Synchronized Phasor and Frequency Measurement Under Transient Conditions

A. G. Phadke, *Life Fellow, IEEE*, and Bogdan Kasztenny, *Fellow, IEEE*

***Abstract*—Synchronized phasor measurements are becoming an important element of wide area measurement systems used in advanced power system monitoring, protection, and control applications. The recently issued revised standard C37.118 for synchrophasors has facilitated interoperability of phasor measurement units (PMUs) from different manufacturers. This standard defines performance for compliance when the input signals are in steady state. The performance of PMUs under transient conditions is not considered by the standard at this time, although clearly PMUs will be subjected to inputs under transient conditions. This paper is an attempt to provide the authors' views on how one may approach the question of standardizing PMU response under transient conditions.**

***Index Terms*—Electrical transients, electromechanical transients, global positioning system (GPS), phasor, phasor measurement unit (PMU), power system, real-time measurements, synchronized measurements, synchrophasor.**

I. Introduction

SYNCHRONIZED phasor measurements have become an important component of wide area measurements in power systems. Since phasor measurement units (PMUs) provide voltage and current phasors synchronized with high precision to a common reference of the global positioning system (GPS), they facilitate a number of wide-area applications including measurement-assisted state estimation, adaptive protection, remedial action schemes (RAS), improved system analysis and control, and many others.

The Power System Relaying Committee of the Power Engineering Society recently issued a revised standard C37.118 ("Synchrophasor"), which defines the performance requirements of PMUs under steady state conditions [1].

In general, power system voltage and current waveforms are not steady state sinusoids, particularly during system disturbances. They frequently contain sustained harmonic and nonharmonic components. In addition, because of faults and other switching transients, there may be step changes in the magnitude and phase angles of the waveforms. Other disturbances are the relatively slow changes in phase angles and magnitudes due to oscillations of machine rotors during electromechanical disturbances.

The standard cited above does not address the definition and performance requirements for phasor measurements when the input signals are changing due to system transients. Nonetheless, it is expected that for slowly changing phasors compliant PMUs of different manufacturers will display a high degree of interoperability.

In this paper, the concept of phasor and frequency measurement under transient conditions is explored. Phasor and synchrophasor basics are covered in Section II. The nature of power system transients is reviewed in Section III. Section IV considers a possible approach towards formulating a standard which would lead to interoperability of PMUs under transient conditions. Section V summarizes the key points presented in this paper.

It is hoped that future revisions of the standard will draw from new thoughts and opinions as these concepts are explored and discussed in the technical literature.

II. Basics of Phasor Measurement

A. Classical Definition of a Phasor

The concept of a phasor is more than a century old and dates back to Steinmetz, who proposed complex numbers for analysis and synthesis of linear electrical networks with sinusoidal sources under steady state conditions [2].

A sinusoidal signal of a known frequency f is fully described by its magnitude X_m and angular position ϕ with respect to an arbitrary time reference

$$x(t) = X_m \cos(2\pi f t + \phi). \tag{1a}$$

The phasor representation $\boldsymbol{X}$ of the sinusoid of (1a) is given by

$$\boldsymbol{X} = (X_m/\sqrt{2})\varepsilon^{j\phi}. \tag{1b}$$

The magnitude of the phasor is the rms value of the sinusoid, and the frequency does not appear explicitly in the phasor representation; but is an implied property of the phasor.

B. Phasor Measurement Concepts

Applications related to processing actual power system signals, either in real-time (protection, control, visualization) or for off-line analysis, call for synchronized phasor measurements. The latter developed into a mature field of engineering in the last few decades [3]–[7].

Fig. 1 presents two possible architectures used for real-time phasor measurements. As shown in Fig. 1(a) and (b), the input signal $x(t)$ is sampled at a variable sampling frequency equal to the actual frequency of the power system, or at a constant frequency depending upon the nominal power system frequency. An analog anti-aliasing filter is used to limit the bandwidth of the input signal to be compatible with the sampling frequency

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A. G. Phadke is with Virginia Polytechnic Institute and State University, Blacksburg, VA 24061-0202 USA (e-mail: aphadke@vt.edu).

Bogdan Kasztenny is with General Electric Company, Markham, ON L6E 1B3, Canada (e-mail: Bogdan.Kasztenny@ge.com).

