Retraction

Retraction: Simulation and Measurement of Conducted Emission in DC-DC converter (J. Phys.: Conf. Ser. 1916 012135)

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This article (and all articles in the proceedings volume relating to the same conference) has been retracted by IOP Publishing following an extensive investigation in line with the COPE guidelines. This investigation has uncovered evidence of systematic manipulation of the publication process and considerable citation manipulation.

IOP Publishing respectfully requests that readers consider all work within this volume potentially unreliable, as the volume has not been through a credible peer review process.

IOP Publishing regrets that our usual quality checks did not identify these issues before publication, and have since put additional measures in place to try to prevent these issues from reoccurring. IOP Publishing wishes to credit anonymous whistleblowers and the Problematic Paper Screener [1] for bringing some of the above issues to our attention, prompting us to investigate further.

[1] Cabanac G, Labbé C and Magazinov A 2021 arXiv:2107.06751v1

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Simulation and Measurement of Conducted Emission in DC-DC converter

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Abstract. In recent days testing of a product with the EMI standard using test set up is a mandatory as most of the product has the electronic circuitries which possess the high-speed signals. This paper discusses about the conducted emission and the implementation of filters for mitigating the conducted electromagnetic emissions. A DC-DC Buck converter which can be used in vehicle electronics was simulated using the software tool with and without filter and the results were analyzed for mitigating the conducted electromagnetic emission.

Key words: EMI; Conducted emission; EMI Filter; DC-DC Converter

1. Introduction

Most of the Electronic devices are affected by Electromagnetic Interference in the presence of electromagnetic waves caused by either source device or proximity device which is an operational disturbance [1]. Unwanted signal can be emitted by electrical or electronic circuits due to various reasons. Unintended electromagnetic emission happens because of the high speed clock signals, processor noise, high switching frequency, transmission interferences and network interferences. Due to this performance of the signal at the receiver side degrades [2]. This causes unwanted performance or malfunction of electromechanical equipments, circuits and components may happen.

This paper covers the following topics:

- Basic understanding of Electro Magnetic Interference, EMI and its standard
- EMI at various levels such as component, PCB and Product levels
- Measurement of conducted emission in DC-DC converter using simulation tool without filter.
- Measurement of the same after implementing the filter considering the defined standards for the conducted emission.
Figure 1. Events of the EMI

As shown in the Figure 1, there are three main events of EMI which are source, coupling path and receiver [3]. Source is the generation of interference, is conducted and radiated through coupling path to the receiver. Due to this disturbance, receiver is not receiving the expected signal. Care should be taken at both the ends, source and transmission side or conduction path.

EMI mitigation is required for high density semiconductor packaging technology advancement with complex stacked chip and multi chip packages [4]. This is equally important due to the other reasons such as increase of electromagnetic pollution and emerges of Internet of Things (IoT). EMI is regulated and enforced at international and national standard to overcome these problems. Some of the bodies are

- International Electro technical Commission (IEC)
- Verband Deutscher Electrotechniker (VDE)
- International special committee on radio interference (CISPR)
- IEEE - Institute of Electrical and Electronics Engineers
- Other standards organizations, including ISO, SAE and also defined a number of standards geared towards specific applications or industries.

Standards are classified as Basic standard, Generic standard, and Product standard. They are based on various parameters such as frequency band or wavelength and the testing parameters or metrics. Figure 2. Shows various frequency ranges with the wavelength.

![Figure 2. Frequency range with wavelength](image)

Various applications operate with the different frequency ranges. The table 1 shows the typical communication examples with their operating frequency.

| Description | Frequency Range   |
|-------------|-------------------|
| Wireless    | 500 MHZ           |
| Wi-Fi       | 2.4– 5 GHz        |
| Bluetooth   | 2.4 – 2.485 GHz   |
| 4G cellular | 0.7 – 2.7 GHz     |
| 5G cellular | 6 GHZ             |

Table 1. Application and their frequency range
EMI problem arises in the high frequency, and it has to be observed at various levels to overcome the issue.

