A MATLAB-based PMU Simulator

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***Abstract*—The use of Phasor Measurement Unit (PMU) data in power system operation is of increasing importance. These data are currently used for real-time operation monitoring and off-line analysis. A good understanding of the phasor measurement process is essential for phasor quality analysis as well as for the design of advanced control and protection schemes. In this paper the main computational algorithms involved in the phasor measurement process are illustrated using a MATLAB based PMU simulator.**

***Index Terms*—PMU, phasor data processing, power system analysis, phasor estimation algorithms.**

I. INTRODUCTION

Nowadays Wide Area Measurement Systems (WAMS) are being built around the world [1–3]. and will be an important tool for improving the reliable operation of power systems. A WAMS is composed of Phasor Measurement Units (PMUs), high-speed communication channels, and Phasor Data Concentrators (PDCs) [4]. The main idea is to measure the voltage and current data, which are synchronized with the Global Positioning System (GPS), and to send these data to a central location (substation or Energy Management Center) where the PDC is located.

In recent years, many real-time and off-line application tools have been developed using phasor measurement data. In particular, PMU data are used extensively for postmortem analysis [5]. Some examples can be found in recent Brazilian [6] and Colombian blackouts [7].

Despite the high level of research activities in the development of PMU applications, the dissemination of phasor processing within a PMU is quite limited. In addition to being a high-sampled-rate digital recording device with GPS-signal time-tagging, a PMU uses signal processing techniques to provide frequency and phasor information on voltages and currents. The signal processing part is not specified in the IEEE C37.118 Synchrophasor Standard [8]. As a result, there are implementations with different algorithms and data windows. A good understanding of the tradeoff between various algorithms would be useful to engineering designing and implementing synchrophasor applications.

The objective of the paper is to present a MATLAB software platform that can be used as a teaching tool and research framework to explore the algorithms involved in the phasor measurement process. This software platform can process simulated and real measured signals. It is intended that this software tool will provide a hands-on experience for understanding the algorithms and tradeoffs involved in the phasor measurement process, such as off-nominal frequency and unbalanced phase operation, the influence of the complex gains P_n and Q_n in the process, and the methods used to minimize their influence.

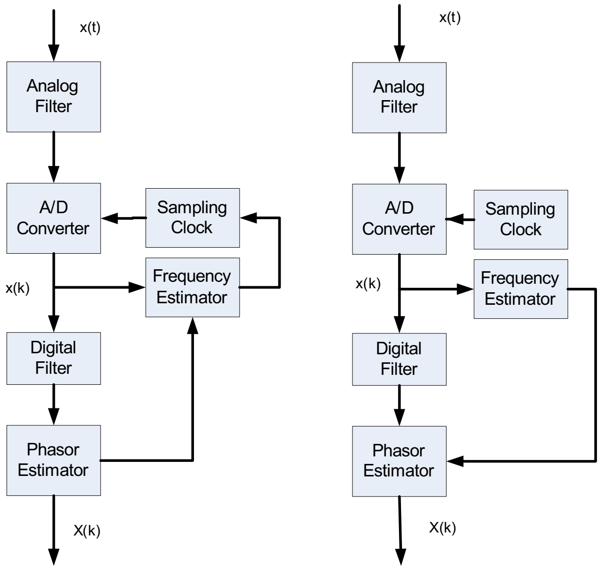

Fig. 1. Basic Phasor estimation architectures [9]

The paper is organized as follows. In Section II, PMU architectures and the phasor measurement process are presented. In Section III a MATLAB based simulator is presented. In Section IV results of the proposed approach are presented. The conclusions are presented in Section V.

II. PHASOR MEASUREMENTS ARCHITECTURES

Figure 1 illustrates the two basic PMU architectures [9]. The basic block diagrams for the two schemes are similar and can be divided into:

- Sampling and filtering;
- Frequency and Phasor (Discrete Fourier Transform - DFT) estimators.

The main difference between the architectures is in the way the signal is sampled:

- A uniform (fixed) sampling rate;
- A non-uniform (variable) sampling rate.

