Estimating Clock Synchronization Correction Factor from Synchrophasor Phase Angle Drift

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***Abstract*—PMU vendors perform clock synchronization, time-disciplining, and phasor estimation using different methods, which can have a significant impact on the phasor data's suitability for applications. GPS time stamps at 1 pulse per second are used as a reference to discipline the reported phasor estimates' time stamps continuously. In the case of infrequent clock disciplining to this signal, angle drifts between different parts of the system can occur, posing issues to downstream applications. To address this issue, we propose a method for estimating clock synchronization correction factors to perform ex-post time-stamp correction for synchrophasor data from devices having irregular and infrequent clock disciplining. The effectiveness of the proposed method is demonstrated for a real-world time synchronization problem observed in synchrophasors from the Dominion Energy system.**

***Index Terms*— Synchrophasors, clock error, estimation, PMU, time synchronization, GPS, clock disciplining**

I. Introduction

The lack of transparent dynamic models makes traditional model-based analysis difficult for utilities, leaving measurements as the only source of actionable information. However, inconspicuous data quality issues such as discrepancies in the phasor estimation techniques inside PMUs from different vendors [1] can largely impact applications [2].

Issues relating to the accuracy of reported time stamps are among the most difficult to detect and address. Regarding that, the IEEE C37.118 std [3] defines a Total Vector Error (TVE) limit of 1%, which equates to a phase angle error of 0.5730 (degrees) or a time synchronization inaccuracy of 21.6 μs at 60 Hz or 31.8 μs at 50 Hz. Therefore, a majority of the existing body of work focuses on detecting severe clock related issues, such as GPS signal loss events [4], and their effects on PMU applications.

However, because power grids are largely operated under "ambient" conditions, the real-world challenge of leveraging synchrophasor data from these conditions stems from the fact that ambient data applications are far more sensitive to small errors that would otherwise meet the above standards. As an example, [5] presents an inconspicuous error resulting from faulty synchronization in PMUs. A theoretical analysis of this problem and an approach to discern it from true ambient dynamics was proposed in our previous work [6]. To give more details, this is a PMU clock related issue, which stems from the approach used by some synchrophasor devices to correct errors between time stamps supplied by their internal oscillator and the GPS time stamps (once a second). For devices that attempt to correct the timestamps at precisely every one second, the error never grows large enough to not meet the standards. However, because of this periodic correction, prominent spectral spikes in phase angle at 1 Hz and its multiples as observed as shown in Fig. 1 in the blue plot Θ_A. These fictitious peaks can be misinterpreted as narrow band system dynamics (e.g. forced oscillations [7]) impacts applications such as oscillation monitoring, that aim to detect undamped oscillatory behaviors.

Next, we consider PMU which is manufactured by a different vendor than PMU A. Note that PMU B (Θ_B, red trace in Figs. 1 and 2) does not discipline its internal clock for several minutes, and consequently, it reporting phasors without correcting their time stamp (i.e., with an error). As a result, while it does not have the spectral spikes from periodic correction, as seen for PMU A (blue) in Fig. 1, there is a much more severe problem that is inconspicuous. This problem can be understood from Fig. 2, which shows the phase angle data in the time domain. Notice how Θ_B drifts w.r.t. Θ_A, this can be understood because PMU A corrects the time stamps periodically every second, albeit drastically due to its internal clock drift, but nevertheless allowing it to re-synchronize with true time. Observe that since both are within the same substation, one expects their phase angles to be synchronized. This helps to point out to the irregular and infrequent clock disciplining of PMU B.

