Experimental Characterization of Dynamic Methods for Synchrophasor Measurements

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Abstract— This paper presents the results of an experimental characterization performed to assess the accuracy of custom algorithms developed for Phasor Measurement Units (PMUs). In particular, some of the most recent and efficient methodologies used for synchrophasors estimation under dynamic conditions are considered. The techniques are implemented in a modular measurement platform and are validated by means of test signals under both static and dynamic conditions defined in IEEE Standard C37.118.1. The comparison of the results obtained by means of simulations with those resulting from experimental tests is also reported in order to evaluate the impact of possible measurement hardware on the overall PMU accuracy.

Keywords — Phasor Measurement Unit, Accuracy, Synchrophasor, IEEE C37.118.1.

I. INTRODUCTION

System operators require very accurate measurements, provided with high reporting rate, to rapidly monitor the state of the electricity grids. In this context, the most promising measurement devices are Phasor Measurement Units (PMUs), which allow estimating synchronized phasors, the so called synchrophasors. Synchrophasor measurements have been defined by several IEEE Standards. The last Standard was released in 2011. It is divided into two parts, 6 and 6, taking into account measurements and communication aspects, respectively. In 2014, the amendment C37.118.1a-2014 6 has been published to update or suspend some of the compliance limits. In particular, the Std. C37.118.1-2011 6 is focused on the behavior of PMUs under dynamic conditions. Complementary to the previously defined steady state compliance, the Standard 6 reports new measurement requirements for synchrophasors, frequency and rate of change of frequency (ROCOF) in presence of amplitude and phase modulated signals, linear ramp of frequency and step changes. This is a crucial stage in the standardization process, because these new requirements allow the PMUs to be tested with signals that are more similar to those actually present in the electricity grid than before.

The Standard 6 defines two performance classes of PMUs, namely P and M. The P-class is intended for applications requiring fast measurement response time, especially oriented to protections in power system, while the M-class should be considered for the case where measurement accuracy is crucial. A standard compliant PMU should meet all the requirements for at least one class. The main differences between the two performance classes are the specific test conditions for steady state performance and the requirements for dynamic performance, especially as far as frequency and ROCOF estimations are concerned. On the other hand, the Standard 6 leaves to PMU manufacturers free choice on hardware, software architecture and algorithm for phasor, frequency and ROCOF computation. Thus, in order to ensure interoperability between devices from different manufacturers, the compliance to the requirements indicated in the Standard is necessary. Algorithms implemented in the devices, in particular, are based on several principles 6-6 and thus they may reveal different behaviours for the same test conditions. This opens an interesting field of research in the characterization of the proposed algorithms. A brief review of recent proposals for synchrophasor estimation is reported in the following, to show the rich context.

In 6-6 the phasor estimation under dynamic conditions is improved by approximating the slowing changing phasors with a complex Taylor series expansion around the estimation time instant. In 6 and 6 the estimation errors of sequential phasors computed with Discrete Fourier Transform (DFT) and Short-Time Fourier Transform (STFT) are corrected in a post-processing way. In 6 and 6 an algorithm based on a linear non-orthogonal transform, defined as a Taylor-Fourier Transform and based on Weighted Least Square (TFT-WLS), is introduced. Unlike the algorithms in 6 and 6, the TFT-WLS algorithm directly acts on the samples, without any DFT computation. As investigated in 6, the TFT-WLS algorithm provides very good performance in all the conditions except under step tests. In order to overcome this issue, an adaptive version of the TFT-WLS, which detects when the signal is undergoing fast changes and, then, refines phasor estimation, has been proposed in 6 and 6 to enhance the performance under transient conditions. Based on this approach, the PMU proposed in 6 is simultaneously compliant with P-class and M-class requirements for synchrophasor and frequency measurements.

6 presents a new method to compute the Taylor phasor expansion coefficients that somehow generalizes the interpolated DFT and allows to compute also frequency and ROCOF.

Finally, in 6 an algorithm based on the space vector transformation of the phase quantities using a rotating reference frame and a proper filtering is proposed.

