TESTING SYNCHROPHASOR DATA QUALITY FOR APPLICABILITY TO TRANSMISSION SECURITY AND OPTIMISATION TOOLS

R. Lira, MSc
Psymetrix
Edinburgh, UK
ricardo.lira@psymetrix.com

D. H. Wilson, PhD
Psymetrix
Edinburgh, UK

K. Hay, PhD
Psymetrix
Edinburgh, UK

T. Cumming
Scottish Power
Glasgow, UK
tom.cumming@sppowersystems.com

D. Cole
Qualitrol
Belfast, UK
dcole@qualitrolcorp.com

Abstract – This paper summarises a testing exercise carried out by a utility, a Phasor Measurement Unit (PMU) manufacturer and a developer of systems and applications to qualify the PMU for use in applications of interest for transmission system security and optimisation. The testing goes beyond the IEEE standard requirements for synchrophasor measurement in terms of both the static and dynamic requirements. It was proven that the PMU met the requirements for the applications considered. The features tested characterise the time-domain and frequency domain performance and can be applied to other application areas.

Keywords: PMU performance, WAMS applications, WAMS requirements, phasor accuracy, line parameter, stability monitoring.

1 INTRODUCTION

Wide Area Measurement Systems (WAMS) are increasingly used to monitor and improve the observability of power systems, in terms of static and dynamic performance. The number of Phasor Measurement Units (PMUs) installed around the world has been growing rapidly. Increasingly, there is a recognition in the industry that phasor measurements and wide-area monitoring have significant potential to improve power system security.

This paper describes collaborative work between a transmission system owner, a WAMS application provider and a PMU supplier to validate the PMU performance of a multifunction fault recorder*. From the utility's perspective, standard and type testing is valuable, but it is also necessary to have the capability to perform tests for:

1) Applicability of the unit for the intended operational and analytical uses of the WAMS
2) Testing of different configurations of the unit and firmware upgrades
3) Interoperability between different models of used PMUs within the network and from external sources

For these reasons, an in-house, repeatable test process is required that validates the static and dynamic behaviour of the PMU for the applications. The goals of the project included both the initial validation of the PMU and a repeatable test process can be used for on-going maintenance of the WAMS system.

*The help and support received from OMICRON in this project is acknowledged, and in particular for the provision of a test unit for the testing exercise.

The performance of PMUs has become an important issue regarding the increasing use of WAMS for monitoring and control of power systems. A precise definition of generic accuracy requirements for PMUs is a challenge for engineers, given the diversity of application areas. Requirements for steady state and dynamic performance must be carefully addressed to ensure reliable performance of such applications. For oscillatory stability applications (Figure 1), it is important that the dynamic performance of the PMUs meets the requirements of the application.

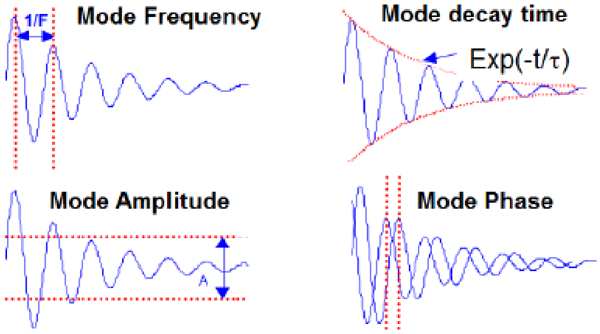

Figure 1: Dynamic characteristics of a system oscillation which composes the mode shapes along the system.

The present IEEE C37.118-2005 standard for synchrophasor measurement [1] defines the steady state performance of PMUs, but dynamic performance is not covered. Nevertheless, different approaches for phasor estimation and requirements under transient and dynamic conditions can be found in the literature [2, 3, 4]. Also, some steady-state requirements can be more stringent than the C37.118 requirements.

While PMU performance testing has been addressed in literature [5, 6], it is generally not related to the specific requirements of the applications using the data. In this paper, the testing exercise reported is related directly to the requirements of the applications, and the focus of the testing was to qualify a specific PMU model for use in the intended applications.

There are other sources of error, in particular because of the accuracy of the instrumentation channels including the current and voltage transducers. It is known those errors can be larger than the PMU itself [7]. The instrumentation channels are important for applications requiring accurate results, such as the line parameter estimation. However, it is generally less significant for dynamics application. This paper does not address instrumentation channels issues, but rather focuses on testing and qualification of the PMU.

The main drivers for implementing a WAMS system were to do with increasing the utilization of the transmission while maintaining system security. This is increasingly challenging in view of the renewable generation targets in Scotland.

