Application of Spread Spectrum Techniques for the Reduction of Disturbances of Automotive Power Electronic Converters

A. Bendicks, H. Haverland, S. Frei
TU Dortmund University, On-Board Systems Lab
Dortmund, Germany
andreas.bendicks@tu-dortmund.de

N. Hees, M. Wiegand
Leopold Kostal GmbH & Co. KG
Lüdenscheid, Germany

***Abstract*—This work deals with the application of spread spectrum techniques on power electronic converters to reduce the electromagnetic disturbances. Both, peak and average detector measurements are considered. For these emissions, respective optimum parameters are elaborated. These results are discussed and applied to a power electronic test setup. In this setup, the impact of spread spectrum on the emissions, the output voltage ripple, and the efficiency is investigated. By doing so, the advantages, disadvantages and possible problems of spread spectrum are pointed out.**

***Keywords*—Spread Spectrum, Power Electronics, EMI, Peak Detector, Average Detector**

I. Introduction

Power electronic converters are major sources for electromagnetic interferences (EMI) in automotive systems. As the number of converters is steadily increasing due to the proceeding electrification, there are more and more EMI sources. To prevent the disturbance of communication systems or e.g. safety critical sensor systems, the emissions of converters are limited by legal regulations [1] that are based on international standards [2]. Vehicle manufacturers often set even lower limits to ensure a proper function of every single component. Due to the demand for increasing power densities of the individual converters, effective solutions for EMI reduction are a necessity. Different passive strategies like filters and shields have been developed and investigated in the past. These strategies reduce the EMI that has been already caused by the power electronic system. Spread spectrum, on the other hand, is an active solution that partially prevents the occurrence of disturbances. Normally, power electronic converters operate at a fixed switching frequency causing distinctive harmonics in the frequency spectrum. By the application of spread spectrum, the switching frequency is varied over time. So, the power of the harmonics is distributed in the frequency spectrum and the respective maximum values drop.

There are many different works, e.g. [3], [4], [5], [6] and [7], analyzing the impact of spread spectrum on the peak emissions of clocked systems. In this work, additionally the average emissions are considered.

At first, the basics of a spectrum analyzer and the spread spectrum technique are introduced. Afterwards, the influence of spread spectrum on the peak and average emissions is analyzed. These results are discussed and applied to a test setup. In this setup, the peak and average emissions, the output voltage ripple and the efficiency are investigated for the application of spread spectrum. A summary and an outlook close this work.

II. Spectrum Analyzer Basics

For the analysis of emissions, a spectrum analyzer is used. In Figure 1, the basic structure is depicted [5]. There is a band-pass filter with a resolution bandwidth (RBW). As the spectrum analyzer shall measure a wide frequency band and the band-pass filter is fixed to its center frequency, the intermediate frequency, the input signal needs to be shifted in the frequency domain by a mixer and a local oscillator. Behind the RBW filter, there is an envelope detector to find the envelope of the signal. This signal is low-pass filtered with the video bandwidth to reduce noise on the instrument screen. At last, there is a detector block to evaluate the signal. In this work, two detectors are analyzed: peak and average. The peak detector searches for the highest value of the envelope of the signal. The average detector takes the mean of the envelope over time.

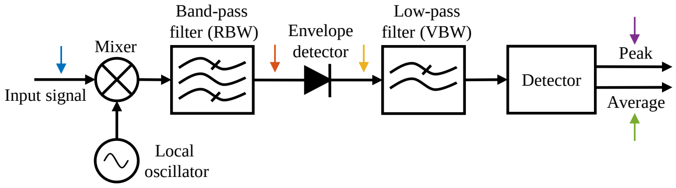

Figure 1: Basic structure of a spectrum analyzer [5]

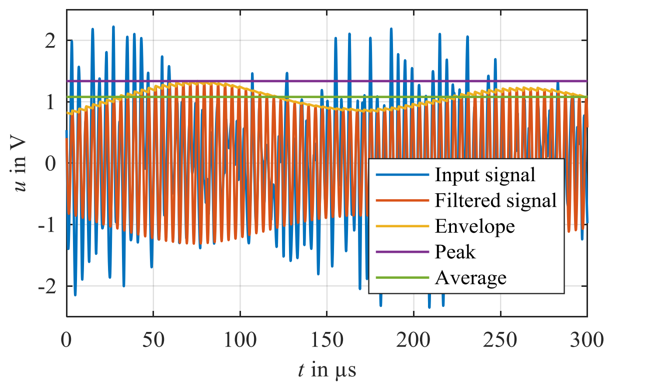

Figure 2: Simulated signals of a spectrum analyzer

In Figure 2, simulated signals are depicted. There is an amplitude modulated input signal that is superposed with white noise. The carrier frequency of the signal is at the center of the RBW filter (therefore the mixer can be neglected). Hence, a large part of the noise is blocked and the signal is passed. Next, the envelope is detected. This signal is measured by either peak or average detector (the VBW filter is neglected).

