Applicability of PMU Based Frequency Measurements for Power System Applications

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Abstract

Synchrophasor based wide area monitoring, protection, and control applications are widely used all over the world. The latest IEEE synchro-phasor standard C37.118.1a-2014 provides necessary steady-state and dynamic performance requirements for two different application categories namely the "Protection (P) Class" and the "Metering (M) Class" [1-2]. Satisfactions of these application classes require inclusion of digital filters into the standard phasor calculations. Although the IEEE standard provides benchmark test cases for dynamic and steady state frequency measurements, from application point of view, it is essential to understand their applicability for various protection and control applications specified by authorities and standards such as NERC, BAL-0003-1. The information discussed in this paper is useful for users to understand the impact of the performance filters introduced in the latest synchro-phasor standard applicable for frequency related power system applications.

Introduction

This section provides a brief introduction to frequency calculation methods, performance filters and their intended applications.

Power Frequency Calculations

Power frequency calculations can be performed in many different ways. Out of these methods, the zero crossing method is considered as the most established method. However, most of the digital fault recorders application uses the rate of change of phase angle calculation method for frequency estimations. The IEEE synchro-phasor standard C37.118.1a-2014 also recommends the same method assuming that the calculations are performed in relation to the nominal sampling rates, i.e. non frequency tracking calculations. This method calculates frequency deviations with respect to the nominal frequency and use to derive the actual frequency and the rate of change of frequency calculations.

Performance Classes

The IEEE synchro-phasor standard provides two filter classes P class and M class. The P class has been proposed for applications requiring fast response and mandates no explicit filtering. The M class has been proposed for applications that could be adversely effected by aliased signals and do not require the fastest reporting speed.

Impact of Performance Class Filters and Suitability for Different Applications

Filtering methods applied for above two classes are different and output response depends on the nature of the filter. Thus, the standard recommends careful consideration and analysis of application requirements before selecting a suitable filter class. In addition, accuracy requirements are different for two filter classes. All these factors make the filter selections complicated for the end user.

Simulation Based Investigation

This section of the paper provides the steps involved with simulation based investigations carried out to evaluate the performance of different class of filters, beyond the standard frequency requirements. The results from the standard test cases are discussed to highlight the application challenges.

Hardware Test Setup

Fig.1 shows the test setup used to test and evaluate the performance of the PMU.

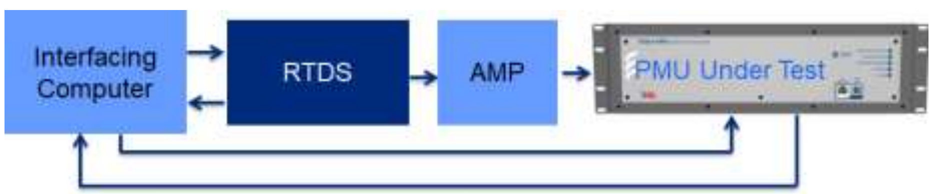

Fig. 1: PMU Test Setup Using a Real Time Digital Simulator

PMU Setting

A setting example for PMU filter class selection including other details is shown in Fig .2.