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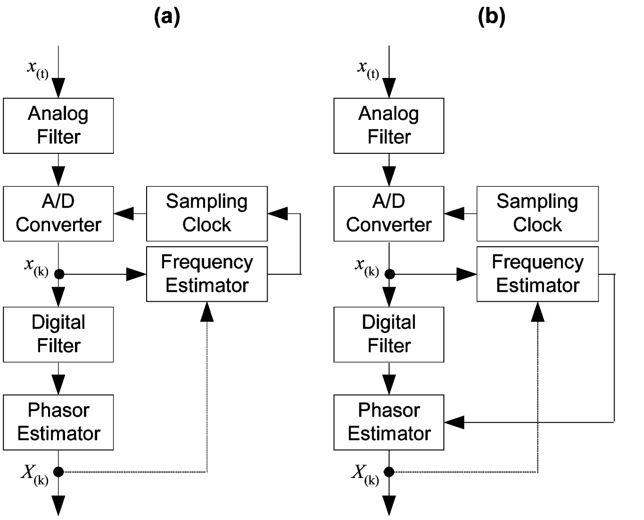

Fig. 1. Basic phasor estimation architectures. (a) Frequency tracking. (b) Frequency compensation.

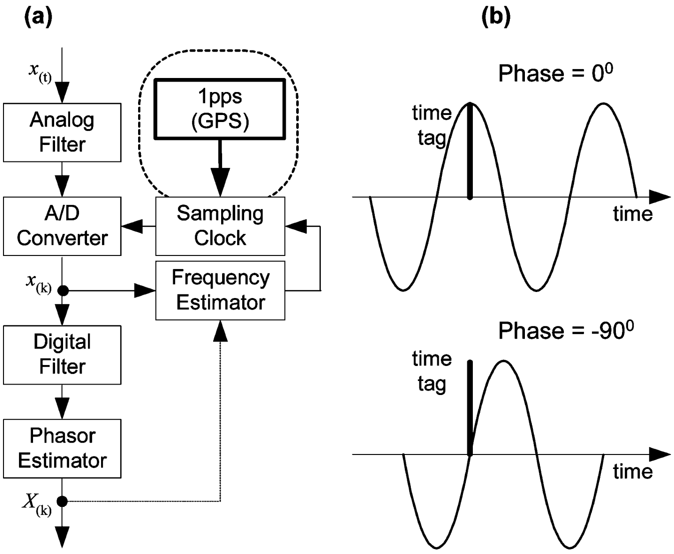

Fig. 2. Sample synchrophasor phasor architectures with (a) frequency tracking and (b) synchrophasor angle convention.

chosen. A digital filter may be used to provide band-pass filtering and removing frequency components that may create problems for a specific application. The phasor estimator calculates the phasor representation of the input signal complying with the definition given in (2). The discrete Fourier transform (DFT) is a simple widely used method for phasor estimation

$$\boldsymbol{X}_{(k)} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_{(k+n)} \cdot \varepsilon^{-j\cdot\frac{2\cdot\pi\cdot n}{N}} \tag{2}$$

where k is the first sample in the data window, and N is the number of samples in a cycle of the fundamental frequency component. Applying this definition of phasor produces a phasor estimate which uses the sampling instant of the first sample in the data window as the time-tag of the phasor.

It should be noted that other methods of estimating phasors (such as Kalman Filter, weighted least squares, artificial neural networks (ANNs), etc.) have been discussed in technical literature. However, to the best of the authors' knowledge, DFT-based phasor estimation is the most commonly used technique in currently available PMUs. The considerations of response to transients, which is the main concern of this paper, is not dependent on the phasor estimation technique used.

C. Synchrophasor Definition and Measurements

Synchrophasor is a phasor with the angle referenced to an absolute GPS-driven time reference. Fig. 2(a) explains the phase angle reference convention imposed by the standard [1]. With reference to Fig. 2(b), a PMU is required to have a time-tag that is referred to the absolute time. This means each sampling instant in the data window must be capable of being correlated with the absolute time provided by the GPS clock.

When the variable frequency sampling clock phase-locked to the prevailing power system frequency as used in Fig. 1(a), the phasor calculation given by (2) is without error. However, in this case, a correction must be made to calculate the phase angle to correspond to the phasor time-tag as specified in the synchrophasor standard.

