Phasor Measurement Unit (PMU) Performance Test Report for TESLA 4000

IEEE C37.118.1 – 2011 (IEEE C37.118.1a – 2014)

Introduction

This report summarizes PMU performance test results for the TESLA 4000 Digital Fault Recording System. Its PMU function was tested as per the latest synchrophasor standard IEEE C37.118.1-2011 (with IEEE C37.118.1a -2014 amendments) [1-2]. Testing was carried out using the automated test suite (PMU utility) available in RTDS [3] for both steady-state and dynamic test scenarios defined in [4], as listed below.

- Signal frequency range test
- Signal magnitude test (voltage and current)
- Phase angle test
- Harmonic distortion test
- Out-of-band interference test
- Measurement bandwidth
- Frequency ramp test
- Step response test

RTDS - Test Setup

Fig. 1 shows the test setup used for PMU performance evaluation. Test waveforms generated by the RTDS are sent to the PMU via the analog output cards (GTAO) and voltage/current amplifiers. The PMU utility software provides interfacing for the RTDS and the PMU under test. More details about the RTDS PMU utility can be found in [3].

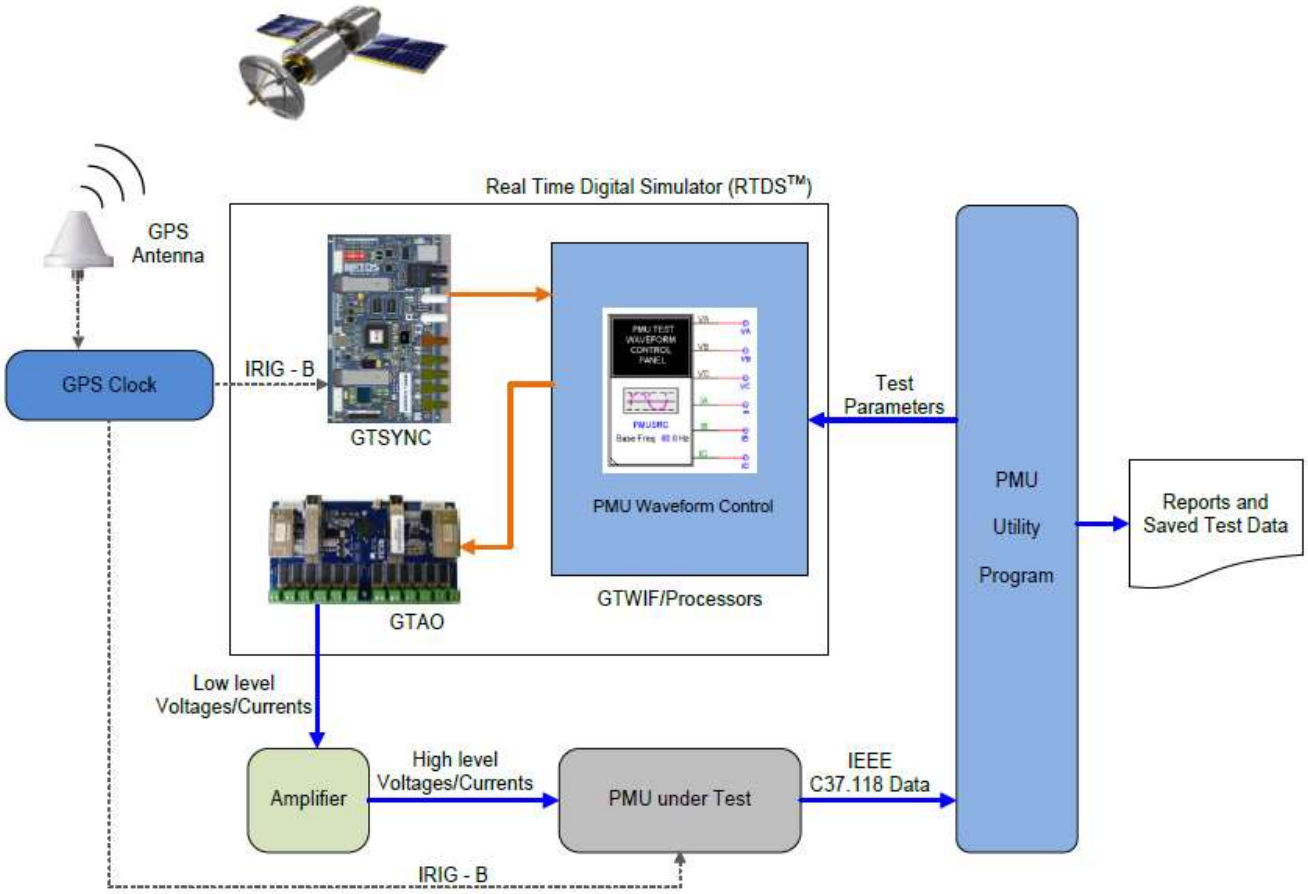

Fig.1: RTDS Test Setup [3]

Test Signals and Settings

Testing was performed for both 50Hz and 60 Hz signals. Basic test configurations and setting used during this testing are summarized in Table-1. Testing is repeated for both P class and M class case studies.