Besides the evaluation of synchrophasors, as discussed in 6, the frequency and ROCOF measurements can be very difficult tasks, given that very strict requirements are defined in 6, particularly in the presence of off-nominal frequency, harmonics or out-of-band signals.

In the literature, the algorithms are introduced, compared and usually tested with respect to the Standard test suite by means of computer simulations. In this paper, some of the most recent synchrophasor measurement solutions, designed to comply with the Standard 6 requirements, are considered for an experimental comparative analysis. Results are reported for methodologies presented in 6-6 and for a methodology compliant with the P-class of the Standard 6 based on 6 and 6. The validation of the considered approaches is performed by means of a suitable experimental platform. In order to highlight the impact of the considered setup, the results are also compared with those achieved through simulations under the same conditions.

II. Dynamic Methods for Synchrophasor Measurements

In the following, a brief report concerning the considered methodologies is presented:

A) *P-class method of IEEE C37.118.1*

The P-class method reported by the Standard 6 in Annex C is considered as a first example of PMU algorithm. It is based on a DFT performed on two nominal cycles, with triangular weighting. The suggested phase derivatives are employed for computing frequency and ROCOF. In the following, this method will be referred to as P – C37.118.1.

A) *P-Class TFT method*

A P-class algorithm, based on the TFT principle presented in 6 and with the frequency feedback proposed in 6 to have a fast estimation method during possible problems in wired networks is considered. In particular, the order $k = 1$ is used for the Taylor expansion, in order to improve estimation performance in presence of step changes. A Kaiser window with $\beta = 5$ is adopted. An additional one-cycle boxcar filter is applied to obtain a better rejection of harmonics in frequency estimation. The additional filter would give a further half-cycle delay to frequency computation. However, to keep the latency limited to one cycle, frequency is given by the current estimations corresponding to the synchrophasor time tag. Frequency value is thus corrected using ROCOF estimation to compensate the lack of alignment. In the following, this method will be referred to as P – TFT.

A) *Space Vector (SV) method*

Another technique that allows estimating both the positive sequence synchrophasor and the frequency has been proposed in 6.

It is based on the well-known space vector transformation using a reference frame which rotates at the rated angular frequency $2\pi f_0$. Since the frequency f is close to its rated value, the positive sequence vector rotates at a very low speed with respect to this reference frame. Thus, it generates low frequency terms in the real and imaginary parts of the space vector, which can be easily extracted through IIR low pass filtering. When considering a short N-samples window, both the magnitude and phase can be assumed to have a constant rate of change. Using this model, the magnitude, phase and frequency can be estimated in a least square sense. In the following, this method will be referred to as P – SV and M – SV, when the filter is designed to comply with classes P and M, respectively.

A) *Method compliant with P and M Classes*

A PMU algorithm, compliant simultaneously with the classes of performance P and M and presented in 6, has been considered. The basic idea is to give a two-channels design (one channel is conceived for slow varying conditions and the other for higher dynamics) that provides a single output, so that the PMU can guarantee performance compliant with both classes. This technique is validated in 6 for all test conditions defined in the Standard, and all the requirements of both P and M classes are met for synchrophasors and frequency. In the following, this method will be referred to as P+M.

A) *Method based on interpolated dynamic DFT*

In 6, a discrete Fourier transform (DFT)-based algorithm founded on a dynamic phasor model (referred to as interpolated dynamic DFT-based synchrophasor estimator, IpD^{2}FT) is presented.

This method permits to estimate synchrophasor, frequency, and ROCOF. The simulation results reported in 6 suggest that, if the synchrophasor Taylor series is truncated to the second order and a proper maximum side-lobe level decay (MSD) window is chosen, most of M-class requirements can be met using observation intervals corresponding to six cycles. For this reason the method implemented in this paper is applied on six cycles and will be referred to as 6c-IpD^{2}FT. Therefore, only the results obtained in the M-class compliance tests will be discussed.