When constant frequency sampling clocks synchronized with the nominal power system frequency are used as in Fig. 1(b), a positive sequence phasor calculation based upon (2), is different from the true value of the input positive sequence phasor. The measured positive sequence phasor $\boldsymbol{X}'(\boldsymbol{k})_1$ is related to the true phasor $\boldsymbol{X}(\boldsymbol{k})_1$ as follows:

$$\boldsymbol{X}'(k)_{\mathbf{1}} = P\boldsymbol{X}(k)_{\mathbf{1}}\varepsilon^{jk(\omega-\omega_0)t} \tag{3}$$

where the coefficient P is given by

$$P = \left\{\frac{\sin\frac{N(\omega-\omega_0)\Delta t}{2}}{N\sin\frac{(\omega-\omega_0)\Delta t}{2}}\right\}\varepsilon^{j(N-1)\frac{(\omega-\omega_0)\Delta t}{2}}. \tag{4}$$

The magnitude and phase angle of P depends upon the sampling rate N and the difference between the nominal and actual frequencies. As an example, for a sampling rate of 24 samples per cycle and a frequency range of ± 5 Hz around the nominal frequency, the magnitude and phase angle of P is as shown in Fig. 3. A PMU using a constant frequency sampling clock must apply correction factors to the estimated phasor to account for the factor 'P' in (4) before the result is posted in the output.

III. Transients in Power Systems

For the purpose of the present discussion, transients in power systems may be classified into two categories: 1) electromagnetic transients and 2) electromechanical transients.

A. Electromagnetic Transients

Switching operations and faults produce step changes in the voltage and current waveforms. Resonances in the power network create additional frequencies in the waveforms during these phenomena. Such transients may be classified as electrical or electromagnetic transients. The effect of these transients is to introduce high frequency components in the signals. These

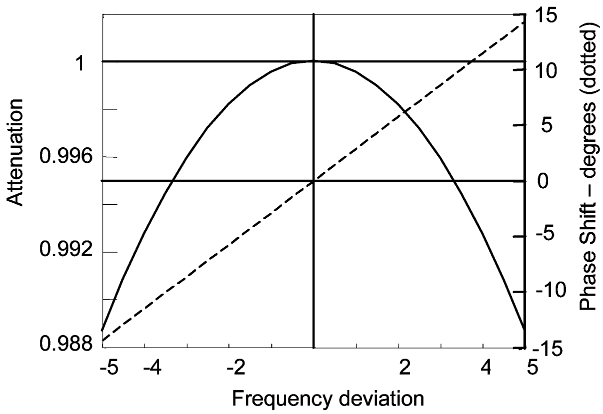

Fig. 3. Variation of magnitude and phase angle of $\boldsymbol{P}$ for a frequency variation of ± 5 Hz around the nominal frequency. Sampling rate of 24 samples per nominal period.

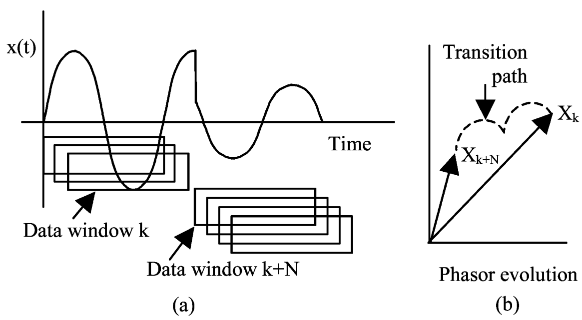

Fig. 4. (a) Input signal with a step change in amplitude and phase angle. (b) Phasor estimate evolution through the transient period.

transients dissipate within a short time and the waveforms then return to a steady state condition. Anti-aliasing filters used in the PMUs attenuate the high frequency signals to insignificant values.

The estimation of phasors is typically performed over one period of the nominal system frequency. Step changes in the input signals due to electromagnetic transients may occur within the data window, in which case, one needs to consider whether the phasor estimate obtained in that window is valid.

Consider the step change in the signal shown in Fig. 4(a). As the phasor computation progresses with one cycle data windows when new samples are obtained, the window "k" is the last one to contain data belonging to the pre-disturbance signal, while window "$\mathrm{k+N}$" represents the first window to contain data belonging only to the post-disturbance signal. All other windows between these two contain mixed data from two different sinusoids. The calculated phasor transition is shown in Fig. 4(b).

It should be clear that the phasors calculated in the "$\mathrm{k+1}$" through the "$\mathrm{k+N-1}$" windows do not represent the existing waveforms during pre- or post- transient periods. Use of these phasors for any type of control or protection functions may be inappropriate. A technique for flagging such invalid phasors has been discussed in literature [8], and some such technique should be used to flag an unusable phasor.

As mentioned earlier, very high frequency transients are removed by anti-aliasing filters, and the PMU will not actually be faced with a step change as illustrated in Fig. 4. The step change will be modified to a more gradual change by such filters. In addition, transducers, nonlinearities caused by saturation of magnetic elements will also introduce harmonics and distortion. It should be noted that harmonics can be eliminated by DFT-type phasor estimators. Taking all of these effects into consideration, it is clear that the mechanism of jump changes and distorted waveforms can be handled by the phasor quality measure described here.

