Model of Errors Caused by Discrepancies in Gain and Phase of Input Channels in TDEMI system

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Abstract. *Multiresolution analog-to-digital converter (MRADC) is used for very fast signal sampling with sufficient dynamic range in Time domain electromagnetic interference (TDEMI) measuring system for spectrum measurements. Properties of resulting spectrum influenced by imperfections in MRADC are analyzed in the paper. For precise estimation of errors caused by differences of gain and phase shift in parallel channels concept of error signal of cosine shape pulses have been considered in the model. Mathematical model of spectral error using this concept has been created.*

Keywords: Time Domain EMI Measurement, Multiresolution Quantization, Gain and Phase Error

1. Introduction

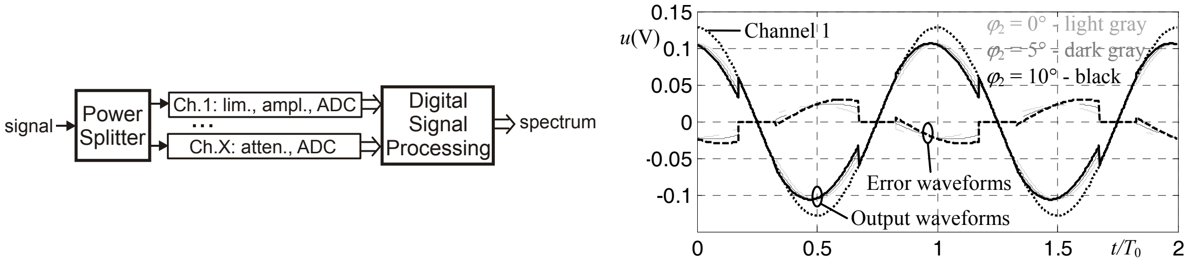
Measuring of electromagnetic interference (EMI) spectra is obviously long lasting procedure. Super heterodyne principle used in conventional analog EMI receivers or spectrum analyzers provides high dynamic range. However, only one narrow frequency band is transferred to the detector via the intermediate frequency amplifier at the time. Therefore time-consuming sweeping through the whole bandwidth is needed and several tens of minutes are often required to complete the whole EMI spectrum measurement by measuring receiver.

EMI measurements according to standards are required for commercial production of electronic equipment. Development of new faster principles leads to reduction of costs and time to market. Time domain EMI (TDEMI) system [1] was introduced quite recently. It is based on FFT spectrum estimation performed by fast DSP aids in connection with multiresolultion analog-to-digital converter (MRADC) technology, which engages several parallel ADC channels to achieve required high dynamic range of the system [2].

In traditional systems with one input channel or individual channels (like spectrum analyzer or oscilloscope) there is always compromise between bandwidth processed at the time and dynamic range. TDEMI devices process complete spectral content at the time. However new error sources arise in the system where parallel channels with different characteristics are used. Errors caused by those differences seem to be serious sources of spurious spectral components. Model of error spectrum is discussed in the paper, which should help to understand leakage of spurious higher harmonics in spectrum obtained for simple harmonic input signal. The model considers gain and phase error of MRADC.

2. TDEMI and concept of error model

Principal block structure of TDEMI device is depicted in Fig. 1a. Power splitter distributes analog signal to all parallel paths. Recently 3 channels are usual. Limiter protects ADC from out of range voltage. Separate amplifiers/attenuators provide different range and voltage resolution of individual channels. All channels are simultaneously sampled and converted by identical 8 or 10 bit very fast flash ADCs. Final discrete value is created by extracting the output from that ADC offering the best resolution but with the range still covering the actual input value. Short time Fast Fourier transform (FFT) is finally applied to sampled data [3].



a) b)

Fig. 1. Principal of TDEMI: a) Block structure of TDEMI system; b) examples of waveforms

Even if perfectly realized a quantization system like MRADC generates disturbance in spectrum of e.g. harmonic signal [4] due to quantization error. However practical experience shows that in real systems there are more serious sources of errors. Amplitude and phase frequency characteristics in each channel are not perfectly matched in the whole frequency range. Moreover it is hardly possible to avoid slope difference between channels. So serious signal discontinuities arise in points where the system switches from one ADC output to another. Spurious spectrum components generated by those discontinuities significantly restrict spurious free dynamic range of real TDEMI device for continues input signal types.

Harmonic input signal may be considered as suitable for modeling the measured interference of devices operating on switched mode power supply principle, where disturbance is like a mixture of sinusoids. For harmonic input signal differences between channels result in disturbances similar to time-domain error pulses like sketched in Fig. 1b (see error waveforms). For theoretical analysis of discontinuities present in the waveform reconstructed from sequence of samples the erroneous waveform could be simply modeled as additive impulsive error signal. In [5] simplified error model was based on rectangular pulses. However for gain and phase error it more suitable to use pulses of cosine shape like proposed in this paper.

3. Derivation of the model

Consider pure harmonic input signal

$$u_{\mathrm{in}}(t) = A_{\mathrm{in}} \cos(\omega_0 t) \tag{1}$$

Spectrum of ideal harmonic signal has only one component. As spectrum of sum of two signals is the sum of both signal spectra the higher harmonics present in MRADC output waveform are just higher harmonics of error signal. If we identify higher harmonics of error pulses, those could be regarded as theoretical spurious components in measured spectrum. The first harmonic of error waveform still means corruption of value of the first harmonic shown by the measuring unit.