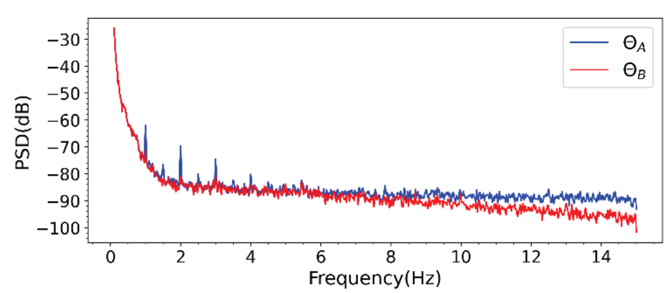

Fig. 1. PMU Angle Spectra Showing Effect of Time Stamp Correction

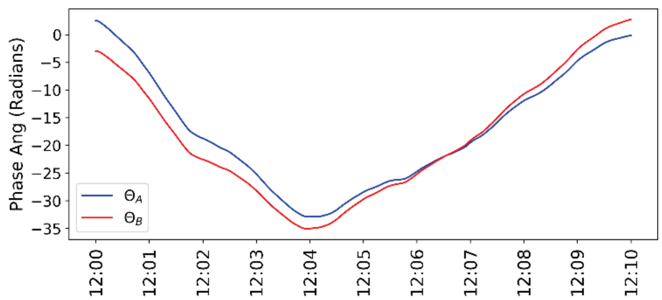

Fig. 2. Phase Angle Measurements form PMUs A and B

Note that any type of errors in synchrophasor data time stamps distort the signal in a manner that cannot be adequately addressed by removing obvious erroneous components like spectral spikes [8] and or phase angle drifts. To properly address the effect of clock errors is to estimate the true time stamps followed by resampling. In this regard, the work in [9] proposes an approach to estimate a constant and small time delay between a device's reported time stamp and reference. However, this is certainly not the case when the device clock and true time are not synchronized (as can be seen in Fig. 2), where the phase difference diverges as a result of time-varying time stamp errors. [5] proposes a Kalman filter based approach to estimate such clock drifts. It is, however, limited in its analysis of the problem, specifically what signal properties allow us to estimate these errors. In this paper, we show how even a simple ordinary least squares (OLS)-based approach can work with different time windows of data, even short time windows by considering the stability of the underlying power system ambient dynamics.

This paper is organized as follows. Section II of this paper gives a theoretical analysis of how clock errors can influence the perceived dynamics. Next, Section III proposes an approach to estimate clock errors that is illustrated in Section IV. Section V summarizes this work's main conclusions.

II. Clock Issues

A. Perceived Dynamics

The clock time stamps denoted by τ are generated by an individual device's oscillator (i.e., internal clock), which are usually disciplined using GPS signals at one pulse per second (pps) obtained from Global navigation satellite system (GNSS) station clock and then distributed within the substation via IRIG-B signals.

Let use denote the "true" time by t, which we do not have access to. Our goal is to estimate a de-corruption function $\psi(.)$ that reclaims t from τ, i.e., $t = \psi(\tau)$. Now, if true system trajectory is $x(t)$, what is observed is a distorted signal $x(\psi(\tau))$. In this work, we assume a linear model of the form $\psi(\tau) = k_0 + k_1\tau$, which represents the device's clock being faster / slower than true time, at a constant rate. Before proceeding, let us try to understand the effect of such corruption in terms of the perceived signal through the following examples,

Example 1 (ramp)**:** Let true dynamics be $x(t) = 3t \Rightarrow x\left(\psi(\tau)\right) = 3k_0 + 3k_1\tau$. Thus, the perceived dynamics not only have a different ramp rate ($3k_1$ vs 3), but there is also a phase shift of $3k_0$. Therefore, in Fig. 1, the clock in PMU B should be slower than $t \left(\frac{d\tau}{dt} < 1\right)$, and therefore $k_1 > 1$.

