Dynamic Phasor Measurement Unit Test System

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Abstract-- **This paper presents the plans and progress towards the development of a dynamic phasor measurement unit (PMU) performance test system at NIST. We describe an algorithm for taking time-synchronized samples of single-phase voltage and current power signals and calculating their dynamic parameters, in particular the signal magnitude, phase, frequency, and rate of change of frequency that a PMU reports. PMUs must time stamp their values at periodic Coordinated Universal Time (UTC) markers called the update times. Thus, to provide a reference for PMU testing the sampled data can be fit to a model to define the value of a dynamic parameter at a specific time. The analysis model proposed in this paper assumes that the dynamic magnitude and frequency parameters of the signals are constant over the sampling interval analyzed. This analysis interval is usually the same as the update period or an integer multiple of that period. In the proposed analysis model the dynamic magnitude and frequency parameters are considered a polynomial in time about the update times. The order of the polynomial can be adjusted in a way that meets the needs of the signal being analyzed, yet minimizes the computational effort and sensitivity to noise. We show that when the dynamic variations are analyzed in this way, a single matrix can be used to iteratively converge on a good estimate of the dynamic frequency and magnitude parameters. The polynomial model can be used to generate and analyze test signals. Several test patterns are proposed, which include linearly changing magnitudes or frequencies. As expected, during low voltage tests of the system, the analysis does very well when the generation model matches the analysis model. Several other generation models are also proposed, such as sine waves or damped sine waves. The proposed analysis model is shown to be very accurate in these cases as well.**

Index Terms—**calibration, dynamic measurement, electric power grid, Global Positioning System, phase measurement, PMU, power system reliability, synchronization, time-synchronized metrology.**

I. Nomenclature

This paper describes a test system for PMUs (phasor measurement units) under dynamic conditions. The paper does not use the concept of "dynamic phasors" as used in [1] to describe time varying Fourier coefficients.

The term *model* in this paper refers to the set of equations used, how those equations are used, and any assumptions. How this term is used in this paper is described more fully in Section IV.

Small frequencies, below 1 Hz, are given in mHz or milli-hertz. Frequencies larger than one million Hz are given in MHz or mega-hertz. GPS (Global Positioning System) clocks usually provide a pulse on the second called 1 pps (one pulse per second).

II. Introduction

Studies of previous blackouts by U.S. Department of Energy (DoE) and the electric power industry have identified grid observability as an important factor in monitoring the state of the grid, predicting imminent instabilities, post event analysis, and eventual automatic control. A recent DoE report to the U.S. Congress [2] outlines "steps that must be taken to establish a system to make available to all transmission owners and Regional Transmission Organizations (RTOs) within the Eastern and Western Interconnections real-time information on the functional status of all transmission lines within such Interconnections." The report also states "All time-synchronized data recorders (i.e., digital fault recorders, digital events recorders, phasor measurement units, and power system disturbance recorders) are time-stamped at the point of observation using a GPS synchronizing signal. Time-synchronized devices, such as PMUs, could be beneficial for providing a wide-area view of power system conditions in real-time."

To promote the interchangeability of PMUs and thus facilitate their rapid introduction into the electric power grid network, the Power System Relaying Committee (PSRC) of the IEEE Power Engineering Society (PES) developed a Standard for Synchrophasors [3] published in December 2005, IEEE C37.118-2005. This Standard specifies the performance requirements of PMUs with respect to the input signals magnitude, phase, and frequency, as well as interference signals such as harmonics and interharmonics. This Standard defines the uncertainty requirements for the PMUs in terms of the Total Vector Error (TVE). This error measurement assures that compliant PMUs have minimal uncertainty in both their magnitude and time-synchronization errors. This latter error is the error in the PMU's time stamps

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with respect to Coordinated Universal Time (UTC). To promote better measurement procedures for this type of testing, the National Institute of Standards and Technology (NIST) has established a SynchroMetrology Laboratory [4]. This laboratory was established to develop test and calibration methods where traditional waveform parameter metrology is combined with referencing these values to a synchronized timing source such as UTC. NIST has established a calibration service to calibrate PMU performance for parameters referenced in IEEE C37.118. This testing is being done in support of the Consortium for Electric Reliability Technology Solutions (CERTS), which sponsors the Eastern Interconnect Phasor Project (EIPP) [5]. This project, through a series of work groups, is promoting wide area measurement, monitoring, and control to improving the power system reliability.

