Analysis of PMU Algorithm Errors During Fault Transients and Out-of-Step Disturbances

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***Abstract*— Various applications of synchrophasors in power system protection may be impacted by the measurement errors and limitations originated from the estimation algorithms in the Phasor Measurement Units (PMUs). While standard C37.118.1a-2014 has specified the permissible limits for PMU measurement errors under various static and dynamic test conditions, the impacts of such errors on the protection related applications in power systems are rather unknown. Knowledge on how the errors introduced by various phasor estimation algorithms affect the accuracy of protection applications could help speeding up the deployment of synchrophasor technology in real-world protection applications. This paper introduces an analytical support tool that is able to evaluate the performance of PMU estimation algorithms under fault transients and out-of-step disturbances. Actual tests are performed using the synchrophasor calibration set up.**

***Keywords*— Application error; fault location; out-of-step protection; phasor measurement; PMU error; synchrophasor algorithm.**

I. INTRODUCTION

Since 2005, 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. The IEEE C37.118.1-2011 standard defines the acceptable performance of synchrophasor measurements in power systems [1]. 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 able to meet the standard [2]. 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) [3]. TSS provides a suite of unambiguous test plans in accordance with Smart Grid Interoperability Panel Recommendations and Interoperability Process Reference Manual. The IEEE C37.118.2-2011 standard covers requirements for the PMU data transfer in power systems [4] and the IEEE C37.242-2013 document provides guidance for synchronization, calibration, testing, and installation of PMUs applied in power system protection and control [5]. 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 [6].

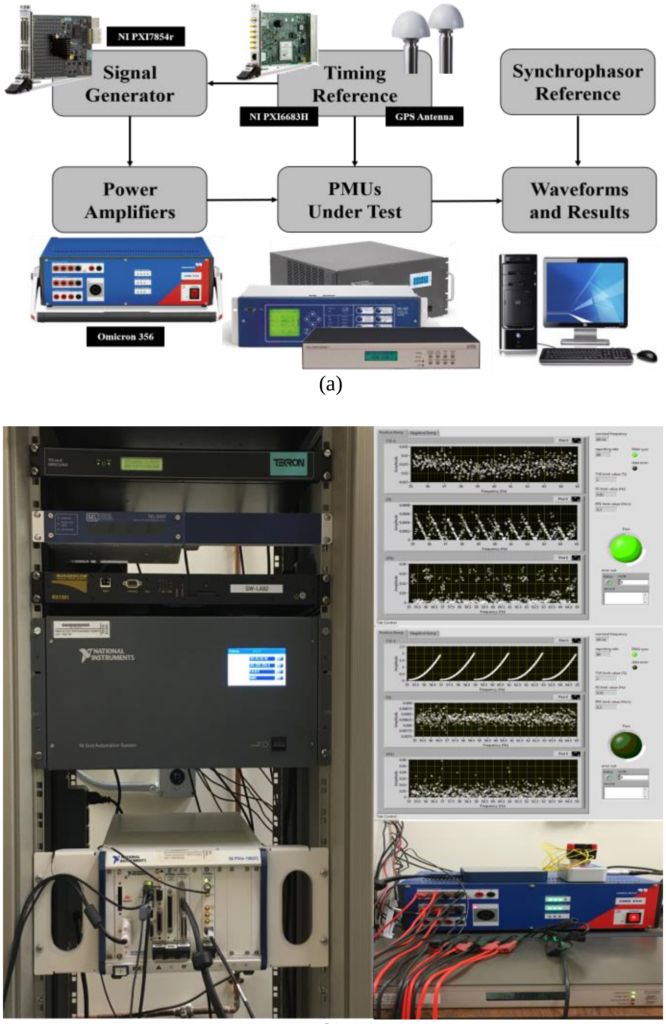
According to the above standards, two performance classes of PMUs, namely P and M, are defined where the P-class is intended for protection applications demanding fast measurement response time, while the M performance class is utilized in applications that require high measurement accuracy [1]. A standard-compliant PMU should meet all the requirements, at least for one class, for the type-test steady state and dynamic performance. While compatibility of commercial PMUs with the IEEE standard C37.118.1a-2014 is commonly confirmed, calibration laboratory tests reveal noticeable inconsistencies among the phasor estimates obtained by PMUs from different manufacturers due to different algorithm performance under the conditions not specified in the standards. Such wide range of phasor estimation techniques and resulting performance differences necessitate quality assessment [7]-[17], compliance analysis [18], calibration [19], [20], and field testing [21], [22]. Additional studies also revealed a noticeable difference between the simulation results and real-world outcomes captured by PMUs [23]. This suggests that there is no guarantee that different end-use applications would perform satisfactorily even if the PMUs pass standard type-tests. Our paper describes a comprehensive analytical tool developed in conjunction with a PMU calibration test set to quantitatively assess the accuracy of synchrophasor measurements under fault transients and out-of-step disturbances.

