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Interference of Spread-Spectrum Switching-Mode Power Converters and Low-Frequency Digital Lines

Francesco Musolino and Paolo S. Crovetti
Dept. of Electronics and Telecommunications (DET), Politecnico di Torino, I-10129 Torino, Italy
E-mail: {francesco.musolino},{paolo.crovetti}@polito.it
Phone: +39-011-090.4220

***Abstract*—The interference between switching mode power converters and wireline digital communications is addressed in this paper and the impact on communication errors of different Spread Spectrum (SS) modulation techniques, which are commonly used in power convertors to comply with EMC regulations, is experimentally investigated in a particular case. Experimental results do not highlight significant differences in terms of communication error rate induced in the victim data line between power converters featuring conventional and SS pulse width modulations.**

I. Introduction

Electromagnetic emissions (EME) from switching-mode power converters can be a threat to the operation of present-day information and communication technology (ICT) electronic systems and need to be carefully controlled in order to meet the more and more stringent Electromagnetic Compatibility (EMC) regulations [1-3].

In this context, several techniques based on the frequency modulation of periodic signals potentially generating electromagnetic interference (EMI), generally known as *Spread-Spectrum (SS) techniques*, have been extensively proposed as simple, low cost solutions to mitigate EMC problems and are widely employed in practice [4].

The real value of SS techniques as a mean to reduce the potential adverse effects of EMEs is a more controversial matter and has been sometimes questioned [5-6]. Under this perspective, however, the effectiveness of SS techniques in mitigating interference in a case of practical importance has been shown in [7]. Nonetheless, in that work, a specific aggressor (a digital circuit) and a specific victim (an analog FM radio) have been considered and the results presented there are not sufficient to state the general value of SS as a mean to avoid interference in all the potential aggressors in which such techniques are nowadays commonly employed. In particular, the effectiveness of SS techniques in low-frequency switching mode electronic power converters, whose radiated and conducted EMEs could interfere with present day baseband ICT digital systems has not been specifically considered.

To this purpose, characteristics of EMEs originating from power converters and their interfering potential is first compared with [7], highlighting important differences. Then, the interference of a DC-DC power converter with a baseband digital data line is considered as a test case and the impact of SS modulations on the transmission errors induced in the digital line by the DC-DC converter is discussed to investigate the effectiveness of such a technique in that specific case.

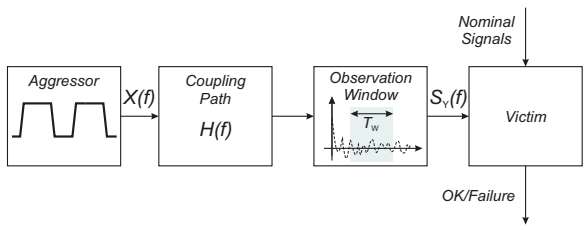

Fig. 1. Generic interference scenario.

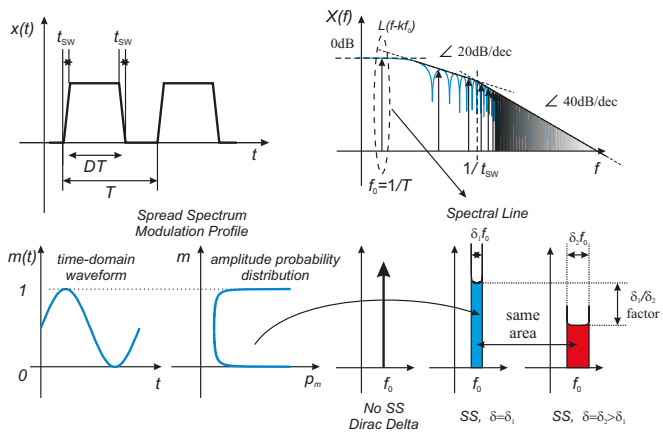

Fig. 2. Relevant waveforms and definitions: square wave signal in the time and in the frequency domain, spread spectrum modulation profile and its amplitude distribution, impact of the modulation index on the shape of the spectral line.

