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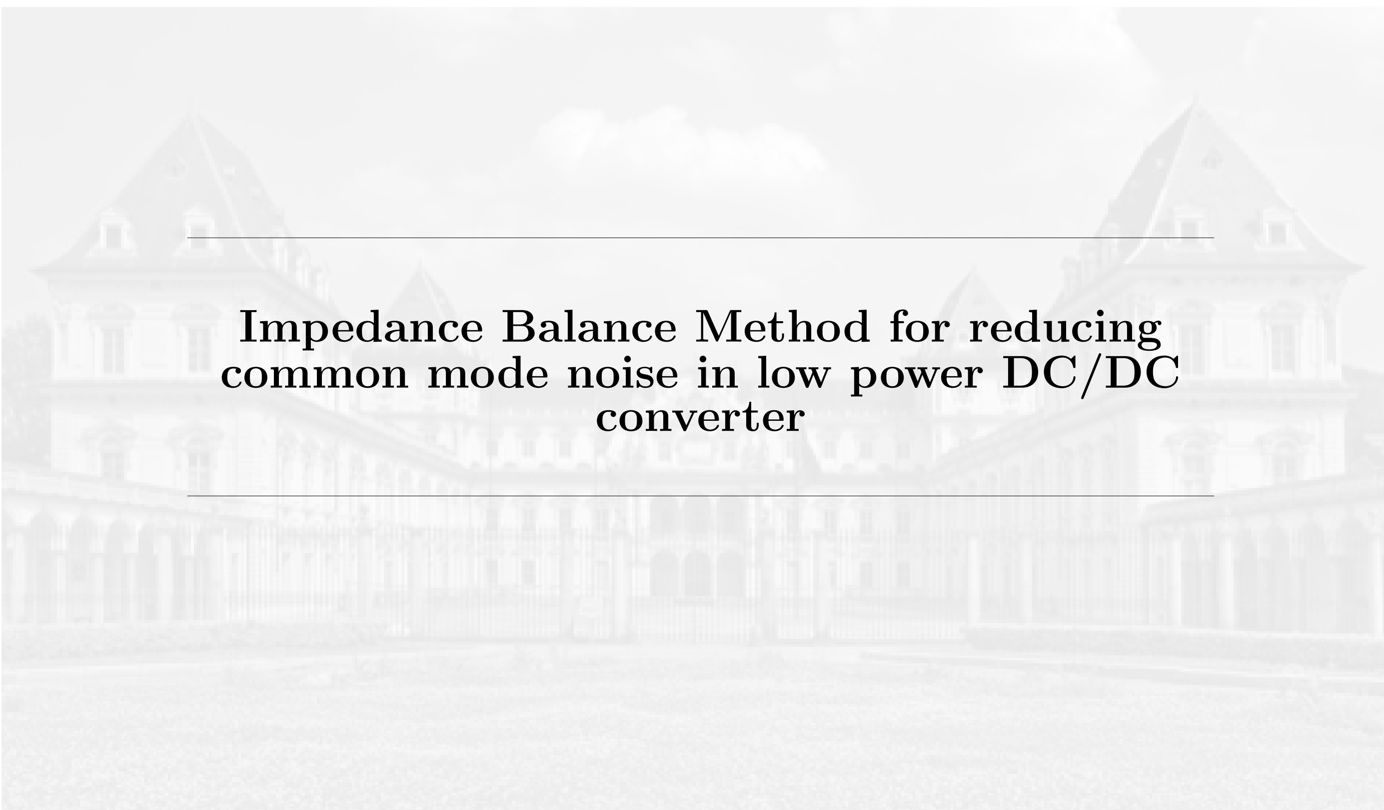

Impedance Balance Method for reducing common mode noise in low power DC/DC converter

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Acronyms

AC	Alternative Current
CISPR	Comité International Spécial des Perturbations Radioélectriques
CM	Common Mode
DC	Direct Current
DM	Differential Mode
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMS	Electromagnetic Susceptibility
FAT	Frequency Amplitude Time
FCC	Federal Communication Commision
IEC	International Electrotechnical Commision
IGBT	Isolated Gate Bipolar Transistor
JFET	Junction Field Effect Transistor
LISN	Line Impedance Stabilization Network
LPF	Low Passive Filter
MRA	Mutual Recognition Agreement
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PCB	Printed Circuit Board
PFC	Power Factor Corrector
RC	Resistor Capacitor
RL	Resistor Inductor
SiC	Silicon Carbide
SMD	Surface Mounted Device
SMPS	Switch Mode Power Supply
US	United States (of America)
UUT	Unit Under Test
VNA	Vector Network Analyzer

Chapter 1

Introduction

This work makes use of the impedance balance method to decrease common mode conducted emissions in a DC/DC converter, in particular the case study is a boost converter.

In the first chapters, conductions modes and emissions are presented and defined via analytical notations. In this manner, electromagnetic compatibility is introduced and explained. Issues about common mode noise are investigated, as well as its causes, with particular consideration to switching mode power supplies. Moreover, basic countermeasures are shown and the topic about suppressing conducted noise is developed with focus on the state of art.

In the last chapters, the case study is designed then simulated in LTspice environment to verify its correct operation. After that, the method is applied and improvements or method's failures are analyzed. In conclusion, there are presented several approaches, considered as further works, that can be used with the impedance balance method.

Chapter 2

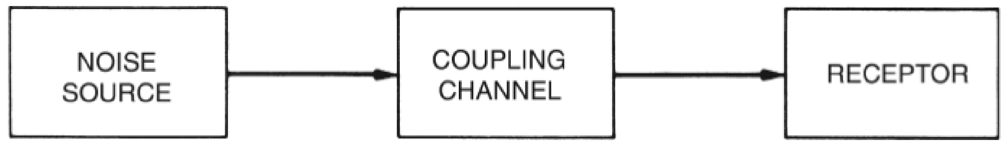
Conducted emission

Cables connected to a device carry unwanted transient signals and other disturbances to other devices. This is a general conducted emission definition. The conducted emissions are measured with voltage and current measurements on the cables. Such measurement methods are also standardized according to the type of test or product.

Conducted emission limitations are intended to mitigate the radiation from alternating current power distribution system, which results from noise currents conducted back onto the power line. Usually, although these currents are small, they are large enough to cause the power line to radiate and become a source of interference. The limits exist below 30 MHz, where most electrical systems themselves are not big enough to be efficient radiators, but the AC power distribution may generate noise. It is therefore reasonable to say that conducted emission requirements are actually radiated emission requirements in disguise. [4] Failures from conducted emissions may also arise within system itself or other other electrical systems in the surrounding.

2.1 Causes

[7] An understanding of the nature of the noise source goes a long way in determining how to mitigate its impact and also to define requirements. Noise can be low frequency, 50 Hz or 60 Hz line frequency coupled for example, or at the switching frequency of the power supply (typically in the 50 kHz to 300 kHz range) or high frequency of switching transitions of power devices which can be in the megahertz range. The understanding of what the designed system may be sensitive to will help determine acceptable solutions.



2.1.1 Typical noise path

A typical noise path is shown in the previous block diagram. Three elements are necessary to produce an interference problem: first, a noise source; second, a receptor circuit that is susceptible to the noise; third, a coupling channel to transmit the noise from the source to the receptor.

In addition, the characteristics of the noise must be such that it is emitted at a frequency that the receptor is susceptible, an amplitude sufficient to affect the receptor, and a interval of time the receptor is susceptible to the noise. A good way to remember the important noise characteristics is with the acronym FAT (Frequency, Amplitude, Time).

The first step in analyzing a noise problem is to define the problem. This is done by determining what is the noise source, what is the receptor, what is the coupling channel, and what are the FAT characteristics of the noise. It follows that there are three ways to break the noise path: (1) the characteristics of the noise can be changed at the source, (2) the receptor can be made insensitive to the noise, or (3) the transmission through the coupling channel can be eliminated or minimized. In some cases, the noise suppression techniques must be applied to two or to all three parts of the noise path. In the case of an emission problem, we are most likely to attack the source of the emissions by changing its characteristics (FAT). For a susceptibility problem, we are most likely to direct our attention to modifying the receptor to increase its immunity to the noise. In many cases, modifying the source or receptor is not practical, which then leads to only the option of controlling the coupling channel.

As an example, consider the circuit shown in figure 2.1. It shows a shielded DC motor connected to its motor-drive circuit. Motor noise is interfering with a low-level circuit in the same equipment. Commutator noise from the motor is conducted out of the shield on the leads going to the drive circuit. From the leads, noise is radiated to the low-level circuitry.

In this example, the noise source consists of the arcs between the brushes

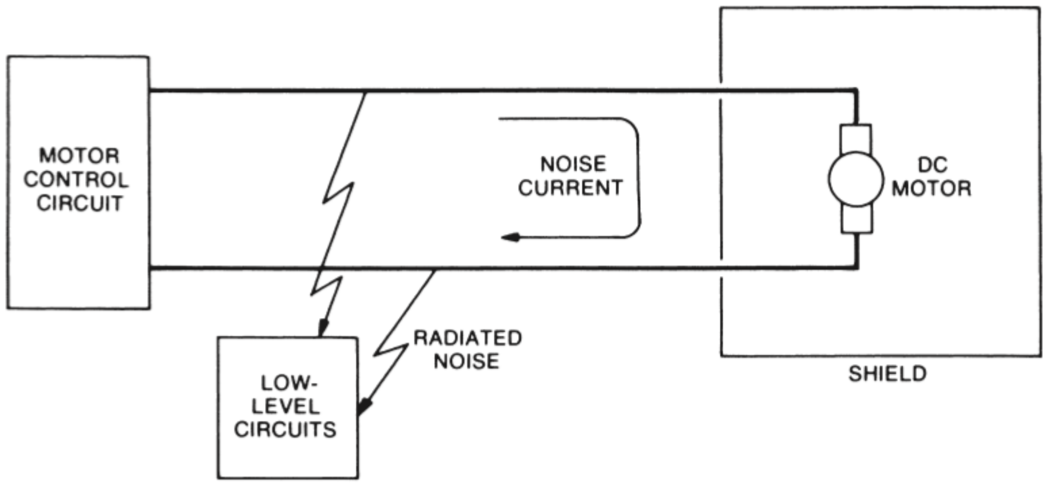


Figure 2.1: Motor-drive circuit

and the commutator. The coupling channel has two parts: conduction on the motor leads and radiation from the leads. The receptor is the low-level circuit. In this case, not much can be done about the source or the receptor. Therefore, the interference must be eliminated by breaking the coupling channel. Hence noise conduction out of the shield or radiation from the leads must be stopped.

2.1.2 Noise coupling

For this work, common mode conducted interference is of interest. Conduction is one of the most obvious, but often overlooked, ways to couple noise into a circuit. A wire run through a noisy environment may pick up noise and then conduct it to another circuit. There it causes interference. The solution is to prevent the wire from picking up the noise or to remove the noise from it by filtering before it interferes with the susceptible circuit.

The major example in this category, as part of the main topics of the thesis, is noise conducted into a circuit on the power supply leads. If the power supply, or other equipment connected to the power supply, cannot be changed, it becomes necessary to decouple or filter the noise from the wires before they enter the circuit. A second example is noise coupled into or out of a shielded enclosure by the wires that pass through the shield.

2.1.3 Electric and magnetic fields

[4] Radiated electric and magnetic fields provide another means of noise coupling. All circuit elements, including conductors, radiate electromagnetic fields whenever a charge is moved. In addition to this unintentional radiation, there is the problem of intentional radiation from sources such as broadcast stations and radar transmitters. When the receiver is close to the source (near field), electric and magnetic fields are considered separately. When the receiver is far from the source (far field), the radiation is considered as combined electric and magnetic or electromagnetic radiation.

2.2 Electromagnetic compatibility

Any electrical system is a possible interference to its surrounding and it is also susceptible to external disturbances. Electromagnetic compatibility (EMC) refers to the correct behavior of electrical systems and it ensures that electrical equipment does not generate, or is not affected by, electromagnetic disturbance. EMC concerns the mutual disturbances that devices establish and it is divided into two parts: electromagnetic interference (EMI) and electromagnetic susceptibility (EMS). The former deals with the electromagnetic interferences emitted by the unit under test (UUT), whereas the latter concerns the immunity of the UUT placed in a noisy electromagnetic environment.

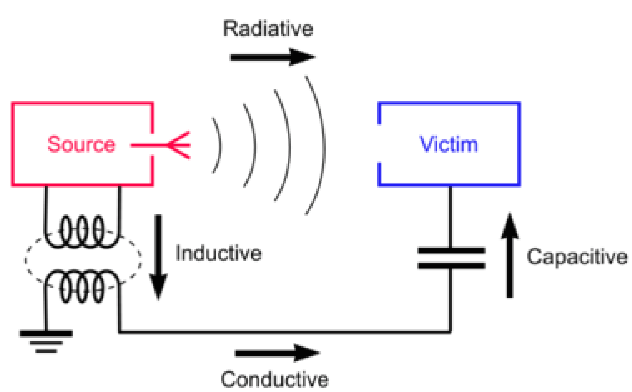


Figure 2.2: Conducted and radiated interferences [1]

When addressing EMC issues, the UUT working in an electromagnetic system should operate without failures and, from another point of view and conditions, the emitted noise generated by a UUT is mitigated. For both EMI and EMS, interferences are divided according to the range of frequency where they are effectively a possible harm. There are different regulations depending on the country and the type of product under test. Usually standards and regulations establish limits for conducted interferences, from 150 kHz to 30 MHz, while for radiated interferences restrictions are made from 30 MHz to 1 GHz.

2.3 Regulations

In order to sell a electrical product, EMC requirements must be met. The procedure for regulatory compliance depends on the product type and market standards. It usually consists of three steps [3].

- Verification: the product is tested to the applicable EMC standard.
- Declaration: of conformity - the responsible party declares conformity of the product.
- Certification: the test report from an accredited laboratory is presented to a third party for examination. If the product complies, it is certified.

