Smart Grids Technologies
Module 1, Lab 3 - 10/03/2025
Time Synchronization for PMUs

1 Organization of the lab

1.1 Objectives

We are progressing closer to a realistic implementation/simulation of a PMU. Lab 1.1 discussed the extraction of the DFT spectrum of a single observation window, while Lab 1.2 applied IpDFT synchrophasor estimation to a sliding window. This session, you will see the implementation of a PMU in an embedded systems device, a National Instruments CompactRIO. With this hardware, this session will focus on the time synchronization aspect of PMUs as discussed in Lecture # 5. Specifically, the following exercises will examine the impact of various failures in time dissemination and synchronization due to synchronization/syntonization errors and clock drift.

To accomplish this, you will compare the performance of two PMUs. The first PMU, synced to reference time, will be used as the baseline for the phasor estimation. The second PMU is implemented with the possibility to control the time offset, frequency offset and frequency drift of the PMU's clock, simulating the effects of communication delays, oscillator malfunctions, or sync failures.

1.2 Lab report

This report will not be graded; however, its submission is mandatory. The purpose of the questions within this document is to enhance your comprehension of the subject matter. Your acquired knowledge from **all three laboratories of Module 1** will be evaluated in a quiz scheduled for **Monday, March 17th** from **9:15 to 10:00**. The deadline for submission of the reports is **Sunday, March 16th** at **23:55**.

2 Theoretical Background

Phasor Measurement Units (PMUs) require an accurate and reliable time source to correctly phase align synchrophasors relative to geographically-distant substations. Typically, PMUs rely on the time reference made available by the Global Positioning System (GPS). If a GPS signal is not available and the telecommunication infrastructure is already installed, various network-based alternatives exist to substitute or support the GPS (e.g. synchronous-Ethernet based systems like the Precision Time Protocol (PTP) or the White Rabbit (WR) Time Protocol).

For transmission applications, the IEC/IEEE 60255-118-1:2018 Std. requires a maximum uncertainty in the synchrophasor time jitter of 1 μs[1]. Distribution PMUs, requiring an increased level of accuracy, expect a lower level of uncertainty, in the order of tens of ns. Indeed, modern PMUs embed synchrophasor estimation algorithms exhibiting phase accuracies of a few μrad, corresponding to 10 ns for a power system at 50 Hz.

GPS provides an uncertainty in the order of 100 ns when coupled with commercial receivers, whereas PTP is characterized by an uncertainty of 1 μs. Therefore, these time references could negatively affect the phase estimation performance of the PMUs. Conversely, WR achieves sub-nanosecond accuracy, assuming only fiber interconnections and dedicated switches.

Time synchronization is a key factor in any PMU-based monitoring systems. The IEC/IEEE 60255-118-1:2018 Std. defines the phase of a synchrophasor as the instantaneous phase angle relative to a cosine function at the nominal power system frequency, synchronized to Coordinated Universal Time (UTC). In that sense, any uncertainty in the time synchronization Δt linearly translates in a phase uncertainty $\Delta\varphi$, depending on the instantaneous frequency f of the signal:

$$\Delta\varphi = 2\pi f \Delta t + \varepsilon_{alg} + \varepsilon_{acq} \tag{1}$$

where ε_{alg} and ε_{acq} account for two additional uncertainty sources: the phase

[1] This value is indirectly determined by the requirement for a maximum Total Vector Error (TVE) of 1%, corresponding to a phase uncertainty of 0.01 rad in case the TVE is only influenced by the phase error. When time is the only source of error, this corresponds to 31 μs at 50 Hz. A reliable time source should be characterized by an uncertainty at least 10 times better, giving some allowance for sources of error other than synchronization, leading to the recommended time uncertainty of 1 μs. PMUs operating in distribution networks are expected to meet more stringent accuracy requirements, at least two orders of magnitude lower than those met by transmission PMUs (TVE lower than 0.01%). Therefore, the uncertainty contribution coming from the timing unit should be reduced to the order of tens of ns.

error introduced by the adopted synchrophasor estimation algorithm and the phase noise produced by the acquisition process (including the measurement chain from the sensor to the PMU analog input), respectively. Since these errors come from independent devices, these two contributions are assumed to be statistically independent and uncorrelated.

The time error is often modeled as

$$x(t) = a + b \cdot t + D_r \cdot t^2/2 + \epsilon(t) \tag{2}$$

where a is the initial time error, $b = \frac{\Delta f}{f_{clock}}$ is the normalized frequency offset (relative to the reference frequency of the clock), D_r is the frequency drift constant and ϵ represents random variations (i.e., noise). Figure 1 demonstrates the effects of a few common time errors. Systematic errors like time offset and frequency offset can often be characterized and compensated for in PMU devices with frequent synchronization updates from a more stable and accurate reference clock. Various protocols also exist to minimize clock drift by including the reference frequency in the synchronization update. For example, the SynchE protocol embeds frequency information in messages over the Ethernet physical layer so that an embedded PLL-based oscillators can lock to this rate. On the other hand, random processes like jitter (i.e., noise) are unavoidable and represent the actual uncertainty of the measurement system.