II. Effectiveness of Spread Spectrum Modulations in Different Application Scenarios

In order to discuss the effectiveness of SS techniques, the general scenario depicted in Fig.1 is considered in this paper. Here, an aggressor - like a power converter or a digital circuit - whose operation is based on a square-wave switching waveform, as depicted in Fig.2, interferes with an electromagnetically coupled victim circuit in a time window T_W, potentially causing failures. Within such a system, it is assumed that the signal originating interference (e.g. the clock signal in a digital circuit or the control signal of power

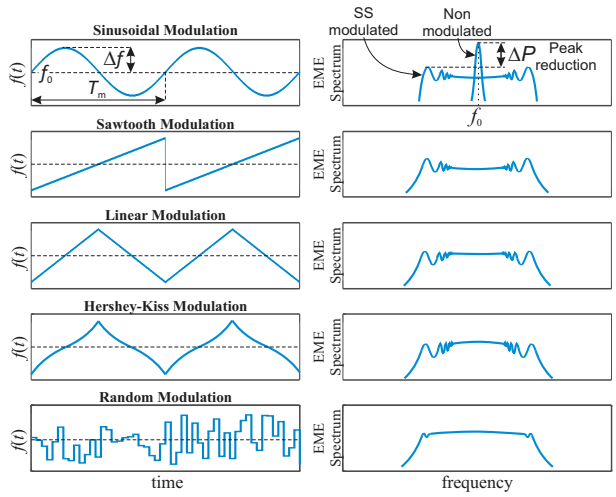

Fig. 3. Spread spectrum modulations and their output spectra.

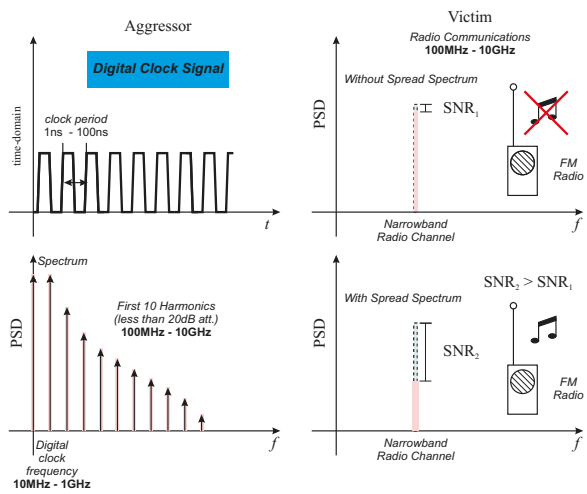

Fig. 4. Interference of digital devices with analog radio communications.

transistors in a converter) is a square wave with a period T, a duty cycle D and equal rising/fall times t_{SW}, expressed as

$$x(t) = \sum_{k=-\infty}^{+\infty} p_{DT,t_{\mathrm{SW}}}(t - kT) \tag{1}$$

where $p_{DT,t_{\mathrm{SW}}}(t)$ is the convolution product

$$p_{DT,t_{\mathrm{SW}}}(t) = \Pi_{DT}(t) * \Pi_{t_{\mathrm{SW}}}(t), \tag{2}$$

and the rectangular pulse $\Pi_\tau(t)$ is defined as

$$\Pi_\tau(t) = \begin{cases} 1 & 0 < t < \tau \\ \frac{1}{2} & t = 0 \wedge t = \tau \\ 0 & \text{elsewhere.} \end{cases}$$

Since the Fourier transform of the signal $x(t)$ can be expressed as

$$X(f) = \mathrm{sinc}\,(f t_{\mathrm{SW}}) \sum_{k=-\infty}^{+\infty} |k| f_0 \,\mathrm{sinc}\,(kD) L\,(f - k f_0)\, \mathrm{e}^{-jkD} \tag{3}$$

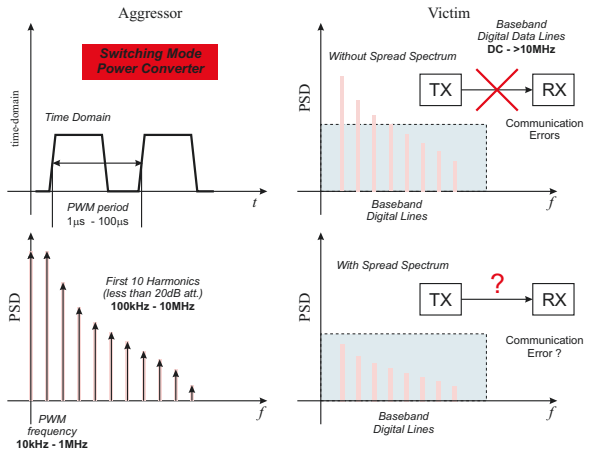

Fig. 5. Interference of power electronic converters with baseband wireline communications.

where $f_0 = \frac{1}{T}$ is the fundamental frequency and $L(x)$ is the spectral line function, which tends to the Dirac distribution $\delta(x)$ for an ideal periodic signal, the power spectral density of EME coupled with a victim equipment in a time window T_W can be written in the form

$$S_y(f) = T_W^2 \left|[H(f)X(f)] * \mathrm{sinc}(fT_W)\right|^2 \tag{4}$$

where $H(f)$ is the transfer function describing the coupling between the aggressor and the victim.