It is important to target the markets around the world because different rules apply depending on the country. A product may complete EMC testing for Europe but may require other tests to be sold in Canada. Strict additional conditions may apply depending on the type of product (automotive, medical, military), emission and immunity limits of radiation and conduction. In the US, the Federal Communications Commission (FCC) is the government agency that imposes requirements on the placement of electrical products on the market, whereas European standards are regulated by the Comité International Spécial des Perturbations Radioélectriques (CISPR), part of the International Electrotechnical Commission (IEC). Fortunately, mutual recognition agreements (MRA) leverage EMC testing to cover larger geographical or market areas. In the case of conducted emissions, FCC and CISPR limits are the same. The following image shows masks of limits for two types of detection mode, quasi-peak and average, for class A (commercial, industrial, business) and class B (residential) products. [4]

2.4 Switching Mode Power Supplies

Nowadays, switching mode power supplies (SMPS) have replaced most linear supplies. Switching mode converters bring many benefits to power supply systems. SMPS operate with great efficiency, output voltage can be increased (with a linear regulator there is always the voltage drop), they can

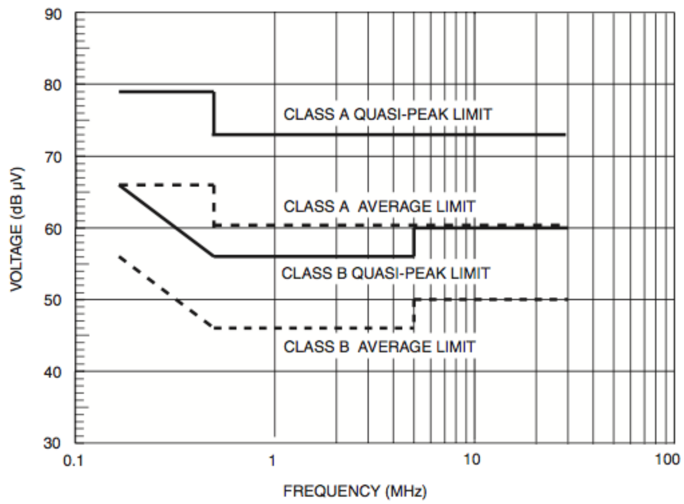


Figure 2.3: FCC/CISPR limits for conducted emission [4]

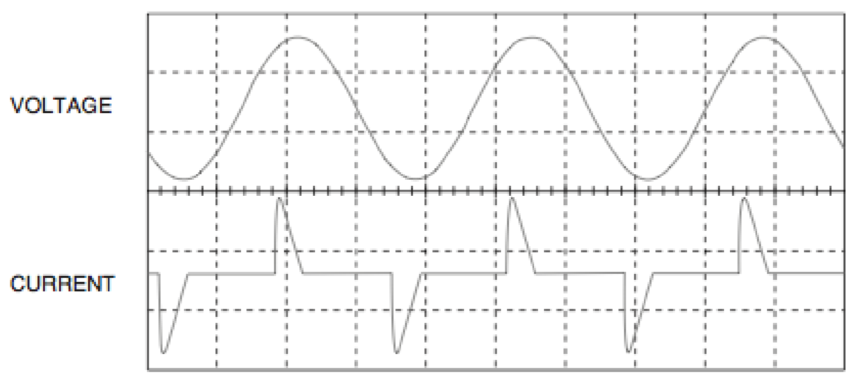


Figure 2.4: SMPS input waveforms [4]

be isolated, they can have multiple outputs and universal AC input (there is no mechanical switch to select 150 V or 230 V like in some old travel hairdryer), their components are usually smaller and cheaper. Anyhow, linear supplies are fast to react and do not generate electromagnetic noise. While, SMPS's design and control are not trivial tasks, and the fast time-transitions of voltages and current create substantial interferences.

Furthermore, the full wave rectification of the input AC voltage results in current spikes on the power line as the input filter capacitor recharges. Since the current is not drawn over the entire cycle, the current waveform is rich in harmonics. This can cause overheating in transformers and in three-phase power distribution systems it may produces excessive neutral conductor currents. The pulsating current may also have a much larger peak amplitude than a sine wave would have for the same power rating. To prevent hazards and mitigate distortion, harmonics magnitudes are regulated too. [8]

Typically DC/DC converters are power stages and control circuitry to regulate the output voltage. Moreover, power supplies consist of an AC/DC rectification stage followed by a high frequency switching DC/DC converters.

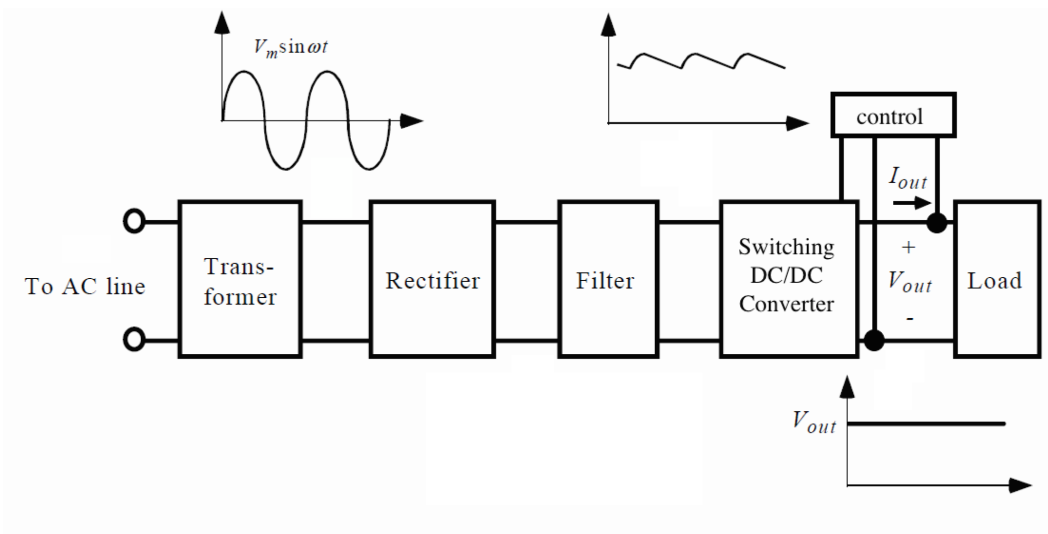


Figure 2.5: Stages in typical DC/DC SMPS

As it was discussed before, noise from the power supply mainly originates from the switching power semiconductors. Switch mode power supplies are much more efficient, smaller and more economical than linear power supplies they have displaced during the past few decades. Power supply designers have made improvements in reducing noise generated in the power supply from leaking out to connected or nearby equipment. But noise is still a challenge and common mode noise is often overlooked. [4]

By nature, switching power supplies work with steep variations in time of currents and voltages in order to achieve high efficiency, reduced size and cost. With parasitic capacitance as part of the product due to the nature of physics of materials, we have a natural high harmonic noise source within the power supply.

2.4.1 Technology

Depending on technology and power level, SMPS operate at much higher frequency than the AC input's. For small converters with power less than 100 W, operating frequency is in the range of 1 MHz down to 250 kHz and MOS technology is used. Moreover, for higher power, lower frequencies are involved: from 100 W to 1 kW, frequency goes from 100 kHz to 10 kHz and IGBT technology is preferred. The switching voltages of converters resemble square waves and generate noise currents at harmonics of the operating frequency. [9] Silicon semiconductor has traditionally been

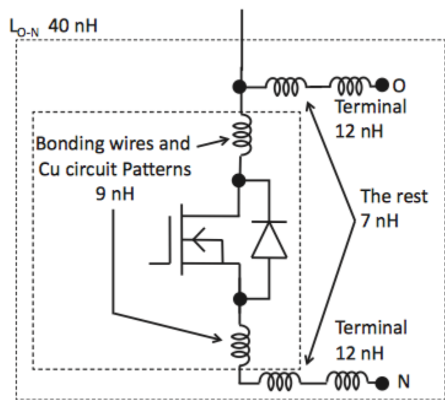


Figure 2.6: Stray inductances in power MOSFET

employed in fabricating power circuits. However wide band gap semiconductors, e. g. aluminum nitride, gallium nitride, silicon carbide, etc., have shown the capability to meet higher performance demands of the evolving power equipments. The advantages include better efficiency (less switching losses), reduction in system volume and weight (more power density), improved electrical characteristics, such as speed and reliability.

Moreover silicon carbide is superior to silicon in terms of greater electric-breakdown field strength, higher thermal conductivity, higher power density, and promises a further improvement of the attainable system efficiency [10]. In addition, the switching speed of SiC devices can be two to six times higher. Due to the steep variations in time of power device's current and the presence of stray inductances (figure 2.6), voltage overshoots can be generated as shown in figure 2.7. Previous research has shown that in specific circuit configurations, the high-frequency noise level of an SiC JFET-based motor drive system can be 20 dB higher than that of a comparable Si insulated gate bipolar transistor (IGBT) based motor drive. [11] Therefore, when using wide band gap devices which leads to higher operating frequency, high frequency harmonics have larger magnitudes and EMI issue should be

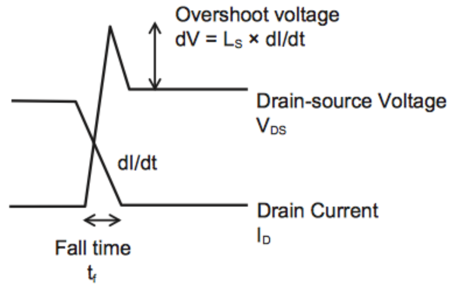


Figure 2.7: Voltage overshoot due to stray inductances

carefully analyzed.

2.5 Conduction modes

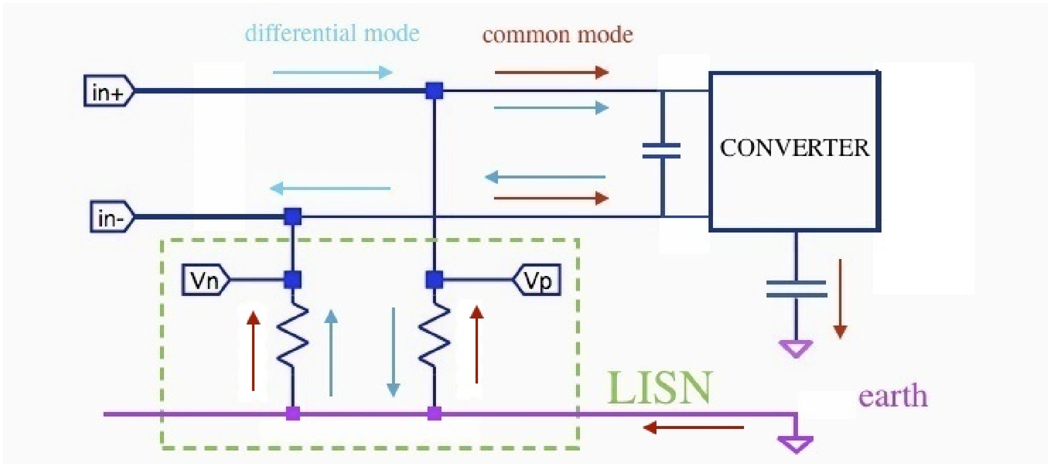


Figure 2.8: Common mode and differential currents in SMPS

SMPS generate significant conducted electromagnetic interference in a broad spectrum and interference must be suppressed to an acceptable level. Thanks to their efficiency and small size, SMPS are widely used and noise issue should be addressed as an important stage of SMPS's design. The line impedance stabilization network (LISN) is a device used in EMC tests for measurements.

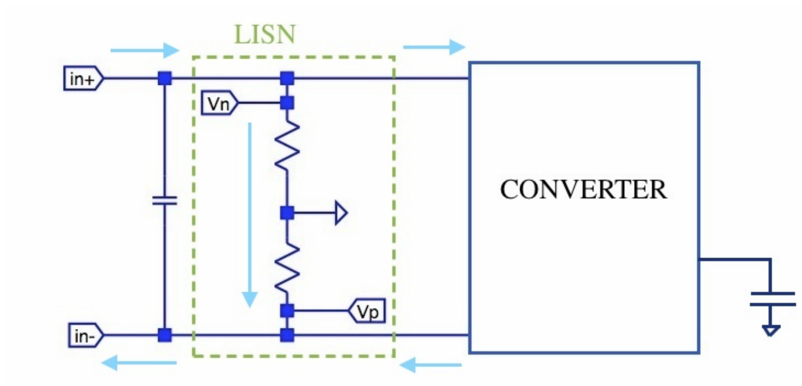


Figure 2.9: Equivalent circuit for differential mode conduction

EMI noise is classified into two types of conduction. Differential mode (DM) currents flow though positive and negative lines in opposite direction, while common mode (CM) currents flow in the same direction on lines and in opposite direction via earth. Referring to figure 2.8, it is possible to represent the schematic by two equivalent circuits that consider separately the condition modes. [12] EMI currents are injected into the input source and most

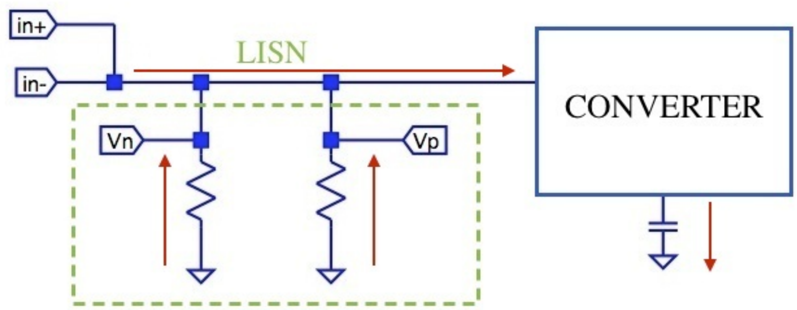


Figure 2.10: Equivalent circuit for common mode conduction

often it is necessary to design an EMI filter to mitigate interferences and meet regulations. Passive EMI filters are basic countermeasures and they are widely used. As a result of the high content of EMI from SMPS, the size of EMI filter is usually up to 1/4 of the whole system. Hence, in order to improve power density, EMI filter size should be reduced.

Usually common mode noise is higher than the differential one between tens of kilohertz to tens of megahertz. The major contributor to common mode noise in SMPS is the parasitic capacitance between the switching node and the earth reference. This is most often the capacitance between the switch's drain and heat sink and, in cases of isolated converters, winding and interwinding capacitances of transformers.

