Probabilistic Assessment of PMU Integrity for Planning of Periodic Maintenance and Testing

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***Abstract*—The standard C37.118.1a-2014 has specified the permissible limits for PMU measurement errors under various static and dynamic test conditions. This paper proposes a statistical measure to evaluate the probability of PMU performance degradation with regards to certain standard requirements. The proposed approach is implemented using a field calibrator system for phasor measurement units (PMUs). Assessment of the test results provides an additional insight about: (a) whether the expected functionality and integrity of the PMUs is maintained over time; (b) which synchrophasor standard requirements are most vulnerable for a given device over time; (c) when the maintenance schedule needs to be expedited on certain PMUs based on observed performance degradation probabilities; and (d) the risks of loss of trustworthiness of various end-use synchrophasor-based applications. The applicability of the suggested technique is verified through implementation on several PMUs in a calibration and testing set-up.**

Keywords— calibration; periodic maintenance; phasor measurement; probabilistic; standard type-tests; synchrophasor.

I. INTRODUCTION

Since synchrophasor technology was introduced, developed, and partly integrated into the electric power systems in early 1980s, it has been shown that it offers great advantages in control and monitoring of the grid thanks to its high-resolution time synchronized measurements [1], [2]. Phasor Measurement Units (PMUs) are instruments that can provide a precise and comprehensive view of the system dynamics. They can track the state of the system in real time by measuring the voltage and current phasor, frequency and rate of change of frequency at a rate of 10 to 120 phasor frames per second [3]. PMUs serve as the backbone for many system-wide applications and algorithms in electric power systems. Some of the applications, out of many that have been reported, are: accurate measurement of frequency and magnitude of voltages and currents, state estimation, instability detection and evaluation, contingency analysis, adaptive relaying, system-wide control and monitoring, etc. [4].

Since 2005, various standards for the static and dynamic performance of the phasor measurement units (PMUs), as well as communication requirements for the synchrophasor data transfer have been developed and eventually adopted. Standard IEEE C37.118.1-2011 defines the acceptable performance of synchrophasor measurements in power systems [5]. In 2014, this standard was revised where some tests were removed and some requirements were revisited due the fact that most of the PMU devices and Intelligent Electronic Devices (IEDs) with PMU capabilities available on the market at the time were not meeting the standard [6]. The procedures and requirements for test equipment, such as timing reference, signal sources, calibration devices and environmental conditions, are specified in the IEEE Synchrophasor Measurement Test Suite Specification (TSS) document published by the IEEE Conformity Assessment Program (ICAP) [7]. TSS provides a suite of unambiguous test plans in accordance with Smart Grid Interoperability Panel Recommendations and Interoperability Process Reference Manual. Standard IEEE C37.118.2-2011 covers requirements for the PMU data transfer in power systems [8] and standard IEEE C37.242-2013 provides guidance for synchronization, calibration, testing, and installation of PMUs applied in power system protection and control [9]. Testing procedures for the Phasor Data Concentrators (PDCs) are presented in the IEEE C37.244 Guide for Phasor Data Concentrator (PDC) Requirements for Power System Protection, Control, and Monitoring [10].

Considerable research has been devoted to compliance analysis of PMUs through calibration type-tests and algorithm testing [11]-[18], and field-testing procedures [19]-[22]. General evaluation of PMU dynamic performance in both the lab environment and under field operating conditions is reported in [19]-[22].

By utilizing the standard type test results under both dynamic and static test conditions, this paper tries to introduce an analytical methodology to probabilistically evaluate the deterioration of PMU performance over time with regards to the standard requirements. The proposed probabilistic technique can quantitatively reveal the PMU response to various test performance thresholds specified by corresponding IEEE standards and also the probability of specific failures to meet the standard requirements. The trends revealed by such probabilistic metrics could help in better planning the maintenance periods and future in-filed testing procedures.

The remainder of the paper is structured as follows. Section II elaborates the general structure of the developed PMU calibration test set up as well as its various functionalities. The proposed technique for assessment of synchrophasor device integrity for periodic maintenance and testing is introduced in Section III. Experimental results from the test studies on several PMU devices are presented in Section IV followed by the concluding remarks in Section V.