In this framework, a SS modulation of the instantaneous frequency $\hat{f} = \frac{1}{T(t)}$ of the square wave $x(t)$

$$\hat{f}(t) = f_0 \left[1 + \frac{\Delta f}{f_0} m(t)\right] = f_0 \left[1 + \delta \cdot m(t)\right], \tag{5}$$

where f_0 is the central frequency, Δf is the maximum frequency deviation and $0 \leq m(t) \leq 1$ is the modulation profile, that is normally chosen among sinusoidal, sawtooth, linear, Hershey-Kiss or pseudo-random/chaos based SS modulations, as shown in Fig.3 [4] and $\delta = \Delta f / f_0$ is the modulation index, is often applied to mitigate the interfering potential of the aggressor.

By applying the modulation in (5), in fact, the spectral line function appearing in (3) can be expressed as

$$L(f) = \frac{1}{\Delta f} \cdot p_m\left(\frac{f}{\Delta f}\right) \tag{6}$$

where $p_m(x)$ is the amplitude probability distribution function (pdf) of the modulation profile $m(t)$ appearing in (5), as illustrated in Fig.2. Being the integral of the pdf normalized to one, the integral over frequency of the spectral line functions appearing in (3) are not affected by the modulation. Nonetheless, the energy content of the spectral line is spread over a frequency interval proportional to the modulation index δ and the peak value of the spectral line is scaled by the same factor. Under the hypothesis that the time window T_W is much larger compared with the modulation frequency, the same reduction can be observed in the power spectral density of the signal received by the victim and such a reduction in the PSD of the

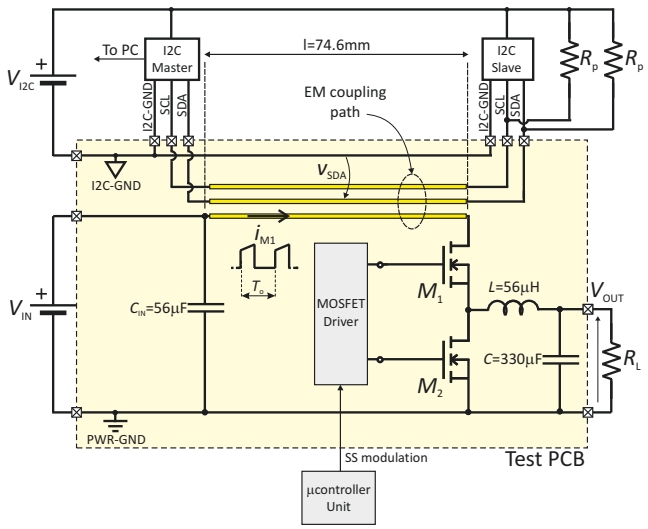

Fig. 6. Schematic view of the test setup.

disturbances coupled with the victim motivates the adoption of SS techniques for EMC purposes. The validity of such an assumption is considered in what follows.

When the interference of a digital device with analog FM radio is considered, as in [7], EMEs are mostly related with the clock waveform, which can be identified with the signal $x(t)$ considered the previous Section. Such square wave has a period T in the 1ns-100ns range, and rising/falling edges t_{SW} in the 100ps-10ns range. As a consequence, EMEs have a fundamental frequency ranging from 10MHz up to 1GHz or more and, depending on the coupling $H(f)$, may show relevant energy content in the whole 10MHz-10GHz frequency range, as depicted in Fig.4. As such, a digital aggressor device, may interfere with victims operating in a wide frequency range, which includes frequencies used for radio communications. Focusing on narrow-band analog FM radio channels, if one of the first harmonics of the clock frequency falls in correspondence of a narrowband (<9kHz) radio channel, it gives rise to a significant degradation of the signal-to-noise ratio (SNR) and impairs the operation of radio receivers close to the aggressor, as highlighted in the same figure.

In this specific case, SS modulations, distribute the spectral content at the harmonics of the clock signal over a wider a bandwidth, give rise to a significant increase of the signal-to-noise ratio (SNR) in the bandwidth of the victim and make it possible to preserve the functionality of the victim FM radio receiver, as demonstrated in [7].

When potential interference originated by electronic converters is considered, however, the period T of the square wave waveform originating from the operation of the power switches and their drivers, is in the 1μs-100μs range and the rising/falling edges t_{SW} are in the 10ns-1us range. In such a situation, which is depicted in Fig.5, potential interfering EMEs from power converters have a fundamental frequency ranging from 10kHz to 1MHz and show relevant energy content only below 10MHz.