The performance requirements in IEEE C37.118 reference steady state signal conditions for the PMUs, that is, the various signal parameters are held constant during each test. However, the Standard recognized that during use in the power grid the PMUs must measure signals that are dynamic. The Standard references tests for these conditions in its appendices. At the time the Standard was developed much testing of the performance of PMUs with respect to these dynamic conditions had been performed [6-8]. However, the systems that performed these tests lacked the necessary accuracy to specify the errors of the PMUs. Primarily these tests highlighted the difference in performance of various PMUs [9] or PMU analysis models.

In addition to voltage and current phasors, PMUs also report the frequency and rate of change of frequency. The Standard does not address accuracy requirements for these frequency measurements, nor does it address accuracy under dynamic signal conditions. Other instruments and test algorithms have focused on power grid frequency measurements [10] and rate of change of frequency measurements [11, 12]. These papers have referred to analysis methods that involve expanding the frequency measurements in a time power series. The methods proposed here are based on these techniques.

NIST is developing testing equipment, procedures, and algorithms to measure the static and dynamic performance of PMUs. This includes recommended dynamic signal patterns, methods for calibrating these test signals, and measurements of the dynamic behavior of commercial PMUs. This paper describes the basic plans for the test equipment, and test signals and focuses on an analysis model for calculating the dynamic parameters of the test signals. These analysis model values are the "true" values to which the PMU values will be compared. The dynamic test system is currently generating and analyzing low voltage level dynamic test signals. This level is sufficient to test the basic analysis model. The proposed analysis model has proven robust for measurement of typical power system dynamic signals. It is very accurate for determining the time-varying phasor values, frequency, and rate of change of frequency of these signals. The next section describes the plans for the complete dynamic PMU test system. Section IV describes the basic proposed analysis model, Section V describes some proposed test signals with dynamic magnitude and frequency variations, and Section VI describes the performance of the proposed model in measuring these parameters at low signal levels. Proposed tests for the dynamic characterization of PMUs are discussed in Section VII, followed by conclusions and a summary of test results.

III. Planned Dynamic Test System

The tests reported here use a subset of the complete planned dynamic test system. The complete system, which is shown in Fig. 1, consists of a GPS clock used to synchronize the system to UTC, a generation and sampling system, three voltage amplifiers, three transconductance amplifiers, three voltage attenuators, and three current transducers, connected to a device under test (DUT). The generation and sampling system outputs six voltages with amplitudes of ±10 V peak at a strobe rate up to 1 mega-samples per second, and samples those voltages with the same amplitude range at up to 500 kilo-samples per second. The three voltage amplifiers output voltages with up to 140 V rms, and the three transconductance amplifiers output currents up to 5 A rms, which are typical test levels for electric power instrumentation.

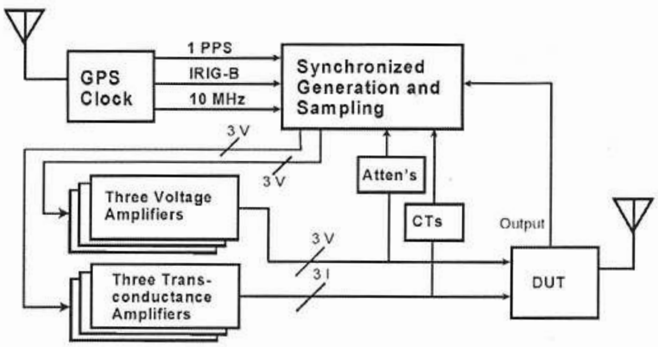

Fig. 1. Diagram of NIST dynamic test system.

For our low voltage tests, the subset we used consisted of the GPS clock and the signal generation and sampling system. One low voltages output channel was connected directly to a voltage sampler, bypassing the voltage and transconductance amplifiers and the transducers. The signal generation and sampling system includes a computer used to calculate the generated dynamic waveforms and to analyze the sampled waveforms.

IV. Description of Model

The dynamic nature of the power grid results in signals with magnitudes and frequencies that vary in time. In many cases the changes are relatively slow; occurring at frequencies ranging from fractions of a Hz to several Hz. To calibrate a

PMU for these conditions, the DUT must be tested against signals with these variations and known dynamic parameters. The test system generating the signals must have a smaller uncertainty than the PMUs being calibrated. This paper describes the methods and hardware that the NIST staff, with help from a Virginia Tech student, have developed to achieve this goal. The methods depend on generating stable power simulation signals with the desired dynamic behavior, on sampling the applied signals, and on calculating the PMU parameters from the sampled data.

