Evaluating Methods for Measuring Grid Frequency in Low-Inertia Power Systems

Preprint

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Evaluating Methods for Measuring Grid Frequency in Low-Inertia Power Systems

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***Abstract*—Accurate measurement of grid frequency is a critical component of reliable grid control. Traditionally, inverters and phasor measurement units (PMUs) have used methods such as phase locked loops (PLLs) and discrete Fourier transforms (DFTs) to measure frequency. However, as inverter-based resources (IBRs) such as solar and wind have increased, these conventional frequency measurement methods have yielded incorrect frequency measurements leading to unreliable control in some cases. One challenge is measuring frequency during transient events. During these events, measured frequency may contain significant spikes due to the disrupted waveform, much more rapid and significant than any expected physical frequency dynamics. New methods must balance between suppressing spikes in frequency during faults, and providing fast, accurate, measurements in all other grid operation conditions, especially during events with a high rate-of-change-of frequency (ROCOF), which are more prevalent in high-IBR power systems. This paper first surveys frequency measurement methods that have been proposed to reduce measurement errors during transient events in low-inertia grids. Then, both conventional and more novel frequency measurement methods are tested against an IEEE standard and industry recommendations, and their performance is evaluated for events simulated in PSCAD. Results quantify trade-offs in performance during different grid conditions and lead to suggestions for the most appropriate frequency and ROCOF measurement methods for low-inertia grids.**

***Index Terms*—inertia, frequency, phase-locked loop, phasor measurement units, rate of change of frequency**

I. Introduction

Frequency is measured in grid devices for important control purposes such as under frequency load shedding, wide area control, and IBR control and protection. One of the most widely cited events where IBR controls failed due to incorrect frequency measurement was the Blue Cut Fire in 2016 [1]. Due to faults caused by the fire, some IBRs' PLL algorithms incorrectly measured a frequency of < 57 Hz, and 1200 MW of solar tripped offline or entered momentary cessation. One solution proposed by NERC to avoid false tripping was to increase the time delay before inverter trip. However, this solution would not work for other purposes as near-instantaneous controls are needed in grids with high penetrations of renewables [2], [3]. As IBR use increases, we must develop fast frequency measurement algorithms that can handle large frequency and ROCOF deviations [4].

We surveyed the literature for algorithms that address frequency measurement during transient events. One study [5] of the high-IBR distribution network on Bornholm Island, Denmark, found that phase steps due to short lived faults were the most common cause of frequency measurement spikes. Furthermore, NERC found that in the 6 months after the Blue Cut Fire event, inverters in SCE/CAISO disconnected 10 more times due to brief, 2-4 cycle faults [1]. Accordingly, many research efforts focused on rejecting frequency spikes by detecting phase steps: one author proposed a DFT-based method with a phase-step detector which freezes the frequency measurement during the phase step [6], [7]. Another author modified the extended Kalman filter (EKF), quadrature PLL (QPLL), and adaptive notch filter (ANF) methods with a corrector which freezes frequency measurement during a transient then ramps back to real-time measurement [2]. A PMU-based method employed an estimator block, which replaced real-time phasor data when a phase step was detected [5]. Finally, another study tested a box-car filter algorithm and phase sensitive frequency estimation algorithm [8]. We evaluate 8 frequency measurement methods, 4 conventional and 4 more experimental, using tests in [9] and [8]. We also quantify the error and delay in each method for faults and frequency events in a small PSCAD test system. Validation against measured field data is also valuable but is not in the scope of this paper. While it is difficult to define frequency, especially far away from synchronous generators, for the purposes of our paper frequency was either defined by the tests or the rotor speed of a modeled synchronous generator.

