Detection limitation of high frequency signal travelling along underground power cable

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Detection Limitation of High Frequency Signal Travelling along Underground Power Cable

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***Abstract*—high frequency pulse injection is part of many diagnostics techniques, e.g. cable fault location. An injected pulse along an underground power cable will reflect at an impedance impurity, for instance a cable joint. These joints can be identified based on pulse reflections only if sufficiently high-frequency components can be detected. Signals with higher frequency components can provide more accurate spatial resolution but experience stronger attenuation and dispersion. This paper discusses whether pulse reflection from a cable joint can be better distinguished if detection is focused on high frequency signal content. Two aspects, considering effects of noise level and applied equipment, are discussed in detail: averaging and high-pass filtering. It is shown that in presence of noise, averaging can improve signal to noise ratio also for signals below the quantization error of digital detection equipment. High-pass filtering is realized in hardware but similar results can be achieved by software implementation. However, simulation study shows that a high-pass filter itself hardly improves reflection recognition.**

Keywords—condition monitoring; filtering; power cable insulation; signal to noise ratio; signal resolution

I. INTRODUCTION

High frequency signal corresponds to short wavelength which means small objects, like cable joints, are easier to detect from higher frequency signal components. A high pass analog filter can be applied to focus on high frequency components of a signal. However, higher frequency implies more attenuation and dispersion during signal propagation, which means lower signal to noise ratio (SNR). Averaging may promote the "visibility" of small signals reflecting back from local impedance distortions. Pulse injection technology is integrated in some PD diagnostic tools as calibration tool for power cables. It allows for repeatedly measuring reflection patterns consisting of the injection pulse and its reflections from joints [1,2]. This paper aims to study the behavior of high frequency signal components to identify cable joints based on pulse reflection.

The paper is organized as follows: Firstly, the parameters to study a typical analog-to-digital conversion (ADC) system is described; Next, two aspects helpful for high frequency signal detection are discussed: averaging and high pass filter. Furthermore, the effect of averaging and filtering either analog before the AD conversion or digitally after recording is demonstrated on test measurements. Finally, conclusions are given.

II. SYSTEM AND PARAMETER DESCRIPTION

A. AD conversion system

The detected analog signal is digitized through an ADC and may be averaged before being digitally stored. In addition, an amplifier can be applied before the analog to digital (AD) conversion. Filtering can also be included in the conversion. It can be achieved by adding an analog filter before the AD conversion or a digital filter afterwards. Its vertical resolution and vertical sensitivity settings of the ADC are crucial for signal detection. A typical AD conversion process is shown in Fig. 1.

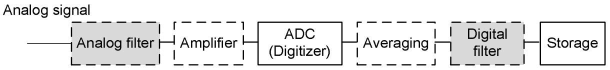

Fig. 1. A typical AD conversion process; the dashed blocks indicating additional filtering and amplification as well as signal averaging are optional; either analog filter or digital filter can be applied in one system

B. ADC limit

The ADC is constrained by two parameters: vertical resolution and vertical sensitivity. The vertical resolution is the number of bits supported by the ADC; the vertical sensitivity relates to the measured value, e.g. mV per division. ADC with m bits defines $M = 2^m$ levels. The quantization step (Qs) is the difference between adjacent levels. For widely used oscilloscopes, an 8 bits ADC is applied having vertical sensitivity ranging down to 2 mV/div with 8 divisions on the screen; quantization step (Qs) is 0.0625 mV. Qs changes with adjustment of the vertical sensitivity. The quantization considered here is always the rounded analog value to nearest integer.