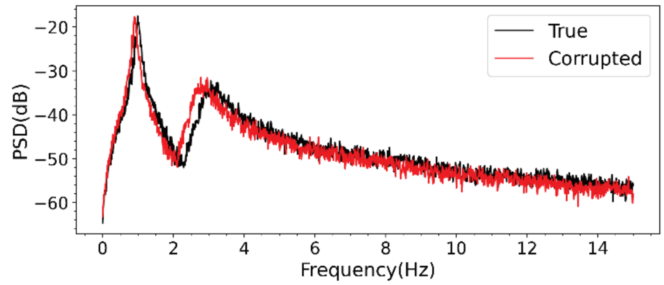

Fig. 3. Example 2 Effect of Clock Error on Spectrum

Example 2 (stochastic linear system)**:** Let $x(t)$ be an output of a linear system driven by white noise with modes at 1 and 3 Hz. Here, we study the effect of device clock being 1.1 times true time, i.e., $k_0 = 0, k_1 = 1/1.1 = 0.909$ on the perceived signal spectrum [10], which is a key quantity in modal analysis applications. Fig. 3 compares the power spectral density (PSD) estimates [10] for the ground truth and clock corrupted signal, which shows that the modal frequencies are scaled by a factor of $1/k_1$. This could deceive modal analysis applications where the shifted modes could be seen as a shift in a mode due to changes in the grid's conditions [11].

On the surface, the problem of estimating correct time stamps appears complex due to the way in which these errors enter the signal. However, certain types of ground truth signals $x(t)$ can be exploited to simplify the complexity of the estimation process. To understand this, let us assume at least a one-time differentiable $x(t)$, by mean value theorem,

$$x(k_0 + k_1\tau) = x(\tau) + \frac{\partial x}{\partial t}|_{t^*(\tau)} \times (k_0 + (k_1 - 1)\tau) \quad (1)$$

where $t^*(\tau) \in [\tau, k_0 + k_1\tau]$. For heavily regulated power system quantities, $\left|\frac{\partial x}{\partial t}|_{t^*(\tau)}\right|$ is tightly bound (by controls), and therefore, the clock error effect $(x(k_0 + k_1\tau) - x(\tau)$ is not as pronounced, making those signals bad observers to estimate the errors.

B. Effect on Waveform Data (Voltage Magnitude vs Angle)

To select good observers, it is important to understand the effect of clock errors entering the waveform data. A voltage waveform in ambient conditions can be modeled as a modulated carrier wave with frequency $f_c \approx 60\ Hz$,

$$\begin{aligned} V_{wav}(t) &= V(t)e^{j\Theta(t)} \\ \Theta(t) &= 2\pi f_c t + v(t) \end{aligned} \quad (2)$$

where, $V(t)$ and $\theta(t)$ are the amplitude and phase of the voltage waveform signal and $v(t)$ represents ambient dynamics. The phase angle reported by PMU can then be approximated as $2\pi(f_c - 60)t + v(t)$ (for 60 Hz nominal frequency). Note that during ambient conditions the derivative of the voltage magnitude $\left|\frac{\partial V}{\partial t}(t)\right|$ is tightly bounded, and therefore, the deviation in $V(t)$ and $V(\tau)$ is not as pronounced (as discussed before). On the other hand, $\Theta(t)$ has a large ramp component $2\pi f_c t$ and consequently, its derivative has a large DC component, making it a good observer of the error and the signal of choice for estimation.

III. ESTIMATING CLOCK ERROR

To estimate the clock de-corruption model, i.e., to estimate (k_0, k_1) coefficients of $\psi(\tau) = k_0 + k_1\tau$, we need measurement from a different vendor to serve as a reference $\Theta_{ref}(t)$. An ideal choice obviously would be one from the same location. However, we will later demonstrate how this condition can be relaxed. Assume that we have a long enough data window spanning T seconds.

