Impact Analysis and Mitigation of Losing Time Synchronization at Micro-PMUs in Event Location Identification

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***Abstract*—Prior studies have shown that most phasor measurement units (PMUs) in practice suffer from some level of time synchronization loss at least once every day. We address this issue in the context of distribution-level PMUs, i.e., micro-PMUs, and with focus on the application of micro-PMUs in event location identification in situational awareness. We show that a state-of-the-art method that is highly successful in identifying the correct event location when the micro-PMUs are synchronized, fails when time synchronization is lost among the micro-PMUs. An alternative method is proposed to identify the location of events not only when the micro-PMUs are time synchronized but also when micro-PMUs lose time synchronization. The proposed model works for different scenarios for losing time synchronization among some or all micro-PMUs.**

***Keywords*: Time synchronization, power distribution, micro-PMUs, event location identification, synchronization operator.**

I. Introduction

Distribution-level phasor measurement units (D-PMUs), a.k.a, micro-PMUs, are increasingly deployed in recent years in power distribution systems [1]. An important application of micro-PMUs is in achieving situational awareness. A common approach to achieve situational awareness is to capture and investigate the *events* in the micro-PMU measurements. Events are defined broadly, such as capacitor bank switching, load switching, transformer tap changing, and device malfunction.

A critical feature in micro-PMUs is their ability to provide *time-synchronized* phasor measurements. Time synchronization is achieved by various means, such as with the use of Global Positioning System (GPS) [2], [3]. However, GPS signals can be lost in practice due to different reasons, such as atmospheric disturbances, solar activity, etc [4].

Accordingly, in this paper, we raise the following questions: What happens to the analysis of events using micro-PMU measurements if the micro-PMUs lose time synchronization? And how can we mitigate the loss of time-synchronization?

We seek to address the above questions with focus on the problem of identifying the *location* of events in micro-PMU measurements. The contributions of this study are as follows:

- We show that a state-of-the-art method that is highly successful in identifying the correct event location when the micro-PMUs are synchronized, fails to do so when time synchronization is lost among the micro-PMUs.
- We propose a method to address this shortcoming. To the best of our knowledge, this is the first method to correctly identify event locations in distribution feeders by using measurements from unsynchronized micro-PMUs.
- Our method works by introducing new synchronization operators that capture the relative drift in measuring phase angle in the absence of time synchronization. We select any micro-PMU to act as a reference to define synchronization operator for all other micro-PMUs in comparison with the micro-PMU that acts as reference. The proposed method is applicable to any arbitrary scenario for the loss of time synchronization among the micro-PMUs.
- The enhanced and more robust performance of the proposed method is confirmed in various case studies.

Our focus in this paper is on the application of micro-PMUs in event location identification. Different methods are used in the literature for event or fault location, including impedance-based methods [2], [5], [6], traveling wave [7], and methods based on machine learning [8]. Of particular interest is the work in [2], which uses synchrophasors from two or more micro-PMUs on a power distribution feeder. While the method in [2] performs very well when there is no issue with time synchronization among the micro-PMUs, we will show in this paper that the performance of the method in [2] can degrade drastically if the micro-PMUs lose time-synchronization.

Mitigating loss of time synchronization has been addressed in a few recent studies. The focus has been on the application of PMUs (not micro-PMUs) on fault location in long transmission lines (not power distribution networks). In [9], Newton-Raphson iterations are used to handle certain scenarios with a mix of synchronized and unsynchronized voltage phasor measurements. The idea is to use only the magnitude data from the PMUs that have lost time synchronization; and use phase angle data from the PMUs that are fully synchronized. In [10], [11], synchronization operators are used to derive the fault position under unsynchronized measurements in long transmission lines, including untransposed transmission lines.

Unlike in [9]–[11], the focus in this paper is on power distribution feeders with radial topologies, laterals, and several load buses. Furthermore, our analysis is *not* specific to faults; as it does *not* use any technical aspect that would be specific only to faults. It is rather applicable to both faults and various other events; where the events are defined in a broad sense, as we discussed in the first paragraph in Section I.A.

II. Problem Statement

Consider a power distribution feeder with n buses and $n-1$ lines, as in Fig. 1. For now, we assume that the feeder does not

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include any lateral. We will relax this assumption in Section III.D. Two micro-PMUs are installed in this system, one at the substation at bus 1 and one at the end of the feeder at bus n. Under normal conditions, the two micro-PMUs are time-synchronized. Thus, the two micro-PMUs report synchronized voltage and current phasor measurements at buses 1 and n.

Suppose one or both micro-PMUs lose time-synchronization. A micro-PMU that loses time-synchromization can still report its measurements, but the measurements are no longer precisely time stamped. Different reasons can cause losing time-synchronization. For example, GPS signals can be jammed due to natural causes, e.g. irregularities of the ionosphere, geomagnetic storms, solar radio bursts [12]. GPS signals can also be jammed due to adversarial reasons, e.g. GPS jamming attack or spoofing attack [13]. Importantly, losing the GPS signal is a common issue in practice. In fact, it is reported that more than 60% of PMUs suffer from some level of GPS signal loss at least once every day [14].

Once the GPS signal is lost, the internal crystal oscillators in the local receiver operate *without* GPS correction. Since there is an arbitrary frequency drift for crystals oscillators, timing error may occur; which can most notably cause error in measuring *phasor angle* [14]. The error in measuring phase angle can affect the performance of various applications that make use of the synchronized phase angle measurements.

