



PS5 – S6-06



Vision of Standard C37.118 by PMU Developers

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1 INTRODUCTION

Rapid development of WAMS technology in the power industry has prompted many companies to market their own PMU products. However, the industry still lacks comprehensive norms addressing PMU issues. Standard C37.118-2005 [2] currently in place is hardly helpful to developers of equipment, since it does not specify PMU parameters in case of dynamic signals. Worse, it contains contradicting requirements that cannot be implemented in any real device. The present report provides vision of the current standard and new edition of C37.118 by PMU developers, as well as some comments and proposals for improvement of the norm.

Section 1 addresses the current standard followed by discussion of its new edition [1] with comments and proposals. Appendix provides information on research of properties of instantaneous frequency and frequency variation rate referred to in the report.

2 COMMENTS ON CURRENT C37.118-2005 STANDARD

Let us start from formal assessment of current C37.118-2005 standard. In Section 5.3 in Table 3 [2] we find requirements to testing of equipment for compliance with the said standard. Requirements to Level 1 (page 9, the first paragraph) [2] are as follows: "Effects of the influence quantities shall be considered cumulative, and the TVE shall not exceed the error listed for the given compliance level under any combination of influence quantities shown in Table 3." In particular, this means that both signal with frequency $F_{nominal} + 5\text{Hz}$ and signal with infinitely small frequency deviation from $F_{nominal} + F_s/2$ (out-of-band interfering signal) may be applied to input of a device. At $F_s = 10\text{Hz}$ (that is one of reporting rates that must be supported by a standard PMU) this is $F_{nominal} + 5\text{Hz}$. So, testing requires creation of conditions that cannot be passed by any device. There is no channel that may distinguish "useful signal" and "interference signal" when their frequencies are infinitely close (see examples on pages 68 and 69 in [3]).

3 DISCUSSION OF DRAFT STANDARD

3.1 Definition of Synchrophasor and Elaboration of Requirements

Now let us discuss conversion of a continuous input signal into a synchrophasor. Real and imaginary synchrophasor components of input signal are linear:

$$x(t) = X_r(t) \cdot \cos(2\pi f_0 t) - X_i(t) \cdot \sin(2\pi f_0 t).$$

Linear conversion may be defined by a number of different (equivalent) methods. For example, we may do it by amplitude/frequency and phase/frequency response. Alternatively, we may do it by pulse response or step-function response in time domain. Therefore, frequency, pulse and unit step function responses are all self-sufficient for description of channel for synchrophasor conversion of continuous input signal.

In order to exclude aliasing, synchrophasor must be formed by a part of spectrum of electric signal that is F_s -wide (this is reporting rate) and has its center at nominal frequency of the system f_0 , since synchrophasor is obtained by projecting to this reference frequency (see Fig. 1). Components of spectrum of the signal shown in red shall have any noticeable effect neither on synchrophasor, nor on frequency, nor on rate of change of frequency (ROCOF).

