An Automated Test Setup for Performance Evaluation of a Phasor Measurement Unit

Dinesh Rangana Gurusinghe*, Dean Ouellette, and Rick Kuffel
RTDS Technologies Inc., Winnipeg, Canada
(*Corresponding author: dinesh@rtds.com)

ABSTRACT

Steady-state and dynamic performances of phasor measurement units (PMUs) are critically important to ensure reliable and secure operation of the synchrophasor based wide area monitoring, protection, and control (WAMPaC) systems. Therefore, it is essential to assess PMU performances in the different stages of PMU life cycle; from research and development (R&D) to their operation in power system with diverse WAMPaC applications. The current IEEE synchrophasor standard C37.118.1-2011 [1] with its amendment C37.118.1a-2014 [2] and the IEEE synchrophasor measurement test suite specification (TSS) [3] provide necessary guidelines and test procedures to comprehensively evaluate both steady-state and dynamic performances of PMUs. However, testing of a PMU to meet all steady-state and dynamic performances is a challenging task as PMU test procedures involve hundreds of measurements and calculations.

This paper presents an automated PMU test setup implemented in the real time digital simulator (RTDS^{TM}). The interface software to the RTDS simulator, RSCAD comprises with a tool named PMU Utility, which executes a series of tests, collects measurements, calculates errors, and checks conformity (pass/fail assessment) as per the synchrophasor standard [1], [2] and the TSS [3] guidelines with minimal user interaction. The proposed test setup was applied to a bench-mark PMU model as well as an actual PMU to access their performances in the automated environment and interesting test results are presented.

Keywords – Phasor measurement unit (PMU), PMU testing, synchrophasor standard, total vector error, real time digital simulation

1. INTRODUCTION

The current IEEE synchrophasor standard C37.118.1-2011 [1] with its amendment C37.118.1a-2014 [2] provides necessary guidelines and error limits to evaluate both steady-state and dynamic performances of a phasor measurement unit (PMU). The standard neither specifies detailed test procedures nor specific calculations; that yield ambiguities in PMU testing as different test procedures and calculations may produce different test results for the same PMU. Therefore, the IEEE standards association conformity assessment program published IEEE synchrophasor measurement test suite specification (hereinafter referred to as the TSS) [3] in late 2014 to address that issue. Since test procedures stated in the TSS involve hundreds of measurements and calculations testing of a PMU to meet all steady-state and dynamic performances is a challenging task.

Over the years, many efforts have been made to evaluate performances of PMUs. The most common and simple approach is known voltage and current waveforms are played back into the PMU under test using a playback equipment with precise global positioning system (GPS) synchronization and the PMU response is compared against the theoretical input phasors [4], [5]. The major drawback of this approach is that considerable time and effort have been expended to test a PMU as the entire evaluation process requires frequent user interaction. In [6], authors proposed an automated test-bench where different waveforms are produced with the aid of a signal generator and an interface unit, which is controlled using a graphical programing tool. However, the availability of test-bench is limited to their internal PMU testing.

PMU performance testing can be divided into five stages:

1. *Preliminary type test* : This test is essential to verify that a particular PMU model or a specific PMU algorithm (typically a proprietary algorithm) satisfies the performance requirements of the PMU standard during the R&D phase. The test is conducted by the PMU manufacturer and used to fine-tune parameters of the PMU model with the proprietary algorithm.
2. *Type test* : This test proves that a particular PMU model complies with the PMU standard. The test is typically done at a certified testing laboratory.
3. *Routine test* : This test verifies that PMUs are accurate during the manufacturing stage. This test helps to identify possible errors of individual PMUs. Since the comprehensive testing of individual PMUs is time consuming PMUs are randomly tested under critical conditions decided by manufacturers depends upon their past manufacturing experiences. The test is typically conducted by the PMU manufacturer.
4. *Commissioning test* : This test confirms the performances of PMUs in power system with diverse WAMPaC applications. This test helps to calibrate PMUs and testing is conducted by the commissioning staff.
5. *Maintenance tests* : Periodic maintenance is required to identify failures and degradation of PMUs in-service. This test is done by the power utilities as a part of their scheduled maintenance routine.

This paper presents an automated PMU test setup, which can be used at any of the above described testing stages. Therefore, it may be beneficial to PMUs manufacturers, certified testing laboratories, commissioning staff, and power utility engineers. The proposed test set up is implemented in the real time digital simulator (RTDS^{TM}). The interface software to the RTDS simulator, RSCAD comprises with a tool named PMU Utility, which is designed to execute the test procedures prescribed in the TSS [3]. The PMU Utility has ability to adjust sliders that are embedded to a waveform control block, communicate with the PMU under test and collect measurements, and calculate total vector error (TVE), frequency error (FE), and rate of FE (RFE) in each test case. A script is written to allow the user to automate interaction of the PMU Utility during batch mode in RSCAD and create a summary report with pass/fail assessment for the given performance class and the reporting rate.

The remainder of this paper is organized as follows. In Section 2, the proposed test setup in the RTDS simulator is described. Section 3 is devoted to results; it accesses performances and advantages of the automated PMU test setup with a bench-mark PMU model and an actual PMU. Finally, in Section 4, the key contributions of the paper are highlighted.

2. PROPOSED TEST SETUP

The proposed test setup is implemented in the RTDS simulator equipped with a GTSYNC card, which ensures that the simulator time-step clock remains locked to the GPS signal. Precise three phase voltage and current signals were generated by a waveform control block, which is specially designed to produce various steady-state and dynamic waveforms as per the synchrophasor standard [1], [2] and the TSS [3]. The types of interfaces available to send the test waveforms (voltages and currents) from the RTDS simulator are conventional analog signals or IEC 61850-9-2 LE Sampled Values (SV) [7], [8].

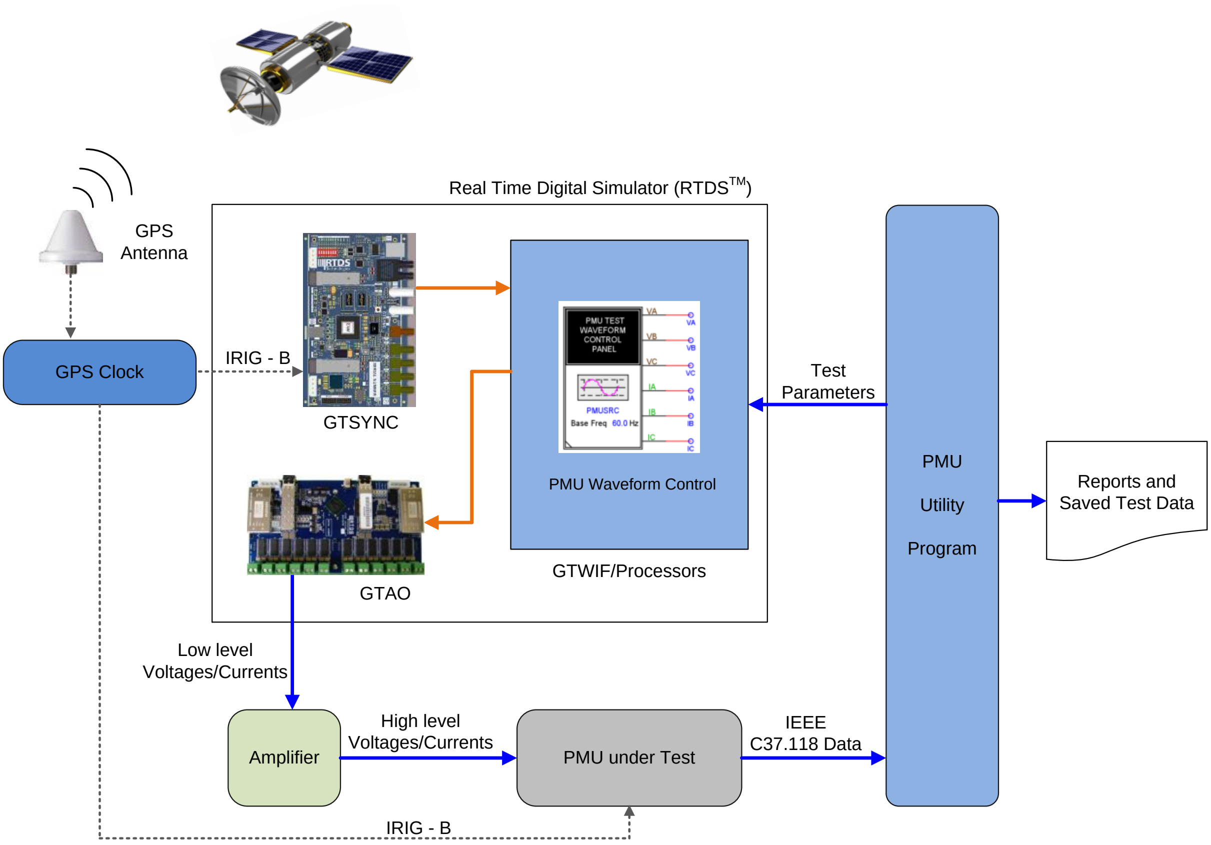


Fig. 1 : Test Setup – Conventional Analog Signals

The conventional approach is shown in Fig. 3, where test waveforms are send through an analog output card (GTAO) and a power amplifier. The voltages and currents from the simulation are in a digital format and must be taken out of the simulator with a digital to analog converter to generate the analog waveforms required by the PMU under test. The GTAO card will produce a +/- 10 V peak maximum signal, therefore, the output hardware must be properly scaled. The output waveforms of the GTAO card are connected to an external amplifier. The amplifier provides precise in-service voltages and currents to the PMU under test. The RTDS simulator can be used with numerous amplifiers manufactured by several vendors. Each amplifier will have a gain for each channel and this gain must be known to properly scale the output waveform from the RTDS simulator.

