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Performance of Phasor Measurement Units for Wide Area Real-Time Control

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Abstract—Phasor Measurement Units (PMU) are becoming a basic building block of modern wide area power system protection, monitoring and control schemes. Such systems rely on accurate time synchronized measurements. PMU operation is governed by the IEEE C37.118 standard. The standard sets out the performance requirements for valid phasor measurements under steady state conditions, but does not specify the response of PMUs under transient system conditions. Since most events requiring action by protection and control systems arise from transients it is important that PMUs report these anomalies in an understood and universal manner. This paper discusses the problem of determining phase during a transition from one cyclic state to another.

Index Terms—Synchrophasor, PMU, Transient, Real-Time Control, Protection

I. INTRODUCTION

Synchrophasor measurement devices are quickly becoming one of the standard building blocks in modern power system protection and control. Advances in electronics, microprocessors, telecoms and computing have seen a dramatic evolution in power system devices from simple microprocessor relays which emulate their electromechanical ancestors to advanced real-time state estimation schemes.

While traditionally confined to the transmission network, Phasor Measurement Units (PMU) are now finding a role in distribution network operation thanks to their increased affordability. This makes solutions for the distribution network previously considered too expensive practical today; for instance differential relaying reliant on time synchronized measurements [1,2].

As with all protection and control devices, careful consideration must be given to their correct operation and calibration. For PMUs this is governed by IEEE Standard C37.118. This standard defines correct performance of PMUs under steady state conditions, stated to be when frequency, magnitude and phase angle of the observed signal

are constant [3]. As the power system does not adhere to such constraints, the problem of interoperability of different PMUs under non-steady-state or transient conditions arises.

PMU transient performance will be affected in various ways; factors such as the analogue side signal processing electronics, the DSP algorithms, the time source and even the computational speed of the device will all differentiate a particular model of PMU from its peers. Huang et al. compare PMUs and discover that under some circumstances phase errors of 12 degrees are possible [4]. Furthermore, a waveform experiencing a rate of change in frequency will be distorted and use of Fourier analysis would be incorrect. This paper will discuss the problem of determining phase during a frequency transition in a cyclic waveform.

II. CONCEPT OF SYNCHROPHASORS

A phasor is a complex number which represents the magnitude and phase angle of a waveform in an AC system. Synchrophasors are phasors measured with respect to a global time base, typically Coordinated Universal Time (UTC).

The measurement convention for synchrophasors is to define the observed waveform with respect to its cosine; that is to say that the reported phase is the angular difference between the instant of the reporting time and the instant the waveform is at its peak. This is illustrated in Fig. 1.

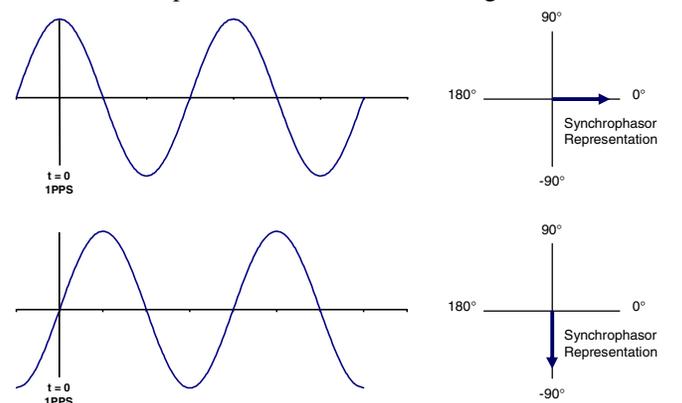


Fig. 1. Synchrophasor representation with respect to waveform and time.

IEEE Standard C37.118 sets out operating guidelines for the synchrophasor measurement system, including the format of the time tag and time synchronization, communication format and data structure, reporting rates, and accuracy limits.

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The phasor measurement greatly reduces the amount of data in the analogue waveform to key characteristics of most interest to the power system operator. This data reduction reduces load on telecommunications and data storage.

The accuracy of a phasor measurement is specified as the Total Vector Error (TVE). The TVE is a combined measure of three sources of error; magnitude error, phase error and timing error. The standard imposes a maximum TVE of 1% on PMUs. For example, a PMU operating with no phase error and perfect timing, but with a 1% error in magnitude would have a TVE of 1%. Table 1 gives the maximum errors for angle and timing corresponding to 1% TVE.

TABLE I
MAXIMUM ERRORS FOR TVE LESS THAN 1%

Angle	0.573°
Time Synchronization (50 Hz)	31.8µs
Time Synchronization (60 Hz)	26.5µs

Neither frequency nor rate-of-change of frequency measurement accuracy is defined in the standard, although both measures are required to be reported. PMUs are usually regarded as excellent frequency transducers [5].