III. Spread Spectrum

In Figure 3, the basic principle of spread spectrum on power electronic converters is illustrated. In an unmodulated PWM signal, there is a fixed fundamental wave $f_{sw,nom}$ (blue) for the fundamental frequency. By the application of spread spectrum, the harmonic $f_{sw}(t)$ (red) is shifted in the frequency spectrum over time. The range for the variation is $\pm\Delta f$ around the nominal switching frequency $f_{sw,nom}$.

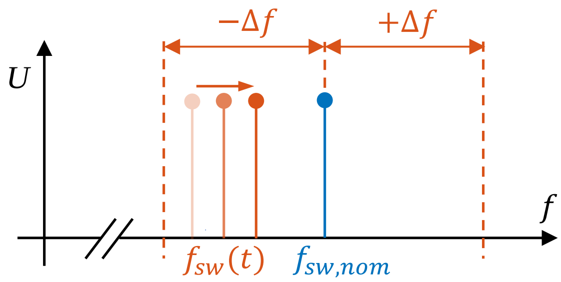

Figure 3: Principle of spread spectrum

As an example, the spectra of an unmodulated and a modulated PWM signal are compared. For both signals, a duty cycle $d = 0.5$, an amplitude of 1 V and a nominal switching frequency $f_{sw,nom} = 250$ kHz are assumed.

In Figure 4, a PWM signal without spread spectrum is depicted. The switching frequency is not modulated and therefore constant at 250 kHz.

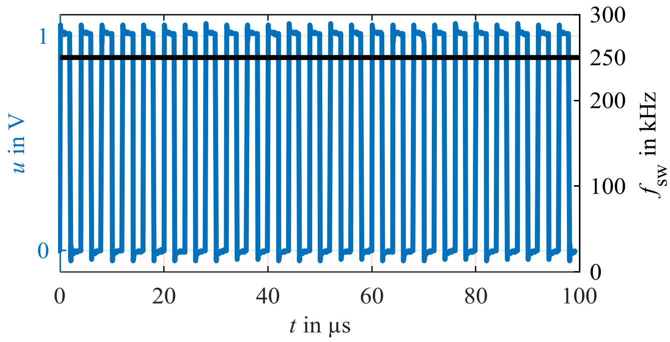

Figure 4: PWM signal without modulation

There are many different frequency modulation (FM) schemes including e.g. sinusoidal [3], cubic [4], triangular [4], or randomized waveforms [8]. As stated in [5], triangular modulation is simple, effective and most common. As theoretically derived in [6] and practically shown in [7], the related ramp modulation is even more effective. Hence, a linear ramp modulation is investigated in this work. In Figure 5, the modulated PWM signal can be seen. The switching frequency is varied by $\Delta f = \pm\ 25$ kHz over a modulation time of $T = 100$ µs. So, the switching frequency is linearly increased from 225 kHz to 275 kHz. Afterwards, the switching frequency instantly drops back to 225 kHz.

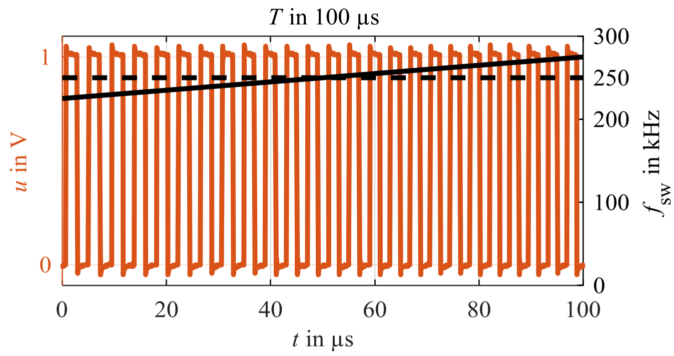

Figure 5: PWM signal with modulation

In Figure 6, the measured spectra of a PWM signal with and without modulation are shown. A RBW of 9 kHz has been used. According to [2], the sweep time of the spectrum analyzer is set so large, that multiples of the modulation time T are observed for each frequency point. This is valid for all measurements in this work. For the unmodulated PWM signal, the harmonics are at integer multiples of the switching frequency of 250 kHz [9]. Additionally, the harmonics drop with 20 dBµV per decade [9]. As there is a duty cycle of 0.5, the even harmonics are only weakly developed. For the first harmonic of the modulated signal, a plateau, known as Carson's bandwidth, can be identified reaching from 225 kHz to 275 kHz. This is the spreading caused by the modulation [10]. By this measure, the amplitude of the first harmonic is reduced by approximately 5 dBµV. For each following harmonic, the Carson's bandwidth is proportionally increased [10]. Due to this fact, the power of the harmonics is spread wider and the harmonics are attenuated even further.