The second interfacing approach is IEC 61850-9-2 LE, where voltage and current waveforms from the simulation are in a digital format and passed from a GTNETx2 card in the SV protocol defined in the IEC 61850 standard [7], [8]. This approach is only possible if the PMU under test complies with the IEC 61850-9-2 LE.

Fig. 2 illustrates IEC 61850 SV interfacing method with the GTNET-SV component, which provides IEC 61850-9-2 SV communications using the GTNETx2 card. The GTNET-SV component when combined with the GTSYNC card can transmit SV messages up to two streams of 4 current and 4 voltage channels at a rate of 80 samples/cycle or one stream of 4 current and 4 voltage channels at a rate of 256 samples/cycle. The GTNETx2 allows sample timestamping to be synchronized to an internal or external electrical one pulse-per-second (1 PPS), IEEE 1588 [9] or inter-range instrumentation group time code format B (IRIG-B) signal [10] using the GTSYNC card.

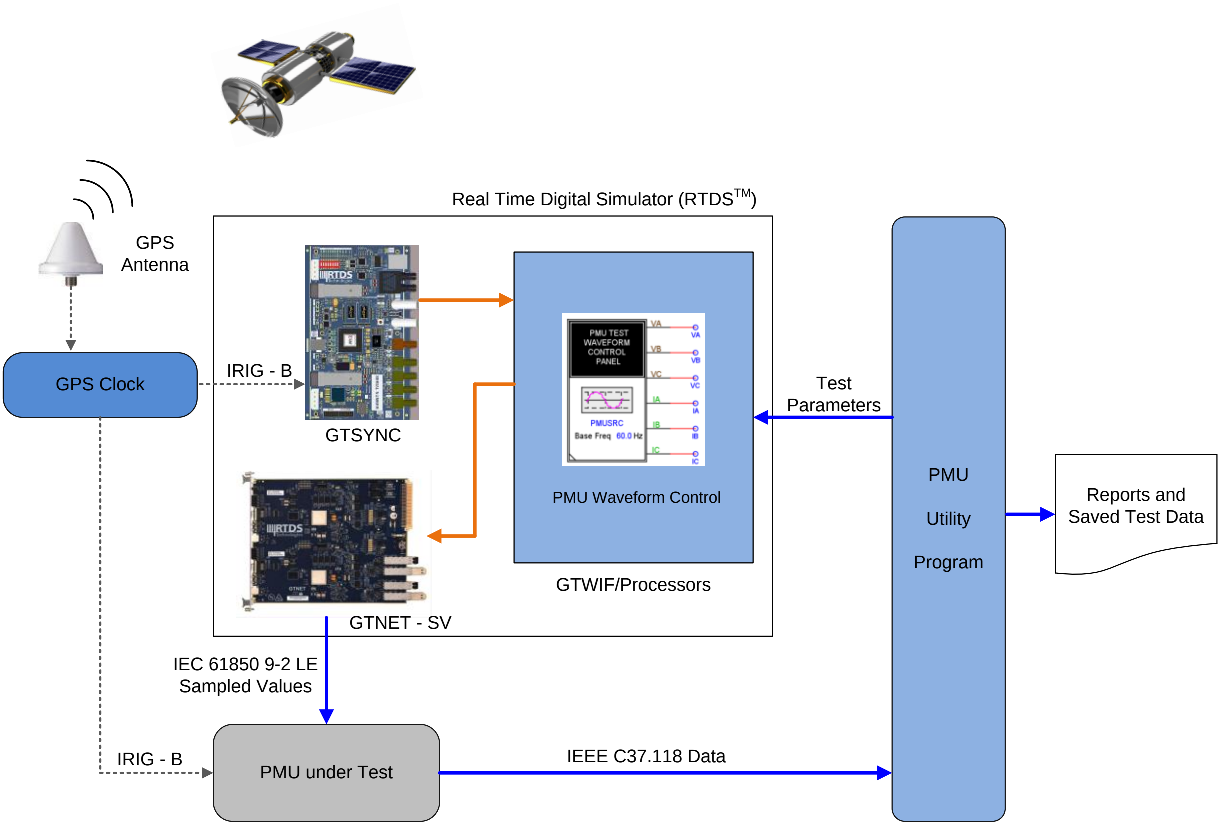
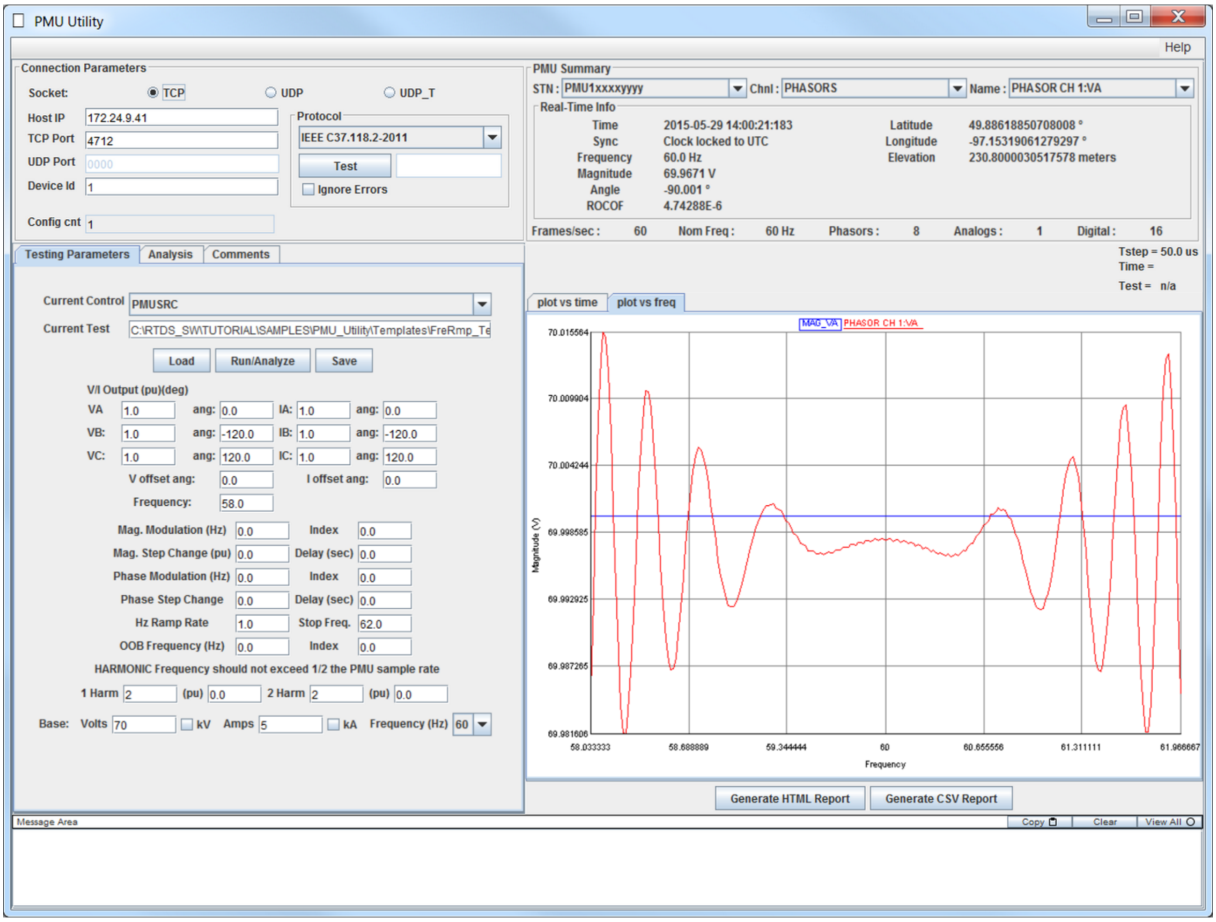


Fig. 2 : Test Setup – IEC 61850-9-2 LE Sampled Values

The PMU Utility program is available in RSCAD and it is used to set various sliders that are embedded to a waveform control block. The test signals are generated and then sent to a GTAO card or a GTNETx2 card depends upon the interfacing option. The slider values are also used by the PMU Utility to calculate the theoretical phasor values for each test. The PMU utility can communicate with the PMU under test and collect measurements made by the PMU under test. The collected measurements are then compared to the theoretical values to determine TVE, FE, and RFE in each test case.

A screen capture of the PMU Utility is shown in Fig. 3. The screen area can be divided into four sections; connection parameters, PMU summary, testing and analysis, and results/reports. The connection parameters section is used to specify the type of communication that will be used to connect the PMU under test. The PMU utility supports TCP, UDP and UDP_T (TCP handshaking is used for the commands and UDP is used for the data stream) communication protocols. The PMU summary displays the data from the PMU when the connection parameters are being tested. The testing and analysis section allows to view/edit/create/save the test parameters into a test file or load testing parameters from a saved file.

The analysis tab shown in Fig. 4 is used to select analysis options such as test duration, pre/post test durations, number of pre/post settle frames and result plot options; for example, TVE, FE and RFE. This section can also be used to specify error limits defined in the IEEE synchrophasor standard [1], [2].