The first architecture was the first being used because uniform sampling simplifies the data acquisition process and the signal-processing analysis. Most of PMU algorithm development activities are based on exploring and improving

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uniform sampling methodologies [4], [5], [10], [11], [12] and [13]. As a result, this paper will focus on the uniform sampling rate approach.

There are some non-uniform sampling methodologies available from the literature. An early result is available in [14], followed by a few papers [12]; and some US patents [15] [16]. The main technical issue is to relate the time-tag given by the GPS clock to the sampling clock generated by the local power system frequency measurement.

A. Uniform Sampling Phasor Measurement Processing

The uniform sampling phasor measurement process is divided in three main parts: phasor estimation using (recursive or non-recursive) discrete Fourier Transform (DFT), frequency estimation, and post-processing (using calibration factors and filtering), as shown in Figure 2. Under off-nominal frequency operation, the post-processing layer is necessary to correct the effects caused by leakage phenomenon. Leakage phenomenon results from the truncation of sampled data outside the data window. Consequently, the estimated phasor is attenuated by two complex gains, P_n and Q_n. [1] From Equation (1), the effects of the complex gain P_n (shown in Figure 2) can be readily computed from the sampling window size (N), the frequency deviation ($\Delta\omega$) and the sampling period ($\triangle t$) [4]. The magnitude of P_n is an attenuation factor, and the phase angle of P_n is a constant offset in the measured phase angles. As the window size (N) and sampling period ($\triangle t$) are fixed, P_n can be readily estimated for a frequency range and stored in a table (Block 1 in Figure 2). In real-time, frequency deviation estimation is necessary to compute the correct P_n value.

The complex gains

$$P_n = \left\{ \frac{\sin \frac{N(\omega-\omega_0)\Delta t}{2}}{N \sin \frac{(\omega-\omega_0)\Delta t}{2}} \right\} e^{j(N-1)\frac{(\omega-\omega_0)\Delta t}{2}} \tag{1}$$

$$Q_n = \left\{ \frac{\sin \frac{N(\omega+\omega_0)\Delta t}{2}}{N \sin \frac{(\omega+\omega_0)\Delta t}{2}} \right\} e^{-j(N-1)\frac{(\omega+\omega_0)\Delta t}{2}} \tag{2}$$

introduces a magnitude and phase angle variation at frequency $2\omega_0 + \Delta\omega \simeq 2\omega_0$ (approximately) in the estimated single-phase phasor. The second harmonic ($2\omega_0$) oscillation is shown in Figure 7 (blue curve). In contrast to a static offset, this oscillation is not easily removed. A conventional way to minimize its influence is to use a three-point-average filter (Block 2 in Figure 2) [4], which can reduce the harmonic components by more than 50%.

1) Frequency Estimation: In normal power system operation, the power system frequency is never steady. This deviation can be small, when related to generation load mismatch, or large, during loss of generation disturbances. Thus, the frequency estimation methodology plays a key role in the phasor computation process. An interesting overview of the power system frequency concept is found in [9].

Several frequency measurement methodologies can be found in the literature [17–23]. The main available methods are: Zero Crossing [18], Least Error Squares [24], Kalman filters [25], Demodulation [19], [23], Phasor-Based [18],[21],[22].

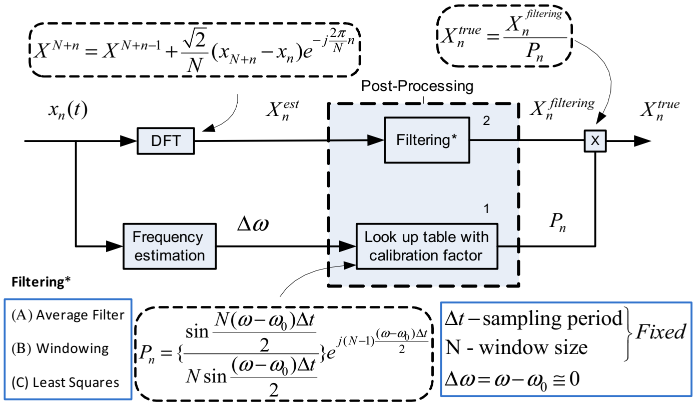

Fig. 2. Phasor processing algorithm for uniform sampling [5]