III. SYNCHROPHASORS AND TRANSIENTS

For repetitive waveforms, phase is the fraction of a complete cycle of the waveform between the measured point and a reference point. Phase can only be readily defined when the frequency of the waveform is constant, and as a consequence the waveform is continuous in time (cyclical). If the frequency of the waveform varies, the definition of phase becomes ambiguous.

To demonstrate this, Fig. 2 shows a continuous 50 Hz tone (dotted) and a tone which begins at 50 Hz and then increases in frequency (solid). The rate of +100 Hz/s is much greater than typical power system conditions; it is exaggerated for the benefit of this illustration.

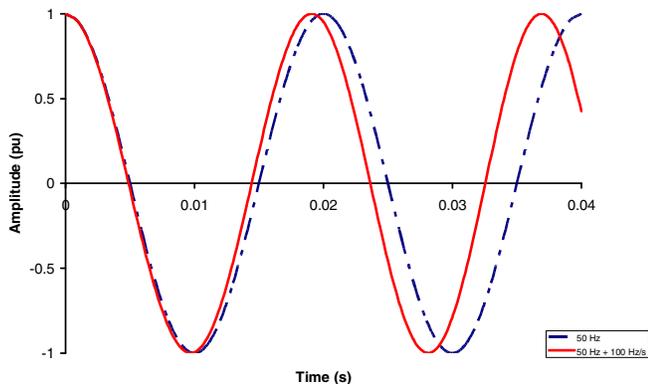


Fig. 2. Continuous waveform and time varying waveform.

The two waveforms start at the same instant, but the red trace increases continuously in frequency. Consequently it soon begins to drift away from the continuous tone. The dotted waveform may be ‘stitched’ end to end to generate a

continuous representation of itself. The solid waveform cannot, Fig. 3.

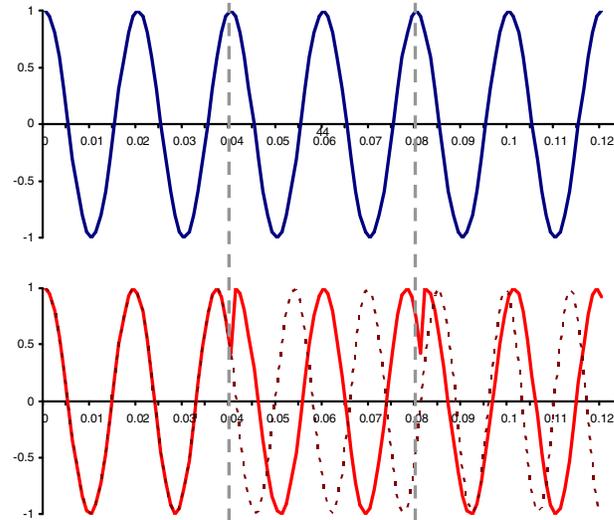


Fig. 3. Cyclical (top) and non-cyclical (bottom) waveforms.

Consider that the solid trace of Fig. 2 is the sampled data being processed by a PMU. The PMU will attempt to find the fundamental frequency of the sampled waveform. Since the tone varies in frequency with respect to time, and is non-cyclical, the concept of fundamental frequency does not apply. However, a good algorithm may yet determine the average frequency of the sampled data to be 52 Hz. The PMU would then use 52 Hz as the reference to compute the phase of the red waveform, Fig. 4.

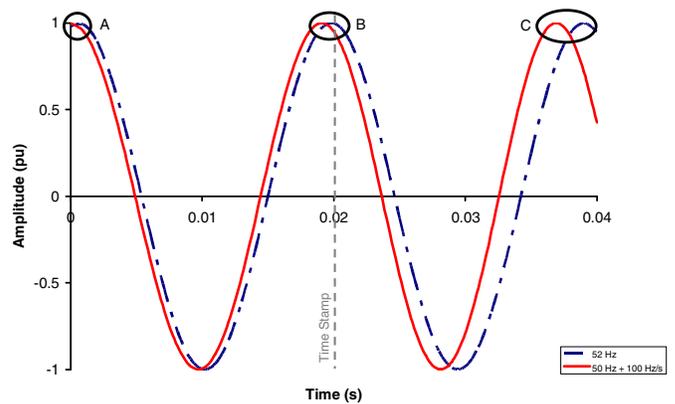


Fig. 4. Varying waveform and reference freq 52 Hz.

Notice how the reference waveform does not match the shape of the sampled data, they are not symmetrical. Depending on the point that the PMU chooses as reference, the measured phase will be different. At point A, the phase is near -5° , while at B and C it is nearer -10° and -20° respectively. Since reconstructing a waveform of 52 Hz at any of these phase angles does not accurately represent the original signal, this phasor measurement is ambiguous.