2.5.1 Definitions

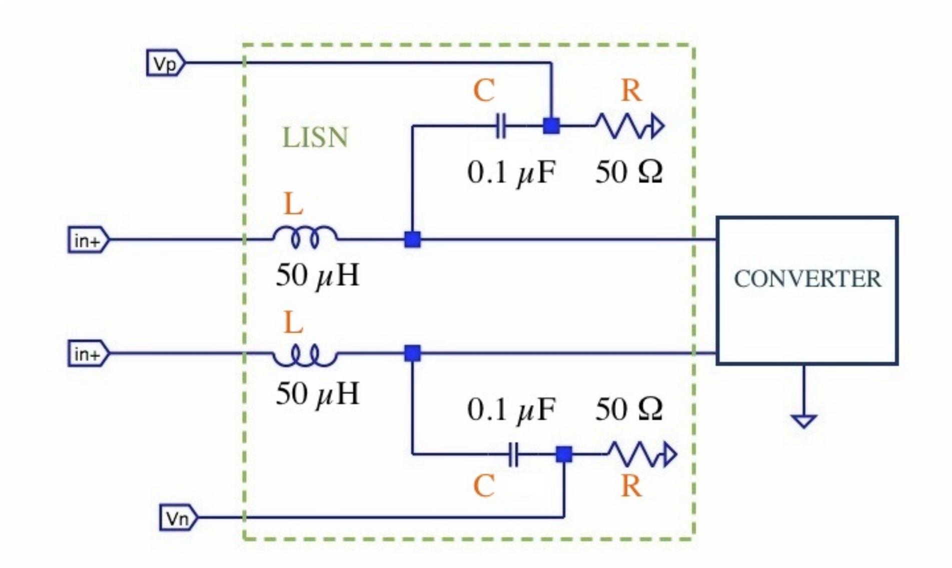


Figure 2.11: Voltages definition

Referring to figure 2.10, common mode voltage is defined. The currents and voltages of the measuring instrument (LISN) are of interest. For next considerations, common mode voltage is expressed as

$$V_{cm} = V_p + V_n \quad [1] \tag{2.1}$$

whereas differential mode voltage can be defined as

$$V_{dm} = V_p - V_n \tag{2.2}$$

For common mode conduction, it is important to remark that at the input side of the converter and at the output of the main power source (i. e. between the LISN), there are large capacitors that have low impedance above few kilohertz.

Then, with the shown schematic of figure 2.11, it can be derived that the equivalent LISN resistance becomes 100 Ω for common mode conduction and 25 Ω for differential mode conduction. Next pictures better show equivalent circuits of figure 2.11, these circuits consider separately common mode and differential mode.

[1] In literature, a "$\times\frac{1}{2}$" factor is sometimes used. Since for this work the difference between one configuration to other is analyzed, multipliers are not important.

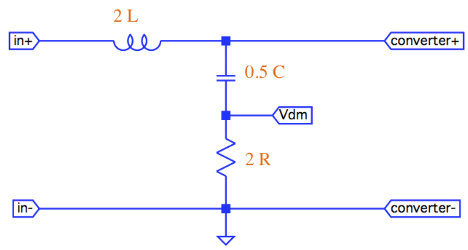


Figure 2.12: Equivalent circuit for differential mode

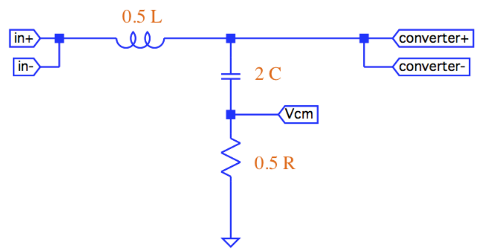


Figure 2.13: Equivalent circuit for common mode

2.6 Line impedance stabilization network

Sometimes referred to as an artificial mains network, the LISN is used to measure disturbance voltages in the mains' power lines. It is placed between the UUT and the power lines in order to present a known impedance to the UUT's power terminals over the frequency range of EMC tests.

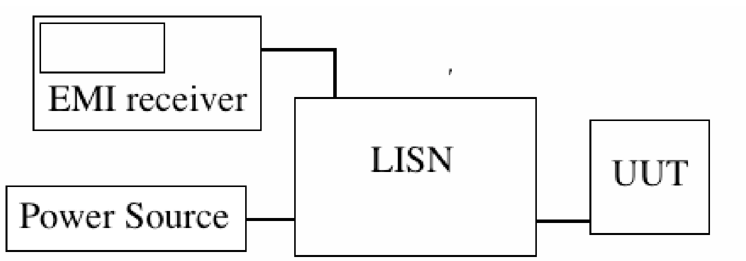


Figure 2.14: Measurement setup for conducted interferences

Chapter 3

Common mode noise issue

Common mode noise may be a harmful electrical interference within the earth/chassis frame. The electrical noise, composed of high frequency spikes with high voltage excursions, may reside on either the positive or the negative wire with respect to earth.

The inherent problem associated with SMPS is electromagnetic interference noise arising due to the high switching transition rate. This interference propagates within the system via common and differential modes and it may also be an issue for radiation. The main coupling path for the CM noise is provided by parasitic capacitance occurring between the switching node and earth.

3.1 Countermeasures

EMC countermeasures refer to electronic components used against noise. The traditional ones are passive components, such as capacitors and inductors. These component then provide no isolation, no gain, losses, bulky. Anyhow, view the benefits of high-frequency SMPS and their related EMC issues, active topologies and other EMC improvements are often used.

3.1.1 Basic and general noise improvements

[13] Standard countermeasures to improve noise levels are components that can be attached additionally. Depending on the strength of attenuation on an electrical characteristic, basic countermeasures can be classified as follows.

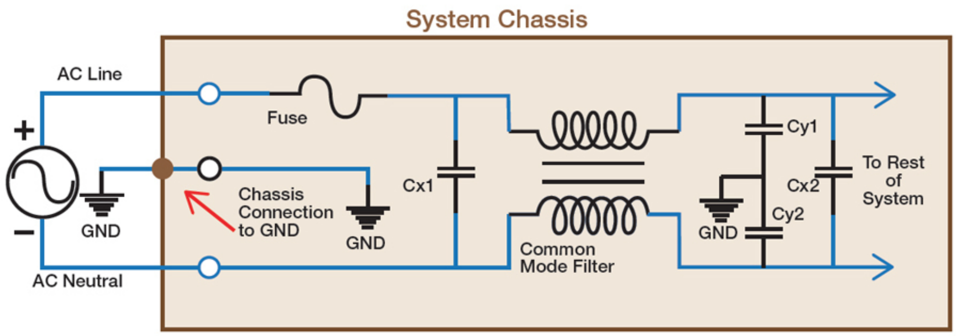


Figure 3.1: AC filter [22]

Separating noise according to frequency

Generally, noise has high frequency components and, therefore, it can be separated by making use of its harmonic content. An EMC countermeasure component in this case can be called an LPF (Low Pass Filter). A inductor, a bead, a capacitor, a three-terminal filter, etc. are classified as LPFs. For obtaining sharper attenuation characteristics, a three-terminal filter can be made by combining a coil, bead, and a capacitor, and an RC filter can be made by combining a resistor and a capacitor (which are both cheap).

A filter for an AC power line is typical of such filters and it is show in figure 3.1. It can be made by combining capacitors and a common mode filter, which can be replaced by a coil. The capacitors of the AC filter are often called X and Y capacitors. Those letters refer to the figures the capacitors form when connected. The X capacitors are used for DM currents while Y capacitors are meant for CM currents. Moreover, sometimes these capacitors are called safety capacitors too. They are a class of capacitors that are intended to be connected across the AC lines. Due to this connection, if they were to fail in a shorted condition, no shock hazard is created since they have no connection to the chassis.

According to modes

When the transmission mode of noise is different from that of information (necessary signals), noise and information can be separated from each other according to the difference in their mode. For example, in differential transmission, necessary signals are in the differential mode, and, normally, unnecessary components are in the common mode (information may be put in the common mode, depending on standards.) A common mode filter, ferrite core, and a transmission transformer are components for suppressing such common mode components. Clamp filters are also included: they consist of

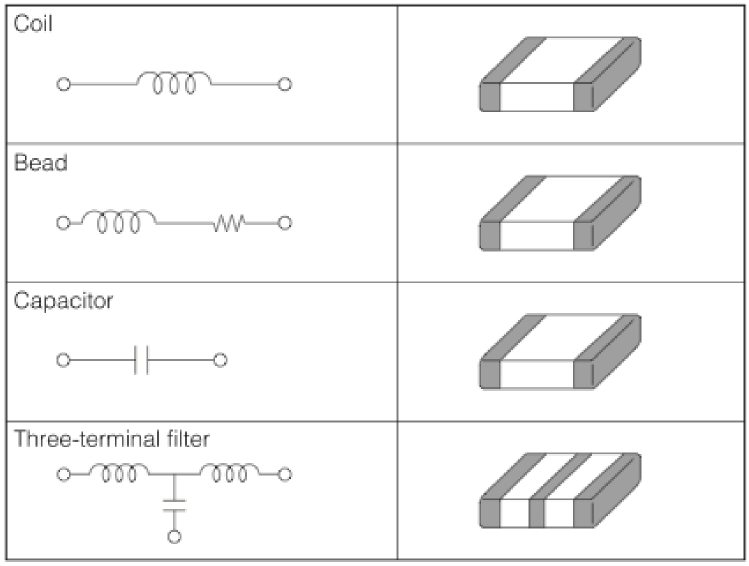


Figure 3.2: Components that separate signals according to their frequencies [13]

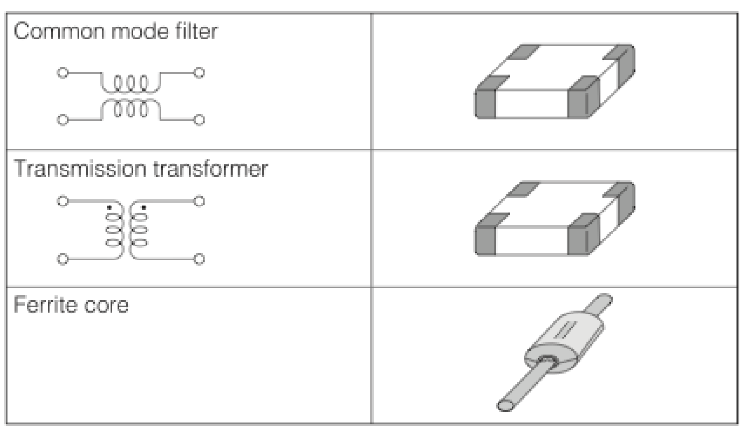


Figure 3.3: Components that separate signals according to their modes [13]

two semi-circle ferrite cores encased in a plastic body and they can be easily mounted onto a cable in a single operation, without cutting the cable. All of these components use magnetic coupling in an effective way so that they do not affect the differential mode and act only on the common mode. Furthermore, these components are inserted into series circuits. In other cases both differential mode and common mode noise have to be reduced. A common mode filter is still a good choice, for instance a common mode choke, but its leakage inductances have to be larger enough to attenuate differential currents too. This is because the equivalent impedance for differential mode of coupled inductors manly consists of leakage inductances.

According to amplitudes

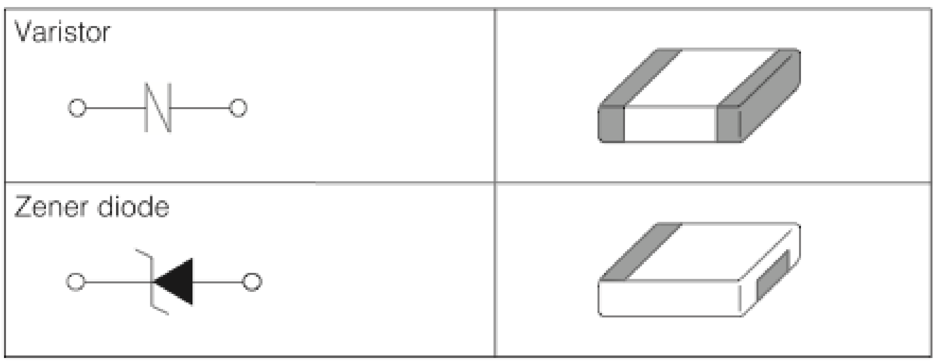


Figure 3.4: Components that separate signals according to their amplitudes [13]

EMC issues can be created from high voltages and high currents. There are devices that work only when high electrical magnitudes are generated. For instance, a varistor and a zener diode do not act on signals with low amplitudes, but they transform themselves into an extremely low resistance when high voltage (noise) occurs, and they prevent the noise from being transmitted. They exert an effect on sudden noise, such as static electricity. These parts are inserted into shunt circuits.

3.1.2 Common mode noise improvement

A brief list for minimizing common mode noise is presented. [7] These next techniques mostly act on external parts of the system as previous ones. With these approaches, the noise source is left within its stage or system, and countermeasures components are connected additionally to mitigate noise level and its propagation.

- Use of CM noise filters: this involves time-consuming designs, which are commonly used in many SMPS designs. Usually, in order to gain satisfactory results, a bulky CM noise suppression filter is required. This is becoming more undesirable as the product size is shrinking and the filter actually lies on the power path. Attention should be paid to the size of the CM choke filters and SMD CM choke designs. Although the size of the CM choke is small, the result is only effective from
1 MHz or above, therefore the low frequency cannot be suppressed. The problem remains with use of large size CM choke to tackle the low frequency end up to 1 MHz. CM choke filter design is furthermore emphasized because it is often difficult to design a low power loss, minimal size filter. An active CM filter is then proposed to try to further reduce the CM noise. Although this way the designer has greater flexibility to fine tune the CM filter than just use the passive component alone, the effect of such active filter is not easily modeled and the gain bandwidth is influenced by the active component.

- In case of isolated SMPS, the parasitic coupling capacitance from the primary winding of transformer to the secondary winding should be minimized.

- Bypass capacitors: the role of Y capacitors on common mode noise has been discussed, furthermore their applicable capacitances are always limited by safety standards and this method alone usually cannot provide a low enough impedance to shunt all the CM current flowing along this path.

- Faraday shielding: the method requires careful integration of a piece of conducting sheet into the transformer to shunt away noise current. This is not always effective because there are many paths from which the CM noise current can go through. The shield must be properly installed in order to meet the safety requirement.

3.2 State of art

Standard countermeasures (passive filters) to reduce noise levels consist in indeed more volume, weight, money, losses to SMPS systems. Furthermore, EMI filters work well in low megahertz range but their performances get worse at higher frequencies due to parasitic effects. In order to fix this issue, more sophisticated approaches have been developed during the last 20 years. They can be categorized in four groups: filters, shielding, impedance, and symmetry. Actually, this last refers to balanced impedances and symmetrical structures. Moreover balanced impedances and symmetrical structures lead to current/voltage cancellation concept.