2.1 Global Positioning System (GPS)

The operation principle of satellite systems is based on the time measurement of synchronizing signals between satellites and terrestrial receivers. The satellites are equipped with atomic clocks, daily monitored and controlled to be highly synchronized and traceable to the UTC time. The receivers are equipped with an internal clock, and are able to determine the actual UTC time by collecting and processing messages from several satellites.

In a very approximated form, GPS satellites broadcast radio signals providing their locations, status, and precise time t_1 from on-board atomic clocks. The GPS radio signals travel through space at the speed of light c (circa 299,792 km/s). A GPS device receives the radio signals, noting their time of arrival t_2, and uses these to calculate its distance d from each satellite in view:

$$d = c \cdot (t_2 - t_1) \tag{3}$$

being the signal's travel time the difference between the time broadcast by the satellite t_1 and the time the signal is received t_2. Once a GPS

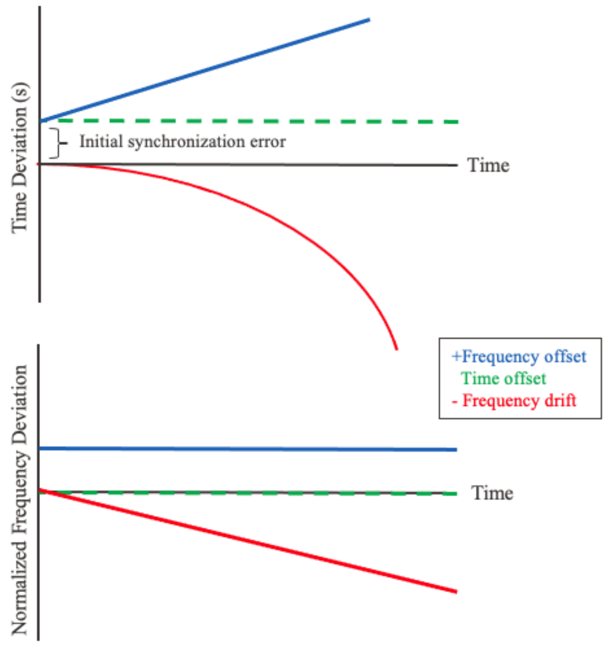

Figure 1: Time and frequency error.

device knows its distance from at least four satellites, it can use geometry to determine its location on Earth in three dimensions, based on the Bancroft algorithm.

To correctly lock satellites, the GPS receiver requires a clear view of the sky. Indeed, being in an enclosed space such as a high rise urban environment, reduces the number of tracked satellites and determines signal reflections and wakening, resulting in a degradation of the time information accuracy.

A GPS timing module is typically coupled with a GPS receiver mounted on the rooftop of the installation with a full-sky visibility. The two units are connected by means of RG-213 shielded cables that introduce an unavoidable propagation delay of 5.05 ns/m that should be suitably compensated at the timing unit. Commercial GPS receivers embed an active GPS antenna with a high-gain preamplifier and dual passband filters. The preamplifier enables preserving the GPS signal even for long cable lengths, whereas the filters improve rejection to interfering radio signals and reliability.

2.2 Precision Time Protocol (PTP)

The core element of the PTP is the exchange of time-tagged messages in a peer-to-peer link between timeTransmitter and timeReceiver clocks, used to calculate the link delay between the two clocks. Specifically, at time t_1 the timeTransmitter node sends a *Sync* message, that is received at time t_2 by the timeReceiver. Similarly, at time t_3, the timeReceiver node sends a message, received at time t_4 by the timeTransmitter. Knowing these four time-stamps, the one-way delay between the two clocks can be estimated as:

$$\delta = (t_2 - t_1 + t_4 - t_3)/2 \tag{4}$$

The timeReceiver node accounts for this offset when adjusting its clock time with respect to the one of its timeTransmitter clock. The PTP assumes that all network nodes are equipped with PTP-aware routers or switches, (also called boundary or transparent clocks), implementing the so-called hardware-assisted time-stamping, a technique to measure and compensate for the time spent by messages in queuing at their own ports.

The first limitation of the PTP is that it assumes that the one-way delay is exactly half of the two-way delay, which, due to link asymmetry is true only as long as the cable is very short. The second limitation is that the final PTP accuracy is limited by the precision and resolution of the timeTransmitter and timeReceiver clocks to measure the time when sending or receiving messages, typically of 100 ppm. The third limitation is that these clocks are typically free-running oscillators, without any guarantee of synchronism between oscillators at different nodes. This results in uncontrolled time drift between timeTransmitters and timeReceivers. The higher the exchange rate of PTP messages, the lower the time drift, the higher the bandwidth needed for PTP-related traffic.