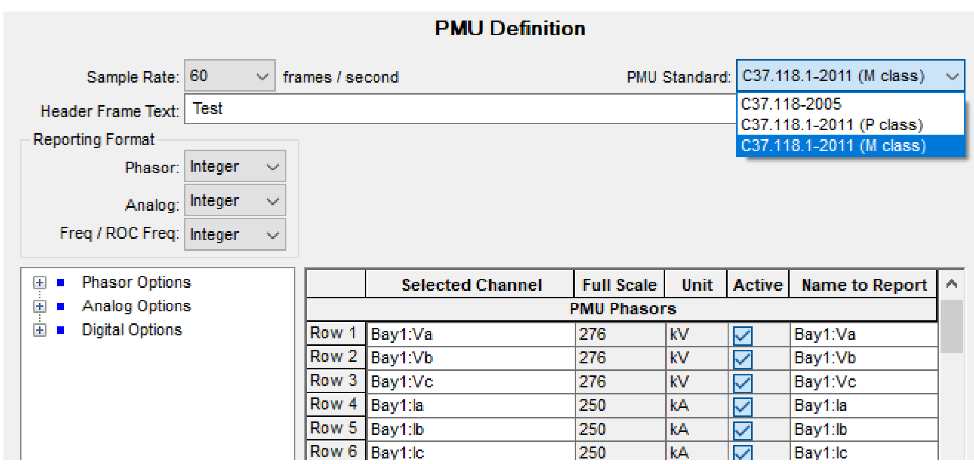

Fig. 2: PMU Setting Example

PMU Performance Testing Software Program

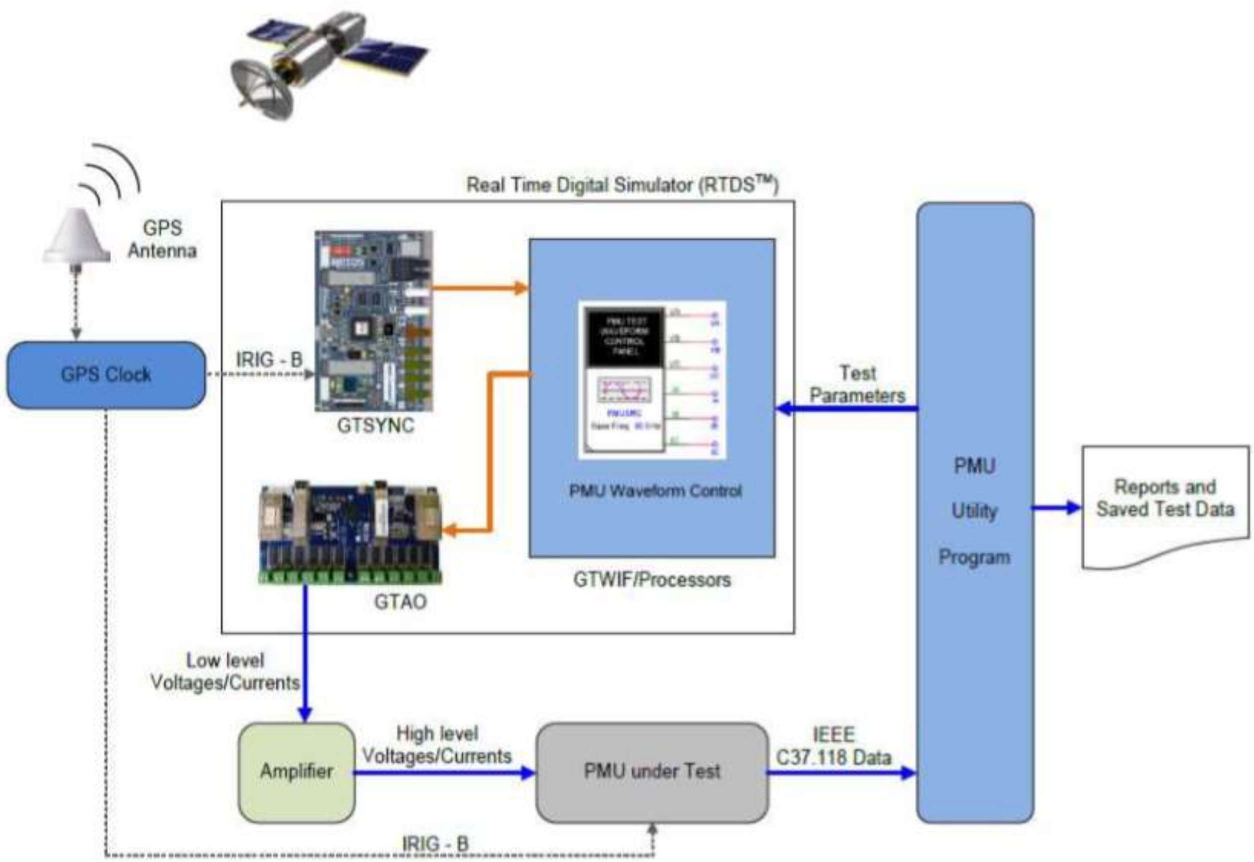

Fig.3: PMU Utility Software in RTDS

The performance of the PMU was tested using the PMU utility software available with Real Time Digital Simulator. This software tool is capable of generating test signals as per the IEEE standard test requirements, read from the actual PMU and generate automated reports including PASS/FAIL status.

