Alignment Method for Synchronized Phase Angle Measurement With Presence of Practical Time Shift

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***Abstract*—Synchronized Phase Angle Measurements (SPAMs) are widely used in power systems in the applications of situational awareness. However, the practical time shifts can lead to unexpected angle differences among Phasor Measurement Units (PMUs) manufactured from various vendors. Moreover, since most of PMUs calculate phase angle via Discrete Fourier Transform based approaches, this issue becomes even worse under the off-nominal frequency condition. To mitigate the impact of practical timing shift, this letter presents a fast method to rectify the SPAM for appropriate alignment. To verify the performance of the proposed method, laboratory and field tests have been conducted by implementing the method in PMUs and phasor data concentrators, respectively. The results demonstrate that the standard deviations of the phase angle differences have significantly decreased to 0.1° order with the adoption of the proposed method.**

***Index Terms*—Discrete fourier transform, phase angle alignment, synchronized measurement devices.**

I. Introduction

SYNCHRONIZED Phase Angle Measurement (SPAM) estimated from Phasor Measurement Units (PMUs) have substantial contributions to the power system applications such as event detection [1] and islanding detection [2]. To achieve a high-precision synchronization, PMUs obtain the Pulse Per Second (PPS) signal in nanosecond accuracy from Global Positioning System (GPS) receivers for waveform sampling and then stamp calculated SPAM with UTC time index before transmitting to Phasor Data Concentrators (PDCs), where SPAM will be unwrapped and aligned before fed into various analytical applications [3].

However, due to several uncontrollable factors such as hardware malfunction and unstable GPS signal [4]–[6], the practical time shift existed in PMUs manufactured from various vendors leads to unexpected angle drift, which would aversely influence the SPAM alignment in PDC. These time shifts are widely existed in real world deployed PMUs [4]. Moreover, SPAMs can be calculated via Discrete Fourier Transform (DFT), Phase-Locked Loop (PLL), Unified Three-phase Signal Processor (UTSP), or Kalman Filter [7] according to IEEE C37 standard [8] in which DFT is the most widely used method. Different DFT window sizes and sampling rates may be employed for different commercial PMUs, which would worsen the issues of angle drift, especially under the condition of off-nominal frequency [9]. According to C37 standard, an angle drift larger than 0.57° corresponding to 26 μs time shift causes the total vector error exceeding the 1% limit [8].

In [4], the time shift detection method can be effectively conducted by utilizing the similarity analysis between relative phase angle and frequency. However, no solution is provided to correct the angle drifts smaller than 0.57° in real-time manner. As the applications that rely on SPAM are vulnerable to this inaccurate alignment, for example, false event trigger, it is crucial to rectify the angle difference among onsite PMUs and mitigate the adverse impact of this inevitable time shift.

The aim of the proposed method in this letter is to correct the value of SPAM with presence of practical time shift for the proper alignment in PDC. First, the impact of time shift on SPAM drifts among PMUs is investigated. Then the angle error estimated by DFT is calculated theoretically considering off-normal conditions. Third, an alignment method, which can be either implemented in PMUs or PDCs, is designed to rectify the SPAM. The performance is evaluated via implementation test in PMUs and PDC.

II. Angle Drift Analysis and Alignment Method

A. Angle Drift Analysis

The SPAM reported by PMUs are the phase angle value at the sampling time. Assuming there is an actual reference phase angle measured by one PMU at time instant T_r, referred as $A_{r,a}$ and an actual phase angle measured by the ith PMU at time instant T_i, referred as $A_{i,a}$, $A_{r,a}$ and $A_{i,a}$ would shift each other