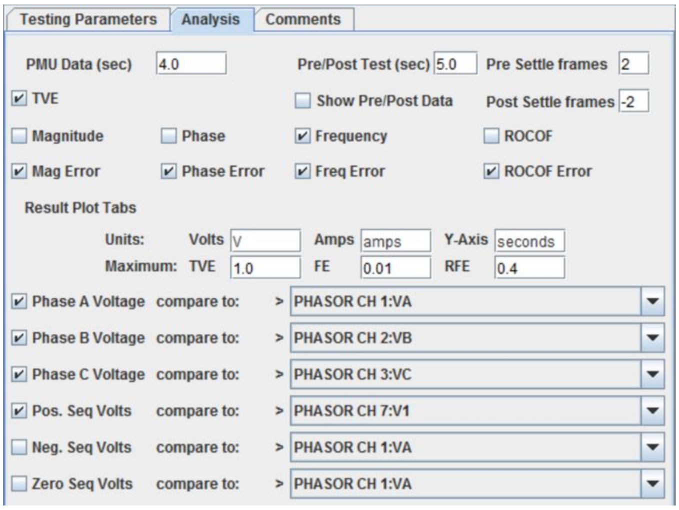


Connection Parameters
Socket: ● TCP ○ UDP ○ UDP_T
Host IP 172.24.9.41
TCP Port 4712
UDP Port 0000
Device Id 1
Config cnt 1
Protocol IEEE C37.118.2-2011
☐ Ignore Errors

PMU Summary
STN : PMU1xxxxyyyy Chnl : PHASORS Name : PHASOR CH 1:VA
Real-Time Info
Time 2015-05-29 14:00:21:183
Sync Clock locked to UTC
Frequency 60.0 Hz
Magnitude 69.9671 V
Angle -90.001 °
ROCOF 4.74288E-6
Latitude 49.88618850708008 °
Longitude -97.15319061279297 °
Elevation 230.8000030517578 meters
Frames/sec : 60 Nom Freq : 60 Hz Phasors : 8 Analogs : 1 Digital : 16
Tstep = 50.0 us
Time =
Test = n/a

Current Control PMUSRC
Current Test C:\RTDS_SW\TUTORIAL\SAMPLES\PMU_Utility\Templates\FreRmp_Te
V/I Output (pu)(deg)
VA 1.0 ang: 0.0 IA: 1.0 ang: 0.0
VB: 1.0 ang: -120.0 IB: 1.0 ang: -120.0
VC: 1.0 ang: 120.0 IC: 1.0 ang: 120.0
V offset ang: 0.0 I offset ang: 0.0
Frequency: 58.0
Mag. Modulation (Hz) 0.0 Index 0.0
Mag. Step Change (pu) 0.0 Delay (sec) 0.0
Phase Modulation (Hz) 0.0 Index 0.0
Phase Step Change 0.0 Delay (sec) 0.0
Hz Ramp Rate 1.0 Stop Freq. 62.0
OOB Frequency (Hz) 0.0 Index 0.0
HARMONIC Frequency should not exceed 1/2 the PMU sample rate
1 Harm 2 (pu) 0.0 2 Harm 2 (pu) 0.0
Base: Volts 70 ☐ kV Amps 5 ☐ kA Frequency (Hz) 60

Fig. 3 : A Screen Capture of the PMU Utility



PMU Data (sec) 4.0
Pre/Post Test (sec) 5.0
Pre Settle frames 2
☑ TVE
☐ Show Pre/Post Data
Post Settle frames -2
☐ Magnitude ☐ Phase ☑ Frequency ☐ ROCOF
☑ Mag Error ☑ Phase Error ☑ Freq Error ☑ ROCOF Error
Result Plot Tabs
Units: Volts V Amps amps Y-Axis seconds
Maximum: TVE 1.0 FE 0.01 RFE 0.4
☑ Phase A Voltage compare to: > PHASOR CH 1:VA
☑ Phase B Voltage compare to: > PHASOR CH 2:VB
☑ Phase C Voltage compare to: > PHASOR CH 3:VC
☑ Pos. Seq Volts compare to: > PHASOR CH 7:V1
☐ Neg. Seq Volts compare to: > PHASOR CH 1:VA
☐ Zero Seq Volts compare to: > PHASOR CH 1:VA

Fig. 4 : The PMU Utility - Analysis Tab

The results/report section of the PMU Utility is used to view test results and generate reports in html or csv format. The html report is a graphical report of all plots and all of the test parameters and details while the csv report contains two files; one with the test parameters and the other with the theoretical test values, test data from the PMU under test, and calculated error values.

Since PMU performance evaluation involves hundreds of measurements and calculations the PMU Utility is interacted with a RSCAD Runtime's script, which can automate the PMU testing process. The script mainly follows the below steps.

1. Check the PMU connection and keep PMU configuration for subsequent analysis.
2. Load a template setting file, which comprises with appropriate parameters to the PMU waveform control block for a particular test (for example, frequency ramp test). The template setting files are created in advance with appropriate parameters.
3. Adjust Runtime sliders according to the required test conditions, which then override the template settings. The modified setting file is saved as a new setting file.
4. Perform the PMU testing.
5. Save test results for each sub-test as a html or/and a csv report.
6. Create a summary report with pass/fail assessment for a given configuration (performance class, nominal system frequency, and reporting rate).

The PMU Utility and the automated script are capable to test following electrical performances of the PMU under test, prescribed in the IEEE synchrophasor standard [1], [2].

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

3. RESULTS AND DISCUSSION

This section accesses the performances of the proposed PMU test set up in the automated environment. The preliminary type tests were conducted for a bench-mark PMU model and an actual PMU. The GTNET-PMU model [11] was selected as the bench-mark PMU model. The actual PMU was tested with the co-operation the PMU manufacturer, who used the PMU Utility to adjust parameters of their PMU device. In this paper, performances of the P-class [1] are illustrated at the reporting rate of 60 frames/s (fps) and voltage signal measurements are shown. The performances of the actual PMU before and after adjusting device parameters are also compared to demonstrate the effectiveness of the PMU Utility.

Even though the illustrated results are limited to the P-class at the reporting rate of 60 fps, similar approach can be applied for all other reporting rates as well as to evaluate performances of the M-class [1].

3.1.1. Signal frequency range test

Under the signal frequency range test, the frequency of the waveforms was varied from 58.0 Hz to 62.0 Hz with a step resolution of 0.1 Hz while all other quantities were kept constant. Fig. 5 shows the maximum TVE, FE, and RFE variations with signal frequency range.

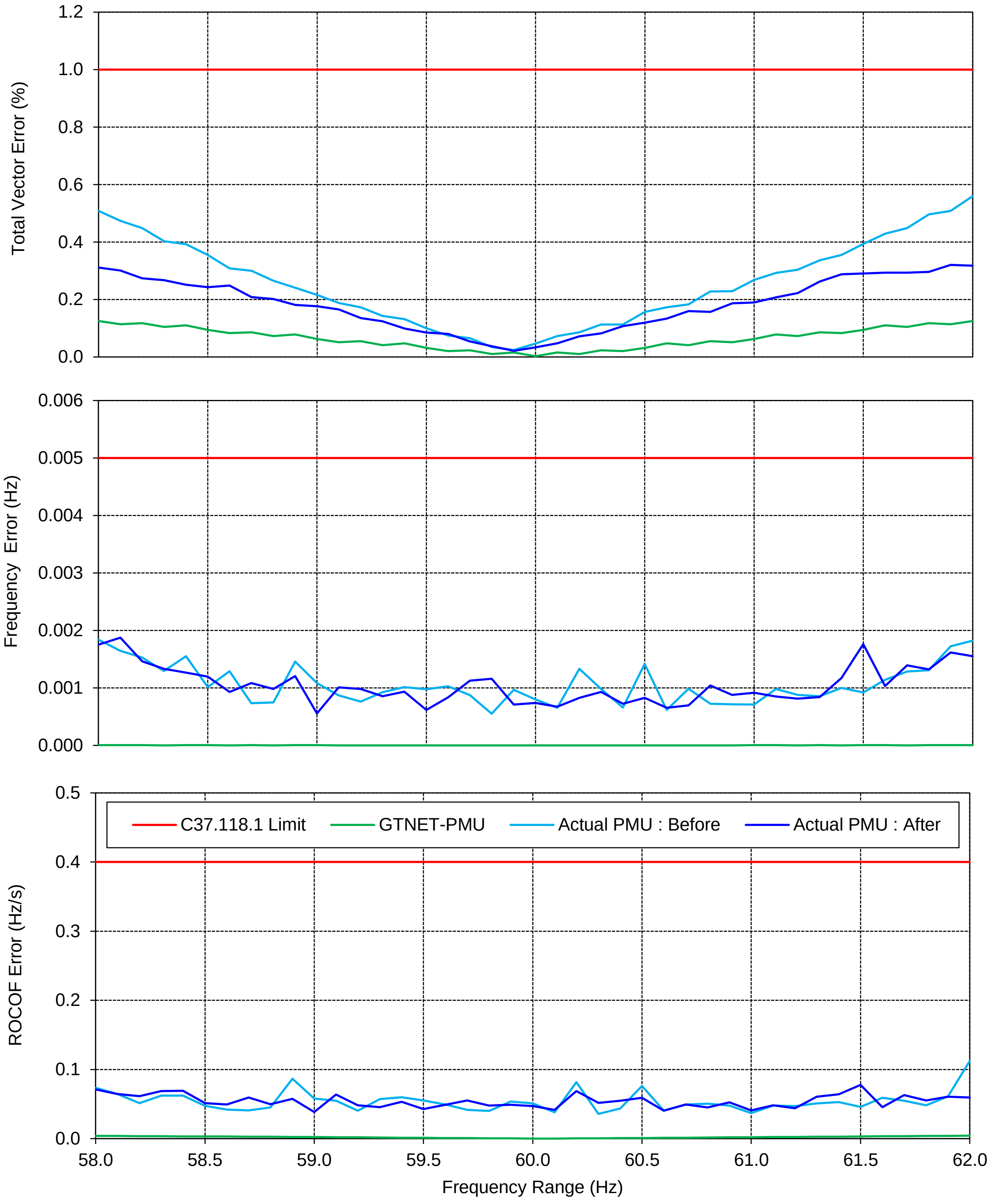


Fig. 5 : TVE, FE, and RFE variations in signal frequency range test

The GTNET-PMU showed adequate performances as errors throughout the frequency range were minimal. The actual PMU satisfied the requirements of the synchrophasor standard [1], [2] even without adjusting parameters; however, performances were improved after fine-tuning.