Let us consider gain error and phase between channels. For the harmonic input signal two error pulses are typical within the interval of one period (t_0; t_0+T_0) for zero offset and amplitude higher than range R_1 of the channel 1 but still in range of channel 2, like in examples depicted in Fig. 1b. Time representation of error could be expressed as

$$u(t) = \begin{array}{ll} A_{\mathrm{e}} \cos(2\pi f_0 t + \varphi_{\mathrm{e}}) & \text{for} \quad \left(\left[(t - t_0) \bmod T_0\right] + t_0\right) \in \langle t_{\mathrm{r}1}, t_{\mathrm{f}1}) \cup \langle t_{\mathrm{r}2}, t_{\mathrm{f}2}) \\ 0 & \text{for} \quad \left(\left[(t - t_0) \bmod T_0\right] + t_0\right) \notin \langle t_{\mathrm{r}1}, t_{\mathrm{f}1}) \cup \langle t_{\mathrm{r}2}, t_{\mathrm{f}2}) \end{array} \tag{2}$$

Time values of rising and falling edge $t_{\mathrm{r}1}$, $t_{\mathrm{f}1}$ apply for the first pulse while $t_{\mathrm{r}2}$, $t_{\mathrm{f}2}$ for the second one. We assume that the MRADC system switches from the first channel to the second, or vice-versa, when the value from the first channel is just crossing its range R_1. And we will take the signal from channel 1 for reference so (1) represents channel 1 signal. To start with rising edge we could write following formulas for time parameters of one period ($-T_0/4$; $-T_0/4+T_0$) of error pulse signal

$$t_{\mathrm{r}1} = -\frac{T_0}{2\pi}\arccos\left(\frac{R_1}{A_{\mathrm{in}}}\right) \ ; \ t_{\mathrm{f}1} = -t_{\mathrm{r}1} \ ; \ t_{\mathrm{r}2} = t_{\mathrm{r}1} + \frac{T_0}{2} \ ; \ t_{\mathrm{f}2} = t_{\mathrm{f}1} + \frac{T_0}{2} \tag{3}$$

If there is phase shift φ_2 between channels we should expect nonzero phase φ_{e} of harmonic signal forming inner part of error pulses. Phase φ_{e} and amplitude A_{e} of error could be found from difference of voltage phasors of both channels

$$A_{\mathrm{e}}\angle\varphi_{\mathrm{e}} = A_{\mathrm{in}}\angle 0 - A_{\mathrm{in}}\left(\delta G_2 + 1\right)\angle\varphi_2 \tag{4}$$

where δG_2 is relative gain error of channel 2 in comparison with channel 1.

As there are two error pulses per period T_0 we will form the model of error spectrum from two members

$$\mathbf{U}_{\mathrm{COS},n} = \mathbf{U}_{\mathrm{CP},n}\left(f_0, t_{\mathrm{r}1}, t_{\mathrm{f}1}, A_{\mathrm{e}}, \varphi_{\mathrm{e}}\right) + \mathbf{U}_{\mathrm{CP},n}\left(f_0, t_{\mathrm{r}2}, t_{\mathrm{f}2}, A_{\mathrm{e}}, \varphi_{\mathrm{e}}\right) \tag{5}$$

We have already recognized all parameters entering into analytical expression (5) of error model. However formulas for spectral components $\mathbf{U}_{\mathrm{CP},n}=f(f_0,A,t_{\mathrm{r}},t_{\mathrm{f}},\varphi)$ of a pulse of cosine shape have to be identified. Considering exponential form of Fourier series we have derived following expressions for real and imaginary part of complex spectral components

$$\mathrm{Re}\left\{\mathbf{U}_{\mathrm{CP},0}\right\} = \frac{A}{2\pi}\left[\sin\left(2\pi f_0 t_{\mathrm{f}} + \varphi\right) - \sin\left(2\pi f_0 t_{\mathrm{r}} + \varphi\right)\right] \tag{6}$$

$$\mathrm{Re}\left\{\mathbf{U}_{\mathrm{CP},1}\right\} = \frac{A f_0}{2}\left(t_{\mathrm{f}} - t_{\mathrm{r}}\right)\cos(\varphi) + \frac{A}{8\pi}\left(\sin\left(4\pi f_0 t_{\mathrm{f}} + \varphi\right) - \sin\left(4\pi f_0 t_{\mathrm{r}} + \varphi\right)\right) \tag{7}$$

$$\mathrm{Im}\left\{\mathbf{U}_{\mathrm{CP},1}\right\} = \frac{A f_0}{2}\left(t_{\mathrm{f}} - t_{\mathrm{r}}\right)\sin(\varphi) + \frac{A}{8\pi}\left(\cos\left(4\pi f_0 t_{\mathrm{f}} + \varphi\right) - \cos\left(4\pi f_0 t_{\mathrm{r}} + \varphi\right)\right) \tag{8}$$

and (for $n>1$)