Considering that radiation is less efficient at such low frequencies and that they overlap in a minimum part with the bandwidth allocated for radiocommunications (long-wave LW, medium wave, MW and part of short-wave SW AM analog radio), potential interference with radio equipment can be regarded as a relatively minor concern. By contrast, the frequency range of EMEs from power converters (fundamental and most relevant harmonics) fully overlaps the frequency range of baseband processing and communications, which are mostly digital in present day electronic systems. In such a situation, the overall energy coupled in the victim bandwidth is not affected by SS modulations and the effectiveness of such modulations in reducing the interference potential of power converters is not obvious.

Based on these considerations, the effectiveness of SS in reducing the interfering potential of power converters with digital data lines is investigated on an experimental basis.

III. Experimental Test Setup

The test setup in Fig.6, which includes a DC-DC power converter intentionally designed to interfere with a digital data link, is considered in this paper.

The power converter is a hard-switched synchronous Buck operated from an input voltage $V_{\mathrm{IN}} = 16\mathrm{V}$ and connected to a load $R_{\mathrm{L}} = 10\Omega$ in open-loop mode with a fixed duty cycle $D = 0.375$. Such a converter is driven by a PWM signal generated by a micro-controller programmed so that the instantaneous frequency $f(t) = 1/T(t)$ of the PWM waveform varies according with the modulation law (5), where the modulation profile $m(t)$ can be chosen to implement the sinusoidal, sawtooth, linear, Hershey-Kiss and Random SS modulations shown in Fig.3 and the modulation index δ can be varied from 0% (no SS) to 16%. For periodic modulations (i.e. all except the random SS profile), the period of the modulating signal $T_{\mathrm{m}} = 1/f_{\mathrm{m}}$ is set equal to 100μs.

The digital data link has been established between two units by an Inter-Integrated Communication (I2C) bus which is a two-wire, master-slave, bidirectional serial bus commonly employed for short range digital communications [8]. The link has been configured for a 1 Mbit/s data rate and both the serial data line (SDA) and the serial clock line (SCL) have been connected to the 3.3V positive supply voltage V_{I2C} via two pull-up resistors $R_{\mathrm{p}} = 3.3\mathrm{k}\Omega$. Their ground reference, indicated as I2C-GND in Fig.6, is isolated with respect to the reference voltage PWR-GND of the DC-DC converter.

In order to couple the EME from the power converter to the I2C link, the converter has been designed on a specific two-layer test printed circuit board (PCB), where the power trace carrying the time varying current i_{M1} in Fig.6 and the SDA and the SCL lines of the I2C bus are routed close to each other, causing disturbances to propagate from the converter to the bus due to both inductive and capacitive coupling.

IV. Experimental Results

The experimental procedure described so far has been first performed switching off the DC-DC converter and no trans-

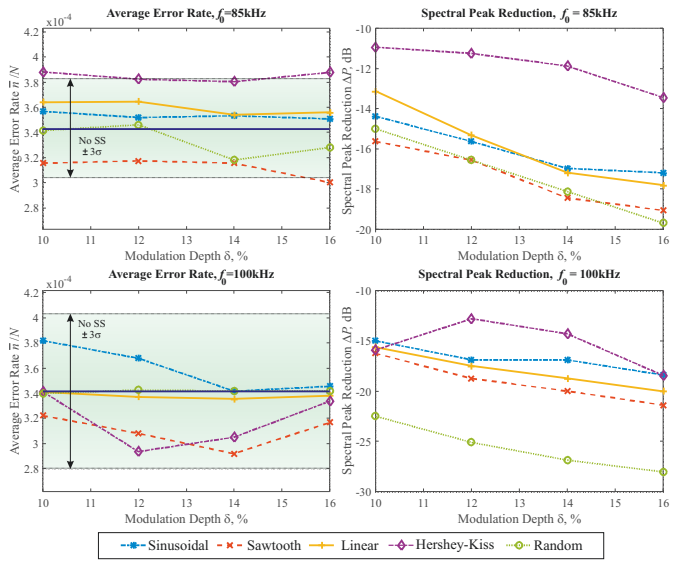

Fig. 7. Measurement results: average error rate $\bar{n}/N$ (left) and spectral peak reduction ΔP (right) versus the modulation depth δ for switching frequency $f_0 = 85$kHz (top) and $f_0 = 100$kHz (bottom) for different SS modulation profiles.

