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Prediction of Conducted Disturbances Generated by a DC/DC Converter

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Abstract: This paper introduces a detailed approach to model and simulate conducted electromagnetic interference (EMI) in the time domain using Lt-Spice software. The focus of the study is on the Buck converter, with the aim of identifying and characterizing electromagnetic disturbance sources arising from the power supply. The research also seeks to analyze their propagation paths and examine the impact of switch selection and control parameters on the electromagnetic compatibility (EMC) signature of the converter. The proposed methodology employs a comprehensive modeling strategy that accounts for the interactions between various converter components and their associated parasitic elements. By accurately representing the electrical and magnetic fields in the time domain, the simulation captures the dynamic behavior of the system, allowing for a realistic assessment of conducted disturbances. The research begins with a thorough examination of the power supply and its switching behavior. Key device characteristics, including switching frequency, voltage, and current waveforms, are carefully analyzed to understand their influence on conducted EMI. Additionally, the model integrates parasitic elements linked to the power device, such as inductive and capacitive components, to address their impact on electromagnetic emissions. Furthermore, the study delves into the propagation paths of conducted disturbances, considering the parasitic elements of the converter's layout, such as PCB traces, cables, and connectors. It evaluates the effects of these elements on electromagnetic emissions, providing insights into propagation mechanisms and potential coupling paths. Various switch types, such as MOSFET or IGBT, are examined, and their effects on conducted EMI are evaluated. Through comprehensive simulations and analysis, the paper offers valuable insights into the conducted disturbances generated by the DC/DC converter, contributing to a comprehensive understanding of the system's electromagnetic behavior. The findings presented in this study can inform the design and optimization of DC/DC converters, facilitating the development of more EMC-friendly solutions.

Keywords: EMC, DC/DC converter, Conducted disturbances, Common mode (CM), Differential mode (DM).

Introduction

Electromagnetic Compatibility (EMC) represents a significant limitation in the design of power electronics structures. Regrettably, it is often treated as a final phase of power converter development, representing the ultimate obstacle to their marketability (Benhadda, 2018).

The advancement of power electronic converters in various electric power sectors imposes new requirements, such as high-frequency switching operations, high power densities, elevated temperatures, and enhanced yields. All specifications must adhere to EMC regulations (Zeghoudi, 2021). The conventional method for EMC prediction involves simulation in the time domain and the use of Fourier transform (Eliana & Koyama, 2014). Despite its simplicity and efficacy, this approach has its limitations.

Our objective is to introduce a predictive model for conducted interference generated by a step-down chopper. This model aims to investigate and analyze the propagation mechanisms of these conducted disturbances, which propagate in both common mode (CM) and differential mode (DM). We seek to comprehend the various parameters that influence the spread and amplification of these disturbances and to quantify the noise level produced by the converter. This study will primarily focus on two specific areas:

1) Time-domain simulation for the analysis of propagation phenomena of conducted disturbances, including the simulation of the conduction and blocking behavior of the MOSFET.
2) Prediction of electromagnetic interference conducted in the Buck converter, with a particular emphasis on the impact of switch types and control parameters.

EMC Modeling of DC/DC Converter

The examined converter, as illustrated in Figure 1, constitutes a series-connected elementary cell of the chopper type linked to the Line Impedance Stabilization Network (LISN). It is supplied by a DC voltage source VDC, and the load converter is depicted by a perfect current source I. Additionally, the diagram includes a combination of resistive elements, inductive components, and capacitors assumed to account for the effects arising from the high-frequency structure's crosstalk.

The impedances Z_{line}, Z_f, and Z_{LP} represent the parasitic inductive coupling at the power level, while the impedances Z_{Load} and Z_{CP} respectively represent the stray coupling in the differential mode and in the common mode at the load. We can differentiate between the parasitic impedances Z_f and Z_{LP}, which are part of the switching cell and therefore closely associated with the cell's switching and the generation of disturbances. The Z_{line} impedance and Z_{Load}, Z_{CP}, are components of the external coupling that enables disturbances to propagate to the load and the power supply (Wu, 2019).

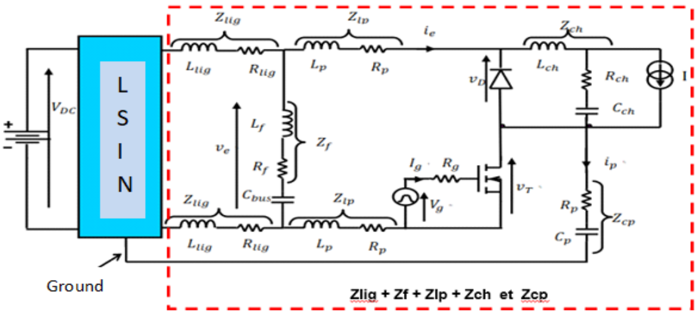


Figure 1. Illustration depicting the effects of crosstalk in a converter.

