Pulsar-Calibrated Timing Source for Synchronized Sampling

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***Abstract*—The Global Positioning System (GPS) is critical to the real-time synchronized sampling of phasor measurement units (PMUs). Unfortunately, GPS signals are occasionally unstable due to several factors such as weak satellite signal and GPS spoofing, thereby leaving the PMU with a degraded sampling performance. In this letter, a novel Pulsar-calibrated Timing Source (PTS) is proposed as the alternative timing source for synchronized sampling. The PTS can generate the timing signal with a 1μs drift error within 91 holdover minutes to ensure continuity of sampling accuracy. Experimental tests are conducted and the results reveal the reliability and accuracy of the PTS for PMU synchronization.**

***Index Terms*—Phasor measurement units, pulsar-calibrated timing source, synchronized sampling.**

I. Introduction

PHASOR measurement units (PMUs) have become an indispensable part of the Wide-area Monitoring System (WAMS) for power grid situation awareness. PMUs can generate the synchronized real-time data streams based on the pulse per second (PPS) from Global Positioning System (GPS) [1]. The accuracy of the synchronized data, such as the angle and frequency data, is highly affected by PPS. The IEEE C37.118.1-2011 defines that total vector error cannot exceed 1% for PMU, of which the corresponding angle and PPS timing errors are ±0.573° and ±26.5 μs, respectively, for a 60 Hz power system [2]. Unfortunately, there are two issues that plague the accuracy of sampling, including the weak satellite signal and GPS spoofing [3], [4]. Consequently, the measured angle will drift due to cumulative effects.

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To mitigate the negative effect caused by the above problems, several backup timing sources are proposed in the literature. Compensating the offset is one of the most common methods with the assumption that the frequency of the internal oscillator does not change. In [5], an angle compensation strategy is proposed and the tolerable length of GPS loss is 51 minutes. However, the assumption that the frequency of the internal oscillator does not change can be valid in the short term. And it cannot fully compensate for the angle drift since the actual frequency of the oscillator will be affected by the temperature and external factors such as the supply voltage. Thereafter, some other synchronization schemes are developed. For example, the chip-scale atomic clock (CSAC) is utilized for the synchrophasor measurement in [6], which can reach an 0.0046° angle error standard deviation (SD). However, to realize the high accuracy, each PMU should be equipped with an additional timing source, thus increasing the manufacturing cost. Besides, the double-oven controlled oscillator (DOCO) is also used for the PMU holdover performance improvement with a 1.8 μs timing error in three hours [7]. By controlling the temperature of the oven, a small frequency change rate can be obtained. The warm-up time and higher power consumption limit its wide application. In general, the above-mentioned timing source mainly works according to its own stability, but its actual frequency is changed.

Observations have proven that pulsars emit periodic pulse signals of which the periods are extremely stable, which can reach 10^{-15} for 10 years [8], [9]. Utilizing the known periodicity and stability of the pulsar signal, the real-time frequency of the local oscillator can be estimated with the reference of the pulsar pulse. This process is called a Pulsar-calibrated Timing Source (PTS) in this letter. The PTS can generate precise periodic signals, e.g., PPSs to provide an alternative solution for synchronized sampling. Compared with the GPS signal, the PTS can reduce the possibility of signal loss and cyber attack due to the following two reasons. 1) The radio telescope can search for multiple pulsars to avoid the signal loss problem. 2) The period of the pulsar can be considered fixed, and the radio telescope is not searching for the strongest signal as its target signal. Thereafter, the effectiveness of the PTS is verified through the experimental test.

II. Principle of Pulsar-Calibrated Timing Source

The motivation of the pulsar-calibrated timing source is to serve as the alternative timing source when the GPS signal is not reliable. By estimating the real frequency of the crystal oscillator that the pulsar sampling equipment used, the timing

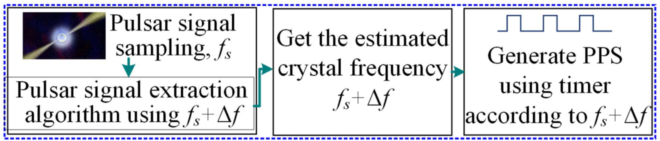

Fig. 1. Setup of Pulsar-calibrated clock.

