A MATLAB-based PMU Simulator

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Abstract—The use of Phasor Measurement Unit (PMU) data in power system operation is of practical importance. These data are currently used for real-time operation monitoring and off-line analysis. Understanding of the mechanisms involved in the phasor estimation process is necessary for correct phasor data interpretation and analysis, as well as for design of advanced control and protection schemes. In this paper the main phenomena 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, 2, 3]. Despite the different development stages and applications found in different countries, the Independent System Operators (ISOs) recognize this technology's potential. WAMS are composed of Phasor Measurement Units (PMUs), high-speed communication channels and Phasor Data Concentrators (PDCs) [4]. The main idea is to measure three phase voltage and current waveforms, to estimate phasors synchronized with the Global Positioning System (GPS) using these waveforms and to send the resulting data to a central location (substation or Control Center) where the PDC is located.

In recent years, significant research effort was dedicated to develop applications using phasor measurement data. In particular, PMUs became an indispensable tool for post-mortem analysis [5]. Some examples can be found in Brazilian [6] and Colombian blackouts [7].

Despite the great level of the research done in the PMU applications, a detailed understanding of the phasor estimation process could be helpful. Compared to the traditional measurement devices, like analog current and voltage oscillography, or digital devices, like digital disturbance recorders (DDR) (where the voltage/current waveforms are directly measured and converted to digital data), the PMU device uses signal processing techniques not familiar to every power system engineer. The approach to carry out this process in estimating phasors may raise concerns for the use of PMU data for advanced control and protection applications, as well as the interpretation of the data measured for real-time monitoring and off-line analysis. Additionally, WAMS provide the base platform for advance control and protection applications necessary for the future smart transmission grids. To reach this

goal the PMU network and the measurement process need to be clear and easily understandable, in order for the power system engineers to feel confident about using this data for advanced applications.

The aim of this article is to present a MATLAB software that can be used as a teaching tool and research framework to explore the algorithms involved in the phasor measurement process. This software can process simulated and real measured signals. The main idea is to provide a software tool to better understand the phenomena involved in the phasor measurement process, such as off-nominal frequency and unbalanced frequency operation, the influence of the complex gains P_n and Q_n in the process, and the methods used to minimize their influence.

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 commercial PMU architectures available [8]. These schemes are necessary to reduce the effect caused by leakage phenomena. The basic block diagrams are the same and can be divided in:

- 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:

- Uniform (fixed) sampling rate;
- Non-uniform (variable) sampling rate.

The first architecture was the first used because uniform sampling simplifies the acquisition process and the signal processing tasks. Previous works are dedicated to exploring and improving uniform sampling methodologies, presented in [4], [5], [9], [10], [11] and [12]. Since uniform sampling is well described in the literature, it will be the main architecture to be explored in this paper.

Non-uniform methodologies are not well explored in the literature. From the first published work [13], a few papers have been published regarding it [11]; and some US patents are found in [14] [15]. 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

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Fig. 1. Basic Phasor estimation architectures [8]

or nonrecursive) 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 phenomena. Leakage phenomena 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. Fortunately, 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 (Δt) [4]. The magnitude of P_n is the 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 (Δt) 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, the frequency deviation estimation is necessary to take the correct P_n value.

The complex gain

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

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*: During normal operating conditions, the power system the frequency is always changing. This deviation can be small, when related to generation load mismatch, or large, when considering large disturbances. Under these conditions, the frequency estimation methodology bears a key role in the phasor computation process. An interesting

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

overview of the power system frequency concept is found in [8].

Several frequency measurement methodologies can be found in the literature. An evaluation of the frequency estimation methodologies can be found in [16, 17, 18, 19, 20, 21, 22, 23]. The main available methods are: Zero Crossing [17], Least Error Squares [24], Kalman filters [25], Demodulation [18], [22], Phasor-Based [17],[20],[21].

The methods used in the PMU Simulator are Demodulation and Phasor-Based. These methods are chosen because they presented satisfactory performance under large frequency variation and noisy environment, and are built into commercial PMUs (phasor-based).

III. MATLAB-BASED PMU SIMULATOR

The software is suitable to explore the phasor measurements estimation process described in Figure 2. The MATLAB PMU simulator considers single-phase and three-phase measurement signals, the last one allowing positive sequence phasor estimation. Step and ramp (frequency modulation) frequency disturbances can be introduced. Simulations can be realized considering off-nominal frequency operation 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;
- Influence of the post-processing level in the phasor measurement;
- Real digital 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

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

Fig. 3. Software Diagram

Fig. 4. Input Signal - Sine Wave

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, respectively, the estimated phasor and frequency. The window size is set to 48 points per cycle, that is, a sampling rate of 2.88 kHz.

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 shows the influence of the complex gain P_n in the phasor magnitude and phase. It should be noted that the influence of the complex gain Q_n , a second harmonic oscillation, is filtered by the three-phase estimation.

Fig. 5. Three-Phase Positive Sequence Performance

Fig. 6. Three-Phase Positive Sequence Performance

Fig. 7. Single-Phase Phasor Estimation Performance

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. 8. Single-Phase Phasor Estimation Performance

Fig. 9. Single-Phase Real Data

Fig. 10. Single-Phase Real Data

Fig. 11. Single-Phase Real Data

Fig. 12. Single-Phase Real Data

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 Hydro Generator Load Rejection Test is processed by the simulator. The hydro unit 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 presents some spikes related with the circuit breaker operation. The frequency estimation before 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 phasor angle is shown in the Figure 12.

V. CONCLUSION

In this paper a PMU MATLAB simulator was presented. The aim of this software is to aid in the understanding of the behaviour 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 academic 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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