The remainder of the paper is structured as follows. Section II elaborates the general structure of the developed PMU calibration set up as well as its various functionalities. The importance of an extensive test support analytics for result analysis is illustrated through two synchrophasor-based power system protection applications, namely fault location and out-of-step protection, and briefly highlighted in Section III. Experimental results and numerical case studies are presented in Section IV following by the concluding remarks in Section V.

II. PMU CALIBRATION TESTBED

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 shown in Fig. 1(a) and the actual implementation of such test environment is illustrated in Fig. 1(b). As shown in Fig. 1(a), the PMU test system consists of a timing reference (GPS receiver), signal generator, power amplifier, and data management and results analytics tools. The timing reference provides GPS clock and time-code information to the calibration equipment and to the device under test so that the entire system is synchronized and time-stamped. Test signals are generated by the signal generator according to test types determined by the IEEE TSS document [3]. The calculated and theoretical reference synchrophasor can be, hence, used for the comparison, and then followed by a result analysis and documentation.

The PMU test and calibration platform is implemented using National Instrument (NI) hardware as shown in Fig. 1(b). 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 356 power amplifier to generate 3-phase voltage and current signals feeding the PMU device under the 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, analyzed, and the reported using the NI LabVIEW software interface [24]. Reports consist of all data reported by tested PMU as well as true values of phasors sent to the device, which allows extensive post-analysis of the collected results.



(a)

(b)

Fig. 1. Calibration platform for PMU testing.

III. PMU CALIBRATION AND APPLICATION TESTS

Various applications for power system protection have different sensitivities to the data errors in the input measurements. Moreover, different PMU algorithms for synchrophasor estimations may have different responses to the input signals experienced during different protection application disturbances. The impacts of such input signal uncertainties and related application errors are largely unknown to the end-users and need to be fully investigated.

PMUs provide different types of calculated values such as voltage and current magnitude, angle, frequency, rate of change of frequency, etc. According to the IEEE standard C37 118.1, 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 the measurements are captured according to the standard procedure. 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. Dynamic type-tests involve testing PMUs with the modulated signals, chec-king 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. Even though the IEEE standards define the basic type-tests that PMUs have to undergo with certain precision, the test procedure does not reveal the impact of such results on the system-wide applications. In addition, the error impacts of the signal components being present at the time of a specific protection event are not known. The performance is further affected by different requirements in terms of calculation speed, accuracy of estimated frequency, angle and magnitude measurements, etc., which are different for different protection applications. Making meaningful trade-offs between such performance indicators to reduce the error impact is, hence, an imperative. Since such decisions are made at the time of the PMU design, the user is primarily interested in evaluating the performance under various application scenarios. In order to build a trustworthy mindset for the protection end-users, the first step is to recognize the critical parameters of interest for a given application and then evaluate how the estimation algorithm matches the application requirements using the results acquired from the calibration tests. Such analyses could build the confidence about the quality of the synchrophasor application outputs.

A. *Synchrophasor-Based Fault Location*

PMU measurements, if judicially employed, can help in more accurate fault detection and fault location. Information on the magnitude and angle of the current signals and voltage phasors are also crucial to accurately locate the faults in electric power systems [25], [26]. In fault location applications, accurate measurement of the frequency is commonly not the priority, but knowledge about the change in frequency can help improve some of the fault-location algorithms. Observations on the performance of various phasor estimation algorithms under such application conditions can offer a more realistic view on whether the PMU measurements can be employed for such applications and which fault location algorithm is expected to be fundamentally more accurate.