The performance of the PMUs was tested for the following application requirements:

- Oscillatory stability monitoring, requiring knowledge of gain and phase, and good attenuation of aliased components
- Transient detection and reporting, requiring fast response to disturbances
- Line parameter estimation, requiring high steady-state accuracy

In this paper, the testing methodology for each of these application areas is described, and test results reported. It was concluded that the PMU was suitable for the areas of application that were intended, within certain boundaries, which were clearly understood through the testing exercise.

2 APPLICATION REQUIREMENTS

2.1 Oscillatory Stability Monitoring

One of the benefits of synchrophasor monitoring over conventional SCADA is that the dynamics of the system are reproduced in the measurements. Since the data is synchronized, it is possible to process the data to determine the amplitude and phase of oscillations across the network, as well as the damping.

For monitoring a range of oscillation frequencies, it is necessary for the PMU to have the following qualities:

- Negligible attenuation within the frequency band of interest
- Negligible phase delay in the band of interest
- Sufficient attenuation of aliased components to avoid misleading results

Specifically, the performance targets for the oscillation are listed in Table 1. The values listed in Table 1 are based on requirements for a commercial phasor-based real-time oscillation monitoring application [8]. The application identifies the frequency, amplitude, damping and relative phase of dominant oscillations observed in the power system. The underlying measurement system should not introduce errors that could lead to the user drawing false conclusions from the results.

The bandwidth currently used covers the electromechanical range of frequencies for local and inter-area modes as well as governor control modes. The extended frequency range is of interest for smaller machines, such as distributed generators. The higher frequencies are also of interest for control modes in generator testing.

It should be noted that the frequency band of interest includes lower frequency inter-area modes under 1Hz and also higher frequency local modes. The phase shift is important for the lower frequency modes where it is useful to compare the phase of oscillations at different points in the network and in different signals. Phase relationships are used in methods to identify coherent oscillations and contributions to oscillations from different areas of the grid.

There can be frequencies above 10Hz present in the power system. Sub-Synchronous Resonance (SSR), for example, may occur between 10 and 50Hz. It is not possible to observe higher frequency SSR issues using phasor measurements without degrading the performance for other issues. The higher frequency components are out of the scope of measurements of PMU-based stability applications.

Frequency band of interest	0-4Hz (future 0-10Hz)
In-band attenuation	> -3dB
Attenuation of aliasing	< -20dB
Phase shift in-band	< 10 º (main interest 0-1Hz)

Table 1: Target performance for oscillation monitoring.

2.2 Transient Detection and Analysis

The fast synchronized data from PMUs is very valuable for detecting and presenting wide-area disturbance data. From a monitoring perspective, it is important to know the precision with which the observations can be interpreted.

The timing of the relative changes in the power system state is a useful measure for identifying the nearest measurement to the source of the disturbance. Since a disturbance propagates through the system with a finite speed, the precise delay can be useful in determining a sequence of events.

It is also important to distinguish the characteristics of a disturbance in terms of the plant control behaviour and step response characteristics of the measurement process, such as overshoot and settling time. There are few real step responses in the power system – the system does not instantaneously change state – however, the step response is a useful test because it allows comparison between devices. Figure 2 shows a standard step response test, evaluated by:

- **Rise time** from 10% to 90% of step
- **Overshoot** beyond the final value
- **Settling time** from initiating event reaching and remaining within 1% of step size

Knowing the step response of the PMU enables a user to know the boundaries of conclusions that can be derived from the measurement of an event. This helps to distinguish the true behaviour of the power system from artefacts of the measurement process. Also, if different types of PMU are used in the same system, it is important to know the extent to which comparisons can be made between the types of PMU.

From the monitoring perspective, the step response is required for information, however there may be further specific requirements for control schemes. This would involve not only assessment using the above criteria, but would also involve capturing the time at which the information was delivered by the PMU, thus identifying the latency of the PMU itself. This is outside the scope of this project, which focuses on monitoring rather than control.

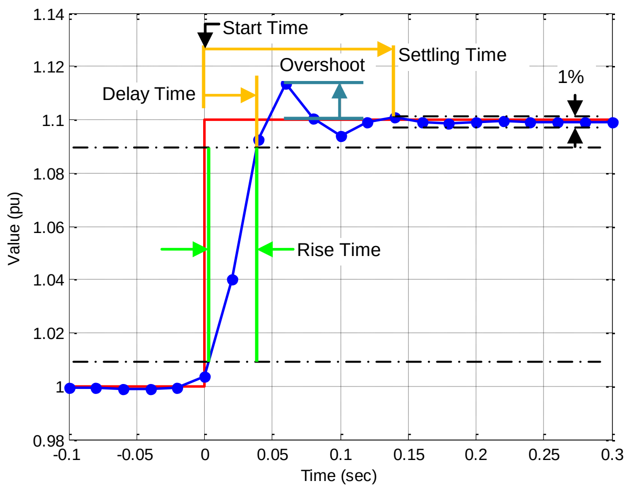

Figure 2: Amplitude Step Response Test.

