An Advanced Automation Tool for Testing Electrical Performances of Phasor Measurement Units

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ABSTRACT

The current standard for synchrophasors, i.e. IEC/IEEE 60255-118-1:2018, specifies error limits to evaluate electrical performances of phasor measurement units (PMUs). However, the standard specifies neither test plans nor error calculation methods; leading to ambiguities in PMU testing as different test procedures and calculations may produce different test results for a given PMU. Therefore, the IEEE standards association conformity assessment program (IEEE-ICAP) published the test suite specification (TSS) to remove ambiguities in PMU testing. However, testing of a PMU according to the test plans prescribed in the IEEE-ICAP TSS is a challenge due to the number of measurements and calculations needed.

This paper introduces an automation tool for testing steady-state and dynamic electrical performances of PMUs according to the test plans prescribed in the latest TSS. The proposed testing tool is implemented as an integrated application in a digital real-time simulator (DRTS). The tool has the capability to generate numerous test signals from the DRTS, communicate with the PMU under test, capture synchrophasor measurements, calculate error quantities, and produce a summary report with a pass/fail assessment for a given PMU configuration. The presented PMU testing tool is applied to validate performances of a benchmark PMU model and physical PMUs from numerous vendors. This paper presents the features of the tool, test methodology used for testing PMUs and some interesting test results observed.

Keywords – Phasor measurement unit (PMU), PMU testing, synchrophasor standard, C37.118, total vector error, digital real-time digital simulator.

1. INTRODUCTION

Steady-state and dynamic measurement performances of PMUs are critically important to ensure reliable and secure operation of synchrophasor applications. Therefore, it is essential to assess the performance of a PMU in different stages of its life cycle; from research and development (R&D) stage to their deployment in power systems. The existing standard for synchrophasors (IEC/IEEE 60255-118-1:2018 [1]) and the IEEE-ICAP TSS [2] provides necessary guidelines and test plans to comprehensively evaluate steady-state and dynamic performances of PMUs. Since there are hundreds of tests prescribed in the TSS and each test requires thousands of measurements and hundreds of thousands of calculations, manually testing the performance of a PMU is a challenging task.

Over the years, many efforts have been made to evaluate electrical performances of PMUs. One simple approach is to playback known waveforms into the device (i.e. PMU) under test (DUT) using a playback device synchronized to a common time reference. The response of the PMU is then captured and compared against the theoretical input phasors to evaluate performance [3]. However, high time consumption and requirement of frequent user interaction are major drawbacks of this approach. In [4], an automated test-bench has been implemented, which increases the efficiency of testing significantly, but its availability is limited for internal use of a specific vendor. In [5], authors has proposed a PMU test setup in a digital real-time simulator (DRTS) and using the simulators' scripting capability to automate the testing process. However, writing a new script or modifying of an existing one to fit a particular testing procedure is time intensive and requires a broad knowledge of programming.

This paper presents an advanced automation tool that can be used for evaluating the electrical performance of PMUs. The automation tool named the PMU Test Utility (PTU) is integrated to a DRTS and is designed to execute the test plans prescribed in the TSS [2]. The PTU has the ability to generate test signals from the DRTS, communicate with the DUT and collect measurements, and calculate evaluating quantities and produce a summary report with assessments (pass/fail) for a given PMU configuration with minimum user interaction. This tool offers a number of advanced features and is beneficial to PMU manufacturers, PMU testing laboratories, commissioning staff, and power utility engineers.

The remainder of this paper is organized as follows. Section 2 briefly introduces the tests involved in evaluating the performance of a PMU as defined in the relevant standards. The functional overview of PTU is provided in Section 3 and in Section 4, test setup used by the PTU for testing PMUs is described. Section 5 is devoted for tests and results; it assesses performances and advantages of the automation tool with a benchmark PMU model and physical PMUs from numerous vendors. Here, PMUs with both analog and digital inputs are evaluated. Finally, in Section 6, the key contributions of the paper are highlighted.

2. PERFORMANCE EVALUATION OF A PMU

The IEC/IEEE 60255-118-1:2018 standard [1] and the IEEE-ICAP TSS [2] provide guidelines to comprehensively evaluate performances of PMUs using hundreds of test scenarios. There are tests specifically designed to evaluate both the steady-state and dynamic performance of PMUs, which are listed below,

<u>Steady-state Tests</u>

- Frequency Range
- Voltage Magnitude
- Current Magnitude
- Harmonic Distortion
- Out-of-band Interference

<u>Dynamic Tests</u>

- Amplitude Modulation
- Phase Modulation
- Frequency Ramp
- Magnitude Step Response
- Phase Step Response

Note that there are number of sub-tests in each test, which are generally run sequentially, one at a time. The standard specifies parameters for each test, which essentially defines sub-test cases in each test. For example, the "*Frequency Range Test*" is carried out as a series of sub-tests, where each sub-test is performed with the frequency of input signals is fixed at certain value within a specified frequency range. Here, for an M-class PMU reporting at a rate of 60 frame/s (fps), the frequency range is defined as 55.0-65.0 Hz, and with a step size of 0.1 Hz, this test comprises of 101 sub-tests cases. Similar parameters are defined for each of the other tests resulting in hundreds of sub-tests in total for a given PMU configuration.

3. OVERVIEW AND FEATURES OF PMU TEST UTILITY

The PTU is an integrated tool that comes with the main interface software suite of the DRTS. Once launched, the PTU operates as a standalone application. Fig. 1 illustrates the functional overview of the PTU and its interaction with the DRTS and the DUT.