Voltage magnitude, phase angle, and TVE variations with time when the signal frequency of 62.0 Hz is shown in Fig. 6.

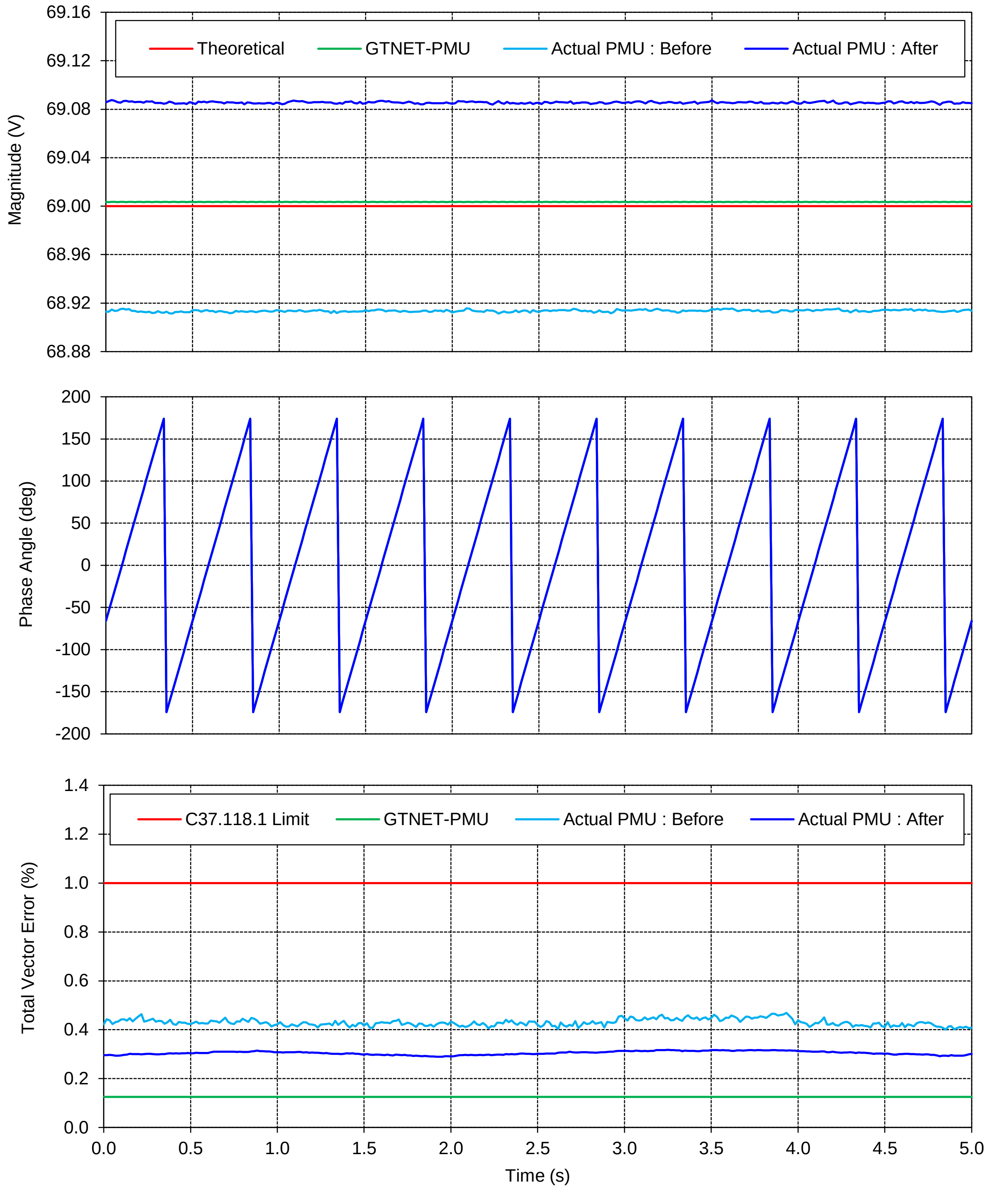


Fig. 6 : Magnitude, phase angle, and TVE varitions with time (Signal frequency = 62.0 Hz)

It was observed that measured magnitudes and phase angles closely followed the theoretical values in all cases and therefore, TVE was within the limit specified in the synchrophasor standard [1], [2].

3.1.2. Measurement bandwidth : Magnitude modulation test

In the magnitude modulation test, the modulation frequency was varied from 0.1 Hz to 2.0 Hz with a step resolution of 0.2 Hz while all other quantities were kept constant. Fig. 7 shows the maximum TVE, FE, and RFE variations with modulation frequency.

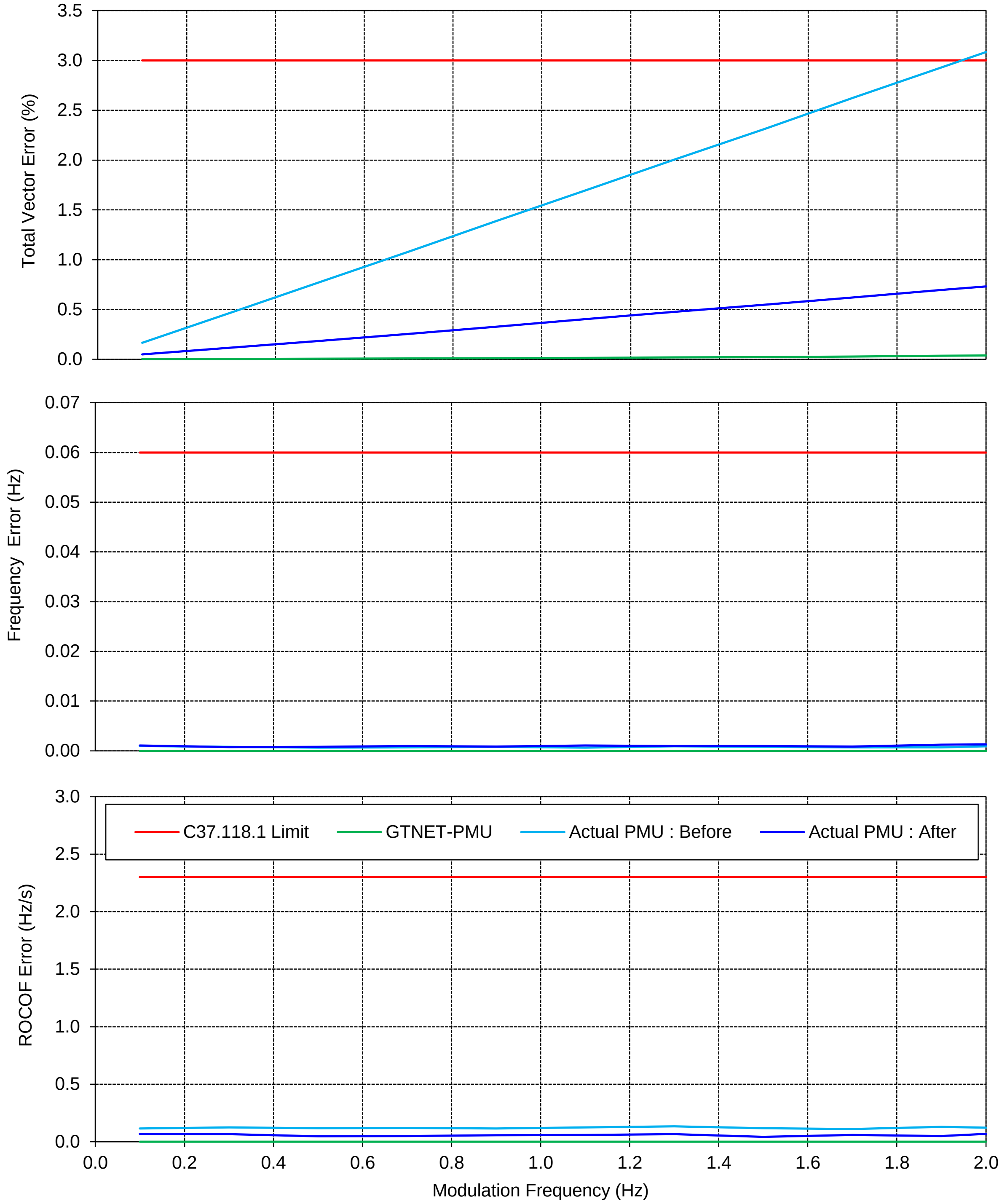


Fig. 7 : TVE, FE, and RFE variations in magnitude modulation test

The performance of the GTNET-PMU was excellent under this test as errors were minimal in all modulation frequencies. The actual PMU satisfied FE and RFE requirements of the synchrophasor standard [1], [2], however, violated the TVE limit at higher the modulation frequencies. Voltage magnitude, phase angle, and TVE variations with time when the magnitude modulation frequency of 2.0 Hz is shown in Fig. 8 and it indicates a measurement offset between the measured magnitudes of the actual PMU (before adjusting its device parameters) and the theoretical magnitudes. Thus, the PMU Utility helped the PMU manufacturer to identify the root cause (i.e. measurement offset) and therefore, it can be easily rectified by adjusting the device parameters. Fig. 7 also shows the performances of the actual PMU after adjusting the device parameters.

