Sampling Rate Comparison for Distribution System Voltage Measurements

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***Abstract** – Measurement of the voltage delivered by an electric distribution is a relatively straight forward task. When determining the harmonic distortion in the voltage, matters associated with what orders of the 50/60 Hz harmonics to be analyzed dictate the sampling rate. A study addressing this matter is presented.*

***Key Words:** electric grid, utility distribution, sensors, analysis*

1. Introduction

Harmonic distortion in electric grid distribution systems has increased as the number of nonlinear loads and sources attached to the grid has increased. This has led to the Institute of Electrical and Electronic Engineers (IEEE) to develop and issue in 1992 standard 519-1992. This standard provides guidelines for applying limits to the level of harmonic distortion that a utility customer may inject into the power system. An update to IEEE 519 was issued in 2014 [1]. Models have been developed regarding the "acceptable level" of distortion based on harmonic of the line's fundamental oscillatory frequency are available from various vendors [2, 3]. Regardless of the model, measurement and data analysis (DnA) questions remain regarding topics such as:

- Is there information pertaining to the grid operation in high order harmonics?
- Should line voltage measurements be made in a frequency range from the fundamental f_0 up to f_n?
- What sampling rate should an analog to digital data acquisition system use for optimal measurement?

When sampling an analog waveform, then converting it to a digital representation of that waveform, the Nyquist-Shannon sampling theorem provides guidance on sampling rate. In the case of a "clean" (distortion free) sinewave with frequency F, the theorem states that the sampling rate should be at (or above) double the frequency F. Therefore in the case of a 60Hz sinusoidal waveform, the sampling rate should be at least 120 samples/second.

As stated in IEEE 519-1992, nonlinear loads (and sources) cause harmonic distortion of the fundamental grid sinusoidal waveform of 60 Hz. Fourier analysis permits a periodic distorted waveform to be decomposed into a series of sinewaves containing DC (0 Hz) components and frequencies ranging from the fundamental (first harmonic) (e.g. 60Hz), second harmonic (e.g. 120Hz), third harmonic (e.g. 180Hz), and so on. In general, the amplitude of each harmonic decreases. When combined, the individual harmonics add to reproduce the original electrical grid waveform. The highest harmonic of interest in power systems is usually the 25th (1500Hz), which is in the audible range [4].

Studies pertaining to Fourier analysis of harmonic distortion in transmission and distribution systems are summarized and referenced in *Fourier Analysis for Harmonic Signals in Electrical Power Systems [5]*. The model described in that paper examines the effect that nonlinear systems may have on the grid distribution system including: power lost through heating, with an emphasis on the effects that transformer materials with inherent nonlinear characteristics may play in transformer saturation effects, hysteresis (major and minor) loops, and eddy currents. A multitude of factors that influence additional losses and the generation of harmonic signals – each with lesser effect - in the transformer include temperature and possible resonance between transformer winding inductance and supply capacitance.

The question as to what is the highest harmonic to measure and analyze has fundamental implications on the design and operation of the DnA system, specifically on the sampling rate.

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2. A DnA System

A digitizing data acquisition system has a number of parameters most notably, sampling rate, number of bits per sample, and the amount of storage available (for the samples). The additional detail is the frequency composition of the analog waveform that is to be sampled. Anecdotes reveal that a variety of power engineers are considering if there is relevant grid operation information in significantly higher harmonics than the aforementioned 25th. A target for this investigation was detection of the 50th harmonic of a 60 Hz power signal at 3000Hz. The Nyquist-Shannon theorem then implies that the minimum sampling rate, f_s, should be 6000 samples/second. Aliasing effects will be minimized if the frequency bandwidth of the signal being measured is lower than half the sampling frequency. In the case of analyzing up to the aforementioned 50th harmonic, no antialiasing filter is required for a sampling rate exceeding 6000 samples/second.