Simulation Results

The aim of the conducted simulations was to analyze the propagation phenomena of the conducted disturbances and to characterize their sources in the DC/DC converter, utilizing the Line Impedance Stabilization Network (LISN). The LTSpice software system facilitated time-domain simulations, enabling us to swiftly obtain a realistic assessment of the interference emitted by the converter in both the differential mode (DM) and common mode (CM). Figure 2 displays the simulation diagram, encompassing the numerical values of the various components, as well as the amplitude of the electrical quantities, set at a frequency of 10 kHz (with V_{DC} = 300 V and I = 5 A).

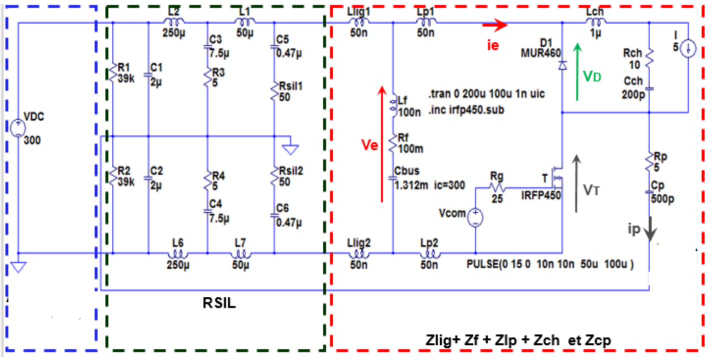


Figure 2. Simulation diagram of the series chopper supplied by a voltage source through the LISN.

MOSFET Conduction Switching

For the analysis of the phenomenon, one should focus on quantities at the input and output of the switching cell. The current i_e initiates an evolution until it reaches the maximum value determined by the diode during the reverse recovery phenomenon. Meanwhile, the voltage across the MOSFET V_t begins to decline due to the voltage drop induced by the parasitic inductances L_f and L_p of the switching cell. The switch terminates as the diode recovers its blocking capability following a substantial current variation (di_e/dt). This abrupt fluctuation in the current i_e at the cell's input results in an overvoltage across the DC bus (Figures 3 and 4).

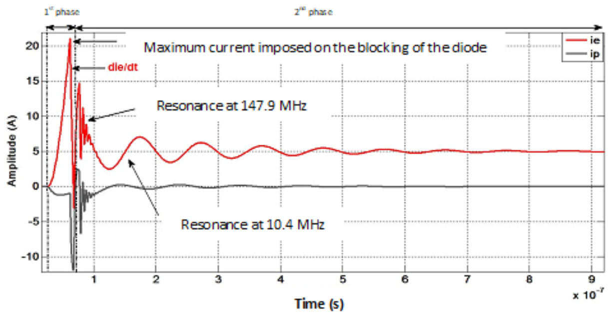
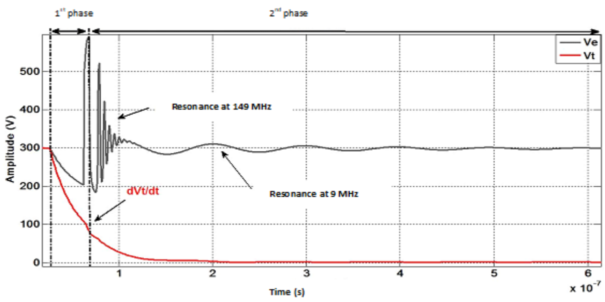
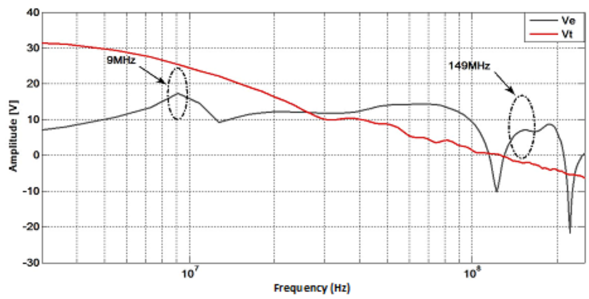


Figure 3. Currents I_e and I_p during MOSFET conduction switching in time domain.



(a)



(b)

Figure 4. Voltages V_i and V_e during MOSFET conduction switching : (a) Time domain ; (b) Frequency domain.

The MOSFET conduction is considered rapid owing to the reverse recovery phenomenon in the blocking diode. The presence of highly variable quantities (current and voltage) implies that via crosstalk, oscillatory modes in the high frequency range could severely disrupt the environment outside the converter. The second phase corresponds to the propagation of CM and DM disturbances (Rezini, 2016).