The performance of the frequency measurements from the PMU was evaluated for the standard test requirements as specified in [1].

Frequency Test Results

The IEEE PMU standard defines two main categories of test requirements, namely 'steady state' and 'dynamic'. The steady state covers standard steady state conditions under normal operating conditions. The dynamic case covers dynamic conditions such as faults, oscillations, etc. Table-1 and Table-2 shows the steady state and dynamic performance required for the frequency related quantities.

Table-1: Steady State Test Requirements and Results for Frequency Measurements

Influence quantity	Reference condition	Error requirements for compliance							
		P class				M class			
Signal frequency	Frequency = f_0 ($f_{nominal}$) Phase angle constant	Range: $f_0 \pm 2.0$ Hz				Range: $f_0 \pm 2.0$ Hz for $F_s \le 10$; $\pm F_s/5$ for $10 \le F_s < 25$; ± 5.0 Hz for $F_s \ge 25$			
		Max. |FE|		Max. |RFE|		Max. |FE|		Max. |RFE|	
		Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz
		0.005 Hz	**0.003/ 0.002**	**0.4 Hz/s**	**0.12/ 0.04**	**0.005 Hz**	**0.034/ 0.003**	**0.1 Hz/s**	**0.07/ 0.02**
Harmonic distortion (single harmonic)	< 0.2% THD	Range: 1%. each harmonic up to 50th				Range: 10%. each harmonic up to 50th			
	$F_s > 20$	**0.005 Hz**	**0.0008/ 0.001**	**0.4 Hz/s**	**0.102/ 0.02**	**0.025 Hz**	**0.0005/ 0.007**	**None**	**None**
	$F_s \le 20$	**0.005 Hz**	-	**0.4 Hz/s**	-	**0.005 Hz**	-	**None**	**None**
Out-of-band interference	< 0.2% of input signal magnitude	Range: No requirements				Range: Interfering signal 10% of signal magnitude			
		None	**None**	**None**	**None**	**0.01 Hz**	**0.003**	**None**	**None**

Table-2: Dynamic Test Requirements and Results for Frequency Measurements

F and ROCOF performance limits	Error requirements for compliance									
	P class					M class				
		Max. |FE|		Max. |RFE|			Max. |FE|		Max. |RFE|	
Reporting rate F_s Hz	F_r Hz	Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz	F_r Hz	Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz
50	2	**0.06**	**0.002**	**2.3**	**0.061**	5	**0.30**	**0.192**	**14**	**10.41**
60	2	**0.06**	**0.011**	**2.3**	**1.45**	5	**0.30**	**0.015**	**14**	**1.56**
Formulas	min (F_s/10.2)	$0.03 \times F_r$		$0.18 \times \pi \times F_r^2$		min (F_s/ 5.5)	$0.06 \times F_r$		$0.18 \times \pi \times F_r^2$	

It should be noted that the IEEE standard requirements specify the error limitation within +/- 2 Hz and +/- 5Hz frequency deviations for “P-Class” and “M- Class” respectively. These requirements are not adequate for some special situations and applications such as islanding conditions in which frequency goes beyond these limits.

