FLEXIBLE ENERGY SYSTEMS - FLEX^{e}
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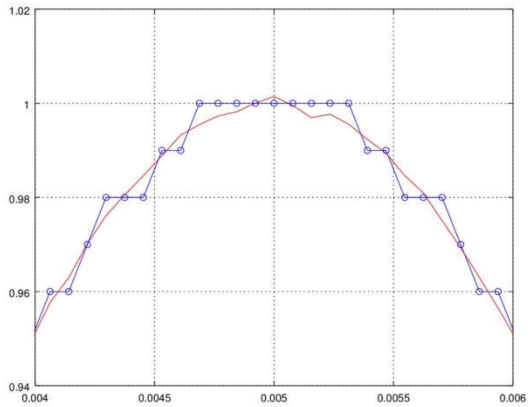
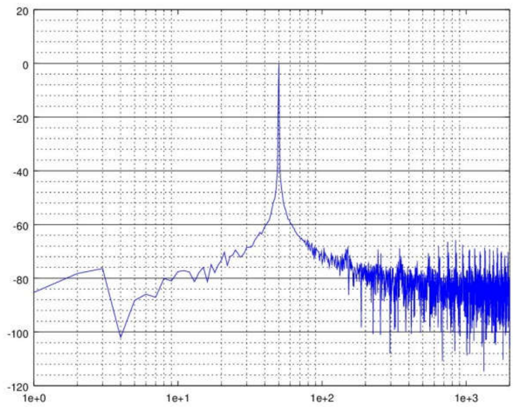
Report on IEC61850-9-2 sample rates on measurement accuracy





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1. Introduction

IEC 61850 is a design standard for automation within digital substations in electric power systems. It contains rules for e.g. substation device models, data communication and real-time data transmission in a substation LAN. One aspect of the standard is "61850-9-2: Sampled values (SV) over ISO/IEC 802.3", i.e. transmission of VT and CT data over Ethernet [1]. An implementation guideline, IEC 61850-9-2 LE, is available from a group of stakeholders [2]. It contains clearly defined sample data profiles to be used in transmitting voltage and current samples over Ethernet.

One of the drawbacks from a strictly metrological point of view of IEC 61850 is the restrictions concerning the sample rates and data quantization specified in [2]. Typically most accurate sampled a.c. measurements are made with coherent sampling, where a relationship between the sample rate f_s and frequency of measurand f_1 is given by

$$\frac{f_S}{f_1} = \frac{n_S}{n_{CYC}},$$

where n_S is the number of samples taken over n_{CYC} periods of the measurand. With predefined sample rates of 4000 Hz (protection) and 12800 Hz (power quality) the only truly free variable is f_1. In a live 50-Hz electricity network the value of f_1 is constantly changing, and even in laboratory conditions the frequency resolution of many sources is not high enough to ensure sufficient coherence of sampling. Furthermore, specified data resolution may introduce additional errors. IEC 61850-9-2 LE defines a 32-bit integer value for voltage and current, where the respective least significant bit (LSB) values are 10 mV and 1 mA. Especially for small signal amplitudes the quantization of sampled values becomes an error source, which needs to be considered.

This aim of this report is to test algorithms intended for extracting the amplitude and phase of non-coherently sampled signals. The algorithms are tested with simulated data, where a known amplitude and phase for a sinusoidal signal can be created. The simulated sinusoids are corrupted with known parameters of harmonic content, noise, frequency offset, and modulation to test how different algorithms perform under conditions that imitate real electricity network phenomena.

2. Test signal definition

The signal used for testing of the algorithms is given by

$$\begin{aligned} V(t) = A_1 S_{AM} \sin(2pif_1 t + S_{FM} + \varphi_1) + noise \\ +A_3 \sin(6pif_1 t + \varphi_3) \\ +A_5 \sin(10pif_1 t + \varphi_5) \\ +A_7 \sin(14pif_1 t + \varphi_7), \end{aligned}$$

where {A_1, A_3, A_5, A_7}, {f_1, f_3, f_5, f_7} and {φ_1, φ_3, φ_5, φ_7} are respectively the amplitude, frequency and phase of the 1st, 3rd, 5th and 7th harmonic frequency of the 50-Hz mains signal. Noise signal is a normally distributed random signal with variance (i.e. RMS value) given by

$$V_{noise} = 10^{\frac{(20\log(A_1) - 20\log(\sqrt{2}) - SNR)}{20}},$$

where SNR is the desired signal-to-noise ratio of the signal in dB. S_{AM} and S_{FM} are denote the amplitude and frequency modulation signals given by

$$S_{AM} = 1 + \alpha_{AM} t$$

and

$$S_{FM} = 2pi\alpha_{FM} t,$$

where α_{AM} and α_{FM} are respectively the rate of change of amplitude and frequency. Both modulation signals affect only the main frequency component in the case where harmonic signals are present.