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when $T_r \neq T_i$ which is likely to occur in practice. According to [4], the difference between T_r and T_i is in millisecond level which is smaller than the reporting interval of PMU. Thus it is difficult to be detected through normal data screening. The time shift is assumed to be a constant value in this paper. After unwrapping the phase angles, the relationship between $A_{r,a}$ and $A_{i,a}$ can be written as,

$$A_{r,a} = A_{i,a} + 2\pi \int_{T_r}^{T_i} (f - f_0) dt, \tag{1}$$

where f is the frequency reported in the latest PMU data frame and f_0 is the nominal frequency [3]. Considering the time between T_r and T_i is far smaller than the reporting interval, the frequency f can be assumed to be constant (Note that the f is assumed to be the same for both reference PMU and the ith PMU. The frequency estimated from the ith PMU will be utilized in (2).) Thus (1) can be rewritten as,

$$A_{r,a} = A_{i,a} + 2\pi(T_r - T_i)(f - f_0). \tag{2}$$

Since both PMUs can only get the measured phase angle, the off-nominal frequency has influences on the DFT based phase angle estimation. According to [9], the measured phase angle by DFT algorithm consists of three components in equation (3): 1) actual phase angle, $A_{i,a}$; 2) invariant error; and 3) variant sinusoidal form error through which the measured phase angle by the ith PMU can be written as,

$$A_i = \underbrace{A_{i,a}}_{1)} + \underbrace{\frac{(N_i - 1)\pi \triangle f}{N_i f_0}}_{2)} \underbrace{- \frac{N \triangle f}{2f_0 + \triangle f} sin \left[A_{i,a} + \frac{(N_i - 1)2\pi(f_0 + \triangle f)}{N_f f_0} \right]}_{3)}, \tag{3}$$

where A_i is the measured phase angle of the ith PMU; $\triangle f$ is $f - f_0$; and N_i is the size of the DFT window in the ith PMU. According to [9], the variant sinusoidal form error can be suppressed in quasi-positive-sequence DFT algorithm while the invariant error can be canceled out by adding an "offset". The "offset" can be written as,

$$offset_i = \frac{(N_i - 1)\pi(f - f_0)}{N_i f_0}. \tag{4}$$

Considering the impact of variant sinusoidal form error is negligible compared with offset error, the variant sinusoidal form error is ignored in this paper thus (3) can be simplified as,

$$A_i \approx A_{i,a} + offset_i. \tag{5}$$

Now, by substituting (5) into (2), the $A_{r,a}$ can be computed as,

$$A_{r,a} = A_i - offset_i + 2\pi(T_r - T_i)(f - f_0). \tag{6}$$

If the "offset" of the reference PMU is also taken into consideration, the measured phase angle of the reference PMU can be written as,

$$A_r = A_i - offset_i + offset_r + 2\pi(T_r - T_i)(f - f_0), \tag{7}$$

$$offset_r = \frac{(N_r - 1)\pi(f - f_0)}{N_r f_0}, \tag{8}$$

where A_r is the measured phase angle of the reference PMU, $offset_r$ is the "offset" of the reference PMU, and N_r is the size of the DFT window in the reference PMU. Since the frequency for two PMUs are assumed to be a constant value between T_r and T_f, the A_r can be further simplified as,

$$A_r = A_i + H(f - f_0), \tag{9}$$

where the drift coefficient H is,

$$H = 2\pi(T_r - T_i) - \frac{(N_i - 1)\pi}{N_i f_0} - \frac{(N_r - 1)\pi}{N_r f_0}. \tag{10}$$

Note that the f in (9) is instantaneous frequency and thus it may have a small delay if the window size for frequency estimation is too large.

B. Angle Drift Alignment Method

Since H is related to T_r, T_i, N_r, and N_i which are usually not available to the end user of PMU, an experiment-based alignment method is proposed to estimate the H in following three steps:

- Step 1: Connect the PMUs to a time synchronized signal generator and run the frequency ramp profile. The frequency ramp profile should start from the nominal frequency and end at the limits of the PMU measurement range, e.g., 2 Hz is utilized in this paper. In addition, the frequency slope should be a low value to make sure both the SPAMs and frequencies are continuous, e.g., 5.26 mHz/s is utilized in this paper.
- Step 2: Record the SPAMs and frequency from all PMUs and calculate the angle drifts between the reference and other PMUs.
- Step 3: The aligned phase angle, $A_{aligned}$ can be calculated as,

  $$A_{aligned} = A_{raw} + H(f - f_0), \tag{11}$$

  where the A_{raw} is the raw phase angle. $H_{estimated}$ can be calculated as,

  $$H_{estimated} = \frac{\sum_{k=1}^{N} \frac{A_{r,k} - A_{i,k}}{f_k - f_0}}{N}, \tag{12}$$

  where $A_{r,k}$ and $A_{i,k}$ are the reference and the ith PMU's phase angles at time stamp k; N is the number of stamps. If the data frame is lost caused by communication delay [10], the $A_{aligned}$ would not be available and this data frame would be dropped.

