Phase jumps in PMU signal generators

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***Abstract*—The understanding of the word "phase" has changed over the years, and power engineers in particular have a different understanding than some others. The matter was examined in a 1946 paper by the Dutch engineer Balth. van der Pol. In the paper, he highlighted a problem with the ordinary definition, but he did not explain it in detail. In our work with phasor measurement units, we have encountered the problem. This paper explains what is going on, and examines ways around it. We examine the question of testing devices such as phasor measurement units, and show that some workers have failed to observe the effects of what we call the "van der Pol problem." It is suggested that the PMU standard be amended to allow PMUs to show that they can perform well under changing conditions.**

***Index Terms*—PMU, phase jumps, van der Pol, power-system frequency, signal generation.**

I. The Meaning of "Phase"

IN THE MIDDLE of the last century, radio transmission was being changed from amplitude modulation only to add a frequency modulation band at VHF. The topic of FM was not widely understood, and papers were being written to clarify the technology. For example, many engineers imagined that the bandwidth needed would be smaller than for AM, so more channels could be packed into a given part of the spectrum.

One of the papers was written by the Dutch engineer Balthasar van der Pol, presented in London in 1945, and published the following year [1]. The author began by looking at the definitions of amplitude, phase and frequency. He observed right away that in the signal represented by

$$A\sin(\omega t+\psi) \tag{1}$$

the term ψ was called the phase by some workers. However, he noted that others called it the "phase angle" and yet others used the word phase for the same term in the description

$$A\sin(\omega t-\psi). \tag{2}$$

Yet others used the term phase to mean the constant t_0 in the expression

$$A\sin[\,\omega(t+t_0)].$$

Pacific Northwest National Laboratory (PNNL) is operated for the U.S. Department of Energy by Battelle under Contract DE-AC05-76RL0 1830.

This work was supported in part by the Baltic-American Freedom Foundation professional internship program, and in part by the US Department of Energy, Office of Electricity Delivery and Energy Reliability.

According to van der Pol, Max Plank, in a work identified only as "Mechanik,"[1] referring to $A\sin(\omega t+\psi)$ says: "The angle which varies with time and which follows 'sin' is called the phase." Van der Pol continues:

> "Finally, a similar, but still somewhat extended, definition ... is to be found in Weber-Gans ('Repertorium der Physik') ... It runs as follows: in the expression
>
> $$A\sin(\omega t+\psi)$$
>
> the angle $(\omega t+\psi)$ is called the phase."

In the space of a few column inches, van der Pol identifies several different mathematical interpretations of the word phase. He makes a recommendation:

> "In this matter of a somewhat confused nomenclature I would therefore strongly recommend the following definition of phase: *In the expression for a harmonic motion*
>
> $$y=\mathrm{A}\cos(\omega t+\psi) \tag{4}$$
>
> *the whole argument of the cosine function, namely* $(\omega t+\psi)$ *is the phase*. [The italics are in the original.] This definition has, among others, the advantage of enabling one to speak of a phase difference of two oscillations of different frequencies. This phase difference is then simply a linear function of the time, just as one phase by itself is already such a function of the time."

For power engineers, at least, the recommendation was not adopted. To us, the phase is customarily just the term in the cosine argument that is not dependent on the time. This interpretation is consistent with our use in the phasor diagrams that are so conveniently used.

However, it should be pointed out that when we say that "frequency is the derivative of phase" we really do mean the whole argument of the cosine, for the derivative of what we power engineers name the phase is zero.

II. Modulation

A. Amplitude Modulation

Amplitude modulation can be represented as a modified version of the expression for harmonic motion, as shown in equation (4) above. The parameter A is made into a function of the time, as in $A=a_0[1+mg(t)]$ where $g(t)$ is the modulating (audio) signal.

[1] We believe the reference is to Planck's *Einführung in die allgemeine Mechanik*, (Introduction to General Mechanics) Leipzig, Hirzel, 1916.