2.3 Line Parameter Estimation

With PMUs at either end of a transmission line, it is possible to measure the line parameter in real time. However, this application is sensitive to errors, and measures must be taken to differentiate results with higher confidence (i.e. the measurements that are consistent at both ends). The accuracy of the PMUs and the instrumentation channels influence the number of coherent results obtained that can be treated with confidence.

The requirement for accurate line parameter estimation is accurate steady-state measurements. The dynamic performance of the PMU is not relevant in this case. The C37.118 standard requires a steady-state accuracy defined as 1% of the Total Vector Error (TVE). This error is too great for accurate measurements of line parameter, however PMUs can provide much better accuracy than 1% TVE during normal operating conditions.

Table 2 shows the typical measurement accuracy that is required in order to achieve the target levels of line parameter accuracy. The accuracy figures are taken from a typical transmission line model, as single-end phasor errors are introduced to examine the sensitivity to errors in those variables. It is clear that the different line parameters will be sensitive to different measurement errors. The following error modes are considered:

- **Single-end V magnitude accuracy**. This is the magnitude error, in percentage, in just one end of the line, given that the rest of measurements are correct
- **Single-end I magnitude accuracy**. As above, for current magnitude
- **Single-end V angle accuracy**. This is the angle error, in degrees, in just one end of the line, given that the rest of measurements are correct
- **Single-end I angle accuracy**. As above, for current angle

A line parameter measurement method should include error-checking for data sets used, but it is clear that better measurements lead to more consistent and accurate line parameter estimates. It should be noted that this paper deals with the accuracy of the PMU only, rather than the instrumentation channels. In an implementation of the process, the errors introduced by the instrumentation channels are important and should also be considered.

In practice, more detailed accuracy requirements are built up for a particular application of line parameter estimation prior to operational use [7]. Different line loading conditions and error combinations are considered. However, this example illustrates the typical values of accuracy required. Note that each line parameter responds differently to errors in each phasor value.

Accuracy	Target	Magnitude Error [%]		Angle Error [°]	
		|V|	| I |	ang(V)	ang(I)
R	3%	0.05%	8.0%	0.20°	0.70°
	5%	0.10%	15.0%	0.32°	1.10°
X	3%	1.50%	6.0%	0.15°	> 10°
	5%	3.0%	10.0%	0.25°	> 10°
B	3%	6.0%	2.0%	> 10°	0.40°
	5%	10.0%	4.0%	> 10°	0.65°

Table 2: Typical one-end accuracy requirements for line parameter estimation of a medium length, medium load transmission line

Another aspect of PMU testing that is important for line parameter estimation is measurement noise. Individual short-window phasor samples tend to have higher random measurement noise than samples using a longer window or averaged results. It is useful to reduce measurement noise by filtering results; however this should not filter out real variations in the power system.

3 TEST PROCEDURE

The testing process was carried out by injecting 3-phase 50Hz test signals into the PMU front-end using a relay test set that is capable of time synchronization and COMTRADE file playback. The accuracy class of the test set for magnitude and angle is suitable for the tests carried out [9]. The tests can be replayed either into a single PMU or simultaneously replayed into several PMUs simultaneously for comparative tests. The PMU(s) stream data to a Phasor Data Concentrator (PDC) that captures and stores the data for later analysis. Separate tests are designed for testing specific application requirements.

3.1 Steady-State Tests

Steady-state tests involve running balanced 3-phase steady-state signals into the PMU. The signal is maintained for a period at least of 10 seconds, and the mean value and standard deviation are recorded relative to the test signal. The steady-state tests include a range of steady-state voltage and current tests in the ranges:

- 0.10 – 1.20pu voltage
- 0.03 – 1.00pu current
- 45 – 55Hz nominal frequency
- 45° angle step

A much smaller range of voltage and current is used in practice for line parameter estimation. However, it is necessary to configure the line parameter estimation to provide results in value ranges where the measurements are sufficiently accurate to yield results. Also, an assessment of the measurement accuracy is of interest for the use of the measurements in post-event analysis.

Imbalanced test signals were applied to ensure that there was no inter-dependence between the measurements of each phase. The steady-state tests were also run at different frequencies to ensure that the results were not influenced by frequency deviation from the nominal.