Table-1: Test Configurations and Settings

Description	50 Hz Settings	60 Hz Settings
Voltage (sec/primary)	69.0 V/ 69.0 kV	69.0 V/ 69.0 kV
Current(sec/primary)	5.0 A/ 5.0 kA	5.0 A/ 5.0 kA
PMU reporting rate	50 samples per sec	60 samples per sec
Signal sampling rate	128 samples per cycle	96 samples per cycle

Results

Steady-State Synchrophasor Measurement Test — Status: **Pass**

Table D.2: Steady-state synchrophasor measurement standard requirements and test results

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit					
		Performance – P class			Performance – M class		
		Range	Max. TVE %		Range	Max. TVE %	
			Standard Requirements	Results 50/60Hz		Standard Requirements	Results 50/60Hz
f_{dev} where $f_{in} = f_0 \pm f_{dev}$	Frequency = f_0 ($f_{nominal}$)	±2.0 Hz	**1**	0.397-0.379/ 0.245-0.296	±2.0 Hz for F_S< 10 ±F_S/5 for 10 ≤ F_S < 25 ± 5.0 Hz for F_S ≥ 25	**1**	0.508-0.655/ 0.210-0.256
Voltage	100% rated	80% – 120% rated	**1**	0.061-0.063/ 0.045-0.056	10% – 120% rated	**1**	0.663-0.039/ 0.69-0.059
Current	100% rated	10% – 200% rated	**1**	0.062-0.379/ 0.055-0.076	10% – 200% rated	**1**	0.023-0.047/ 0.0051-0.010
Phase angle	Constant or slowly varying angle	±π radians	**1**	0.056/0.042	±π radians	**1**	0.030/0.021
Harmonic distortion (single harmonic)	< 0.2% (THD)	1%. each harmonic up to 50th	**1**	0.058-0.053/ 0.050-0.048	10% each harmonic up to 50th	**1**	0.079-0.076
Out of band interference	< 0.2% of input signal magnitude		**None**	**None**	10% of input signal magnitude for F_S ≥ 10. No requirement for F_S < 10.	**1.3**	1.018/1.033

Steady-State Frequency and ROCOF Test

Status: **Pass**

Table D.3: Steady-state frequency and ROCOF measurement requirements and test results

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 ± 2.0 Hz				Range: f_0 ± 2.0 Hz for F_S ≤ 10; ± F_S/5 for 10 ≤ F_S < 25; ± 5.0 Hz for F_S ≥ 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**	**0.0034/ 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 ≤ 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**

Modulation Test

Status: **Pass**

Table D.4: Synchrophasor measurement bandwidth requirements and test results using modulated test signals

Modulation level	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit					
		P class			M class		
		Range	Max. TVE		Range	Max. TVE	
			Standard requirements	Results 50/60Hz		Standard requirements	Results 50/60Hz
k_x = 0.1. k_a = 0	100% rated signal magnitude. $f_{nominal}$	Modulation frequency 0.1 to lesser of F_S/10 or 2 Hz	**3%**	**0.13/ 0.150**	Modulation frequency 0.1 to lesser of F_S/5 or 5 Hz	**3%**	**0.195/ 1.24**
k_x = 0. k_a = 0.1	100% rated signal magnitude. $f_{nominal}$		**3%**	**0.082/ 0.072**		**3%**	**0.2/ 0.4**

Table D.5: Frequency and ROCOF performance requirements and test results under modulation tests

F and ROCOF performance limits	Error requirements for compliance									
	P class					M class				
Reporting rate F_s Hz	F_r Hz	Max. |FE|		Max. |RFE|		F_r Hz	Max. |FE|		Max. |RFE|	
		Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz		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)	$0.06 \times F_r$		$0.18 \times \pi \times F_r^2$	

Frequency Ramp Test Status: **Pass**

Table D.6: Synchrophasor performance requirements and test results under frequency ramp tests							
Test signal	**Reference condition**	**influence quantity test limits over which PMU shall be within given TVE limit**					
		Ramp rate (Rf) (positive and negative ramp)	**Performance class**	**Exclusion interval**	**Ramp range**	**Max. TVE**	
						Standard req.	**Results 50/60Hz**
Linear frequency ramp	100% rated signal magnitude, and $f_{nominal}$ at a non-excluded point during the test	±1.0 Hz/s	P class	Larger of 2/Fs or 2/f0	±2 Hz	**1%**	**0.377/ 0.314**
			M class	Larger of 7/Fs or 7/f0	Lesser of ±(Fs /5) Hz or ±5 Hz	**1%**	**0.837/ 0.628**