3.2.1 Active filters

There are several advantages of active filters over passive ones:

- Less cost due to the variety of cheaper op-amp combined with smaller passive components.
- No loading problem: active filters provide an excellent isolation between the individual stages due to the high impedance, ranging from a few kilo ohm to a several thousand mega ohm, and low output impedance, ranging from less than 1 ohm to a few hundred ohm.
- Size and weight are smaller in size and less voluminous.

3.2.2 Shielding

This part is an in-depth continuation of noise countermeasures. In fact, shielding protects electric equipments from electromagnetic radiation and near-field too. Nevertheless, radiative noise can sometimes be related to conducted emissions and a full understanding of system's electromagnetic behavior helps design.

A shield is a metallic partition placed between two regions of space. It is used to control the propagation of electromagnetic fields from one region to the other. Shields may be used to contain electromagnetic fields, if the shield surrounds the noise source. This configuration provides protection for all susceptible equipment located outside the shield. A shield may also be used to keep electromagnetic radiation out of a region. This technique provides protection only for the specific equipment contained within the shield. From an overall systems point of view, shielding the noise source is more efficient than shielding the receptor.

New module designs have to be optimized for fast switching semiconductors like IGBTs and SiC MOSFETs, in terms of efficiency and EMI. The integration of a common mode EMI shielding is implemented in a ultra-low inductive 600V / 200 A half-bridge power module and large sized common mode filter devices are then avoided. Operating switching frequencies range from 20 kHz and more. Although EMI shielding integration slightly augments noise levels for first harmonics, the common mode noise level can be significantly reduced up to 25 dBμV at frequency of 100 kHz and above.

3.2.3 Impedance

Many noise-reduction methods change the impedance of circuit using parasitic components. A similar procedure to the main topic of this thesis is a "general balance technique". [15] First three noise sources are identified: the high frequency high voltage noise-emitting source (focusing on the switching node and paths for the noise to reach ground), output and input parasitic components. A Wheatstone bridge is used to attenuate noise from the switching node, whereas, in a second step, more balanced configurations of stray components augment even more the noise suppression.

In a similar manner, another technique uses three additional circuits to reduce common mode noise in a totem-pole bridge less power factor corrector (PFC). This last in fact has unsatisfactory noise performance compared with conventional diode-bridge PFC. So, switches are enclosed between additional diodes and inductors, while capacitors are added at the input and output ports. [16]

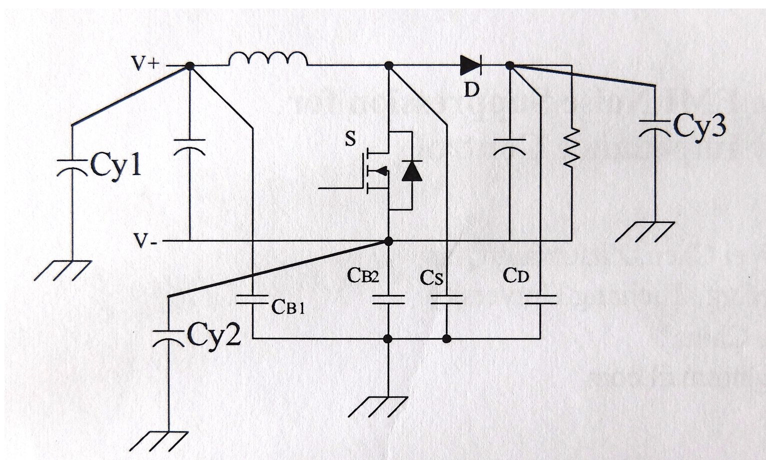


Figure 3.5: Y-capacitors connections to suppress CM noise

Another simple approach, valid for boost, forward, flyback, buck-boost converters, is increasing Y-capacitance, that is lines to ground capacitance. This is because the equivalent capacitance, made up of parallel capacitors in common mode, is inversely proportionated to the voltage noise. [17]

Following this method, an inductor motor drive with three-phase active filter can be analyzed too. [18] In this case, electromagnetic interference is improved by balancing the capacitance of each common mode current loop.

3.2.4 Symmetry

In common mode, symmetrical and balanced structures (such as same sources, receptors, and impedance paths) lead to cancellation of interference. A balanced circuit is a two-conductor circuit in which both signal conductors, and all circuits connected to them, have the same nonzero impedance with respect to a reference (usually ground) and all other conductors. The purpose of balancing is to make the noise pickup equal in both conductors; in which case, it will be a common mode signal, which can be made to cancel in the load, at the measurement equipment for instance. If the impedances of the two signal conductors to ground are unequal, then the system is unbalanced. A circuit with a grounded return conductor therefore is unbalanced, and sometimes it is referred to as a single-ended circuit. Balancing is an often overlooked, although in many cases cost-effective, noise reduction technique. Moreover it can be used, in some applications, as the primary noise-reduction technique. For a balanced circuit to be most effective in reducing common mode noise, not only must the terminations be balanced, but also the interconnection (cables) must be balanced, as well as impedances susceptible to noise sources. [4]

As discussed before, wide bang gap devices provide much better figures of merit compared to silicon devices. With high frequency operation, transformer winding can be realized within the printed circuit board, hence downsize weight and losses. But compared to conventional litz-wire based transformer, the inter-winding capacitance increases significantly due to much larger overlapping area and shorter distance between windings. This forms a low impedance path for common mode current, together with intrinsic high dv/dt and di/dt, CM noise is significant. Anyhow, with no additional hardware, a symmetrical resonant converter with PCB transformer has been studied [19] with focus on EMC. PCB transformer is also implemented in a symmetrical structure in order to cancel out common mode currents of primary and secondary sides.

Another symmetrical structure is shown in the following images. Here, the inductor of a boost converter is split into a coupled inductor. In this manner, the common mode impedance due to the leakage inductance of a coupled inductor can be used to reduce CM noise, which is verified with gapless and gapped core inductors. It has been theoretically explained and experimentally validated that this solution does not affect normal operation of the converter. [20]

Other similar configurations, that use also the benefits of balancing, can be found in [21] for boost and buck-buck topologies.

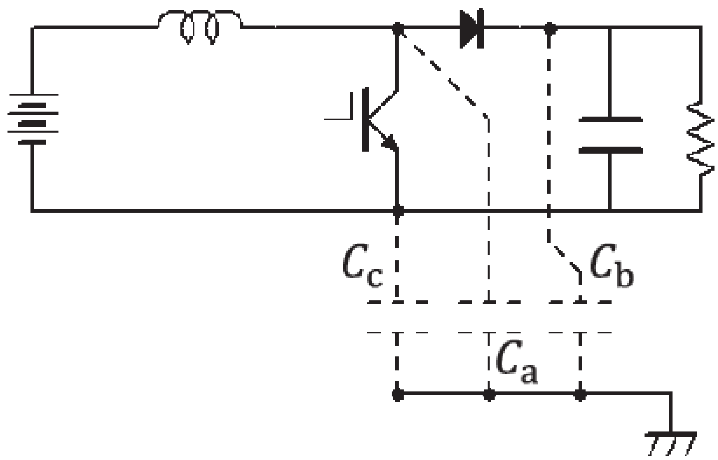


Figure 3.6: Boost converter with conventional inductor

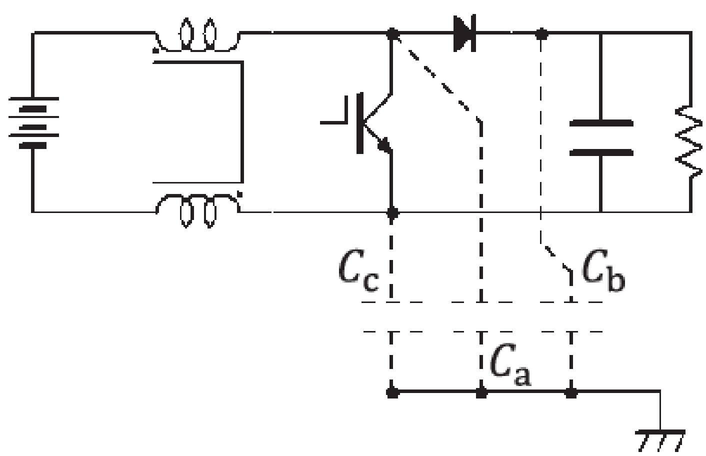


Figure 3.7: Boost converter with coupled inductor

Chapter 4

Aim of thesis

With the present work, it is demonstrated, through analytical representations and simulations, that the impedance balanced method is a valid improvement to decrease conducted common mode noise.

4.1 Impedance balance method

The impedance balance method was proposed by professor Osami Wada from Kyoto University. [5] The key idea of this method is to detect the noise-emitting source and place it into a balanced Wheatstone bridge. This can be done by exploiting the stray components of the converter and by adding other ones to complete the bridge.

In the frame of this work, a boost converter is taken as example, it is designed and analyzed. Moreover, the method is also suited for other topologies of power converter. For next pictures, parasitics components are highlighted in red.

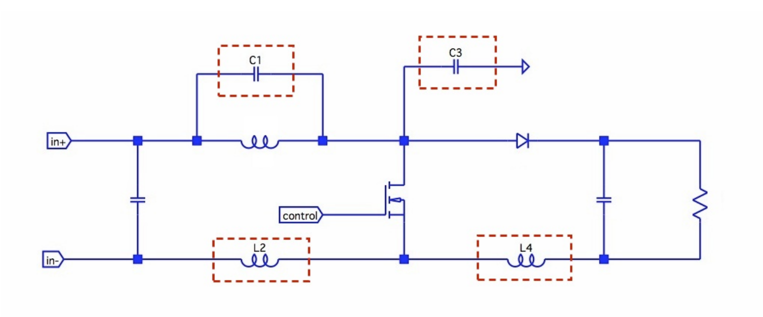


Figure 4.1: Boost converter with parasitics

The node in common to the switches and the inductor is where noise is generated. The diode and the switch form the noise-emitting source, while the inductor's stray capacitance, drain-to-ground capacitance and trace inductances constitute part of the impedances of the bridge.

To complete the bridge, Y-capacitors are added to the converter's output. These are usually used to enhance common mode noise filtering but their values are limited because they carry leakage currents.

4.2 Wheatstone bridge

In order to attain a Wheatstone bridge configuration, a voltage source is defined. It will be shown later how both switch and diode are parts of this source. Referring to figure 4.2, if the impedances of the bridge are balanced according to

$$\frac{Z_1}{Z_3} = \frac{Z_2}{Z_4}$$

the voltage transfer ratio from the noise-emitting source to common mode voltage $\frac{V_{out}}{V_{source}}$ becomes zero.

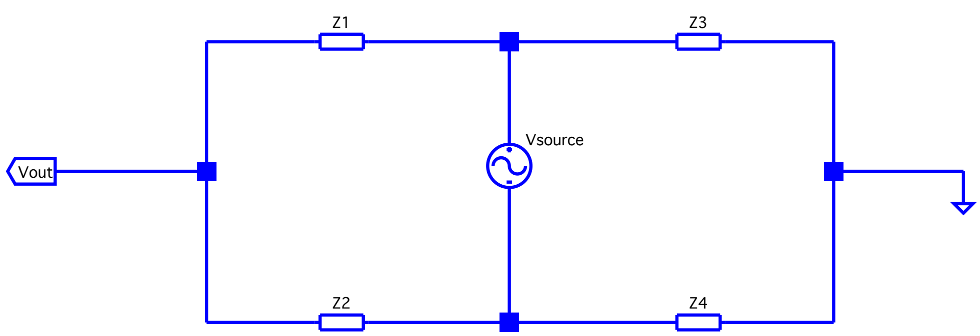


Figure 4.2: Wheatstone bridge

4.3 Method application

The impedance balance method comes from a common configuration, the Wheatstone bridge, which is not difficult to design. Once defined the noise-emitting source, a bridge structure should also be attained.

For the case study of this thesis, boost's inductance between input and output capacitors is decreased at the expense of the inductance between switch's source and output capacitor. Hence at the MOSFET's source, there is a larger inductance when the method is applied. The following images show the changes in the case of a boost converter and how to properly design connections.

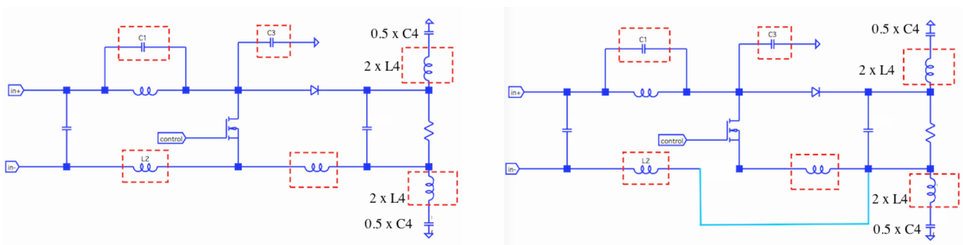


Figure 4.3: Connections in boost converter to get Wheatstone bridge

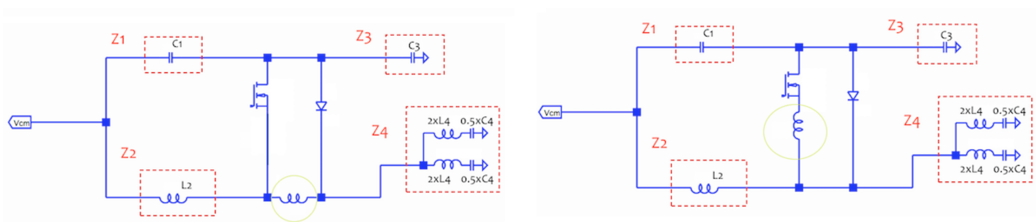


Figure 4.4: At high frequency. Left figure cannot be considered a Wheatstone bridge

At high frequency large input and output capacitors have low impedance, whereas converter's inductor acts as an open circuit. The schematics are illustrated and the components that form the bridge circuit are highlighted.