An example for applying the proposed angle drift alignment method is given to align two PMUs which use the same DFT algorithm with 1.7 ms sampling time shift. First, two PMUs are connected to the GPS-time synchronized signal generator running the frequency ramp profile and then the angle drifts are calculated as $A_r - A_f$, shown in Fig. 1. H_k at each time step can be calculated through (12). The H is theoretically estimated as 0.0109 through (10) while $H_{estimated}$ can be calculated as 0.0118 by taking the average value of H_ks in the experiment.

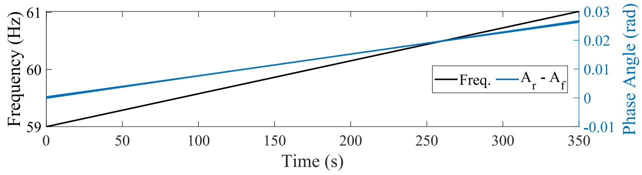

Fig. 1. The frequency ramp and phase angle difference responses.

TABLE I
PMU CONFIGURATION

PMU	SPAM Algorithm	$H_{estimated}$
PMU_1	Quasi-positive -sequence DFT in [9]	0
PMU_2	Quasi-positive -sequence DFT in [9]	-0.42
PMU_3	Conventional DFT	0.38

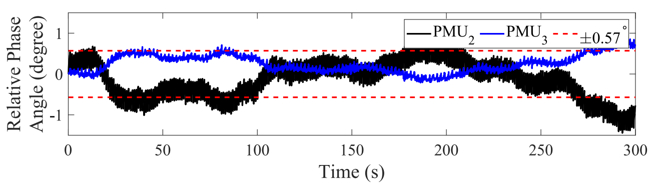

Fig. 2. The relative raw phase angles in laboratory test.

III. EXPERIMENT VERIFICATION

A. Laboratory Test

The proposed alignment algorithm can be applied in the real world PMU to align the phase angles. To verify the effectiveness of the abovementioned phase angle alignment algorithm, two PMUs with different estimation algorithms are utilized to be aligned to a reference PMU in a laboratory. The detailed configuration for the PMUs are listed in Table I. Among three PMUs, the PMU_1 and PMU_2 use the same Quasi-positive-sequence DFT algorithm with different unknown time shifts. The other PMU uses conventional DFT algorithm. Note that the PMU_1 is taken as the reference. After running the frequency ramping profile, the $H_{estimated}$ parameter of each PMU can be calculated via (12) as listed in Table I.

Then the PMUs under test are installed in a distribution level power grid. Before utilizing the proposed algorithm, the relative phase angles between the PMU_1, PMU_2, and PMU_3 are shown in Fig. 2. It can be seen that there is phase difference among these PMUs while most of the phase differences are within $\pm 0.57^\circ$.

To eliminate the phase difference, the SPAM can be corrected through (11) using calculated H parameters in Table I and the frequency in Fig. 4. To quantify its effect, the relative phase angles are calculated as,

$$A_{relative,i,k} = A_{1,k} - A_{i,k}, \tag{13}$$

where k is the time stamp; $A_{relative,i,k}$, $A_{1,k}$, and $A_{i,k}$ are the relative phase angle, phase angle of PMU_1, and phase angle of PMU_i. The relative phase angles after utilizing the proposed algorithm are given in Fig. 3. According to the results in Table II, both the mean and standard deviation (STD) of the aligned phase angles are significantly smaller than raw phase angles.

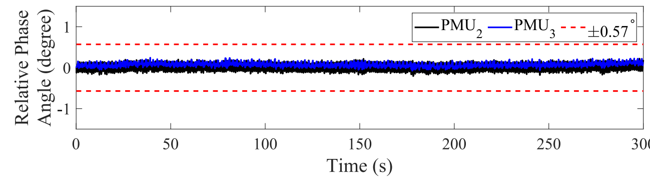

Fig. 3. The relative aligned phase angles in laboratory test.