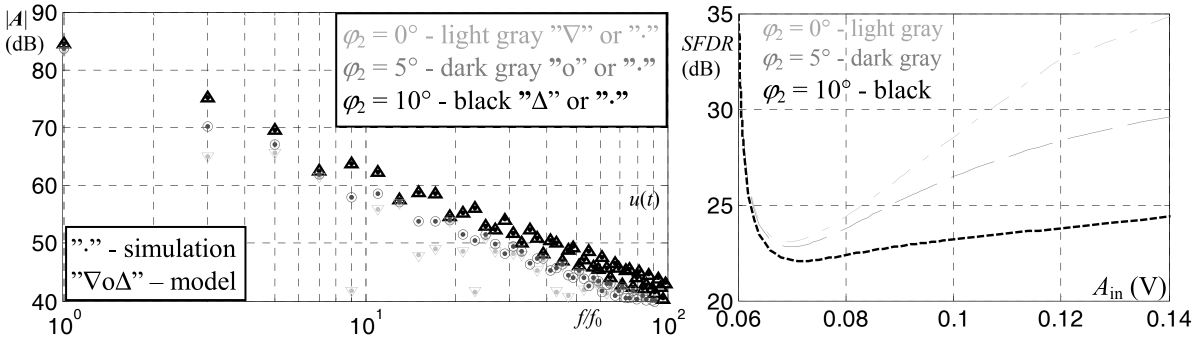
$$\begin{aligned}\mathrm{Re}\left\{\mathbf{U}_{\mathrm{CP},n}\right\} = \frac{A}{2\pi\left(n^2-1\right)}\Big\{& n\cos\left(2\pi f_0 t_{\mathrm{f}} + \varphi\right)\sin\left(n 2\pi f_0 t_{\mathrm{f}}\right) - \sin\left(2\pi f_0 t_{\mathrm{f}} + \varphi\right)\cos\left(n 2\pi f_0 t_{\mathrm{f}}\right) \\ & - n\cos\left(2\pi f_0 t_{\mathrm{r}} + \varphi\right)\sin\left(n 2\pi f_0 t_{\mathrm{r}}\right) + \sin\left(2\pi f_0 t_{\mathrm{r}} + \varphi\right)\cos\left(n 2\pi f_0 t_{\mathrm{r}}\right)\Big\}\end{aligned} \tag{9}$$

$$\begin{aligned}\mathrm{Im}\left\{\mathbf{U}_{\mathrm{CP},n}\right\} = \frac{A}{2\pi\left(n^2-1\right)}\Big\{& n\cos\left(2\pi f_0 t_{\mathrm{f}} + \varphi\right)\cos\left(n 2\pi f_0 t_{\mathrm{f}}\right) + \sin\left(2\pi f_0 t_{\mathrm{f}} + \varphi\right)\sin\left(n 2\pi f_0 t_{\mathrm{f}}\right) \\ & - n\cos\left(2\pi f_0 t_{\mathrm{r}} + \varphi\right)\cos\left(n 2\pi f_0 t_{\mathrm{r}}\right) - \sin\left(2\pi f_0 t_{\mathrm{r}} + \varphi\right)\sin\left(n 2\pi f_0 t_{\mathrm{r}}\right)\Big\}\end{aligned} \tag{10}$$

4. Results

Properties of proposed theoretical model were compared with simulation results. Parameters of simulated TDEMI system are roughly apparent from curves shown in Fig. 1b. Switching level R_1=60 mV was used while input signal amplitude was A_{in}=128 mV. For generalization channel 1 is considered ideal with zero phase and unity gain. Simulated error parameters associated with differences between channels are comparable with a real TDEMI device [5]. Gain error of the second channel is δG_2=-17%. As visible from waveforms depicted in Fig. 1b three values of phase shift between channels were simulated: φ_2=0°; 5°; 10°. For all of them the spectrum of error is depicted in Fig. 2a. The model quite precisely estimates spectra as values obtained from model lie close to dots representing simulation results not only for zero phase but also for significant phase shift between channels.

The results also demonstrate how spurious free dynamic range (SFDR) of TDEMI system could be restricted by discrepancies between channels. It should be expected that with increasing phase φ_2 amplitude of dominant spurious component rises and therefore SFDR drops. To investigate also influence of signal amplitude or ration A_{in}/R_1 on quality of spectrum measurement SFDR dependency from A_{in} was depicted in Fig. 2b for constant R_1=60 mV. Shown results were collected from designed error model which made analysis easier and faster. Finally we can see that drop in SFDR is significant for amplitude A_{in} rising just above threshold R_1. Then there is a point of minimum representing the worst case from where SFDR increases with rising A_{in}. This fact encourages thinking about possibility of system adjusting to amplitude of input signal using e.g. cascade of switchable attenuators at the input of system. It is interesting that positions of SFDR minima are not affected by phase difference between channels - φ_2.



a) b)

Fig. 2. Analysis of error spectrum for δG_2=-17% and three different φ_2 using proposed error model: a) error spectra – model compared with simulation; b) SFDR dependencies on input signal amplitude.

Acknowledgements

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