Before describing the complete proposed analysis model, consider the case of a single-phase power line voltage with either slowly varying magnitude or frequency. If the change is small over the period of the PMU update, a first order time-dependant model may suffice. In the case of magnitude variation, let the signal V with a magnitude V_0, time rate of change of magnitude V_1, frequency f_0, and phase φ at UTC time t_0 be given by $V=(V_0+V_1\,t)\sin(2\pi\,f_0\,t+\varphi)$, where $t=0$ at UTC time t_0. To determine the synchrophasor values for this signal at UTC time t_0, use the vector of voltage samples $\bar{v}$ centered about t_0 by approximately plus and minus half the update interval t_u. Let $\bar{t}$ be the vector of times for these samples relative to t_0, that is, the first time in the vector $\bar{t}$ is approximately - $t_u/2$, the time at t_0 is 0 and the last time in the vector is approximately $t_u/2$. Then the samples can be fit to the matrix model H consisting of the four column vectors as

$H=\lfloor\sin(2\pi\,f_0\,\bar{t})\quad\cos(2\pi\,f_0\bar{t})\quad\bar{t}\sin(2\pi\,f_0\,\bar{t})\quad\bar{t}\cos(2\pi\,f_0\bar{t})\rfloor$.

The vector of fit coefficients $SC^t=\lfloor S_0\quad C_0\quad S_1\quad C_1\rfloor$, where SC^t is the transpose of SC, are determined such that $\bar{v}\cong H\cdot SC$ in the least squared error sense. From the above we see that at UTC time t_0 $V_0=\sqrt{S_0^2+C_0^2}$, $\varphi=\arctan(C_0\,/\,S_0)$, and $V_1=(S_0\,S_1+C_0C_1)\,/\,V_0$. In the case of frequency variation, let the signal V with a magnitude of V_0 and phase φ, frequency f_0, time rate of change of frequency $2\times f_1$ at UTC t_0, be given by $V=V_0\sin(2\pi\,(f_0+f_1\,t)\,t+\varphi)$, where $t=0$ at UTC time t_0. If we let A represent the true values of f_0 and f_1 and A' represent their initial estimates f_0' and f_1' and perform a Taylor series expansion of V about these estimates, we can approximate V as

$$V(t,A)\cong V(t,f_0',f_1')+\left(\frac{\partial V}{\partial f_0}\right)_{A'}\Delta f_0+\left(\frac{\partial V}{\partial f_1}\right)_{A'}\Delta f_1$$
$$=V_0\sin(2\pi\,t\,(f_0'+f_1'\,t)+\varphi)+2\pi\,V_0\,t\cos(2\pi\,t\,(f_0'+f_1'\,t)+\varphi)$$
$$+2\pi\,V_0\,t^2\cos(2\pi\,t(\,f_0'+f_1'\,t)+\varphi)\,.$$

Thus, if we expand the model matrix H to include two additional columns, $\bar{t}^2\sin(2\pi\,f_0\,\bar{t})$ and $\bar{t}^2\cos(2\pi\,f_0\,\bar{t})$, and add two corresponding fit coefficients S_2 and C_2 to SC, we see that to first order $\Delta f_0=(S_0C_1-C_0S_1)/(2\pi\,V_0^2)$, $\Delta f_1=(S_0C_2-C_0S_2)/(2\pi\,V_0^2)$, $f_0\cong f_0'+\Delta f_0$, and $f_1\cong f_1'+\Delta f_1$. These updated values can be substituted for the first estimates and this approximation procedure iterates until either the change in the mean-squared fit error reaches some cutoff value, or a maximum number of iterations is performed. These conditions are called the cutoff criteria.

The expanded model used for the first order time-varying frequency above is also used to determine the coefficient of a second order time-varying magnitude signal with magnitude $V_0+V_1\,t+V_2\,t^2$. This shows that the same model can be used to determine the coefficients of a magnitude that is a polynomial in time or to estimate the coefficients of a frequency that is a polynomial in time.

