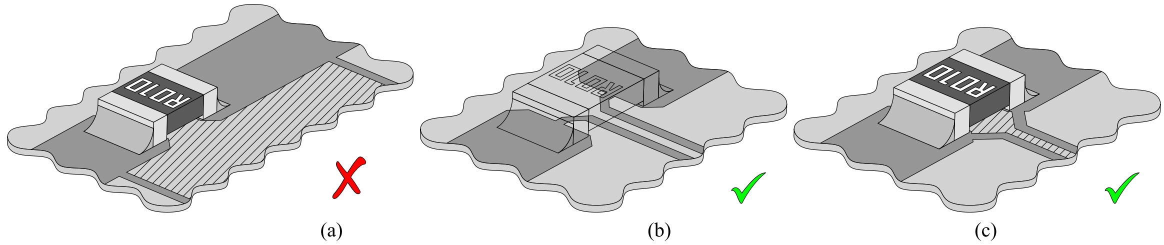

FIGURE 6. Connection of sensing lines.

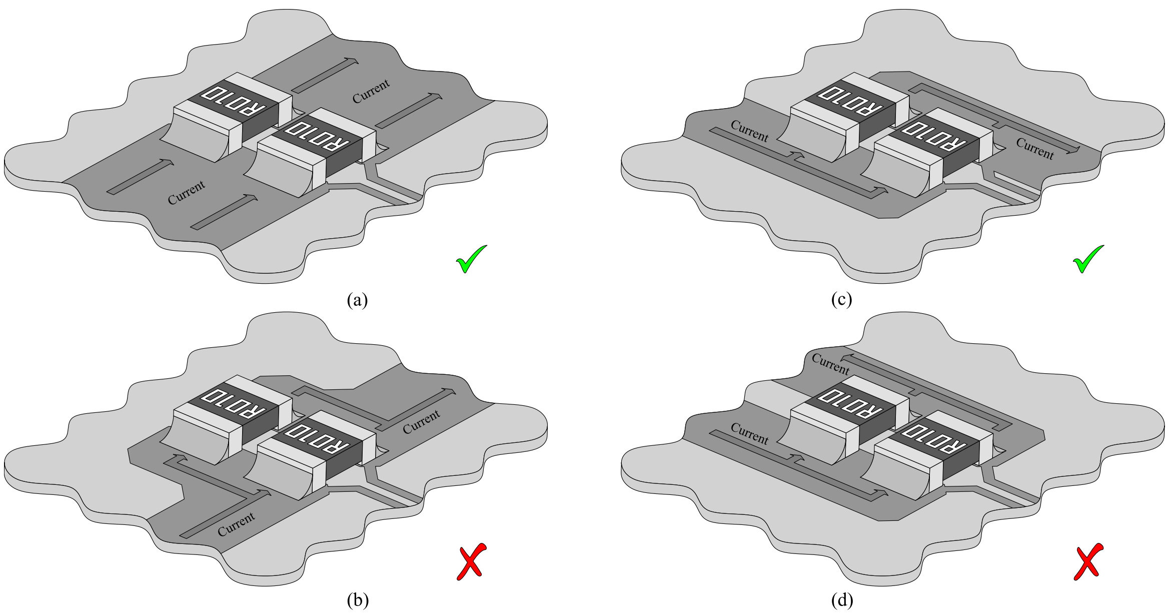

FIGURE 7. Parallel shunt connection.

that line should be separated from the ground plane in order to prevent its sharing with other currents. The ground line from the shunt should be directly connected to the input of preamplifier, parts of the preamplification circuit or analog ground plane near the preamplifier.

C. EXCLUDE PARASITIC RESISTANCE IN SHUNT CIRCUITS

When designing a PCB layout and connections, it is extremely important to control the measurement resistance to be as expected. In order to do this, several rules must be followed:

Proper connection of sensing lines. The sensing lines must be connected to shunt the way, that excludes additional conducting paths, otherwise effective value of measurement resistance increases, providing incorrect results [22], [52], Fig. 6(a). It could be done by connecting the voltage sensing lines to the inner edges of the shunt solder pads (if size allows), Fig. 6(b) or to the current traces as close as possible to the inner edges, Fig. 6(c).

Proper connection of parallel shunts. If sensing shunts are connected in parallel, it is of great importance to provide equal current distribution between them. Therefore, current path to each shunt must be similar, which provides equal resistance of those traces, equal current distribution between shunts and equal voltage drop. This rule is illustrated by Fig. 7, where cases "a" and "c" illustrate good design, while cases "b" and "d" demonstrate mistakes. It should be noted, that the connection demonstrated in Fig. 7(c) is valid only for two resistors and provides unequal distribution with higher number of shunts.