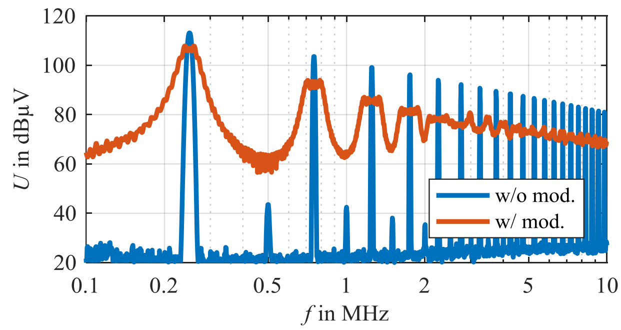

Figure 6: Spectra of an unmodulated and a modulated PWM signal, detector: peak, RBW = 9 kHz

IV. Effect on Peak Emissions

In this chapter, the influence of spread spectrum on the peak emissions is discussed. To do so, the peak value of the first harmonic is investigated. The nominal switching frequency is set to $f_{sw,nom} = 250$ kHz. The frequency derivation Δf and the modulation time T are varied over a wide range. The measured results are presented in Figure 7.

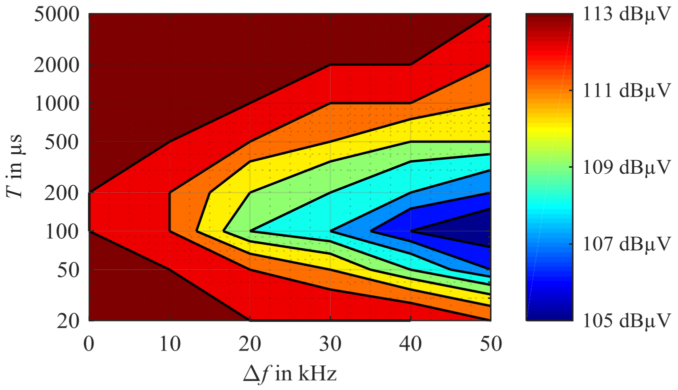

Figure 7: Parameter study on peak emissions, RBW = 9 kHz

If there is no modulation ($\Delta f = 0$ kHz), the peak is at approximately 113 dBµV. The higher the value of the frequency variation Δf, the lower the values of the peak drop. This is due to the fact that the power of the harmonic is spread over a wider frequency range. Interestingly, for all considered frequency variations, there is a dependency on the modulation time T. There is a minimum for $T \approx 100$ µs that roughly corresponds to the RBW of 9 kHz. This effect has also been shown in [5], [6] and [7]. For explanation, the Carson's bandwidth has to be investigated further.

At first, the ideal case is shown in Figure 8. It can be seen that the unmodulated signal has a peak value of 113 dBµV. Due to the modulation, the harmonic is spread over a wide frequency range. In the measurement with a RBW of 200 Hz, discrete frequency components with a spacing of $1/T = 1/100$ µs ≈ 10 kHz become visible [11]. If a RBW of 9 kHz is used, there are maximum values at 240 kHz and 260 kHz. Under consideration of the RBW at 260 kHz, it is obvious that there is only one frequency component having a significant influence on the peak value. So, a peak value of approximately 108 dBµV results.