Since the methods P – SV and M – SV are intrinsically based on a three-phase analysis, the results of all the other methods have been recombined to estimate the positive sequence synchrophasor. In this case, the frequency estimation is obtained by averaging the three estimated frequencies corresponding to the three phases of the system.

Furthermore, since the ROCOF evaluation is not defined for some of the considered methods, the ROCOF estimation will not be considered in this paper.

III. TESTS AND RESULTS

In this section, the results obtained by means of both experimental setup and simulations are presented and discussed, so that the relevance of the performance degradation due to experimental conditions can be clear.

A) Hardware Implementation

The experimental platform used for testing is based on the signal generator OMICRON CMC 256plus. Table I shows a partial summary of its main technical data 6.

TABLE I. CMC 256PLUS TECHNICAL DATA (PARTIAL)

Generator	Technical Data
Voltage setting range 4-phase AC (L-N)	4 x 0 ... 300 V
Accuracy	error < 0.015 % rd. + 0.005 % rg. Typical at 0 ... 300 V error < 0.04 % rd. + 0.01 % rg. Guaranteed at 0 ... 300 V rd. = reading, rg. = range
Frequency	range sine signals 10 ... 1000 Hz
accuracy / drift	±0.5 ppm / ±1 ppm
Phase	resolution 0.001° error at 50 / 60 Hz < 0.005° typ., < 0.02° guar.
Time Synchronization	Timing accuracy
IRIG-B synchronization with CMIRIG-B	error < 1 μs typ., < 5 μs guar.
GPS synchronization	error < 1 μs typ., < 5 μs guar.

The CMC 256plus is managed through the "Test Universe Suite" composed by different tools. In particular, for this work, the Advanced Transplay tool is used to generate the required signals. The tool allows the generation of a waveform from a COMTRADE file. A LabVIEW program has been implemented to prepare the COMTRADE files containing the test signals indicated in 6.

In order to guarantee the time alignment between the generation and the acquisition of the test signals, a common time reference is used to manage the test setup. A Global Positioning System (GPS) receiver (Symmetricom XL-750) is considered as the time source, obtaining the Coordinated Universal Time (UTC) as an IRIG-B signal, that is delivered to the CMIRIG-B unit of the CMC 256plus and, at the same time, provides the PPS signal to the acquisition system.

The acquisition system is composed by a PXI modular system by National Instruments, with embedded dual-core controller NI PXI-8106, the data acquisition module NI PXI-6133 6, and the NI PXI-6682 timing and synchronization module 6. The NI PXI-6133 has a maximum simultaneous sampling rate of 2.5 MSa/s per channel, a 14-bit analog-to-digital converter resolution, a 1.3 MHz 3 dB bandwidth and a system noise of 0.78 LSBrms.

In order to accurately detect the synchronization instant, the acquisition system acquires the three-phase test signals generated by the CMC 256plus at a sampling frequency of 1 Msa/s. Then, downsampling is applied, so that an equivalent 10 kSa/s sampling frequency is obtained, which is suitable for the practical implementation of the considered algorithms. For the P-SV and M-SV techniques, the test signals have been further downsampled to a frequency of 800 Sa/s. All the considered signals are in the voltage range of ± 10 V.

The duration of the tests is equal to 2.5 s. The acquisition is triggered by the PPS signal. Each test starts at the occurrence of the PPS event: the CMC 256plus starts the generation of the pre-loaded test signal and the acquisition system starts the acquisition and remains in acquisition mode up to the end of signal generations.

In the following, the estimation results are presented in terms of total vector error (TVE) and frequency error (FE) for each algorithm and for each test condition, limiting the analysis to the reporting rate of 50 frame/s, for which most of the considered algorithms are designed. The maximum TVE and FE observed during the test time are reported. The experimental results are always compared with the results obtained by simulation, to better assess the impact of the whole measurement chain. The results are, where needed, separated for each performance class, using only the corresponding version of the methods. The method P+M is purposely designed for simultaneous compliance with both classes and thus is present in all the reported comparisons.

For each test, the limit defined by the Standard 6 (updated according to the Amendment 6) for the specific condition is reported, for a fair comparison.