II. Frequency measurement tests

Three groups of tests were used to evaluate frequency measurement accuracy and performance. The first test group was the standard for synchronized phasor measurement systems in power systems, IEEE 60255-118-1 [9]. The P-PMU standard was chosen over the M-PMU standard as the faster measurement time better reflects the requirements of low-inertia grids. The tests and criteria are summarized in the first 2 columns of Table I; however, these tests were still designed primarily for large interconnected grids and do not address

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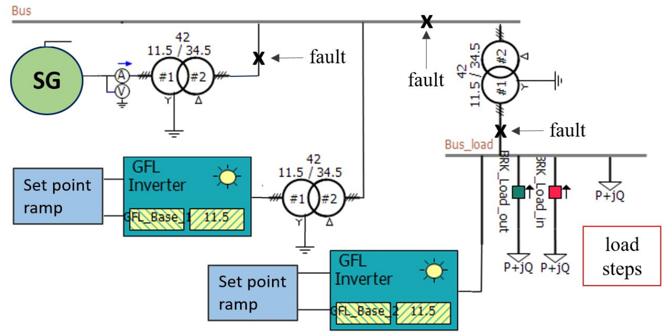

Fig. 1. PSCAD grid model used to simulate the dynamics of faults and contingency events on a low-inertia grid.

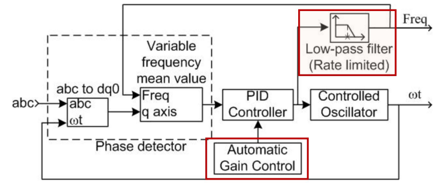

Fig. 2. MATLAB PLL (3ph) block diagram. The red boxed Automatic Gain Control (AGC) and Low-pass filter (Rate limited) components were removed to create "unfiltered" MATLAB PLL measurement versions.

some events that affect low inertia grids. Thus, we also use more extreme tests proposed by Dr. Rietveld [8] based on the responses of 5 different transmission and distribution system operators and an ENTSO-E report which identify key needs for more accurate ROCOF measurements. The "Rietveld" tests and criteria are summarized in the first 2 columns of Table II. The requirements for the Rietveld tests were determined by comparing to analogous pass requirements from the P-PMU standard in Table I.

The two aforementioned test groups use synthetically generated voltage waveforms. To test the performance against more realistic events, a small grid model was built in PSCAD and faults and contingency events were simulated to create a third group of tests. Line-to-ground, line-to-line and three-phase faults with a clearing time of 4 cycles (0.08 seconds) were simulated at each of the locations pictured in the diagram in Figure 1. Contingency events with an initial ROCOF of 3-5 Hz/sec were simulated by step changes in load. Waveform data were recorded at the synchronous generator node. Shaft rotation speed of the synchronous generator was used as the "ground truth" baseline frequency. We used a binary pass/fail approach to rank algorithm performance, but a graduated approach could provide more insight [10].

III. Frequency Measurement Methods

A. Conventional frequency measurement methods

Four conventional frequency measurement methods were evaluated. Phase-locked loop (PLL) and DFT based methods are common algorithms in grid protection and grid-connected devices. Variability in PLL implementation and performance has been reported to cause issues for grid operators, especially with high penetration of customer distributed energy resources. Thus, we evaluated three different PLL methods. The first PLL method we call "MATLAB PLL", referring to 1ph and 3ph PLL blocks provided in the Simulink library. These PLL blocks include extra features such as Automatic Gain Control, ROCOF limiting and frequency measurement low pass filtering. They were tested with the features turned on and off and from now on will be referred to as "filtered" or "unfiltered", respectively. The PLL (3ph) block diagram provided by MATLAB is shown in Figure 2.

The PSCAD/EMTDC master library PLL component was also tested. While the full details of this PLL are not available, PSCAD provides a representative open source model [11]. Another generic PLL model has been developed in PSCAD by Kenyon [12] based on parameters from [13].

The standard DFT algorithm was based on the example in IEEE 60255-118-1 [9], with a slight modification in the anti-aliasing filter. The code was provided by Wilches-Bernal [2].