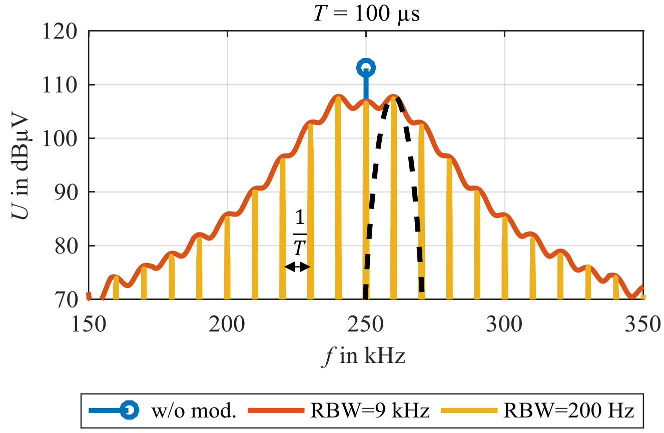

Figure 8: Peak spectra for an ideal modulation time and $\Delta f = 25$ kHz. Black line: RBW of 9 kHz at 260 kHz

Now, the modulation time is increased (Figure 9). Due to the finer spacing of $1/T = 1/200$ µs ≈ 5 kHz, the power is distributed to more frequency components and the individual values measured with a RBW of 200 Hz further drop. Nevertheless, there are now more frequency components inside of the RBW of 9 kHz that add up to a higher peak value (109 dBµV) than for $T = 100$ µs.

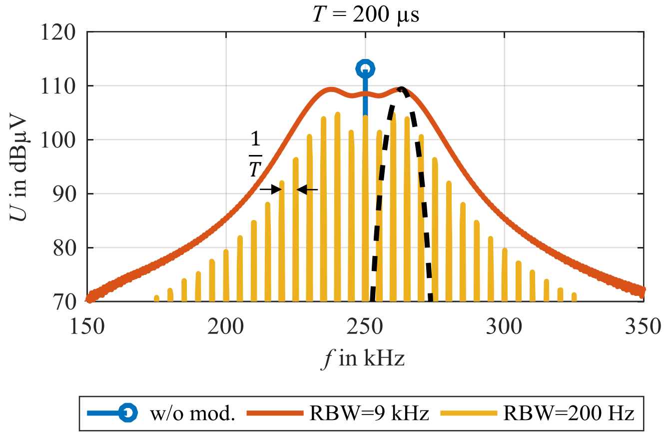

Figure 9: Peak spectra for a too large modulation time and $\Delta f = 25$ kHz. Black line: RBW of 9 kHz at 260 kHz

At last, the modulation time is decreased below the optimum value. In this case, there is still only one frequency component inside of the RBW. But, due to the higher frequency spacing $1/T = 1/50$ µs ≈ 20 kHz, each individual component carries more power. So, the peak value for the RBW of 9 kHz is increased to 112 dBµV.

So, to minimize the emissions measured with the peak detector, a modulation time of $T = 100$ µs is recommended. It is notable that the corresponding frequency of 10 kHz is in the audible spectrum. So, an annoying whistle may occur [4]. The frequency variation Δf should be as large as possible to minimize the measured peak emissions.

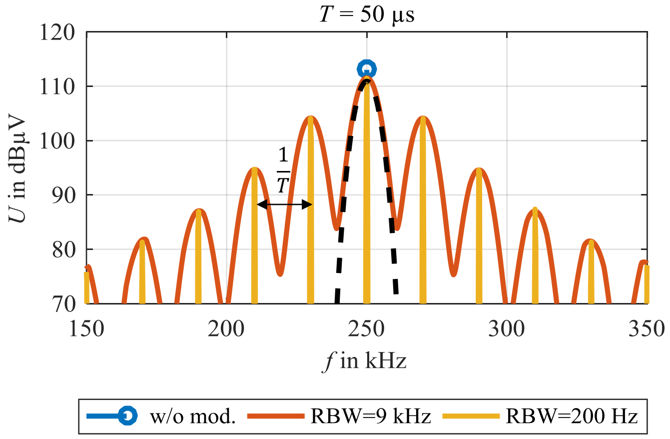

Figure 10: Peak spectra for a too small modulation time and $\Delta f = 25$ kHz. Black line: RBW of 9 kHz at 250 kHz

V. Effect on Average Emissions

In this chapter, the effects of spread spectrum on the average emissions of the first harmonic are discussed. At first, a parameter study is done with $f_{sw,nom} = 250$ kHz and RBW = 9 kHz. The result is shown in Figure 11.

For the unmodulated case, the emissions are at 113 dBµV again. From the discussion in II and III, it is clear that the average drops with an increasing frequency variation Δf as the power of the harmonics is spread in the frequency spectrum. Interestingly, there is no optimum value for the modulation time *T*. From the measured results, it can be seen that *T* should be above 1 ms. This value is much higher than the optimum value of 100 µs for the peak detector. To understand this effect, the time domain is investigated. The settling time of the input bandwidth filter may be calculated by $t_{settling} = 1/RBW = 1/9\ kHz \approx 111\ \mu s$ [11].