Note that since we only have access to corrupt time stamps τ, all the calculations involving time will be done using τ and not t. Here, the ground truth ambient phase angle dynamics $\Theta(t)$ are modeled using a zero-mean stationary gaussian colored noise $v(t)$ along with a trend term (representing the frequency drift) [12] and given by

$$\begin{aligned}\Theta(t) &= \mu_\Theta + 2\pi f_c t + v(t) \\ &= \mu_\Theta + 2\pi f_c(k_0 + k_1\tau) + v(k_0 + k_1\tau).\end{aligned} \quad (3)$$

In (3), the phase shift factor k_0 introduced by the clock is not separable from the operating point μ_Θ making it an ill posed problem, and therefore, estimating it would require additional information, e.g., other measurements on a line from the corrupted measurement node, computed using $\Theta_{ref}(t)$ available on the other end, which is fairly restrictive.

In the present work, we will only be focusing on estimating the clock correction factor k_1, to appropriately speed up/slow down the reported time stamps, getting rid of the more severe angle drift issues. To this end, let us define a reference angle where $\tau \approx t$ and therefore,

$$\begin{aligned}\Theta_{ref}(t) &= \Theta_{ref} + 2\pi f_{c_{ref}}\tau + v_{ref}(\tau) \\ \frac{d}{d\tau}\Theta_{ref}(\tau) &= 2\pi f_{c_{ref}} + \dot{v}_{ref}(\tau).\end{aligned} \quad (4)$$

From the $\frac{d}{d\tau}\Theta_{ref}(\tau)$ we can estimate $f_{c_{ref}}$ through ordinary least squares (OLS). Next, we show the asymptotic convergence of this estimate, as it pertains to actual power system ambient dynamics $v_{ref}(t)$, which results in

$$\lim_{T\to\infty}\left(\hat{f}_{c_{ref}} - f_{c_{ref}}\right) = \lim_{T\to\infty}\frac{\int_0^T \dot{v}_{ref}(\tau)d\tau}{2\pi T} \to \frac{1}{2\pi}E\left(\dot{v}_{ref}(\tau)\right). \quad (5)$$

From (5) note that since $v_{ref}(t)$ is an output of a stable linear system driven by gaussian white noise, which is an ergodic system [13], it yields $\frac{1}{2\pi}E\left(\dot{v}_{ref}(\tau)\right)$. Now, since this process is also mean stationary, this yields $E\left(\dot{v}_{ref}(\tau)\right) = 0$. Thus, (5) tends to 0 making $\hat{f}_{c_{ref}}$ asymptotically unbiased.

Now, for $f_c = f_{c_{ref}}$, i.e., the reference node has the same base frequency (ignoring ambient dynamics), we estimate k_1 using OLS on (6), as follows

$$\begin{aligned}\frac{d}{d\tau}\left(\Theta(t)\right) &= 2\pi\hat{f}_{c_{ref}}k_1 + \underbrace{k_1\dot{v}(k_0 + k_1\tau)}_{\epsilon(\tau)} \\ \to \hat{k}_1 &= \frac{\int_0^T \frac{d}{d\tau}(\Theta(t))d\tau}{2\pi\hat{f}_{c_{ref}}\int_0^T d\tau}.\end{aligned} \quad (6)$$

Using the fact that for a mean stationary $v(\tau)$, $v(k_0 + k_1\tau)$ is also mean stationary, the same line of proof as for (5) can be used to show asymptotic convergence of $\hat{k}_1$.

Next, let us relax the condition of $f_{c_{ref}} = f_c + \Delta f_c$, i.e., $\Theta_{ref}(t)$ is obtained from a remote location on the grid, which is not perfectly synchronized to the substation where the corrupted measurements are obtained. In this case, $\hat{k}_1 \to \frac{1}{1+\frac{\Delta f_c}{f_c}}k_1 = k_1 \times (1 - \frac{\Delta f_c}{f_c} + O(2))$. Now, other than during transient conditions, frequency deviations between even two remote points in an interconnected system are tightly bounded, i.e., $\left|\frac{\Delta f_c}{f_c}\right| \leq$ a small ϵ and therefore, k_1 will only be slightly biased.