B. Phase modulation

Phase modulation can be treated the same way. To model phase modulation, van der Pol writes

$$\psi = \psi_0[1 + mg(t)]$$

C. Frequency modulation

But then van der Pol goes on to say that it would be "erroneous simply to write

$$\omega = \omega_0[1 + mg(t)]$$

for this would lead to a physical absurdity."

In fact, we had been simulating PMUs for a little while with the idea of making the measurements as a fitting problem [2] [3] when we encountered the van der Pol paper, and this phrase. We had been using exactly this form of the equation in our signal source, and we had not noticed any particular physical absurdity. When we looked further into the matter of changing the frequency, however, we did see a problem. We have called it "the van der Pol problem."

III. The van der Pol Problem

When we simulated the PMU, we had submitted to it a signal at nominal frequency and zero rate of change of frequency (ROCOF), and we had (typically) caused the rate of change of frequency to become non-zero after some time had elapsed. We would then examine the results from the simulated PMU. This we had done many times without seeing anything absurd.

It was only after we added a further change in the signal (say, back to zero ROCOF) that the problem became evident. At the second change, there was usually a phase jump, and sometimes a large one.

The problem arises because of the nature of the mathematics of sines and cosines. The domain of each is from minus infinity of time to plus infinity of time. That fact is built into all of the equations above. It follows that any implementation of those equations will suffer the problem.

One can demonstrate the problem in a very straightforward way. Suppose we are using a spreadsheet to generate the values for the signal generator. These could be thought of as sampled values going to a D/A converter for signal generation. Suppose that for the first second or so, we want a constant frequency slightly above the nominal value, and after that we wish to set the frequency back to nominal. After some spreadsheet rows for headers, we write the equation into row 3 as something like

=COS((E3*H3/1000)+G3)

where E is a column of numbers for the frequency, and H is a column for the time. G is a column for the phase (as understood by the power engineer). The number 1000 allows us to use ms for the time.

Part-way down the column, we change the value of the entries in column E.

What we find is that there is a phase jump at the sample where the frequency is changed. The point is that it would be the same if we were generating two signals at the same time, and switching from one to the other part way along. Figure 1 shows the situation.

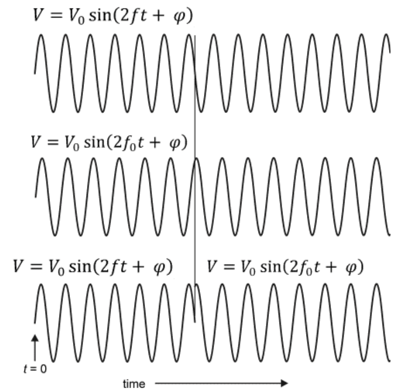

Figure 1. Changing the frequency parameter

It must be stressed that this jump occurs not because the implementation is in a spreadsheet, nor because the frequency change is particularly large. (In the diagram, it is hard to see the difference without close examination.) The jump is there because of the mathematics of the sine and cosine. For every value of time, *it is as if the wave has existed since time zero.*

This effect has significant implications.

IV. Discussion

In our work on simulating PMUs, we were interested in the measurement of ROCOF, and we would change the ROCOF parameter, rather than the frequency as shown in Figure 1. However, the effect is the same. What is going on is that the phase (considered in the sense that van der Pol wanted to use the word) was evolving with the time. Therefore, a change to any of the parameters involved in this phase at a time other than zero would likely cause a phase jump to appear.

The simple assumption that we could change the parameters part way through a run therefore proved to be invalid because the resulting signal is not representative of the real world. That phase jump is van der Pol's physical absurdity.

A. Another example

We are not the only people to experience the problem. A paper in the Transactions of our Society includes the graph shown in Figure 2.

In the graph, the test signal is shown on the top. We have added fat arrows to show where the three largest phase jumps take place. Each of those jumps corresponds to a step in frequency.

The amplitude is also stepped, but (unsurprisingly) without any evidence of a phase jump.