B. Electromechanical Transients

Electromechanical transients are characterized by magnitude and phase angle modulation of power system voltages and currents with low frequency signals corresponding to the movement of rotors of large electric machines around the synchronous speed. Numerous examples of practically observed modulations of this type can be found in technical literature. [10]. In most large power systems, these oscillation frequencies are in the range of 0.1–10.0 Hz. The oscillations may produce cyclic variations in system frequency, although, in some cases, a ramped change of frequencies may also occur.

The positive-sequence voltage generated by a generator can be represented by

$$e_1(t) = \sqrt{2}E_1(t)\cdot\cos(\omega_1(t)\cdot t + \phi(t) + \delta_0). \tag{5}$$

In (5), the initial angle δ_0 is the rotor angle at $t = 0$, and ω_1 is the radian frequency corresponding to the time dependent speed of the rotor.

The rotor speed deviates from the nominal synchronous speed ω_0 by a relatively small deviation

$$\Delta\omega(t) = \omega_1(t) - \omega_0 \tag{6}$$

which could be a damped oscillatory or ramp function of time.

The concept of phasors is intuitively founded on the observation that the magnitude $E_1(t)$ and frequency $\omega_1(t)$ change much more slowly than the variations corresponding to the power system frequency.

When the power system is energized by machines with differing time dependent rotor speeds of several machine rotors, the resulting voltages and currents have modulated magnitudes, modulated phase angles, or both, due to superposition of sources operating at different speeds. In the following text, magnitude and phase angle modulations are considered first separately for clarity, and then simultaneously.

1) Magnitude Modulation: Mathematically, magnitude modulation of a signal $e(t)$ by a small amount "x" with a modulating frequency "ω_m" can be expressed as follows:

$$e_1(t) = \sqrt{2}E_1\cdot\{1 + x\cos(\omega_m t)\}\cos(\omega_1(t)\cdot t + \phi + \delta_0) \tag{7}$$

or using trigonometric identities

$$\begin{aligned} e_1(t) = {} & \sqrt{2}E_1\cdot\cos(\omega_1(t)\cdot t + \phi + \delta_0) \\ & + \frac{1}{2}\sqrt{2}E_1\cdot x\cos(\{\omega_1 + \omega_m\}t + \phi + \delta_0) \\ & + \frac{1}{2}\sqrt{2}E_1\cdot x\cos(\{\omega_1 - \omega_m\}t + \phi + \delta_0) \end{aligned} \tag{8}$$

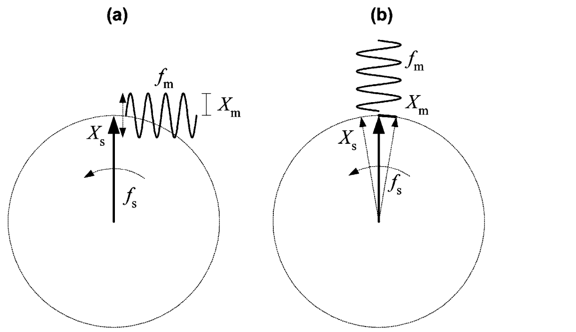

Fig. 5. Phasor modulation principle. (a) Amplitude and (b) phase oscillations.

which illustrates that the magnitude modulation is equivalent to adding sum and difference frequency components to the original signal. Since the modulating frequency is quite small when compared with the power system frequency, the additive frequencies are quite close to the nominal power system frequency.

2) Phase Angle Modulation: Phase angle modulation by a small amount "y" with a modulating frequency "ω_m" can be represented by

$$e_1(t) = \sqrt{2}E_1 \cos(\omega_1.t + \phi\{1 + y\cos(\omega_m t)\} + \delta_0). \quad (9)$$

Using the Taylor series expansion of (9) and recognizing that "y" is much smaller than 1, the equation becomes

$$\begin{aligned} e_1(t) = &\sqrt{2}E_1 \cos(\omega_1 \cdot t + \phi + \delta_0) \\ &+ \frac{1}{2}\sqrt{2}E_1 y \sin(\{\omega_1 + \omega_m\}).t + \phi + \delta_0) \\ &+ \frac{1}{2}\sqrt{2}E_1 y \sin(\{\omega_1 - \omega_m\}).t + \phi + \delta_0). \quad (10) \end{aligned}$$

As in the case of magnitude modulation, the modulating signals in this case are additive, and contain sine functions of the sum and difference of the modulating frequency and power system frequency.

The magnitude and phase angle modulations can be illustrated by the variations in the pure nominal frequency phasor along the length of the phasor, or in a direction perpendicular to the phasor as illustrated in Fig. 5.