B. *Out-of-Step Protection*

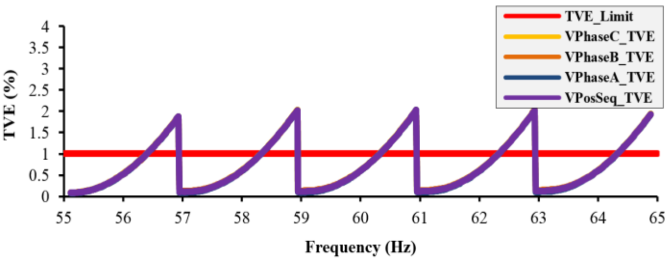
Power system frequency during the steady state conditions is very close to the nominal value (i.e. 60Hz in US). Sudden changes in the frequency or deviations from the nominal value can be used as an alert signal, indicative of an abnormal phenomenon in the grid. By using the precise PMU measurements to derive the frequency and the rate of change of frequency indicators, it would be possible to notice the probable loss of synchronism between network generators [27], [28]. The test results obtained from the calibration lab can be used to quantify the precision of different algorithms employed in the out of step protection applications.

IV. Numerical Results

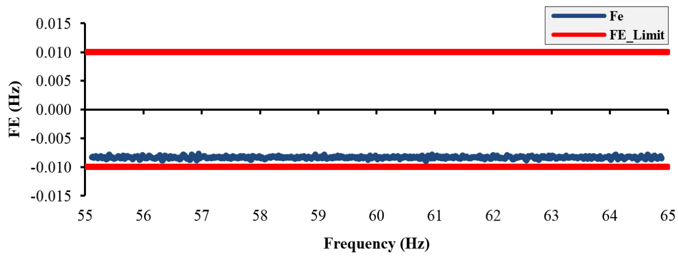
Some of the PMU devices are equipped with various options for the estimation algorithms (in both P and M performance classes). The options include different windowing functions and filters, adaptive tuning capability of the estimation algorithm, number of cycles used for calculation of the phasors, and are provided to user as the optional parameters to be defined and used within a given PMU device. Correct choice of such parameters is crucial for an accurate synchrophasor measurement.

To prove the hypothesis that different protection applications may be affected differently by unfolding signal components during the events, several PMUs were tested using the mentioned calibration test set. PMUs were exposed to different test signals and the performance of each product is thoroughly analyzed. Fig. 2 demonstrates example results during the frequency ramp test for three different windowing functions corresponding to one of the tested PMU devices: Blackman, Hamming and Flat Top. It can be seen in Fig. 2(a)-(c) that the Flat Top windowing approach has the best comparative performance regarding the voltage magnitude and angle measurements. Estimation errors are presented in the form of Total Vector Error (TVE) for which the definition is provided in the IEEE Std. C37 118.1-2011 [1]. While measuring voltage vectors precisely, it can be seen in Fig. 2(d)-(f) that the error in measuring the frequency is higher using the Flat Top algorithm compared to the Blackman windowing function. The reason for this observation is activation of the adaptive frequency tracking option for better estimation performance during the off-nominal frequency measurements. As a consequence, the time offset is present and the measurement of the frequency is not deemed accurate. On the other hand, the Blackman filtering approach has the best performance regarding the accurate measurements of the frequency, while the TVE is insignificantly above the allowed limits. The Hamming windowing function was proved to have the worst performance compared to the other two algorithms during this specific test. It can be generally concluded from Fig. 2 that: (1) different PMU algorithms can perform differently for a given application and (2) even if a given algorithm does not pass some type-tests according to the standard requirements, it still can perform as expected for a specific application in real world scenarios.