3. Tested algorithms for determining signal amplitude and phase

Several algorithms for determining the amplitude and phase of an asynchronously sampled sine wave can be found in the literature. Many are conveniently implemented in Quantum Wave ToolBox (qwtb) [3] and can be run under Matlab or Octave. The following algorithms are selected for testing:

fourPSF Fits a sine wave to the recorded data using a 4 parameter (frequency, amplitude, phase and offset) model. The algorithm is in accordance with IEEE Standard for Terminology and Test methods for Analog-to-Digital Converters 1241-2000 [4].

FPNLSF Fits a sine wave to the recorded data by means of non-linear least squares fitting method using a 4 parameter (frequency, amplitude, phase and offset) model. An estimate of signal frequency is required. Due to non-linear characteristic, convergence is not always achieved.

iDFT3p An algorithm for estimating the frequency, amplitude, phase and offset of the fundamental component using interpolated discrete Fourier transform. Rectangular or Hann window can be used for DFT [5].

PSFE An algorithm for estimating the frequency, amplitude, and phase of the fundamental component in harmonically distorted waveforms. The algorithm minimizes the phase difference between the sine model and the sampled waveform by effectively minimizing the influence of the harmonic components [6].

4. Test results

The algorithms are tested for a one second capture of the signal defined in 2. A record length of one second is selected due to native IEC 61850 time-tagging of 0…n-1 for samples within a single second, after which the time tag rolls-over providing ease of implementation in a real system. According to discussion with the author of [3], a smaller number of samples might result in the algorithms failing to converge. On the other hand, higher number (i.e. several seconds) may increase the unreliability of the results due to fluctuation of the measured signal in real operating conditions, since the algorithms are intended to be used with stationary signals.

The following sub-chapters list different scenarios and parameters for the test signals, and summarize the performance of selected algorithms for the considered cases. All tests are repeated for A_1 = √2*20/√3 kV and A_1 = √2*230 V voltage signals (including LSB quantization to 10 mV) with 4000 Hz and 12800 Hz sample rates. Current signals are not considered, since the only difference would be in data quantization of 10 mV vs 1 mA per LSB.

Results for **magnitude** are given as relative error in **parts-per-million (ppm)** between generated signal fundamental frequency RMS value and algorithm output. Results for **phase** are given in **micro radians (µrad)** for difference between generated signal fundamental phase φ_1 and algorithm output.

4.1. Ideal signal

Signal parameters: $\{A_3, A_5, A_7\} = 0$, $f_1 = 50.0$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = 0$, SNR = 170 dB, sufficiently high to consider the signal noise-free, and $\alpha_{AM} = 0.0$ 1/s and $\alpha_{FM} = 0.0$ mHz/s.

This test is made to establish a base-line for performance. All algorithms work very well, with only sub-ppm and sub-µrad errors. Only 230 V case produces a small difference between generated signal and algorithm output. This is due to signal level quantization, which is relatively high for a small value of voltage. iDFT3p for 230 V failed to converge due to interpolation failing without signal in adjacent bins.

		fourPSF		FPNLSF		iDFT3p		PSFE	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	0	0	0	0	0	0	0	0
	Phase [urad]	0	0	0	0	0	0	0	0
230 V	Magnitude [ppm]	3	0	3	0	n/a	n/a	3	0
	Phase [urad]	0	0	0	0	n/a	n/a	0	0

4.2. Harmonic frequencies present

Signal parameters: $\{A_3, A_5, A_7\} = \{0.0005A_1, 0.002A_1, 0{,}001A_1\}$, $f_1 = 50.0$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = \{0, 0.5, 0.25, 0.75\}$, SNR = 170, sufficiently high to consider the signal noise-free, and $\alpha_{AM} = 0.0$ 1/s and $\alpha_{FM} = 0.0$ mHz/s.