B. Experimental frequency measurement methods

Four experimental frequency measurement methods designed to be robust to transient events were also evaluated. The first method, referred to as "DFT fit + detector", detects and suppresses phase steps by freezing the output to the last "reliable" measurement if a frequency error threshold is exceeded [6]. The other 3 methods were EKF, QPLL, and ANF, all with a frequency measurement corrector developed by Wilches-Bernal [2]. This "corrector" uses internal signals from each algorithm to calculate an "inverse reliability metric" (IRM). Similarly to the DFT detector, the corrector freezes the output to the median of the last 0.1 seconds of measurement when the IRM exceeds a tuned treshold.

DFT fit + detector was implemented based on the description in [6], while the EKF + corrector, QPLL + corrector, and ANF + corrector methods were tested using code provided by Wilches-Bernal. All experimental algorithms were tuned to track a 5 Hz/s ROCOF as soon to be required for IBRs by [14]. The gains for EKF, QPLL, and ANF algorithms were tuned to meet the max $|FE|$ (absolute FE) < 0.06 Hz requirement of the P-PMU standard during phase modulation tests [9]. Notably, increasing reaction speed increases noise, and increasing the IRM threshold makes it harder to reject phase steps.

1ph, 3ph, filtered, and unfiltered versions of the experimental methods were tested. The single-phase experimental methods were run on each of the 3 phases and then the 3 outputs were averaged to give a "3ph" measurement. The ROCOF limiter and low pass filter from Figure 2 were applied to both "1ph" and "3ph" measurements to create the "filtered" methods.

IV. Results and Discussion

The results of the P-PMU standard and Rietveld tests are plotted in Figure 3. Method results are ordered from top to bottom based on their top performing measurement. The

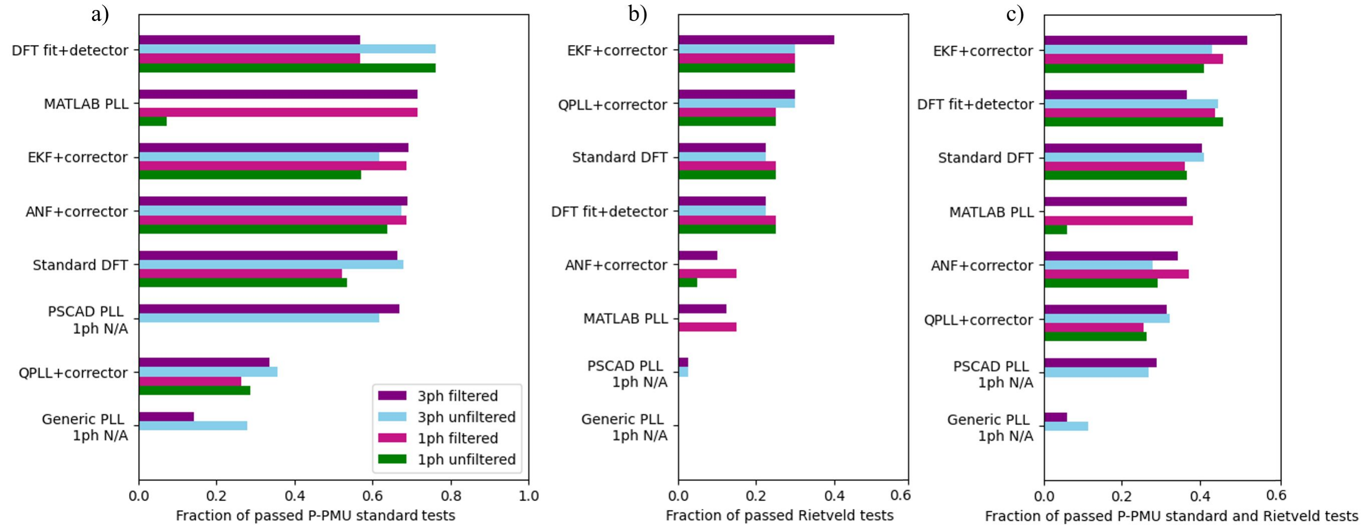

Fig. 3. Fraction of synthesized tests passed. a) P-PMU standard tests b) Rietveld tests c) Combined P-PMU standard and Rietveld test results. A longer bar means more tests passed and better performance.