D. DECREASE IMPACT OF ELECTROMAGNETIC NOISES

Electromagnetic radiation is the most frequent source of the noises in measurement s circuits. The general measures on EMR decrease are discussed in [53], while this paper enhances them with the rules applicable to power converter PCBs.

All current paths in PCB produce EMR, which induces back-EMF in all PCB circuits, however their impacts are different. The current path radiates noise, which is proportional to the area of its loop, amount of the current in this loop and frequency, however the energy of radiation decreases with the inverse square law [54]. Besides that, when the radiation passes through the metals, it decreases exponentially, therefore, even thin layers may significantly decrease noise

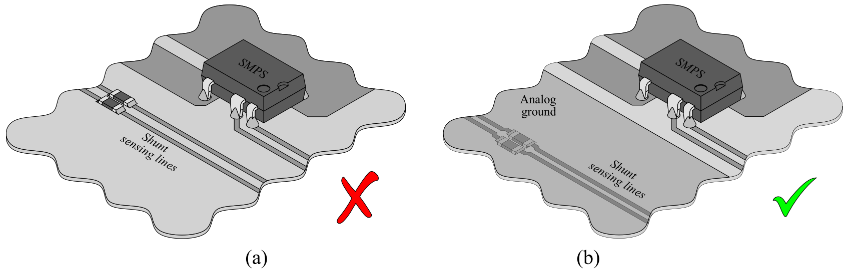

FIGURE 8. Placement of analog circuits.

intensity. At the same time, the value of the back-EMF induced in the circuit is proportional to the energy flow passed through this circuit, which in turn is proportional to the area of the circuit projected at the plane normal to radiation. These considerations will be used in PCB design in order to decrease the noise to signal ratio of the sensing circuits.

Typical power converter PCBs contain several elements which produce significant EMR. They are power modules with its connections to a load and SMPS with its output circuit before filters. If the PCB under design includes a power factor corrector (PFC) or other switching devices, they also must be taken into consideration. The power modules commutate higher currents and produce the most powerful EMR, however they typically have built-in shields, which decrease the radiation, therefore, other parts may need more attention.

Considering these features of PCBs, rules for decrease of EMR can be formulated:

Place analog circuits distantly from high-EMR parts. Sometimes, several centimeters shift can significantly decrease noise.

Place ground plane between analog circuits and source of EMR, if possible. Fig. 8(a) and (b) demonstrate “bad” and “good” designs, respectively.

Decrease the areas of radiating and analog circuits. In order to do this, the current forward and return paths should be put as close as possible [55]. Examples of incorrect and proper designs of analog circuits are demonstrated Fig. 6(a) and (c), respectively, where dashed area illustrates antennas.

Consider spatial position of radiating and analog circuits. The induced noises are defined by the energy received from the emitting circuits, therefore the analog circuits have to be oriented to minimize its projection on the direction of radiation. Therefore, radiating and analog circuits could be placed perpendicular or in the one plane, but not overlapping.

Do not cross power lines. The analog circuits and traces should not cross the power lines.

Finally, a proper design example of analog circuits in power converter PCB is demonstrated in Fig. 9. It illustrates commercial inverter board used for control of air conditioners.

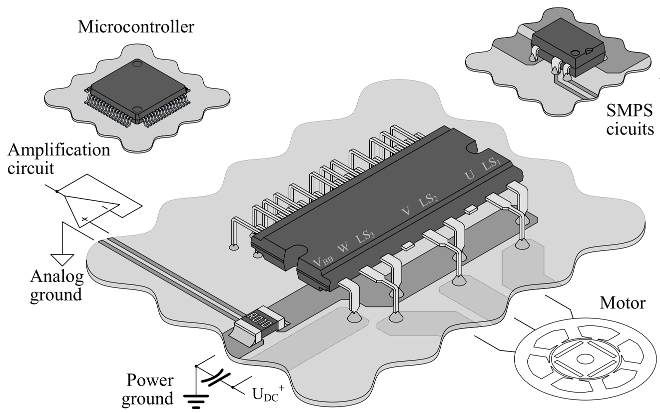

FIGURE 9. Proper design of analog circuits.

V. BRIEF DESIGN ALGORITHM

In order to summarize suggestions on the proper design of shunt sensing circuits, a brief algorithm is provided. It gives recommendation to be followed at each step of design.