3) Phase and Magnitude Modulation: When magnitude and phase angles of phasors are modulated simultaneously, the effect is represented by an equation similar to (8) or (10), which contains both sine and cosine components of the sum and difference frequencies. The addition of sum and difference frequency components to produce modulation of the nominal frequency signal is illustrated in Fig. 6.

C. Measurement of Frequency

Frequency is defined unambiguously for a steady state periodic signal. When harmonics of the fundamental frequency are present, the frequency is usually associated with the fundamental frequency component. However, when the signal of interest is modulated with low frequency signals, the definition of frequency becomes less clear. In power systems, frequency is conceptually tied to the speed of rotation of synchronous generators. Angular velocity of the rotor measured in electrical radians per second is the frequency. In power systems where

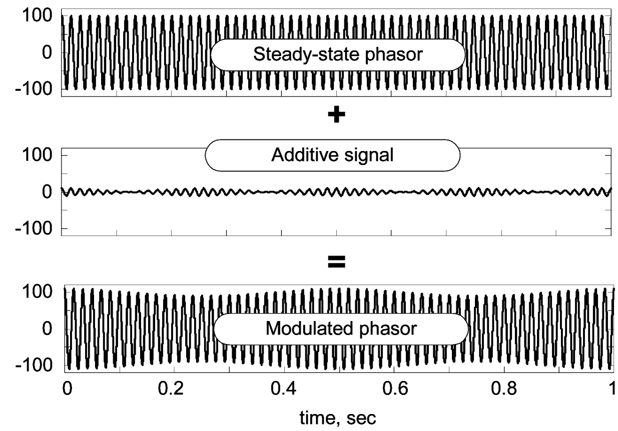

Fig. 6. Illustration of equivalency between modulated phasors and the additive signal component.

each generator may be rotating with slightly different speeds, the voltages and currents in the power system contain modulation effects due to all generator speeds. The concept of frequency measurement under these circumstances needs careful consideration.

A simple and consistent approach is to define frequency as the speed of rotation of a phasor [3], [7], the same way the speed of rotation of a generator's rotor defines its frequency

$$f = \frac{1}{2 \cdot \pi} \cdot \frac{d\phi}{\mathrm{dt}}. \quad (11)$$

The problem with this approach is that the same factors that make the frequency definition ambiguous make the phasor definition unclear as well. In addition, the angular position of voltage and current can change abruptly due to electrical transients yielding large invalid changes in the frequency defined by (11).

Despite the aforementioned limitation, (11) is often used to calculate the frequency in today's PMUs. In order to reduce the effect of measurement noise on the differentiation operation in (11), averaging over several phase angle measurements is used. Some synchrophasor-based applications draw on the aforementioned definition at the client/application level to ensure relative interoperability of frequency measurements by avoiding the use of direct measurements from PMUs.

Consider a positive sequence phasor computed with a data window of one cycle of the nominal frequency using the recursive algorithm. As discussed in Section III-A, if a phasor calculation spans a data window with a switching operation taking place within the window span, then that phasor should be discarded, and frequency estimation delayed until all phasors are free of any step changes. In addition, if a switching operation in the network produces a step function displacement in the phase angles, the displacement must be compensated for before frequency estimation is attempted. One method for accomplishing such compensation is to set a tolerance on an allowable change in the phase angle between successive samples which is compatible with largest expected excursion in power system frequency. This is illustrated in Fig. 7.

Assume that the phasors are estimated over one period of the nominal frequency, and that the phasors calculated with several

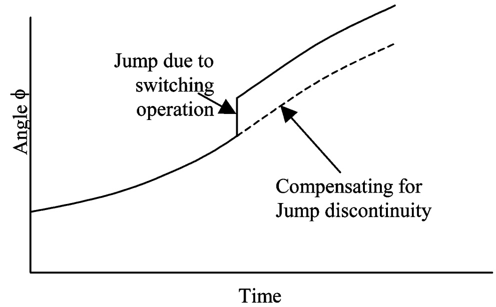

Fig. 7. Correcting phase angles for frequency and rate of change of frequency estimation.

consecutive data windows (for example, ranging from three to six nominal cycles) are used for frequency and rate of change of frequency estimation.

Let $[\phi_{\mathrm{k}}]\{\mathrm{k} = 0, 1, \ldots \mathrm{n} - 1\}$ be the vector of "n" samples of the phase angles of the positive sequence measurement. The vector $[\phi_{\mathrm{k}}]$ is assumed to be monotonically changing over the window of "n" samples. "Δt" is the time interval between samples.

As the phase angles of the phasor estimated may be restricted to a range of 0–2π, it is necessary to make the angles monotonically changing over the entire spanning period.