Impedance balance method can prevent switching voltage from propagating in common noise. In fact, if the impedances of the bridge are balanced, i.e. $\frac{Z_1}{Z_3}=\frac{Z_2}{Z_4}$, common mode voltage V_{cm} at the input side is nulled. Referring to figure 2.5, in order to balance the bridge:

$$sL_2sC_1 = (sL_4 + \frac{1}{sC_4})sC_3 \tag{4.1}$$

$$sL_2C_1 = sL_4C_3 + \frac{C_3}{sC_4} \tag{4.2}$$

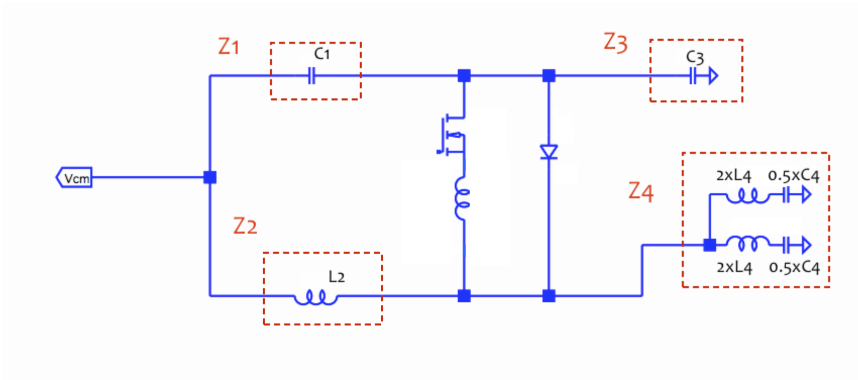


Figure 4.5: Equivalent bridge circuit for common mode conduction

$$\frac{L_2}{L_4} = \frac{C_3}{C_1} \quad (1) \tag{4.3}$$

Equation (1) is now called the balance condition and it is only valid at high frequency. This is an approximation for high frequency, where capacitance impedance becomes small compared to its inductance part.

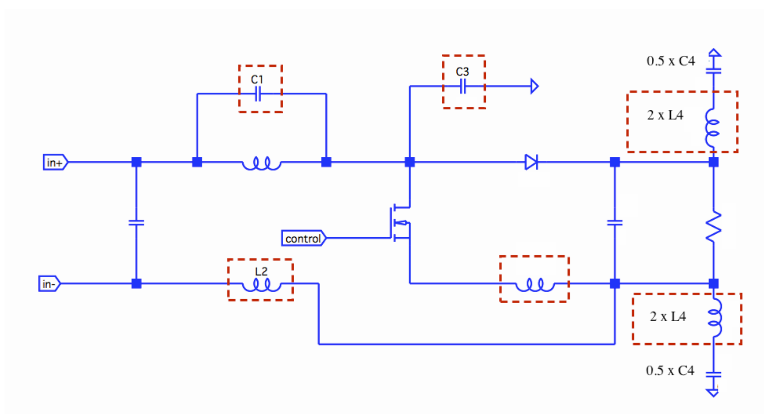


Figure 4.6: Boost converter with impedance balanced method

Chapter 5

Case study: boost converter

A low power DC/DC boost converter is designed and analyzed for this work. As it has been discussed before, the method itself and its similar ones work well in other topologies. It is here presented the design of the converter, starting from listed specifications below. These specifications are arbitrarily chosen in order to have a working converter to analyze with the use of the impedance balance method.

In LTspice environment, the normal operation of the converter is verified. Later, the effects of the application of the method are shown via Fourier Fast Transform in a wide range of frequency (from tens of kilohertz to tens of megahertz). Always in simulations, common mode voltage at the input port of the converter is measured though a LISN.

5.1 Design

The converter is attached to the European mains and provides a maximum power of 72 W. For this study, the aim is to prove that the impedance balance method is a good solution to mitigate EMC issues and standards' requirements are not of interest. To respect regulations with a good margin, it is usually necessary to add an EMI filter too. In the following list, there are presented the main characteristics of the converter:

- 50 kHz operating frequency f
- 30 V input rectified voltage V_{in}
- 50 Ω to 100 Ω output load R
- Continuous current mode
- Output voltage limited by duty cycle, from 42.8 V to 60 V

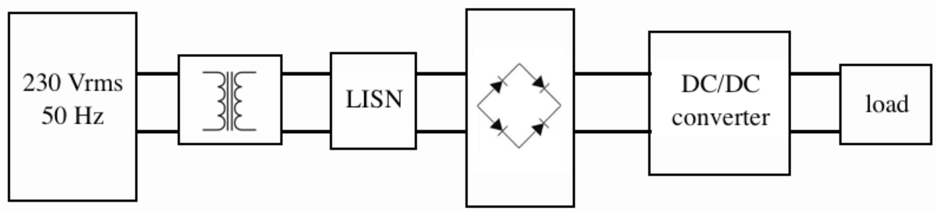


Figure 5.1: Block diagram of case study

An inductor of 330 μH is chosen in order to operate in continuous current mode. Inductor's peak current is equal to input DC current plus half of the current ripple.

$$I_{L,max} = \frac{V_{out,max}}{R_{min}(1 - D_{max})} + \frac{V_{out,max} D(1 - D_{max})}{2fL} = 2.85 \text{ A}$$

Still using the maximum value of duty cycle, the lower edge of inductor's current is:

$$I_{L,min} = \frac{V_{out,max}}{R_{min}(1 - D_{max})} - \frac{V_{out,max} D(1 - D_{max})}{2fL} = 1.94 \text{ A}$$

With additional requirements for input and output voltage ripples, capacitors' values can be found analytically by the use of equivalent series resistances, zero-frequencies of capacitors, diode's and inductors' currents. Anyhow, capacitors' values are important for control which is not discussed in this work. So, for input and output large capacitors of 1 mF are used for both.

Input capacitor maximum voltage is 30 V, while output capacitor's is 60 V. In addition, voltage ripple is unwanted and it should be minimized. Output voltage ripple is larger than the input voltage ripple because of the nearby diode, hence a low ESR capacitor is a good choice. Output capacitor's stress is derived through a flat top approximation, referring to a rectangular waveform instead of a trapezoid one, whereas input capacitor's current stress is obtained though a parabolic area:

$$I_{Cout,rms} = I_{out,max}\sqrt{\frac{D_{max}}{(1-D_{max})}} = 1.2\text{ A}\sqrt{\frac{0.5}{(1-0.5)}} = 1.2\text{ A}$$

$$I_{Cin,rms} = \frac{I_{L,max} - I_{L,min}}{\sqrt{12}} = \frac{0.91\text{ A}}{\sqrt{12}} = 0.26\text{ A}$$

For the switch and diode, the peak currents and reversed voltage are taken into account.

$$I_{switch,max} = I_{diode,max} = I_{L,max} = 2.85\text{ A}$$

$$V_{switch,rev} = (-V_{out,max} + V_{diode}) = -60\text{ V} + 1\text{ V} = -59\text{ V}$$

$$r_{on} = \frac{V_{switch}}{I_{switch,max}} = 0.53\ \Omega$$

$$V_{diode,rev} = -V_{out,max} + V_{switch} = -60\text{ V} + 1.5\text{ V} = -58.5\text{ V}$$

V_{switch} represents drain-source voltage of the power MOSFET. The main cause of common mode noise generation is the high voltage difference at the drain of the MOSFET that at the frequency switching regimes makes a low impedance path though ground lines. Usually, the important part of this path is the capacitance between switch's drain and heat sink/ground. This capacitance has to be calculated or measured according to the heat sink dimensions, layout, metal planes, harness, etc. It can range from tens of pico farad to tens of nano henry. For this design, it is considered a drain-to-ground capacitance of 15 pF. In the next table, there are the components for the design.

inductor	capacitors	diode	switch
murata ps 60B334C	100V Al	BYV28-100	STP11N60DM2

Inductor's and capacitors' stray components are obtained through datasheet's information: via self resonant frequency for inductor's parallel capacitance and from capacitors' zero-frequencies for capacitors' series inductances (ESR are stated). For what concerns copper trace inductances, they are sized roughly according to their length.

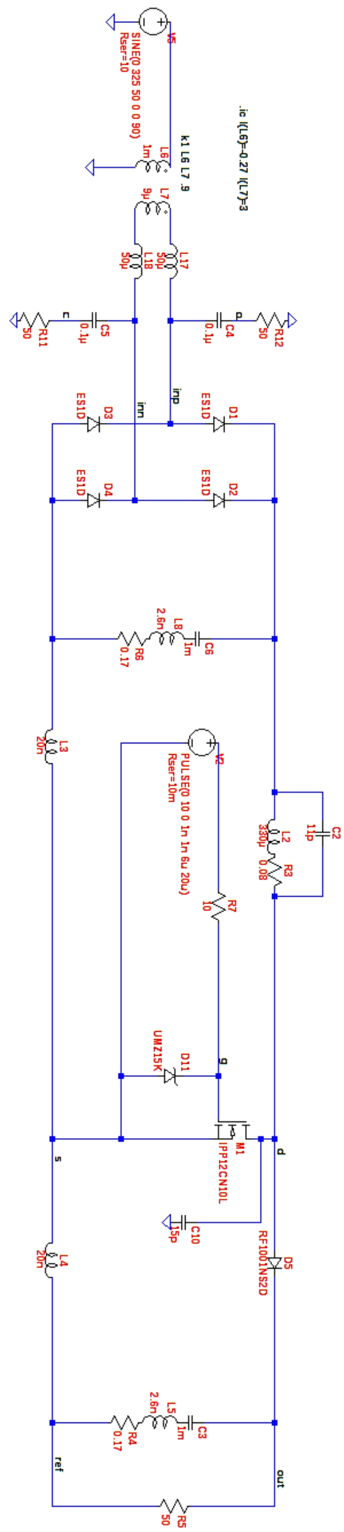


Figure 5.2: Schematic of boost converter with method

Chapter 6

Simulations

Circuits are analyzed in LTspice environment. The AC input voltage is decreased by a transformer that also isolated the converter from the mains. Between the secondary winding and the diode bridge, there is a LISN in order to measure interferences and to provide a known impedance at the converter's input.

Inductor's stray capacitance is calculated through the self resonant frequency (2.66 MHz typical) stated in the component's data sheet. The starting circuit of figure 5.2 is changed in accordance to the impedance balanced method, 220 pF Y-capacitors are added and trace paths are modified, the resulting schematic is shown in figure 6.1.

Y-capacitors' values, inductor's stray capacitance, and trace inductances being set, the balance condition leads to obtain a capacitance 11pF $\cdot \frac{35nH}{5nH} =$ 77 pF$\rightarrow$ 100 pF at the MOSFET's drain.

The stray inductance are sized with an approximation of 2 nH per mm of trace. Of course more advanced tools allow to measure them though PCB layout.

In order to employ the impedance balance method, trace inductance and drain's capacitance are changed to satisfy the balanced condition. Trace inductance can be modified through layout and drain's capacitance can be increased by adding a discrete component.
For all simulations, transient analysis of 5 ms with 1 ns resolution are performed. Fast Fourier transform (FFT) is applied and CM voltages at LISN's resistors are plotted in figure 6.2. It can be noted that the method reduces CM noise by around 10 dB from 50 kHz to 10 MHz. However, at about 30 MHz the method increases interferences because of unwanted resonance at 33 MHz. Figure 6.3 shows the first three harmonics of CM voltages (50 kHz,

100 kHz, 150 kHz) where it can be seen that the method reduces noise by 12 dB.

In order to better understand the effects of Wheatstone's bridge components on the high frequency peaks and overall spectrums, parametric simulations are performed. Moreover, inductor's stray capacitance and Y-capacitors' stray inductances are not easy to change in practice, hence only trace inductance and capacitance at MOSFET's drain are modified. Referring to images of chapter 4 and respecting the balance condition (1), it can be written as follows:

$$\frac{L_2}{L_4} = \frac{C_3}{C_1} \ (1) \quad \rightarrow \quad \frac{L_{trace}}{0.5\ L_{Y-cap}} = \frac{C_{drain}}{C_L}$$

$$C_{drain} = C_L \frac{L_{trace}}{0.5\ L_{Y-cap}} = \frac{11\ pF}{5\ nH} L_{trace} = 0.0022\ \frac{F}{H} L_{trace}$$

