Critical analysis of PMU testing procedures for step response evaluation

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***Abstract*—The Phasor Measurement Units (PMUs) are becoming an important element for the measurement systems of the electrical grid. To assure the high penetration of these measurement devices, the interoperability of the PMUs from different vendors must be ensured. The IEEE Standard C37.118.1-2011, with its amendments of 2014, defines two accuracy classes, P and M, and provides the steady state and the dynamic tests to be passed to achieve compliance. This paper focuses on the dynamic compliance in presence of step changes in phase and magnitude. In particular, the approach proposed by the standard to evaluate the performance of a PMU when it is exposed to a step change signal input is analyzed and compared with a complete sample by sample approach in a simulation environment. The measurement results, in terms of response time, delay time and undershoots/overshoots and their accuracies, for different reporting rate, are discussed.**

Keywords*— *Phasor Measurement Unit; step change test; PMU dynamic behavior; total vector error; response time; delay time; overshoot.

I. Introduction

The Synchrophasor Standard IEEE C37.118.1 of 2011 [1] is dedicated to the requirements and accuracy limits for synchrophasor, frequency and Rate of Change of Frequency (ROCOF) measurements. It defines the PMU as a standalone device or a functionality in another device as the IED (Intelligent Electronic Device) [2] [3]. The Standard IEEE C37.118.1-2011 has been recently updated with its amendment IEEE C37.118.1a of 2014 [4] with modified performance requirements, especially for ROCOF and latency. The Standard, as indicated in the following, does not specify the hardware, software solutions or methods for evaluating the synchrophasor, frequency and ROCOF, and this allows a heterogeneous choice of algorithms for the estimations and of technical solutions and architectures for PMUs from different vendors.

In this scenario, one of the most important goals of the Standard is to guarantee the interoperability of the PMUs [1]. To achieve it, the Standard proposes two different classes of accuracy: the P class, specific for protection and fast applications, and the M class, specific for measurement applications. To obtain the compliance, the PMU needs to overcome the tests for the specific accuracy class. The Standard provides different tests for each class and they are divided in steady state and dynamic test. The most important parameter to evaluate the synchrophasor measurement performance of any PMU under test is the Total Vector Error. TVE can include errors in magnitude, phase or synchronization. The standard also provides the parameters to evaluate the performance in the frequency (FE, frequency error) and ROCOF measurements (RFE, ROCOF error).

A particular class of dynamic tests is the one of step change conditions used to simulate the switch operation or a fault [5]. To evaluate the performance in these conditions, the Standard does not suggest a maximum limit of TVE, but introduces three more indices: the response time, the delay time and the maximum overshoot/undershoot. Such indices describe the step response of the device under test. The limits for all the indices generally depend on the reporting rate the PMU is using. Therefore, it is necessary to implement specific measurement procedures to derive a value for each index starting from discrete measurement points at a given reporting rate. In fact, it is necessary to increase the resolution of each test [5].

In [6] and [7] an interleaving technique, called equivalent time sampling, based on repeated steps is presented. The results of different tests are overlapped on the same timescale to determine a response curve to evaluate the specific indices for the step tests. The Standard [1] relies on the equivalent time sampling concept when it describes its specific procedure to perform response time, delay time and overshoot/undershoot measurements from repeated step tests and suggests a number of ten tests for each reporting rate value.

Such techniques are generally used in the test and calibration operations of these devices [8], [9]. On the contrary, in the simulation studies (see for example [10]), where the reporting rate can be equal to the generation frequency of the signal, the time resolution is usually considered sufficient to avoid the need for equivalent time sampling techniques.

In this paper, the differences and the accuracies of step response assessment procedures are investigated in a simulation environment. The aim is to point out, in a controlled situation, limits and problems of the practical testing techniques, in particular for P-class PMU algorithms. Subtle differences characterize the procedures, depending on the specific test signal generation and measurement collection and interleaving methodologies, thus leading to different results in compliance tests. For this reason, the values and accuracies obtained for response time, delay time and undershoot/overshoot by two analyzed testing procedures are compared with the results of a complete sample by sample approach, used as a reference. Problems introduced in case of different type of step responses and different reporting rates are also discussed.