2. EMI at various level

2.1 EMI at Component level

Behaviour of an electronic component in the low frequency is differs from high frequency. For example, in the case of resistor under low frequency, it works as resistor as expected. But during the high frequency operation, the equivalent circuit will not be a resistor alone; instead some inductance effect is also added [5]. This is same for other components also. The Figure 3. Shows the passive components and its behaviour at high and low frequency. In resistor, at higher frequencies, parasitic capacitance (between windings or end-to-end) limits the impedance value. Capacitor impedance is actually low at resonance, which might be seen as good. But above the resonant frequency, the capacitor actually behaves like an inductor, increasing in impedance with frequency [6-7].

Selection of capacitor is important based on the operating frequency. With the lead of the capacitor, the performance will degrade. The table 2 shows without lead values.

EMI shielding is applicable to several component levels such as System-in-Package (SiP), System-on-Chip (SoC), Microcontrollers, Application processors, Power amplifiers, wireless modules, radio frequency modules, memory, sensors, Digital signal Processors (DSP), Application specific integrated circuits (ASIC), Field programmable gate arrays (FPGA), Analog Digital Converters (ADC) and so on.

![Figure 3. Equivalent circuit of component with operation frequency](image)

2.2 EMI at PCB level

In Printed Circuit Board, there will be conducted emission and radiated emission due to the power supply and signal speed. The source of EMI is the place or module where the interference is generated. A receptor for EMI is the block being affected by the interference. PCB has various modules such as power supply, memory, filters, Synchronizer and Other components - Cable, PCB traces, Connector, Res-Ind-Cap, and Switch. Each module has to be taken care for EMI issue. Two different domains are used to analyze EMI, named time and frequency domain. In time domain and frequency domain signals are analyzed with respect to time and frequencies. Table 2 shows the very high frequency signal PCB requires electronic band gap (EBG) which acts as low pass filter, which is used for mitigating EMI issues.
Table 2. Application and their frequency range

| Type                        | Maximum frequency |
|-----------------------------|-------------------|
| Aluminium Electrolytic      | 100 kHz           |
| Tantalum Electrolytic       | 1 MHz             |
| Paper                       | 5 MHz             |
| Mylar                       | 10 MHz            |
| Polystyrene                 | 500 MHz           |
| Mica                        | 500 MHz           |
| Ceramic                     | 1 GHz             |

2.3 EMI mitigation techniques

Solution for the EMI issues can be applied as hardware solution, software solution and system level solution.

a) Using Hardware: Fundamental and lower order harmonics produces the radiation. This radiation, interfere with other possible signals. Different reduction or elimination techniques can work out for Electromagnetic Interference issues. Broadly it can be done by applying the following.

- Fabric-over-Foam (FoF)
- Shielding
  - Coaxial Transmission Line Method
  - Dual TEM Cell Method
  - Rectangular Waveguide Method
  - Nested Reverberation Chamber Method
  - Shielded Box Method
  - Shielded Room Method
  - Free-Space Method
- Conductive filler CM and DM noise
- Form-in-Place
- Ferrite
- Grounding
- Bonding,
- Spatial placement of hardware
- Circuit topology modification and spread spectrum

Noise due to High frequency in power lines can be eliminated by adopting the proper filters in the circuit. EMI filters normally consist of a combination of inductors and capacitors. The requirement of capacitors and inductors is based on the node impedance where capacitors are used in high-impedance node and inductors are used in low impedance node. Enclosing the system with a conductive material completely called shielding eliminates the EMI effect. This is the costliest solution, but it works. Radio-frequency (RF) emitting devices have to be isolated to limit the propagation of their interference to nearby components. Now-a-days, the world is moving towards miniaturization, light weight, and high speeds. This becomes a challenge to overcome the problem.

b) Using software: There are various software tools available in the market to test the EMI parameters in the printed circuit board. Once the native CAD design files are imported into the tool, design rules can be checked. Prior to the simulation, EMC engineer identifies the critical nets and critical
components which are most important to EMC performance. Clock signals, fast rise time or data rate data signals are called as critical nets. Critical components might be decoupling capacitors, filter components, termination resistors, etc.

c) System level solution: Optimization of the assemble level code improves the EMI related problem. This method eliminates the physical redesign of the system.