II. PMU Calibration and Testing Testbed

A. Test Needs and Requirements

In addition to standard type-test practices that need to be performed during acceptance tests performed in the calibration lab environment and during the early commissioning stages of PMU deployment, testing is also desirable after the PMU has been in service for a longer time to ensure that the PMU functionality over time still complies with the standard requirements. Testing PMUs in the field needs to be performed using a portable test device, namely field calibrator. Tools need to be developed to provide an in-field test opportunity for the users to (1) implement the type-tests in the field mainly to meet periodic maintenance plans, and (2) perform the application testing to ensure the trustworthiness of the PMU results for end-use synchrophasor applications. Focusing on the applications, periodic testing of the PMUs under static and dynamic test conditions provides a database containing valuable information to the users on how the PMU measurements are affected over time in face of device wear and tear mechanism and environmental/operational conditions in real-world. Such information further helps in detecting possible origins of the measurement abnormalities and can be used to develop risk mitigation plans to constantly ensure the synchrophasor application trustworthiness.

B. Software and Hardware Implementaion

A PMU test and calibration platform used to verify the conformance of the evaluated PMUs under various static and dynamic tests according to the IEEE standards is developed at Texas A&M University. The software and hardware design can be used for PMU calibration and testing in both laboratory and in-filed environment. A general structure of the PMU calibration lab is shown in Fig. 1 and the actual implementation of such testing environment is illustrated in Fig. 2. As shown in Fig. 1, the PMU test system consists of timing reference (GPS receiver), signal generator, power amplifier, and data management and results analytics tools. Timing reference provides GPS timing clock to the calibration equipment and to the PMU under test so that the entire system is time-synchronized and time-stamped. Test signals are generated by the signal generator according to the test types determined by the IEEE TSS document [7]. Synchrophasor measurements from the device under test are compared with reference values calculated using mathematical formulations given in IEEE C37.118.1 standard, then followed by an analysis and documentation of the test results.

The PMU test and calibration platform is implemented using National Instrument (NI) hardware as shown in Fig. 2. The entire system consists of the PXI virtual instrument system with embedded Controller NI PXIe-8105, a user-programmable FPGA, which is a part of NI PXI-7854R multifunctional reconfigurable I/O module to generate the required waveforms, and an OMICRON CMS 356 power amplifier that generates 3-phase voltage and current signals feeding the PMU device under test. As a part of the system, software based Phasor Data Concentrator (PDC) module that receives and parses the data is running on the PXI system. Measurements from the tested PMU are acquired through fast speed Ethernet communication ports, then analyzed, and reports are generated using the NI LabVIEW software interface [23]. Reports consist of all data resulting from PMU tests which allows extensive post-analysis of the collected results. While the standard tests are conducted in the laboratory environment, they are also designed to be used in calibrator set-up for testing the PMUs in the field.

C. Dynamic and Steady-State Testing of PMUs

PMUs provide information such as voltage and current magnitude, angle, frequency, rate of change of frequency, etc.

According to the IEEE C37 118.1a standard, each device that is capable of providing GPS synchronized measurements has to undergo various steady state and dynamic test scenarios while being calibrated. During the steady state tests, PMUs are exposed to various type-test scenarios where all variables are kept unchanged during each test and measurements are captured according to the standard procedure. As shown in Table I, such static type-tests include performance evaluation of PMUs over a range of frequency values, voltage/current amplitudes as well as influence of harmonic and inter-harmonic interferences.