II. Step Tests

The Standard [1] defines the generic balanced three-phase step test signals to be used in the test of PMU dynamic response as follows:

$$
\begin{aligned}
X_a(t) &= X_m\big(1 + k_x f_1(t)\big)\cos\big(2\pi f_0 t + k_a f_1(t)\big) \\
X_b(t) &= X_m\big(1 + k_x f_1(t)\big)\cos\left(2\pi f_0 t - \frac{2\pi}{3} k_a f_1(t)\right) \\
X_c(t) &= X_m\big(1 + k_x f_1(t)\big)\cos\left(2\pi f_0 t + \frac{2\pi}{3} k_a f_1(t)\right)
\end{aligned} \quad (1)
$$

where X_m is the amplitude of the input signal, f_0 is the nominal frequency (50 or 60 Hz), k_x and k_a are the relative magnitude step size and the phase step size in radians, respectively. $f_1(t)$ is a step unit function. The generic translation $f_1(t - t_r)$ implies the translation of the step occurrence at the time instant t_r.

Three main indices are used to describe and verify the dynamic response to step signal inputs:

1. The response time, that is the duration of the time interval during which the measurement error of the quantity under investigation is outside the limits given for measurement errors under steady-state tests. In particular, for synchrophasor estimation, the percent TVE limit of 1 % is used. For FE a limit of 5 mHz is considered, while for RFE a limit of 0.4 Hz/s for P-class and of 0.1 Hz/s for M-class is considered, respectively.
2. The delay time, that is the time distance between the step occurrence and the instant when the measured parameter reaches the halfway point between the starting and the ending values of the step change. In particular, the quantity of interest is the amplitude for amplitude steps and the phase angle for phase steps, respectively.
3. The overshoot/undershoot, that is the maximum/minimum value reached by the changing quantity (amplitude and phase angle, as for delay time) during the step response.

The third index describes a parameter of the dynamic response, while the first two refer to time durations. The Standard prescribes that "*the times when error limits are crossed and the measurement crosses the 50% line shall be determined to an accuracy of one-tenth of the reporting rate that is being tested*". For instance, for a reporting rate (RR) of 10 frames/s, the accuracy required for each point is 10 ms, meaning a maximum deviation of 20 ms for response time and 10 ms for delay time evaluation, respectively. In particular, for response time the maximum deviation would be 20 ms with respect to a compliance limit for P-class of 40 ms ($2/f_0$) for the nominal frequency of 50 Hz [4]. For the delay time, the maximum deviation would be 20 ms with respect to a limit equal to 25 ms.

While response time and delay time measurements are directly affected by the time resolution of the performed tests, even the over/undershoot identification and measurement are strictly related to the possibility of accurately following the step response shape. For these reasons, it is important to correctly identify the limits of each proposed test procedure and to understand their impact on the compliance verification.

Since PMU outputs reflect the set reporting rate, the Standard itself recognizes that [1]: "*The PMU response times and delay times are small compared to the PMU reporting intervals. The specified response times …… are less than three or five reporting intervals, and delay times are less than a quarter of a reporting interval. It is unlikely that reported data points will fall on the specified measurement points, so determining those points with a single step test may be insufficient. A series of tests with the step applied at varying times relative to the reporting times can be used to achieve this result*".

Following such note, to reach a time resolution corresponding to the aforementioned point identification constraints, the Standard suggests how to increase the time resolution for the step tests. The idea of an equivalent time sampling approach is recalled and described in details. In particular, the Standard states that [1]:

"*This equivalent time sampling approach can achieve the required measurement resolution. In effect, this technique moves the step time to derive points on the measurement to "fill in" a curve. The PMU measurement reports are at fixed points in time relative to the UTC second, so moving the steps a fraction of the reporting interval gives reports at different points on the measurement curve. These measurements are combined to give a step response result with a time resolution less than the reporting interval. This technique controls the relation between the step time t in the unit step function $f_1(t)$ and one of the reporting times. The unit step function time is adjusted to fall on a reporting time for one step test. Successive step tests are performed with the unit step function times falling at increasing fractions of a reporting interval after a reporting time. .... The resulting measurement points are interleaved by aligning all of the steps at the same point and combining the measurements with their corresponding offsets from the step. This gives an equivalent measurement step response with a time resolution of T/n. In general, an accurate measurement of the PMU response time, the delay time, and the overshoot percentage can be made with n = 10.*"