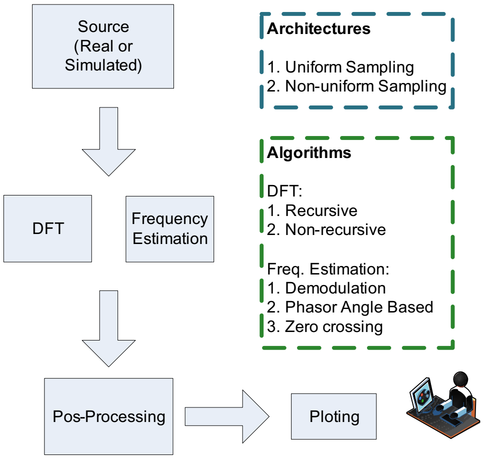

Fig. 3. Software Diagram

The methods used in the PMU Simulator are Demodulation and Phasor-Based. These methods are chosen because they provide satisfactory performance under large frequency variation and noisy environment, and are generally used into commercial PMUs.

III. MATLAB-BASED PMU SIMULATOR

MATLAB PMU simulator platform is suitable for exploring the phasor measurement estimation process described in Figure 2. The latter considers single-phase and three-phase measurement signals, allowing positive sequence phasor estimation. Step and ramp (frequency modulation) frequency disturbances can be be simulated to observe the influence of the complex gains (P_n and Q_n) and filtering in the phasor estimation process. The processing of real digital measurement data can also be realized. The main software blocks and algorithms involved in the MATLAB PMU simulator are shown in Figure 3.

The main features of the PMU Simulator are:

- Recursive and Non-Recursive DFT;
- Off-nominal frequency simulation: frequency step and ramp;
- Influence of the complex gains in the phasor measurement;

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[1] $X^{est} = PX^{true} + Q(X^{true})^*$ [4].

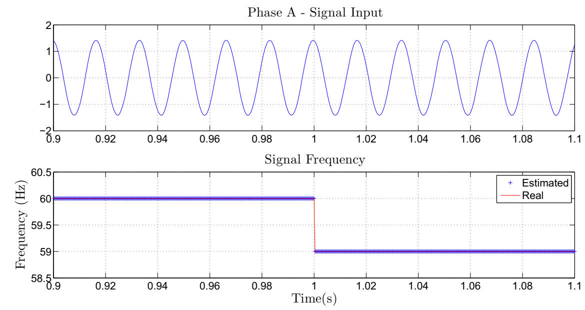

Fig. 4. Input Signal - Voltage Sine Wave

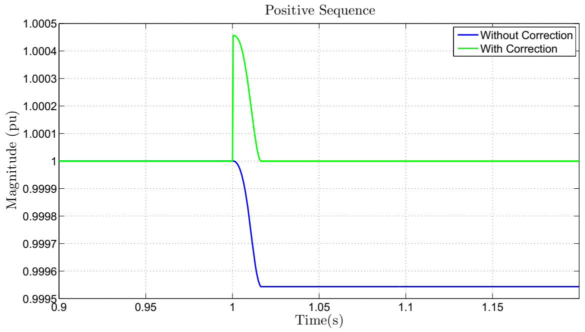

Fig. 5. Three-Phase Positive Sequence Performance

- Real data processing.

IV. Simulation Results

The main goal of this section is to describe the performance of three-phase and single-phase phasor estimation under off-nominal frequency operation, using simulated data. To illustrate the phasor performance a frequency step disturbance is applied, after $1s$, in the sine wave signal source. This disturbance is shown in Figure 4. The non-recursive DFT and demodulation algorithms are used, respectively, for the estimated phasor and frequency. The window size is set to 48 points per cycle, that is, a sampling rate of 2.88 kHz (it can be adjusted by user).