A. SCHEMATIC DESIGN

- Use separate ground for analog part. It is also recommended to separate digital and power grounds. It decreases impact of more powerful circuits on the operation of lower power circuits;
- Draw current return paths, separating them from common grounds. It helps in proper routing of the analog part;

B. PART ARRANGEMENT

- Locate power module as close as possible to the power connector in order to decrease radiation of power circuits;
- Place shunts from the side of power module, which is closer to MCU. It minimizes length of sensing lines and decrease aperture of receiving antenna;
- Deposit parts with high EMR (ex. SMPS circuits) as far as possible from sensing circuits, preferably at the opposite side of PCB;
- Consider radiation direction of parts with high EMR and rotate them to decrease projection of this radiation onto measurement circuits;

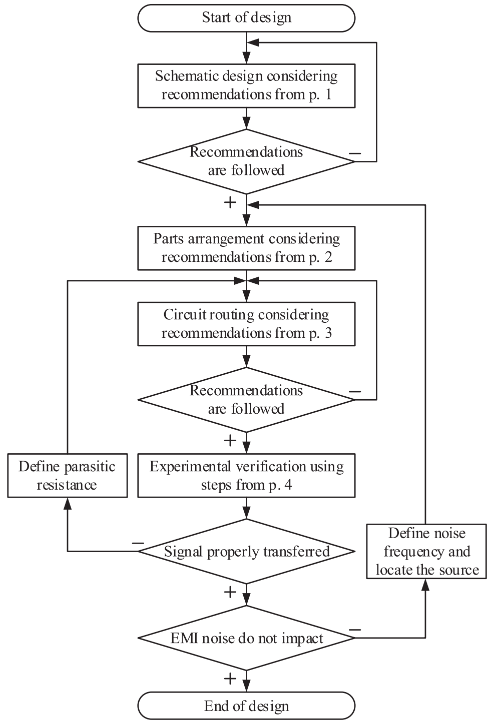

FIGURE 10. Flowchart of the design algorithm.

C. CIRCUITS ROUTING

- Make the power lines close to each other in order to decrease aperture of the emitting antenna;
- Separate current return part from ground. It decreases impact of other circuits on the measurements;
- Do not cross power lines with sensing lines. High frequency and high current signals may induce significant noise in the measurement circuits;
- Exclude parasitic resistance in shunt circuits, which may increase effective shunt value and increase error. In order to do it, follow the rules on terminal connection and parallel shunts connection;
- Trace the sensing lines as close to each other as possible, decreasing the aperture of receiving antenna;
- Place ground plane on the side of PCB opposite to sensing lines. The ground operates as a shield decreasing the energy of electromagnetic radiation passing through;

D. EXPERIMENTAL VERIFICATION

- Check the transfer of analog signal from shunt to amplifier. If these signals significantly differ, additional parasitic resistance may be included into measurement circuit;
- Check the noise at input of ADC. If significant noises are detected, the circuit has low immunity to EMR and has to be redesigned. The frequency is a key point to investigation of the noise source;

The flowchart of the proposed design algorithm is depicted in Fig. 10, which summarizes abovementioned statements.

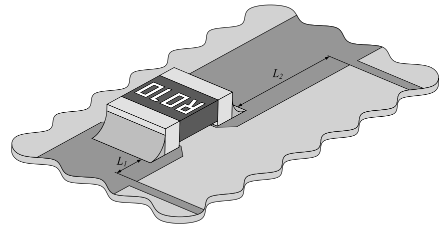

FIGURE 11. Increase of measuring resistance effective value.

VI. TYPICAL DESIGN ERRORS AND AFTEREFFECTS

One of the most popular mistakes is the unintended increase of measuring resistance effective value. If the shunt traces are not connected directly to solder pads, they include additional parts of track L_1 and L_2 aside of shunt, Fig. 11, which adds resistance to shunt.

A PCB consists of a flat piece of insulating material and layers of laminated copper foil. The thickness of copper foil is defined by the manufacturer and is measured in ounce per square foot (oz/ft^2). They are not SI units so must be converted as: 1 oz = 28.35 g and 1 ft = 0.3048 m. Therefore, one ounce per square foot means that the foil thickness is:

$$h_{1\ oz/ft^2} = \frac{m}{D \cdot S} = \frac{28.35}{8.96 \cdot 10^6 \cdot 0.3048^2} \approx 34.06\ \mu m \quad (3)$$

where D, m, S are the density, mass and surface of copper foil, respectively. The parasitic resistance added to the measurement circuit is:

$$R = \rho \frac{L_1 + L_2}{w \cdot h} \quad (4)$$

where w, h, ρ are width, height and resistivity of the current traces, respectively. The resistivity of pure copper at 20°C is 16.78 nΩ·m, but PCB manufacturers use technical copper with resistivity of about 18 nΩ·m, so this value is recommended for calculations.