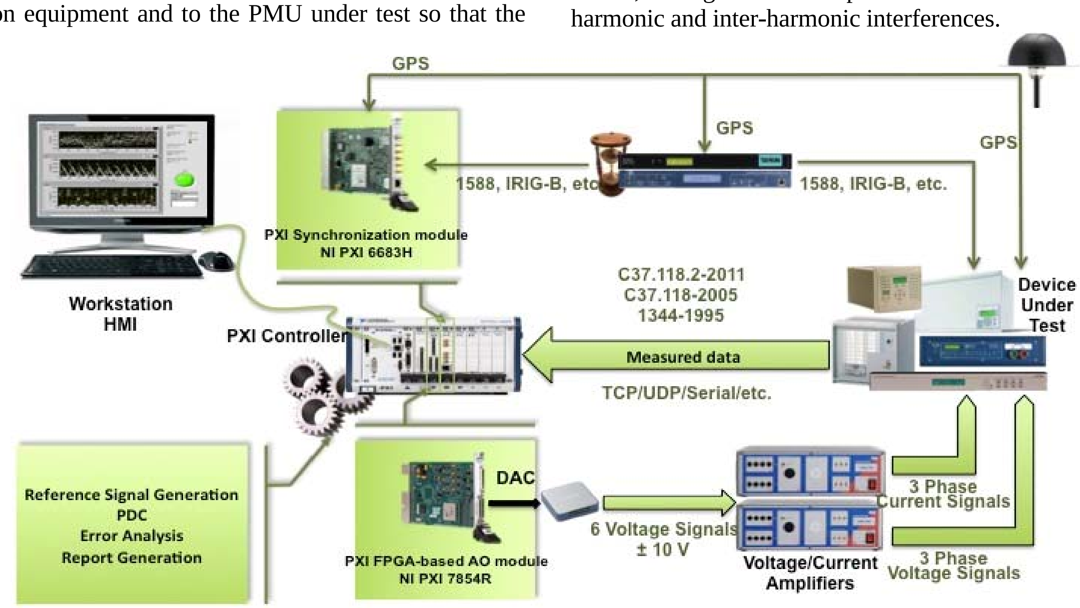


Fig. 1. Calibration and testing platform for PMUs.

TABLE I. PMU STEADY STATE AND DYNAMIC STANDARD TYPE-TESTS

Test Category	**Test Name**	**Input Range**	
		P Class	**M Class**
Steady Tests	Magnitude Sweeping	0.8-2 pu	0.1-2 pu
	Frequency Sweeping	±2Hz	±2Hz, or ±5Hz
	Harmonic Distortion	1% each harmonic up to 50th	10% each harmonic up to 50th
	Latency	1000 consecutive messages	1000 consecutive messages
	Out-of-Band Interference	N/A	Depending on reporting frequency, harmonic infiltration from 10Hz to twice nominal frequency; interfering signal 10% of signal magnitude
Dynamic Tests	Amplitude Modulation	Modulation frequency from 0.1Hz to 2Hz Modulation level 0.1	Modulation frequency from 0.1Hz to 5Hz Modulation level 0.1
	Angle Modulation		
	Frequency Ramp	±1Hz/s, frequency range within ±2Hz	±1Hz/s, frequency range within ±5Hz
	Magnitude Step Change	±10% Step	
	Angle Step Change	±pi/18 radians	

Fig. 2. Actual implementation of the PMU testing platform.

Dynamic type-tests involve testing PMUs with the modulated signals, checking their performance during the step occurrence in amplitude and angle, as well as testing the PMU response to the frequency ramp events. As a part of the standard requirements, latency of a PMU device has to be measured too. The PMU performance conformity under the aforementioned static and dynamic conditions needs to be ensured during the life-cycle of the PMUs and, hence, periodic maintenance and testing of the PMUs can help checking the desired functionality over time.

III. PROPOSED METHODOLOGY

A practical approach to evaluate the performance degradation of PMUs considering various steady-state and dynamic test signals is devised. Conducting the standard tests on the PMUs in the field, various PMU responses corresponding to each type-test and sets of data in terms of various error indicators are captured and recorded. The error indicators calculated are typically the Total Vector Error (TVE), Frequency Error (FE), and error in estimation of Rate of Change of Frequency (RFE). A normal probability distribution can then be assigned to each test measurement error data as demonstrated in Fig. 3. The proposed approach is, however, generic enough to be adopted with different types of probability distributions as data may dictate in various applications. In many practical cases, the methods developed using the normal distribution assumption work quite well even when the distribution is not normal. To proceed with the methodology, the minimum and maximum bands are adopted from the IEEE standard for each test signal. If one value x_i falls in the desirable margin, then it indicates a proper functionality of the PMU reflected by that specific test. Similarly, one new value of x_i may fall out of the desirable band leading to the test failure. In general, and according to the probability distribution assigned, the probability of a given test success can be calculated in (1)-(2), respectively for the steady-state and dynamic conditions.