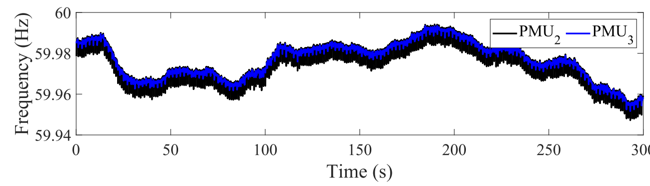

Fig. 4. The frequency (for PMU_2 and PMU_3) in laboratory test.

TABLE II
FIELD TEST RESULTS (°)

PMU	Raw Angle Mean	Raw Angle STD	Aligned Angle Mean	Aligned Angle STD
PMU_2	-0.0761	0.4560	0.0152	0.0889
PMU_3	0.2522	0.2257	0.0740	0.0499

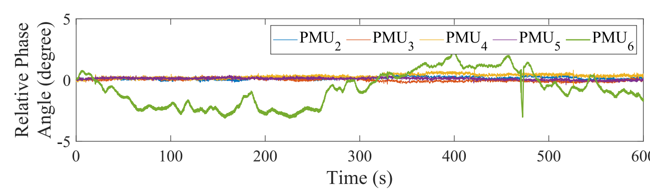

Fig. 5. The relative raw phase angles in the field Test.

B. Field Test

In addition to implementation in PMUs, the correction (step 3) can also be utilized in the PDC). Note that the time shift caused by hardware malfunction between the same type of PMUs can not be aligned in field test remotely. The H parameters for the PMUs need to be calculated in laboratory through using the same type of PMUs deployed in the field. To verify its effectiveness, a ten-minute phase angles recorded by six onsite PMUs (PMU_1 to PMU_5 are with the same phase angle estimation algorithm while the PMU_6 is with another algorithm) are collected by a PDC.

Since six PMUs are deployed in an area with small electrical distance, the relative phase angles should be close to zero in ambient condition. As shown in Fig. 5, the relative angles for five PMUs are given. Note that the PMU_1 is taken as the reference. It can be viewed that the PMU_6's relative angle can not follow the PMU_2 to PMU_5 due to the different SPAM estimation algorithms and presence of time shifts. To align the SPAM of PMU_6 with other PMUs, the correction step is exploited on the

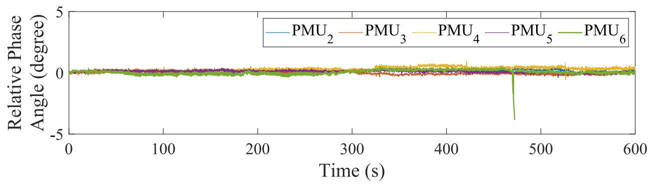

Fig. 6. The relative aligned phase angles (for PMU_6) in the field test.

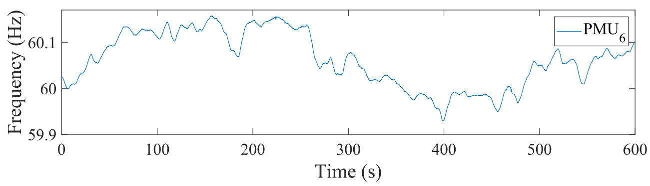

Fig. 7. The frequency (for PMU_6) in the field test.

PDC and the frequency of PMU_6 is shown in Fig. 7. As shown in Fig. 6, the phase angle difference between PMU_6 and PMU_1 has been greatly reduced from 0.7617° to 0.0643°. Note that the minor misalignment and spike are caused by the small electrical distance between PMUs and real world local disturbances.

IV. Conclusion

This letter introduces an alignment algorithm for SPAM calculated by different PMUs with the presence of practical time shift. The correction process, which can be either implemented in PDC or PMU, is capable of minishing the phase angle error in real-time. Laboratory and field tests with onsite PMUs demonstrate the effectiveness of the proposed method to rectify the angle difference for proper SPAM alignment. In order to further improve the proposed alignment algorithm, the future work would focus on aligning PMUs with different SPAM algorithms such as PLL, UTSP and Kalman Filter.

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