TABLE I
P-PMU STANDARD TEST DETAILED RESULTS – BEST PERFORMERS. EACH CELL SHOWS THE NUMBER OF TESTS PASSED.

60255-118-1 standard test	**Requirement**	**DFT fit + detector 3ph unfiltered**	**MATLAB PLL 3ph filtered**	**EKF + corrector 3ph filtered**	**ANF + corrector 3ph filtered**	**Standard DFT 3ph unfiltered**	**PSCAD PLL 3ph filtered**
Steady 60,58 & 62 Hz	max |FE| < 5e-4 Hz	/ 1	+ 3	+ 3	+ 3	+ 3	+ 3
Harmonics, 2nd-50th	max |FE| < 5e-4 Hz	+ 49	+ 49	+ 49	/ 48	+ 49	/ 33
Phase mod, 0.1-2 Hz	max |FE|<0.06 Hz	+ 20	+ 20	/ 17	/ 17	/ 15	+ 20
Amp mod, 0.1-2 Hz	max |FE|<0.06 Hz	+ 20	+ 20	+ 20	+ 20	+ 20	+ 20
±1 Hz/sec ramp	max |FE|<0.01 Hz	- 0	- 0	- 0	- 0	- 0	- 0
±0.1 Amplitude step	Response time < 4.5/f_0	+ 2	+ 2	+ 2	+ 2	+ 2	+ 2
±10 deg phase step	Response time < 4.5/f_0	+ 2	- 0	- 0	- 0	/ 0 - failed by only 3 ms	- 0

\+ Passed all subtests   / Passed some subtests   - Failed all subtests

TABLE II
RIETVELD TEST DETAILED RESULTS – BEST PERFORMERS. NUMERICAL VALUES ARE GIVEN FOR EITHER MAX |FE| OR RESPONSE TIME. FOR TESTS CONTAINING MULTIPLE SUBTESTS, THE AVERAGE VALUE IS SHOWN.

Rietveld tests	**Constructed requirements**	**EKF + corrector 3ph filtered**	**QPLL + corrector 3ph filtered**	**Standard DFT 1ph unfiltered**	**DFT fit + detector 1ph unfiltered**	**ANF + corrector 1ph filtered**	**MATLAB PLL 1ph filtered**
Harmonics	max |FE| < 5e-4 Hz	- 0.014	- 0.005	+ 0	+ 0	- .009	+ 0
Additional zero crossings	max |FE| < 5e-4 Hz	+ 0	- 0.001	+ 0	+ 0	+ 0	- 0.002
Balanced | unbalanced noise	max |FE| < 0.01 Hz	- 0.023	- 0.017	- 0.0295	- 0.0905	- 0.0285	- 0.0471
8 Hz/s ramp, 58-62 Hz	max |FE| < 0.01 Hz	- 3.986	- 2.824	- 0.669	- 1.024	- 1.501	- 1.597
Freq step, +8 Hz/s ramp	Response time < 4.5/f_0	- >6 seconds	- >6 seconds	- 0.327	- 0.278	- 0.388	- 0.396
Freq step, -5 Hz/s ramp	Response time < 4.5/f_0	- >6 seconds	- 0.498	- 0.32	- 0.276	- 0.521	- 0.517
Interharmonics + flicker	max |FE| < 0.01 Hz	- 0.055	- 0.06	- 0.141	- 1.078	- 0.068	- 0.277
Amplitude steps	Response time < 4.5/f_0	+ 2.08E-04	+ 2.08E-04	/ 0.08	/ 0.0518	/ 0.100	/ 0.0753
20 & 60 deg phase steps	Response time < 4.5/f_0	+ 2.08E-04	+ 0.0149	- 0.163	- 0.102	- 0.298	- 0.266
Phase + amplitude step	Response time < 4.5/f_0	+ 2.08E-04	+ 2.08E-04	- 0.16	- 0.104	- 0.241	- 0.261