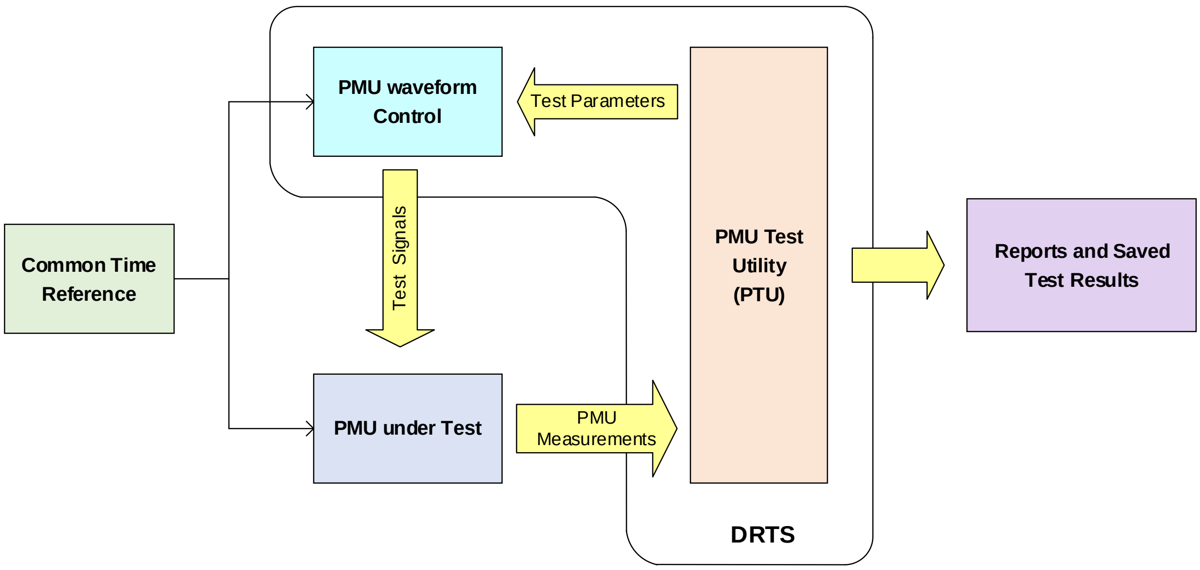


Fig. 1 : Functional overview of the PTU

The waveform control block is essentially a signal generator component that can produce a specified set of waveforms. During testing, the PTU application interfaces with the DRTS and provides necessary input parameters to the waveform control block to generate the theoretical signals prescribed for a particular test. The digital signals generated in the simulation are conveyed to the DUT as analog signals or digital samples depending on the interfacing method. The PTU can communicate with the DUT and collect measurements, which are then compared against the theoretical values to determine total vector error (TVE), frequency error (FE) and rate of change of FE (RFE) in each test scenario as well as magnitude and phase step responses when applicable.

Fig. 2 presents the process executed by the PTU in carrying out testing for a given PMU. Next sections provide details of its key functionalities.

3.1. Connecting with the PMU under Test

Users can specify the communication parameters to be used to connect with the DUT. The PTU supports TCP, UDP and UDP_T (TCP handshaking is used for the commands and UDP is used for data streaming) communication protocols. A real-time summary of the data from the DUT is displayed in the PTU once a successful connection has been established. Users can observe information such as phasor measurements of each channel, time stamp, frequency, rate of change of frequency of the DUT in this summary view. This has two main uses, firstly to confirm that the PTU can successfully communicate with the DUT and secondly to verify that the DUT is streaming a reasonable set of values. Moreover, the users can save the communication parameters and configuration information of the DUT to a configuration file that can be reloaded for future testing.