If the frequency deviation from the nominal value, and the rate of change of frequency at $\mathrm{t} = 0$ are ω_0 and ω', respectively, the frequency at any time "t" is given by

$$\omega(t) = (\omega_0 + t\omega'). \tag{12}$$

The phase angle is the integral

$$\phi(t) = \int \omega dt = \int (\omega_0 + t\omega')dt = \phi_0 + t\omega_0 + \frac{1}{2}t^2\omega'. \tag{13}$$

If $\phi(t)$ is assumed to be a second degree polynomial of time

$$\phi(t) = a_0 + a_1 t + a_2 t^2 \tag{14}$$

it follows that at $\mathrm{t} = 0$:

$$\begin{aligned} \omega_0 &= a_1 \\ \omega' &= 2a_2. \end{aligned}$$

Or in terms of Hertz and Hz/s

$$f_0 = a_1/(2\pi) \quad \text{and} \quad f' = a_2/(\pi). \tag{15}$$

The vector of "n" angle measurements is given by

$$\begin{bmatrix} \phi_0 \\ \phi_1 \\ \phi_2 \\ \vdots \\ \phi_{n-1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & \Delta t & \Delta t^2 \\ 1 & 2\Delta t & 2^2\Delta t^2 \\ \vdots & \vdots & \vdots \\ 1 & (n-1)\Delta t & (n-1)^2\Delta t^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}. \tag{16}$$

Or in matrix notation

$$[\phi] = [B][A] \tag{17}$$

where $[\mathbf{B}]$ is the coefficient matrix in (16). The unknown vector $[\mathbf{A}]$ is calculated by the weighted least squares (WLS) technique [9]

$$[\boldsymbol{A}] = [\boldsymbol{B}^T\boldsymbol{B}]^{-1}\boldsymbol{B}^T[\boldsymbol{\phi}] = [\boldsymbol{G}][\boldsymbol{\phi}] \tag{18}$$

where

$$[\boldsymbol{G}] = [\boldsymbol{B}^T\boldsymbol{B}]^{-1}\boldsymbol{B}^T. \tag{19}$$

The matrix $[\boldsymbol{G}]$ is pre-calculated and stored for use in real time. It has "n" rows and three columns. In real time, $[\boldsymbol{G}]$ is multiplied by $[\boldsymbol{\phi}]$ to obtain the vector $[\boldsymbol{A}]$, and from that, the frequency and rate of change of frequency at any time t (which is a multiple of Δt) can be calculated. This time is usually associated with the time tag for which the measurement is posted.

IV. Towards a Transient Synchrophasor Standard

A. Scope of the Present Standard (C37.118)

As mentioned before, the current standard [1] is restricted to steady state conditions. The out-of-band frequency requirement in the standard does not concern dynamic conditions, but refers to the need to suppress phasor modulating frequencies, given the chosen phasor reporting rate. This is to satisfy the Nyquist criterion for the process of sampling phasors. The standard mandates a stop-band, taking the reporting rate as the only relevant factor. For example, when reporting at ten phasors per second, a compliant PMU shall suppress phasor oscillations faster than 5 Hz, or else the results will alias when received at the client/application. This means that the standard calls for a stop-band of $\pm$5 Hz away from the frequency of the dominating signal when reporting at ten phasors per second.

B. Phasor Measurement During Slow Transients

As mentioned earlier, the effect of electromechanical transients is to confine the frequencies of interest around the nominal power system frequency f_0 in the range of $f_0 \pm 10$ Hz. Measuring these frequencies by using consecutive independent observation windows would lead to an accurate estimate of the electromechanical transient frequencies.

C. Suggested Features of a Transient Synchrophasor Standard

There are two possible methods of creating a standard for "transient" phasor measurement systems: 1) mandating a set of inputs for which the PMU performance is to be defined, or 2) mandating algorithms to be used by the PMUs for computing phasors, frequency, rate of change of frequency, etc., so that all PMUs will have identical transient responses. These two possibilities are considered next.

1) Specifying PMU Response to Mandated Transient Conditions: This is probably the simplest method of defining a defacto interoperable transient phasor measurement requirement and a logical continuation of the existing synchrophasor standard. The approach is based on a set of representative transient patterns. These may include a step change in magnitude and phase, angles and frequency ramps, magnitude and phase angle oscillations, and perhaps some other patterns.

For each pattern, an exact signal model is created to avoid ambiguity. For each transient pattern, a constraint is imposed in terms of the rate of change of frequency or magnitude ramp, frequency, and magnitude of phasor oscillations, etc.