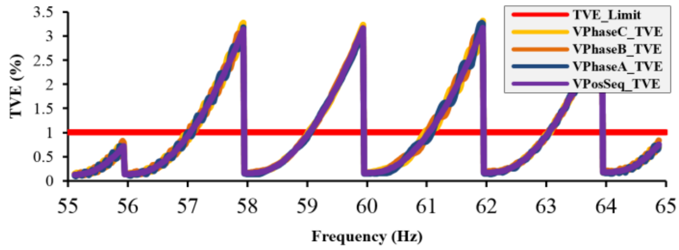
Table I summarizes the results obtained from the frequency ramp test using different windowing algorithms. Given the errors in estimating the voltage and current phasors, the induced error in calculating the distance to the fault can be assessed as tabulated in Table I. The calculated errors are ranging from 0.6% corresponding to the Flat Top algorithm up to 7% associated with the Hamming function.



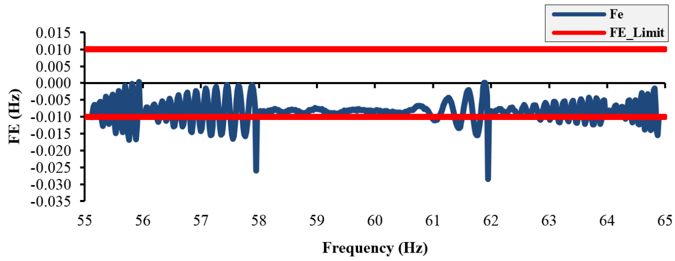
(a) Blackman windowing



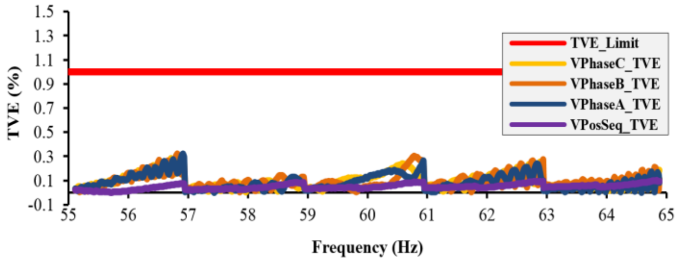
(d) Blackman windowing



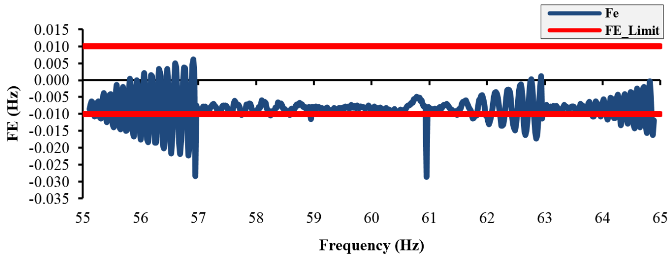
(b) Hamming windowing



(e) Hamming windowing



(c) Flat Top windowing



(f) Flat Top windowing

Fig. 2. Frequency ramp test performance of PMU algorithms using different windowing algorithms: voltage TVE (a)-(c) and frequency error (d)-(f).

TABLE I
PERFORMANCE OF VARIOUS PMU ALGORITHMS IN FREQUENCY-RAMP TESTS FOR FAULT LOCATION CALCULATIONS

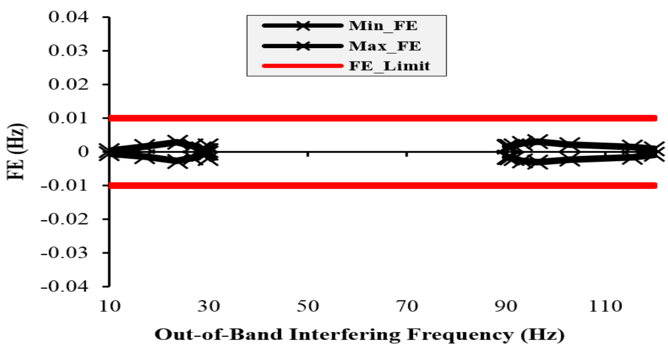
Windowing Algorithm	Voltage Error TVE (%)		Current Error TVE (%)		Impedance Error (%)	Frequency Error FE (%)	
	mean	max	mean	max	max	mean	max
Flat Top	0.086	0.321	0.115	0.348	0.6667	8.316 E-3	0.022
Nuttal	0.467	1.511	0.458	1.473	2.9407	8.328 E-3	0.009
Blackman	0.705	2.027	0.691	1.996	4.1049	0.183 E-3	0.008
Hamming	0.966	3.276	0.953	3.243	6.7375	8.325 E-3	0.019

For the application evaluation, errors from the instrumentation channel, data errors, and errors induces by the network should be also included along with those represented in table I. This further highlights the fact that some phasor estimation algorithms may not provide an accurate fault location in real world applications.