This frequent mistake can be illustrated by the first prototype of PCB developed for project considered in [56]. It was a 2 oz/ft^2 PCB with 20 mΩ shunt resistors in the bottom legs of inverter, where sensing lines were incorrectly connected to one shunt, including about 52 mm of current trace with a width of 4 mm. The calculation using (4) indicated that the effective value of the measurement resistance was increased at 3.4 mΩ which is 17% of the shunt value. The oscillogram illustrating this case is demonstrated in Fig. 12. It is clearly seen that the voltage at input of amplification circuit is higher than the voltage drop at shunt sensor, thus phase currents were incorrectly measured providing values 17% higher than the real currents.

Formulae (4) may also be used for analysis of mistakes demonstrated in Fig. 7(b) and (d). If the resistances of shunt branches differ k times, the currents through shunts becomes unequal and the measurement error is:

$$\Delta I = \frac{k-1}{k+1} \quad (5)$$

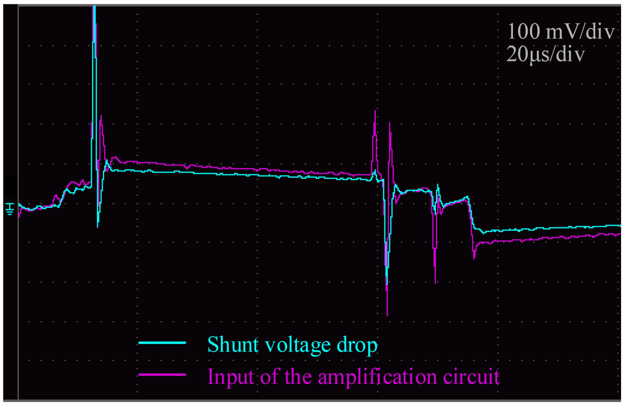

FIGURE 12. Impact of the additional resistance on the measurement results.

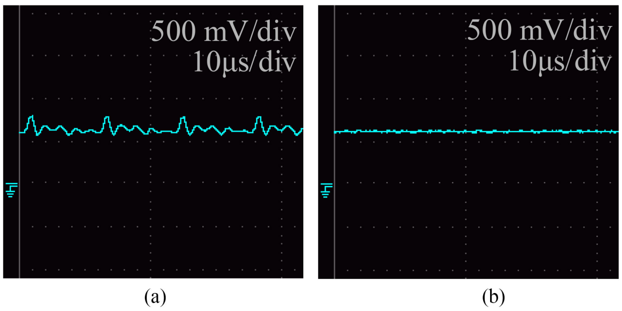

FIGURE 13. Signal at analog input: a) Distorted; b) Normal.

Thus, 1% resistance increase of one shunt branch results in 2% of the measurement error.

The design mistakes related to EMR noise can be easily detected using analysis of the preamplifier input signal. In case of a mistake, this signal is distorted with higher harmonics, which frequency identifies their source. An example of this kind of mistake taken from the project discussed in [57] is shown in Fig. 13(a), which demonstrates shunt signal after shift. At that time the motor was not operating, thus the sensed current was expected to be a straight line at 0.6 V, which corresponded to zero stator current. However, the real signal contained significant distortions as demonstrated in Fig. 13(a). The frequency of this noise was 166 kHz, which helped to identify the source of this disturbance. It was an SMPS, which modulation frequency was the same. Therefore, impact of the SMPS on the current sensing circuit was studied and PCB design was improved by increasing the distance between SMPS circuits and shunt sensing lines. The same signal in the improved prototype is demonstrated in Fig. 13(b), which shows that the noise was significantly decreased.

VII. CONCLUSION

This paper provides recommendations on the design of power converter PCBs with shunt-based sensors. It discusses the specifics of these printed circuit boards and indicates design problem points. The author pointed out the problems specific to those PCBs, and suggested measures besides those which were discussed in the literature on design of mixed signal boards. This paper analyses the most popular design mistakes and demonstrates their impact on signal measurements. These mistakes are illustrated by examples from real life, which were corrected by the author during his career at various companies. These illustrations will be extremely useful for practicing engineers, and help them to easily identify design errors at the stage of prototyping.

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