MOSFET Blocking Switching

The first phase corresponds to the rise of the voltage V_t until it reaches the value of the DC bus. The initial phase, which involves the actual switching process, is completed. The charging of the common mode parasitic capacitor C_p and the discharging of the parasitic capacitor C_d of the diode until the voltage is zero. The diode then becomes conductive and the current in the latter can then evolve involving a variation of the current i_e at the input of the cell (Figure 5). The current variation in the switching mesh (di_e/dt) induces an overvoltage at the terminals of the DC bus followed by a highly damped oscillation phase at the frequency of 73 MHz. The second phase corresponds once again to the propagation of the disturbances of CM and DM (Figure 6).

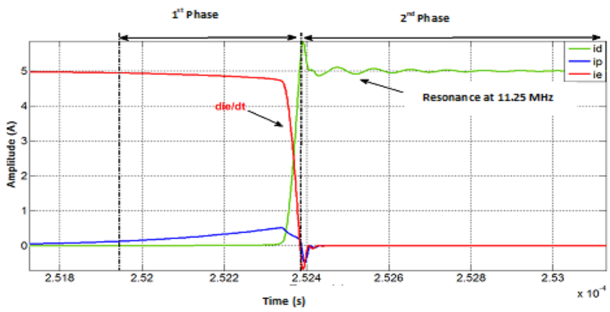


Figure 5. Current I_d, I_p, and I_e during MOSFET blocking switch.

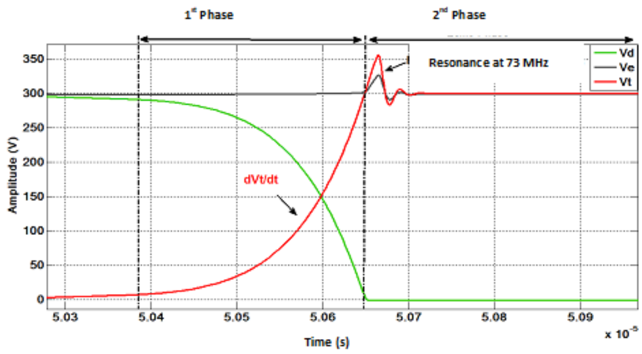
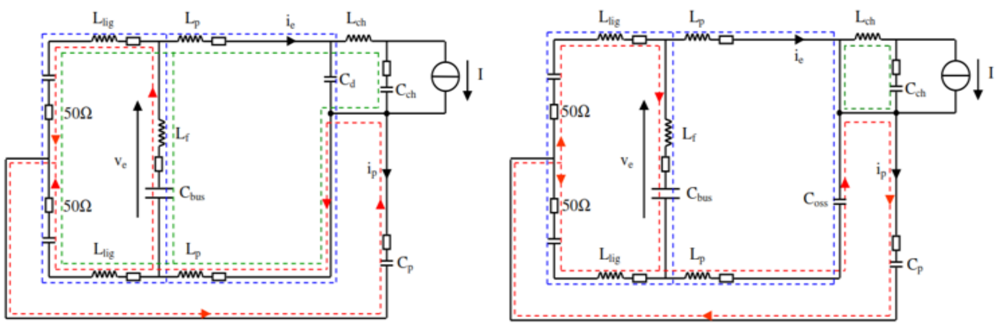


Figure 6. Voltages V_d, V_e, and V_t during MOSFET transition to the locked state.

The diagram in Figure 7 illustrates the various paths of disturbance propagation resulting from the interactions of the two signals, represented in blue and green for the differential mode, and in red for the common mode.



(a) (b)

Figure 7. Disturbance propagation paths of MOSFET: (a) conduction switching, (b) blocking switch

- ✓ On the conduction layout diagram:

The MOSFET is represented as a perfect conductor. The diode is represented by its parasitic capacitance C_d. The propagation of disturbances CM in this case corresponds to the discharge of the parasitic capacitance C_p due to the decrease in voltage V_t. The blue color indicates the interaction in the differential mode between the equivalent parasitic inductance of the entire circuit (L_{eq}) and the parasitic capacitance of the diode (C_d). The green clor indicates the interaction arising from the parasitic differential mode elements of the load (Z_{Load}).

- ✓ On the blocking scheme:

The diode is replaced by a perfect conductor. The MOSFET is represented by its C_{oss} output capacitance.
The propagation of disturbances CM in this case corresponds to the charging of the parasitic capacitance C_p due to the increase in voltage V_t.
The bleue color represents the interaction between the Coss output capacitance of the MOSFET and the equivalent parasitic inductance (L_{eq}).
The green color represents the interaction observed only by the diode and the load during the freewheeling phase.