The phase angle tests are evaluated based on the absolute reference phase, where the 0° angle is defined at the second transition provided by PPS clock [1]. Given that the signal generator output was triggered by PPS, the angle values reported by the PMU should corresponds exactly to the signal generator output.

3.2 Transient Response

The transient response is important to assess how quickly the unit responds to a change in the system conditions. Upward and downward steps are used to check the consistency of the delay in response. Steps are applied to both the magnitude and the angle signals.

Thus, the following transient response tests were done:

- Step V&I magnitude 1.0 → 1.1pu
- Step V&I magnitude 1.1 → 1.0pu
- Step V&I magnitude 1.0 → 0.9pu
- Step V&I angle by 15 degrees
- Step V&I angle by 3 degrees

The point of change of the signal is accurately defined using the synchronization of the test signal generator. The transient response is also compared with other models of PMU to check the consistency between the PMU under test and other PMU models.

3.3 Oscillation Analysis

The oscillation tests look at the gain and phase of oscillations through a range of frequencies. A series of oscillation frequencies are applied with constant oscillation amplitude and known phase. The output is analysed in terms of the gain of the oscillation and the phase relative to the input oscillation.

The frequency responses of following signals were tested:

- Voltage and Current Amplitude
- Voltage and Current Angle
- Frequency

The frequencies applied include:

- 0.1 – 10Hz: In-band response
- 10 – 20Hz: Gain roll-off
- 24 – 26Hz: Around Nyquist frequency
- 40 – 49Hz: Attenuation of aliasing

Each oscillation frequency is maintained for a period of at least 10 seconds. The magnitude and phase of the output oscillations were compared with the input oscillations for each test.

4 TEST RESULTS

4.1 Steady-State Tests

It can be seen in the results in Figure 3 and Figure 4 that the magnitude error in voltage and current measurements in the range of interest for line parameter estimation is small. The voltage and current error is less than 0.17% at 0.6pu and above.

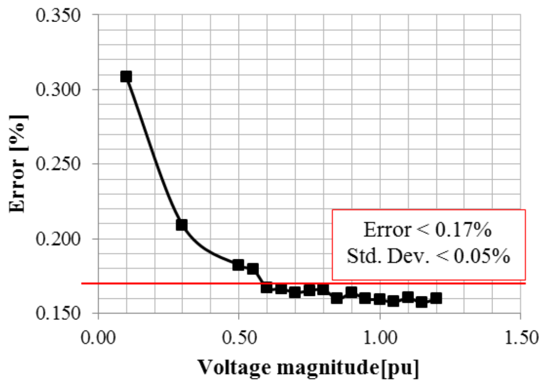

Figure 3: Steady-State Voltage Amplitude Test.

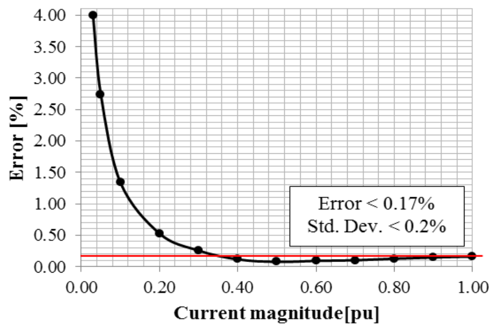

Figure 4: Steady-State Current Amplitude Test.

It was noted that the voltage input is clipped above 1.35pu. The PMU has both high resolution and low resolution (wide range) inputs that can be used simultaneously. It was found that it was necessary to use the high resolution inputs for synchrophasor applications. It is possible to use the low resolution inputs for disturbance recording to capture waveforms for large deviations during faults, as the same time as using the high resolution inputs for phasor measurements. Thus, the use of the PMU function does not restrict the unit's capability for disturbance capture.

The current accuracy degrades at low values because the relative error increases when the expected value is low. The same performance is observed for the voltage measurement, but the applications considered do not require high accuracy during low voltage 'fault on' conditions.

Figure 5 shows the cumulative error deviation from the average for voltage and current magnitudes at 0.5 and 1.0 pu. It can be observed that the current error presents greater deviation than voltage error. Also, the standard deviation tends to increase considerably for lower magnitude levels for both voltage and current phasors.

The results reported in Table 3 were cross-checked with other PMUs measuring the same signals, and also at several values of angle. The results show that the steady-state accuracy of the phase angle is better than 0.20° for voltage and current at nominal values. The voltage phasors are not degraded at 0.7pu. The same performance is observed for the current phasors at 0.3pu.