The paper indicates the following:

> For the first 250 samples, freq = 50 Hz; for 250–400 samples, freq = 48.5 Hz; for 400–600 samples, freq = 51.3 Hz; and thereafter, freq = 50 Hz. Similarly, for the first 150 samples, A = 1 pu; for 150–250 samples, A = 1.2 pu; and then, it comes back to its initial value. Similarly, for the first 90 samples, $\Phi = \pi/4$; for 90–200 samples, $\Phi = \pi/5$; and then, it comes back to its initial value.

It should be pointed out that the paper in question claims to show a way to *measure* the PMU parameters, and that the solid lines in the second, third and fourth graphs are claimed

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to be the results of measurement. They are further claimed to be *good*, a claim that is not supported by the evidence of large (and unreported) phase changes in the signal.

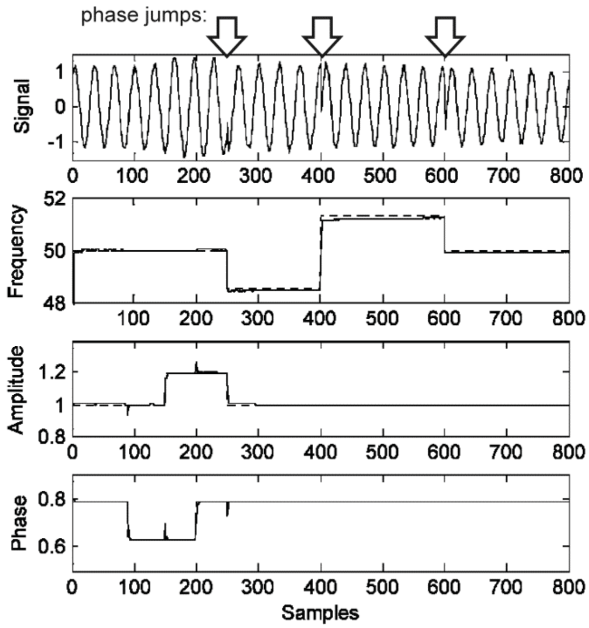

Figure 2. Phase jumps in a test signal

These large changes were not observed by the authors of the paper in question, or by the measuring equipment they were demonstrating. (We think those authors should remain anonymous at present. We do not sense that there was any attempt to deceive, when they did the work and wrote the paper.)

B. What might evidence of the problem look like?

The third IEEE standard for PMUs [4] was the first to attempt to cope with the sort of changing conditions in the real world. Recognizing that the power system was not, really, in steady state all the time, the effort to cope with changing signals had been recommended in an earlier revision of the standard [5]:

> Harmonizing a common set of dynamic performance requirements should be undertaken once the range of implementations and measurement applications has been more fully explored. At this time, dynamic performance under transient conditions should be specified and verified by the users to meet their application needs.

The later standard therefore undertook to examine PMU performance with changing signals.

We speculate (and we underline that this is speculation) that some early tests on PMUs produced odd results around the time of such changes, and the testers did not think it fair to penalize the device.

Would they have seen the van der Pol problem, had they been looking for it? What would a phase jump do to a PMU? An example from 2012 is shown in Figure 3, where a *deliberate* phase jump was introduced [6]. For over 100 ms, the two PMUs whose results are shown misinterpreted it as a momentary (and large) change in amplitude. (The PMUs are not identified in the presentation.)