$$P_{e_k,i}^{ST_k} = \int_{k=\sigma_{e_k}^{\min}}^{k=\sigma_{e_k}^{\max}} f_{e_k,i}^{ST_k}(k)dk \tag{1}$$

$$P_{e_k,i}^{DT_k} = \int_{k=\sigma_{e_k}^{\min}}^{k=\sigma_{e_k}^{\max}} f_{e_k,i}^{DT_k}(k)dk \tag{2}$$

Where the following nomenclature applies:

$P_{e_k,i}^{[.]_k}$	Success probability of a type-test k regarding the error indicator e_k for PMU i in the system.
e_k	Error indicator for test type k (i.e., TVE, FE, RFE).
ST_k	Steady-state type-test k.
DT_k	Dynamic type-test k.
$\sigma_{e_k}^{\min}$	Minimum threshold for error indicator for test k.
$\sigma_{e_k}^{\max}$	Maximum threshold for error indicator for test k.
$f_{e_k,i}^{[.]_k}(k)$	Probability density function of an error indicator for type-test k of PMU i in the system.

There are several error indicators for some PMU tests that all need to be in compliance with standard requirements. In order to be able to conclude a probabilistic measure for the success/failure of a given test on a PMU, equations (3)-(4) are

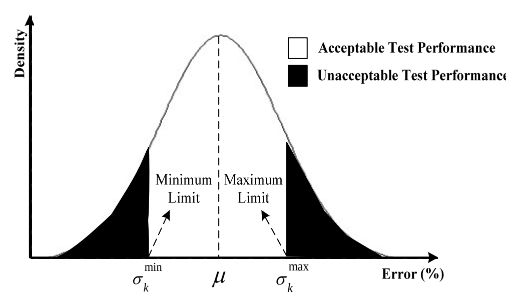


Fig. 3. Probability distribution and the bands assigned to the error indicators for each PMU type-test k.

proposed to integrate such indicators, where applicable, into one metric:

$$P_i^{ST_k} = \prod_{k=1}^{3} P_{e_k,i}^{ST_k} \qquad e_k = \text{TVE, FE, RFE} \tag{3}$$

$$P_i^{DT_k} = \prod_{k=1}^{3} P_{e_k,i}^{DT_k} \qquad e_k = \text{TVE, FE, RFE} \tag{4}$$

Where, $P_i^{ST_k}$ and $P_i^{DT_k}$ are the success probability of the static and dynamic tests, respectively, considering all the required error indicators within the desirable thresholds.

Even though PMUs may pass the standard tests, it may be desirable for the user to know how far the measurement errors corresponding to various tests are from the desirable standard thresholds. The equation (5) indicates a probabilistic metric for the distance of the reported error mean values from the desirable standard thresholds. This metric is useful in trying to understand how reliable a given PMU is with regards to a given test and what adjustments need to be made and how fast. That is, it can differentiate various PMUs that need periodic maintenance and troubleshooting by knowing which test requirements are more likely to cross the standard requirements over time.

$$\eta_{e_k,i}^{[.]_k} = \frac{1}{n} \sum_{n=1}^{N} \left(\sigma_{e_k}^{\max} - \left| e_{k,n} \right| \right) \tag{5}$$

where, $\eta_{e_k,i}^{[.]_k}$ is the probabilistic metric representing the distance between the mean error value and the maximum standard threshold; *N* is the total number of error observations for a given type-test *k*.

In order to have an overall evaluation of the PMU performance robustness considering all the requisite static and dynamic tests, a probabilistic measure representing the integrity of the PMU *i* in terms of testing results in face of all the static and dynamic test conditions is suggested in (6).