3. EMI Simulation and Measurement

3.1 EMI Simulation Tool

During the design-stage of EMI analysis, S-parameter (scattering parameter) model extraction in frequency domain can be done to know transmission and reflection characteristics by finding out the amplitude and phase information of a signal. There are three types of simulators available which can be used to find the EMI levels before manufacturing the product.

1. Electromagnetic (EM) simulators, which can be solve Maxwell’s Equations and simulate the electric and magnetic fields at various locations in time domain or frequency domain. There are several EM simulation technologies have emerged based on Maxwell’s equations. Electromagnetic full wave simulation includes the Method of Moments (MoM), Finite Element (FEM), Finite Difference Time Domain (FDTD) and the partial-element equivalent circuit (PEEC) technologies.

2. Circuit simulators, which can be solve differential equations corresponding to several circuit elements and includes the Kirchhoff’s current and voltage relationships to predict the voltages and currents at several circuit nodes, in time or frequency domains. It is a mathematical model depicting the behavior of an actual circuit.

3. Behavioral simulators, which used for modeling based on the tables and transmission lines and other passive component elements modeling based on transfer functions, which quickly predict the voltages and currents at various nodes, typically in the time domain.

3.2 Software Tool Selection

In the paper, Advanced Design System (ADS) and Electronic Design Automation (EDA) tool from Keysight Technologies is used for simulation, to model the DC-DC power converter and measure the conducted EMI noise. Then the noise data is used to design filters which are also incorporated into the schematic and simulated to verify their effectiveness. Keysight ADS is software package which supports every step of various design process like – schematic capture, layout, design rule checking, frequency domain and time domain circuit simulation and electromagnetic field simulation. Therefore, this software tool has found prominence in the design of RF electronic products in various commercial applications such as electric vehicle, mobile phones, wireless networks, satellites communication and radar systems. The tool has also been used for power converter design. The software provides various features such as S parameter simulation and inbuilt mathematical functions which can help the designer in making complex analysis from simulation data. The tool also has the feature of tuning wherein the component parameters can be changed and results viewed in real time without having to rerun the simulation. This allows designers to have minimum design turnaround times.

3.3 DC-DC Convertor Design and Topology Selection

In a modern automobile, the most commonly used power converter is DC-DC converter. These converters are mainly used to power all the electronic loads present in it. Loads can be Engine Control Unit (ECU), Infotainment System, etc. In modern times, with the advent of EVs, HEVs and PHEVs, and with better battery material technology, the nominal voltage of batteries tend to increase. One
modern battery voltage that is widely becoming mainstream is the 48 V battery voltages. This nominal battery voltage is highly preferred, as it is efficient to drive Permanent Magnet Synchronous Motors (PMSM), commonly used in Electric Traction, at this voltage than at 12 V. Therefore, it also becomes widely important to develop power converters that can power the electronic systems at the required voltage level from a 48 V power source. Therefore, a 48 V / 12 V DC-DC converter is developed that can be used to convert the 48 V nominal battery voltage to 12 V which can be further reduced to the required levels by the existing DC-DC converters. All electronic systems in an automobile have to undergo stringent conducted and radiated EMI emission standards. Therefore, the Power converter design will also incorporate EMI filters to reduce conducted EMI emissions.

For implementing a 48/12 V DC-DC converter, various topologies are available. For powering electronic systems bidirectional converters are not required. Likewise, isolated topologies are also not preferred due to higher cost, volume and weight due to isolating transformer and transformer has leakage inductance which contributes to conducted and radiated EMI noise. Therefore, the non-isolated buck topology is selected to implement the 48/12 V DC-DC converter.