C. Noise

The analog signal consists of the original signal impeded with noise. For simplicity, the analog filter and amplifier are considered as ideal, without adding noise. The ADC will contribute to the noise level known as quantization error. Noise

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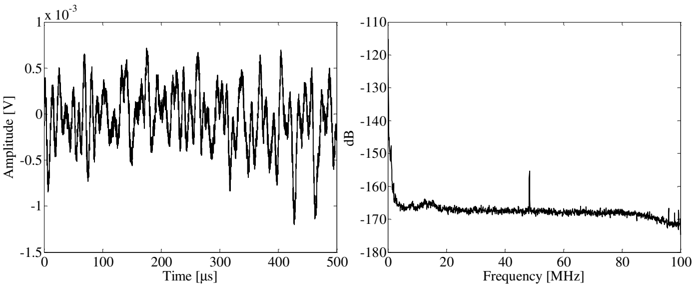
in a RMU of a 10 kV cable system is measured and a typical spectrum is shown in Fig. 2. The range of the noise power spectral density function (PSDF) is measured up to 100 MHz.



(a) Original measured noise (b) PSDF of original measured noise

Fig. 2. Measured noise in a MV cable system

D. Signal to Noise Ratio (SNR)

SNR is used as parameter to analyze the detection limitations. SNR is defined distinctively for continuous, e.g. sinusoidal, signal (S_s) and pulse signals (S_p). For S_s, assume the analog signal x is [1]:

$$x[k] = S_s[k] + n[k] \qquad (1)$$

where $1 \le k \le B$, B is the length of the signal record. SNR is defined as

$$SNR = 10\log\frac{P_{Ss}}{P_n} \qquad (2)$$

where P_{Ss} and P_n are the power of signal and noise:

$$P_{Ss} = \frac{1}{B}\sum_{k=1}^{B} S_s^{\,2}[k]; \quad P_n = \frac{1}{B}\sum_{k=1}^{B} n^2[k] \qquad (3)$$

For pulsed signals, the signal power is calculated over the full width at half maximum (FWHM), i.e. the part between index i and j:

$$Ps_s = \frac{1}{j-i+1}\sum_{k=i}^{j} S_s^{\,2}[k], \quad S_s[i] = S_s[j] = \frac{1}{2}\max(S_s) \qquad (4)$$

III. COMPLETE SYSTEM STUDY

To make a complete system analysis, this section will focus on the averaging and signal filtering. The simulation procedure is shown in Fig. 3.

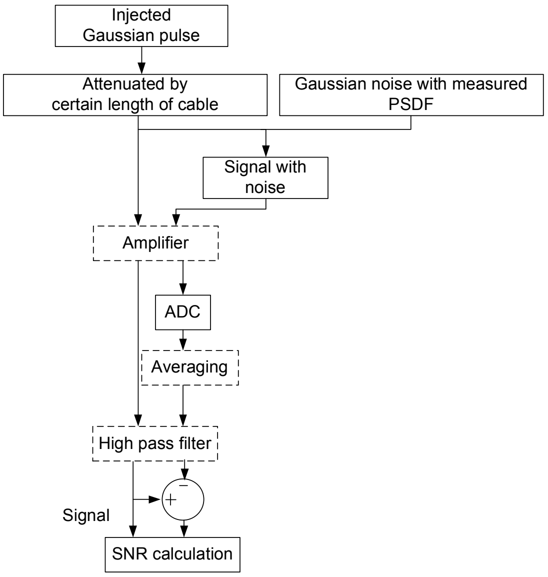


Fig. 3. Simulation procedure; dashed block means optional for simulation

A. Averaging effect

Averaging can increase the SNR. Even if the signal below the quantization level prevents it to be detected by the ADC directly, with the aid of noise, it is possible to extract the original signal still [3],[4]. The random value of noise adds to the signal and may promote the total level to pass the quantization level. One example of the averaging effect is shown in Fig. 4. The amplitude of the observed signal is 0.5 mV, smaller than the chosen ADC setting for Qs with 0.625 mV (e.g. because also larger signals could be expected). It is observed that the SNR increases by 10 dB with 10 times more averaging. The pulse becomes clearly distinguishable from the noise above about 20 dB. It should be noted that a pulse can also be extracted from noise with lower SNR depending on specific situations [2].