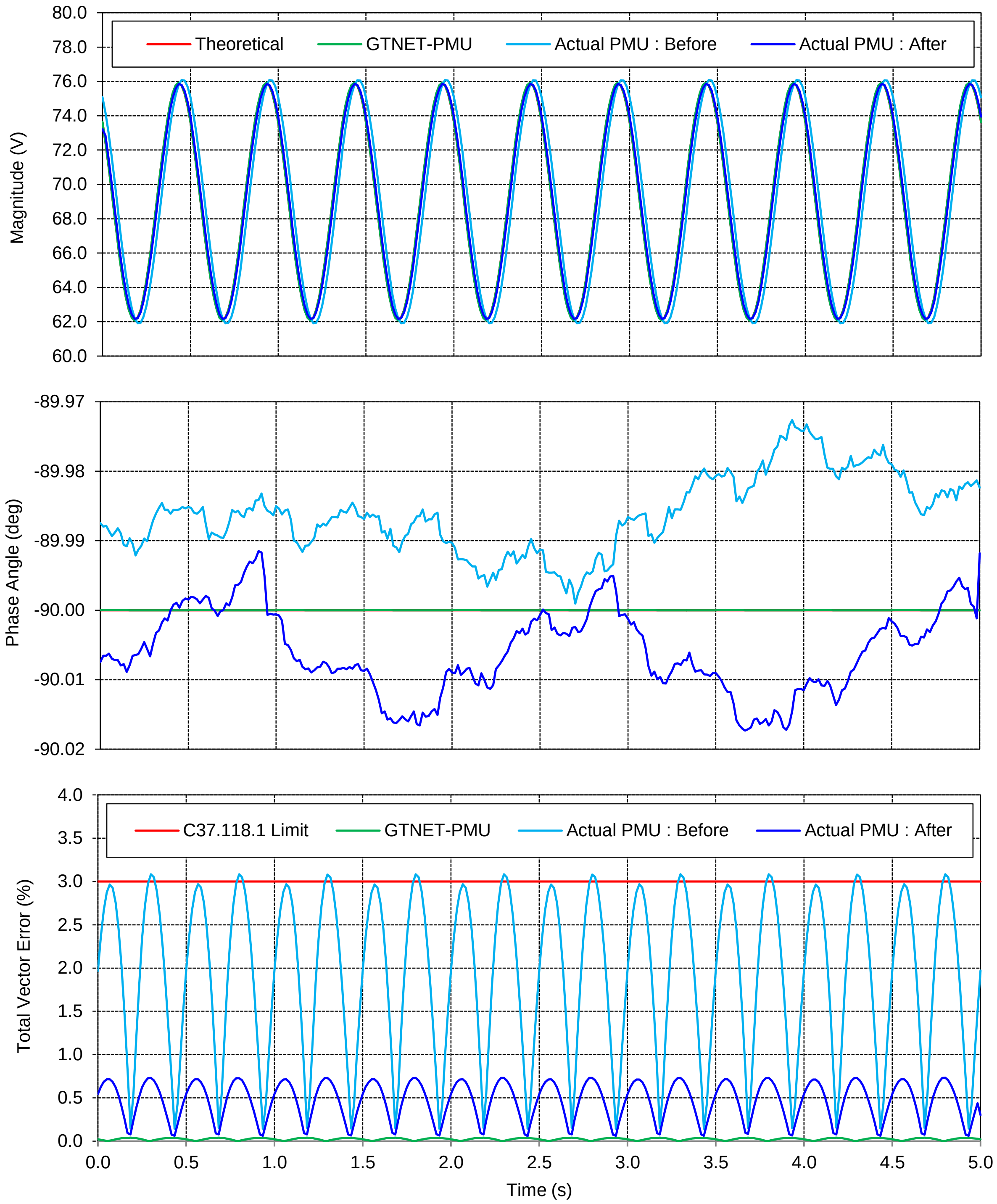


Fig. 8 : Magnitude, phase angle, and TVE variations with time (modulation frequency = 2.0 Hz)

3.1.3. Measurement bandwidth : Phase angle modulation test

Under the phase angle modulation test, the modulation frequency was varied from 0.1 Hz to 2.0 Hz with a step resolution of 0.2 Hz while all other quantities were kept constant. Fig. 9 shows the maximum TVE, FE, and RFE variations with modulation frequency.

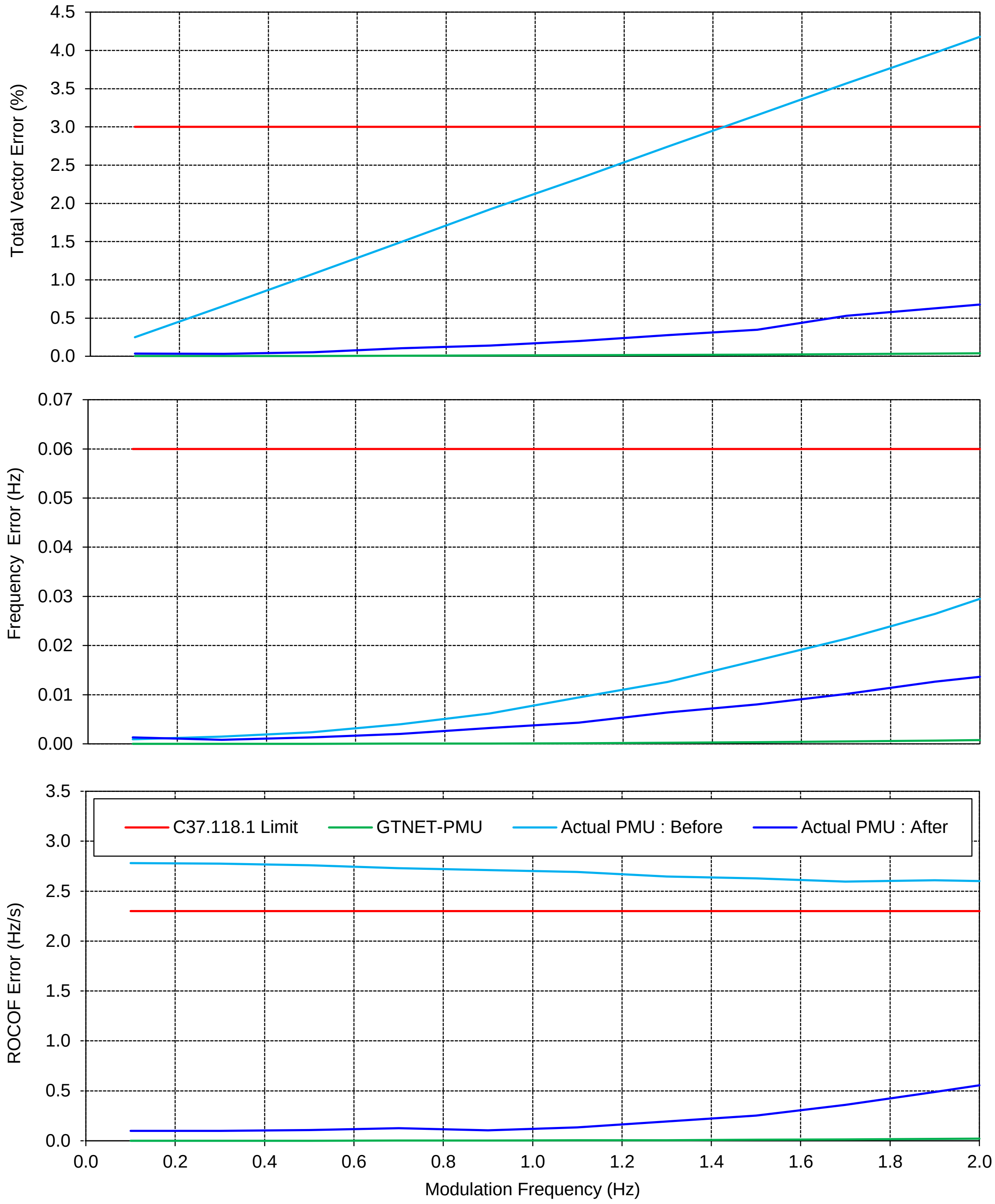


Fig. 9 TVE, FE, and RFE variations in phase angle modulation test

Results of the phase angle modulation test were very similar to the magnitude modulation test. The GTNET-PMU satisfied all error limits (TVE, FE, and RFE) specified in the synchrophasor standard [1], [2] whereas the actual PMU violated the TVE limit at higher the modulation frequencies. Voltage magnitude, phase angle, and TVE variations with time when the magnitude modulation frequency of 2.0 Hz is shown in Fig. 10 and it indicates a measurement offset between the measured phase angles of the actual PMU (before adjusting its device parameters) and the theoretical phase angles. Again the PMU Utility helped the PMU manufacturer to identify the issue and the PMU satisfied the requirements of the standard after adjusting device parameters as shown in Fig. 9.