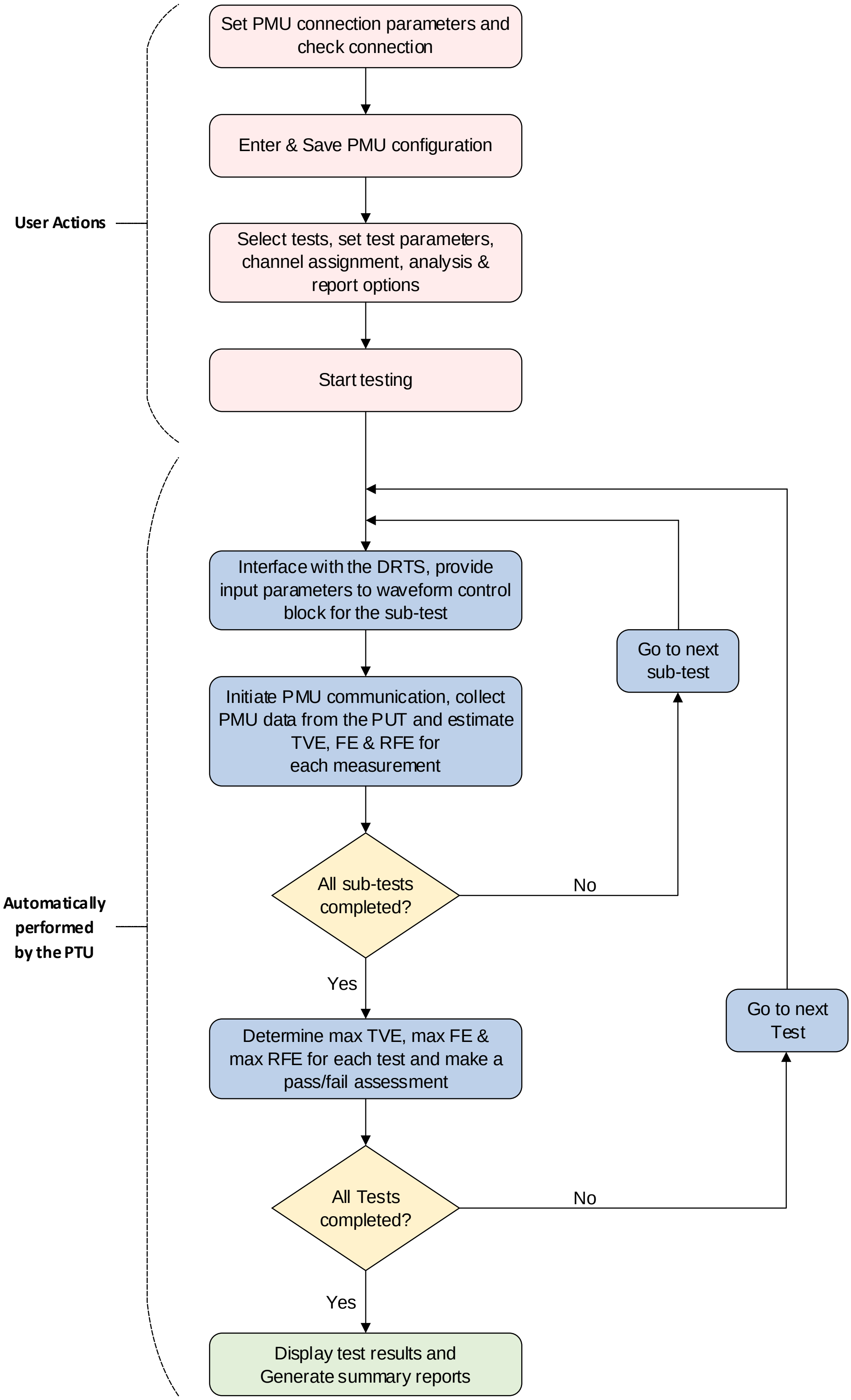


Fig. 2 : Flow chart of the PTU

3.2. Selecting Tests and Specifying Test Parameters

Once a connection has been established, the initial configuration of the PTU needs to be carried out, which involves specifying the nominal voltage and current ratings and the performance class of the DUT. A common angle offset for voltage and current channels can also be specified here. The nominal frequency and the reporting rate of the DUT is automatically detected by the PTU during the initial communication session.

The PTU is capable of performing all the tests prescribed in the IEEE synchrophasor standard [1] and IEEE-ICAP TSS [2] on a PMU.

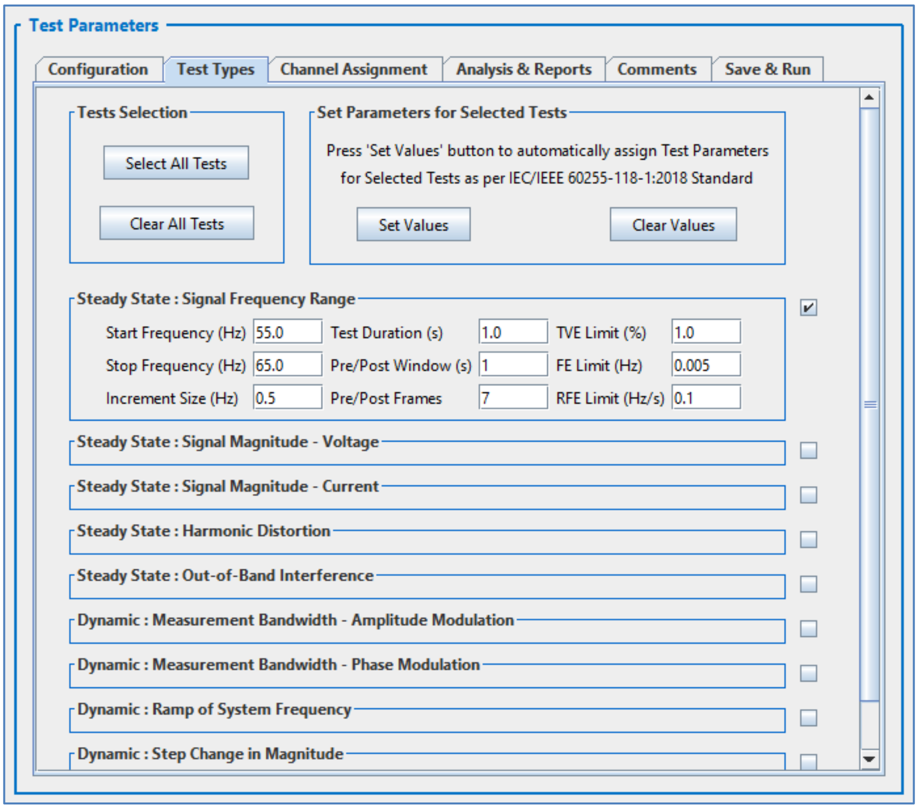


Fig. 3 : Setting test parameters

During a testing session, users of the PTU can conveniently select the tests to be performed on the DUT as shown in Fig. 3. Each selected test requires a certain set of test parameters, which are entered in corresponding fields. The PTU also has provisions to automatically populate these fields to the values specified in the IEC/IEEE 60255-118-1:2018 standard.

3.3. Channel Assignment and Analysis & Report Options

Assigning the channels of the DUT to corresponding ones in the PTU is carried out as the next step of the configuration process. Assignments can be made for phases A, B, C and the positive sequence for both voltage and current channels; however, testes can be performed even with only one assigned channel. "*Analysis & Report*" section allows users to select performance parameters such as TVE, FE, RFE, delay time, response time and over/undershoot for which the compliance of the DUT is to be tested. It also offers a number of reports to choose from, which are to be created at the completion of testing.