The full model used to analyze the power signals is based on a power series expansion of the signal magnitude and frequency with time. The order of the model can be selected to match the needs of the signal. Let $A=(V_0,V_1,V_2,\cdots,\varphi,f_0,f_1,\cdots)$ represent the dynamic model parameters. Then a dynamic voltage, V, is given by $V(t,A)=V(t,V_0,V_1,V_2,\cdots,\varphi,f_0,f_1,\cdots)$ or

$$V(t,A)=(V_0+V_1\,t+V_2\,t^2+\cdots)\sin(2\pi t\,(f_0+f_1\,t+\cdots)+\varphi).\quad(1)$$

The ellipses represent higher order magnitude and frequency time variation terms.

The size of the model matrix corresponds to the order of the model, that is, the order of the magnitude and frequency time polynomials, which are always the same. To determine magnitude V_0 and phase φ, only two columns in the model matrix are required. To determine the time rate of change of the magnitude V_1 and to estimate the correct frequency f_0 from an initial estimate, four columns are needed and so forth. From the initial estimate for the frequency parameters $f'=(f_0'\quad f_1'\quad\cdots)$, the first two columns of the model are developed with the time vector $\bar{t}$, which is the relative time of the sampled signals as described above. The first two columns of the model are $\mathrm{X}(\bar{t},f')=\sin(2\pi\bar{t}\,(f_0'+f_1'\bar{t}+\cdots))$ and $\mathrm{Y}(\bar{t},f')=\cos(2\pi\bar{t}\,(f_0'+f_1'\bar{t}+\cdots))$. The initial estimate of the model is

$$H(\bar{t},f')=\lfloor \mathrm{X}(\bar{t},f')\;\;\mathrm{Y}(\bar{t},f')\;\;\bar{t}\,\mathrm{X}(\bar{t},f')\;\;\bar{t}\,\mathrm{Y}(\bar{t},f')\;\;\bar{t}^2\mathrm{X}(\bar{t},f')\;\;\bar{t}^2\mathrm{Y}(\bar{t},f')\;\;\cdots\rfloor.$$

This model is fit to the measurement vector $\bar{v}$ corresponding to the time vector $\bar{t}$ to get the coefficients SC in a least squared error estimate using the normal equations as

$$SC(\bar{t},f')=inv(H'(\bar{t},f')*H(\bar{t},f'))*(H'(\bar{t},f')*\bar{v})\,.$$

The coefficients are used to update the values of f'. This process iterates until one of the stopping criteria is met. The coefficients of the final fit are used to determine the magnitude and frequency time polynomial coefficients. This iteration process is shown in Fig. 2. The term *model* in this paper refers to the set of equations used, how those equations are used, and any assumptions. The equations used in this proposed model are defined by (1). They are used by fitting the sampled data to the column vectors of H in the least squared error sense to obtain the dynamic frequency parameters. Note the magnitudes of the columns are held constant during the iteration procedure. After the frequency parameters have converged, the final fit parameters are used to calculate the dynamic magnitude parameters. This model assumes that the parameters of the model remain constant over the period of the sampled interval analyzed.