With respect to the sensing/measurement of distribution line voltages, analysis techniques involving the application of Gaussian integrals to optical voltage sensors have resulted in high voltage measurement accuracy [6, 7]. However, temperature changes in these Pockel's cell based optical sensors may cause the expansion and concentration of electro-optical crystals due to their material properties, influencing the measurement results [8-10]. In addition, optical voltage sensors are a precision instrument and their large-scale application is restricted by their high manufacturing cost and ease of damage during long-distance transportation [11–14]. In comparison with optical methods, D-dot sensors [15, 16], which have a simple structure, low cost and a wide dynamic range, are easier to use and are more extensively used [8, 17]. In addition, applying Gaussian integrals to the D-dot sensor measurement system, with its simple structure and low cost, should result in high fidelity measurements appropriate for a range of applications. Regardless of the type of sensor, the sampling rate is paramount for accurate digital representation of the measured analog, sinewave distribution voltage signal.

Measurements of a 120VAC, 60Hz distribution voltage were made using a wide bandwidth, linear optical voltage sensor. This sensor provides an optical intensity – suitably converted into a 0-5 V electrical signal - that varies with distribution voltage level. This electrical output was connected to a Tektronix MS054 Mixed Signal Oscilloscope digital acquisition system. The system configuration is illustrated in Figure 1. The MS054 has a 12/16 bit digitizer with variable sampling rate (from 12.5k samples/second (12.5k sps) to 6.25G sps) and a record length of 62.5M sampled points. Note that the record length, set by the MS054's available memory, then specifies the sampled waveform duration, see Table 1.

Sampling rate (per sec)	12.5k	31.25k	62.5k	125k	312.5k	625k	1.25M	3.125M	6.25M	12.5M	31.25M	62.5M
Duration (Secs)	5000	2000	1000	500	200	100	50	20	10	5	2	1

Table 1. Record duration as a function of samples per second (for total record length of 62.5M sampled points).

The fundamental frequency of the observed distribution line voltage is 60Hz (60 cycles/second). In terms of Fourier analysis of the recorded line voltage, the question of how many oscillatory cycles of the various frequency components (fundamental and harmonics) are recorded during the variable sampling rate duration arises. The number of cycles of the 60 Hz fundamental frequency that are sampled within the recording duration is shown in Table 2.

Sampling rate (per sec)	12.5k	31.25k	62.5k	125k	312.5k	625k	1.25M	3.125M	6.25M	12.5M	31.25M	62.5M
Duration (Secs)	5000	2000	1000	500	200	100	50	20	10	5	2	1
# 60 Hz cycles	300000	120000	60000	30000	12000	6000	3000	1200	600	300	120	60

Table 2. Number of 60Hz cycles recorded as a function of sampling rate and recording duration.

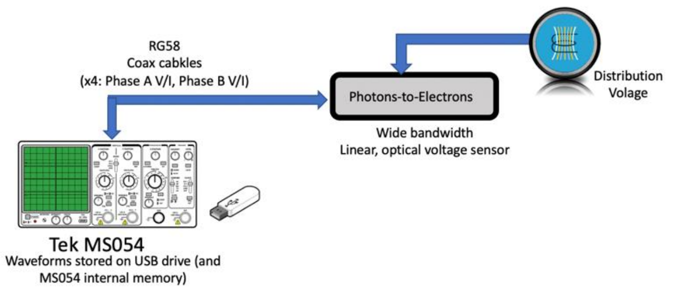

Fig. 1. Measurement system configuration.

The oscilloscope temporal display of the distribution system's low voltage (115VAC, 60 Hz) is presented as Figure 2. Ripples on the sinusoidal waveform are indicative of distortion.