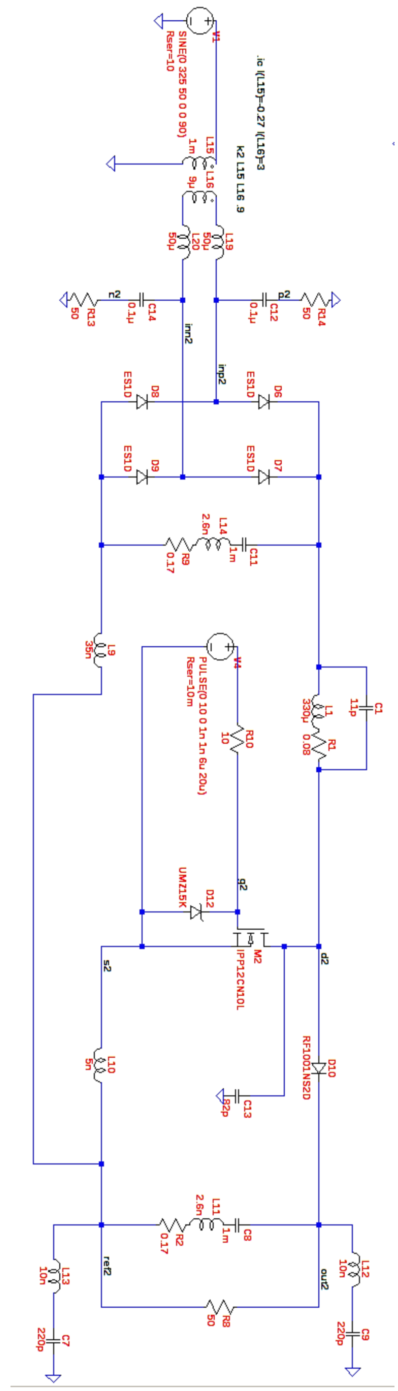


Figure 6.1: Schematic of boost converter with method

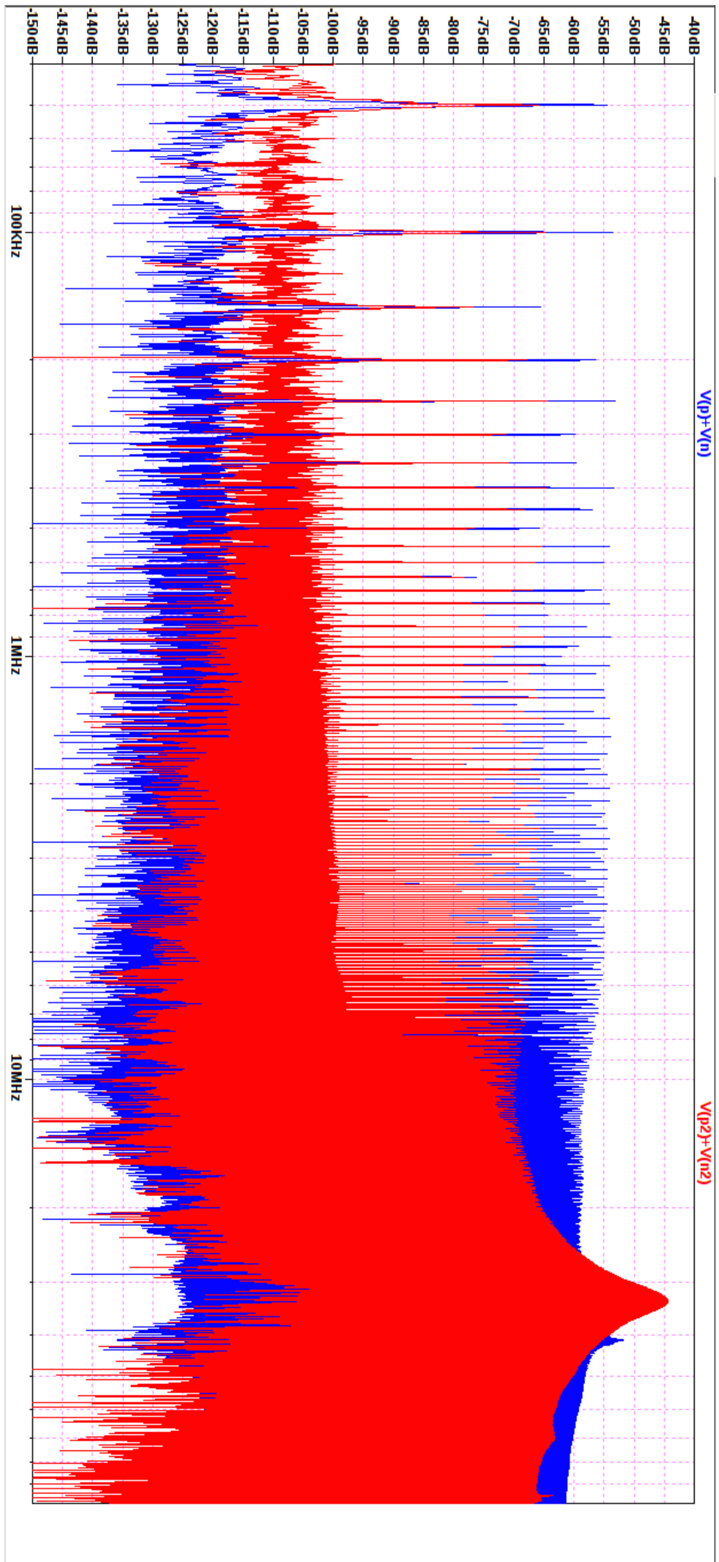


Figure 6.2: FFT of CM voltages: without method (blue), with method (red)

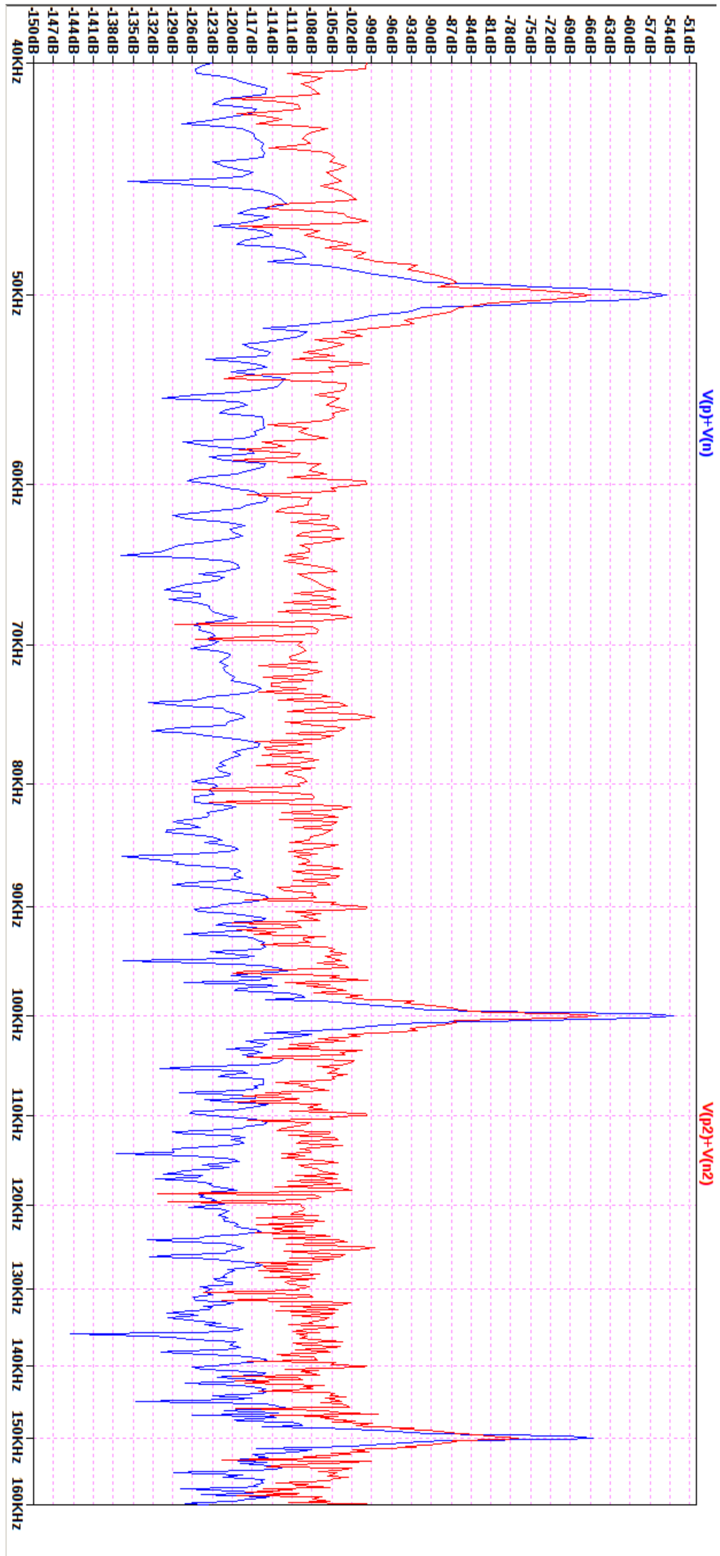


Figure 6.3: First, second, and third harmonic of CM voltages: without method (blue), with method (red)

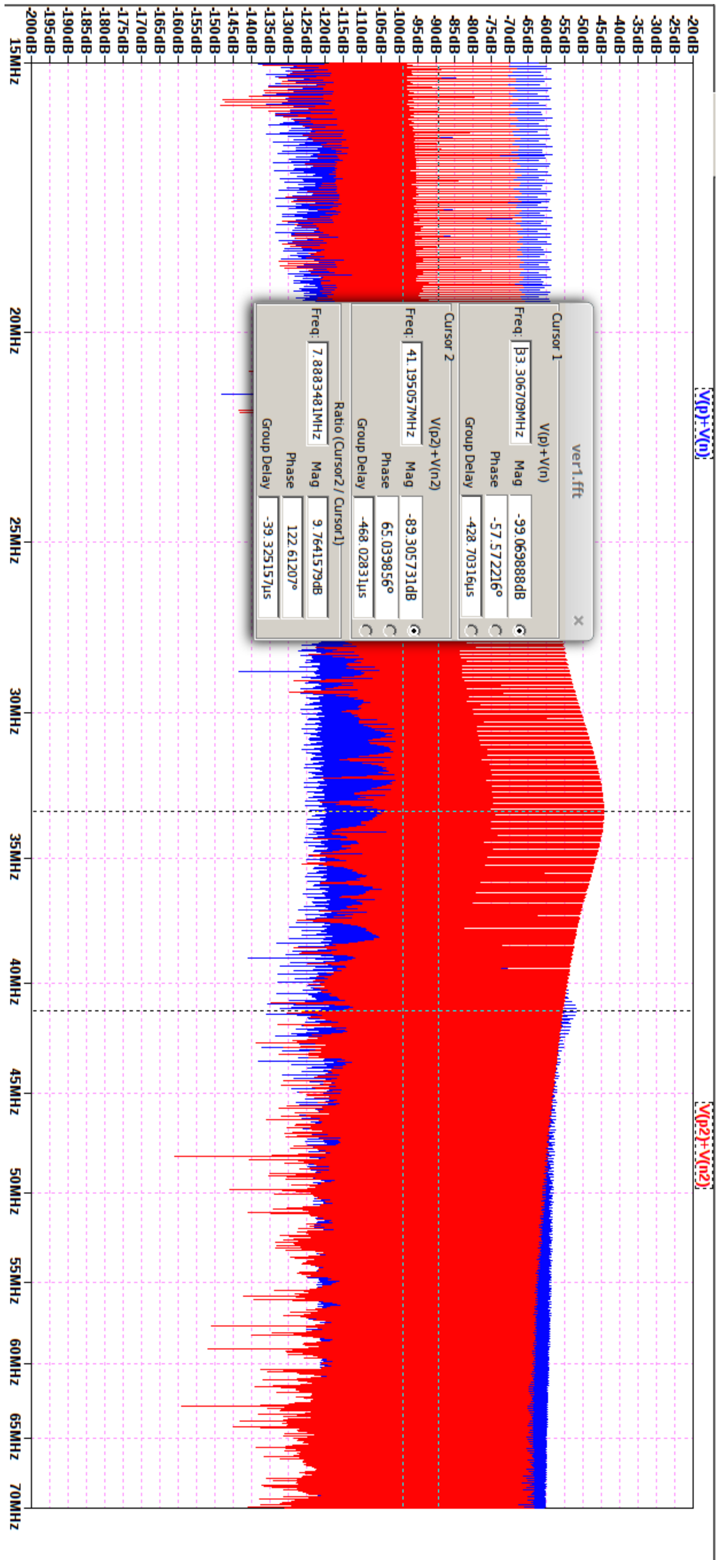


Figure 6.4: High frequency peaks of CM voltages: without method (blue), with method (red)