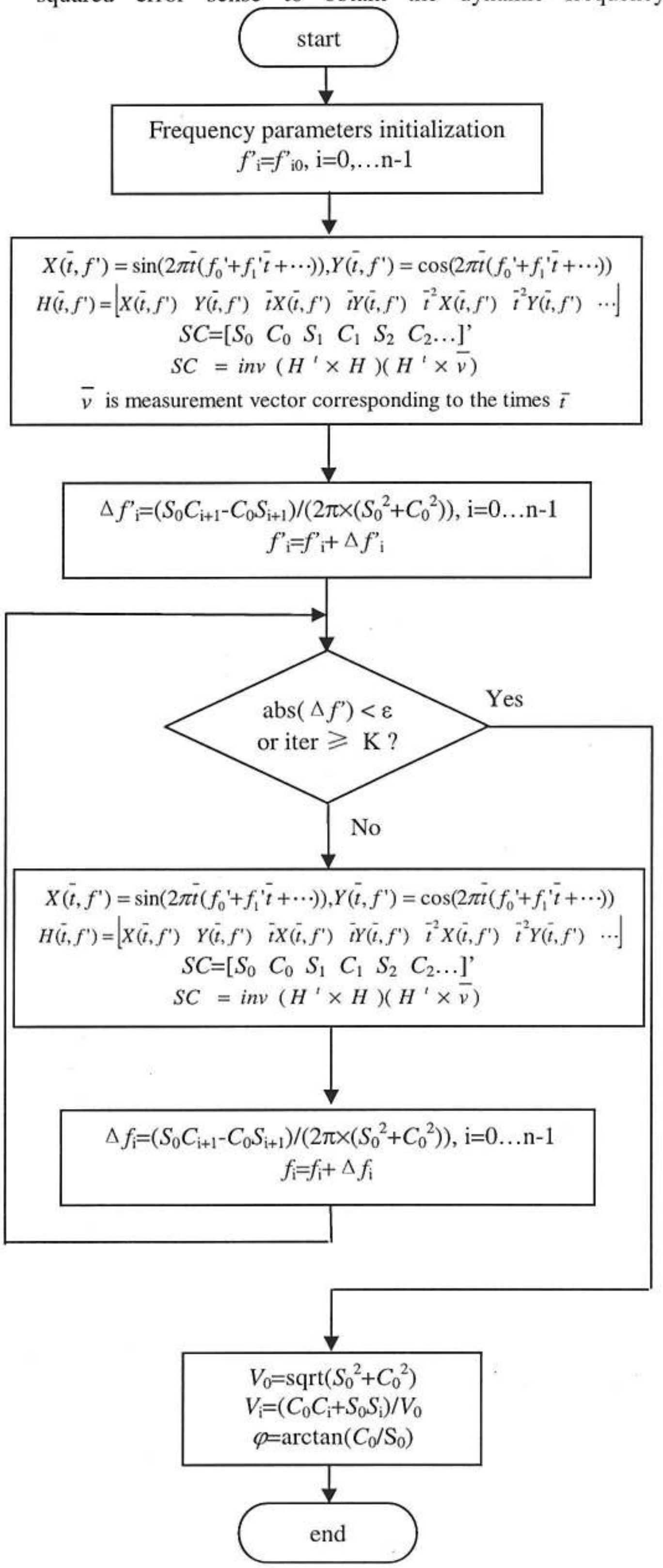

Fig. 2. Flow chart of model fitting process.

To test the validity of the approach described above and the resultant errors, the proposed model is used to generate test signals with various orders of magnitude and frequency variations with known dynamic parameters at given update times. The test signals are sampled, the proposed analysis model is used to analyze the data, and the results compared to the known dynamic parameters. Tests analyzing signals generated with the same model as the analysis model verify that the algorithm has been programmed correctly. In addition to signals that follow the model, test signals with sinusoidal magnitude and frequency variations are also generated. Sampled data taken on these signals are analyzed with the model to determine the errors of various orders of the model. These test signals are described in the next sections.

V. Measurement Test Patterns

A. Magnitude variations

Fig. 3 shows a test signal pattern with linear magnitude time variations. The test signal has a constant frequency and the figure shows only the test signal magnitude. The update time samples on the figure are arbitrary time steps, which will depend on the magnitude ramp rate and the maximum magnitude variation desired. The test signal has an initial period of constant magnitude followed by a period of constant positive magnitude ramp, followed by another period of constant magnitude, followed by a constant negative ramp. This pattern can be repeated many times. The sharp transitions can also be smoothed with a second-order magnitude transition period. Periods that span any transitions violate the assumption that the model parameters are constant over the sample analysis interval. Thus, there is no correct value to compare with the analysis value. Even with second order smoothing of the transitions, there are then two transition intervals over which the model parameters are not constant.

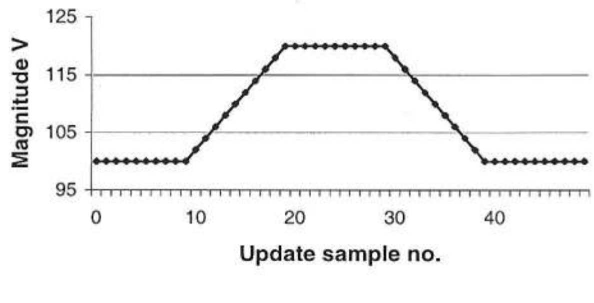

Fig. 3. Magnitude of test signal with linear magnitude variations.

Fig. 4 shows a test signal pattern with second-order magnitude time variations. The test signal has a period of constant positive second-order variation, followed by a period of constant negative second-order variation, then a period of constant positive second-order variation. The last two periods can be repeated several times. Again, the calculated values for periods that span the transitions do not have correct values to use as reference.