In terms of Total Vector Error (TVE), which the C37.118 stipulates should be better than 1%, it may be noted that at nominal values, the voltage phasor is accurate to 0.45% TVE and the current phasor is accurate to 0.53% TVE. These are both substantially better than the value required by the standard. This is to be expected, as the range of measured values of interest for line parameter estimation is smaller than the C37.118 standard defines. However, it is significant that the near-nominal performance of the PMU is much better than the standard, and the testing process means that the line parameter application does not need to assume the limitation that the accuracy is 1% TVE as defined by the standard.

Regarding the system frequency deviation tests, Figures 6 and 7 show that between 46.5Hz and 55Hz, the errors are practically independent of system frequency. The errors degrade below 46.5Hz, however the power system observed is not expected to survive a frequency under 46.5Hz. In such a severe disturbance, data on the general behaviour of the system is useful, but high steady-state accuracy is not critical.

Unbalanced phase had no significant effect on the steady-state accuracy. This confirms that the PMU measurement channels are independent.

Figure 8 shows that measurement scatter can be reduced by filtering measurement noise. The measurement noise, as measured by the standard deviation of the filtered signal, reduces exponentially as the window length increases. This suggests a window length of around 25 samples would be appropriate for line parameter estimation, for instance. A relatively short window is useful, enabling to capture the real movement of the power system, without introducing more measurement noise than necessary.

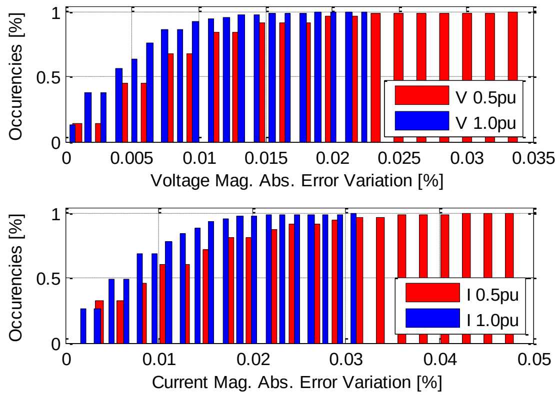

Figure 5: Cumulative error deviation from the average for different V&I magnitudes.

In terms of the accuracy for line parameter estimation, it is noted that the PMU performs well for estimation of impedance and susceptance measurements, however accurate resistance measurement is challenging.

	Average Angle Error (°)
Voltage (1.0pu)	0.172°
Voltage (0.7pu)	0.158 °
Current (1.0pu)	0.186 °
Current (0.3pu)	0.180 °

Table 3: Steady-State Voltage and Current Phase Angle Tests.

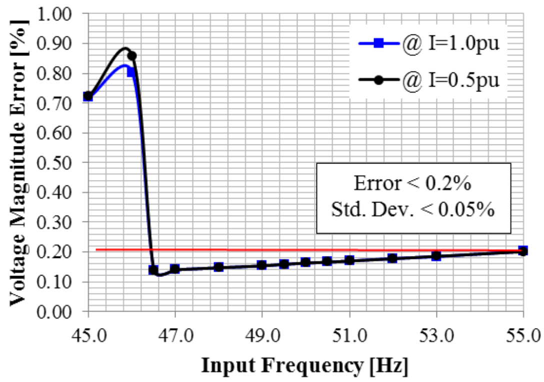

Figure 6: Voltage error with system frequency deviation.

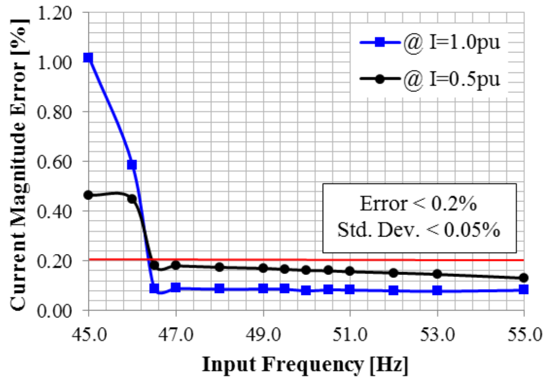

Figure 7: Current error with system frequency deviation.

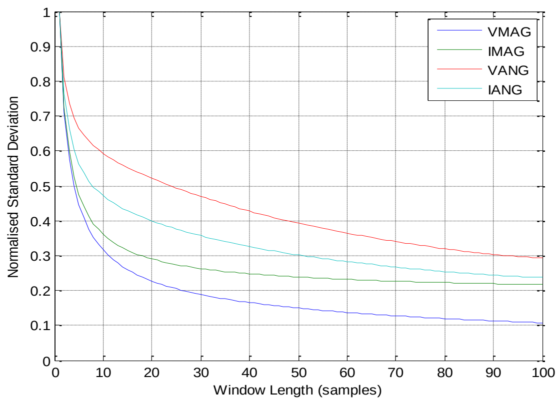

Figure 8: Reduction of Measurement Noise with Moving Average Filter.