Prediction of Driving Disturbances in the BUCK Converter

The simulation enabled us to anticipate and analyze the behavior of the Buck converter using two types of MOSFETs, specifically the IRFP450 and IRFP440, as provided by the LTspice software. Figures 8 and 9 illustrate the spectral profiles of the disturbance levels in DM and CM, respectively, in comparison with the standard conducted EN-55022 for both types of MOSFETs."

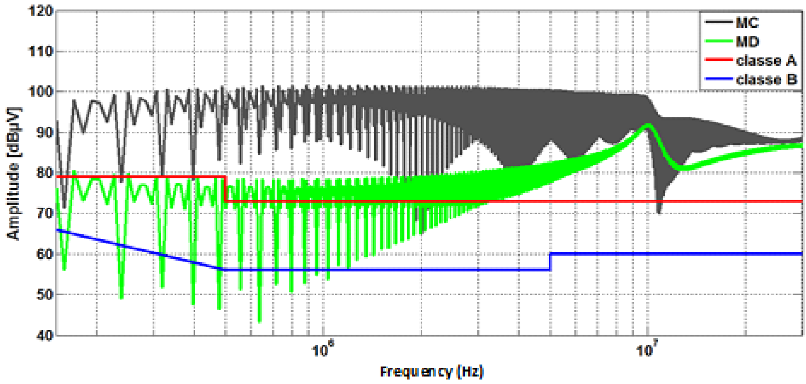


Figure 8. Simulation of the level of electromagnetic disturbances in CM and DM for IRFP 440

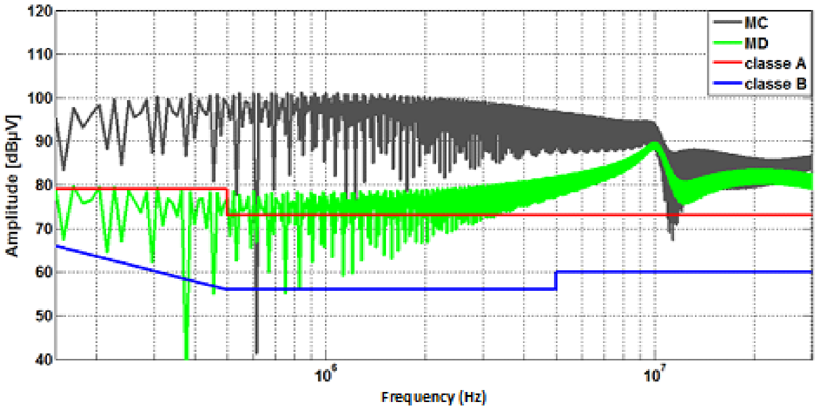


Figure 9. Simulation of the level of electromagnetic disturbances in CM and DM for IRFP 450.

The spectra of CM and DM from the two MOSFETs take on the same appearance with different amplitudes. The spectra are very disruptive because it greatly exceeds the standard templates. The common mode spectrum of the two MOSFETs is dominant over the entire frequency range while the DM gains amplitude in HF.

Comparison of the Voltage Simulations of CM and DM for the Two Types of MOSFETs.

The switching speed (dV/dt) for the IRFP440 MOSFET is higher than for the IRFP450 MOSFET, the levels of disturbances in CM become more important (Figures 10 and 11).

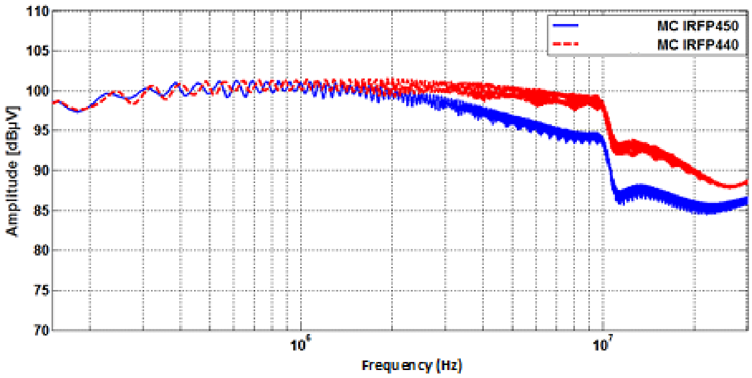


Figure 10. Comparison of the common mode (CM) spectra for IRFP440 and IRFP450.