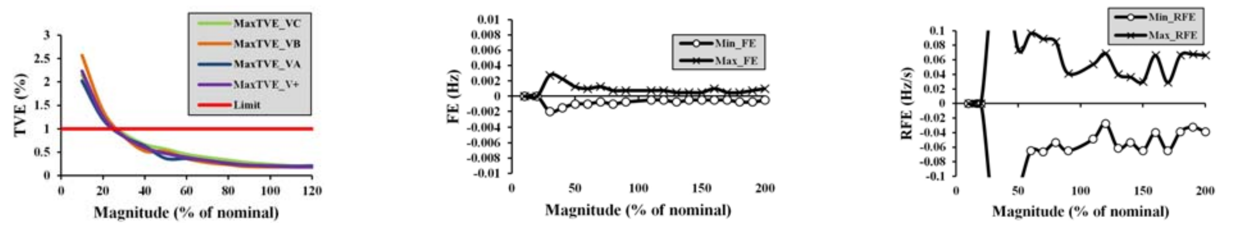
$$P_i^{Integrity} = \left(\prod_{k=1}^{K} P_i^{ST_k} \right) \times \left(\prod_{k'=1}^{K'} P_i^{DT_{k'}} \right) \tag{6}$$

In which K and K' represent the sets of static and dynamic tests, respectively. Observations on the $P_i^{Integrity}$ using the proposed in-field tests over time show how the PMU type-test errors are moving with respect to the desirable thresholds representing the degradation of the PMU measurements as the time goes on. The trend on such observations could also help better plan for periodic maintenance over the PMU life-cycle as needed.

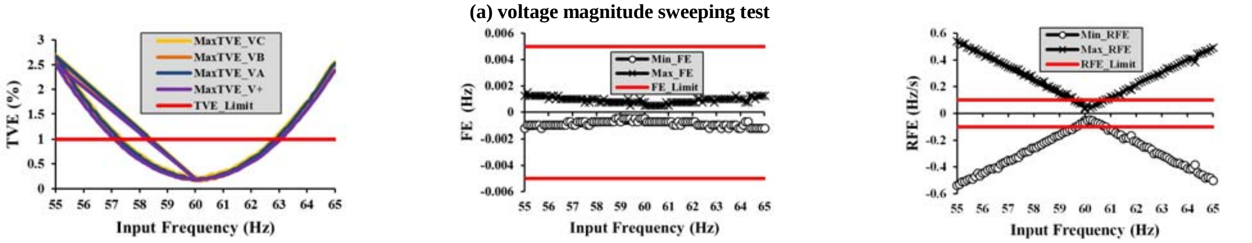
IV. Numerical Results

The proposed technique for PMU in-field testing is applied to several PMUs from various manufacturers with different operational characteristics and settings. Sample test results on a given PMU are presented in Fig. 4 using the aforementioned calibration test set. Various PMUs were exposed to different test signals and the performance of each product was thoroughly analyzed. As can be seen in Fig. 4, one of the PMU under test has failed most of the tests (e.g., voltage magnitude sweep, frequency sweep, out-of-band interfering frequency) while it has passed only one (i.e., harmonic distortion).

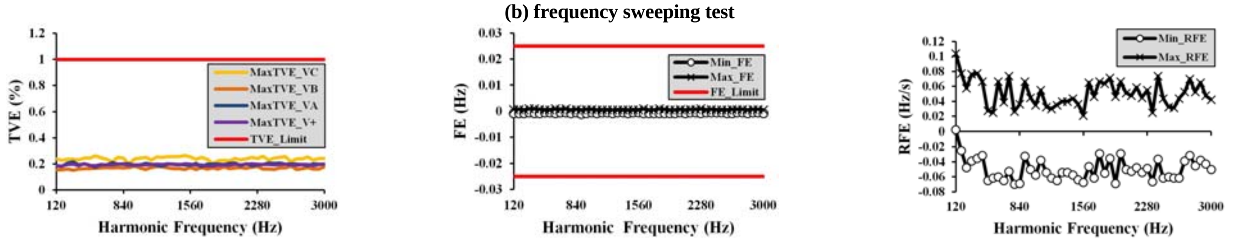
The suggested probabilistic metrics are calculated for various static and dynamic tests for the PMU under study. The results are tabulated in Table II. The success probability indicators for various static and dynamic tests are evaluated in columns 3-5. As can be seen in Table II, while the error values for some standard tests are perfectly within the desired thresholds in all the test scenarios (e.g., harmonic distortion), the success probability of some other tests is very low (as low as 0.18% for out-of-band test) reflecting the fact that the probability of incorrect or not accurate reported measurements is extremely high with unacceptable level of uncertainty. Some conditions that PMU under test is seeing,