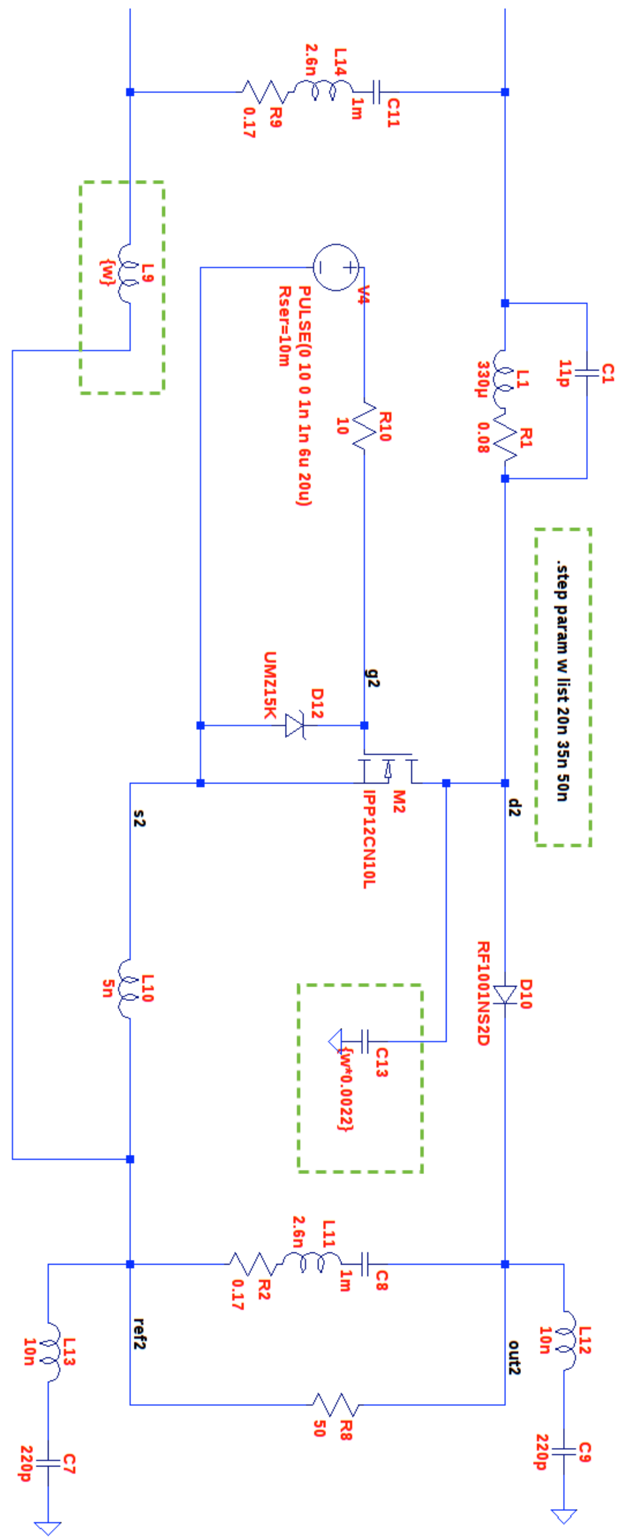


Figure 6.5: Part of parametric schematic

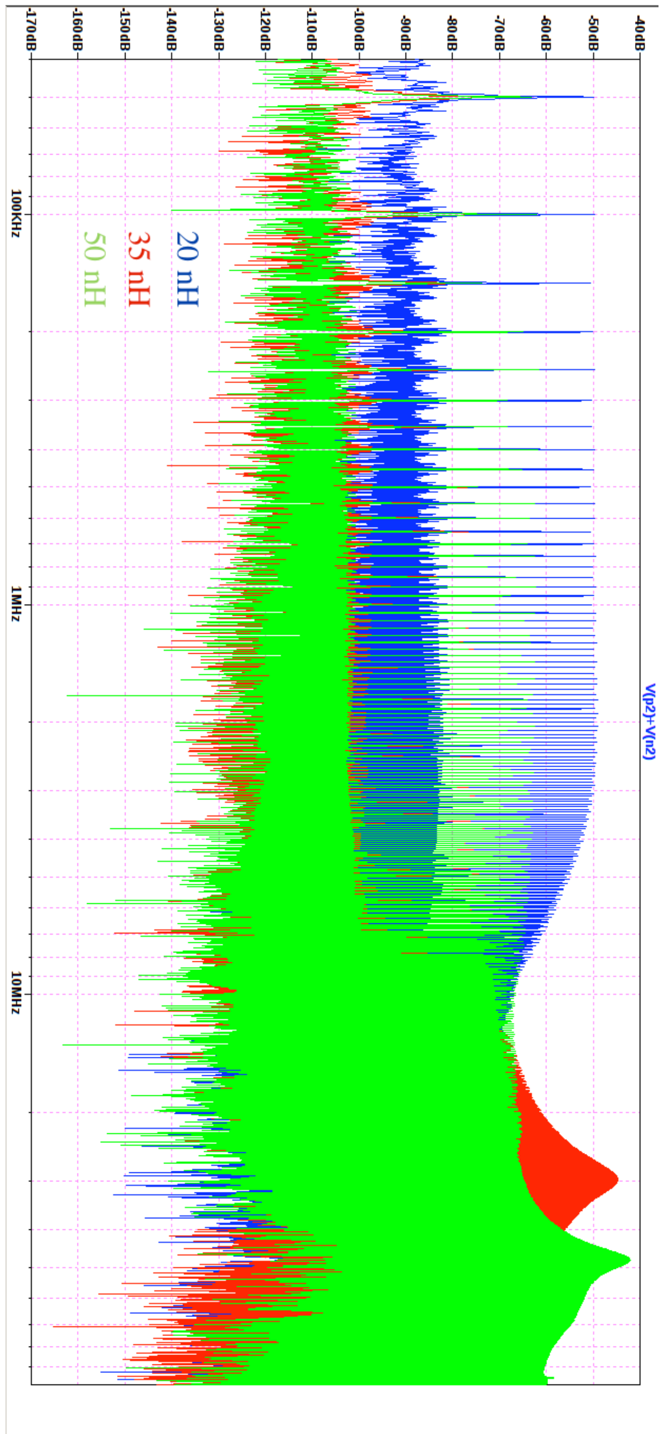


Figure 6.6: Parametric analysis of circuit with method

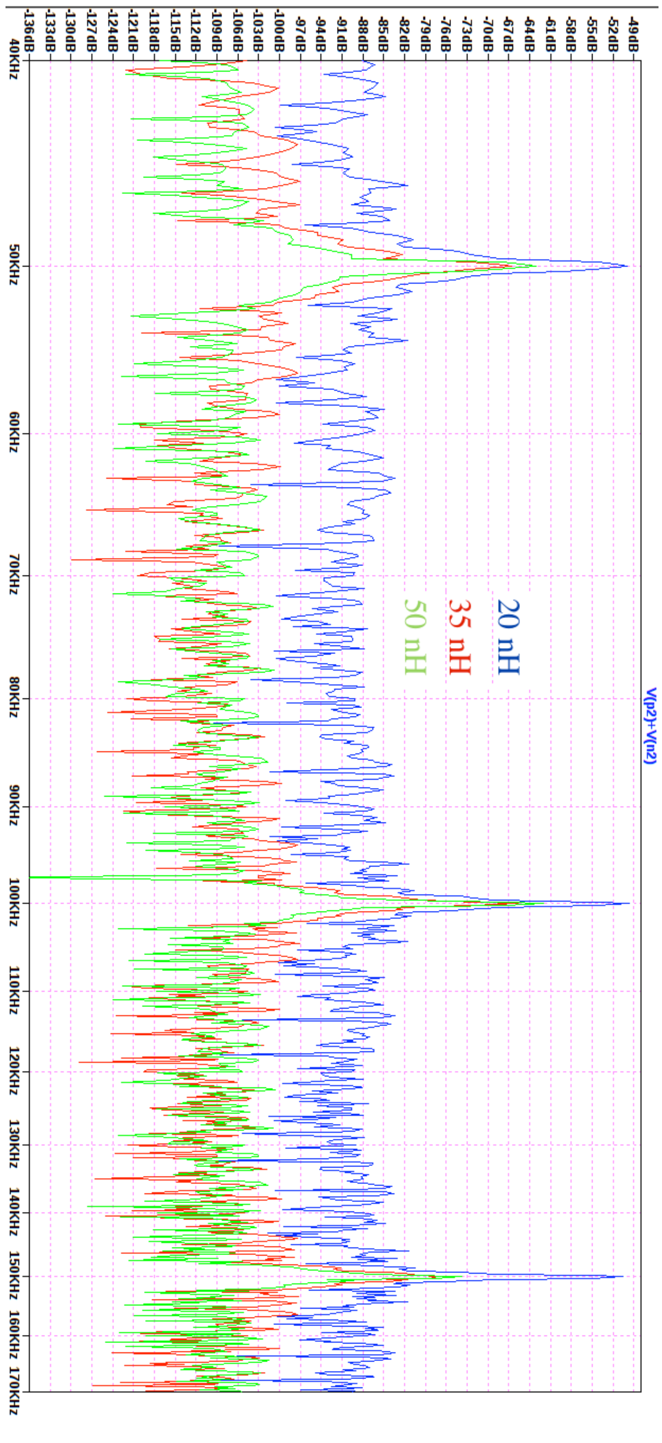


Figure 6.7: Parametric analysis of circuit with method, first harmonics

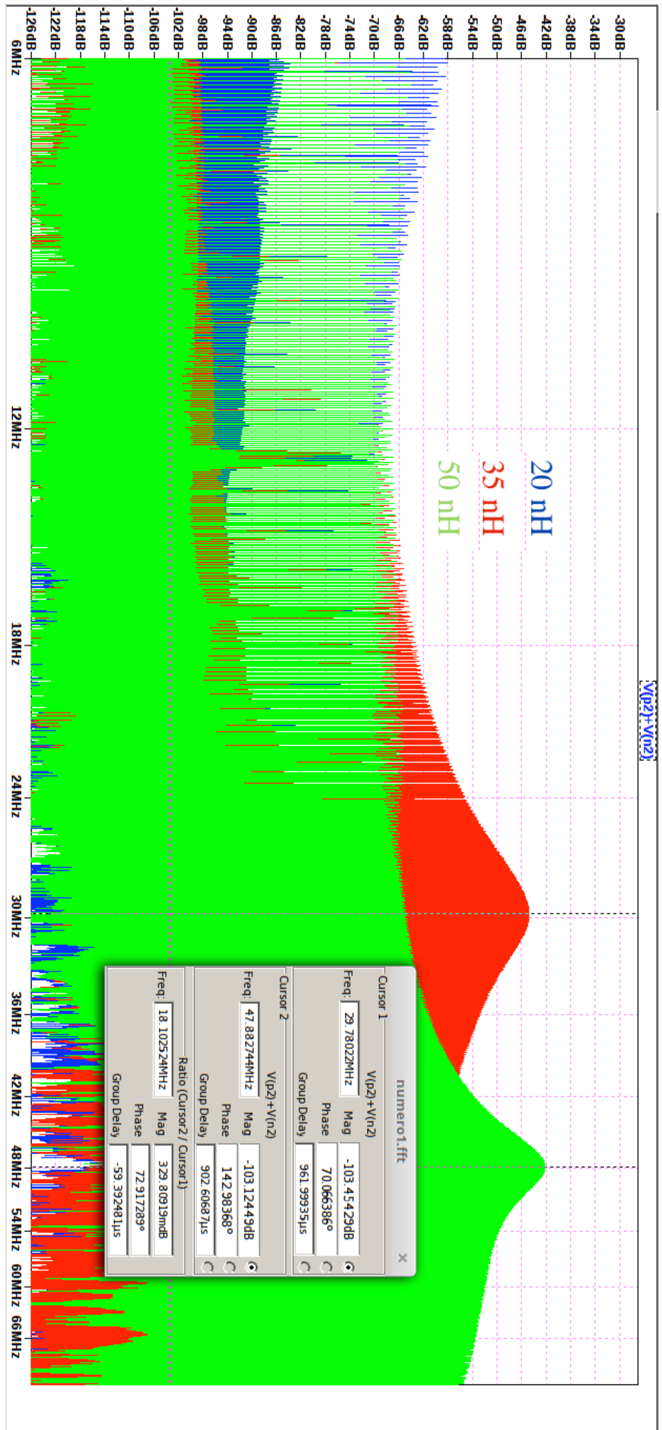


Figure 6.8: Parametric analysis of circuit with method, high frequency peaks

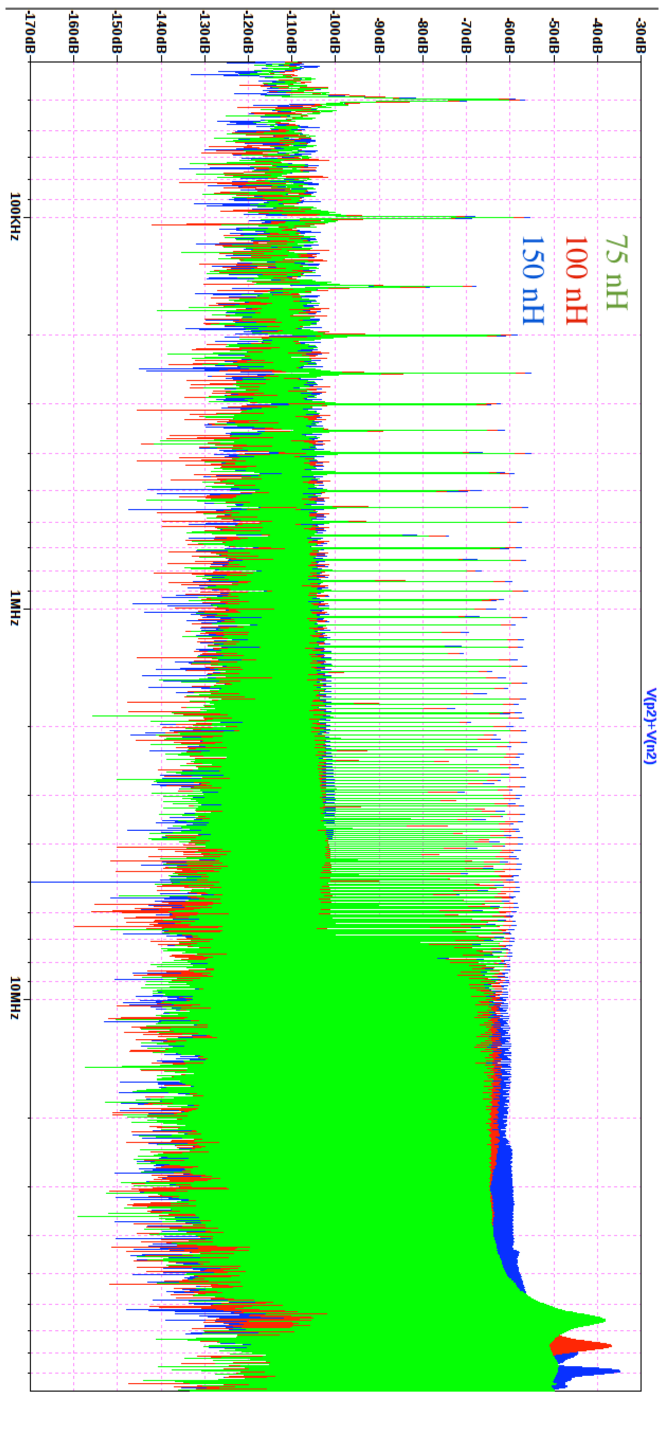


Figure 6.9: Parametric analysis of circuit with method

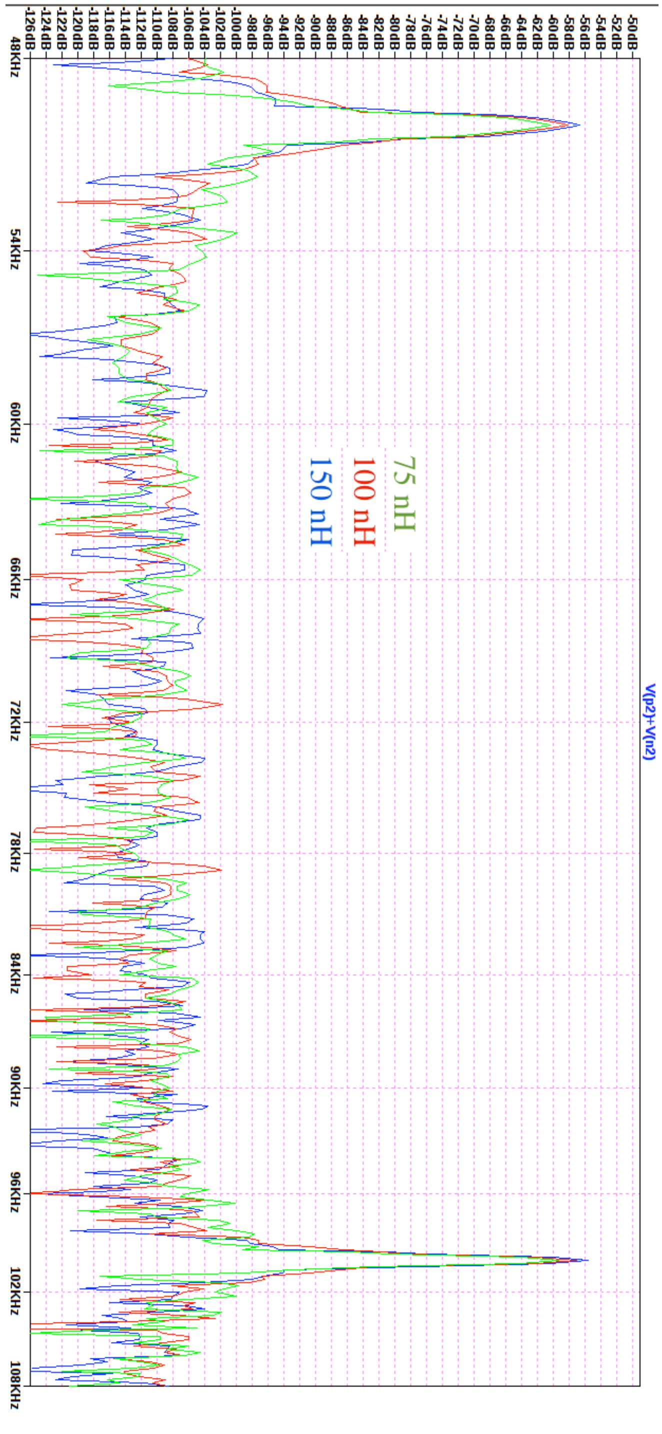


Figure 6.10: Parametric analysis of circuit with method, first harmonics

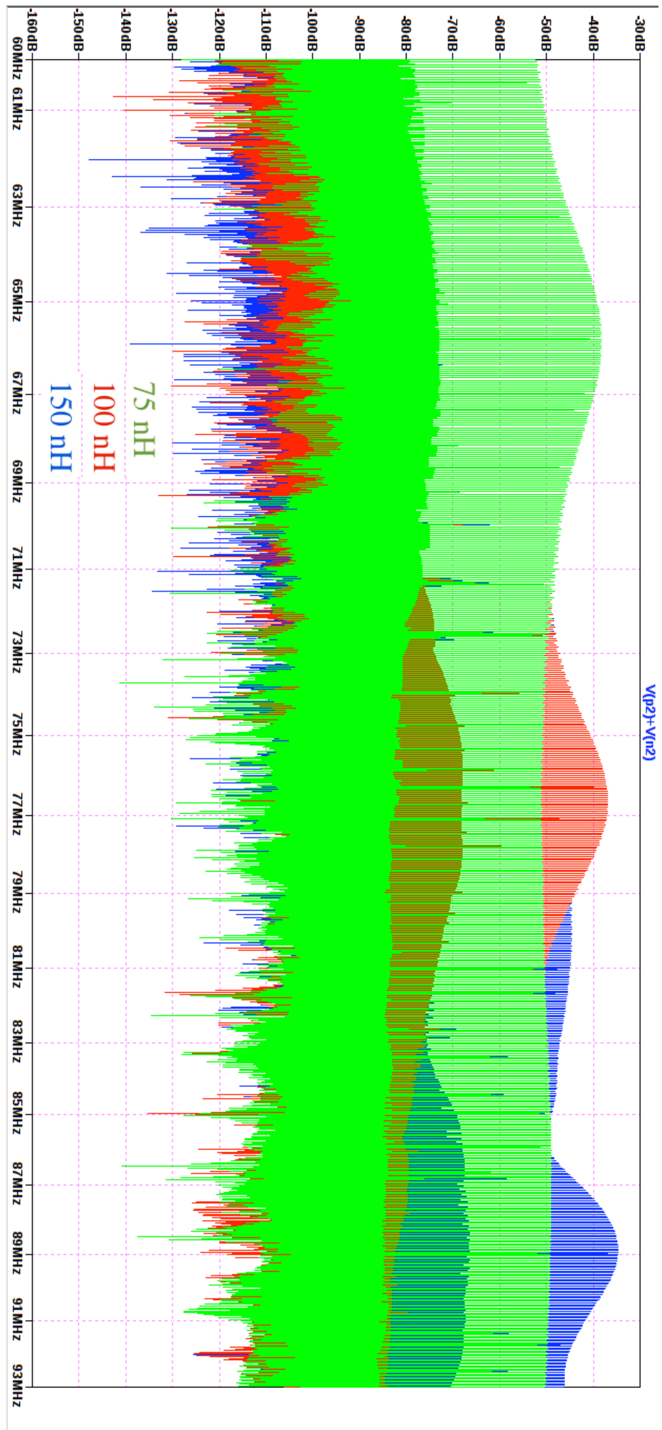


Figure 6.11: Parametric analysis of circuit with method, high frequency peaks

Previous analysis also allow to tune the components used as parameters. In fact, it can be noted from magnitude heights of CM noises that the initial values used in the design are actually the ones that present the best spectrum over all. With a L_{trace} of 35 nH, CM voltage has the lowest magnitude of -66 dB. There is a small difference between the high frequency peaks of figures 6.4 and 6.8 (33.3 MHz and 29.8 MHz), although 35 nH is used in both as trace inductance. This happens because the capacitance at MOSFET's drain is standardized in the first case, while in parametric analysis an equation is respected.

As L_{trace} and C_{drain} increase, CM interferences increase as well by a few decibel and high frequency peaks are shifted to higher frequency. This is not as one may anticipate since peak frequency is inversely proportional to inductance and capacitance that generate resonance in a standard LC circuit. But in this case, more than just two reactive components are involved in the resonance and expressing true resonant frequencies is not a trivial task.

Chapter 7

Further works

7.1 Damping

As it was discussed in the previous chapter, the impedance balance method fails to improve conducted interferes around 30 MHz. A resistor can be then used to damp the resonance and change the quality factor Q of the resonance. A resistor is therefore placed in series with the drain's capacitance, this configuration is also known as snubber.

$$Q = \frac{R}{Z_0}$$

From the next image, it can be said that, at the green points, voltages are almost constant. Hence, capacitors are in parallel. With a quality factor of 0.5 and with capacitors' values of best configuration of chapter 4, the damping resistor placed in series to L_2 can then be calculated as:

$$R = Q\sqrt{\frac{L_2}{C_{tot}}} = 0.5\ \sqrt{\frac{35\ nH}{(11 + 440 + 100)\ pF}} = 4\ \Omega$$

A resistor of 10 Ω is chosen. Although a smaller value than 4 Ω should be used to better damp resonance, a large value is instead selected for efficiency. In fact, the lower the resistance, the higher the losses from charges and discharges of drain's capacitor. In the last image, it can be noted that indeed the damping resistor well improves resonance's attenuation.

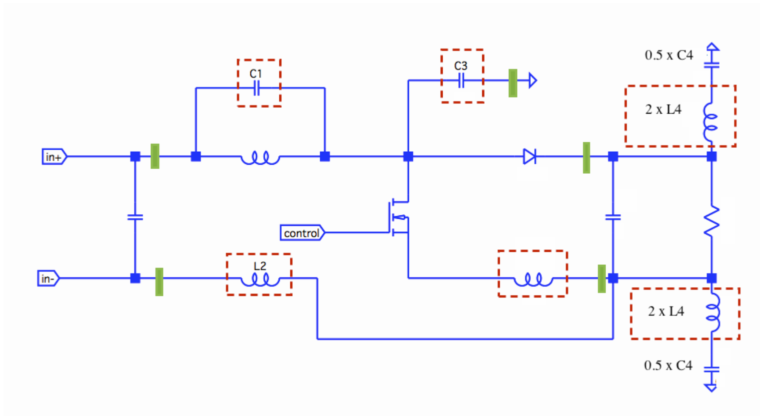


Figure 7.1: Boost converter, green points refer to almost constant voltage nodes

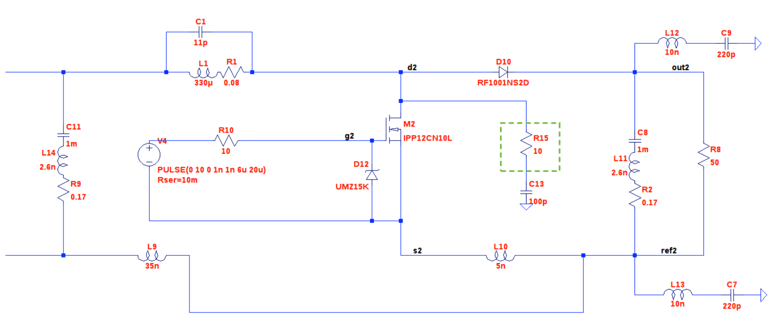


Figure 7.2: Added damping resistor

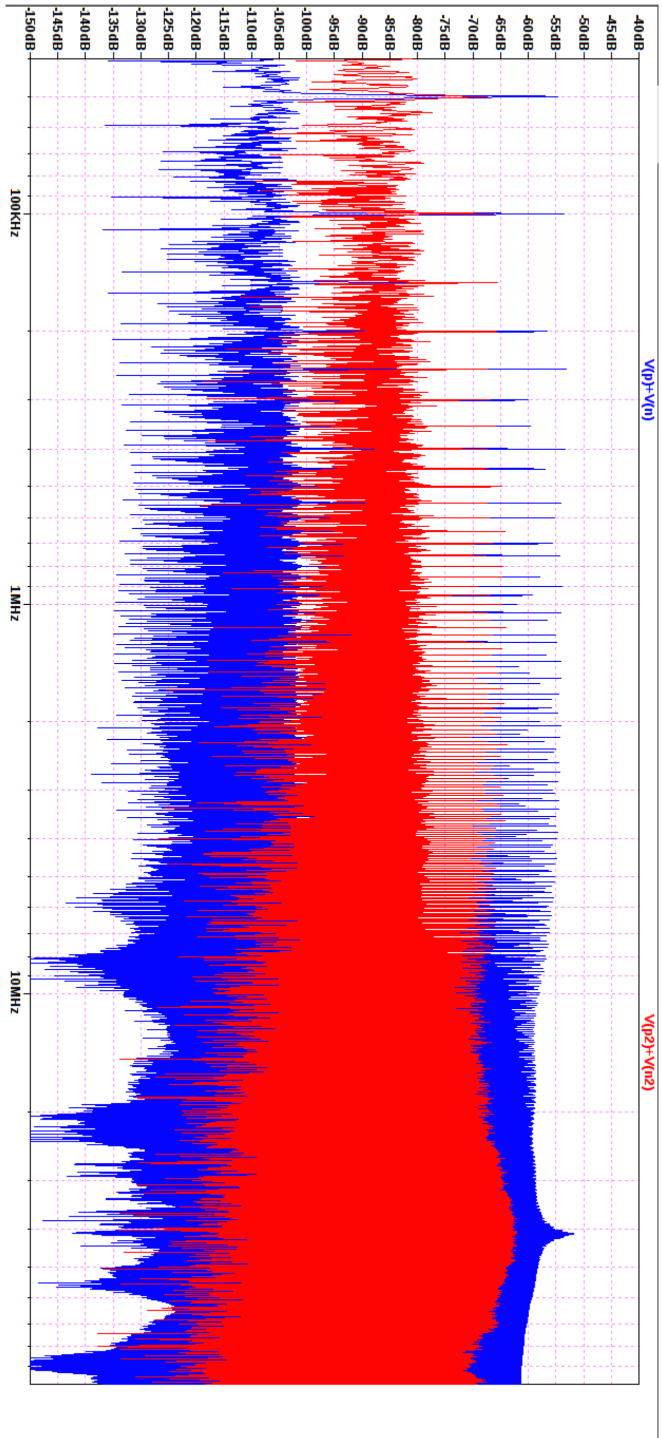


Figure 7.3: FFT of CM voltage, with damping resistor: without method (blue), with method (red)

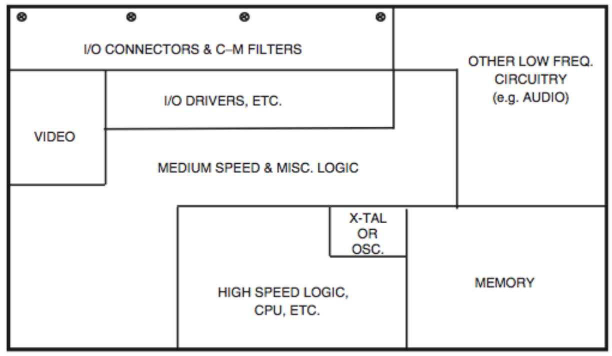


Figure 7.4: Proper partitioning of functional blocks

7.2 Layout