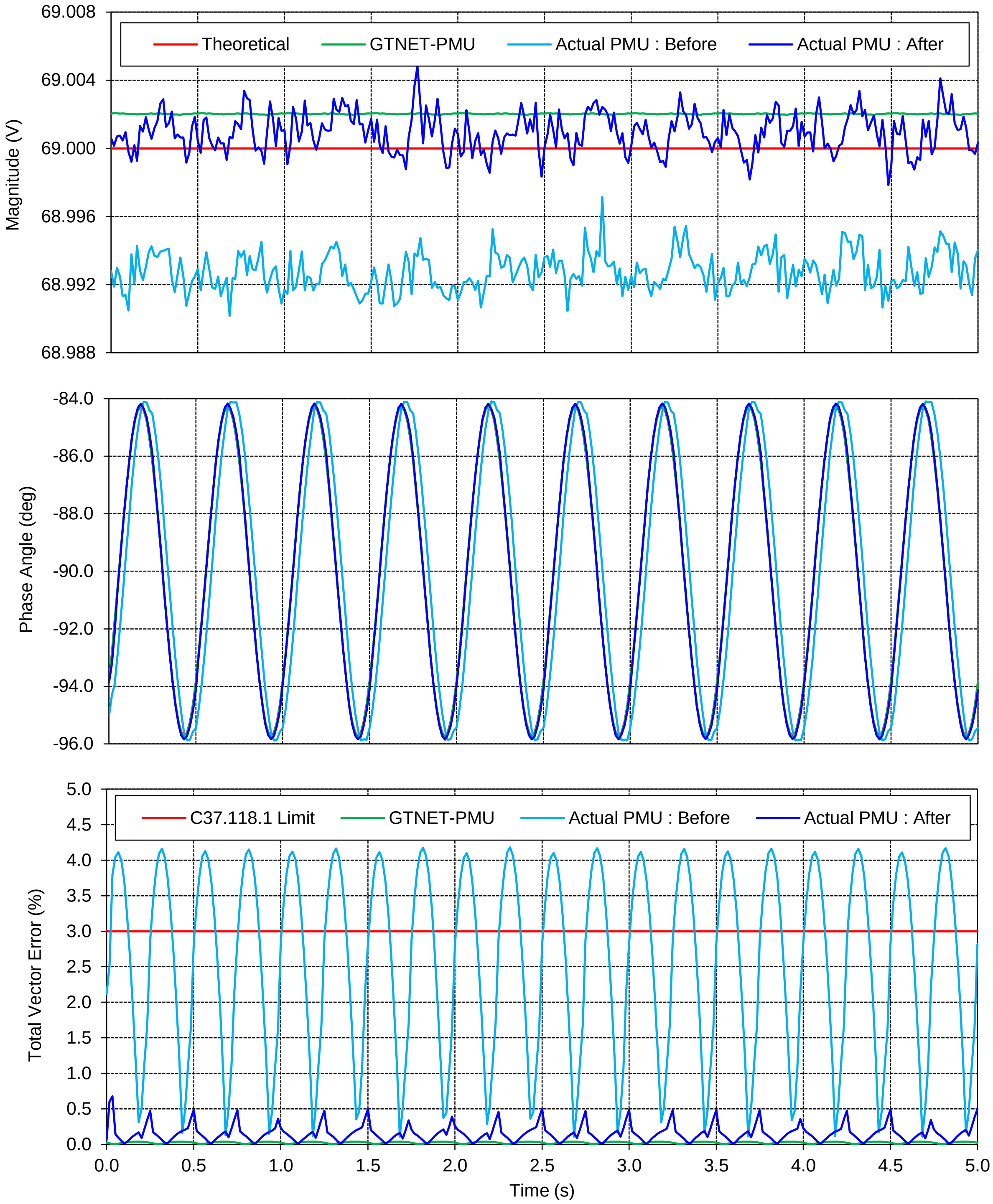


Fig. 10. Magnitude, phase angle, and TVE variations with time (modulation frequency = 2.0 Hz)

3.1.4. Frequency ramp test

In the frequency ramp test, the frequency of the waveforms was linearly varied from 58.0 Hz to 62.0 Hz with the ramp rate of +1.0 Hz/s while all other quantities were kept constant. Fig. 11 shows the maximum TVE, FE, and RFE variations with frequency ramp.

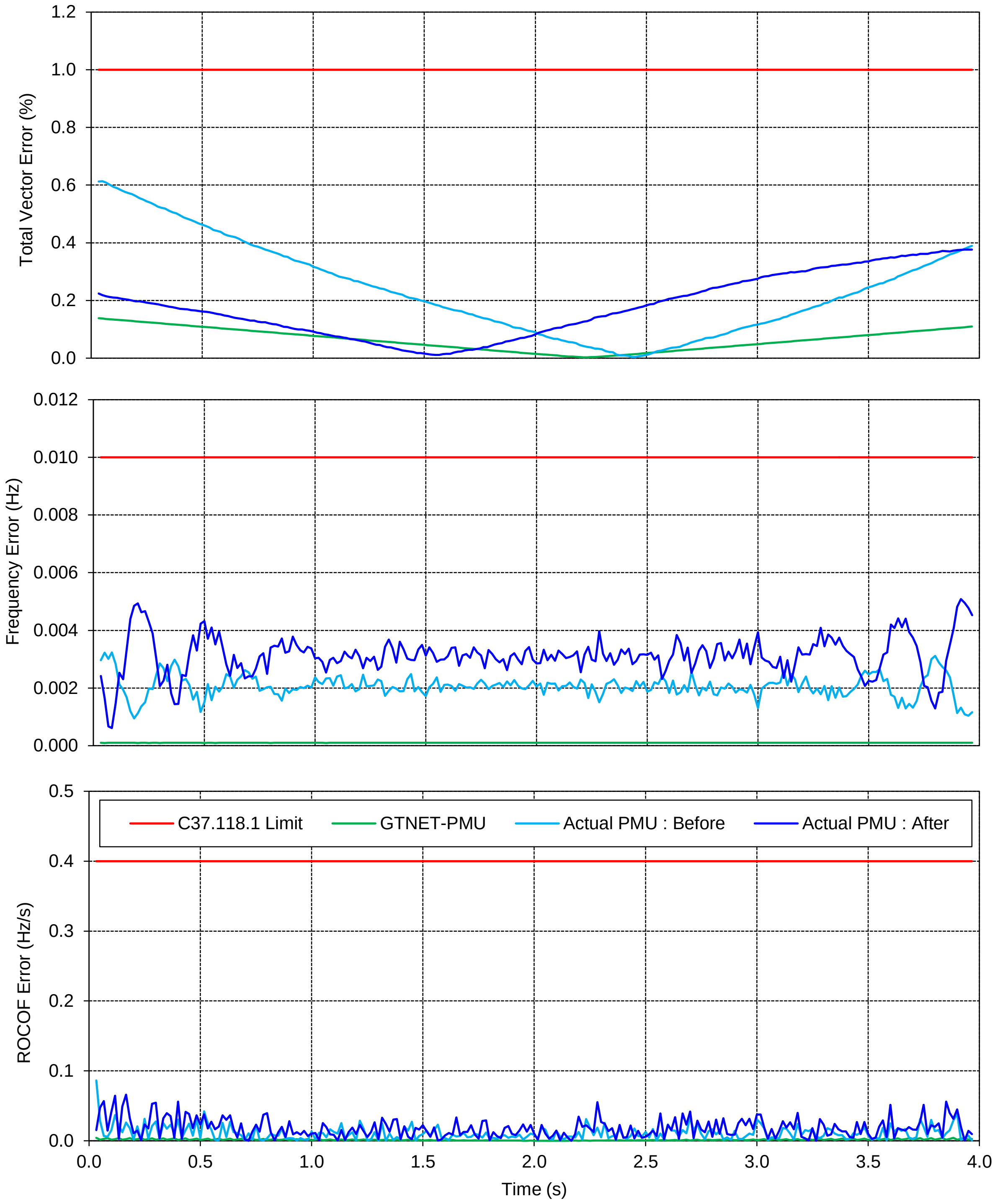


Fig. 11. TVE, FE, and RFE variations in frequency ramp test (ramp rate = +1 Hz/s)

The GTNET-PMU showed adequate performances as errors under the frequency ramp were minimal. The actual PMU satisfied the requirements of the synchrophasor standard [1], [2] even before adjusting parameters; however, performances were improved after fine-tuning.

Voltage magnitude, phase angle, and TVE variations with time is shown in Fig. 12. It was observed that measured magnitudes, phase angles, frequency, and ROCOF closely followed the theoretical values and therefore, TVE, FE, and RFE were within the limit specified in the synchrophasor standard [1], [2].