Here is important to mention that, in practice, using infinite T is not feasible. Firstly, the internal device oscillator may not have a stationary drift rate, i.e., k_1 may change with variables such as temperature (long time scales). Furthermore, $f_{c_{ref}}$ would also change, as can be seen in Fig. 2, where the angles have very slow time varying slopes as a result of changing operating conditions. This poses questions on convergence of $\hat{k}_1$ for small windows T. To study that, we compute the variance $\hat{k}_1$ from (6),

$$\begin{aligned}&E\left(\left(\hat{k}_1 - k_1\right)^2\right) \\ &= \left(\frac{k_1}{2\pi\hat{f}_{c_{ref}}}\right)^2 \times \frac{\int_0^T\int_0^T E\left(\dot{v}(t_1)\dot{v}(t_2)\right)dt_1dt_2}{T^2} \\ &= \left(\frac{k_1}{2\pi\hat{f}_{c_{ref}}}\right)^2 \times \frac{\int_0^T\int_0^T \gamma_{\dot{v}}(t_1 - t_2)dt_1dt_2}{T^2}\end{aligned} \quad (7)$$

where $\gamma_{\dot{v}}(t)$ is the autocorrelation function of $\dot{v}$, which for stable linear system, exponentially decays with Λt, where Λ is a diagonal matrix with the eigenvalues of the underlying power system. Thus, more stable the system (more damped the eigenvalues), smaller the value of the double integral for the same value of T and therefore, smaller the overall variance of the estimate. Remember here that the inner integral is finite for stable systems even as $T \to \infty$ so asymptotically variance decays to 0 anyway. The reason for the above discussion is to understand when small windows of data can be used.

IV. RESULTS

In this section, we demonstrate the effectiveness of our approach using both synthetic and real-world synchrophasor data from Dominion Energy's power system.

A. Synthetic Data

Here, we use the data from Example 2 as ambient phase angle data $v(t)$ with modes at 1 and 2 Hz. A $2\pi f_c t$ term is added to the ground truth with $f_c = 60$. Next, we construct a reference signal $v_{ref}(t)$ as a measurement of the same underlying system, however only observing the mode at 1 Hz.

The true spectra for both are plotted in

Fig. 7. Similarly, a $2\pi f_c t$ term is added to obtain $\Theta_{ref}(t)$, to simulate the case of the reference measurement being electrically close to the corrupted device, though not identical.

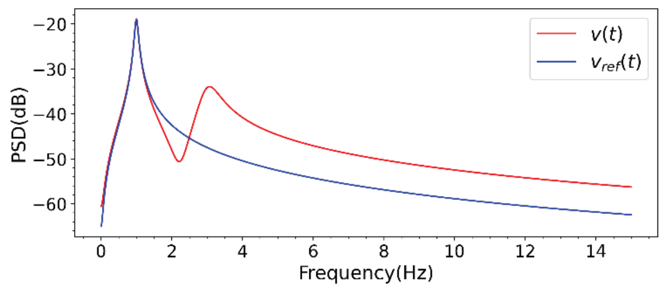

Fig. 4 Example 2 True PSD

We proceed to estimate k_1 from (6) independently for 500 realizations of $\Theta(t)$ and $\Theta_{\text{ref}}(t)$ with $T = 1s$, and plot them in Fig. 5. Note from Fig. 5 that the estimate is empirically unbiased with a low variance, even for a small window data.