Additional measures of performance errors are defined such as a settling time after the beginning of the transient, maximum total vector error (TVE) during the settling time, overshoot, etc. The thrust of this approach is that PMUs responding virtually identically to a broad enough collection of sample transient patterns will ensure a defacto interoperability under any practical system transients.

Another important point is the division of application tasks in the PMU (at the field level), and at the application level. Minimizing the tasks at the PMU level has the merit of making the PMUs independent of future (unforeseen) applications, which may evolve, and their specific measurement requirements. On the other hand, there are data, which are only available to the PMUs and are not available at the application level. Where the use of these data is needed, it is clear that those applications must reside in the PMUs. Based upon these observations, the following starting points for discussing a "transient PMU" may be proposed as a standard.

1) The standard should require that phasors, which have a step change in the waveform, be flagged as being unusable for some applications. The quality of the phasor estimate would be a good indicator of detecting a transient of this kind, as well as errors introduced by other factors. The standard could set a threshold for the "quality" measure, and a quality poorer than this threshold could be used to set a binary flag stating that the phasor should be used with caution. Clearly, this task requires access to raw data, which is only available to the PMU, and must be performed at the PMU level.
2) The standard should require that step changes in phasor angles resulting from switching operations should be compensated before frequency and the rate of change of frequency is estimated. This will eliminate frequency "impulses" in the output.
3) The frequency and rate of change of frequency should be estimated using a sufficient number of phase angle measurements. A reasonable span would be 3–6 cycles of the nominal frequency. The span used by a PMU should be a part of the PMU specification This task also requires that raw data (for example, phasor estimates at each data sample) be available to the frequency and rate of change of frequency estimation. Thus, this task has to be performed at the PMU level.
4) The frequency and rate of change of frequency should be referred to the same time-tag which is used for the phasor.
5) The PMUs should be capable of tracking the ramp modulation of magnitude and phase angle of the inputs within a specified range.
6) The PMU should be capable of tracking sinusoidal modulation of the magnitude and phase angle of the positive sequence inputs within a specified range. A possible range for modulating sinusoidal frequencies may be 0.1–10 Hz.
7) A part of the PMU specification should be the settling time (see Fig. 8) of the algorithms used while tracking the ramp and sinusoidal variations in the input.
8) The aforementioned ramp and sinusoidal tests should be performed for all available reporting rates for the PMUs, and there should be no aliasing errors because of modulating frequencies being outside the Nyquist criterion for the modulating frequencies.
9) The settling time should be interpreted as that period after which the TVE of the output falls within the requirements of the standard C37.118. A possible additional parameter would be maximum TVE during the settling time. This may allow some applications to use the PMU data during the settling time, taking due note of the TVE associated with these measurements.
10) Regarding the TVE specified in the present standard, it would be advisable to define TVE as an average (or maximum) of the TVE measured at successive data points over a certain period—for example, one period of the nominal frequency. A single point measurement of TVE could be misleading.
11) Presently, the out-of-band frequency requirement refers to suppressing phasor oscillations that violate the Nyquist theorem given the reporting rate. The dynamic synchrophasor definition would require both suppressing oscillations to be too fast to be reported and reporting oscillations within the Nyquist band. Therefore, the out-of-band frequency condition will have to be defined accordingly.

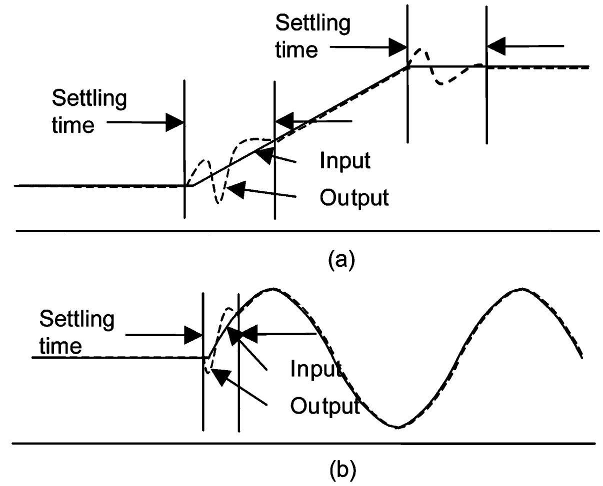

Fig. 8. Testing the PMUs for ramp and sinusoidal modulation of magnitude and phase angles of the positive sequence quantities.

2) Mandating Algorithms to be Used for Measurements Performed by the PMUs: Another possible approach to interoperable phasor measurements under dynamic conditions is to impose a common implementation method for all basic computations.