(a) voltage magnitude sweeping test



(b) frequency sweeping test



(c) harmonic distortion test

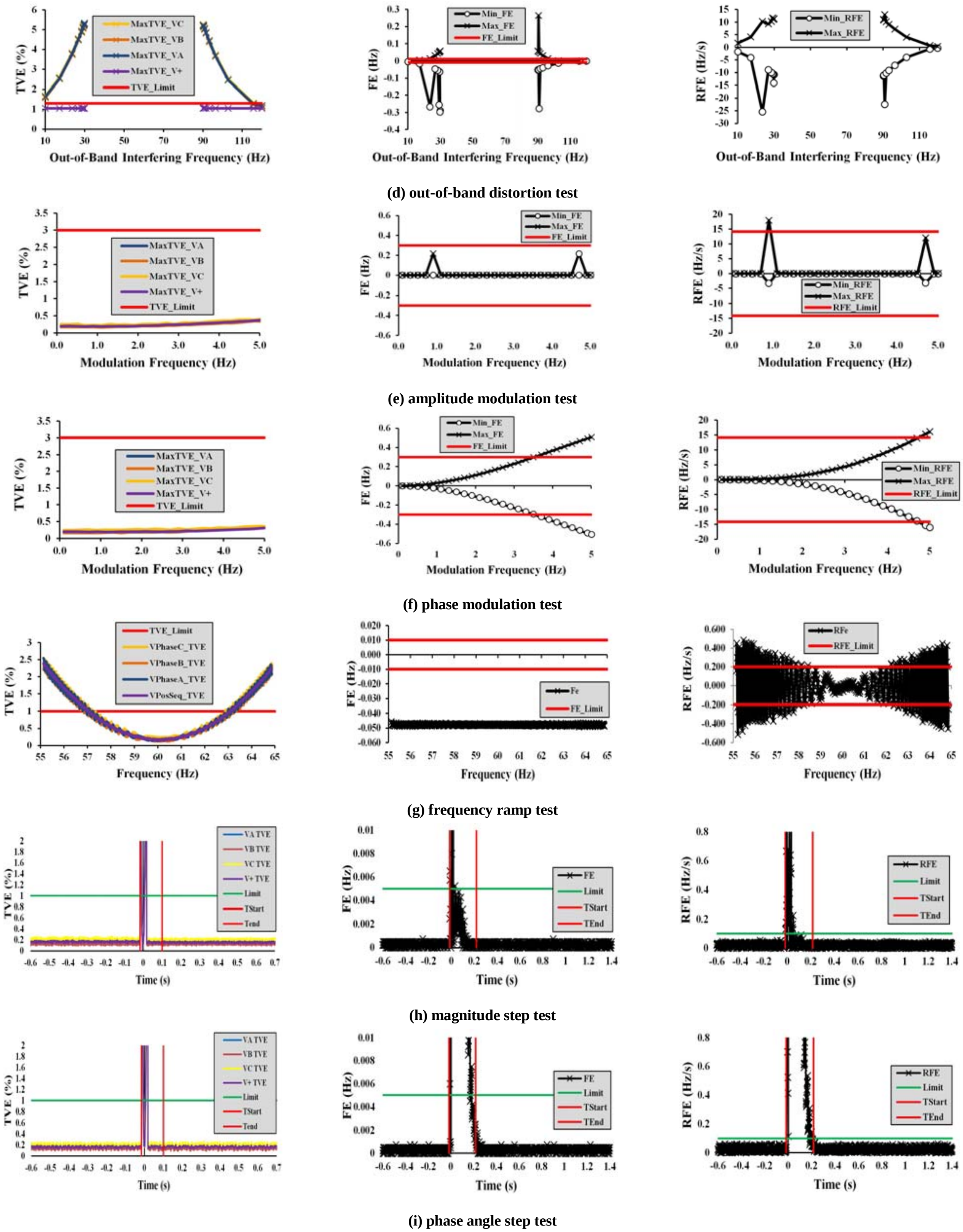


Fig. 4. Test rsults of a given PMU udner various static and dynamic test conditions