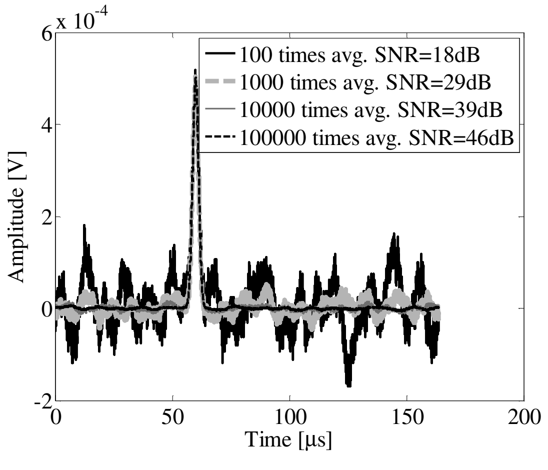


Fig. 4. Averaging effect to increase SNR for 0.5 mV, 3 µs pulse with Qs=0.625 mV and standard variation of noise σ=0.6 mV

It is shown in [4] that the mean-square error (*MSE*) considering both additive noise and quantization error with standard variation of noise σ and averaging time N is:

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$$MSE(\sigma,N)=\frac{\frac{Q_s^2}{12}+\sigma^2}{N}+(1-\frac{1}{N})MSE(\sigma,\infty) \qquad (5)$$

with

$$MSE(\sigma,\infty)\simeq\frac{Q_s^2}{2\pi^2}e^{-4\pi\frac{\sigma}{Q_s}}$$

In the regime σ/Qs>0.3, it is sufficient to retain only the first term in the series expansion and $MSE(\sigma,\infty)$ tends to approach zero monotonically for increasing σ. The averaging effect is valid for $N \ll N_T$, where:

$$N_T=\frac{\frac{Q_s^2}{12}+\sigma^2}{MSE(\sigma,\infty)}-1 \qquad (6)$$

It should be noted that (6) can be approximated with only its first term provided $N \ll N_T$. However, if the noise amplitude σ is not "sufficient", for instance $\sigma \to 0$, the averaging effect will not be applicable [4]. Also the observed 10 dB SNR increase with every 10 times more averaging will not hold.

B. *High pass filter effect*

High-pass filtering can be applied in order to improve the spatial resolution. In order to be consistent with experiments presented later, the filter is set to be a first order RC high-pass filter (HPF). The RC filter used for the experiment is shown in Fig. 5. In practice, the capacitor is composed of three parallel 68 pF capacitors in radial orientation. Its transfer function is:

$$H=\frac{j\omega RC}{1+j\omega RC} \qquad (7)$$

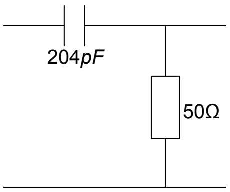

Fig. 5. Equivalent RC high-pass filter used for experiments

Simulation for the same signal as used in Fig. 4 (0.5 mV, 3 µs) employing a 15 MHz HPF is shown in Fig. 6. With its application the amplitude of the original signal decreases to about 2.5×10-3 mV. Accordingly, Qs setting is changed to 6.25×10-2 mV (minimum for 8 bit ADC). It can be seen that with HPF, the high frequency components can be extracted from the signal. However more averaging time is needed to get the same SNR compared with the case without HPF.

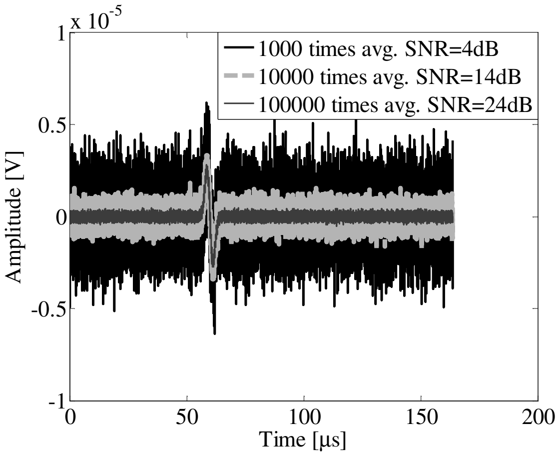

Fig. 6. 15 MHz high pass filter effect for 0.5 mV, 3 µs pulse with 15 MHz one order HPF, Qs=6.25×10^{-2} mV, same noise as in Fig. 5

One potential advantage of using HPF is that with the lowered signal amplitude, Qs can be adjusted to a lower level allowing more precise high frequency component recording. Fig. 7 shows a simulation with 106 times averaging:

- No filtering before ADC but apply HPF after averaging as in software, using the setting Qs=0.625 mV as in Fig. 5
- HPF (15 MHz cut-off frequency) applied before the ADC as in hardware with Qs=0.0625 mV.