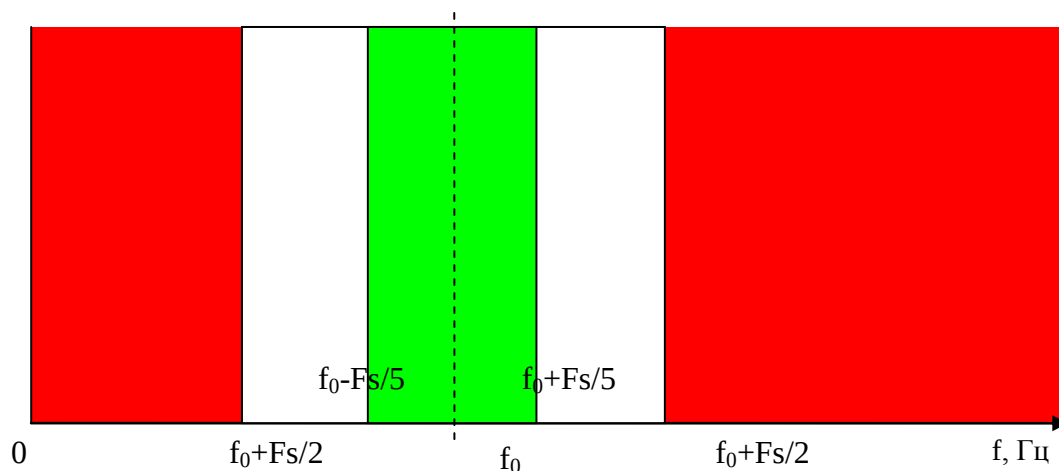


Fig. 1: Continuous Signal and PMU Transfer Function in Frequency Domain

In practice it is not possible to achieve complete suppression in suppression band and absolutely accurate transmission of the remaining signal spectrum. At the same time it is not possible to get strictly rectangular band-pass and band-stop response [3]. Therefore, authors of the standard imply comprehensive testing of frequency response of each device in proximity of the nominal frequency (green area in Fig. 1): see [1], paragraph 5.5.3, line for Signal frequency range; Modulation frequency range in Table 5; paragraph 5.5.5, Ramp range in Table 7. At the same time comprehensive testing of suppression band is required, see [1], Table 4, lines Harmonic Distortion and Out-of-band interference.

It would be better if authors defined specification either in time or in frequency domain only. However, the standard covers both domains, i. e. provides requirements to frequency response, and to parameters of time-domain responses obtained as reaction to selected continuous signals.

3.2 Requirements to Achievement of a Unified Device

Conversion channel may be univalently described in frequency domain, for example as follows:

- I. Passband amplitude/frequency response shall be constant.
- II. Passband phase/frequency response shall be linear.
- III. Shape of amplitude/frequency response in transient bands shall be defined in the standard.
- IV. Phase/frequency response in transient bands shall be either linear or it shall be defined in the standard.

Parameters I-IV shall be defined with proper accuracy, so that TVE, FE and RFE are within the specified limits.

- I. Amplitude/frequency response within the suppression band shall ensure that those components of spectrum of continuous signal have noticeable effect neither on synchrophasor, nor on frequency, nor on ROCOF.

Phase/frequency response within the suppression band is not critical.

3.3 Discussion of Tests Stipulated by the Standard

The sufficiency of testing of frequency response in the course of compliance testing has been demonstrated above. Now let us consider how testing stipulated by the standard covers appropriate bands (completeness) and whether any tests duplicate each other (excessiveness).

Tests by steady-state signals are described in paragraph 5.5.3 [1]. Tests by pure sinusoids resemble measurement of amplitude/frequency and phase/frequency response: a sinusoid is applied to the input, while amplitude and phase are measured at the output providing passband frequency response. Testing by signals with higher harmonics and out-of-band interference with measurements performed as per TVE, FE and RFE (see the Appendix) checks if these interferences are suppressed properly within the suppression band (see Fig. 1).

Tests by modulated signals are described in paragraph 5.5.4 [1]. Phase and amplitude-phase modulated signals are distinguished by infinite discrete spectrum partially covered by the suppression band. Therefore, such signals will see little distortions in synchrophasor representation. The higher is the modulation frequency, the stronger distortions will be observed. Stronger distortions will apply to frequency, and still stronger distortions will apply to ROCOF. This experiment duplicates frequency response testing by steady-state signals.

Testing by ramp of system frequency is described in paragraph 5.5.5 [1]. Spectrum of signal $x(t) = X_m \cos[\omega_0 t + \pi R_f t^2]$ is shown in Fig. 2 (frequency variation is $50 \pm 5\text{Hz}$ at the rate of $R_f = 1\text{Hz/s}$). Such signal tests frequency response over the entire passband. This experiment duplicates PMU testing by steady-state signals within the passband, and does not cover the suppression band.