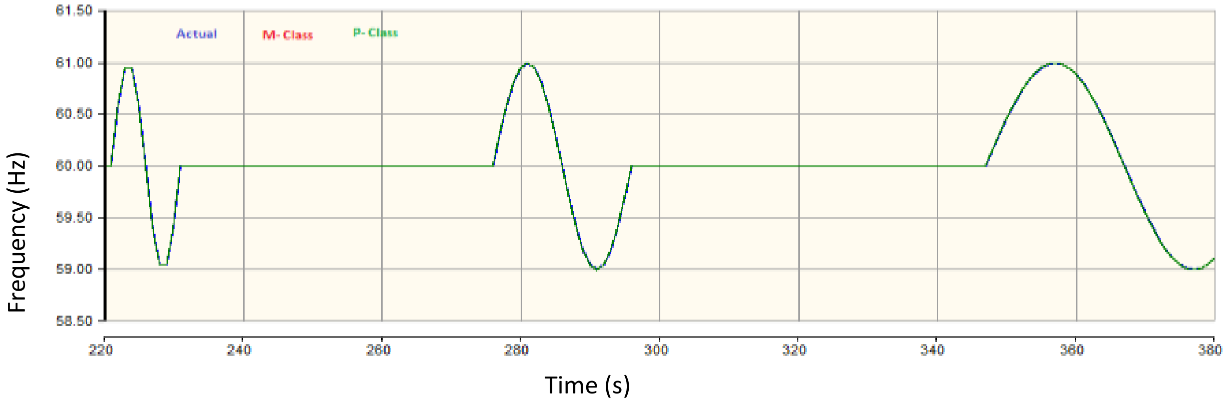

Fig.4: Frequency Measurement Variations for Small Signal Variations

Testing for Abnormal Frequency Variations

In order to evaluate the performance of the PMU based frequency measurements during abnormal frequency variations beyond the IEEE standard requirements, a simulation based investigation was carried out. During this testing frequency was varies +/- 25 Hz from the nominal frequency.