A) Steady state compliance

The first set of tests considers the off-nominal frequency condition. The results of Tables II and III show that, despite the uncertainty introduced by the experimental setup, all the methods largely comply with the relevant limits for synchrophasor measurement. Some more evident effects of this uncertainty can be noticed for frequency measurements, in particular when the estimation is performed through the P-class methods, but again in all the monitored situations the maximum error is well below the corresponding limit.

TABLE II. SYNCHROPHASOR MEASUREMENT COMPLIANCE TEST RESULTS FOR OFF-NOMINAL FREQUENCY CONDITIONS

Algorithm	TVE Limit (%)	Range (Hz)	Max TVE of the estimated phasors -simulation- (%)	Max TVE of the estimated phasors -experimental- (%)
P - C37.118.1	1	±2	~0	0.12
P - TFT		±2	~0	0.13
P - SV		±2	~0	0.08
M - SV		±5	~0	0.11
P+M		±2	~0	0.11
		±5	~0	0.12
6c-IpD^{2}FT		±5	~0	0.13

TABLE III. FREQUENCY MEASUREMENT COMPLIANCE TEST RESULTS FOR OFF-NOMINAL FREQUENCY CONDITIONS

Algorithm	**FE Limit (mHz)**	**Range (Hz)**	**Max FE - simulation-(mHz)**	**Max FE - experimental-(mHz)**
P - C37.118.1	5	±2	~0	1.8
P - TFT		±2	~0	1.5
P - SV		±2	~0	1.8
M - SV		±5	~0	0.4
P+M		±2	~0	0.3
		±5	~0	0.3
6c-IpD^{2}FT		±5	~0	0.2

Then, a single interfering harmonic (second and third, which have the highest impact), superimposed to the fundamental component at 50 Hz, has been considered. Tables IV-VII report the results for both synchrophasor and frequency estimation.

In particular, Tables IV and V show the results for the P-class compliance test, that is when the harmonic level is 1% with respect to the fundamental. The errors obtained by simulations are extremely low for all methods, because a good rejection of harmonics of the nominal frequency is intrinsically considered in the algorithm design. In all the cases it is possible to see that in the experimental tests a residual error is present: such error includes the impact of the measurement chain, and in particular, of the synchronization error and of the noise. Also in this case, the impact of the experimental setup is more significant in case of frequency measurements. For the P-SV method, this implies that the limit on frequency error can be overcome in some situations.

TABLE IV. P-CLASS COMPLIANCE TEST IN THE PRESENCE OF HARMONIC (1%) FOR SYNCHROPHASOR MEASUREMENT

Algorithm	**TVE Limit (%)**	***Harmonic***	**Max TVE of the estimated phasors - simulation- (%)**	**Max TVE of the estimated phasors - experimental- (%)**
P - C37.118.1	1	2	~0	0.04
		3	~0	0.04
P - TFT		2	0.12	0.16
		3	~0	0.05
P - SV		2	0.008	0.07
		3	~0	0.06
P+M		2	0.002	0.04
		3	~0	0.04

Tables VI and VII show the results for M-class compliance, where the relative amplitude of a single harmonic is set to 10%. In this case, obviously, the effect of the harmonic is more evident even in the simulated results, but the deterioration of the estimate in the real case is similar to previous tests.

TABLE V. P-CLASS COMPLIANCE TEST IN THE PRESENCE OF HARMONIC (1%) FOR FREQUENCY MEASUREMENT

Algorithm	**FE Limit (mHz)**	**Harmonic**	**Max FE - simulation- (mHz)**	**Max FE - experimental- (mHz)**
P - C37.118.1	5	2	~0	1.1
		3	~0	1.0
P - TFT		2	~0	0.8
		3	~0	0.8
P - SV		2	4.8	5.2
		3	~0	0.8
P+M		2	0.1	0.3
		3	~0	0.2