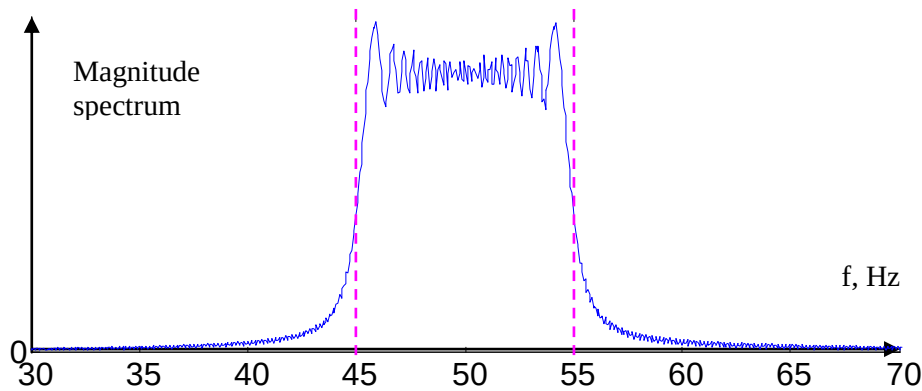


Fig. 2: Spectrum of ramp of system frequency signal

Testing by stepwise signals is described in paragraph 5.5.6 in [1]. Such signals are broadband. Phase step applies stronger action than amplitude step. Therefore, amplitude step must be excluded from testing. Reaction to stepwise input may be used for testing of the transient zone. However, the standard addresses particular parameters of the step-function response, rather than the response as a whole. It is still not clear whether limitations imposed on these parameters by the standard are sufficient for strict definition of frequency response in the transient band, provision of proper accuracy and whether the said limitations are not in contradiction with any other requirements.

3.4 Synchrophasor Properties

Generally speaking, synchrophasor is conventional term (and value) and, as such, requires agreement of procedure of its obtaining. Synchrophasor is formed by certain part of spectrum of wideband electric signal of power supply system. If interharmonics (part of signal of power supply system) appears to be within passband, it is used for synchrophasor generation. If interharmonics appears to be within suppression band, it is regarded as interference. If interharmonics appears to be within the transient band, its contribution depends on the agreement in place.

Synchrophasor is not affected by harmonics and interharmonics frequencies of which are beyond the band $F_{\text{nominal}} \pm F_s/2$. When F_s is small, low-frequency components fall outside the passband and, thus, do not affect synchrophasor. In particular, effects of aperiodic components will be

either suppressed or altered (depending on reporting rate F_s), while effects of free components with natural frequencies over $F_{\text{nominal}} + F_s/5$ will also be either suppressed or altered.

By increasing reporting rate up to $2 \cdot F_{\text{nominal}}$ it is possible to cover the low-frequency band. However, in this case it is necessary to take into consideration peculiarities of synchrophasor representation, i. e. the fact that slow low-frequency components will oscillate fast in the synchrophasor!

3.5 Comments on Standard Draft

Here are comments to particular paragraphs of the document [1]:

- a. Paragraph 4.3 [1] provides assessment of effects of fluctuations of sampling frequency on frequency measurement error. This assessment does not take into consideration that instantaneous frequency may contain spikes value of which may exceed nominal frequency by many times (see the Appendix).
- b. Paragraph 5.4.1 in [1] states: "Note that rates lower than 10/s are not subject to dynamic requirements ...". This means that measurements of Class M at reporting rates under 10Hz must be performed in accordance with specification applicable to Class P.
- c. Paragraph 5.5.3, Table 3, [1] defines "Signal frequency range" for "Performance class M": it is " ± 2.0 Hz for $F_s < 10$ ". There is obvious mismatch between passband of the system and signal frequency at $F_s < 5$ Hz. For example, let us consider $F_s = 1$ Hz. In this case explicit (i. e. without "spectra overlapping") measurements are possible only within the range $f_0 \pm 0.5$ Hz. However, the standard allows measurements of any signals within the range $f_0 \pm 2$ Hz.
- d. Instruments of Accuracy Class P may have measurement aliasing. This must lead to introduction of more strict to synchronization and frequency response. If frequency parameters of signal channel are not specified, variation of even one parameter (like the upper passband frequency) by the manufacturer will lead to variations of results of measurement.
- e. In the same paragraph 5.5.3 [1], in Table 4, errors of frequency and ROCOF measurements are specified for steady-state testing. For line "Harmonic distortion" and column "Error Requirements for compliance" for "Class M" for $20 \text{ Hz} < F_s \leq 60 \text{ Hz}$ we see $RFE = 6 \text{ Hz/s}$, while for $F_s \leq 20 \text{ Hz}$ we see $RFE = 2 \text{ Hz/s}$ (it is important that input ROCOF = 1Hz/s). Do we really need measurements, if error is that high? Here are some more examples: in paragraph 5.5.4 testing by modulated signals leads to TVE rise to 3%. Accuracy of frequency measurements falls to 0.3 Hz for $20 \text{ Hz} < F_s \leq 60 \text{ Hz}$ and to 0.06 Hz for $F_s \leq 20 \text{ Hz}$. At the same time ROCOF measurement accuracy falls to 30 Hz/s (!) for $20 \text{ Hz} < F_s \leq 60 \text{ Hz}$ and to 2 Hz/s for $F_s \leq 20 \text{ Hz}$!
- f. Testing by selected signals [1] often leads to rise of error. However, requirements to a device traditionally stipulate stable performance of that device under diverse conditions.
- g. Many tests [1] do not include interference by harmonics and interharmonics (like testing by modulated signals). However, the vast majority of real signals do include harmonics and interharmonics.
- h. Paragraph 5.5.5 [1] stipulates stepwise input signal frequency variations. "Transition time" is also stipulated: "Note that the allowed TVE, FE, and RFE may be exceeded during a "transition time" after a sudden change is made to the signal frequency." Table 8 specifies maximum permissible "transition time". However, many experts suggest that stepwise frequency variations just never happen in the power industry.
- i. Definition of maximum overshoot ([1], Fig. 3) covers only positive overshoot (close to steady-state value). However, negative overshoot is also possible (close to initial value). Definition of permissible values of transient response may be expanded by inclusion of negative overshoot.
- j. Figures C.2 and C.7 [1] show wrong sequence of frequency and ROCOF decimation. Frequency of filtered synchrophasor shall not be confused with filtered frequency of synchrophasor. Filtration of discrete frequency and ROCOF series (for further decimation) does not make sense. Figure C.7 is correct: real and imaginary synchrophasor components must be filtered. However, then we must use filtered real and imaginary components of synchrophasor to obtain phase. Then phase shall be differentiated to obtain frequency and ROCOF with further aligning of obtained flows taking into consideration delay introduced by

differentiating filters, and decimation. This could be one of reasons for reduced requirements to frequency and ROCOF in [1].

- k. Possibility of creation of a device on the basis of "Reference model" was not checked in Section C4 [1]. Below is Table C1 from standard [1] expanded by additional fields. This is Table 1. Almost all recommended filters do not meet requirements of the standard to permissible latency. The standard requires $(2-3)/F_s$ for the entire device (the last column), while symmetric FIR filters alone are distinguished by quite long delay given in column before the last. At the same time parameters of some filters do not meet requirements of steady-state test stipulated by the standard ([1], paragraph 5.5.4). Highlighted filter parameters in Table 1 are those that obviously do not meet requirements of the standard. "Cutoff frequency" is frequency at which amplitude/frequency response crosses 0.707 line. Therefore, it cannot be less than frequency band specified in Table 3 in [1].

Table 1: Filter Parameters Stipulated in Draft Standard Supplemented with Additional Columns

Reporting Rate F_s		Cutoff Frequency F_{cutoff}	Passband (lesser of $F_s/5$ or 5Hz)	Filter Order N	Only LP filter latency, (N/2)/ f_s	Required PMU reporting latency, 3/ F_s
50 Hz	10	1.920Hz	2	700	0,364583	0,3
	25	4.800Hz	5	280	0,145833	0,12
	50	8.850Hz	5	100	0,052083	0,06
	100	16.000Hz	5	44	0,022917	0,03
60Hz	10	1.920Hz	2	794	0,413542	0,3
	12	2.304Hz	2.4	660	0,34375	0,25
	15	2.880Hz	3	528	0,275	0,2
	20	3.840Hz	4	396	0,20625	0,15
	30	5.616Hz	5	238	0,123958	0,1
	60	10.320Hz	5	96	0,05	0,05
	120	18.960Hz	5	40	0,020833	0,025

4 PROPOSALS TO DRAFT STANDARD

4.1 Revision of Performance Requirements

Requirements to unified device may be compiled as described below.