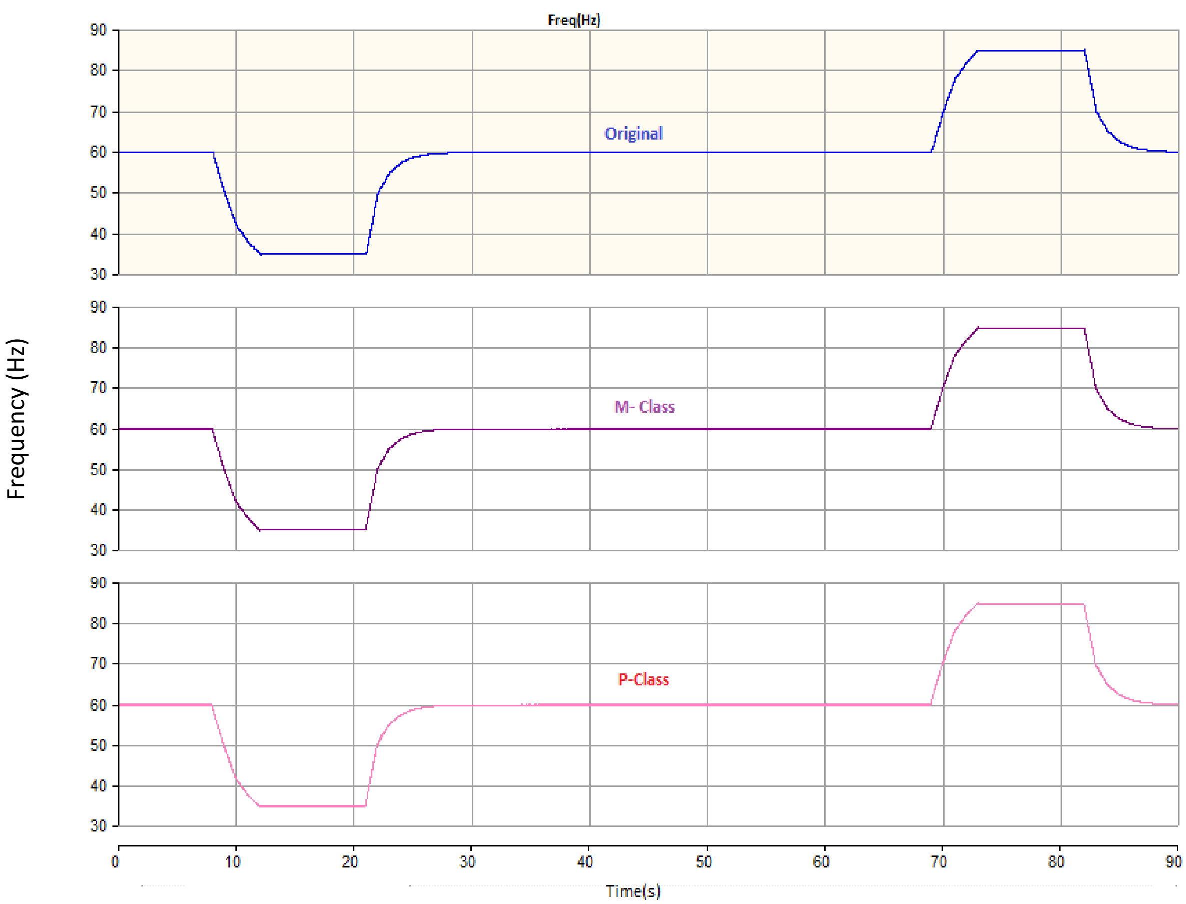

Fig.5: Frequency Variations during Abdominal Conditions

For both P and M classes, frequency variations observed by the PMU were well within the 1% (shown in Fig.5). It should be noted that results for this type of test could vary depending on the manufacture even though the PMU meets the IEEE requirements.

NERC Frequency Oscillation Conditions for Interconnector

The performance of the PMU was tested for the frequency oscillation example provided by the NERC [3]. Fig. 6 shows the results observed for both classes of filters. These dynamic conditions are captured under the IEEE dynamic test conditions. The results from the PMU confirmed accurate measurements accounting to the standard requirements.

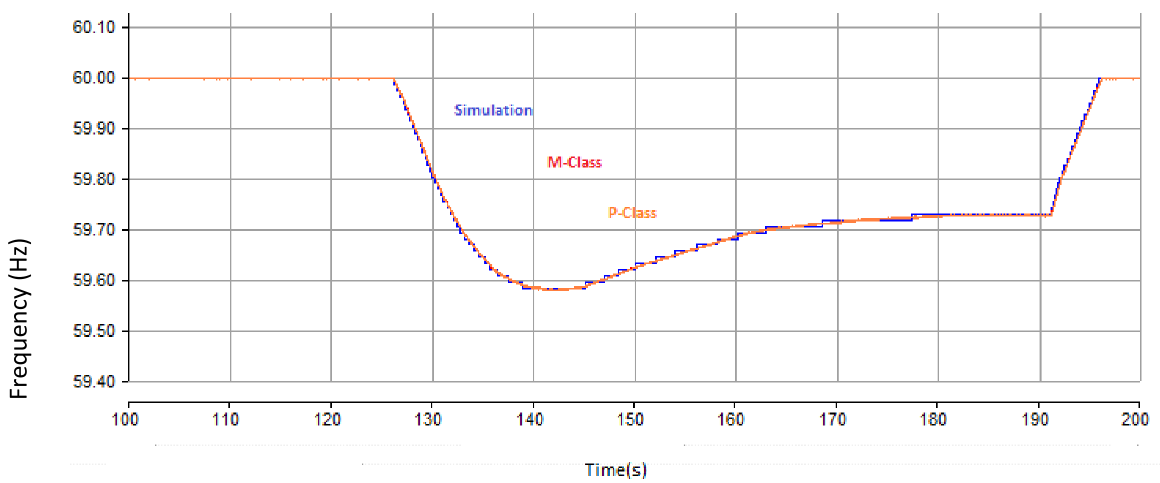

Fig.6: Frequency Measurement Variations during NERC Example

Transient Impact on PMU Frequency Calculations

As explained in above sections, the frequency measurements on PMU are derived from the digital measurements. Transient faults and events could lead to numerical errors during transient conditions. In addition, P and M class filters may also affect the measurements. Thus, the standard recommends ignoring few PMU data samples in error calculations and applications.

In order to investigate the transient impact on the frequency, simulation based investigation has been carried out. Table-3 shows the impact of the filtering on frequency measurements during transient conditions due to the numerical calculations.

Table-3: Impact of Frequency Calculations due to Filtering

Filter Class	Affected Duration
No filtering	1 cycle
P Class	3 cycle
M class	5 cycles

As it can be observed from the results, frequency calculations are affected by the filtering. Any non-frequency type transient conditions could also reflect as a frequency change. Therefore it is recommended to add pick-up delays according to the type of the selected application level (i.e. protection or control device that uses frequency).