TABLE VI. M-CLASS COMPLIANCE TEST IN THE PRESENCE OF HARMONIC (10%) FOR SYNCHROPHASOR MEASUREMENT

Algorithm	**TVE Limit (%)**	**Harmonic**	**Max TVE of the estimated phasors - simulation- (%)**	**Max TVE of the estimated phasors - experimental- (%)**
M - SV	1	2	0.002	0.08
		3	0.001	0.07
P+M		2	0.015	0.09
		3	0.007	0.06
6c-IpD^{2}FT		2	~0	0.07
		3	~0	0.06

TABLE VII. M-CLASS COMPLIANCE TEST IN THE PRESENCE HARMONIC (10%) FOR FREQUENCY MEASUREMENT

Algorithm	**FE Limit (mHz)**	**Harmonic**	**Max FE - simulation- (mHz)**	**Max FE - experimental- (mHz)**
M - SV	25	2	~0	0.3
		3	~0	0.4
P+M		2	0.6	0.9
		3	~0	0.4
6c-IpD^{2}FT		2	~0	0.4
		3	~0	0.5

Tables VIII and IX show the results for M-class compliance in case of out of band interference, where the relative amplitude of a single interharmonic is set to 10%. The Tables refer to the situations where the interharmonic frequencies (25 Hz and 75 Hz) are the closest to the fundamental component, in the range considered by 6 for a reporting rate of 50 frame/s. The impact of such components strongly depends on the specific frequency responses of the filters and thus the results represent only an example of possible behaviors under interharmonic interference. However, considerations similar to those arising from the previous tests can be done about the impact of the uncertainty introduced by the measurement hardware.

TABLE VIII. M-CLASS COMPLIANCE TEST IN THE PRESENCE OF OUT OF BAND INTERFERENCE (10%) FOR SYNCHROPHASOR MEASUREMENT

Algorithm	TVE Limit (%)	Interharmonic (Hz)	Max TVE of the estimated phasors - simulation- (%)	Max TVE of the estimated phasors - experimental- (%)
M - SV	1.3	25	0.029	0.09
		75	0.029	0.10
P+M		25	0.049	0.15
		75	0.049	0.15
6c-IpD^{2}FT		25	0.007	0.11
		75	0.009	0.11

TABLE IX. M-CLASS COMPLIANCE TEST IN THE PRESENCE OF OUT OF BAND INTERFERENCE (10%) FOR FREQUENCY MEASUREMENT

Algorithm	FE Limit (mHz)	Interharmonic (Hz)	Max FE - simulation- (mHz)	Max FE - experimental- (mHz)
M - SV	10	25	7.4	7.6
		75	7.4	7.4
P+M		25	3.8	4.0
		75	3.8	4.2
6c-IpD^{2}FT		25	0.3	0.6
		75	0.5	0.9

A) Dynamic compliance

As a first example of PMU test under dynamic conditions, amplitude and phase modulated signals are employed.

The modulation depths k_a and k_x are equal to 0.1, while the modulation frequency is $f_m = 2$ Hz for P-class algorithms and $f_m = 5$ Hz for M-class. Tables X and XI report the TVEs and FEs, respectively, for the amplitude modulation compliance test, while Tables XII and XIII refer to phase modulation.

From the results it is clear that the methods based on a model intrinsically dynamic have better TVE performance, because they are designed to follow phasor variations inside the observation window.

TABLE X. COMPLIANCE TEST IN THE PRESENCE OF AMPLITUDE MODULATION FOR SYNCHROPHASOR MEASUREMENT

Algorithm	TVE Limit (%)	FM (Hz)	Max TVE of the estimated phasors -simulation- (%)	Max TVE of the estimated phasors -experimental- (%)
P - C37.118.1	3	2	0.058	0.09
P - TFT		2	0.035	0.08
P - SV		2	0.077	0.13
M - SV		5	1.988	2.03
P+M		2	0.025	0.07
		5	0.043	0.08
6c-IpD^{2}FT		5	0.117	0.14