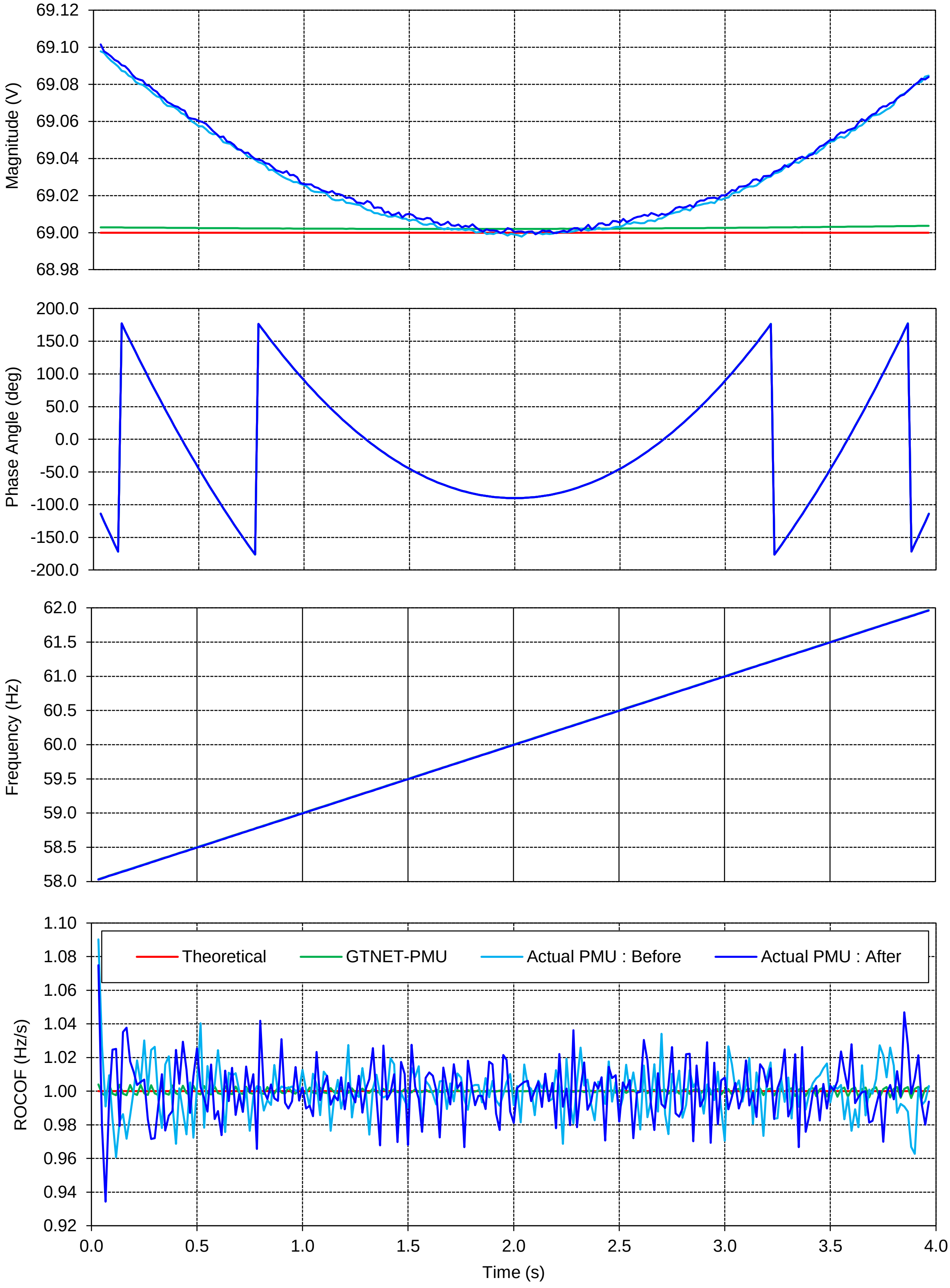


Fig. 12. Magnitude, phase angle, frequency, and ROCOF variations with time (ramp rate = +1 Hz/s)

3.1.5. Step response test : Magnitude

The step is initiated by a signal at a precise time, which allows determining response time, delay time, and maximum overshoot/undershoot. As PMU response time and delay time are small compared to the PMU reporting interval it is difficult to characterize the response of a single step. Therefore, the equivalent sampling approach explained in [1], [12] should be used to achieve the required resolution. In this approach, at least 10 successive step tests [1], [3] are made, where in each event time of the step is shifted within a fraction of the reporting interval. The measurements are interleaved in accordance with their timestamps relative to one timestamp.

Fig. 13 shows 10 successive step response curves (delay times are given in milliseconds) and the interleaved curve derived for the magnitude step according to the equivalent sampling approach.

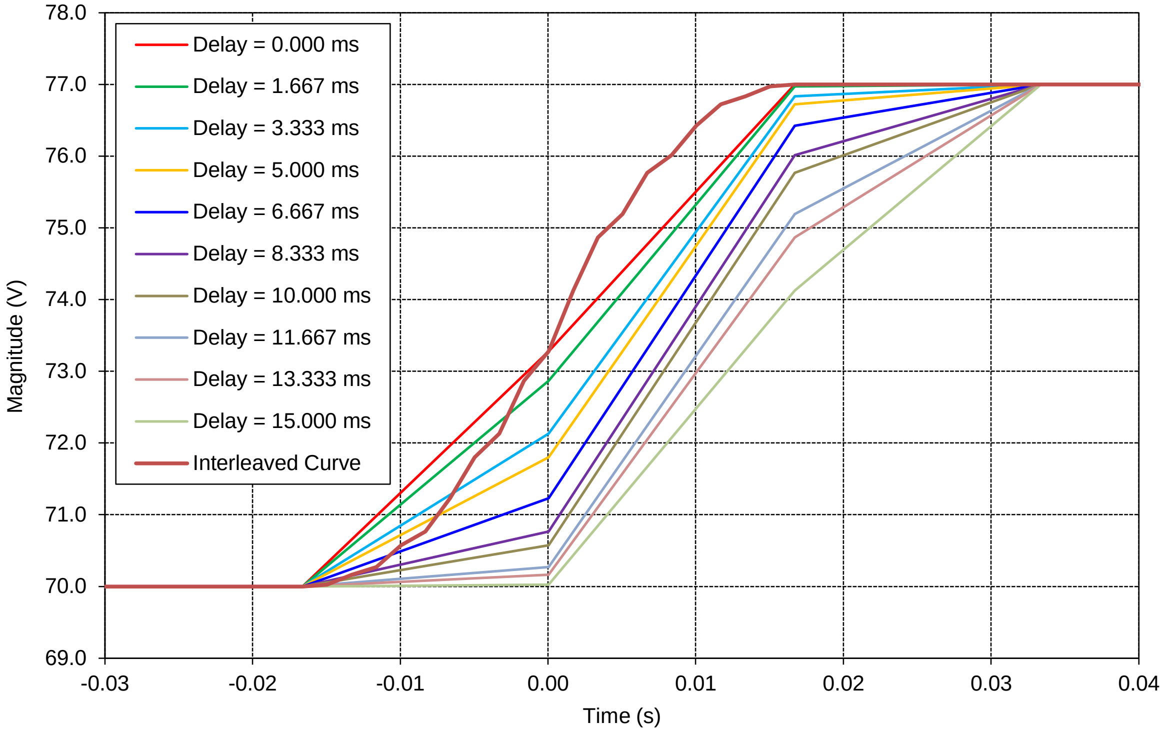


Fig. 13 Magnitude step response with successive step response curves and the interleaved curve

The PMU Utility with the automated script generate successive step curves and derived the interleaved curve, which is then used to determine response time, delay time, and maximum overshoot/undershoot values of the PMU.

Similar approach is applicable for the phase angle step response test as well as negative step response tests in magnitude and phase angle.

Fig. 14 represents magnitude positive step waveforms of theoretical and measured magnitude responses (interleaved curve), TVE response, FE response, and RFE response in the same timeline.