Table D.7: Frequency and ROCOF performance requirements and test results under frequency ramp tests									
Signal specification	**Reference condition**	**Exclusion interval**	**Error requirements for compliance**						
			P class				**M class**			
			Max. |FE|		**Max. |RFE|**		**Max. |FE|**		**Max. |RFE|**	
			Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz
Ramp tests – Linear frequency ramp	100% rated signal magnitude and 0 radian base angle	Same as specified in Table 6	**0.01 Hz**	**0.001/ 0.001**	**0.4 Hz/s**	**0.392/ 0.201**	**0.01 Hz**	**0.009/ 0.008**	**0.2 Hz/s**	**0.083/ 0.053**

Input Step Change Test

Status: **Pass**

Table D.8: Phasor performance requirements and test results for input step change

Step change spec.	Ref. condition	Maximum response time. delay time. and overshoot											
		P class						M class					
		Response time (s)		|Delay time|		Max. Overshoot/ undershoot		Response time (s)		|Delay time|		Max. overshoot/ undershoot	
		Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz	Standard requirements	Results 50/60Hz
Magnitude = ±10%. k_x = ±0.1. k_a = 0	All test conditions nominal at start or end of step	**$2/f_0$**	**0.0025/ 0.01877**	**$1/(4 \times F_s)$**	**0.00212/ 0.00304**	**5% of step magnitude**	**0.65/ 0.33**	**Larger of $7/F_s$ or $7/f_0$**	**0.0282/ 0.024**	**$1/(4 \times F_s)$**	**0.002/0. 0018**	**10% of step magnitude**	**3.63/ 3.71**
Angle ±10°. k_x = 0. k_a = ±π/18	All test conditions nominal at start or end of step	**$2/f_0$**	**0.023/ 0.02051**	**$1/(4 \times F_s)$**	**0.00041/ 0.00150**	**5% of step magnitude**	**0.25/ 0.21**	**Larger of $7/F_s$ or $7/f_0$**	**0.0332/ 0.038**	**$1/(4 \times F_s)$**	**0.0004/ 0.0013**	**10% of step magnitude**	**3.55/ 5.81**

Table D.9: Frequency and ROCOF performance requirements and test results for input step change

Signal specification	Reference condition	Maximum susceptibility response time							
		P class				M class			
		Frequency response time		ROCOF response time		Frequency response time		ROCOF response time	
		Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz	Standard req.	Results 50/60Hz
Magnitude test as in Table 8	Same as in Table 8	**$4.5/f_0$**	**0.0839/ 0.063**	**$6/f_0$**	**0.016/ 0.075**	**Greater of $14/F_S$ or $14/f_0$**	**0.086/ 0.079**	**Greater of $14/F_S$ or $14/f_0$**	**0.093/ 0.085**
Phase test as in Table 8	Same as in Table 8	**$4.5/f_0$**	**0.086/ 0.058**	**$6/f_0$**	**0.017/ 0.049**	**Greater of $14/F_S$ or $14/f_0$**	**0.048793/ 0.121**	**Greater of $14/F_S$ or $14/f_0$**	**0.047/ 0.033**

Latency Test (Internal Evaluation) Status: **Pass**

Table D.10: PMU reporting latency and test requirements		
Performance class	**Maximum PMU reporting latency(s)**	
	Standard requirements	Results 50/60Hz
P class	**Greater of $2/F_s$ or $2/f_0$**	**< 2 cycles** 40 ms (for 50 Hz, 50fps) 33.3 ms (for 60 Hz, 60 fps)
M class	**Greater of $7/F_s$ or $7/f_0$**	**<6.5 cycles** 130 ms (for 50 Hz, 50fps) 108.3 ms (for 60 Hz, 60 fps)
Note: Latency is limited by the need to include at least one cycle of the power system waveform for synchrophasor calculation.		

References

[1] IEEE Standard for Synchrophasors for Power Systems, IEEE Standard C37.118.1-2011, Dec. 2011.

[2] IEEE Standard for Synchrophasors for Power Systems (Amendment 1: Modification of Selected Performance Requirements), IEEE Standard C37.118.1a-2014, Apr. 2014.

[3] D.Gurusinghe, D. Ouellette and R. Kuffel, “An Automated Test Setup for Performance Evaluation of a Phasor Measurement Unit”, PAC World Conference 2016, Ljubljana, Slovenia.

[4] IEEE Synchrophasor Measurement Test Suite Specification, IEEE Standard Association, Dec. 2014.