If two PMUs are matched and operate the same signal processing algorithms they will compute the same value for phase angle during this transient. However, it is likely that

given mass deployment of PMUs there will be several brands and models of PMU in use with various algorithms. This will make it exceedingly difficult to compare transient data, which is often why a PMU was installed in the first place.

It would be desirable to have PMUs report transients in a common way. Many PMUs will log the full transient waveform at high resolution to their internal storage for post-analysis. It has been proposed that these samples be streamed in full [6] as supported by IEC 61850 [7], but it may be impractical to transmit this volume of data over wide area networks. Agreeing a common algorithm among manufacturers will prove difficult given intellectual property rights to parts of the software.

Fortunately practice has shown that PMU errors during transients are reasonably small and tolerable. There exist advanced computational algorithms which model and compensate for the dynamic operation of the PMU [8,9]. It will be necessary to agree a set of standard responses to which manufacturers can calibrate their algorithms. This will hopefully be addressed in an upcoming release of IEEE C37.118.

For simple control schemes, the authors had considered that PMUs provide time stamps indicating the zero crossings of the measured waveforms. Since it is difficult to determine the phase at a specific time during a transient, it was thought that reporting the time at a specific phase, namely $\pm 90^\circ$ shown in Fig. 5, may achieve better performance.

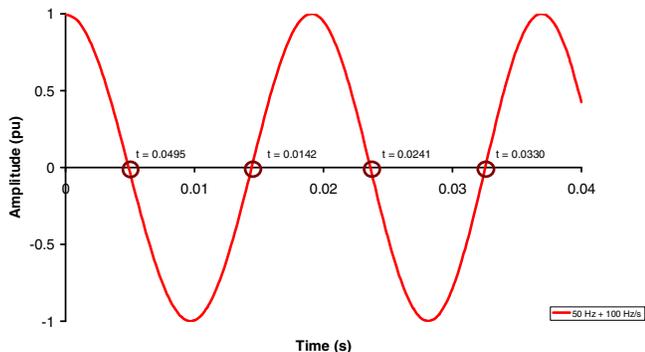


Fig. 5. Sampled data with time stamps of zero crossings.

Using zero crossings does away with the need to find a fundamental tone and instead references the phase angle against earth potential. Measuring zero crossing times is essentially sampling at exactly the Nyquist sampling rate, requiring additional information to indicate the sign of the zero crossing transition and also the RMS amplitude of the waveform. Since the zero crossing may lie between sampled values, interpolation would be necessary to find the times of the zero crossings. Noise and harmonic content are prone to distorting the crossings. This renders the computational savings from avoiding using the advanced methods of [8,9] unworkable for practical control. Consequently development of this measurement method has ceased.

IV. IMPORTANCE IN CONTROL SYSTEMS

In a control system, the PMU is a transducer which acquires the signals representing the process under control. In wide area systems, this may be a frequency stabilization scheme, voltage/VAr control, or the authors' own interest, virtual synchronization of distributed generation.

In many closed loop control scenarios, integral action is used to eliminate steady-state error in the process and can be used to eliminate error from the feedback sensors. However, if the reference signal to which the control system is trying to conform is provided by a sensor giving an undependable measure, this compromises the entire control effort.

Consider the control scenario of Fig. 6. In this scenario, a small generator is synchronized to a remote reference signal, generated by a PMU, due to a lack of a locally available mains signal. An example of such a scenario is back synchronization of a power island on the distribution network to a substation after completion of distribution line maintenance. It is also proposed for use in synchronous islanding of the distribution network [10].

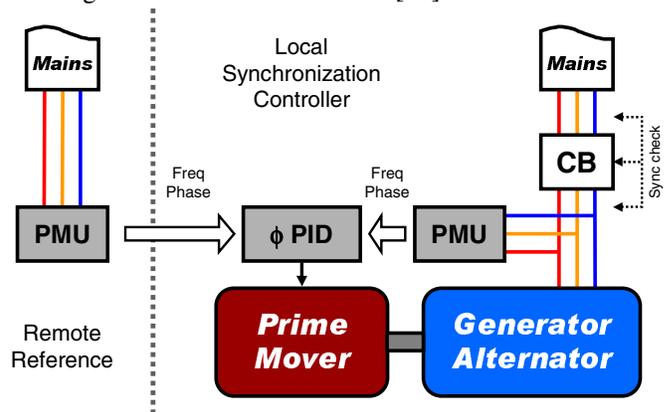


Fig. 6. Control schematic for wide area generator synchronization.

The remote reference PMU delivers synchrophasor measurements via telecommunications to a Proportional, Integral, Derivative (PID) controller at the generator. By comparing the frequency and phase angle at the generator terminals with the received reference signal, the prime mover may be controlled to synchronize the generator.