It is worth noticing that a successful approach to dynamic phasor specifications and other future application trends will have to limit exposure of the field installations (PMUs) to possible changes in phasor definitions. To enhance longevity of PMUs, the local processing at the PMU should be simple and transparent. Software used at the client/application level is much more flexible and cost-efficient in terms of fine-tuning the phasor measurements. In this respect, the approach of mandating the one-cycle Fourier algorithm to just "sample and compress" the waveforms without an attempt for high-quality measurements is quite an attractive way of proceeding. This, of course, does not solve the problem of interpreting phasor measurement under transient conditions, but shifts it into a much more flexible area of software at the application level.

In order to be successful, the mandated implementation methods need to be simple, totally transparent, and linear. The latter is critical for post-processing at the client/application level.

The following can be considered:

1) full-cycle standard Fourier algorithm, with a freely selected but disclosed number of samples per cycle;
2) no frequency tracking or compensation; the window tuned to nominal system frequency;
3) uniform sampling within the window;
4) no digital pre-filtering;
5) freely selected analog filter but with a disclosed characteristic.

A number of sophisticated phasor estimators can be built at the client/application level using the received stream of phasors calculated according to the implementation method proposed above. In particular, off-nominal frequency compensation and longer data windows can be implemented. Reference [7] provides good examples of techniques for post-filtering of synchronously taken one-cycle Fourier phasors.

V. Conclusion

This paper discusses phasor and frequency measurements under transient system conditions. Both electromagnetic and electromechanical transients are considered. After explaining the basics of phasors, synchrophasors, and frequency and system transients, suggestions have been made for improving the interoperability of PMUs under transient conditions.

The main points of the proposed revision of the standard are:

- requiring a "quality of phasor" indication to accompany each phasor estimate;
- requiring a frequency (and rate of change of frequency) estimation procedure, which eliminates noise due to the differentiation of phase angles, and impulses due to phase angle jumps from switching operations.
- Requiring the definition of a settling time for phasor estimations during transient conditions.
- Proposing performance specification for PMUs when sinusoidal and ramp modulations of phasor magnitude and phase angle are present.
- Suggesting a refinement of the TVE and out-of-band frequency requirements in the standard.

It is hoped that the paper will lead to discussion on the definition and measurement of phasors and frequency under transient conditions and inspire more research into the measurement techniques and will eventually lead to a consensus on this important topic within the industry.

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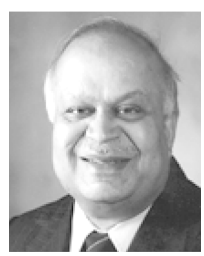

A. G. Phadke (LF'03) is a University Distinguished Professor (Emeritus) at Virginia Polytechnique Institute and State University, Blacksburg. His primary research area is the microcomputer-based monitoring, protection, and control of power systems. He is a co-author of two books on relaying: *Computer Relaying for Power Systems* and *Power System Relaying*, and is the editor of and contributor to the book *Handbook of Electrical Engineering Computations*.

Dr. Phadke was awarded the IEEE Third Millennium Medal in 2000, named the Outstanding Power Engineering Educator by the IEEE in 1991, and received the Power Engineering Educator Award of the EEI in 1986. He received the IEEE Herman Halperin Transmission and Distribution award in 2000. He was the Chairman of the Technical Committee of USNC CIGRE, and Editor-In-Chief of IEEE Transactions on Power Delivery. He was elected to the U.S. National Academy of Engineering in 1993. He was awarded Honorary Doctorate by INP Grenoble, Grenoble, France in 2006.

Bogdan Kasztenny (M'95–SM'98–F'08) is Protection and System Engineering Manager for the Digital Energy business of General Electric (GE), Markham, ON. Prior to joining GE in 1999, he was an Assistant Professor conducting research and teaching power system courses at the Wroclaw University of Technology, Wroclaw, Poland; Texas A&M University, College Station; and Southern Illinois University. He remains hands on and instrumental in new product development at General Electric. He acts as an R&D liaison with several universities and corporate research. He has authored more than 160 papers, has conceived numerous protection and control products, and is an inventor of several patents

Prof. Kasztenny received the Senior Fulbright Fellowship in 1997. Between 2000 and 2004, he was heavily involved in the development of the globally recognized universal relay product line, for which in 2004, he received GE's Thomas Edison Award for innovation. He is a member of the main committee of the IEEE Power Engineering Society Power System Relaying Committee, where he chairs or co-chairs several working groups. He is a registered Professional Engineer in the Province of Ontario, an Adjunct Professor at the University of Western Ontario, and a member of the Canadian National Committee of CIGRE, Study Committee B5—Protection and Automation.