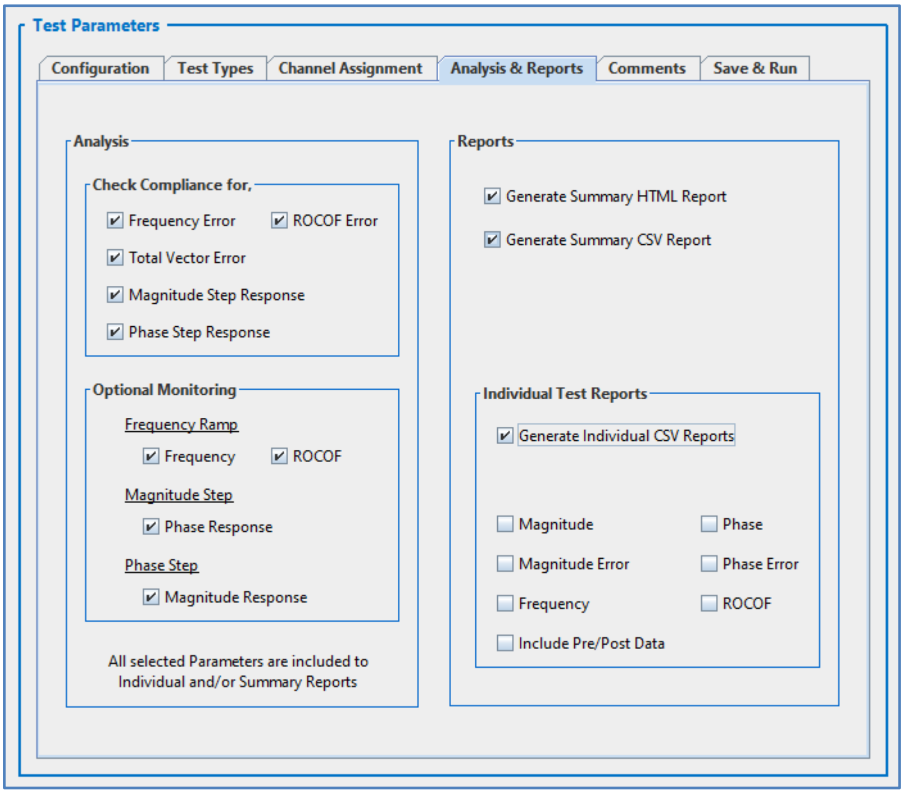


Fig. 4 : Analysis & Report Options

3.4. Running the Tests

After carrying out necessary configurations, the users can add comments and save the test configuration file before running the tests. Finally, when the execution of tests is initiated, the PTU will automatically perform each selected test as mentioned previously in section 3.2. Note that there are number of sub-tests for each test and the PTU runs the entire set of sub-tests of a particular test sequentially one at a time. For example, the "*Frequency Range Test*" with a start and stop frequency set to 55.0 Hz and 65.0 Hz, respectively, and a step size of 0.1 Hz, comprises of 101 sub-tests. This test is performed as a series of sub-tests, where each sub-test is performed with the frequency of input signals fixed at a certain value between 55.0 and 65.0 Hz. The PTU interacts with the DRTS to generate the aforementioned signals, which are fed to the DUT as input signals. The PTU then initiates streaming data from the DUT, and then captures and analyses them to generate the necessary performance parameters (error quantities). As shown in the flow chart in Fig. 2, this process is repeated until all of the selected tests are completed.

Upon completing the tests, the PTU generates a set of plots indicating the maximum values of the estimated performance parameters for each selected test with a pass/fail assessment. In addition, the PTU saves the test results in the generated summary report file.

3.5. Advanced features of the PTU

The PTU offers several advanced features that are beneficial for testing and evaluating the performance of PMUs. Following are short descriptions on few such features,

- The PTU has an option to automatically populate test parameter fields of chosen tests using test ranges and error limits specified in the IEC/IEEE 60255-118-1:2018 standard. Here, the PTU takes into account the nominal frequency, performance class and reporting rate of the DUT for calculating the test parameters. This offers convenience for users who are not familiar with the standard or do not have access to it, while also ensuring reliability of testing. However, note that performing the total number of tests defined in the standard on a PMU takes hours even for a sophisticated tool as the PTU. Therefore, the PTU offers full configurability over test selection and test parameters so that the users can run few specific tests with a particular set of parameters chosen to minimize the number of sub-tests in order to reduce execution time for experimental purposes. Moreover, one can use the auto populate feature to obtain a reasonable set of initial values and then modify them to limit the number of sub-tests as necessary.

- For the out-of-band (OOB) interference test, the input signal frequency (f_{in}) is varied between the nominal frequency (f_0) and ±10% of half of the reporting rate ($F_s/2$) with the maximum variation limited to ±5 Hz. Therefore, the test should be repeated for three different signal frequencies; "$f_{in} = f_0 – (0.1*F_s/2)$", "$f_{in} = f_0$" and "$f_{in} = f_0 + (0.1*F_s/2)$". In addition, it is required that the OOB interfering signal frequency (f) is varied from 10 Hz to the second harmonic and the passband is defined as $|f – f_0| < F_s/2$. The PTU automatically calculates three input frequencies and OOB test range for a given PMU configuration. Notice that the OOB interference test is applicable for the M-class only.
- The step response tests should be 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], [6] should be used to achieve the required resolution. In this approach, at least 10 successive step tests [1], [2] are made, where in each event, the 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. The PTU can generate successive step curves and derive the interleaved curve, which is then used to determine response time, delay time, and maximum overshoot/undershoot values of the DUT.
- The PTU automatically generates a comprehensive HTML summary report, which includes plots (TVE, FE and RFE against the influencing quantity) and a pass/fail assessment for each test. This enables users to easily observe, present, archive and review test results. Moreover, the PTU provides means to export the measurements calculated for performance parameters for further analysis and archiving.