Accuracy of synchrophasor, frequency and ROCOF may be re-calculated to suit requirements described in paragraph 0 of frequency response and accuracy of synchronization in time.

Requirements of the standard to frequency response shall be selected so that step-function response meets all applicable requirements. Latency requirement univalently defines maximum sloping of passband phase/frequency response.

Requirements to shape of frequency response shall take into consideration that it depends both on digital and analog sections. It is necessary to make sure channel is engineerable.

In order to ensure stable accuracy of frequency assessment, suppression band frequency response must fall at rate not less than inversely to frequency, while for stable ROCOF measurement suppression band frequency response must fall at rate not less than inversely to squared frequency (see the Appendix).

Formulae (2) and (3) are useful for assessment of requirements to efficiency suppression in corresponding band. Let us assume that the first harmonics in (1) is a useful signal, while the second harmonics must not be included into synchrophasor. It is possible to determine contribution of the latter to error of instantaneous frequency measurement and consequently calculate suppression needed to achieve the required accuracy of frequency and ROCOF measurements.

Requirements to accuracy of synchronization are calculated on the basis of maximum signal variation rate, maximum ROCOF and maximum second derivative of the frequency. Fluctuations of the parameter are directly proportional to fluctuations of sampling moment of time through these

derivatives (as a proportion factor). Calculation may be performed using formulae given in the Appendix.

4.2 Compliance certification

In order to check continuous signal synchrophasor conversion channel it is enough to make sure there is proper synchronization of measurements and check the device with the use of frequency response testing.

In accordance with provisions of current draft standard [1], PMU must be tested with employment of selected signals that represent generalization of signals from real power engineering practice.

However, time and complexity of testing may be reduced considerably by exercising a different approach. Device may be tested by signals capable of verification of frequency response of that device with minimum number of experiments and assess fluctuation of sampling periods, rather than by any “generalized” signals.

5 CONCLUSION

The report includes comments to current standard and draft of new revision of that standard. Recommendations on improvement of that standard are given at the same time.

Using results given in the report and by implementation of approach described herein it is possible to elaborate standard that may serve as basis for development of unified equipment.

In order to finalize the work it is necessary to verify compliance of requirements put forward to PMU operating environment. Such environment may be simulated with employment of electrodynamic model of NIPT.

APPENDIX:

RELATIONSHIPS FOR CALCULATION OF POSSIBLE DYNAMICS OF PHASE DERIVATIVES AND CALCULATION OF ERRORS OF THEIR MEASUREMENT

Let input signal to be sum of two sinusoids with angular frequencies ω_1 and $\omega_2 = \omega_1 + \Lambda$, while there is the following relationship between frequency of the first sinusoid and nominal frequency of the grid $\omega_1 = \omega_0 + \Theta$. Then continuous input signal is:

$$x(t) = a_1 \cdot \cos((\omega_0 + \Theta)t + \varphi_1) + a_2 \cdot \cos((\omega_0 + \Theta + \Lambda)t + \varphi_2). \quad (1)$$

Synchrophasor components may be determined by decomposition of input signal into projections of reference signal of nominal frequency:

$$\begin{aligned} X_r(t) &= a_1 \cdot \cos(\Theta t + \varphi_1) + a_2 \cdot \cos((\Theta + \Lambda)t + \varphi_2), \\ X_i(t) &= a_1 \cdot \sin(\Theta t + \varphi_1) + a_2 \cdot \sin((\Theta + \Lambda)t + \varphi_2) \end{aligned}$$