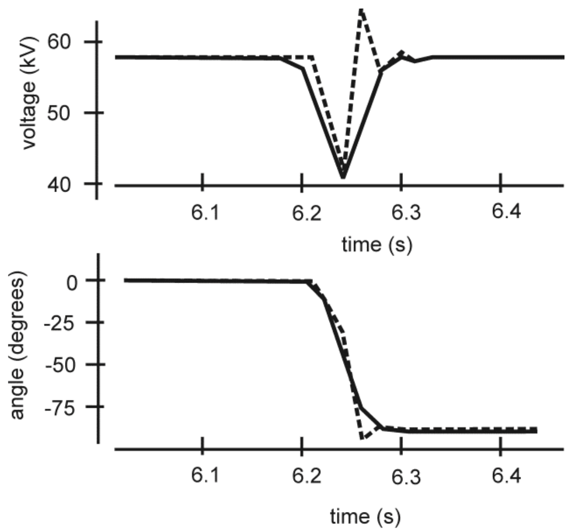

Figure 3. Response to a phase jump, two PMUs

A PMU designer would have every expectation that the signal seen by the PMU would contain no instantaneous jumps in parameter values, and may not have designed to allow for such things.

With a well-behaved signal, and no phase jump (and good test gear would *not* have phase jumps), the gross errors apparently seen when there is a change in frequency or ROCOF would likely disappear. It is possible that a PMU designed for the real world of the power system will handle quite smoothly any "ordinary" sort of change, including a change in ROCOF. We offer evidence of that later.

C. Getting past van der Pol

To avoid generating a signal with a phase jump, all that has to be done is to adjust the phase (in the power engineer sense) at each transition so that the phase (in the van der Pol sense) is continuous.

In essence, this is the reverse of what the PMU does. The PMU examines a small section of signal that lasts a cycle or so, and from that observation, it calculates the frequency (the time-dependent part of the total phase) and the phase. Phase is really the part needed to line up the observed signal with a reference wave defined in advance. Phase has no other significance than that, within the window of observation.

Given that the signal source (assumed to be digital) can calculate the magnitude of the next sampled value in a sequence with no changes, it can also find a set of values that give the same value with one of the parameters changed.

For example, the value of $\omega t + \psi$ would be known for the case where the time advances to the next sample and there is no change in frequency. If a change in frequency is required, the new values of frequency and time can be plugged in, and a new value for the phase found by subtraction.

D. Other tests—without the van de Pol problem

Detailed studies of the problem are not common. However, two sets of results do lend support to the idea that the PMU can handle changes, provided the signal does not contain a phase jump.

1) BPA tests

In a report [7] in 2010, one of us (Faris) tested a number of PMUs in a variety of ways. One of the tests involved subjecting the PMUs to step changes in the parameters of their input signals, including the frequency. While that is not considered a likely event on the power system, it was thought interesting enough to pursue as a way of examining the performance of the various PMUs.

The PMUs reported every cycle. The duration of the cycle was divided into 16, and the step was applied at each in turn. In one test it might be at the start of the window, in the next a sixteenth of the way into the window, then an eighth, three-sixteenths and so on. Each of these tests was delayed by some integral number of reporting intervals, (plus the fractional-cycle increment). The added integral-number delays were subtracted in post-test processing, and the data recombined on one graph.

Results from just two of the PMUs are included here. They can be taken as representative of the larger number.

Figure 4 shows two results that differ in kind.

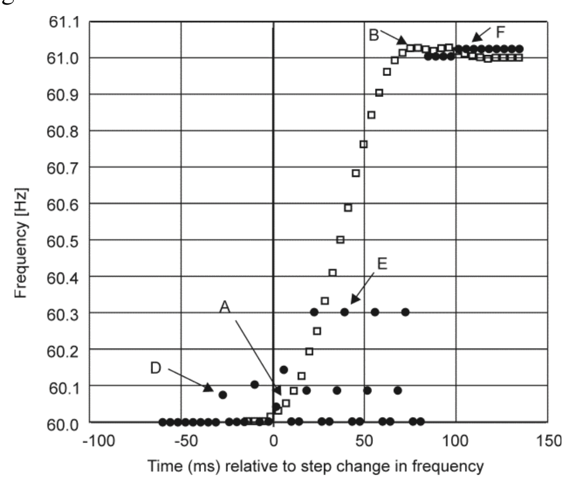

Figure 4. Results of frequency step tests on two PMUs (adapted from [7])

Bearing in mind the test method, only one of every sixteen data points applies for any single step test. Thus the result marked with an "A" (shown here as an open square) would be obtained if the step were near the start of the window. That would then be followed by the one marked "B" 16 steps later. Altogether, the results could be viewed as a fairly smooth transition from one extreme (60 Hz) to the other (61 Hz).