4. PMU TEST SETUP

As explained in Section 3, the PTU is only a part of a test setup for testing PMUs. The DRTS is also an integral element of this test setup, which generates precise three-phase voltage and current signals using a waveform control block component. This component is specially designed to produce various steady-state and dynamic waveforms required to test a PMU as per the synchrophasor standard [1] and the TSS [2]. During testing, the simulator's time-step remains locked to an external time source by feeding a global navigation satellite systems (GNSS) signal to the synchronization card of the DRTS. Notice that the DUT is also synchronized to the same time reference. The test waveforms (voltages and currents) from the DRTS can be fed to the DUT as conventional hardwired analog signals or digitized sampled values (SV) as per IEC 61850-9-2/61869-9 [7]-[9].

Fig. 5 shows schematics of typical connections for both analogue and digital interfacing of a PMU with the DRTS and the PTU. Notice that the PTU running on a workstation computer interacts with the DRTS and the DUT during testing. At the start of each sub-test, the PTU initiates signal injection from the DRTS to the DUT and then commands the DUT to start streaming PMU measurements to start testing.

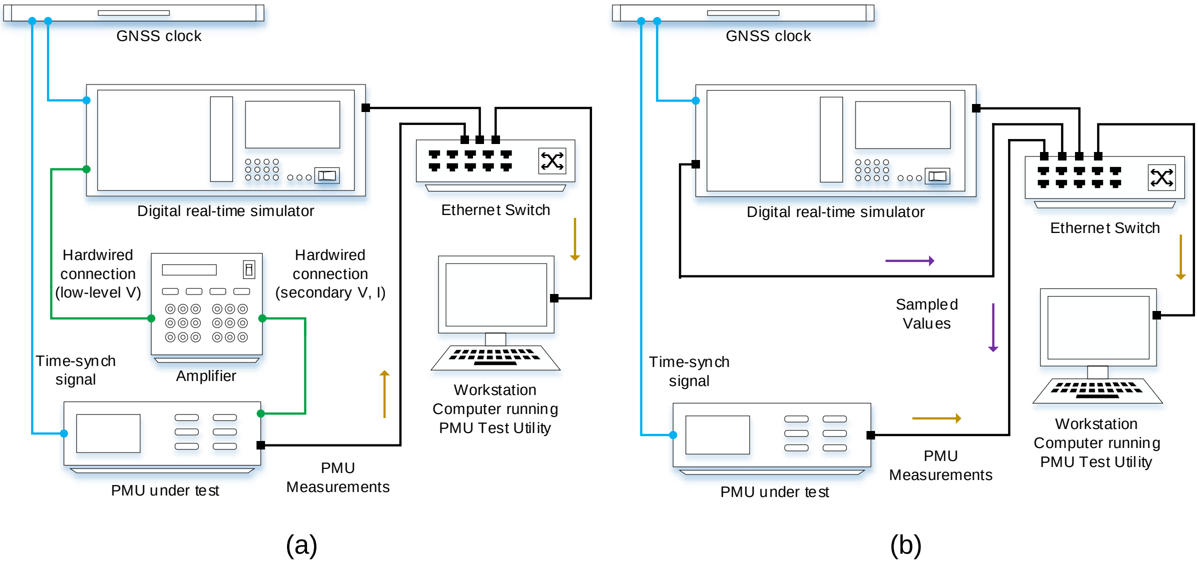


Fig. 5 : (a) Analogue interface, (b) Digital interface

4.1. Analog Interface

The more common approach to interface a PMU with the DRTS for testing is shown in Fig. 5 (a), where test waveforms are fed to the DUT through an analog output card of the simulator using a secondary injection amplifier. It is worthwhile noting that the simulated voltages and currents are digital data and must be converted to an analog form that a conventional PMU can accept. The analog output card of the DRTS performs this task. However, the analog output card can only produce a low energy (±10 V peak-peak) signal, therefore, its output must be properly scaled before injected to the PMU by using an external amplifier. The amplifier provides precise in-service voltages and currents to the DUT.

4.2. Digital Interface

Some of the modern PMUs support acquiring their input measurements digitally as IEC 61850 sampled values. Fig. 5 (b) illustrates such a digital interfacing, where the network interface card of the DRTS publishes the test waveforms as SV directly to the DUT. The synchronization card of the simulator enables time aligning the published SV and the DUT to a common time reference.

5. EXECUSION OF TESTS, RESULTS AND REPORTS

This section highlights tests performed by the PTU and presents some interesting test results observed. In this paper, performances of the M-class are illustrated at the reporting rate of 60 fps.

In the PTU, users can monitor the progress of tests during their execution as shown in Fig. 6 (a). It indicates completed tests, the currently progressing test, and pending tests with the number of sub-test cases. When the test process is successfully completed, the pass/fail assessment of individual test types is displayed as shown in Fig. 6 (b). This helps users to recognize test types where the DUT fails and further investigate test results in the results/plots section.

Fig. 6 : (a) Test in Progress, (b) Summary Test Results

In results/plots section, the test results are plotted for TVE, FE and RFE as well as magnitude and phase step responses when applicable. Results observed for few interesting test types and some of the advanced features of the PTU are presented in following sections.

5.1. Frequency Range Test

In the frequency range test, the frequency of the signals are varied from 55.0 Hz to 65.0 Hz with a step resolution of 0.1 Hz while other influence quantities are kept unchanged during the test. Fig. 7 shows TVE variation of positive sequence voltage plotted against the "*Input Signal Frequency*" for the frequency range test.

Fig. 7 : TVE Variation of +ve Sequence Voltage under Frequency Range

The error limits are drawn in "red" and the maximum errors estimated from the DUT are drawn in "blue". The pass/fail assessment for the positive sequence voltage phasor and maximum TVE are also displayed. The PTU provides similar results/plots for the TVE variation of other assigned phasors. Likewise, it provides the variation of FE and RFE with respect to the limits specified in the synchrophasor standard as well.