Such algorithm, which will be referred to as method Std in the next section, has to be carefully analyzed in order to exactly follow the Standard. By carefully examining the text of the Standard, it corresponds, on a single phase basis, to testing the following generic signals:

$$X_a(t, kT/n) = X_m\left(1 + k_x f_1\left(t - \frac{kT}{n}\right)\right) \cos\left(2\pi f_0 t + k_a f_1\left(t - \frac{kT}{n}\right)\right) \quad (2)$$

where $k = 0, \cdots, n-1$ and $n = 10$. The PMU phasor measurements for each test are:

$$p_a(iT, kT/n) = a_a(iT, kT/n) e^{-i\varphi_a(iT, kT/n)} \quad (3)$$

where the index i is the measurement sampling index of the PMU that corresponds to the specific reporting instants. At least $i = 0$, +1 are needed for a meaningful representation of the transient. Once the samples $a_a(iT, kT/n)$ for amplitude steps and $\varphi_a(iT, kT/n)$ for phase steps are collected, they have to be realigned and allocated at the equivalent time instants $iT - kT/n$ to form the step response shape, from which the indices are computed. Similar concepts hold also for frequency and ROCOF response time evaluations.

Fig. 1 depicts the described procedure graphically. The hypothetical continuous lines represent the PMU responses (for the stepped quantity) that would be obtained by very high reporting rates (sample by sample for instance, as described in the following), when the step instant is moved as described by the procedure. In fact, the given procedure includes different tests, with varying step instants, but with the same initial phase angle of the input signals, that implies different phase angles at the step instants. For this reason, the sampled points obtained by PMU measurement at the reporting instants, when realigned, build an equivalent step response that does not correspond to an actual response, but tends to mix the effects of different signals into the same measurement procedure. This happens even focusing only on a single phase of the system.

It is intuitive that, for response time evaluation, the points that are above the prescribed limit can be chosen without violating the requirements of accuracy. Thus, if m is the number of such points mT/n, $(m-1)T/n$ and $(m+1)T/n$ are all valid response time measurements for the standard. Obviously, the second and the third ones are always underestimating and overestimating the response time, and their variability intervals are (0,2T/n) and (-2T/n,0), respectively. mT/n instead, is equivalent to consider the point crossing the TVE % limit of 1 % as the middle point of the interval delimited by the two points below and above the limit. Thus each instant is identified with a maximum possible error of $\pm T/(2n)$, which thus becomes $\pm T/n$ for the response time . This approach will be used in the next section to report the results.

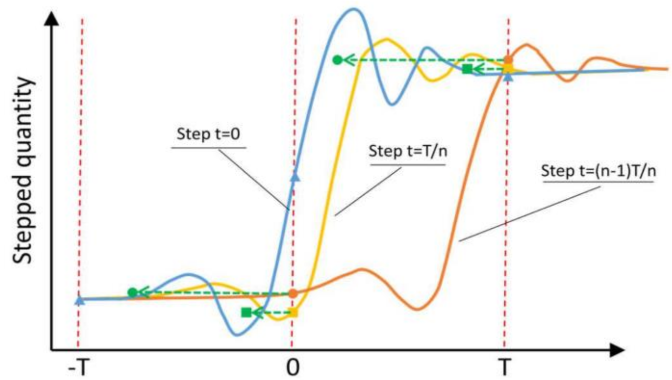

Fig. 1. Method proposed by the standard to analyze the step response

For delay time, both the points that define the 50% step crossing in such discrete domain can be correctly adopted. The two possible choices (the point that is nearer and the point that is further from the step instant) correspond to underestimating or overestimating the delay time and thus they define, respectively, the two intervals (0,T/n) and (-T/n,0). In the next section, the results will be reported following the second approach.

The guide for testing IEEE C37.242 [11] defines the six steps of the practical procedure to generate the signals and collect the measurements needed for the indices evaluation.

Following a different interpretation of the measurement and interleaving approach, another procedure can be defined. The underlying idea is that of an enhanced resolution time sampling, that aims at obtaining through multiple tests and realignment the sampling of a single step signal response at a higher reporting rate.

Equation (2) can be then replaced by the following set of signals:

$$\hat{X}_a(t, kT/n) = X_m\left(1 + k_x f_1\left(t - \frac{kT}{n}\right)\right) \cos\left(2\pi f_0 (t - \frac{kT}{n}) + k_a f_1\left(t - \frac{kT}{n}\right)\right) \quad (4)$$

that are exact translations of the entire signal with step in $t = 0$ (as before, $t = 0$ is considered a valid UTC reporting time).

In this case, with a single-phase notation, the measurements $\hat{a}_a(iT, kT/n)$ and $\hat{\varphi}_a(iT, kT/n)$ can be obtained and realigned with the same allocation as before. Fig. 2 illustrates such procedure, highlighting the difference with the one described by the standard. As aforementioned, the continuous lines indicate the responses that would be achieved with sample by sample measurements. In this case, all the lines are, in theory, just the translated versions of the one corresponding to a step in $t = 0$. Thus, the measured values of such translated signals, when realigned on the same time scale of the first step signal, fall exactly onto the continuous line, representing a denser sampling of such response. For this reason, the method will be indicated in the following as shifted repeated signal method (SRS in the following).