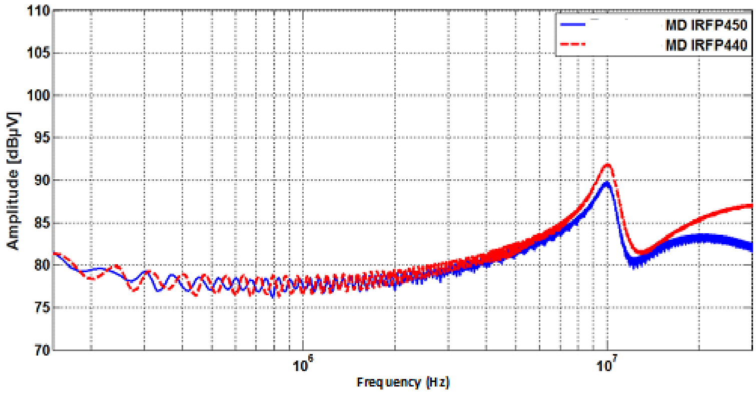


Figure 11. Comparison of the differential mode (DM) spectra for IRFP440 and IRFP450.

Since there are not many differences in the current response for the two components, consequently the voltage for DM is less variable.

Influence of the Gate Resistance

In this section, we examine the influence of the resistance of the gate of the MOSFET on the disturbing level generated by this component. For this purpose, we have varied this resistance from 25 Ω and 100 Ω for a fixed duty cycle equal to 50% and the switching frequency of 10 kHz. We took the converter with the IRFP450 MOSFET for the study and directly compared the interference generated in CM and DM for the two resistor values (Figures 12 and 13).

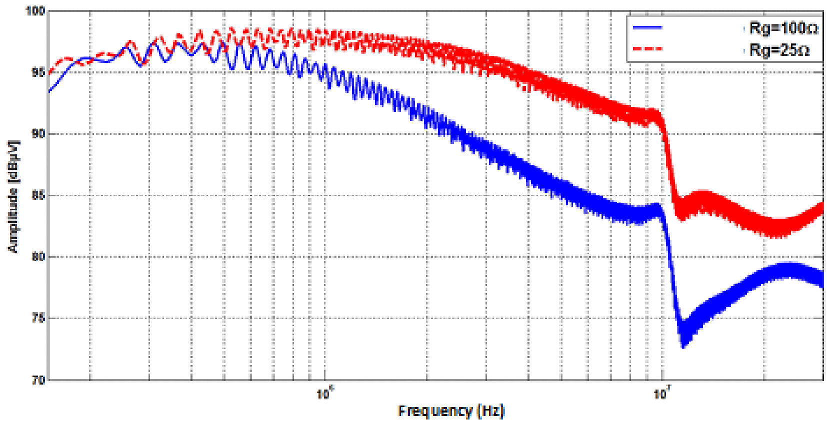


Figure 12. Comparison of the simulated CM disturbances for different resistances of the gate.

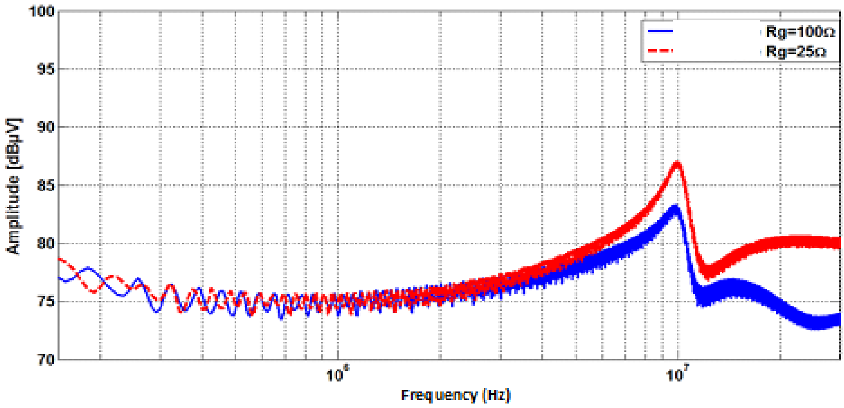
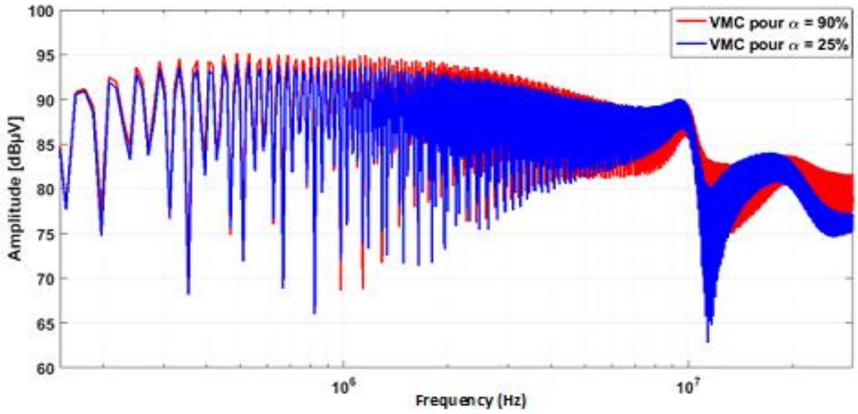


Figure 13. Comparison of the simulated DM disturbances for different resistances of the gate.