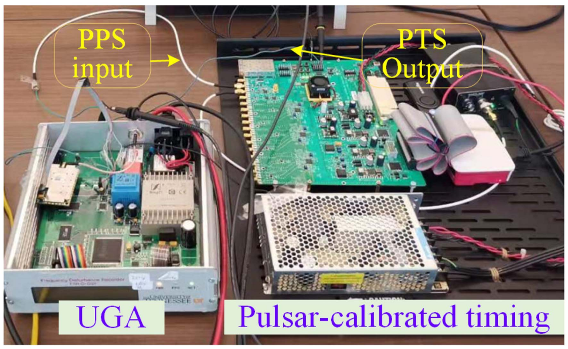

Fig. 2. Setup of Pulsar-calibrated timing source with UGA.

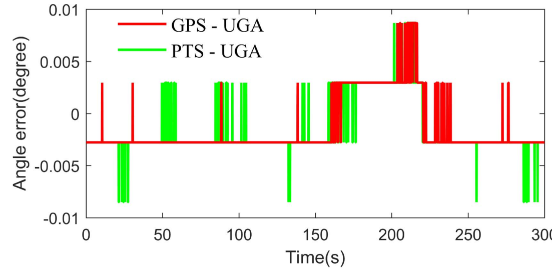

Fig. 3. Angle error of GPS-UGA and PTS-UGA.

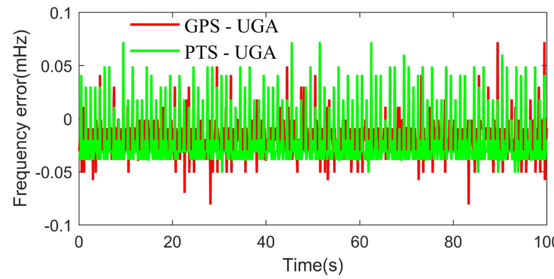

Fig. 4. Frequency error of GPS-UGA and PTS-UGA.

signal can be generated. As shown in Fig. 1, denoting the ideal frequency of crystal oscillator as f_s, the estimated true oscillator frequency $f_s+\Delta f$ can be derived using the extracted periodical pulsar pulse, where a sufficiently high accuracy can be achieved when the period of pulsar data superposition is longer. The detailed pulsar signal extraction method can refer to [10]. After getting the $f_s + \Delta f$, the PPS can be generated utilizing its internal timer.

To verify the effectiveness of PTS, the synchronized measurement device is used for the performance evaluation. Here, the Universal Grid Analyzer (UGA), is selected as an example of synchronized measurement devices to verify the accuracy of PTS [11], as shown in Fig. 2. The workflow of the proposed PTS can be summarized as follows.

1) Lock to GPS satellites: The PTS signal will align to the PPS signal from the GPS when the GPS is available.
2) Calculate oscillator frequency: The frequency of the oscillator used for the pulsar signal sampling will be calculated. An accurate pulse profile (shape, signal-to-noise ratio) will be used for the pulsar extraction.
3) Generate accurate PTS-based PPS: Based on the real-time calculated frequency received from the server, the accurate PPS can be generated as the timing signal for the required devices.

For example, the PTS-based PPS can be fed into the synchronized measurement devices as the alternative timing source when the GPS signal is not stable. When the number of satellites is less than 2, it can be treated as a GPS signal lost and the PTS can start to provide the timing signal. When GPS signal spoofing happens, a GPS spoofing detection method is required. Once the GPS signal is spoofed, a switch signal can be sent to the PTS method and the aligned state of the PPS can be returned to the previous state in which the GPS signal is normal.