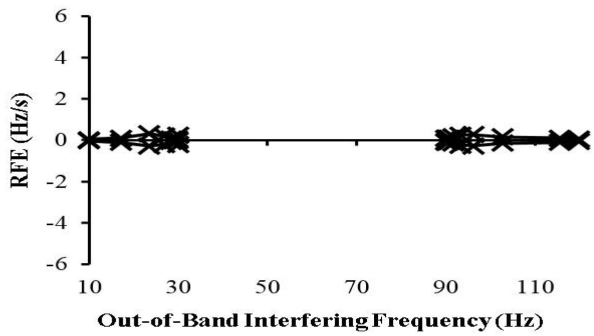
In case where there are some out-of-band signal interferences in the grid, not all the PMU algorithms may be able to estimate the frequency response accurately enough for out-of-step protection applications. As an example, the results from the conducted type-tests using the nominal frequency with inter harmonic add-ons and errors in estimating the rate of change of frequency (ROCOF) are presented in Fig. 3.

It can be seen in Fig 3(a)-(d) that only the Blackman windowing function can measure the frequency and ROCOF within the acceptable limits according to the standard requirements. All the other algorithms have introduced significant errors close to the borders of the band, which causes them not to be the best choice but rather a higher-risk option for the out-of-step protection applications.

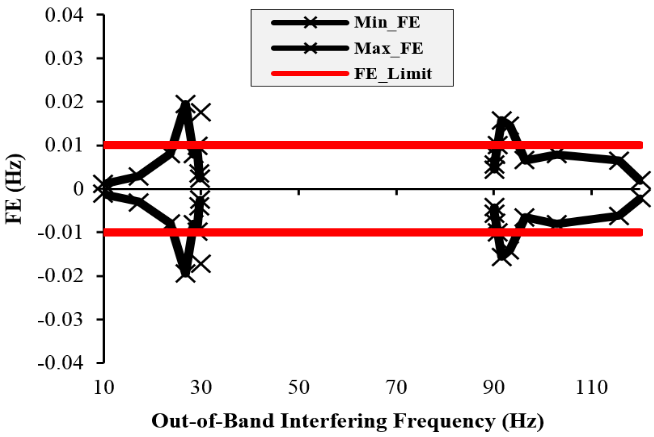
Even though the limits for the existing errors in the measurements of the ROCOF are not specified in the IEEE standard, it is worth to mention that among the different algorithms studied, the deviation is noticeable [see Fig 3(e)-(h)] and if this measurement is going to be used for the application, one should be careful in choosing an appropriate filter function.