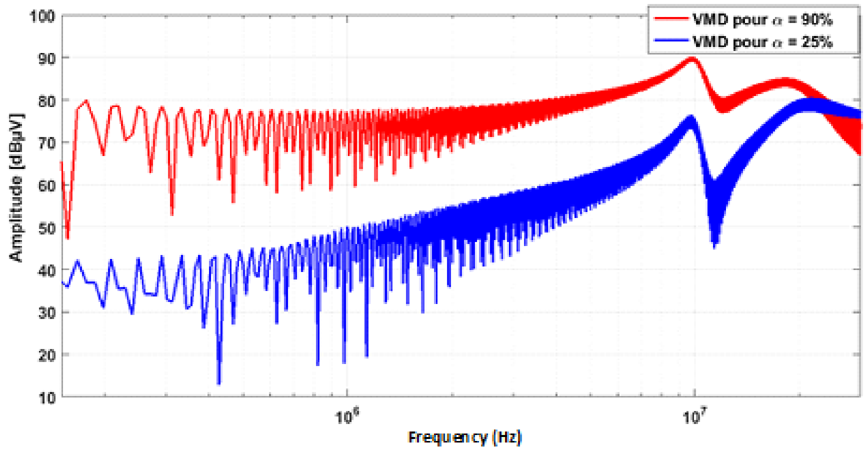
We note that the increase in the resistance of the gate allowed a clear decrease in the amplitude of the voltage in CM and DM. Due to the fact that the gate resistance value is inversely proportional to the switching speed, the results affirm that the disturbances in CM are directly related to the variations in dV/dt which change with the resistance of the gate. For the disturbances in DM, the impact of the switching speed is less significant at the spectrum level.

Influence of the Operating Point on the Conducted Electromagnetic Disturbances

With the same converter, and fixing the gate resistance at 25 Ω for a switching frequency of 10 kHz, we carried out comparisons in simulation of CM and DM voltages with a duty cycle of 25% and 90% (Figure 14).



(a)



(b)

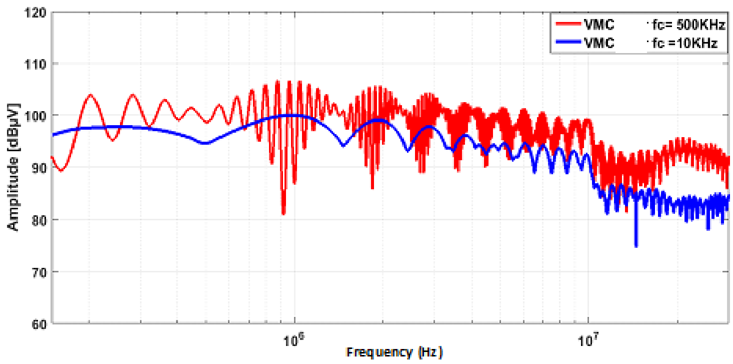
Figure 14. Comparison of the simulated voltage for different duty cycles : (a) CM, (b)DM.

The results show that the impact in the CM for different duty cycles is negligible. This is due to the fact that the switching speed (dv/dt) are not very different when the switched current varies. On the other hand, for the DM, the impact is significant. This can be explained by the fact that the switched current is directly proportional to the duty cycles. This analysis is consistent with the work (Zeghoudi, 2021) where the disturbances in CM are mainly due to variations in the voltage in the switching cell and the disturbances in DM are mainly due to variations in currents.

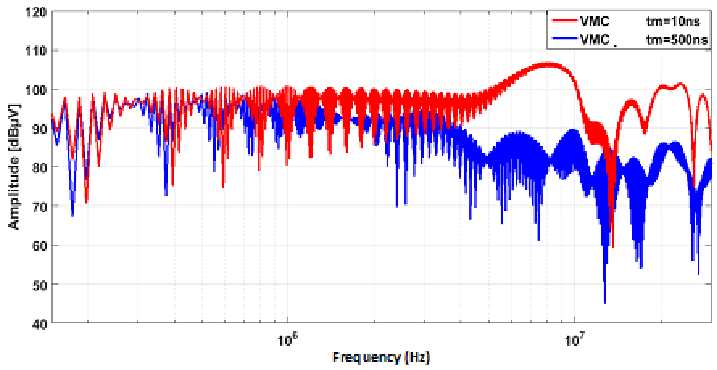
Influence of the Switching Frequency

In order to present the influence of the different times characterizing a voltage or current wave on the voltage spectrum. The following curves represent respectively the spectra of the CM and DM voltages at the level of the LISN and the spectra of the voltage or level of the load for different values of the following parameters: t_m, t_d and f_c.