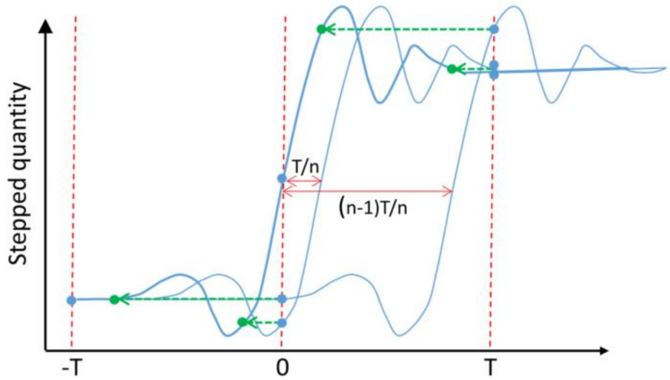

Fig. 2. SRS method for step signal analysis.

To allow a comparison in a controlled environment and the investigation of the subtleties and peculiarities of the step test measurements, it is important to define a complete and reference evaluation procedure that works in a simulation environment. For this reason, a sample by sample procedure is defined. The following signals are considered:

$$\bar{X}_a(t, kT_c) = X_m\big(1 + k_x f_1(t - kT_c)\big) \cos\big(2\pi f_0 t + k_a f_1(t - kT_c)\big) \quad (5)$$

In a simulation environment, t is a multiple of the sampling interval T_c and $k = 0, \cdots, M_c - 1$, where M_c is the number of samples per nominal cycle. The measurements can be obtained sample by sample, thus getting $\bar{a}_a(iT_c, kT_c)$ and $\bar{\varphi}_a(iT_c, kT_c)$, where iT_c now spans the test duration and all the possible translations of the step are considered. With such amplitude and phase angle values, M_c step response graphs can be built. Each graph leads to a computation of the three indices, thus allowing to find the worst case as the maximum (minimum in case of undershoot) for each index. These values can be considered the reference ones, since such procedure allows to completely follow the shape of the dynamic response and to identify the intervals with a time resolution depending only on the sampling interval T_c ($100\ \mu$s for sampling frequency $f_c = 10$ kHz, as adopted in the following). Such procedure will be referred to as SbyS in the next Section.

III. Tests and Results

To illustrate the results of the different measurement procedures for step test evaluation, three different algorithms are used (the chosen sampling frequency is $f_c = 10$ kHz). They correspond to three different filters of the same length (2-cycle duration at nominal frequency $f_0 = 50$ Hz). In particular, the following are used:

- P-class reference filter (P-Std, in the following), described in Annex C of the standard [1]. It corresponds to a 2-cycle triangular window. The amplitude compensation based on frequency estimation is not used in the following.
- A first order Taylor Fourier filter (TFF) with Kaiser weighting [12]. A 2-cycle window with shape parameter β=5 is used. In the following, the method will be referred to as TF_1.
- A second order Taylor Fourier filter (TFF) with Kaiser weighting. A 2-cycle window with shape parameter β=5 is used. Such filter is chosen to better illustrate the behavior in presence of undershoot/overshoot. In the following, the method will be referred to as TF_2.

Such methods are used to show possible scenarios occurring during PMU testing and, in particular, to investigate the responses and the measurement outcomes for different choices of the PMU algorithm. Short filters, candidate to compliance with the P-class of the standard, at least for synchrophasor measurement, are considered. In fact, the P-class has stricter requirements in terms of response time and thus asks for faster transients, thus emphasizing the importance of dynamic behavior measurements. Besides, as aforementioned, P-class response time limits are independent of the reporting rate and, thus, of the time resolution suggested by the Standard.

Since the step tests are performed at nominal frequency, the presence of a frequency tuning method for the filters is not considered in any case and the dynamic response can be considered as intrinsically representative of the response of the digital filter for each method.