\+ Passed all subtests   / Passed some subtests   - Failed all subtests

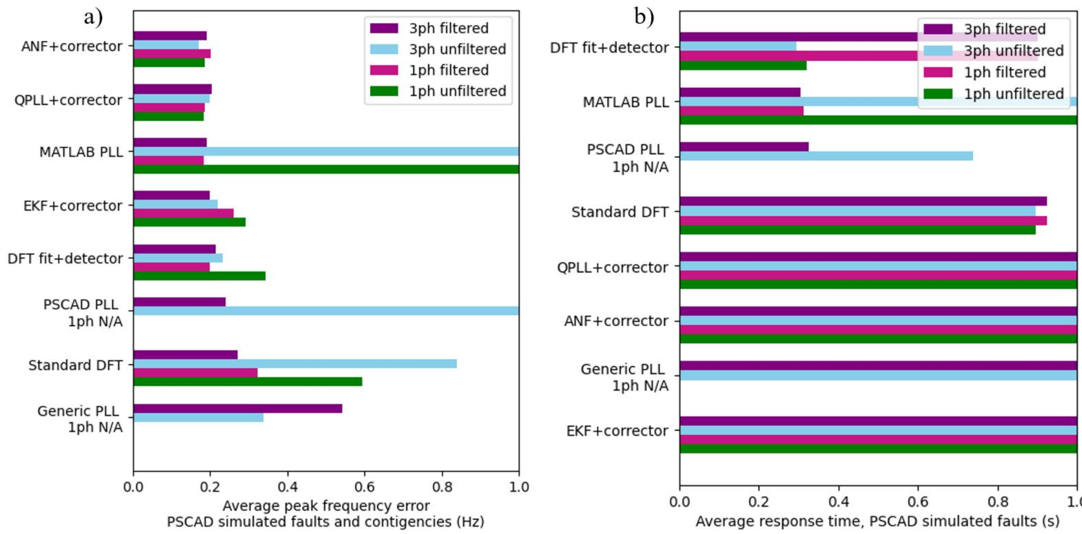

Fig. 4. PSCAD simulation results show trade offs between a) peak |FE| and b) response time. Results are ordered based on the best measurement from each method. A shorter bar indicates lower error and response time and better performance.