A. Three-Phase Performance

The influence of the complex gains P_n and Q_n in the three-phase phasor measurements under off-nominal frequency operation is shown in Figure 5.

The simulation in Figure 5 and Figure 6 shown the influence of the complex gain P_n in the phasor magnitude and phase, respectively. It should be noted that the influence of the complex gain Q_n, a second harmonic oscillation, is filtered by the three-phase estimation.

B. Single-Phase Performance

The performance of the single-phase phasor estimation under off-nominal frequency is shown in Figure 7.

In this simulation, the influence of the complex gains P_n and Q_n under off-nominal frequency operation is clearly revealed. The average three-point filter reduces the influence of the second harmonic, however, a small delay is found in the measurement. The phasor angle is shown in Figure 8.

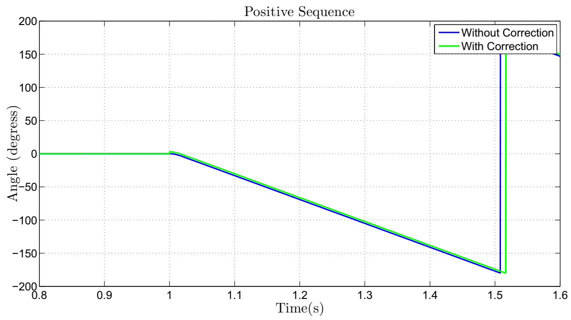

Fig. 6. Three-Phase Positive Sequence Performance

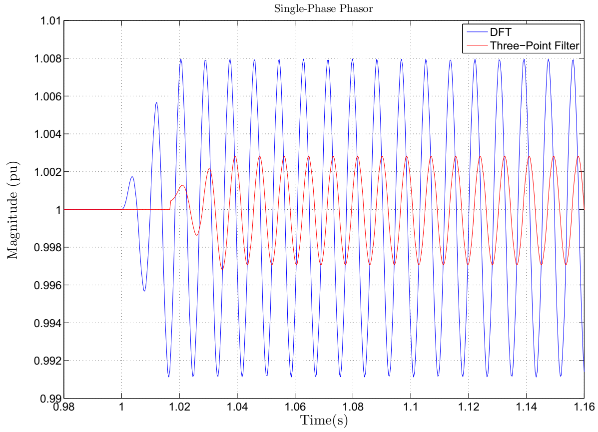

Fig. 7. Single-Phase Phasor Estimation Performance

C. Real Data

Real digital data files can be also processed by the PMU Simulator. In this case, three-phase real digital data acquired during a generator load rejection test is processed by the simulator. The data was recorded at 48 points per cycle, that is, a sampling rate of 2.88 kHz. The voltage data acquired and the frequency estimation during the fault are shown in Figures 9 and 10, respectively.

It should be noted that the load rejection happened around 0.35 s., the voltage wave exihibits some spikes related with the circuit breaker operation. The frequency estimation before