5.2. Out-of-band Interference Test

The out-of-band (OOB) interference test is only applicable for the M-class and the test should be repeated for frequencies of 57 Hz, 60Hz and 63 Hz at 60 fps reporting rate as an example. The PTU also has an option to repeat OOB tests for prescribed input signal frequencies. In addition, the PTU calculates the OOB test range for 60 fps reporting rate, which is 10-30 Hz and 90-120 Hz.

Fig. 8 displays the OOB plots for FE variation against OOB signal frequency. Here, the FE limit is drawn in “red” and the FE plots at 57 Hz, 60Hz and 63 Hz are drawn in “green”, “blue” and “magenta”, respectively.

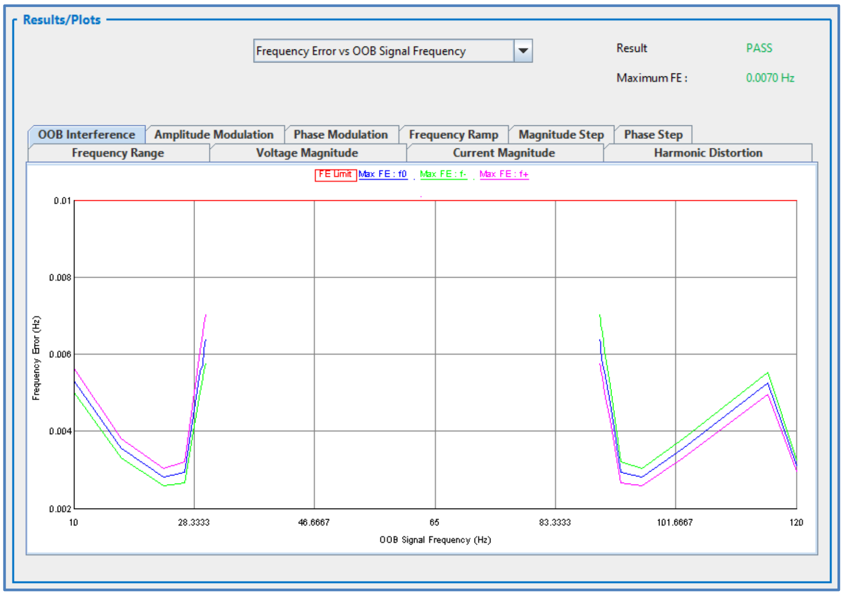


Fig. 8 : FE Variation of Signal under OOB Interference

5.3. Frequency Ramp Test

In the frequency ramp test, the frequency of the waveforms is linearly varied from 58.0 Hz to 62.0 Hz with the ramp rate of +1.0 Hz/s while other influence quantities are kept unchanged during the test. Fig. 9 shows TVE variation of positive sequence voltage for the frequency ramp test.

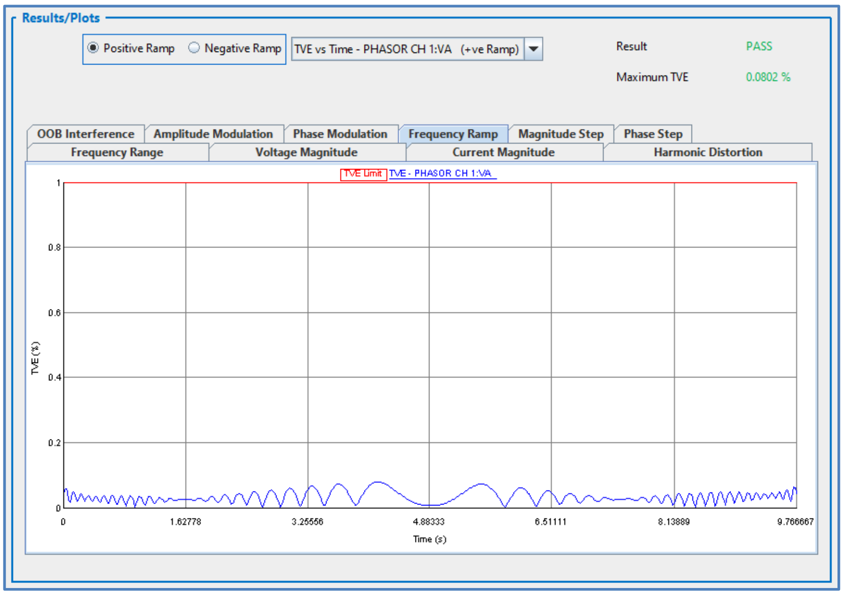
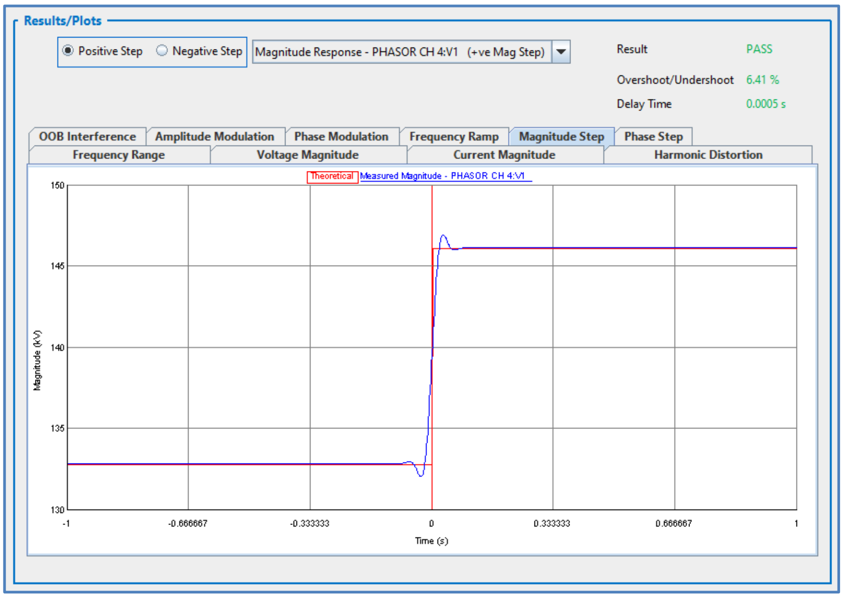