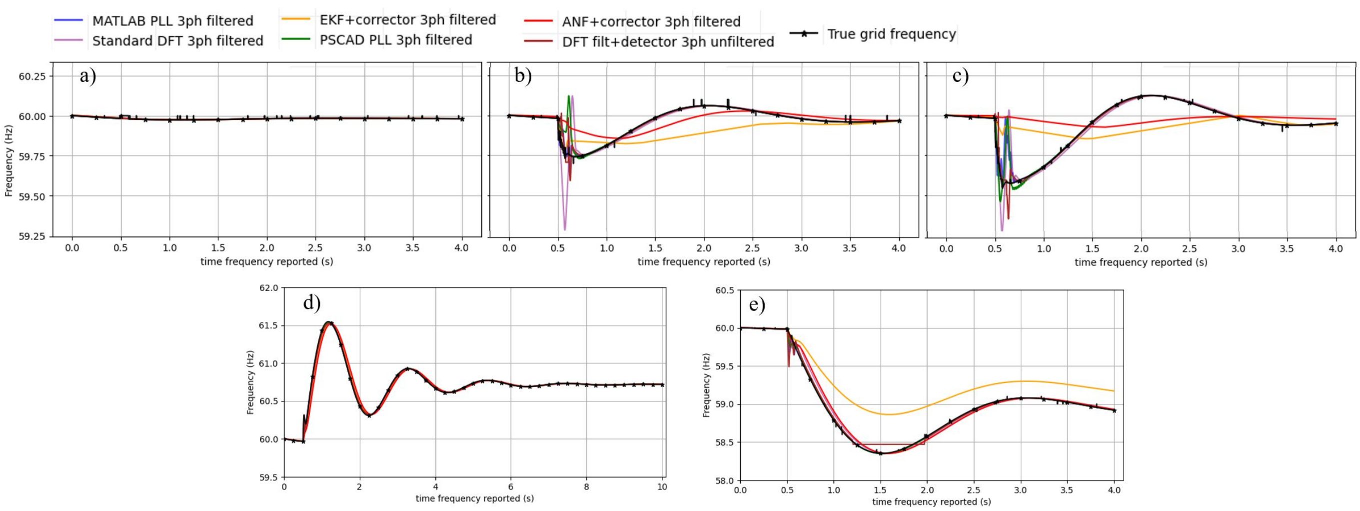

Fig. 5. Fault and contingency event frequencies. Results plotted for the 6 top performing algorithms for the small PSCAD model tests. a) line-to-ground fault b) line-to-line fault c) 3-phase fault d) overfrequency e) underfrequency. Each fault cleared after 0.08 seconds

reported 1ph measurement is the measurement with the worst performance between the a, b, and c phases. For the P-PMU standard tests, the unfiltered DFT fit + detector performed best. 3ph filtered MATLAB PLL, EKF + corrector, and ANF + corrector passed almost as many tests. Standard DFT 3ph unfiltered and PSCAD PLL 3ph filtered also performed relatively well. It should be noted that all tests were weighted equally in Table I. Thus, if a test failed 25/50 of the harmonic tests, this looks the same as failing 1/2 of the phase step tests. More detailed information on P-PMU test performance is shown in Table I. Critically, the DFT fit + detector does not accurately measure steady state frequencies ± 2 Hz away from nominal. Additionally, all tests failed the frequency ramp. However this was not due to failing to track the ramp, but rather a slight time lag in measurement. DFT fit+detector and standard DFT performed the best for phase steps.

Continuing to Rietveld tests, EKF+corrector performed the best. The more detailed results are shown in Table II. In this table, numerical values for max |FE| or response time are given instead of number of tests passed. Again, all methods failed the ramp tests. EKF+corrector and QPLL+corrector fully suppressed the amplitude and phase steps, but all methods recovered within at most 0.266 seconds or 16 cycles. In general, the performance on the Rietveld tests was lower because the tests were more extreme.

Summing the performance over both synthesized test groups, EKF+corrector performed the best, with DFT fit + detector also performing well when unfiltered. The next 2 best algorithms were standard DFT 3ph unfiltered and MATLAB PLL 1ph filtered. There are 7 P-PMU standard tests and 10

TABLE III
APPROXIMATE COMPUTATIONAL COSTS PER EACH FREQUENCY MEASUREMENT

Computational operation	EKF	Standard DFT	Standard DFT + fit	MATLAB PLL 1ph	Zhan detector	Computational cost weights
Add/subtract	25	328	640	17	3	*1
Compare (<, > ==)	0	0	1	5	1	*10
Absolute value	1	0	0	0	1	*2
Multiply	370	334	965	17	3	*4
Divide	67	2	3	5	0	*10
Exponent/logarithm	1	3	0	0	0	*50
Sin/cos/tan	0	2	1	1	0	*60
Total operations	464	669	1610	44	8	
Weighted computational cost	**2227**	**1954**	**4600**	**245**	**27**	

Rietveld tests, so the Rietveld tests are weighted slightly higher in the summed results. Overall, these results suggest that the EKF + corrector and DFT fit + detector are good algorithms for dealing with both conventional and low-inertia grids. The MATLAB PLL and standard DFT also perform well, but recover more slowly from phase steps than the methods that employ phase step detectors.