3.4 Converter Specifications
The specifications for 48/12V DC-DC Buck converter are shows in table 3

| Parameters               | Ranges   |
|--------------------------|----------|
| Input Voltage            | 48 V     |
| Output Voltage (Vo)      | 12 V     |
| Rated Power              | 100 W    |
| Output Voltage Ripple    | 5 % of Vo|
| Output Current Ripple    | 5 % of Ir|
| Rated Output Current (Ir)| 8.333 A  |

The design of 48/12V Non-isolated DC-DC Buck converter is as follows
- Duty Cycle = Vo / Vin = 12 / 48 = 0.25
- Rated power, Prated = 100 W
- Rated output current, Ir = Pr / Vo = 100 / 12 = 8.33 A
- Inductor current ripple, ΔIL = 5 % of Ir = 0.4167A
- Output voltage ripple, ΔVo = 5 % of Vo = 0.6 V
- Switching frequency, fs = 166.7 kHz (Ts = 6 µs)

Therefore, the value of Inductance and Capacitance are as follows

\[
L = \frac{V_0 \times (1 - D)}{\Delta IL \times f_s} = \frac{12 \times (1 - 0.25) \times 6 \times 10^{-6}}{0.4167} = 129.6 \, \mu H
\]

\[
C = \frac{\Delta IL}{8 \times \Delta V_0 \times f_s} = \frac{0.4167 \times 6 \times 10^{-6}}{8 \times 0.6} = 520.9 \, nF
\]

Figure 4. Shows the schematic diagram of DC-DC converter circuit. LISN- symbol is inserted for measure the conducted EMI as per the standard.
Figure 4. Schematic of converter circuit

Also for measuring conducted EMI, the component used in the power converter design has to be considered for non-ideal parasitic components both active and passive components. Conducted EMI noise tends to peak at the self-resonating frequency due to low impedance for the resonating frequency component of the current signal. Therefore, it becomes very important to include all the non-ideal characteristics of active devices as well as the parasitic components of both active and passive devices before measuring conducted EMI.

Figure 5 and Table 4 shows the conducted EMI measurements without filter is shown

Table 4. Measurement of Conducted EMI emissions – without filter

| Frequency (in MHZ) | Design Values (in dBµV) |
|-------------------|-------------------------|
| 0.15 to 0.3       | 143                     |
| 0.53 to 2         | 142                     |
| 5.9 to 6.2        | 126                     |
| 30 to 54          | 114                     |
| 70 to 108         | 104                     |

3.5 CISPR 25

The most commonly used EMI measurement and conformance for automotive application standard is CISPR 25. This standard defines for controlling electromagnetic interference in electrical and electronic devices and is a part of the International Electro technical Commission (IEC). CISPR 25
details limits and procedures for the measurement of on-board radio disturbances in the range of 150 kHz to 2500 MHz. In CISPR 25 standard, the conducted EMI noises are classified into Narrowband and Broadband Noise.

Each of these noises has their own limits as specified in the CISPR 25 standard. For these limits, the broadband noises can be measured by using an average or quasi-peak detector and the narrowband noises can be measured using a peak detector. The tables 5 and 6 show the broadband and narrowband limits respectively.

**Table 5. CISPR 25 standard – Broad band**

| Class | Levels in dB (µV/m) |
|-------|---------------------|
| 0.15-0.3 MHZ | 0.53-2.0 MHZ | 5.9-6.2 MHZ | 30-54 MHZ | 70-108 MHZ |
| 1 | 96 | 83 | 70 | 60 | 47 | 60 | 47 | 49 | 36 |
| 2 | 86 | 73 | 75 | 62 | 54 | 41 | 54 | 41 | 43 | 30 |
| 3 | 76 | 63 | 67 | 54 | 48 | 35 | 48 | 35 | 37 | 24 |
| 4 | 66 | 53 | 59 | 46 | 42 | 29 | 42 | 29 | 31 | 18 |
| 5 | 56 | 43 | 51 | 38 | 36 | 23 | 36 | 23 | 25 | 12 |

1) Peak 
2) Quasi-peak

**NOTES:**
1. For short duration disturbances, add 6 dB to the level shown in the table.
2. All values listed in the table are valid for the bandwidths specified in table 3.