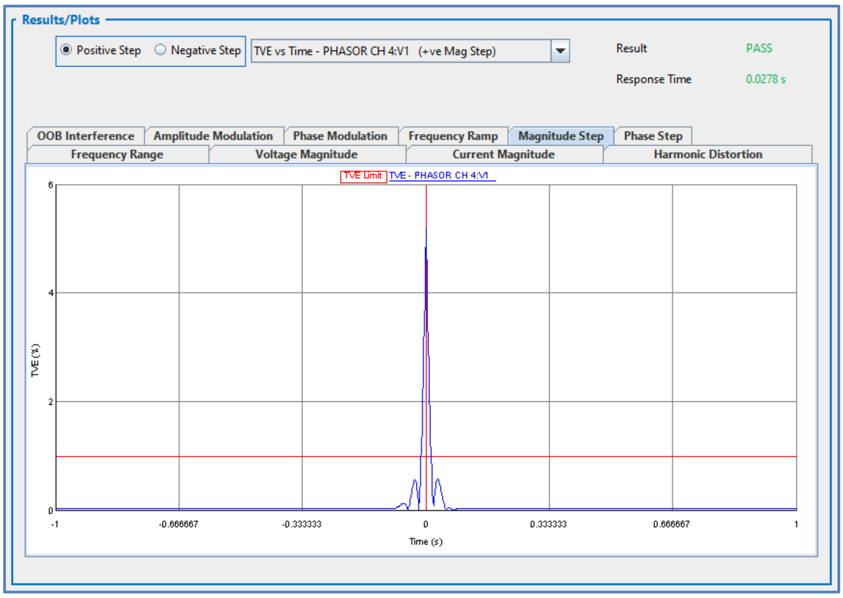
Fig. 9 : TVE Variation of Phase-A Voltage under Frequency Ramp

5.4. Step Response Test

In the step response test, the PTU derives the interleaved curves for step, TVE, FE and RFE responses, which are then used to calculate response time, delay time, and maximum overshoot/undershoot. Here, 10% magnitude step is applied to the input signals while other influence quantities are kept unchanged during the test. Fig. 10 shows interleaved curves for step and TVE responses for the magnitude step response test.



(a)



(b)

Fig. 10 : (a) Magnitude Variation, (b) TVE Variation in Magnitude Step Response (Interleaved Curves)

The PTU provides similar results for the phase angle step response test as well as negative step response tests in magnitude and phase angle.

5.5. Test Reports

The PTU can generate summary test results as a HTML report and a numerical test report. The HTML report is a graphical report with all the plots displayed in the "*Result/Plots*" section and includes all of the test parameters and test results with pass/fail assessments. The report can be viewed in any HTML browser and looks similar to the one shown in Fig. 11.

PMU Test Report

RTDS Technologies Inc.

Date Generated : **2021/07/13 12:24:39** by RSCAD PMU Test Utility

PMU Information	
Make	
Model	
Connection Parameters	
Socket Type	TCP
PMU IP Address	172.24.7.5
TCP Port No.	4712
Device ID	1
Protocol	Config 3 : IEEE C37.118.2-2011
NIC	10.53.0.9=>TAP-Windows Adapter V9
Config Count	1
Ignore Errors	False
PMU Settings	
Nominal Voltage (kV)	132.8
Nominal Current (A)	400.0
Nominal Frequency (Hz)	60
Reporting Rate (fps)	60
Performance Class	M
Test File	C:\RTDS_USER_FX\fileman\Conferences\PAC World 2021\Test.txt
Steady State : Harmonic Distortion Tests	
Influence Quantity	Single Harmonic of Power System Fundamental Signal
Harmonic Range (No.)	2 - 50
Harmonic Level (pu)	0.1
TVE Limit (%)	1.0
FE Limit (Hz)	0.025
Overall Result	FAIL

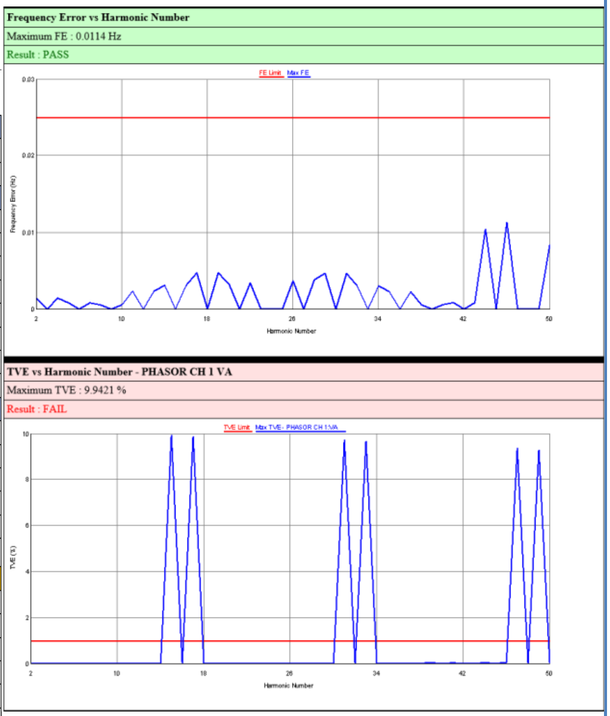


Fig. 11 : A Part of Summary HTML Report

The numerical test report is in CSV format and includes all of the test parameters and numerical test results with pass/fail assessment. In addition, the PTU can produce individual reports for each sub-tests so that the users can perform postmortem analysis of test results to identify root causes of performance issues of the DUT.