The HPF applied before ADC gives a better result for high frequency with the same averaging time, mainly due to the smaller value of Qs. It should be noted that the simulation here assumes that the HPF does not add noise to the system.

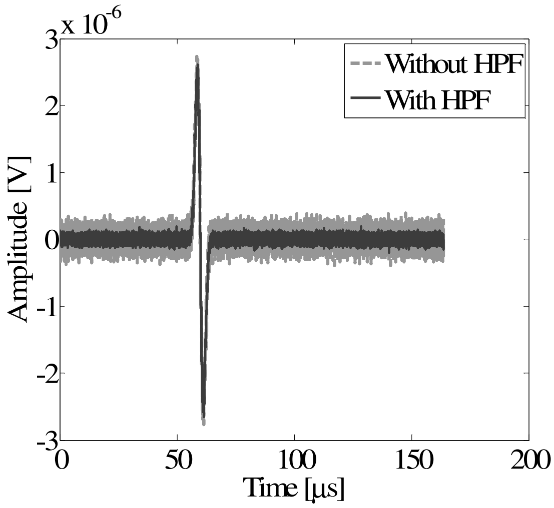

Fig. 7. Comparison of 10^6 averaging with HPF (Qs=6.25×10^{-2} mV) and 10^6 averaging without HPF (Qs=0.625 mV)

IV. EXPERIMENT

Time domain reflectometry measurements using a Gaussian distributed input pulse are performed on the test circuit shown in Fig. 8. It consists of 10 kV three-core XLPE and PILC cables, joints and a 1 MVA transformer. On the right branch under the transformer in RMU1 is the point where pulse is

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injected and measured (bandwidth up to 100 MHz). A 15 MHz high-pass filter is used before the AD conversion.

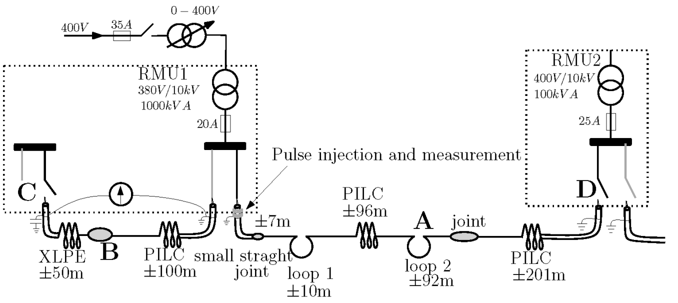

Fig. 8. Test circuit for pulse injection measurements

A comparison between the situation with and without HPF is illustrated in Fig. 9. With HPF, an amplifier (bandwidth 100 kHz to 250 MHz) is used to boost the input signal with a factor up to 20. Clear reflections occurring in Fig. 9 are labeled A, B, C, D; they are indicated also in Fig. 8. It is observed that the pattern with the HPF preserves all location information. However, it does not improve the joint location identification much. A software filtering as post processing is applied to the reflection pattern without HPF; the result is compared with the pattern with HPF hardware in Fig. 9. The utilization of filtering in software results in a comparable pattern as for the hardware implementation. The amplitude of the pattern with HPF in hardware is adjusted to the same level as the pattern without HPF. The slight mismatch may be caused by the shorter averaging time for measurement without hardware high pass filter or the effect of the amplifier.