**Table 6. CISPR 25 standard – Narrow band**

| Class | Levels in dB (µV/m) |
|-------|---------------------|
| 0.15-0.3 MHZ | 0.53-2.0 MHZ | 5.9-6.2 MHZ | 30-54 MHZ | 70-108 MHZ |
| 1 | 61 | 50 | 46 | 46 | 36 |
| 2 | 51 | 42 | 40 | 40 | 30 |
| 3 | 41 | 34 | 34 | 34 | 24 |
| 4 | 31 | 26 | 28 | 28 | 18 |
| 5 | 21 | 18 | 22 | 22 | 12 |

**NOTE:** For 87 MHZ to 108 MHZ, add 6 dB to the level shown in the table.
It is evident that the designed power converter does not confirm to CISPR 25 standards from the table 4. Therefore, in order to satisfy the standard, EMI filter (Low pass) must be included in the design to reduce conducted EMI emissions.

4. EMI Simulation and Measurement with filter

EMI Filters can be designed using various topologies. Some of the most commonly used topologies are π – Type filter, L – type filter, T – type filter, dissipative filter, Cauer filter, RC Shunt filter. From the different filter topologies, some of them cannot be used in this power converter design due to high output impedance at switching frequency, high component count, standalone capability. It is possible to use π – type filter or L – type filter with single-level or multilevel.

4.1 EMI filter requirements

These conducted EMI emissions must be reduced from the values in Table 7 to the values in Table 6 corresponding to the required class of power converter. To achieve this, the attenuation requirements of the EMI filter for each class of CISPR 25 standard is as shown in Table 6. These values are calculated by computing the difference between the conducted EMI emissions obtained by simulations and the narrowband CISPR 25 EMI emissions limit corresponding to each class. The values are further decreased to ensure that the emissions with filter are well below the limits specified by CISPR 25 standard.

Table 7. EMI Attenuation

| Class | 0.15-0.3 MHZ | 0.53-2.0 MHZ | 5.9-6.2 MHZ | 30-54 MHZ | 70-108 MHZ |
|-------|-------------|-------------|------------|----------|-----------|
| 1     | -55         | 70          | -65        | -65      |
| 2     | -65         | 80          | -70        | -70      |
| 3     | -75         | 85          | -80        | -85      |
| 4     | -85         | 95          | -90        | -85      |
| 5     | -95         | 110         | -95        | -90      |

For a given low pass filter if the attenuation at frequency f1 is A1 and at frequency f2 is A2, then the order of the filter is

\[ n = \frac{A_1 - A_2}{6 \log_2 \left( \frac{f_2}{f_1} \right)} \]  

(1)

For filter design, it is confined for class 4 and

- A1 → Required attenuation at f1=0.15 MHz
- A2 → Required attenuation at f2=0.53 MHz

The order of the filter must be greater than or equal to the value of n calculated using the formula.

For a given nth order filter, if the attenuation at frequency f2 is A2, then the cut-off frequency is as follows

\[ f_{cut-off} = f_2 * 2^{\left( \frac{A_2}{6n} \right)} \]  

(2)

The above expression is used to determine cut-off frequency for the nth order filter by substituting A2 as required attenuation at f2 = 0.15 MHz.
The cut-off frequency of the filter is terms of inductance and capacitance is as follows
\[ f_{\text{cut off}} = \frac{1}{\pi \sqrt{LC}} \]  \hspace{1cm} (3)

By taking standard values of Capacitance \( C \), the inductance \( L \) is determined and EMI filter is defined.