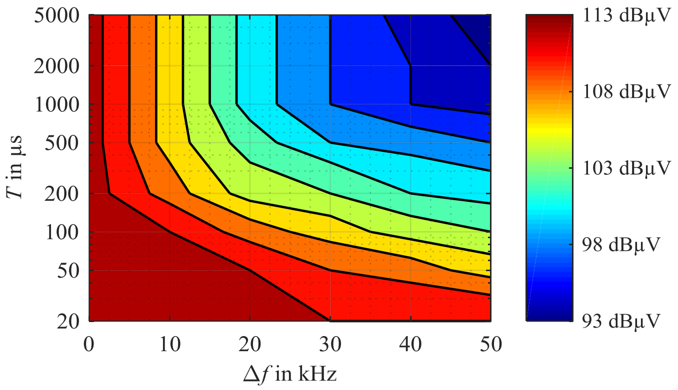

Figure 11: Parameter study on average emissions, RBW = 9 kHz

At first, an unmodulated signal is considered. In Figure 12, the simulated output voltage of the input bandwidth filter is depicted. To analyze the fundamental wave, the filter is virtually set to a center frequency of 250 kHz. Due to the constant envelope, both average and peak have a value of 624 mV.

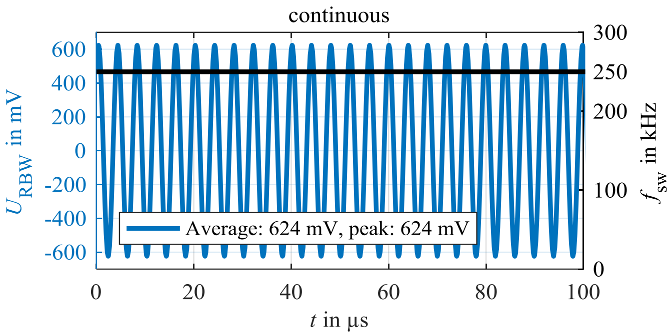

Figure 12: Simulated output voltage of the input bandwidth filter for an unmodulated PWM signal

Now, in Figure 13 (note the different time scale), a large modulation time *T* of 1 ms is considered. This value is much higher than the settling time of the bandwidth filter. So, the bandwidth settles and unsettles over a modulation period. There is a slight overshoot increasing the peak value to 636 mV. Due to the modulation, the average value of the envelope is reduced to 136 mV.

If the modulation time *T* is close to the settling time (e.g. 100 µs), the bandwidth filter does not settle (Figure 14). So, the maximum peak value is not reached. Additionally, there is not enough time for the bandwidth filter to unsettle. Due to this effect, a too short modulation time reduces the attenuation of the average emissions in comparison to a large modulation time.

So, for a maximum attenuation of the average, a modulation time much higher than the settling time of the input bandwidth is recommended.

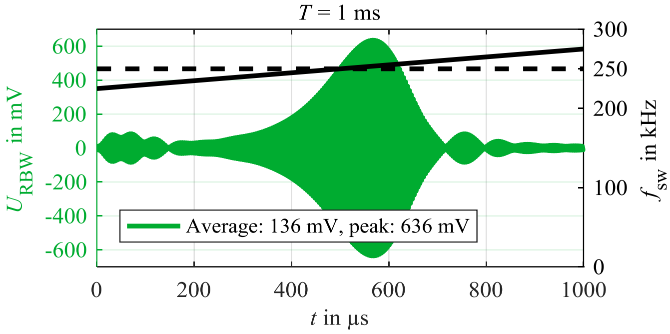

Figure 13: Simulated output voltage of the input bandwidth filter for a sufficient modulation time and Δ*f* = 25 kHz

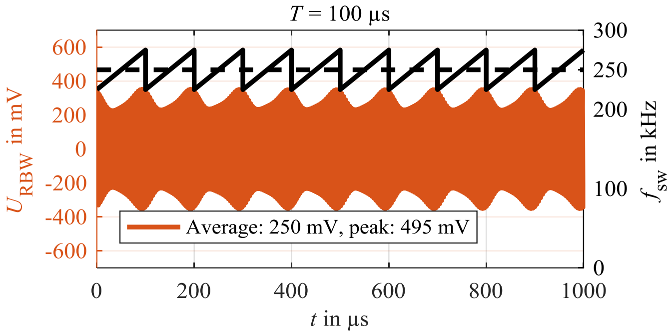

Figure 14: Simulated output voltage of the input bandwidth filter for a too short modulation time and Δ*f* = 25 kHz