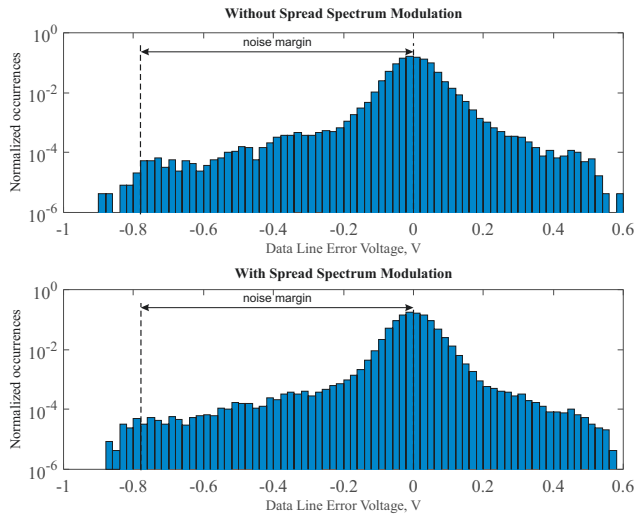

Fig. 8. Histogram of victim line error voltage with $f_0 = 100$kHz with no SS modulation (top) and with random SS modulation for $\delta = 16\%$ (bottom).

mission errors have been observed. Then, the power converter has been operated with a PWM frequency of $f_0 = 85$kHz (100kHz) without SS modulation and an average number of errors due to the EMI from the power converter, of $\bar{n} = 342.9$ ($\bar{n} = 341.7$) with a standard deviation of $\sigma = 13.1$ ($\sigma = 20.3$) have been detected in 30 sequences of 10^6 test cycles. Finally, the same measurements have been repeated with the SS modulation profiles in Fig.3 for different modulation depths $\delta = 10\%, 12\%, 14\%$ and 16%. Moreover, for each of the above modulations, the spectrum of the SDA line voltage (v_{SDA} in Fig.6) has been measured with the data link turned off by means of a spectrum analyser setting the resolution bandwidth as specified in [2]. The spectral peak reduction around f_0 obtained using SS modulations compared to the non modulated case has been evaluated.

The error rate $\bar{n}/N$ obtained in these measurements has been reported in Fig.7 (left plots) where the same quantity measured without SS modulations and its $\pm 3\sigma$ bounds are also plotted. In the same figure (right plots), the spectral peak reduction ΔP is also reported.

The test results shown in Fig.7 confirm a relevant spectral peak reduction due to SS modulation ranging from -10 up to -30dB, generally increasing with the modulation depth. However, it can be observed that the average error rate in the data link is substantially not affected by the SS modulations and the modulation depth since for all the cases it is within the $\pm 3\sigma$ bounds of the non-modulated case.

To get further insight into the effects of SS on the mechanism leading to data line error, the DC-DC converter has been operated with the I2C SDA line in an idle state ($v_{\mathrm{SDA}} = V_{\mathrm{HI}}$) and $L = 1.2 \cdot 10^6$ samples of the SDA line voltage v_{SDA} have been acquired at 1GS/s by a digital oscilloscope. The test has been repeated without SS modulation and with the SS modulations considered above. The histogram of the line error voltage[1] $V_\varepsilon = v_{\mathrm{SDA}} - V_{\mathrm{HI}}$, is reported in Fig.8 for $f_0 = 100$kHz without SS and with a random SS modulation for $\delta = 16\%$. It can be observed that the histograms with and without SS modulation are similar and the percentage of measured samples exceeding the noise margin, which are reported in the same figure for reference, is of the same order of magnitude of the average error rates in Fig.7.

Based on the experimental results reported in Fig.7 and on the histograms in Fig.8, in the specific case here considered, the introduction of SS modulation does not affect the communication errors induced by EME from the DC-DC converter and the I2C data link in a significant way. The same conclusion could be reasonably extended to the interference generated by power converters with other baseband digital ICT equipment, operating in a similar frequency range, which surely represents a large percentage of possible victims. This suggests that more investigations are needed in order to assess the effectiveness and the limitations of SS techniques in reducing EMI between DC-DC converters and digital equipment.

V. Conclusion

In this paper, the effectiveness of SS modulations as a mean to mitigate the potential adverse effect of EME generated by DC-DC power converters on digital data lines is experimentally investigated with reference to an I2C data link. Even if a significant reduction of the power spectral density of the EME generated on the data line has been observed, the experimental results do not highlight a reduction in the communication error rate when SS-modulated PWM rather than conventional PWM is used. Moreover, it has also been observed that the amplitude distribution of disturbances generated by SS-modulated and non-modulated PWM signals are similar.

[1] In each bin at position V the number of the samples with an error ranging from V to V+ΔV, where ΔV=20mV, normalized with respect of the total number of samples L id reported.

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