PSCAD test results are shown in Figure 4. There are a few blips in the true grid frequency from a rounding error which slightly increased average |FE|, but generally the methods with lowest frequency measurement errors during faults or contingency events recover slowly after faults. The methods that both suppress |FE| and recover quickly are MATLAB PLL 3ph and 1ph filtered. DFT fit + detector 3ph unfiltered also performed reasonably well. The methods as tuned favor suppressing peak |FE| instead of fast response time. Looking at requirements for inverter ride-through [14], [15], it may be acceptable for methods to trade off peak error in exchange for a faster response time. However, a higher peak error also corresponds to a higher ROCOF error, which may not be acceptable.

Figure 5 a-c shows the measured frequencies during simulated line-to-ground, line-to-line, and 3-phase faults on the main bus. EKF+corrector and ANF+corrector have very little frequency noise during the fault compared to the other methods, but fail to match the true grid frequency (though they could be tuned to improve tracking at the cost of decreased noise rejection). None of the methods were able to achieve the requirement for P-PMUs to recover in 0.075 seconds. Figure 5 d-e shows the algorithm performance during PSCAD simulated contingency events. All methods were able to track the overfrequency event, but not all were able to track the underfrequency event. Specifically, EKF+corrector fails to track the severity of the frequency drop, and DFT fit + detector triggers around 1.3 s producing a temporarily flat frequency output. The EKF+corrector could probably be retuned to fully track the underfrequency event, though this may affect its good performance in the other tests.

V. COMPUTATIONAL COST

Table III shows estimated computational cost for four methods and one transient detector that performed well in the preceding analysis. This is a complicated topic that was not the main focus of this paper, so these results should be viewed as a starting point to begin the important work of determining computational cost. For each of the 5 algorithms, we estimated the number of several types of computational operations needed to produce one frequency measurement. Each computation type was assigned a weight (multiplier) based on the relative number of processor operations required, and a total weighted computation cost was estimated as the weighted sum of operations. The weights were based on [16]. Standard DFT+fit is the most costly due to the least squares fit used to determine frequency over 1.5 cycles of calculated phases. Encouragingly, the detector does not add a significant amount of complexity to the method. MATLAB PLL has such a low comparative cost to DFT and EKF because it only requires one data point to update output frequency, whereas DFT uses 1 cycle (80 samples) and EKF uses 2 cycles (160 samples) of data per frequency update. Additionally, the way that subroutines within each method are implemented can have a large impact on computational cost. For example, DFT could be replaced with FFT, and there may be more efficient methods for multiplying matrices than considered in this rudimentary accounting method. In future work, we could quantify the operations in the automatic gain control and low pass filter implemented in the filtered MATLAB methods to further elucidate trade-offs in computational complexity and performance.

VI. CONCLUSION AND FUTURE WORK

In this paper, frequency measurement methods were tested against synthesized and simulated grid test conditions. No method was found that satisfies all tests, but methods can be suggested for different use cases. For more conventional grids whose needs align with the P-PMU standard, the DFT fit+detector or a well-developed PLL such as the one in

MATLAB perform well. However, there is the caveat that the DFT fit+detector algorithm requires improvement to enable measurement of frequencies more than 1 Hz from nominal. For low-inertia grids with needs that align with the Rietveld or PSCAD simulated tests, the EKF+corrector method could work if better tuned. Devices that depend on accurate ROCOF measurements should employ a ROCOF limiter or the corrector developed by Dr. Wilches Bernal.

Future work could include further analysis on the causes of accuracy discrepancies of these algorithms, especially comparing MATLAB PLL to the other "filtered" algorithms. It could be beneficial to look into the automatic gain control block that was unique to the MATLAB PLL algorithms. Finally, "enhanced zero-crossing" as reportedly used in proprietary relay algorithms may bear consideration. More generally, this research would benefit from utility data on the most troublesome transient events. The authors hope that grid operators and protection device manufacturers can use their data to cooperate with researchers to choose and tune the algorithm that best fits their requirements.

VII. Acknowledgment

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