VI. Considering EMI Victims

The major influence for both the attenuation of peak and average emissions is the RBW filter of the spectrum analyzer. This filter is designed to represent mainly either AM (bandwidth: 9 kHz) or FM (bandwidth: 120 kHz) broadcasting. So, spread spectrum should have the same impact on broadcast systems as on the spectrum analyzer. [2]

Nevertheless, there are also other possible EMI victims. Especially in automotive, there is an increasing number of susceptible sensors due to e.g. safety features or autonomous driving. Additionally, the number of potential EMI sources increases due to the proceeding electrification. In this requirement, spread spectrum may be a cost efficient solution to reduce the disturbances if the standard measurement is applied. However, there may be EMI victims that are not sufficiently considered by the standards. For the application of spread spectrum in this environment, the complete system has to be analyzed for susceptibilities.

VII. Application

In this chapter, spread spectrum is applied to a DC-to-DC converter that connects the vehicular voltage levels 12 V and 48 V. Figure 15 shows the considered test setup: There is a 12 V battery, a DC-to-DC converter, an artificial network and a load resistance of 26.7 Ω. The nominal switching frequency is $f_{sw,nom} = 250$ kHz. The duty cycle is manually adjusted so that there is always a DC output voltage of $U_{out} = 48$ V. There are three setups that are compared:

1. No modulation of the switching frequency.
2. Optimum attenuation of the **peak** emissions: modulation time $T = 100$ µs. The frequency deviation is chosen to $\Delta f = \pm 10\ \% \cdot f_{sw,nom} = \pm 25$ kHz.
3. Optimum attenuation of the **average** emissions: modulation time $T = 1$ ms. The frequency deviation is chosen to $\Delta f = \pm 10\ \% \cdot f_{sw,nom} = \pm 25$ kHz.

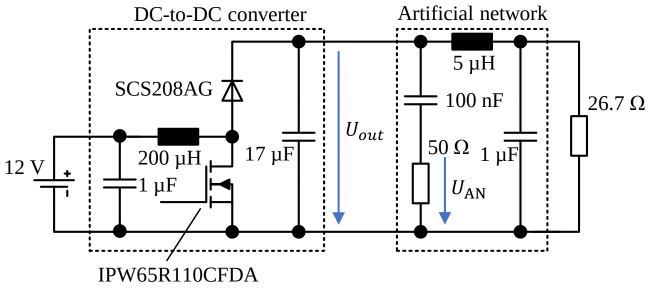

Figure 15: Test setup

A. *Electromagnetic Emissions*

To analyze the electromagnetic disturbances, CISPR 25 is applied [2]. The focus lies on the conducted emissions in the frequency range from 100 kHz to 10 MHz. So, an artificial network is used to measure the voltage U_{AN}. Furthermore, the RBW of the spectrum analyzer is set to 9 kHz. It is assumed that the converter must fulfill the limit for class 5 devices.

In Figure 16, the peak emissions are depicted. Obviously, all three setups produce much more EMI than permitted. As analyzed in IV, the peak emissions are minimized for a modulation time of $T = 100$ µs. A modulation time of $T = 1$ ms has no attenuating effect for the first harmonics of the converter. Even worse, the peak value is increased at some spectral frequencies.

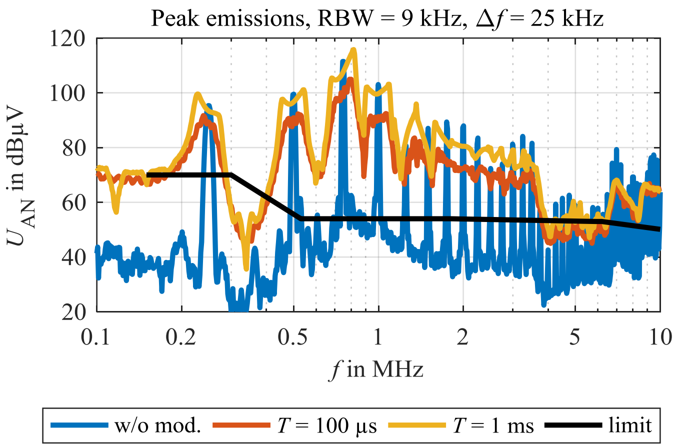

Figure 16: Peak emissions of the test setup

In Figure 17, the average emissions and the respective limit are shown. Both modulation times of $T = 100$ µs and $T = 1$ ms reduce the average emissions of the converter. As shown in V, the emissions are further reduced by a higher T.