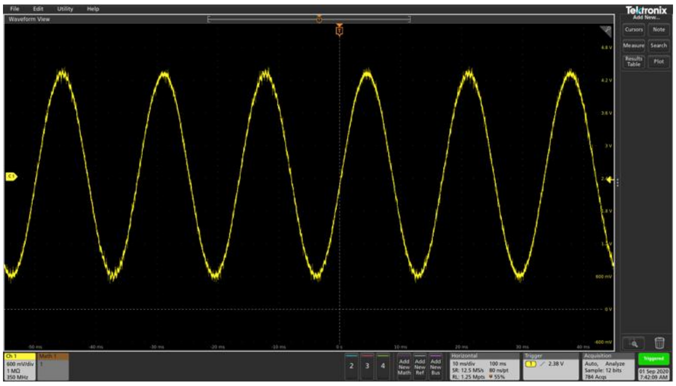

Fig. 2. The low voltage 60 Hz waveform is slightly distorted.

A spectral analysis of the 60 Hz waveform, shown in Figure 3, reveals energy in the fundamental and multiple harmonics.

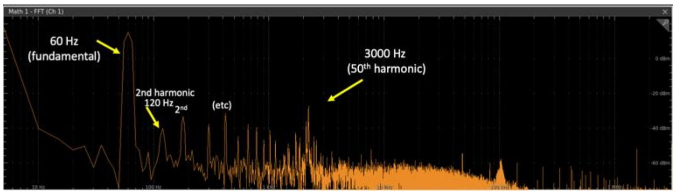

Fig. 3. Spectral analysis of Figure 2's low voltage 60 Hz waveform. [Note that the horizontal and vertical scales are logarithmic].

3. Variable Sampling Rate Time-Frequency

The sampling rate of the MS054 was sequentially varied according to Table 1's values. A Fast Fourier Transform (FFT) of the recorded, digitized voltage measurements for each sampling rate was computed using the MS054. The MS054 screen showing the temporal and frequency (spectral analysis) displays was recorded. The resulting screenshots are presented as Figures 4 and 5.

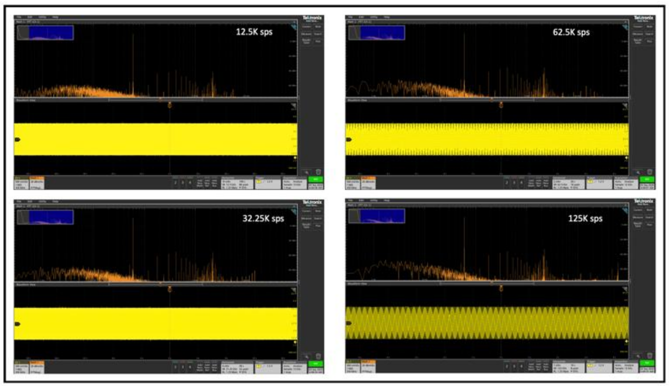

Fig. 4. Time-frequency display for sampling rates 12.5k to 125k sps.

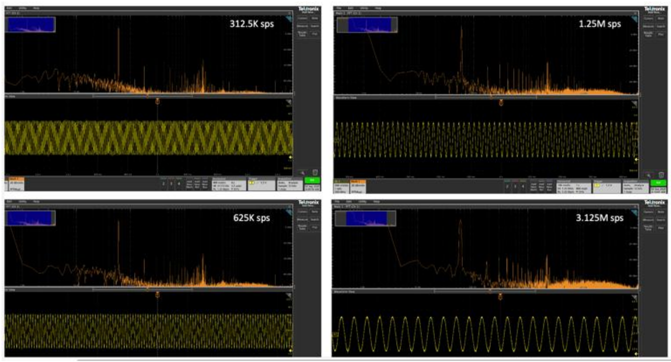

Fig. 5. Time-frequency display for sampling rates 312.5k to 3.125M sps.

As is readily apparent from examining Figure 6, at the very high sampling rates of 32.15M sps and 62.5M sps, few cycles of the 60 Hz waveform are recorded before the available storage memory is filled. The associated frequency analysis is therefore of lesser quality.