4.2 Transient Response

It is shown in Figure 9 that the V&I magnitude step response is very fast. The PMU responds in a single sample to the change in input. The rise time, delay time and settling time are therefore all within one sample, i.e. less than 20ms. There is no significant overshoot or ripple. This response is as good as can be achieved with a PMU. Similar responses were achieved for all phases, for upward and downward steps.

The V&I step response of angle to a large angle step (15º), illustrated in Figure 10, shows a similarly short fast rise time and delay time, which is less than one sample. However, there is a small 1-sample ripple that does not overshoot the target value, and the value takes 100ms to reach the 1% limit for the settling time. Similar results are obtained for voltage steps.

A smaller angle step (3º, Figure 11) shows similar performance to the 15° angle step, but with a smaller overshoot value.

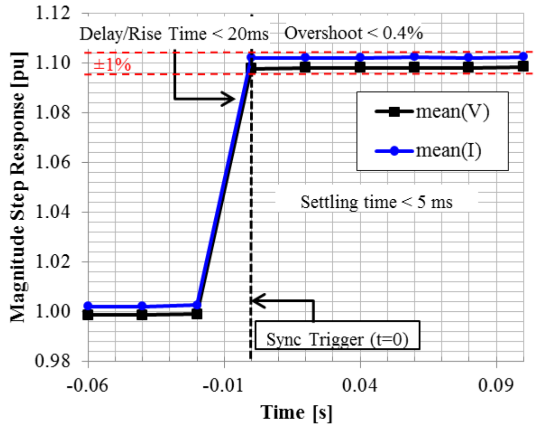

Figure 9: V&I Magnitude Step Response (0.1pu step).

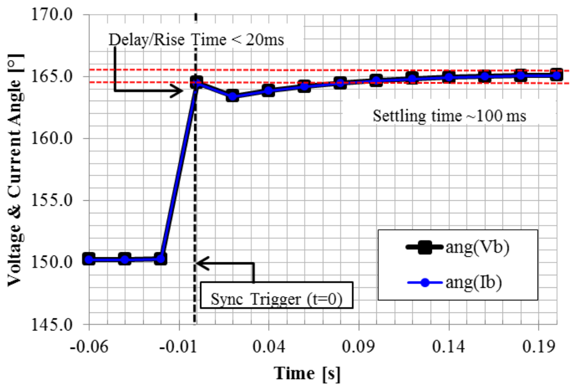

Figure 10: V&I Angle Step Response (15 degree step).

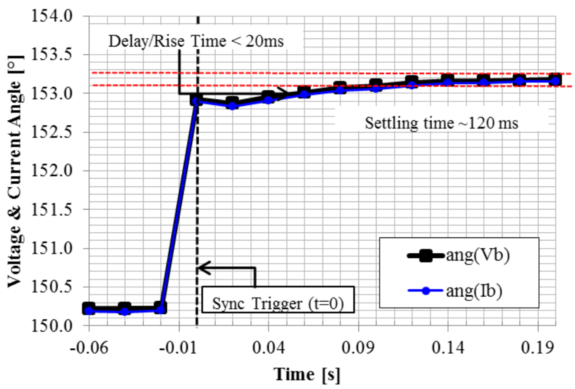

Figure 11: V&I Angle Step Response (3 degree step).

4.3 Oscillation Analysis

In Figure 12, it is shown that the phasor outputs of the PMU have attenuation above -3dB below 10Hz†. This shows that the phasor outputs will effectively reproduce frequency components in the range 0-10Hz, which is the desired range for current and future oscillation analysis.

Also, it is shown that aliased components in the range 40-50Hz are attenuated by a factor of at least four (below -11dB). Frequencies in the range 45-50Hz are attenuated by a factor of about eight (-17dB). In practical terms, these results meet the target value of -20dB for the current requirements for analysis of 0-4Hz oscillations, but care should be taken in measuring higher frequency oscillations due to aliasing. The phase shift is within 10º up to about 1.5Hz (Figure 13), as required.

As shown in Figure 14, the frequency output signal is quite significantly attenuated in the 0-4Hz band. At 4Hz, the attenuation is -6dB, and the -3dB point is around 2.5Hz. Also, the phase is shifted by 20 degrees at 1Hz (Figure 15). The frequency signal does not meet the requirements for oscillation analysis noted in Table 1. The result indicates that it is necessary to restrict the use of the frequency signal to a narrow bandwidth: 0-2.5Hz if only amplitude is required or 0-0.5Hz if <10º phase shift is required. As an alternative, a frequency signal can be derived from the voltage phasors, as a substitute for the frequency signal.