2.3 Time-sync Performance Assessment

The uncertainty requirements of a PMU are expressed in terms of TVE and Frequency Error (FE). However, the analysis of amplitude and phase error separately provides a deeper understanding about eventual error sources. More specifically, inaccuracy related to a poor time-synchronization of the PMU under test, results in a phase error.

2.4 References

- NASPI, “Time synchronization in the electric power system,” technical report, NASPI Time Synchronization Task Force, 2018.

- A. Derviškadić, R. Razzaghi, Q. Walger, and M. Paolone, "The white rabbit time synchronization protocol for synchrophasor networks," IEEE Transactions on Smart Grid, Special Section on Theory and Application of PMUs in Power Distribution Systems, 2019
- Allan, David W. "Clock Characterization Tutorial." (1984).
- Barnes, James. "Measurement of Linear Frequency Drift in Oscillators". (1983) https://tf.nist.gov/general/tn1337/Tn264.pdf

3 LabVIEW Implementation

Perform the following steps to begin the lab:

1. From Moodle, download the zipped folder *"Lab 3 - Time Sync"*
2. Extract the zipped file.
3. Open the LabVIEW project called *"SGT-PMUs.lvproj"*
4. Right-click on the RT target *ELD040-cRIO-xx* and select "Connect". After a few seconds a green light should appear next to the RT target, indicating that the cRIO is correctly connected.

3.1 FPGA code

Under the FPGA chassis, open the VI called *"PMU_FPGA.vi"*. **Do not change anything in this VI.** Changing FPGA code requires recompilation of the VI for deployment on the cRIO. This can take minutes to hours. If you accidentally change something and get a compilation error, it is faster to download the project from moodle again.While **there are no coding tasks for this lab**, you should try to understand the function of each loop.

The top loop ("Signal Generation") is responsible for signal generation and establishing reference time. Think of this as your UTC reference that generates a subPPS square wave to trigger reporting.

The loops labelled "PMU 1 - Acquisition" and "PMU 1- Reporting" are very similar to the code of Lab 1.2: they sample the sine waveform generated in the top loop and, on the report trigger, send the samples to the real-time processor for synchrophasor estimation. PMU 1 will be considered as the reference PMU for the phasor estimation, because the signal acquisition is time and frequency aligned to the generation of the voltage waveform in the top loop. The loops are duplicated for PMU 2: PMU 2 reads in the same signal but has some additional blocks that simulate various sources of time error:

- The **time offset** of the clock of PMU 2 with respect to PMU 1
- The **frequency offset** of the clock of PMU 2 with respect to PMU 1
- The **frequency drift** of the clock of PMU 2 with respect to PMU 1

Q1/ Analyze the FPGA diagram and explain how reporting is managed by both PMUs.

[A1]

3.2 RT programming

Under the RT target *ELD040-cRIO-xx*, open the VI called *"PMU_RT.vi"*. Notice that the synchrophasor analysis code for PMU 1 (reference PMU) has been duplicated for PMU 2. Also notice that we will assume the synchrophasors estimated by PMU 1 as reference values: the errors of PMU 2 will be evaluated with respect to those estimated by PMU 1.

Q2/ Set all the synchronization parameters to False and run "PMU RT.vi". Note the average time error, FE, AE, and pE as your baseline.

[A2]

Set **"Time Delay"** to True (all others to False) and rerun "PMU RT.vi".

Q3/ a) What variable does this scenario change in the FPGA and how does this affect the reporting of the waveform? b) Explain how this setting impacts the phasor estimation errors.

[A3]

Q4/ a) Show how to calculate the time delay from the observed phasor errors. b) Which effect of a real GPS or PTP installation does this simulate?. c) Account for the time delay of PMU 2 and explain the impact on the phasor estimation.

[A4]

Reset the Time Delay of PMU 2 back to 0. Set **"Frequency Offset"** to True (all others to False) and rerun "PMU RT.vi".

Q5/ a) What variable does this scenario change in the FPGA and how does this affect the sampling of your waveform? *Hint: Do you see more or less periods reported by PMU 2 compared to PMU 1* ? b) Does the waveform appear to move? Why or why not?

[A5]

Q6/ a) Explain the impact of the frequency offset on the phasor estimation errors. b) Show how to compute the true sampling frequency of PMU 2 based on the time error. *Hint: export the time error and consider equation (2).*

[A6]

Q7/ Correct the "Sampling Rate for IpDFT (PMU 2)" and explain the impact on the phasor estimation estimation.

[A7]

Reset "Sampling Rate for IpDFT (PMU 2)" to 10 kHz. Set **"Frequency Drift"** to True (all others to False) and rerun "PMU RT.vi".

Q8/ a) Explain the impact on the phasor and time errors. b) Which effect of a real GPS or PTP installation does this simulate?

[A8]