Sources of Errors

The users should also be aware of sources of errors in estimated frequencies. Sampling within the PMU is done based time synchronization (IRIG-B, PTP, NTP or SNTP). When selecting a PMU, time synchronization should also be considered and selected accordingly. The bandwidth of primary sensors such as CCVT and PT should also be considered. Aging effects on primary sensors could lead to incorrect measurements. Secondary level/device errors can be compensated by following the manufacturer specific PMU calibration procedures.

Conclusions

Applicability of a synchrophasor based frequency measurements for power system applications are investigated using an industrial PMU implemented with IEEE C37.118 (2011) capabilities. Testing was carried out using the IEEE standard test conditions including some conditions well beyond the standard frequency limits. Results obtained from this analysis showed the impact of the P and M class filtering methods and it is recommended to select the type of the filters (P/M) based on the application needs and adjust the application settings accordingly.

It should be noted that the results for the testing carried beyond the standard limits could vary depending on the type of the manufacture. Performance under such conditions shall be evaluated based on the application requirements.

References

[1] IEEE C37.118.1-2011 - IEEE Standard for Synchrophasor Measurements for Power Systems

[2] IEEE C37.118.1a-2014 - IEEE Standard for Synchrophasor Measurements for Power Systems - Amendment 1: Modification of Selected Performance Requirements, 2014.

[3] 2017 Frequency Response Annual Analysis, NERC, November 2017.

Biographies

Nuwan Perera (IEEE M’2005, IEEE SM’ 2017) earned his BSc Electrical Engineering degree in 2003 from the University of Moratuwa, Sri Lanka and the M.Sc. and Ph.D. degrees from the University of Manitoba in 2007 and 2012 respectively. He joined ERLPhase Power Technologies in 2011. He works with customers and stakeholders to set the long-term vision and strategy for ERLPhase products. This includes market research, determining feature and product requirements and specifications, and providing technical direction for products and projects from initiation to commercial release. He is a senior IEEE member, actively involved with various IEEE Power Systems Relaying Committee (PSRC) working groups. He is also involved in academic research activities as an adjunct professor at the University of Manitoba.

René Midence (IEEE M’2007, IEEE SM’2009) For over 30 years, Mr. Midence has been involved in the design and commissioning of power substations and power plants including Protection and Control, SCADA, Substation Automation and Substation LAN systems. His well-rounded experience covers the fields of consulting and engineering, construction and commissioning, manufacturing, strategic marketing, technical support and training. In the manufacturing business, he has worked in the design and testing of medium and high voltage substations as well as metalclad switchgear, protection and control panels. During his more than 15 years of experience in manufacturing, he has contributed to the development and introduction to market of new protection and control microprocessor-based relays, Ethernet switches and routers. Mr. Midence actively participates in the development of IEEE Standards, member of the IEEE Power Systems Relaying Committee (PSRC), member of the International Electrotechnical Commission (IEC) TC57 WG10. Mr. Midence graduated in 1983 from the University of Honduras with the degree of Bachelor of Applied Science degree in Electrical and Industrial Engineering. He joined ERLPhase Power Technologies in 2010 and currently holds the position of Director of Technical Services.

Nandaka Jayasekara (IEEE Member) received B.Sc. degree (First Class Honors) in Electrical Engineering from the University of Moratuwa, Sri Lanka in 2000. He obtained his M.Sc. and Ph.D. degrees in Electrical Engineering from the University of Manitoba, Winnipeg, Canada, in 2004 and 2012, respectively. Since 2008 he has been with Manitoba Hydro. Currently he is working as NERC Reliability and System Studies Engineer in the System Planning Department, where he conducts and analyzes transmission system planning studies involving generation station outlet transmission and existing and future interconnection for their impact on the development of the Manitoba Hydro interconnected power system. He is also responsible for coordinating ongoing NERC regulatory compliance with relevant Transmission Planning standards. Nandaka is a registered Professional Engineer in the province of Manitoba and he is also a member of IEEE.