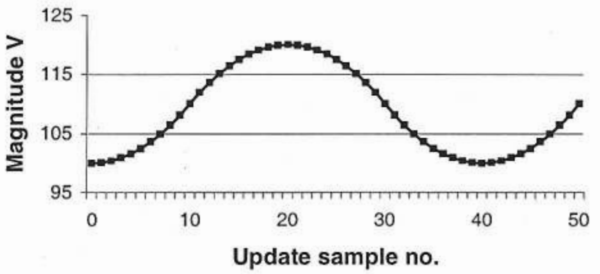

Fig. 4. Magnitude of test signal with second-order magnitude variations.

B. Frequency variations

Fig. 5 shows a test signal pattern with linear frequency time variations. The test signal has a constant magnitude and the figure shows only the test signal frequency. The time samples on the figure are arbitrary time steps, which depend on the frequency ramp rate and the maximum frequency variation desired. The test signal has an initial period of constant frequency followed by a period of constant positive frequency ramp, followed by another period of constant frequency, followed by a constant negative ramp. This pattern can be repeated many times. As with the linear magnitude test signal, the sharp transitions can be smoothed with a second-order frequency transition period. The calculated values for periods that span any transitions do not have correct values to use as a reference.

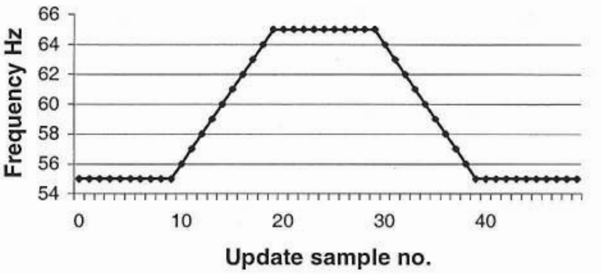

Fig. 5. Frequency of test signal with linear frequency variation.

C. Generation of Correctly Time-Stamped Results

To allow comparison with PMUs the update times must be synchronized to UTC. This is accomplished with the synchronization signals from the GPS clock as shown in Fig. 1. The 10 MHz signal is used to synchronize all the signal generation and sampling strobes. The 1 pps is used to simultaneously start the generation and sampling processes, and the IRIG-B signal is used to put a UTC time stamp on all samples.

VI. Low Voltage Test results

For the low voltage tests the waveform pattern is generated via one of the low voltage instrumentation output channels and then sampled with an input channel. This testing verifies the ability of the system to synchronize the generation and sampling of the signals. With this type of testing the analog signals can be compared to the GPS clock signals and thus verify synchronization of the test system to UTC.

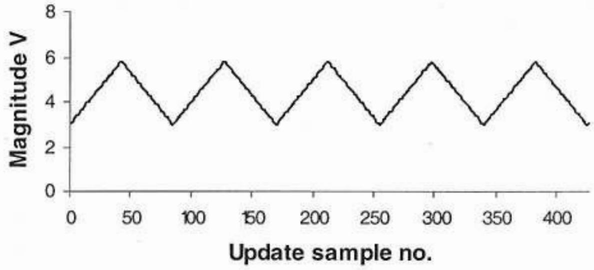

Fig. 6. Linear voltage magnitude pattern.

The linearly varying magnitude test is shown in Fig. 6. The signal had a nominal frequency of 60 Hz and a magnitude that varied from 3 V to 6 V at positive and negative rates of 2 V/s. The analysis was done with a second order model (model matrix H had six columns), on two cycles of the signal, and performing three iterations. Fig. 7 shows the TVE of the phasor for this test. The errors are approximately 0.004 %. If Δv is the phasor magnitude error in percent of full scale and $\Delta\phi$ is its angle error in degrees, the phasor TVE is given by $TVE = sqrt((\Delta v)^2 + (\Delta\phi / 0.573)^2)$. (Note: the value 0.573 is the arcsine of 0.01 or 1 % in degrees.) The frequency and rate of change of frequency had errors of approximately 1 mHz and 40 mHz/s. The values corresponding to intervals with transitions are ignored in this and all the tests described below.

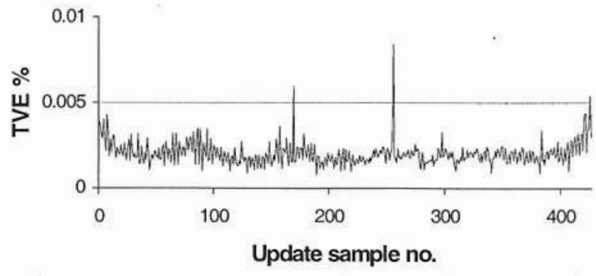

Fig. 7. Phasor TVE for linear voltage magnitude pattern.