taking into account wide range of signals (i.e. frequency equal to 45/65 Hz, or voltage magnitude equal to 10% of nominal value), are not very likely to happen in real-world, but are important to certify a PMU calibration procedure. Therefore, even if the PMU under test fails in one of such test conditions, it does not imply that the tested device is 100% unreliable while exposed to extreme signal conditions. Rather than solely a pass/failed status, this index highlights the success rate of all

TABLE II. PROBABILSITIC METRICS FOR PMU VULNERABILITY AND INTEGRITY ASSESSMENT

Test Category	Test Name	$P_{TVE,i}^{[.]}$	$P_{FE,i}^{[.]}$	$P_{RFE,i}^{[.]}$	$P_i^{ST_k}$	$P_i^{DT_k}$	$\eta_{TVE,i}^{[.]}$	$\eta_{FE,i}^{[.]}$	$\eta_{RFE,i}^{[.]}$
Steady Tests	Magnitude Sweeping	0.91	1	1	0.91	N/A	0.67	N/A	N/A
	Frequency Sweeping	0.60	1	0.52	0.32	N/A	0.34	0.99	0.99
	Harmonic Distortion	1	1	1	1	N/A	0.83	0.99	N/A
	Out-of-Band Interference	0.18	0.39	1	0.072	N/A	0.06	0.90	N/A
Dynamic Tests	Amplitude Modulation	0.98	1	1	N/A	0.98	0.94	0.99	0.99
	Angle Modulation	1	0.89	0.97	N/A	0.86	0.94	0.99	0.99
	Frequency Ramp	0.48	0	0.69	N/A	0	0.11	0	0.99
	Magnitude Step Change	0.81	1	1	N/A	0.81	0.81	N/A	N/A
	Angle Step Change	0.70	1	1	N/A	0.71	0.82	N/A	N/A

the test scenarios within a given type-test and, as a result, is a reliable measure to recognize sustainable problems in a PMU device and differentiate them from ephemeral conditions that might have led to a test failure. Taking into account all various error values, the probabilities reported in columns 6-7 demonstrate the PMU integrity values with respect to all the static and dynamic tests, respectively.

The PMUs may pass all the static and dynamic tests, but the test results do not reflect the uncertainty level of the test acceptance. In other words, the original test results do not reveal how close the errors are to the standard thresholds. The probabilistic values calculated in the last three columns of Table II show, in the range of 0-1, the distance of the measurement errors to the desired thresholds for various tests. The N/A entries in Table II reflect the fact that there is no desirable thresholds reported for a given error metric corresponding to several static and dynamic test in the standards. The closer the distance values ($\eta_{e_k,i}^{[.]}$) are to 1, the more reliable the test results are with respect to the desired thresholds. As the probabilistic distance metrics decrease, the test results are vulnerable to failure in the next test interval and the periodic maintenance plans need to be expedited; otherwise, the PMU measurements and consequently the end-use synchrophasor applications in power system may not be reliable in practice.

V. CONCLUSIONS

The paper accomplishes the following:

- It shows the importance and necessity of testing the synchrophasor devices in the field for a more efficient periodic maintenance planning.
- Probabilistic metrics are proposed to evaluate: a) underlying vulnerability of the PMU responses under both static and dynamic tests, and b) the integrity measure of the PMU devices over time.
- The proposed method could recognize the sustained problems in PMU under test for an expedited maintenance plan.
- The suggested analysis tool offers the user test results in face of various dynamic and static conditions revealing a more realistic view on the vulnerability of PMU, which may lead to fine tuning of the periodic maintenance schedules when and where necessary.

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