4.2 Class 4 design

For Class 4 design, order of the filter must be greater than \( n \), hence \( n \) is calculated using (1)
\[ n \geq \frac{A1 - A2}{6 \times \log_2(\frac{f_2}{f_1})} = \frac{(-85) - (-105)}{6 \times \log_2(\frac{0.53}{0.15})} = 1.830 \]

Therefore, for Class 4 Design, a 2nd order filter can be used, but such a filter will have a very low cut-off frequency and thus cause the output voltage waveform to ripple beyond the specified limits, therefore, a 3rd Order filter is used. The cut-off frequency (2) is
\[ f_{\text{cut off}} = f_2 \times 2^{(\frac{A2}{6n})} = 0.15M \times 2^{\left(\frac{0.5}{1.830}\right)} \cong 5 \text{KHz} \]

For 3rd order filter, \( \pi \)-type filter is used.

Therefore, \( \text{Capacitor Value} = \frac{C}{2} = 100 \mu F \) (standard value) \( C = 200 \mu \) and substituting in (3),
\[ L = \frac{1}{\pi^2 f^2 \times C} = \frac{1}{\pi^2 \times 5000^2 \times (200 \times 10^{-6})} = 20.26 \mu H \]

Since the inductor is split between the power and neutral line,
\[ \text{Inductor value} = \frac{20.26}{2} = 10.13 \mu H \]

The calculated filter components are incorporated in the converter circuit. Figure 6 shows the schematic circuit with filter components. Conducted emission is measured with filter circuit and plotted.

Figure 6. Schematic of converter circuit with filter
Figure 7. Measurement of output voltage and conducted emission

The Figure 7. shows the measurement of output voltage and conducted emission and it is also observed that the emission levels are well satisfied with the CISPR 25 standard.

5. Conclusion

A 48 / 12 V DC-DC Buck converter used for automotive applications was designed using Keysight ADS tool. The converter with the EMI filter was simulated in Keysight ADS to verify conducted EMI emissions and conformance to the CISPR 25 standard.

A noise current which can be circulated internally by proper design of the circuit layout. The common mode current which can be limited to be within the power converter by ensuring that the Common mode noise generated by the power switching device MOSFET is absorbed by the parasitic capacitors in the circuit acting as Y-capacitors. A proper design of the PCB helps to adjust the values of the filter’s capacitors. Use of WBG devices make the converters more efficient and smaller in size compared to the silicon MOSFET’s. The same converter circuit as used with silicon MOSFET is modified to suit the SiC and GaN MOSFET datasheet parameters. Both were simulated with Keysight ADS for conducted EMI noise. Both SiC and GaN devices have significantly reduced on-state resistance as compared to the Si counterpart but have similar EMI noise.

Reference

[1] Chuic Song et al 2019 Modelling of conducted EMI noise in an Automotive LED Driver Module with DC/DC Converters, International Symposium on Electromagnetic Compatibility. 1013
[2] A. Tsukioka et al 2017 Simulation techniques for EMC compliant design of automotive IC chips and modules, International Symposium on Electromagn. Comp. - EMC EUROPE, Angers, pp. 1
[3] Richard Lee Ozenbaugh 2001 EMI Filter Design, Marcel Dekker Inc.
[4] R. Senthil Kumar, K Mohana Sundaram and K. S. Tamilselvan 2021 Hybrid Reference Current Generation Theory for Solar Fed UPFC System Energies vol. 14 no. 6 pp.1527.
[5] Khadar A and Ahamed 2017 Research advancements towards in existing smart metering over smart grid International Journal of Advances in Computer Science Application Vol 8 Issue 5.
[6] Haldorai, A. Ramu, and S. Murugan, Social Aware Cognitive Radio Networks, Social Network Analytics for Contemporary Business Organizations, pp. 188–202. doi:10.4018/978-1-5225-5097-6.ch010
[7] R. Arulmurugan and H. Anandakumar, Region-based seed point cell segmentation and detection for biomedical image analysis, International Journal of Biomedical Engineering and Technology, vol. 27, no. 4, p. 273, 2018.

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