The first case to consider is combination of input sinusoids of equal amplitudes $a_1 = a_2 = a$. In this case:

$$\begin{aligned} X_r(t) &= a \cdot 2 \cdot \left(\cos\left(\Theta t + \frac{\Lambda t + \varphi_1 + \varphi_2}{2}\right) \cdot \cos\left(\frac{-\Lambda t + \varphi_1 - \varphi_2}{2}\right) \right), \\ X_i(t) &= a \cdot 2 \cdot \left(\sin\left(\Theta t + \frac{\Lambda t + \varphi_1 + \varphi_2}{2}\right) \cdot \cos\left(\frac{-\Lambda t + \varphi_1 - \varphi_2}{2}\right) \right). \end{aligned}$$

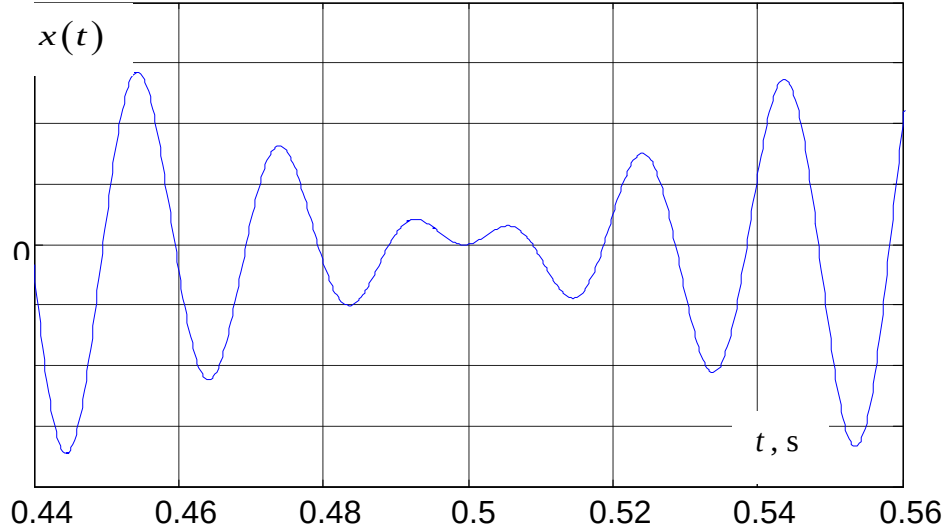


Fig. 3: Stepwise Variation of Phase of Continuous Narrowband signal

One can see that at the time when cosine argument is equal to $\pi/2 + \pi k$, $k \in \mathbb{Z}$, both real and imaginary components become zero at the same time, i. e. this happens every $2\pi/\Lambda$. Such signal (1) in proximity of the said moment of time is given in Fig. 3 (for simplicity the plot was made for $a=1$, $\varphi_1 = \varphi_2 = 0$, $\Theta = 0.1 \text{ rad/s}$, $\Lambda = 1 \text{ rad/s}$).

The signal and quadratures are continuous, while phase has 180° stepwise variations. It is obvious that frequency has infinite spikes here.

This is to note that a signal containing two sinusoids of nearly equal amplitudes is a rare occurrence in power engineering. Unequal amplitudes are far more common. In such case phase has no discontinuity and frequency has non-infinite spike. After differentiating and transformations we get:

$$\omega(t) - \omega_0 = \frac{\Theta + d \cdot (2\Theta + \Lambda) \cdot \cos(\Lambda t + \varphi_2 - \varphi_1) + d^2 \cdot (\Theta + \Lambda)}{1 + 2 \cdot d \cdot \cos(\Lambda t + \varphi_2 - \varphi_1) + d^2},$$

where $d = a_2 / a_1$. Figure 4 shows instantaneous frequencies for $d = 0.1$ и $d = 0.01$ (for simplicity the plot was made for $\varphi_1 = \varphi_2 = 0$, $\Theta = 2\pi \cdot 0.1 \text{ rad/s}$, while $\Lambda = 2\pi \cdot 1 \text{ rad/s}$).