Attention to layout is critical to the success of any printed circuit board. Guidelines should be set in order to not only reduce the cost of boards and minimize the risk of errors due to manufacture, but also with regard to EMC. Described below, there are considerations and procedures to minimize EMC issues. [4]

1. Partitioning: components should be grouped into logical functional blocks according to figure 7.2. On a well-designed PCB, high-speed lines and devices are located far away from input/output area and low-frequency analog areas.

2. Critical signals: high-frequency signals with large currents and fast rise/fall times, such as control signals, clocks, and high-speed buses have large spectra content. EMC problems may luckily arise from these critical signals. Those signals should be routed on no more than two layers, and these layers should be adjacent to the same plane.

3. Properly placed planes improve EMC, while slots should be avoided.

4. Multilayer board configurations provide good-to-excellent EMC performance.

5. Ground-to-chassis: this connection should be very low inductive, in the I/O area of the board.

7.3 Models

Sometimes datasheets are not reliable or some information is missing. A good way to proceed is to make the models of components. By the use of a vector network analyzer (VNA) is possible to measure the scattering parameters of devices. For instance, passive components can be well modeled using a VNA and SMA connectors. Depending on how many ports the component has, a two-port VNA may not be used or modeling may be time-consuming task. For active device, transistor testers can be used.

Chapter 8

Conclusions

It has been proved that common mode noise of low power DC/DC boost converter is reduced by applying the impedance balance method. The method is not an expensive change nor a difficult circuit to realize, although the noise-emitting source has to be well defined. Applying the method helps to reach EMC standards and have less stringent specifications on EMI filters. Hence filters can be downsized, power and volume are reduced. The proposed solution is a competitive procedure to mitigate EMC issues compared to methods listed in the start of art chapter.

For the boost converter example, it is shown that the impedance balance method provides 12 dB of reduction of CM noise over the frequency range of EMC tests for conducted emission. Unwanted resonance at 33 MHz cancels the benefits of the method and it instead increases noise, leading to a worse noise content at around 30 MHz compared to the configuration of the converter without method.

A damping resistor is then employed to fix this issue. It should be noted that it is a good practice to keep noise low even above the limit of frequency range of EMC tests. This is because conducted emissions are often linked to radiation problems, hence radiating emissions can be improved by operating on conduced emissions.

A better configuration for damping may be done by placing resistors in parallel to inductors and away from the switching node at MOSFET's drain. In this case, power dissipation is not compromised because resistors are put in parallel to inductors (static power is null) and charging and discharging phases of inductances are not large.

It should also be reminded that the Wheatstone bridge configuration and the balance condition are attained via ideal cases, approximated for very high frequency, so that very low impedances of input and output capacitors can be considered and Y-capacitors' capacitances can be neglected.

Chapter 9

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