In addition, numerical test reports can be used to compare performances of different PMUs. Fig. 12 provides TVE, FE and RFE variations in the frequency range test for five PMUs. Note that these plots are generated by an external plotting tool using the data contained in the numerical test reports produced by the PTU for each PMU. Four out of the five PMUs tested are commercial PMUs (vendors A, B, C and D) and the fifth one is a reference PMU model in the DRTS. PMUs of venders A and C support a digital interface whereas vendors B and D have an analog interface. Here, all PMUs were set to report at 60 fps and the performance class was chosen as P-class.

5.6. Degree of Automation

As evident from the work presented in this paper, the degree of automation offered by the PTU is substantial. For example, M-class testing at 60 fps requires execution of 339 sub-tests, collection of over 275,000 data frames in total and performing approximately 1 million calculations to determine TVE, FE, RFE, response time, delay time, and maximum overshoot/undershoot. Once initial configurations are completed, the PTU is capable of carrying out all of the abovementioned tests and calculations without any human intervention within a few of hours.

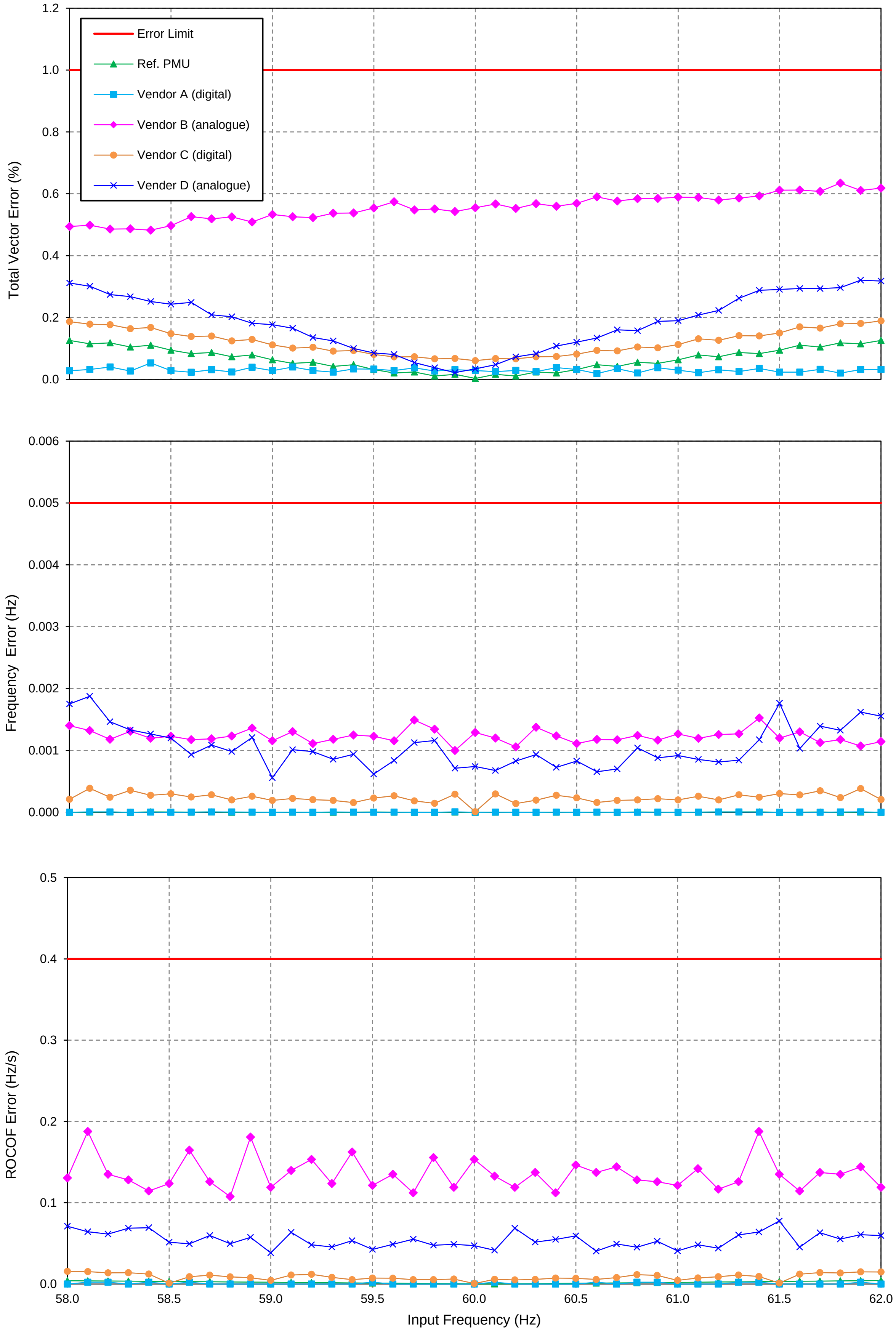


Fig. 12 : TVE, FE and RFE Variation of Multiple PMUs for the Frequency Range Test

6. CONCLUSION

This paper presents the use of an automation tool for testing the electrical performance of PMUs. The authors have provided a comprehensive overview of the tool, its features and advantages, and the methodology used for testing PMUs. The presented automation tool is suitable for testing PMUs in different stages of their life cycle; preliminary type test, type test, routine test, commissioning test and maintenance test. The authors believe that this automation tool is beneficial to manufacturers, certified testing laboratories, commissioning staff, power utility engineers and researchers to conveniently test, validate and benchmark electrical performances of PMUs.

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