In this case, both frequency and phase are used in the control loop. Frequency and phase are intrinsically coupled, frequency being the rate of change, or derivative, of phase. Although in a large power system there are many factors which affect phase, such as line loading and power factor, causing some variation of phase with respect to frequency, in a small system, frequency and phase may result from the action of just a single generator rotor. The frequency is the angular velocity, RPM of the prime mover, and the phase its absolute angle at a given instant in time. In such a case it would be expected that a PMU would report coupled frequency and phase angle data. Analysis of two PMUs has shown that this cannot be taken for granted.

An experiment was set up in which two PMUs, one a commercially available brand name (Commercial PMU) and

another developed at Queen's University Belfast (QUB Labview PMU), were connected in parallel to a common voltage supply. Frequency and phase measurements were recorded for post analysis. Fig. 7(a) shows a plot of the frequency recorded by the two PMUs, and Fig. 7(b) the trace when frequency is realized by calculating the rate of change of phase.

In Fig. 7(a) the frequency traces do not coincide. Although closely matched, there is an error of the order of 10 mHz between the two reports. In Fig. 7(b) the traces do coincide, indicating that the phase is recorded correctly. The frequency measure is derived from a Fourier transform on a window of samples typically covering one to two cycles of the waveform. This gives a near instantaneous measure of frequency. Frequency derived from phase angle requires a history of data spanning several cycles, so in this respect is averaged over a longer period of time.

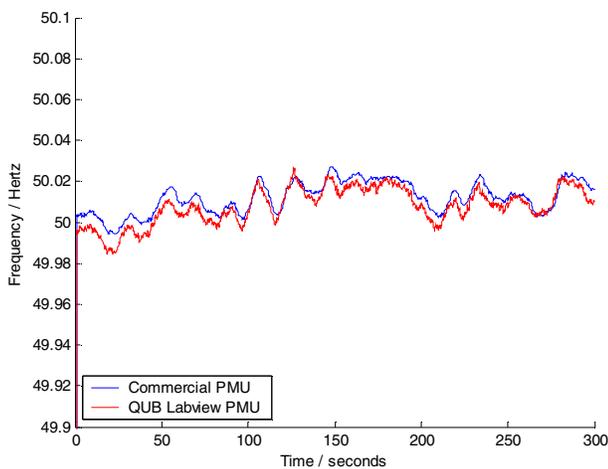


Fig. 7(a). Frequency recorded by PMUs.

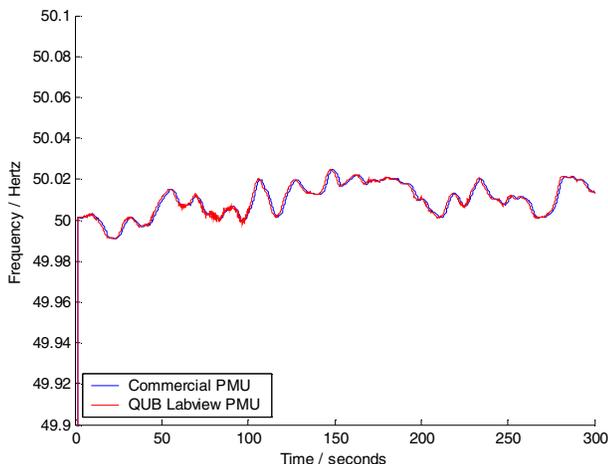


Fig. 7(b). Frequency calculated from differential of recorded phase angle.

Neither frequency measure in Fig. 7(a) accurately reflects the true state of the system. By observation of the phase angle variation, it was determined that the system frequency was almost exactly at nominal (50 Hz) for the first 10 seconds of the trace. PMU1 reported the frequency above nominal

while PMU2 reported below nominal.

In a phase control system, the observed frequency mismatch of 10 mHz equates to a phase angle error of 3.6° per second. This can be corrected using the phase measurement, but the consequence of the frequency mismatch is that the frequency error loop and phase error loop in the control system fight against each other. Controller gains must be selected such as to avoid integrator windup. This is at the expense of controller speed and responsiveness.

V. CONCLUSION

Phasor Measurement Units are an excellent asset to the power system protection and control toolset and are set to continue to revolutionize the way the power system is operated. IEEE C37.118 should be regarded as the first step towards a unifying standard to allow complete cross compatibility between all Phasor Measurement Units.

Currently, synchrophasors measured during the steady state (constant magnitude, frequency and phase) can be regarded as accurate since the continuous cyclical nature of such waveforms lend themselves to Fourier analysis.

Synchrophasors measured during power system transients must be regarded slightly questionable. The distorted shape of the waveform means that it is not suited to the Fourier signal processing typically used in PMUs.

The authors reinforce the forming need for a common method of calibrating and reporting dynamic system behavior across PMUs of various vendors [8,9]. With increasing scope for use of Synchrophasor measurement in protection and control, defined transient behavior is critical.

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