As long as d is low, instantaneous frequency fluctuates around frequency $\omega_0 + \Theta$. These fluctuations are nearly sinusoidal:

$$\omega(t) - \omega_0 \approx d \cdot (2\Theta + \Lambda) \cdot \cos(\Lambda t + \varphi_2 - \varphi_1). \quad (2)$$

It is important to note that fluctuation amplitudes are directly proportional to difference of frequencies of sinusoids incorporated in the signal.

Since Θ is limited by frequency band of the channel, its contribution to frequency measurements is limited. At the same time contribution of differences of frequencies of sinusoids Λ rises linearly and with no limits, as long as Λ rises itself.

Now let us consider contribution of the second harmonics to value of instantaneous ROCOF. After differentiating and transformations we get:

$$\omega'(t) = \frac{(d^2 - 1) \cdot d \cdot \Lambda^2 \cdot \sin(\Lambda t + \varphi_2 - \varphi_1)}{(1 + 2 \cdot d \cdot \cos(\Lambda t + \varphi_2 - \varphi_1) + d^2)^2}.$$

Figure 4 shows ROCOF plot for two $2\pi/\Lambda$ periods (parameters are the same as those used for plotting frequency).

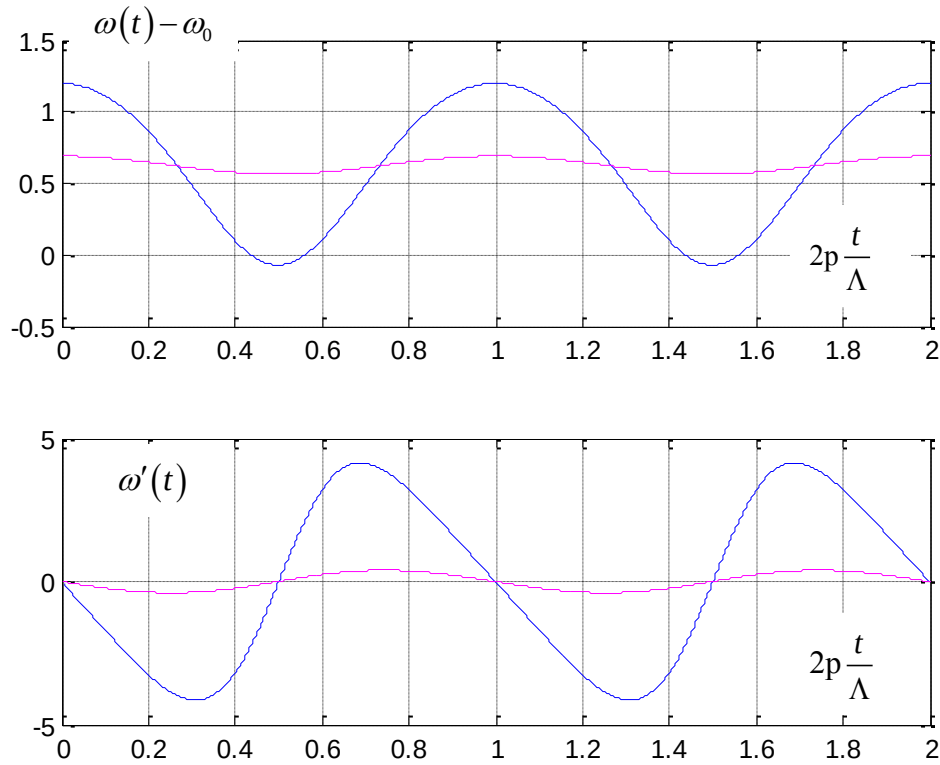


Fig. 4: Instantaneous Frequency and ROCOF

When d is low, ROCOF fluctuations are nearly sinusoidal:

$$\omega'(t) \approx -d \cdot \Lambda^2 \cdot \sin(\Lambda t + \varphi_2 - \varphi_1). \quad (3)$$

This approximate formula demonstrates quadratic proportionality between fluctuation amplitudes and difference of frequencies of the sinusoids.

It is important to note that effects of abrupt phase variations have been studied for narrowband stochastic processes [4]. For Gaussian narrowband process dispersion does not exist (it is equal to infinity).

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