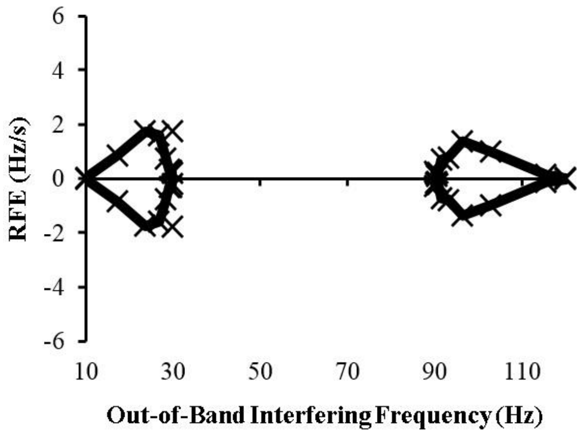
(a) Blackman windowing



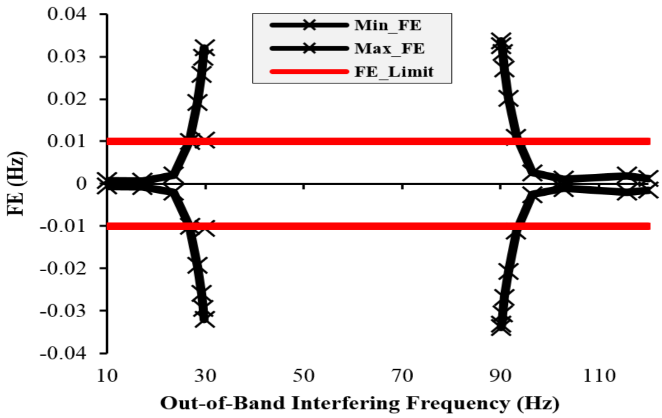
(e) Blackman windowing



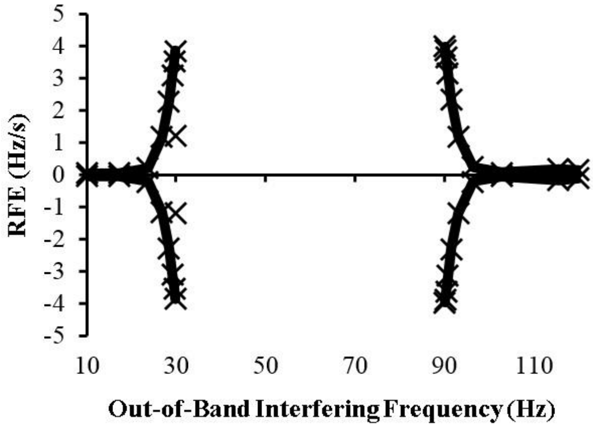
(b) Hamming windowing



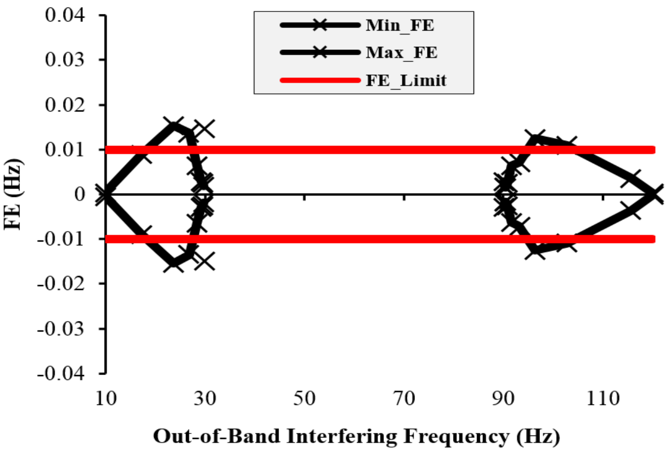
(f) Hamming windowing



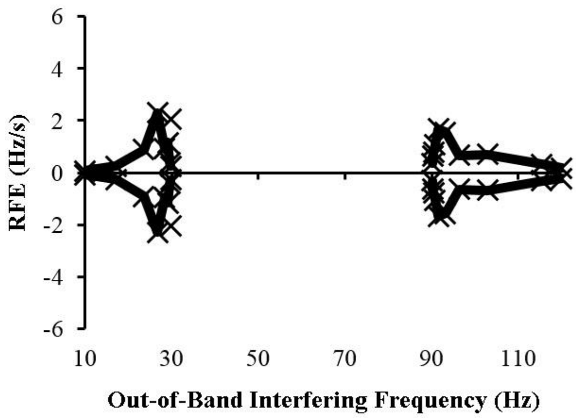
(c) Nuttal windowing



(g) Nuttal windowing



(d) Flat Top windowing



(h) Flat Top windowing

Fig. 3. Out-of-band frequency test performance of PMU at 60Hz using different windowing algorithms: Frequency Errors (FE) (a)-(d); Rate of Change of Frequency Errors (e)-(h).

V. Conclusions

The paper accomplishes the following:

- It shows the importance of application tests when evaluating protection performance by identifying the relevant errors and algorithm limitations that could significantly affect the accuracy of such applications.
- The proposed tests offer a realistic understanding of the impact of the performance of various PMU algorithms under static and dynamic events on fault location and out-of-step protection.

- The proposed test methodology will help the end users assess benefits and evaluate the risks associated with the use of synchrophasors in fault location and out-of-step protection applications.

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