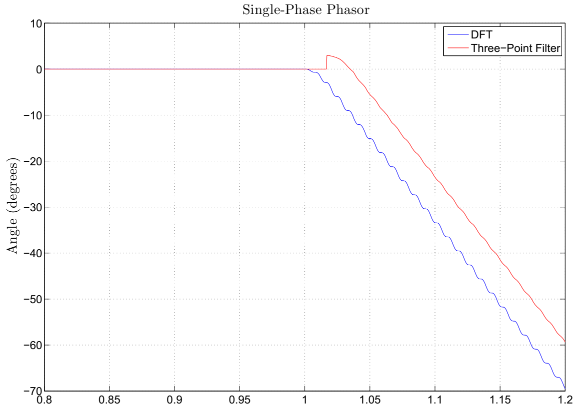

Fig. 8. Single-Phase Phasor Estimation Performance

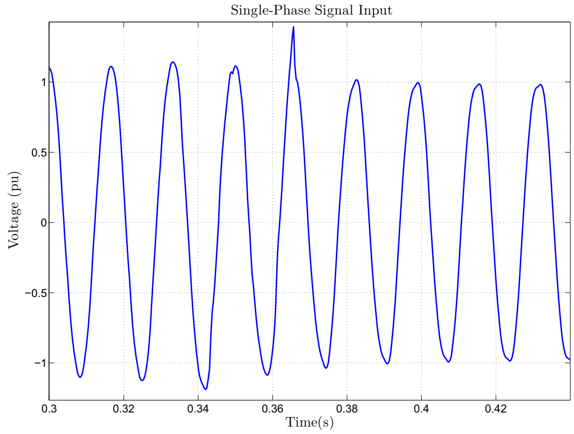

Fig. 9. Single-Phase Real Voltage Data

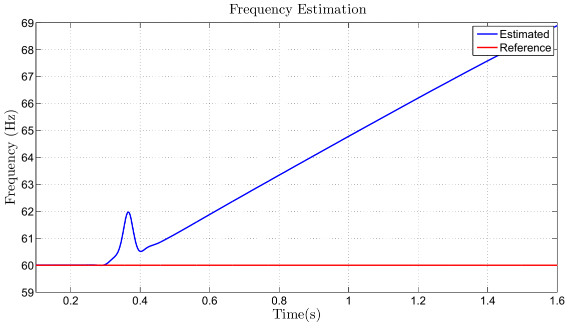

Fig. 10. Frequency Performance

and after the disturbance is shown in Figure 10.

Figure 10 shows the frequency behavior under disturbance. Following the load rejection, the frequency rises significantly because the generator is operating with no load. As expected there is a delay related to the actuation of the speed governor.

The positive sequence voltage magnitude from the phasor estimation is presented in Figure 11.

Figure 11 clearly shows the influence of the complex gain P_n as well as a small oscillation, probably related with a small unbalances between the generator phases. The influence of the complex gain P_n in phasor angle is shown in the Figure 12.

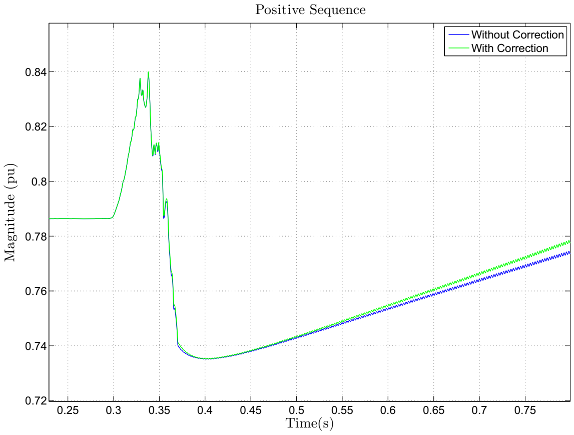

Fig. 11. Three-Phase Positive Sequence Performance

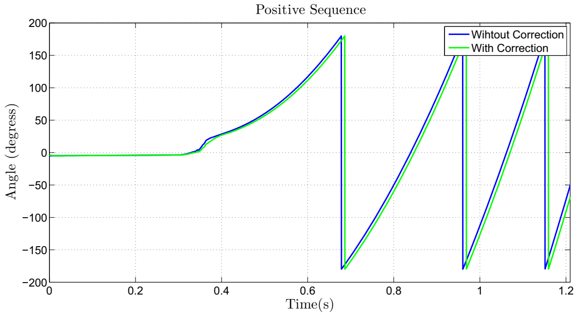

Fig. 12. Three-Phase Positive Sequence Performance

V. CONCLUSION

In this paper a PMU MATLAB simulator was presented. The aim of this software is to aid in the understanding of the behavior of algorithms internal to the PMU and to grasp key factors affecting their performance under off-nominal frequency operation. The PMU simulator is useful for academics and professionals who would like to understand the concepts involved in the phasor estimation process carried out by PMUs. The performance of the simulator was evaluated using simulated and real data from 2.88 kHz measurements. The output of the estimation process was compared with reference traces and phasors from real PMUs. The next step in the development of the MATLAB-based PMU simulator is to implement the non-uniform sampling architecture.

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