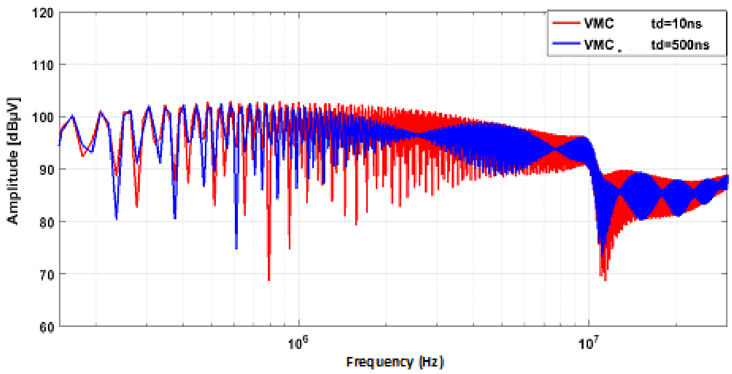
Spectra Measured at the RSIL



(a)

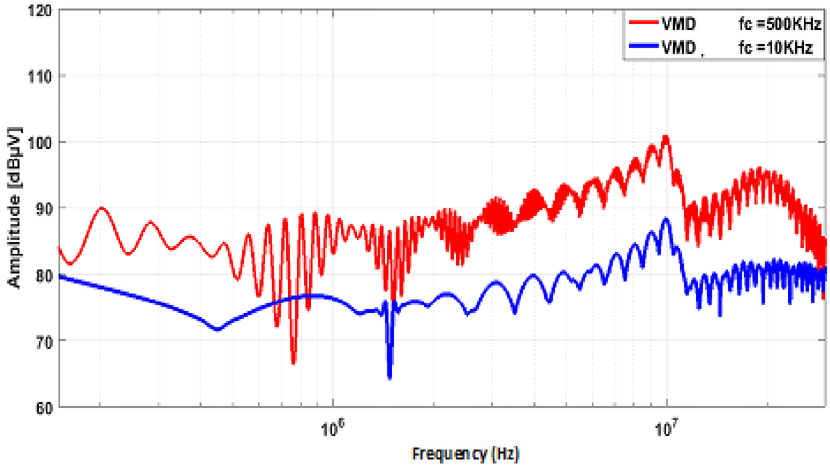


(b)

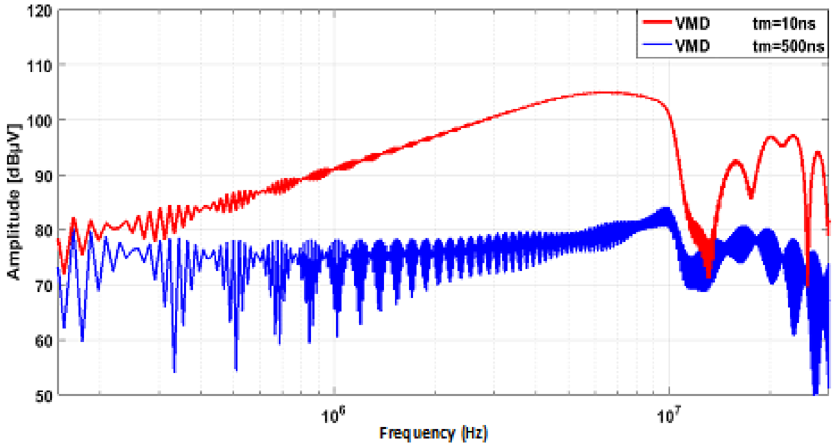


(c)

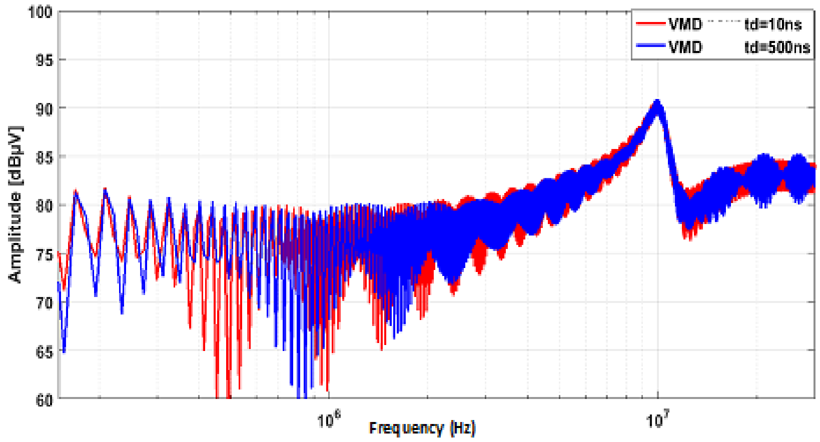
Figure 15. Influence of the switching frequency on the CM spectrum: (a) f_c, (b) t_m, (c), t_d.