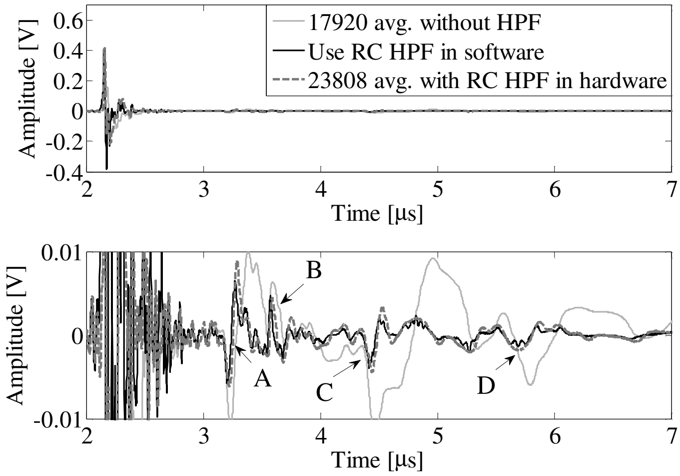

Fig. 9. Comparison of pattern with and without HPF; reflections indicated with A-D correspond to the positions in Fig. 8. High pass filter comparison between software and hardware

Software implementation of high pass filtering is more flexible; higher order filters and cut-off frequencies of FIR high-pass filter in software have been investigated. Fig. 10 shows the effect of different HPF in software. It can be seen that it is delicate to find a HPF with order and cut-off frequency to optimize location of pulse reflection points.

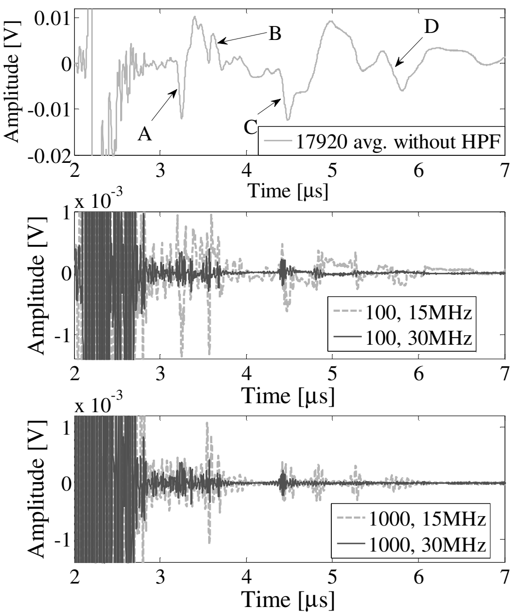

Fig. 10. Comparison of different HPF effect. 100 and 1000 indicate the HPF order used in software, 15 MHz and 30 MHz are the cut-off frequency; maximum frequency for both the measurement and HPF in software is set to 100 MHz

V. CONCLUSION

With "sufficient" noise, averaging can improve SNR. Simulation shows that by utilization of HPF in hardware will result in similar record compared with applying HPF after record (in software). For the same averaging time, simulation shows when neglecting noise of HPF, adjusting Qs to a smaller value with employing HPF in hardware can result in better SNR compared with not using HPF with larger value of Qs.

Experiments confirm that high-pass filtering in hardware can be replaced by software. High-pass filter can extract the fast transient part of the measured pattern, which corresponds to sharp physical transition (cable joint) or overlapping of two reflections, excluding the noise. However, to locate the high frequency parts to the realistic circuit is still not straightforward. Simulation in software shows that the high pass filter itself does not help much for reflection recognition.

REFERENCES

[1] Paul Wagenaars, "Integration of Online Parital Discharge Monitoring and Defect Location in Medium-Voltage Cable Networks," Ph.D. dissertation, Dept. Electrical Eng., Eindhoven Univ. of Technology, Eindhoven, 2010.

[2] J. Veen, P.C.J.M. van der Wielen, "The application of matched filters to PD detection and localization," *IEEE Electrical Insulation Magazine*, vol.19, no.5, pp.20-26, Sep.-Oct. 2003.

[3] Cao Ai and Ai Guoxiang, "Removing the quantization error by repeated observation [image processing]," *IEEE Transactions on Signal Processing*, vol.39, no.10, pp.2317-2320, Oct. 1991.

[4] R. Skartlien and L. Oyehaug, "Quantization error and resolution in ensemble averaged data with noise," *IEEE Transactions on Instrumentation and Measurement*, vol.54, no.3, pp. 1303- 1312, June 2005.