The sinusoidal magnitude test pattern is shown in Fig. 8. Fig. 9 shows the errors for this test. The analysis was done with a second order model, on two cycles of the signal, and performing three iterations. The magnitude varied from 3 V peak to 7 V peak at a frequency of 2 Hz. The phasor TVE errors are approximately 0.002 %. The frequency and rate of change of frequency had errors of approximately 0.2 mHz and 30 mHz/s.

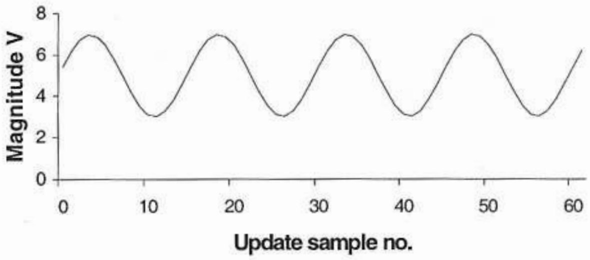

Fig. 8. Sinusoidal voltage magnitude pattern

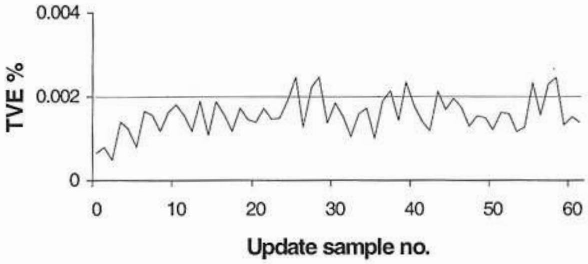

Fig. 9. Phasor TVE for sinusoidal voltage magnitude pattern.

The linearly varying frequency test pattern is shown in Fig. 10. Fig. 11 shows the TVE errors for this test. Note that the frequency and errors at the transitions are not reported. The analysis was done with a second order model, on two cycles of the signal, and performing three iterations. The frequency varied from 60 Hz to 64 Hz at a rate of 10 Hz/s. The phasor TVE errors are approximately 0.0007 %. The frequency and rate of change of frequency had errors of approximately 0.3 mHz and 10 mHz/s.

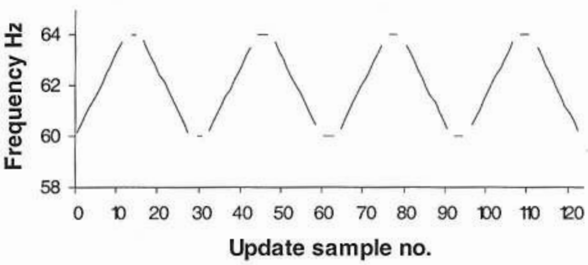

Fig. 10. Linear voltage frequency pattern.

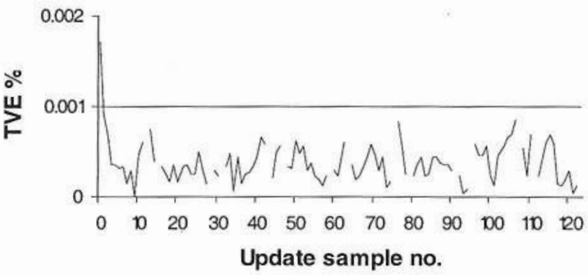

Fig. 11. Phasor TVE for linear voltage frequency pattern.

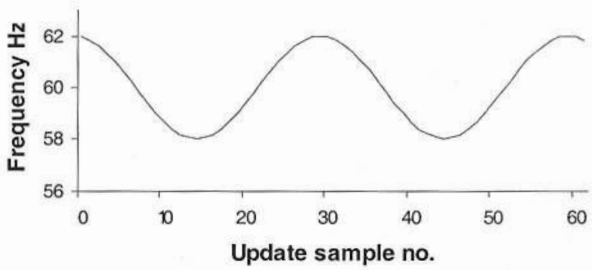

Fig. 12. Sinusoidal voltage frequency pattern.

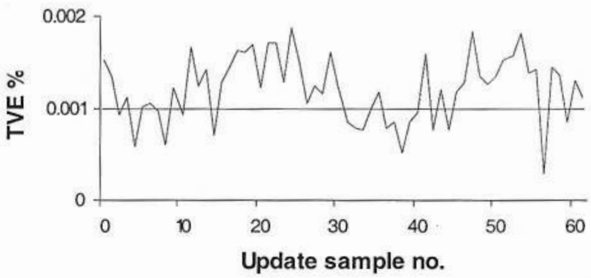

Fig. 13. Phasor TVE for sinusoidal voltage frequency pattern.