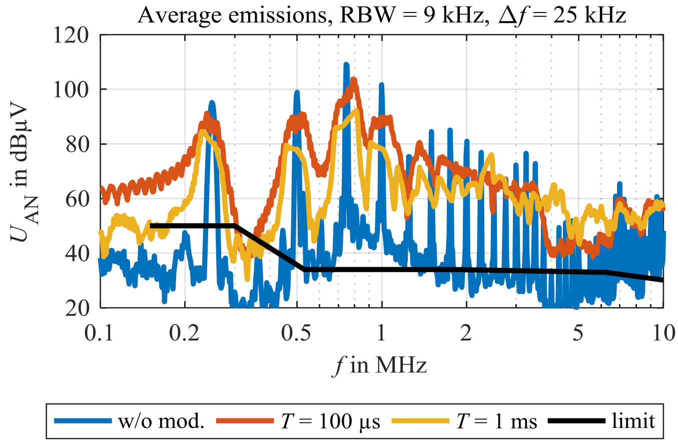

Figure 17: Average emissions of the test setup

To fulfill the EMI limits, additional filters have to be applied. In all spectra, the harmonic at 750 kHz must be attenuated the most. In Table 1, the necessary attenuations are listed. With a modulation time of $T = 100$ µs, the necessary attenuations for peak and average are respectively reduced to 51 and 70 dBµV. A longer modulation time of $T = 1$ ms further decreases the necessary average attenuation to 58 dBµV. Nevertheless, the necessary peak attenuation is increased to 62 dBµV. To evaluate the resulting filter effort, the effect of spread spectrum on the peak and average damping of passive filters has to be analyzed in future works.

Table 1: Necessary filter attenuation around 750 kHz

Setup	Necessary peak reduction	Necessary average reduction
w/o modulation	58 dBµV	75 dBµV
***T* = 100 µs**	51 dBµV	70 dBµV
***T* = 1 ms**	62 dBµV	58 dBµV

B. *Output Voltage Ripple*

At the output of the converter, there is a DC voltage of 48 V. Nevertheless, there is a ripple on U_{out} that is influenced by the application of spread spectrum as depicted in Figure 18. If the switching frequency is not modulated, there is the smallest voltage ripple of 2 V_{pp}. The short modulation time of $T = 100$ µs increases the ripple to 3.5 V_{pp}. The long modulation time of $T = 1$ ms causes a larger ripple of 11 V_{pp}. So, the modulation causes a low frequency oscillation in the system. To keep the resulting ripple low, a short modulation time is recommended. Obviously, the short modulation time of 100 µs is advantageous in this case.

As stated above, the duty cycle is set manually to fulfill the output DC voltage of 48 V. So, there is no voltage controller regulating the output voltage. In a practical application, there might be a feedback control system dynamically adjusting the duty cycle to realize the required output voltage. By doing so, the low frequency voltage ripple may be mitigated or even eliminated.

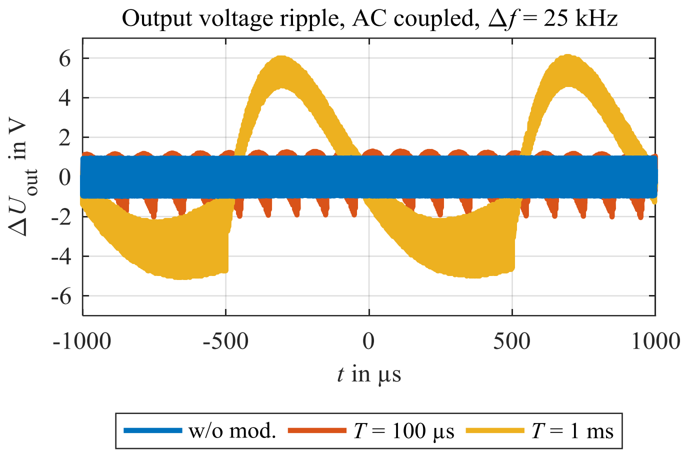

Figure 18: Output voltage ripple

C. Efficiency of the System

As the DC output voltage is set to 48 V, the converter supplies a power of $P_{out} = (48\ V)^2 / 26.7\ \Omega \approx 86.3\ W$ to the load resistor. The input powers for the different setups are listed in Table 2. The application of spread spectrum increases the power consumption of the converter from 112.1 W to approximately 118.7 W. As a result, the efficiency drops from 77.0 % to approximately 72.7 %. In these measurements, the modulation time has no influence. In comparison to [5], the efficiency drop is rather severe. As investigated in [12] and [13], nonlinearities may be the cause for the additional losses. So, in practical applications, this effect has to be considered if spread spectrum shall be applied.