After the PTS-based PPS is generated, the distributed PMU can receive the signal through Precision Time Protocol (PTP) defined by IEEE1588-2019 [12], which can achieve the precise synchronization of the real-time clocks. The path delay measurement errors can reach 0.3ps, and for a residence time of 1 ms, the maximum error is 200 ns (it can be reduced by correcting) [12]. Meanwhile, the tested single link synchronization test error can be lower than 5 ns according to [13] so that the synchrophasor measurement can meet accuracy requirements.

III. PTS Experiment

To compare sampling accuracy, two UGAs will be used including the PTS-UGA and GPS-UGA. The timing signal of GPS-UGA is provided by the GPS. The standard signal source OMICRON CMC 256 Plus is used as the 60Hz sinusoidal voltage signal generator. During the test, a delay of 10 seconds is considered, which means that the current generated PTS-based PPS is referred to the estimated crystal frequency calculated 10 seconds ago. The actual angle and frequency error test, as well as the timing drift, are evaluated in tests.

A. *Sampling Performance of Pulsar-Calibrated Oscillator*

The measurement angle and frequency error results are shown in Figs. 3 and 4, respectively. Here, 100s frequency data is presented to facilitate the observation of data differences.

It can be seen that the error of measured angle and frequency are lower than 0.01° and 0.1mHz, respectively. The reported error of CSAC-frequency disturbance recorder (FDR)[6] is also compared with the proposed method, where the SD of the frequency and angle error are summarized in Table I. As can be seen from Table I, the SD of angle and frequency error are close to each other for GPS-UGA and PTS-UGA. Compared with CSAC-FDR, the angle and frequency error of PTS-UGA are both lower. The sampling error result shows that it can meet the IEEE standard since the angle error is lower than 0.573° [2].

TABLE I
SD OF GPS-UGA, CSAC-FDR, AND PTS-UGA

Method	GPS-UGA	CSAC-FDR [6]	PTS-UGA
SD of angle error	0.0027	0.0046	0.0027
SD of frequency error	1.72e-5	1.42e-4	2.09e-5

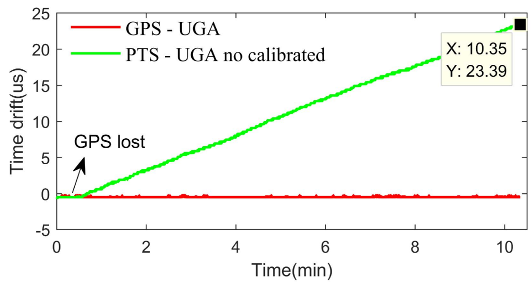

Fig. 5. Timing drifts of GPS-UGA and PTS-UGA without the calibration.

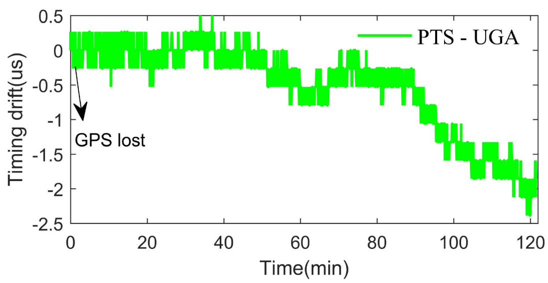

Fig. 6. Timing drift of PTS-UGA in two hours.

B. Timing Drift Testing

Although the PTS has a high timing accuracy, a cumulative error will occur with long-term GPS signal loss. To explore the duration of PTS staying within the accuracy limit of the IEEE standard, the timing drift is tested. At the beginning of the test, the PTS is disciplined using the PPS from GPS. Then the GPS signal is blocked and the synchronization signal of UGA is switched to the PPS generated by the PTS. The time difference between GPS-UGA and PTS-UGA is measured.