Presence of harmonic frequencies does not create any additional errors for any of the algorithms. iDFT3p failed to converge again due to the same reason as in 4.1.

		fourPSF		FPNLSF		iDFT3p		PSFE	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	0	0	0	0	0	0	0	0
	Phase [urad]	0	0	0	0	0	0	0	0
230 V	Magnitude [ppm]	3	0	3	0	n/a	n/a	3	0
	Phase [urad]	0	0	0	0	n/a	n/a	0	0

4.3. Frequency offset of fundamental

Signal parameters: $\{A_3, A_5, A_7\} = 0$, $f_1 = 49.9$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = 0$, SNR = 170 dB, sufficiently high to consider the signal noise-free, and $\alpha_{AM} = 0.0$ 1/s and $\alpha_{FM} = 0.0$ mHz/s.

All algorithms except for iDFT3p work very well. iDFT3p fails to give correct results. Using 1 Hz bin width, as is the case here, means a 10% relative offset from bin centre if the signal frequency is 0.1 Hz off. For a noise free signal this may be too much, since again adjacent bins have very little power for interpolation to work properly.

		fourPSF		FPNLSF		iDFT3p		PSFE	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	0	0	0	0	442	408	0	0
	Phase [urad]	0	0	0	0	6550	6485	0	0
230 V	Magnitude [ppm]	0	0	0	0	442	408	0	0
	Phase [urad]	0	0	0	0	6550	6485	0	0

4.4. Noisy signal

Signal parameters: $\{A_3, A_5, A_7\} = 0$, $f_1 = 50.0$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = 0$, SNR = 70 dB, and $\alpha_{AM} = 0.0$ 1/s and $\alpha_{FM} = 0.0$ mHz/s.

All algorithms work reasonably well showing magnitude error of less than 10 ppm. Lower sampling rate shows an increase of phase error to tens of µrad, which can still be considered acceptable.

		fourPSF		FPNLSF		iDFT3p		PSFE	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	9	2	9	2	9	2	8	2
	Phase [urad]	25	8	25	8	40	7	35	8
230 V	Magnitude [ppm]	3	1	3	1	3	1	7	1
	Phase [urad]	26	8	26	8	27	20	24	5

4.5. Noisy signal with harmonic frequencies and frequency offset

Signal parameters: $\{A_3, A_5, A_7\} = \{0.0005A_1, 0.002A_1, 0{,}001A_1\}$, $f_1 = 49.9$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = \{0, 0.5, 0.25, 0.75\}$, SNR = 70 dB, and $\alpha_{AM} = 0.0$ 1/s and $\alpha_{FM} = 0.0$ mHz/s.

All algorithms except for iDFT3p work very well. iDFT3p again fails to give correct results. Using 1 Hz bin width, as is the case here, means a 10% relative offset from bin centre if the signal frequency is 0.1 Hz off. It seems that interpolation does not work even for noisy signal.

		fourPSF		FPNLSF		iDFT3p		PSFE	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	4	1	4	1	446	409	3	1
	Phase [urad]	0	6	0	6	6551	6479	2	8
230 V	Magnitude [ppm]	6	3	6	3	448	405	4	2
	Phase [urad]	12	4	12	4	6547	6480	5	8

4.6. Noisy signal with harmonic frequencies and frequency sweep

Signal parameters: $\{A_3, A_5, A_7\} = \{0.0005A_1, 0.002A_1, 0{,}001A_1\}$, $f_1 = 50.0$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = \{0, 0.5, 0.25, 0.75\}$, SNR = 70 dB, and $\alpha_{AM} = 0.0$ 1/s and $\alpha_{FM} = 0.01$ mHz/s.