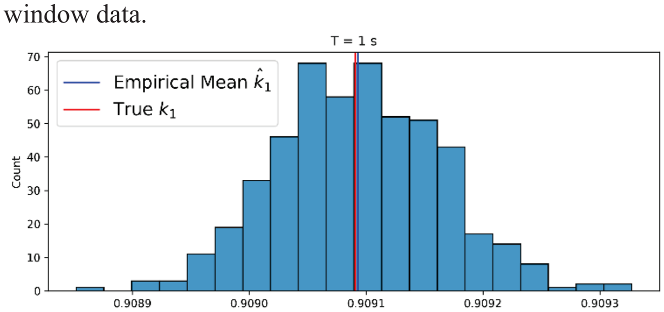

Fig. 5 Example 2 $\hat{k}_1$

Next, we obtain the clock correction as $\hat{t} = \tau \times \hat{k}_1$ to recover a corrected $\Theta(t)$ estimate. To assess the effectiveness of the correction, we compare the true PSD for $v(t)$ along with the one obtained from clock corrected estimate of $\Theta(t)$ in Fig. 6. It can be observed that the applied clock correction successfully reassigns the spectrum (consequently modes) to the original frequencies. Furthermore, the discrepancy in $v_{ref}(t)$ and $v(t)$ doesn't really create issues if they are stable as per the results in (7).

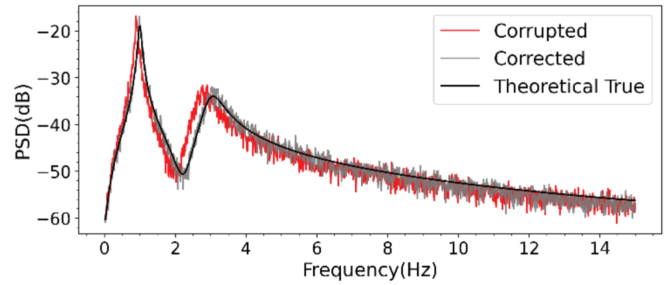

Fig. 6 Example 2 Corrected Signal Spectral Estimate

B. Real World Measurements Dominion system

Next, we demonstrate the efficacy of our approach on real-world synchrophasor measurements from Dominion's power system, specifically the 10 min data shown in Fig. 2. In this case, $\Theta_A(t)$ serves as a reference for estimating the clock correction factors for $\Theta_B(t)$. Since they are from the same substation and kV level, $f_c \approx f_{c_{ref}}$. $\hat{k}_1$ was estimated to be 1.0000369 from the 10 min window with the resulting corrected phase angle estimate plotted in Fig. 7, as Corrected $\Theta_B(t)$. Here, we can see that the corrected $\Theta_B(t)$ is synchronized to $\Theta_A(t)$ while still retaining its dynamics.

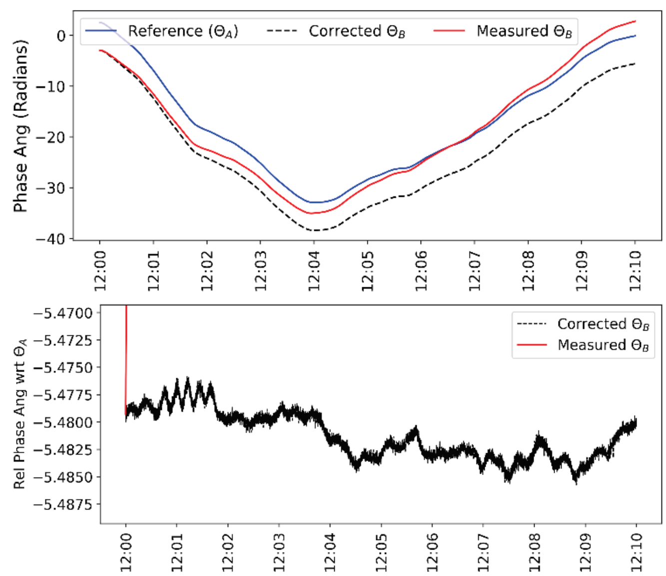

Fig. 7. Phase Angle Estimate from Corrected Clock

V. Conclusions

This paper addresses the issue of synchrophasor device clock and GPS synchronization, which causes phase angle drifts in real-world deployments. To repair the reported and erroneous time stamps, a method for estimating a clock correction factor is proposed. Future research will focus on the more difficult problem of estimating periodic time stamp errors, which are increasingly common in real-world synchrophasor data.

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