The timing drifts without and with the calibration for PTS-UGA are presented in Fig. 5 and Fig. 6. It can be seen that the timing error can reach 23.39 μs in 10 minutes for PTS-UGA since the local crystal oscillator is not calibrated.

As shown in Fig. 6, after the accurate estimation and compensation, this error decreases to 1 μs in 91 minutes, which is equivalent to 0.0216° angle error for 60 Hz power system, and 0.018° angle error for 50 Hz system, satisfying the requirements of the IEEE standard. Meanwhile, it can be seen from Fig. 6 that the PTS has a -0.25 μs error at the beginning of 10 minutes, indicating its good transient performance. Meanwhile, compared with the 51 minutes length using the angle compensation method [5], the PTS has a longer tolerable length for requirements such as oscillation detection and event location.

To further verify the measurement error, the angle compensation strategy from [5] is compared with the proposed method, as listed in Table II. The results show that after the compensation, the angle error is highly reduced from 0.112° to $9.94e-3°$ after 30 minutes. Compared with the compensation strategy, the angle error of the PTS-based method is lower with $6.24e-4°$ angle error, indicating that the validity of the proposed method.

TABLE II
COMPARISON OF ANGLE MEASUREMENT RESULTS

Length of GPS loss	Angle error: Without comp.	With comp.	PTS-based method
1 minute	4.01e-3	1.74e-4	1.39e-4
10 minute	4.32e-2	2.61e-3	5.11e-4
30 minute	1.12e-1	9.94e-3	6.24e-4

C. Timing Error Analysis

Although PTS is an accurate timing source, timing error including the compensation error and frequency estimated error still exists. However, the compensation error can be greatly minimized through testing. Besides, the accuracy of frequency estimation is directly related to timing accuracy. According to the actual pulsar data of J1713 + 0747 from the green bank telescope, 500 ns accuracy can be obtained with a 15.63 s pulsar signal data when $f_s = 200$ MHz. Moreover, 250 ns accuracy can be reached with near 31 s pulsar signal data. For the current test bench, 1 μs in 91 minutes is the best performance. Theoretically, the frequency estimated error can be reduced to a smaller value (less than 100 ns) with a higher sampling frequency or longer sampling window. In reality, two PMUs may locate in different locations that are far apart, the timing error will increase slightly in two cases. If the precision time protocol is used to realize the distribution of the synchronization signal, the maximum timing error is the sum of PPS transmission delay and the timing error of PPS, namely 2.008 μs in 91 minutes. If two PTS devices are used, the maximum timing error caused by the PPS can reach 2 μs in 91 minutes which is double of a single PMU error.

To explore the real-time performance of the proposed method, the time delay is tested. As discussed in Section II, there are three steps in the PTS method. Steps 1) and 3) are embedded in the hardware part (Field Programmable Gate Array, FPGA) of the pulsar-calibrated timing system and these two steps are real-time. Step 3) will cost about 1.5 seconds in the dedicated computing unit (data server) for searching the best-estimated crystal frequency and then send to the hardware part (send one time per second). Therefore, the total delay of step 2) will consume less than 3 seconds. Overall, the real-time applicability of the PTS can be satisfied.

IV. CONCLUSION

In this letter, a Pulsar-calibrated timing source is developed and successfully implemented on the synchronized measurement devices. By estimating the actual frequency of the oscillator from PTS, the periodic sampling pulse can thereby be generated using its timer. The angle and frequency errors are measured. The timing drift test is compared with the GPS based PMU. The following conclusion can be drawn.

1) The PTS can be utilized as the stable alternative PPS signal source for PMU utilizing the stability of pulsars.
2) The timing drift of the tested PTS is 1 μs for 91 minutes, which can provide sufficient timing accuracy for the synchronized sampling.
3) The higher accuracy can be obtained by observing stable pulsars and superimposing longer-term pulse data.

Future work could develop the time distribution system such as that associated with IEEE 1588.C3 to distribute the PTS-based PPS to each distributed PMU.

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