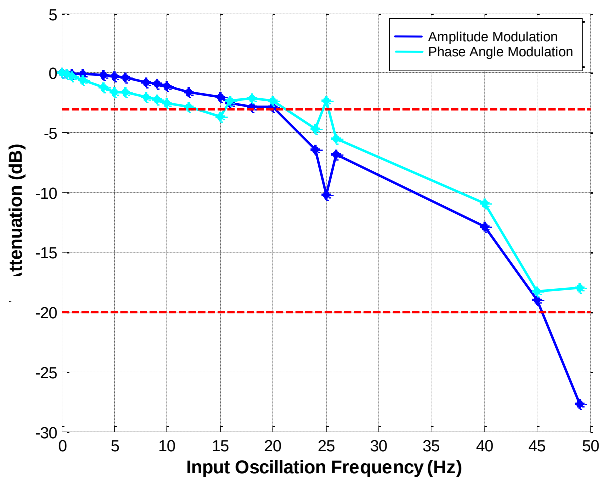

Figure 12: Amplitude Response of Amplitude and Phase Angle Modulation, 0-50Hz.

† The phasor outputs are composed by the voltage and current phasors. In addition, the bus frequency signal is reported by the PMU in the same data frame [1]. Frequency is generally calculated from the voltage waveform and is independent of the phasor calculation.

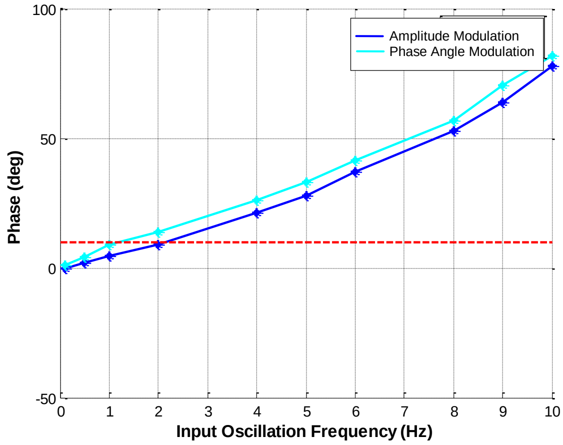

Figure 13: Phase Response of Amplitude and Phase Angle Modulation, 0-10Hz.

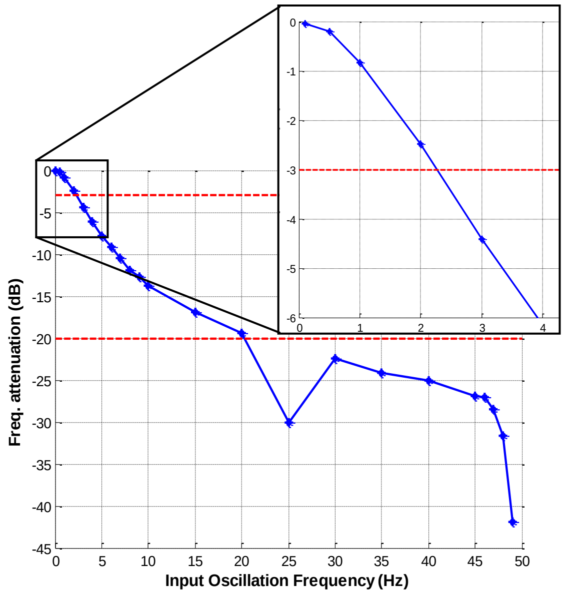

Figure 14: Amplitude Response in Frequency Output Signal to Frequency Modulation, 0-50Hz.

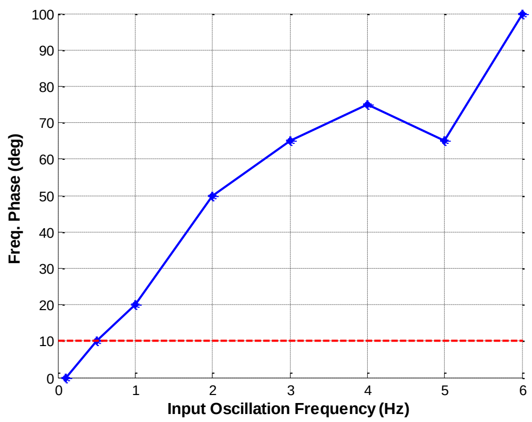

Figure 15: Phase Response in Frequency Output Signal of Frequency Modulation, 0-6Hz.