Results for phase have little significance due to input phase being difficult to define. Still, the algorithms show only small difference between each other. Magnitude results are good for all other algorithms except for iDFT3p, which suffers from input frequency being smeared over the input bin and not enough power in adjacent bins to do interpolation accurately. It should be noted that interpolation does work better for this signal than it does for previous cases due to an order of magnitude smaller overall frequency offset.

		fourPSF		FPNLSF		iDFT3p		PSFE	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	3	1	3	1	96	98	2	0
	Phase [urad]	19	14	19	14	19	7	28	6
230 V	Magnitude [ppm]	0	0	0	0	99	99	1	0
	Phase [urad]	6	18	6	19	10	24	3	17

4.7. Noisy signal with harmonic frequencies and amplitude sweep

Signal parameters: $\{A_3, A_5, A_7\} = \{0.0005A_1, 0.002A_1, 0{,}001A_1\}$, $f_1 = 50.0$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = \{0, 0.5, 0.25, 0.75\}$, SNR = 70 dB, and $\alpha_{AM} = 0.001$ 1/s and $\alpha_{FM} = 0.0$ mHz/s.

Magnitude is compared to the average magnitude in the test signal, which is given by

$$\frac{A_1}{\sqrt{2}}\left(1+\frac{\alpha_{AM}t}{2}\right).$$

All algorithms give good results apart from iDFT3p, which is not able to compute signal phase correctly but does give a good result for magnitude.

		fourPSF		FPNLSF		iDFT3p		PSFE	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	8	0	8	0	8	0	8	0
	Phase [urad]	28	16	28	16	495	507	26	17
230 V	Magnitude [ppm]	0	6	0	6	0	6	3	6
	Phase [urad]	18	6	18	6	528	511	25	5

4.8. Noisy signal with harmonic frequencies and frequency and amplitude sweep

Signal parameters: $\{A_3, A_5, A_7\} = \{0.0005A_1, 0.002A_1, 0{,}001A_1\}$, $f_1 = 50.0$ Hz, $\{\varphi_1, \varphi_3, \varphi_5, \varphi_7\} = \{0, 0.5, 0.25, 0.75\}$, SNR = 70 dB, and $\alpha_{AM} = 0.001$ 1/s and $\alpha_{FM} = 0.01$ mHz/s.

As in 4.6, results for phase have little significance due to input phase being difficult to define. Input signal magnitude is calculated as in 4.7. Even in this case the magnitudes given by all algorithms apart from iDFT3p have very small errors. Errors in signal phases are also similar.

		fourPSF		**FPNLSF**		**iDFT3p**		**PSFE**	
Voltage	Sample Rate [Hz]	4000	12800	4000	12800	4000	12800	4000	12800
20/√3 kV	Magnitude [ppm]	2	10	2	10	101	109	4	12
	Phase [urad]	1	10	1	10	0	5	4	7
230 V	Magnitude [ppm]	3	1	3	1	96	97	4	1
	Phase [urad]	18	1	18	1	25	5	24	5

5. Conclusion

Different algorithms for extracting the magnitude and phase of non-coherently sampled signals are tested for operation with sampled values according to IEC 61850-9-2 LE. The algorithms are intended to be used with stationary signals, but tests for modulated signals were carried out regardless. Algorithms, which rely on sine fitting, i.e fourPSF, FPNLSF and PSFE show very good performance in all test cases. Fourier transform based iDFT3p is too sensitive to non-coherence in many cases and cannot be trusted to give good results. Overall the other three algorithms perform well enough for their errors to not dominate the error budget of the entire measurement chain.

6. References

[1] *Specific Communication Service Mapping (SCSM) – Sampled values over ISO/IEC 8802*, IEC Standard 61850-9-2, April 2004.

[2] *Implementation Guideline for Digital Interface to Instrument Transformers using IEC 61850-9-2*, IEC 61850-9-2 LE, July 2004.

[3] Sira M. *et al.*, “QWTB — Software tool box for sampling measurements,” 2016 Conference on Precision Electromagnetic Measurements (CPEM 2016), Ottawa Ca, July 2016.

[4] Terminology and Test Methods for Analog-to-Digital Converters, IEEE Standard 1241-2000, Dec 2001.

[5] Duda K.: Interpolation algorithms of DFT for parameters estimation of sinusoidal and damped sinusoidal signals. In S. M. Salih, “Fourier Transform - Signal Processing,” chapter 1, pages 3-32, InTech, 2012.

[6] Lapuh, R., "Estimating the Fundamental Component of Harmonically Distorted Signals From Noncoherently Sampled Data," IEEE Transactions on Instrumentation and Measurement, vol. 64, no. 6, pp.1419,1424, June 2015.