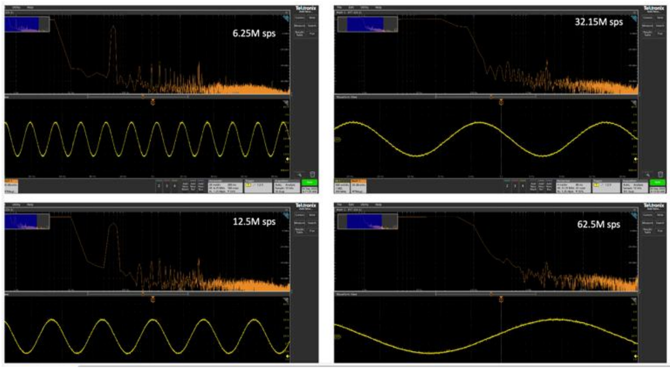

Fig. 6. Time-frequency display for sampling rates 312.5k to 3.125M sps.

4. Enter Point on Wave Distribution Waveform Sampling and Analysis

Analysis of a distribution voltage waveform may differ from the just presented analysis of the temporal and frequency characteristics of the waveform. Fast sampling of the distribution waveform provides information on transients that are too fleeting for a more traditional phasor measurement unit (PMU) to make. For example, fast electromagnetic transients (several to 50 power system cycles) typically include non-sinusoidal behavior and high- and low-frequency components. Some are too fast for PMU detection, which may filter out or distort the events. An instrumentation limitation immediately arises with respect to the volume of data acquired with continuous fast sampling. For instance, Point on Wave (POW [19]) analysis requires sampling of the waveform multiple times per oscillation cycle (in this instance 1/60th of a second). The distribution voltage sinusoidal waveform may be represented in Cartesian/Rectilinear or Polar coordinates, as shown in Figure 7. Note that if you know that the frequency bandwidth of the signal being measured is lower than half the sampling frequency, you can choose not to use an antialiasing filter.

A spectral analysis requires multiple cycles to be captured, combined and then analyzed via, for example, a discrete Fourier transform (DFT). Nyquist requires a sampling at a minimum of twice the highest frequency component of the signal being sampled. For a signal with noise, the general rule is to sample at ten times the highest frequency component.

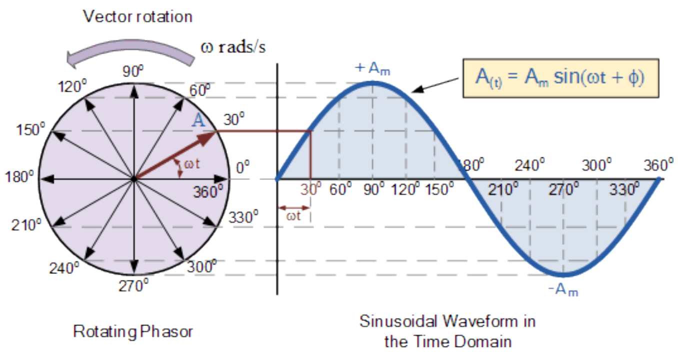

Fig. 7. Cartesian and polar coordinate representation of the 60Hz sinusoidal distribution voltage waveform. [from 18].

When determining the optimal POW sampling, an analogy may be made with respect to phase shift keying (PSK) communications signaling. Figure 8 illustrates 128 and 256 PSK signaling in terms of constant amplitude, varying phase. Sampling the distribution waveform 128 times per cycle provides a POW 2.8^{o} polar coordinate phase resolution. The associated temporal resolution is ~130 microseconds (for a 60Hz signal). Sampling 256 times per 60Hz cycle yields POW phase and temporal resolutions of 1.4^{o} and 65 microseconds.