5 DISCUSSION

From the testing carried out, it is concluded that the PMU under test is suitable for use in the three contrasting applications considered. In particular, it may be noted that:

- The PMU steady-state accuracy in normal situations is significantly better than the requirement for 1% TVE specified in the C37.118 standard. This is important for line parameter estimation.
- The transient response to a change in signal level is very fast. The rise time is short, with negligible delay and very little settling time.
- For analysing oscillations, there is very little attenuation in the band 0-10Hz for V&I measurements, however to achieve sufficient attenuation of aliased components, a bandwidth of 0-4Hz is used. This is sufficient to cover electromechanical and frequency control modes.

There is a trade-off to be made between the transient performance of the PMU and the oscillation performance. Filtering with a sharper roll-off would improve oscillation performance with greater attenuation of high frequency components while providing good in-band performance. However, such filtering would also tend to slow the transient performance and increase the overshoot and ripple. Some further work would be of value to investigate whether further high frequency attenuation is possible without a significant influence on the transient performance, so that the bandwidth 0-10Hz can be used. The extended frequency range would be useful, for example, for generator control system tuning.

The extended bandwidth could also be used if there are no significant components of frequency in the range 40-46Hz. It is thought that such components are unusual in the power system. Since the PMU device is also a disturbance recorder, it would be possible to cross-check using waveform data if observations of frequency at 4-10Hz were correctly represented, or were aliased components.

The testing process has shown that the V&I phasor data is more reliable for oscillation analysis than the frequency output. The frequency output is restricted to a narrow bandwidth, and cannot be used directly if the relative phase of oscillations is important. However, it is relatively straightforward to derive a frequency signal from voltage angle data, and this should provide a more useful representation of dynamic frequency.

The testing process has proved to be valuable in gaining experience in configuring and using the information. It was found, for example, that the application requirements were better served using the high resolution configuration of the PMU, rather than the option of an extended measurement range. The high resolution setting is necessary for any PMUs used for line parameter estimation, and is strongly recommended for at least some, if not all of the oscillation monitoring points. There may be some locations where the extended range may be necessary for the disturbance monitoring functions, but where possible, the high resolution setting is preferred for wide-area monitoring applications.

This paper addresses the accuracy of the PMU itself. As mentioned previously, the instrumentation channels are important for applications requiring accurate results, such as line parameter estimation. The influence of the measurement chain is reported [7] and is the subject of further research.

The testing that has been done has focused on the use of the PMUs as part of a monitoring system, and not for control. Depending on the specific requirements of control applications, there may be further testing to be done on the continuity of data and the latency between a system change and the change being reported.

6 CONCLUSIONS

The testing process has proven the capability of the PMU to be used for three applications that serve as examples of applications requiring:

- High steady-state accuracy;
- Fast response;
- Accurate representation of oscillations.

It has been proven that the tested PMU satisfies the main requirements of all three applications. This paper relates the process and results of PMU testing to the needs of applications, and shows how the PMU performance enables and also bounds the information that can be derived from synchrophasors. The testing process and results can also be applied to requirements for future applications.

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AUTHOR'S BIOGRAPHIES

Ricardo Lira received his MSc in 2010 from Federal University of Santa Catarina, Brazil, focusing on synchrophasor measurement accuracy. He joined Psymetrix Ltd (now part of the Alstom Group) as a Power System Engineer in the same year. Currently working on developments in WAMS applications such as data quality and line parameter estimation.

Dr Douglas Wilson is Chief Technology Officer for Psymetrix Ltd. He has worked with Psymetrix since 1998, and is involved in synchrophasor measurement systems and applications, dynamics analysis and control and renewable generation connection. He graduated B.Eng(Hons) and PhD from the University of Edinburgh and MSc from the University of Manchester. He is involved in R&D, consulting and in commercial application of synchrophasor technology.

Dr Karine Hay received her PhD degree in signal processing from University of Rennes I in 1997. She is a senior engineer with Psymetrix Ltd, having worked in the company since 1998. She is involved in signal processing for online power system stability measurement and analysis.

Thomas Cumming MSc Power Systems and High Voltage Engineering. System Monitoring Engineer for Scottish Power, part of Iberdrola Group Responsible for all aspects of fault recording, system monitoring, fault analysis and location, plant condition monitoring, PD and DGA systems. The development and application of new technologies including PMU's and IEC61850. 35 years experience in the Power Industry.

David Cole BSc Hons - Product Manager at Qualitrol for Fault and System Disturbances responsible for the development and subsequent sales of on-line travelling wave based fault locators and multi function disturbance recorders that include power quality and PMU. Past experience includes testing of HV circuit breakers, research on locating partial discharge sites in drum lengths of polymeric cable and time with a UK Distribution company.