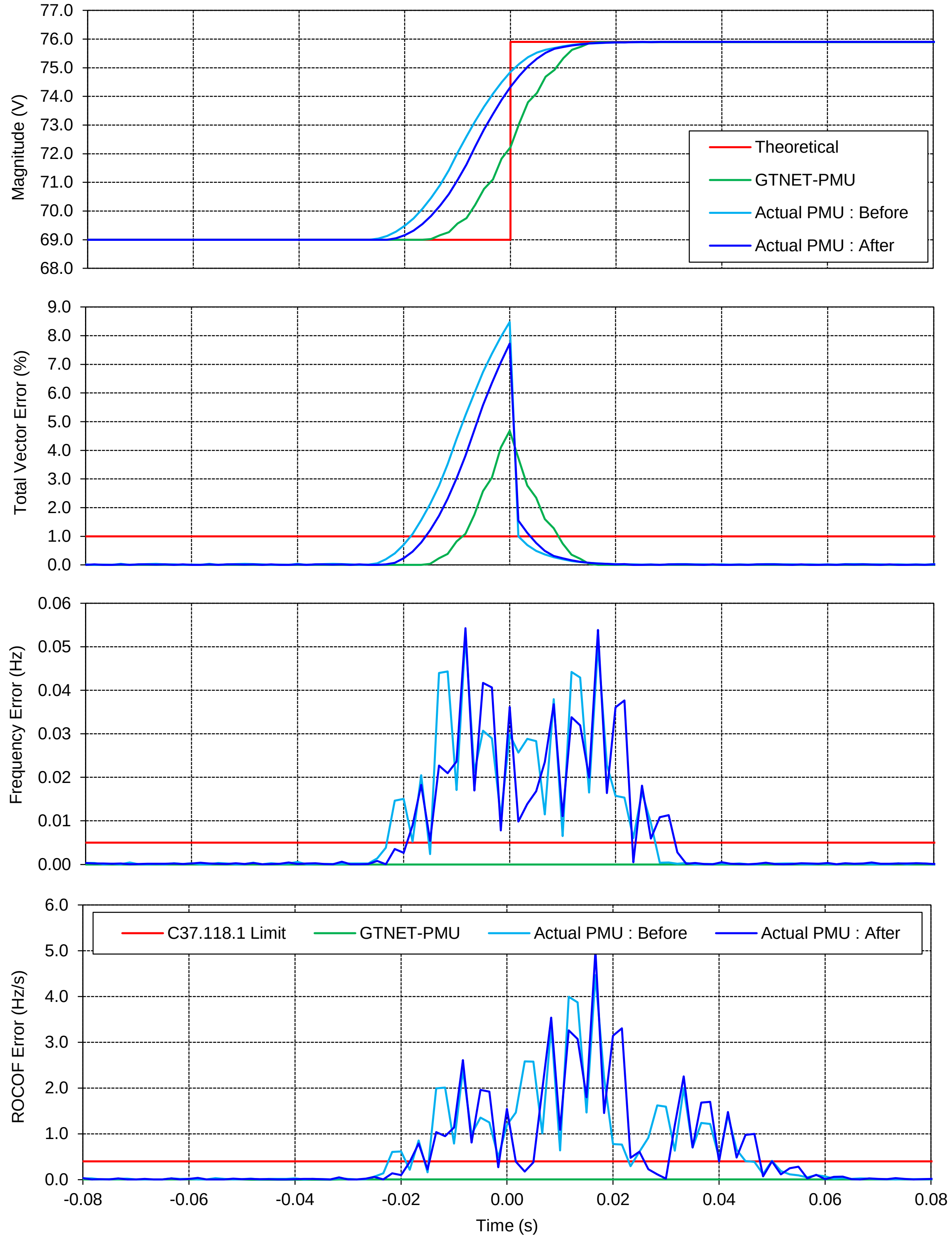


Fig. 14 Magnitude, TVE, FE, and RFE in magnitude step response test

The GTNET-PMU satisfied all the requirements of the standard; however, the delay time of the actual PMU was slightly higher than the specified value of the synchrophasor standard [1], [2]. The actual PMU showed better performances after adjusting its device parameters.

3.1.6. Step response test : Phase angle

Fig. 15 illustrates phase angle positive step waveforms of theoretical and measured phase angle responses (interleaved curve), TVE response, FE response, and RFE response in the same timeline.

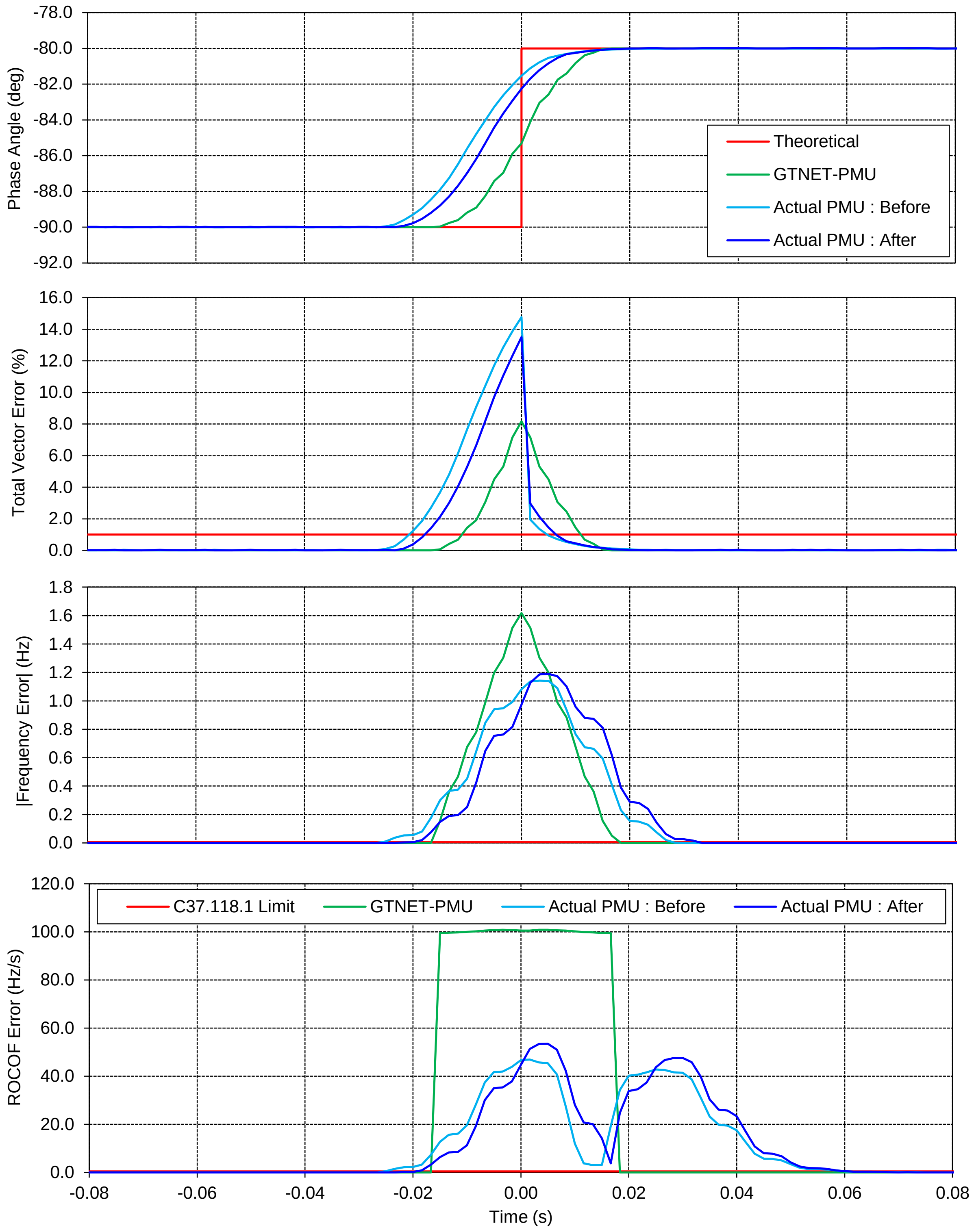


Fig. 15 Magnitude, TVE, FE, and RFE in phase angle step response test

The phase angle step test results were similar to the magnitude step test where, the GTNET-PMU satisfied all the requirements of the standard and the actual PMU showed better performances after adjusting its device parameters.

4. CONCLUSION

This paper presented an automated PMU test setup implemented in the RTDS simulator. The PMU Utility tool in RSCAD was used to execute a series of tests, collects measurements, calculates errors, and checks conformity (pass/fail assessment) as per the synchrophasor standard [1], [2] and the TSS [3] guidelines with minimal user interaction. The RSCAD Runtime's script feature was used to automate the PMU testing process. The proposed test setup was applied to a bench-mark PMU model (i.e. GTNET-PMU) as well as an actual PMU to access their performances in the automated environment. The GTNET-PMU satisfied all the electrical requirements specified in the synchrophasor standard [1], [2]. However, the actual PMU violated some of the error limits specified in the synchrophasor standard [1], [2]. The PMU Utility helped the PMU manufacturer to identify test cases where the PMU failed and to recognize relevant issues. The parameters of the actual PMU were adjusted by the manufacturer and the PMU was retested using the PMU Utility. The actual PMU with adjusted parameters showed much better performances and comparative results (before and after adjusting device parameters) were presented. The demonstrated PMU testing example in this paper was limited to the preliminary type test, however, the proposed automated PMU test setup is suitable for testing PMUs in all other stages; type test, routine test, commissioning test, and maintenance test.

5. ACKNOWLEDGEMENT

The authors would like to acknowledge Dr. Krish Narendra and Dr. Nuwan Perera, ERLPhase Power Technologies, Canada for their technical support.

6. REFERENCES

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

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

[3] *IEEE Synchrophasor Measurement Test Suite Specification*, IEEE Std. Association, Dec. 2014.

[4] D. R. Gurusinghe, A. D. Rajapakse and K. Narendra, "Evaluation of steady-state and dynamic performance of a synchronized phasor measurement unit," in *Proc. 2012 IEEE Electrical Power and Energy Conference*, London, ON, Canada, pp. 57-62.

[5] D. R. Gurusinghe, A. D. Rajapakse, and K. Narendra, "Testing and enhancement of the dynamic performance of a phasor measurement unit," *IEEE Transactions on Power Delivery*, vol. 29, no. 4, pp. 1551-1560, Aug. 2014.

[6] R. Annell, M. Khorami and M. M. Saha, "Automated testing of PMU compliance," in *Proc. 2015 PAC World Conference*, Glasgow, Scotland.

[7] *Communication networks and systems in substations - Part 9-2: Specific Communication System Mapping (SCSM) – Sampled values over ISO/IEC 8802-3*, IEC 61850-9-2, Ed. 2, Sep. 2011.

[8] *Implementation Guideline for Digital Interface to Instrument Transformers Using IEC 61850-9-2, IEC 61850-9-2 LE*, UCA International Users Group, Jul. 2004.

[9] *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems,* IEEE Standards Association, July 2008.

[10] *IRIG standard 200-04,* Telecommunications and Timing Group, U.S. Army White Sands Missile Range, New Mexico: Range Commanders Council, Sep. 2004. [Online] Available: http://irigb.com/pdf/wp-irig-200-04.pdf.

[11] Real-Time Digital Simulator (RTDS) Controls library manual, RTDS Technologies, Winnipeg, MB, pp. 7F.1-7F.15, May 2015.

[12] J. Ren, M. Kezunovic and G. Stenbakken, "Dynamic characterization of PMUs using step signals", in *Proc. 2009 IEEE Power & Energy Society General Meeting*, Calgary, AB, Canada, pp. 1-6.