Table 2: Efficiency of the converter

Setup	Input power	Output power	Efficiency
w/o mod.	112.1 W	86.3 W	77.0 %
***T* = 100 µs**	118.7 W	86.3 W	72.7 %
***T* = 1 ms**	118.6 W	86.3 W	72.8 %

VIII. Summary and Outlook

In this work, the influence of spread spectrum on peak and average emissions has been analyzed. For both the standardized peak and average measurements, it is recommended to spread the switching frequency over a wide range. To minimize the peak emissions, a modulation time slightly higher than 1/RBW is needed. For the maximum reduction of average emissions, the modulation time should be chosen much higher than 1/RBW.

In the setup of a boost converter, the results have been verified. Additionally, it has been shown that the modulation time should be short for a small output voltage ripple. Furthermore, there was a huge efficiency drop from 77.0 % to approximately 72.7 % caused by spread spectrum.

All in all, spread spectrum is a cost efficient solution to reduce the peak and/or average emissions of a power electronic system because only the switching frequency has to be varied over time. Nevertheless, there may occur a huge expense regarding efficiency if nonlinear terms dominate. Furthermore, a low frequency voltage ripple may develop if there is no voltage control. For the application in e.g. automobiles, it has to be evaluated if there are susceptible sensor systems that may be disturbed even though the EMI source fulfills the EMI demands of the manufacturer.

In this work, a ramp modulation has been used. As shown in [5] and [7], this modulation has proven to be the most effective deterministic scheme. Nevertheless, there are randomized modulation strategies that offer even higher performances [5]. It is proposed to analyze the impact of these stochastic strategies on the average detector of the standardized measurement equipment. Again, the susceptibility of peripheral systems has to be investigated.

As shown in this work, spread spectrum has different impacts on the peak and average detection of spectrum analyzers. This is due to the RBW of the input band-pass filter and its corresponding settling time. As passive EMI filters also have transient behaviors, they are affected by spread spectrum as well. So, to successfully implement spread spectrum, not only the standard measurement equipment must be considered but the whole system and its operational environment.

References

[1] "ECE R10 No. 10 – Electromagnetic Compatibility", Rev. 5, 2014

[2] "CISPR 25 – Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers", 2015

[3] F. Lin, D. Y. Chen, "Reduction of power supply EMI emission by switching frequency modulation", Power Electronics Specialist Conference, 1993. PESC '93 Record., 24th Annual IEEE, 1993

[4] K. B. Hardin, J. T. Fessler, and D. R. Bush, "Spread spectrum clock generation for the reduction of radiated emissions", IEEE International Symposium on Electromagnetic Compatibility, 1994

[5] F. Pareschi, R. Rovatti, G. Setti, "EMI Reduction via Spread Spectrum in DC/DC Converters: State of the Art, Optimization, and Tradeoffs", IEEE Access, Volume 3, pp. 2857-2874, 2015

[6] D. Stepins, "Conducted EMI of Switching Frequency Modulated Boost Converter", Electrical, Control and Communication Engineering, Volume 3, Issue 1, pp. 12-18, 2013

[7] B. Weiss, R. Reiner, R. Quay, P. Waltereit, F. Benkhelifa, M. Mikulla, M. Schlechtweg, and O. Ambacher, „Switching Frequency Modulation for GaN-Based Power Converters", Energy Conversion Congress and Exposition (ECCE), 2015

[8] S. Callegari, R. Rovatti, G. Setti, "Spectral Properties of Chaos-Based FM Signals: Theory and Simulation Results", IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, Volume 50, Issue 1, 2003

[9] C. R. Paul, "Introduction to Electromagnetic Compatibility", John Wiley & Sons, Inc., Hoboken, New Jersey, 2006

[10] H. S. Black, "Modulation Theory", New York, NY, USA: Van Nostrand, 1953

[11] J.-R. Ohm, H. D. Lüke, „Signalübertragung", Springer Heidelberg Dordrecht London New York, 2010

[12] J. Jankovskis, D. Stepins, D. Pikulin, "Efficiency of PFC Operating in Spread Spectrum Mode for EMI Reduction", ELEKTRONIKA IR ELEKTROTECHNIKA, No. 7, pp. 13-16, 2010

[13] J. Jankovskis, D. Stepins, N. Ponomarenko, "Effects of Spread Spectrum on Output Filter of Buck Converter", ELEKTRONIKA IR ELEKTROTECHNIKA, Volume 19, No. 7, pp. 45