Another PMU (shown as black circles) produces results that, when the measurement offsets are accounted for, produces a transition that appears far from smooth. It is mere appearance. A series from this PMU might be the points marked "D," "E" and "F" for example.

Most (but not all) of the PMUs tested were of the "smooth" kind. In any case, the results were certainly reasonable in general appearance.

2) PNNL Tests

The more recent effort to solve the PMU measurement problem as a mathematical fitting problem [3] resulted in a method we are calling SEMPR, for Signal Evaluation by Minimizing Parameter Residuals. That method was tried against a ROCOF transition [8] with results that are not unlike those in Figure 4.

As the transition on the input signal is "walked through" the observation window, the measured value transitions, with reasonable grace, from one value to the other, as seen in Figure 5.

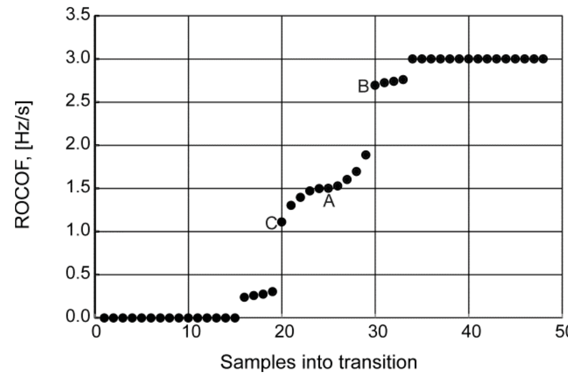

Figure 5. Results of ROCOF measurement as transition moves across measurement window

This graph is different in two ways from the graph shown in Figure 4. First, the change is not directly of frequency, it is a change of ROCOF that is being examined. Second, in this graph there were not sixteen steps in a test sequence, but twenty-four, corresponding to the intervals of the sampling of the input signal. The entire set of results corresponds (after merging all the results) to a time of just two (nominal) cycles. Thus *only one* of the black dots would correspond to an output. It would be "A" if the step in ROCOF were exactly in the middle of the window, and could be "C" or "B" if the step were later or earlier. The device being used to make the measurement here included no filtering in the frequency domain, so that each result is (always) truly an independent reading. The non-smoothness of the results is not characteristic of the method, but it is very reminiscent of the non-smoothness of one of the devices whose results are given in Figure 4.

V. Conclusion

Phase jumps do occur in the power system, but they are not common, and are associated with switching operations, often under fault conditions. The PMU was designed as a quasi-steady-state instrument, and perhaps should not be expected to perform under such conditions.

An unintended phase jump can be inserted into a signal generator when a parameter is changed if the nature of the sine and cosine functions is not accounted for. Such a phase jump may give rise to unexpected results. PMU designers, and those experimenting with PMUs in the laboratory, are advised to check for the absence of unintended phase jumps.

There is a possible impact on the relevant standard [4]. This was the first standard to deal with changing parameters, and we think it conceivable that there were some van der Pol phase jumps that went unobserved in early testing. (There are hints of this in Appendix H of the 2005 standard [5]) At any rate, the 2011 standard was the first to introduce the idea of an exclusion interval, associated with ROCOF changes during

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test. We think that PMUs are actually good enough to allow testing during transitions, and that by removing the exclusion interval, a better performance can be obtained.

We intend to study the matter further, and we expect to report further results.

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VI. BIOGRAPHIES

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Tony Faris obtained his BS degree from the University of Portland in 2004, and his MS from the University of Washington in 2006.

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Matt Engels Matt obtained his BS and MS from Washington State University in 2010 and 2012, respectively, and is currently pursuing his PhD there.

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