For each algorithm, the three different test methods presented in Section II are applied. Table I presents the results, in terms of response time, for $\pm 10\,\%$ amplitude step application. In this test, a reporting rate of 10 frames/s is considered for Std method and SRS method (testing procedures). Std and SRS compute the response time by using the mT/n rule defined in Section II, thus giving a maximum possible error of ± 10 ms. The results show that, for P-Std algorithm, the variability range is, for both the testing procedures, 20-40 ms, that reaches the limit fixed by the standard for P-class methods. For algorithms TF_1 and TF_2, the same uncertainty interval is obtained, even for quite different response times. However, in this case, both the testing procedures give intervals that include the reference value obtained by SbyS.

TABLE I. Response Time results for ±10% Amplitude Steps. RR=10 frames/s

Algorithm	**Response Time [ms]**					
	Step + 10%			***Step -10%***		
	Std	***SRS***	***SbyS***	***Std***	***SRS***	***SbyS***
P-Std	30.0 ±10.0	30.0 ±10.0	22.6 ±0.1	30.0 ±10.0	30.0 ±10.0	23.7 ±0.1
TF_1	10.0 ±10.0	10.0 ±10.0	17.5 ±0.1	10.0 ±10.0	10.0 ±10.0	18.2 ±0.1
TF_2	10.0 ±10.0	10.0 ±10.0	11.8 ±0.1	10.0 ±10.0	10.0 ±10.0	12.1 ±0.1

Different considerations arise for the case of RR=50 frame/s. Table II reports the response time results of the testing procedures (the maximum possible error caused by time resolution is ± 2 ms) compared with the reference SbyS method.

TABLE II. RESPONSE TIME RESULTS FOR ±10% AMPLITUDE STEPS. RR=50 FRAMES/S

Algorithm	**Response Time [ms]**					
	Step + 10%			***Step -10%***		
	Std	***SRS***	***SbyS***	***Std***	***SRS***	***SbyS***
P-Std	22.0 ±2.0	22.0 ±2.0	22.6 ±0.1	22.0 ±2.0	24.0 ±2.0	23.7 ±0.1
TF_1	18.0 ±2.0	18.0 ±2.0	17.5 ±0.1	18.0 ±2.0	18.0 ±2.0	18.2 ±0.1
TF_2	6.0 ±2.0	12.0 ±2.0	11.8 ±0.1	6.0 ±2.0	14.0 ±2.0	12.1 ±0.1

It is possible to see that, for the first two algorithms, the numeric results are very similar, while for TF_2, that presents more complex dynamics, the response time evaluation becomes more critical. This is due to the particular shape of the step response, as shown in Fig. 3. The continuous line represents the sample by sample TVE response when the step is in $t = 0$. The realigned measurement points of the SRS are obviously superimposed to such line, while the measurements of the Std show a different behavior, thus explaining the results in Table II.

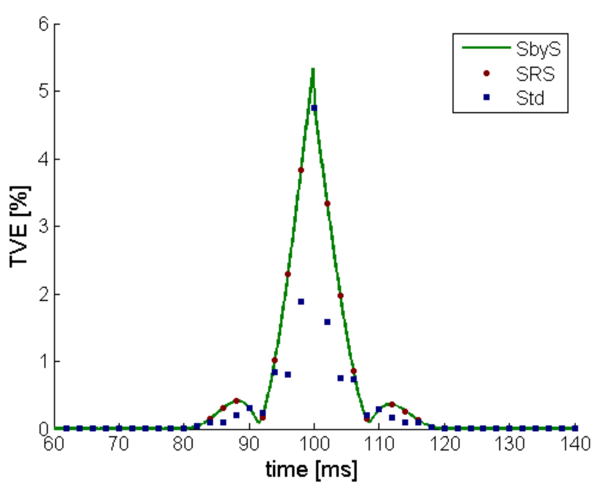

Fig. 3. TF_2 algorithm TVE response for a 10 % amplitude step and realigned measurement points for all the test methodologies and RR=50 frames/s.

The results also show that, in this case, the step at $t = 0$ can be considered as the worst case for response time and this is the reason why SRS and SbyS have similar response time values. It is important to recall that, because of the discretization introduced by equivalent sampling and of the resolution of practical procedure measurements, the values found with the SRS can be even larger than the reference one (that has a time resolution $100\ \mu s$, corresponding to the uncertainty of one sample at 10 kHz).

The sample by sample delay time results for all the three methods and ± 10 % amplitude steps are all below 2 ms (absolute values of 1.6 ms for P-Std, 1.7 ms for T_1 and 1.8 ms for TF_2). For this reason, the overestimated delay times obtained by testing procedures are always 10 ms for RR=10 frame/s and 2 ms for RR=50 frames/s, respectively. In this case, no particular problems arise in the testing process and correct delay compensation is confirmed.