TABLE XI. COMPLIANCE TEST IN THE PRESENCE OF AMPLITUDE MODULATION FOR FREQUENCY MEASUREMENT

Algorithm	FE Limit (mHz)	FM (Hz)	Max FE - simulation- (mHz)	Max FE - experimental- (mHz)
P - C37.118.1	60	2	~0	1.5
P - TFT	60	2	~0	1.1
P - SV	60	2	~0	1.1
M - SV	300	5	~0	0.2
P+M	60	2	~0	0.6
	300	5	~0	0.7
6c-IpD^{2}FT	300	5	~0	0.3

TABLE XII. COMPLIANCE TEST IN THE PRESENCE OF PHASE MODULATION FOR SYNCHROPHASOR MEASUREMENT

Algorithm	TVE Limit (%)	FM (Hz)	Max TVE of the estimated phasors - simulation- (%)	Max TVE of the estimated phasors - experimental- (%)
P - C37.118.1	3	2	0.053	0.12
P - TFT		2	0.03	0.13
P - SV		2	0.069	0.10
M - SV		5	1.780	1.81
P+M		2	0.058	0.14
		5	0.440	0.66
6c-IpD^{2}FT		5	0.110	0.14

TABLE XIII. COMPLIANCE TEST IN THE PRESENCE OF PHASE MODULATION FOR FREQUENCY MEASUREMENT

Algorithm	FE Limit (mHz)	FM (Hz)	Max FE - simulation- (mHz)	Max FE - experimental- (mHz)
P - C37.118.1	60	2	1.2	2.2
P - TFT	60	2	24.9	25.4
P - SV	60	2	1.3	2.4
M - SV	300	5	8.9	8.9
P+M	60	2	18.6	18.6
	300	5	53.5	87.5
6c-IpD^{2}FT	300	5	67.1	67.2

Tables XIV and XV report the TVEs and FEs, respectively, for the frequency ramp test. Every algorithm is compliant with its class of accuracy for both simulations and experimental cases. The algorithms show good performance also for the FE because most of them use a frequency tracking for improving estimation in this operating conditions.

TABLE XIV. COMPLIANCE TEST IN THE PRESENCE OF FREQUENCY RAMP FOR SYNCHROPHASOR MEASUREMENT

Algorithm	TVE Limit (%)	Range (Hz)	Max TVE of the estimated phasors - simulation- (%)	Max TVE of the estimated phasors - experimental- (%)
P - C37.118.1	1	48-52	0.021	0.12
P - TFT		48-52	0.022	0.15
P - SV		48-52	0.023	0.08
M - SV		45-55	0.124	0.14
P+M		48-52	~0	0.11
		45-55	~0	0.10
6c-IpD^{2}FT		45-55	~0	0.10

TABLE XV. COMPLIANCE TEST IN THE PRESENCE OF FREQUENCY RAMP FOR FREQUENCY MEASUREMENT

Algorithm	FE Limit (mHz)	Range (Hz)	Max FE - simulation- (mHz)	Max FE - experimental- (mHz)
P - C37.118.1	10	48-52	0.2	1.9
P - TFT		48-52	0.3	1.7
P - SV		48-52	~0	1.6
M - SV		45-55	~0	0.3
P+M		48-52	0.3	0.7
		45-55	0.3	0.7
6c-IpD^{2}FT		45-55	~0	0.3

Finally, a really limited impact of the experimental setup on the response times has been observed for the step change tests. In every case, all the response times remain far from the limits indicated in the Standard.

IV. CONCLUSION

In this paper, synchrophasor measurement solutions proposed in recent scientific literature are experimentally validated under both steady state and dynamic conditions. The results of the experimental tests, compared to those obtained by means of computer simulations, show that, if the theoretical behavior of a given method guarantees sufficient margins with respect to the accuracy limits defined in the Standard C37.118.1-2011, the uncertainty introduced by a suitable acquisition system does not alter substantially its practical capability to comply with the performance classes defined in the Standard itself. Future work is planned to assess the impact of other devices, namely voltage and current transducers, which necessarily belong to the actual measurement chain and whose behavior can be critical for the performance of the overall measurement system.

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