(a)



(b)



(c)

Figure 16. Influence of the switching frequency on the DM spectrum: (a) $f_{c,}$ (b) t_m, (c) t_d.

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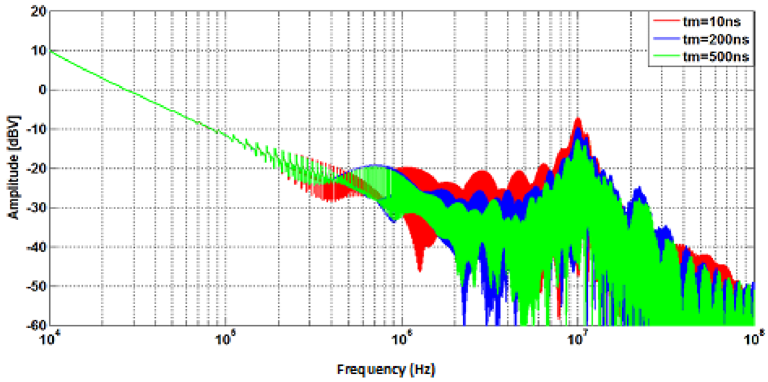
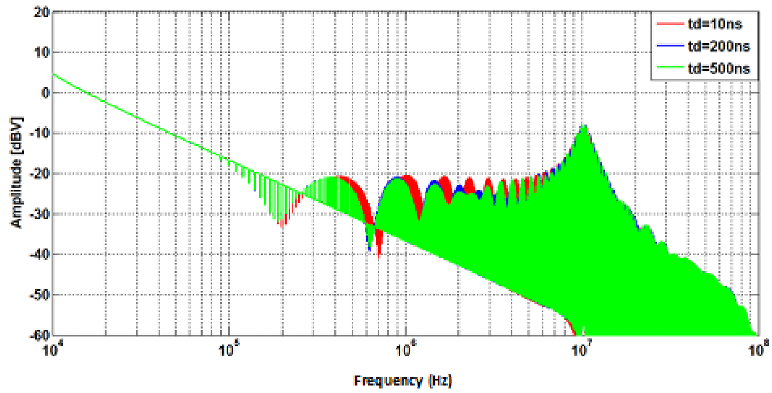
Spectra Measured at the Load

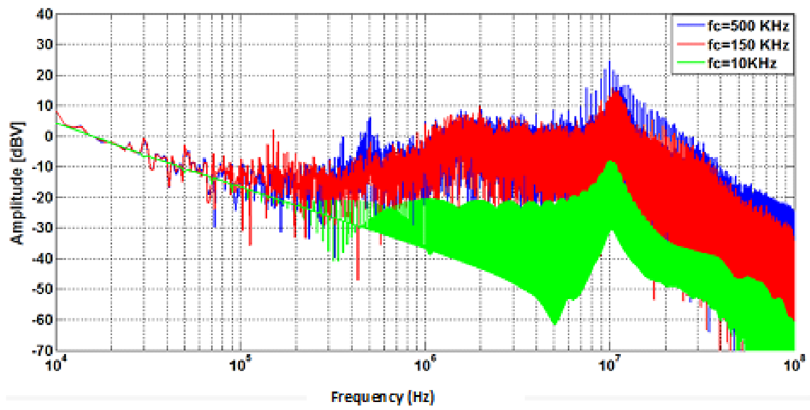
The analysis of the voltage spectra in CM and DM at the LISN, and the voltage at the load show that : The frequency spectrum of the voltage extends towards the HF as the rise time tm of the control signal of the switch considered (MOSFET) is low and it extends towards the LF when the rise time increases. The variation of the descent time t_d does not affect the frequency spectrum of the voltage. The increase in the switching frequency favors the spreading of the spectra towards the HF.



(a)



(b)



(c)

Figure 17. Influences of the switching frequency on the spectrum of the voltage at the load: (a) $f_{c,}$ (b) t_m, (c) t_d.

Conclusion

In this work, a SPICE model for predicting disturbances conducted within a DC/DC step-down converter is presented. The levels of EMC disturbances are directly related to the switching speed of the active components, in particular in common mode, therefore, the judicious choice of the types of power switches can contribute to the reduction of these disturbances.

The more the spectrum of the signal extends towards the HF, the more the EM interferences are more important. By then decreasing the HF content of the spectrum, it will be possible to reduce the effectiveness of the EM interferences. From the EMC problem, it is therefore advantageous to avoid fast switching and high duty cycles. From this work, our perspective is to compare the simulation results with experimental measurements which will do in the future.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgement

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