Table III and 0 report the maximum undershoot/overshoot values for the $+10$ % amplitude step test for RR=10 frames/s and RR=50 frames/s, respectively. Similar results hold for the negative step case. While for the first two algorithms there are no overshoots, for TF_2, as reported in Fig. 4, the overshoot and undershoot are present. The figure shows the amplitude responses obtained with the three methods (RR=50 frames/s). In particular, the green continuous line is the worst case among all the different step instants used in SbyS, that is $t = 3.6$ ms (phase angle at the step occurrence equal to 64.8°), translated back to $t = 0$ ms for comparison purposes.

From the results, it is clear that the two testing procedure are not able to fully capture the transient behavior and thus they indicate a compliance with the 5% limit of the standard, even if the algorithm has worse performance. This effect is due to two main reasons. First, as emphasized by lower RRs (see Table III with respect to Table 0 for the SRS), the low time resolution of the points describing the amplitude dynamics does not allow to accurately find maximums and minimums of the curve. Second, the incomplete description of the possible signal phases at step occurrence prevent the identification of the worst-case dynamics.

TABLE III. MAX UNDER/OVERSHOOT RESULTS FOR +10% AMPLITUDE STEP. RR=10 FRAMES/S

Algorithm	**Under/Overshoot [%]**		
	Std	***SRS***	***SbyS***
P-Std	0	0	0
TF_1	0	0	0
TF_2	2.92	2.92	5.87

TABLE IV. MAX UNDER/OVERSHOOT RESULTS FOR +10% AMPLITUDE STEP. RR=50 FRAMES/S

Algorithm	**Under/Overshoot [%]**		
	Std	***SRS***	***SbyS***
P-Std	0	0	0
TF_1	0	0	0
TF_2	2.92	3.53	5.87

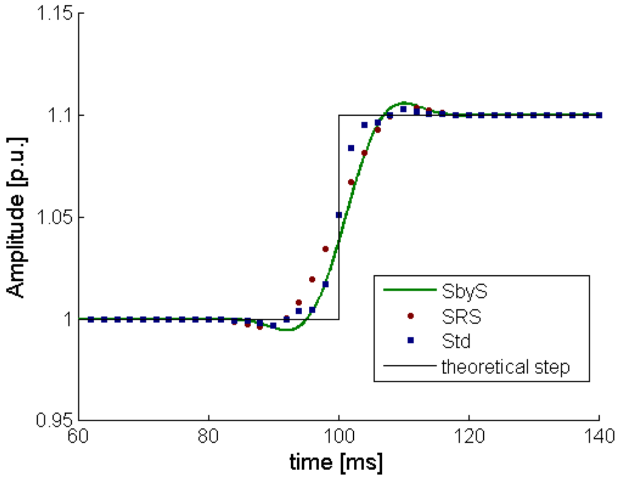

Fig. 4. TF_2 algorithm amplitude response to +10% amplitude step for all the test methodologies and RR=50 frames/s.

Similar considerations hold also for phase angle step tests, but the response time results reported in Table V (for +10° phase step and RR=50 frames/s) can give further insight into the mechanisms of the testing procedures. Depending on the algorithm, Std method gives lower or higher results with respect to SRS and their variability intervals can be non-overlapping. Besides, the values obtained by SbyS are not included in such intervals (except for the P-Std and Std method result). This shows how weaknesses of the two testing procedure (time resolution and step cases representativeness) can have independent effects.

TABLE V. RESPONSE TIME RESULTS FOR +10° PHASE STEP. RR=50 FRAMES/S

Algorithm	Response Time [ms]		
	Std	*SRS*	*SbyS*
P-Std	30.0 ±2.0	26.0 ±2.0	28.8 ±0.1
TF_1	14.0 ±2.0	18.0 ±2.0	21.4 ±0.1
TF_2	14.0 ±2.0	12.0 ±2.0	19.2 ±0.1

IV. CONCLUSIONS

This paper presents a detailed study on the methodologies used to test PMU behavior under the step test signals. In particular, the impact of the chosen procedure on response time, delay time and undershoot/overshoot measurements is discussed.

It is underlined how the measurement results are strongly dependent on the time resolution of the equivalent sampling of the step response. For this reason, in particular for P-class algorithms, different reporting rates under test lead to different measurement results. Besides, when the PMU dynamic response presents undershoots/overshoots, particular attention should be paid to the response reconstruction during the test, because the violation of the limits proposed by the standards C37.118.1 and C37.118.1a could be hidden in practice.

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