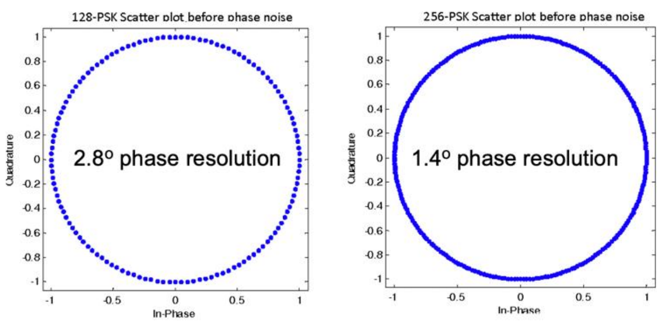

Fig. 8. Polar coordinate representation of 128 and 256 bit phase shift key (PSK) signaling.

FFT and power spectral density (PSD) quantities were computed for each of the waveform captures, and then averaged in each sampling rate set, yielding 10 distinct FFTs/PSDs. The resulting average FFT/PSD magnitudes are then compared using a cross-correlation matrix (Figures 9 and 10).

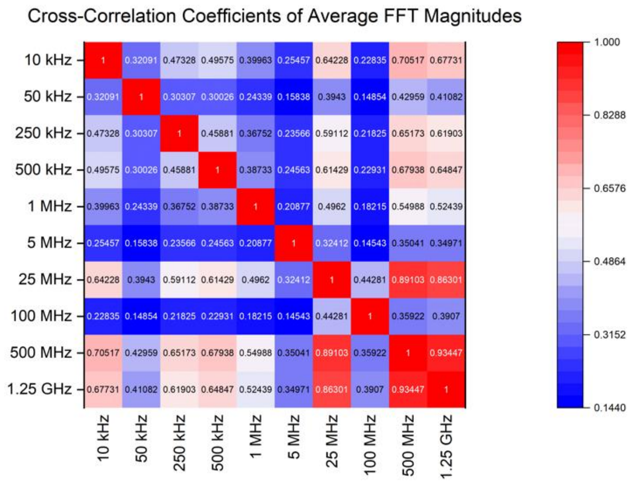

Fig. 9. Cross-correlation for average FFT magnitudes.

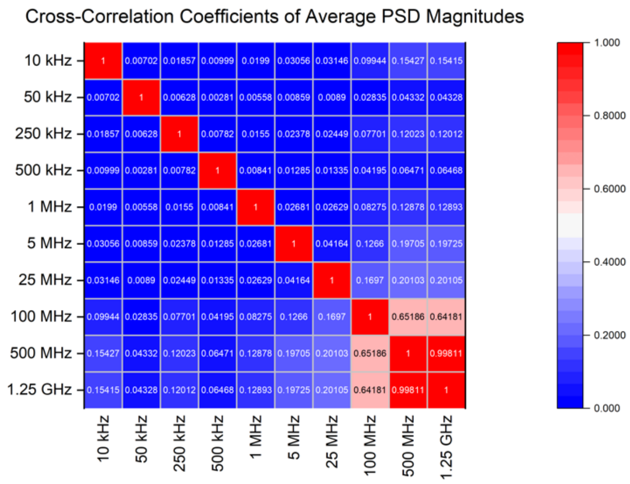

Fig. 10. Cross-correlation matrix for average PSD magnitudes.

5. Summary

Measurement of the voltage delivered by an electric distribution is a relatively straight forward task. When determining the harmonic distortion in the voltage, matters associated with what order of the 50/60 Hz harmonic to analyze as well as the analysis method to be used dictate the sampling rate. In a system with relaxed memory constraints and utilizing Fourier analysis, the sampling rate should be 10x the highest frequency to be analyzed[1]. For Point-on-Wave analysis, the parallels in PSK communications recommend 256 samples per cycle[2] providing 1.4^{o} phase and 65 microsecond temporal resolution.

[1] Analysis of the 50^{th} harmonic of a 60Hz distribution voltage signal (3000 Hz) would then be at 30,000 samples/second.

[2] POW analysis of a 60 Hz signal (16.67 msec per cycle) at 256 samples per cycle (65 μsec/sample) yielding 15,385 samples/second.

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