The sinusoidal frequency test pattern is shown in Fig. 12. Fig. 13 shows the TVE errors for the sinusoidal dynamic frequency test. The analysis was done with a second order model, on two cycles of the signal, and performing three iterations. The frequency varied from 58 Hz to 62 Hz at a frequency of 2 Hz. The phasor TVE errors are approximately 0.0015 %. The frequency and rate of change of frequency had errors of approximately 0.4 mHz and 60 mHz/s.

The test results are sensitive to the parameters of the analysis model, i.e., in particular the number of cycles, c, the number of iterations, I, the order of the model, O, and the magnitude of the signal generated, V. Table I shows the effects of the various parameter choices when analyzing the sinusoidal frequency test pattern. The first data row is the reference parameter values and the values used for the results in Fig. 13. These values are used in all the test examples on the following rows unless another value is listed. The table lists the root-mean-square (rms) differences, Δ, between the measured and theoretical values of the angle, magnitude, frequency, and rate of change of frequency for each of the sets of parameters. All the measurements are significantly larger when only one cycle of sampled data is analyzed. The errors generally decrease as the number of cycles analyzed increases. The data is relatively insensitive to the number of iterations, which shows that the estimates of the model are very accurate. With model order three the number of cycles analyzed must be at least two, preferably three. The output channel has 16 bits of resolution and a fixed range of ± 10 V. Thus, when the voltage magnitude is reduced to 1 V, the effect is to increase the quantization noise to the equivalent of 13-bit data. This increased noise may be representative of the noise that will result from the use of voltage amplifiers, transconductance amplifiers, and transducers, in the full dynamic test system. Note: the number of cycles used in the analysis window does not represent the update rate for this analysis. The analysis window is moved forward the time corresponding to the update rate and the model order is selected to describe the magnitude and frequency variations within the analysis window.

TABLE I
EFFECTS OF TEST PARAMETERS ON MEASUREMENT ERRORS

c	I	O	V	Δ angle m°	Δ mag mV	Δ freq mHz	Δ df/dt mHz/s
2	3	2	9	0.5	0.08	0.4	70
1				4	0.4	5	1200
1.5				0.7	0.2	0.5	100
2.5				1	0.1	0.1	80
3				1.5	0.06	0.1	120
	0			0.7	0.15	0.4	60
	1			0.6	0.12	0.4	60
	2			0.6	0.12	0.4	60
1		3		100	10	100	40 Hz/s
		3		1	0.2	0.5	160
3		3		0.4	0.1	0.1	30
			1	5	0.1	5	200

VII. Planned Tests on PMUs

This system will be used to perform tests on commercial PMUs. The system will report the PMU TVE for the phasors, as well as errors in frequency and rate of change of frequency. At a minimum the tests will include linear magnitude and frequency tests as described by Fig. 3 and 5. Additionally sine wave magnitude and frequency modulation tests will be performed for modulation frequencies ranging from a fraction of a Hz to 5 Hz. For these the difference between the PMU output parameters and those from the proposed analysis method will be determined. Higher modulation frequency magnitude and frequency modulation tests will be done to determine the ability of the PMU's anti-alias filter to suppress aliasing artifacts in the measured results.

VIII. Summary and Conclusions

The development of the NIST dynamic PMU performance measurement system has been described. An analysis model has been proposed that allows the calculation of both magnitude and frequency dynamic parameters to be determined. The model parameters are based on a power series in time about the PMU update times. The system has demonstrated the accuracy necessary to determine the dynamic errors in the PMU measurement quantities, including the TVE for the phasors, as well as the frequency and rate of change of frequency. Several test patterns for dynamic testing of PMUs were proposed.

When the system is expanded to include the voltage amplifiers, the transconductance amplifiers, and the transducers, the measurement uncertainty will increase. However, the results of this low voltage analysis of the performance of the model, the signal generation, and the sampling are very encouraging.

In addition to the data determined in these tests, information on the required accuracy of these dynamic signals to accurately predict the status of the electric power grid must be determined. This latter information will be obtained from network simulators and analysis of data taken on the power grid. This grid requirements information combined with the dynamic test data on commercial PMUs will help in the development of dynamic performance requirements for PMUs.

IX. Acknowledgment

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