For example, as we will see in multiple case studies, the event location identification method in [2] is vulnerable to error in phase angle measurements, which is caused by losing time synchronization in micro-PMUs. This is despite the fact that this method has a very high accuracy otherwise.

Therefore, it is crucial to not only investigate the impact of losing time synchronization on the performance of event-based situation awareness, such as for event location identification in [2], but also develop methods to mitigate such impact. Addressing these open problems is the focus of this paper.

III. Proposed Method

Again consider the power distribution network in Fig. 1. Suppose the line impedances are denoted by z_1, z_2, ..., z_{n-1}, the distances between neighboring buses are denoted by x_1, x_2, ..., x_{n-1}, and the admittances of the loads at the buses are denoted by Y_1, Y_2, ..., Y_n. All these parameters are assumed to be known. We can obtain nodal voltage and nodal injected current at any bus by applying the *forward* sweep as [2], [15]:

$$V_p^f = V_{p-1}^f + Z_{p-1} I_{p-1}^f \tag{1}$$

$$I_p^f = I_{p-1}^f + Y_{p-1} V_{p-1}^f, \tag{2}$$

respectively, where p is the bus number, from 2 to n. The starting points in this forward sweep calculation, i.e., V_1^f and I_1^f, are measured directly by micro-PMU 1. Similarly, we can apply the *backward* sweep as follows:

$$V_q^b = V_{q+1}^b + Z_q I_{q+1}^b \tag{3}$$

$$I_q^b = I_{q+1}^b + Y_{q+1} V_{q+1}^b, \tag{4}$$

where q is the bus number, from $n-1$ to 1. Note that, phasors V_n^b and I_n^b, are measured directly by micro-PMU 2.

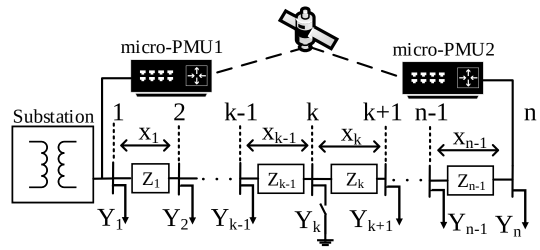

Fig. 1. A power distribution system with micro-PMUs. A switching event occurs at bus k and its impact is observed by the two micro-PMUs.

Under *synchronized* measurements, the forward nodal calculations in (1)-(2) and the backward nodal calculations in (3)-(4) lead to *similar* results; thus, at each bus k we have:

$$V_k^f = V_k^b. \tag{5}$$

However, when micro-PMU 1 and micro-PMU 2 lose time synchronization, the forward and backward nodal calculations do *not* lead to similar results. At each bus k, we would have:

$$V_k^f \neq V_k^b. \tag{6}$$

The discrepancy between the forward nodal calculations and the backward nodal calculations under loss of time synchronization would be mainly due to the fact that *phase angle* measurements at micro-PMU 1 and micro-PMU 2 would *not* be correct, as we previously mentioned in Section II.

Accordingly, the unsynchronized measurement at the two micro-PMUs can be tuned into synchronized measurements by using a *synchronization operator*, which is defined in [17]:

$$V_k^f = V_k^b e^{j\delta}, \tag{7}$$

where δ is the shift in the phase angle measurements at micro-PMU 2 due to losing time synchronization in comparison with micro-PMU 1. Here we assume micro-PMU 1 to *act* as the reference to calculate the *relative offset* between micro-PMU 1 and micro-PMU 2 in measuring the phase angle; thus, we apply the synchronization operator only to micro-PMU 2. Of course, this does *not* mean that micro-PMU 1 has precise timing. It simply means that micro-PMU 1 and micro-PMU 2 are *not* time-synchronized *against each other*, regardless of whether *one or both* of them are off against the true clock.

Importantly, parameter δ is *not* known in practice. Therefore, not only the location of the event, but also the synchronization operator are unknown. When micro-PMU 1 and micro-PMU 2 are synchronized, we simply have $\delta = 0$.

A. Methodology

Suppose an event occurs at bus k, where k is not known. Next, we go through three steps to solve the event location identification problem when time synchronization is lost.

1) First Set of Equations: After an event occurs, we directly measure V_1^f and I_1^f by micro-PMU 1, and we directly measure V_n^b and I_n^b by micro-PMU 2. Given that the phasor measurements by micro-PMUs are three-phase, we may use either the raw phasor measurements at one of the phases, or the positive sequence that is derived from all three phases. Then, for each bus k, we use the forward sweep in (1), the backward sweep from (3), and the relationship in (7) to derive:

$$e^{j\delta} = \frac{V_k^f}{V_k^b} = \frac{V_{k-1}^f + Z_{k-1} I_{k-1}^f}{V_{k+1}^b + Z_k I_{k+1}^b}, \tag{8}$$

where we use the forward sweep to iteratively obtain V_{k-1}^f and I_{k-1}^f based on the measurements at micro-PMU 1; and we use the backward sweep to iteratively obtain V_{k+1}^b and I_{k+1}^b based on the measurements from micro-PMU 2.

2) Second Set of Equations: Next we solve the power distribution circuit in *differential* mode. We substract the *pre-event* voltage phasor measurement from the *post-event* voltage phasor measurement. Similarly, we subtract the differential phasor for current by subtracting the *pre-event* current phasor measurement from the *post-event* current phasor measurement. Accordingly we can conduct the forward sweep and the backward sweep in differential mode, as in [2], [10], [17], to obtain the differential voltage phasors at each bus as:

$$V_{\Delta k}^f = V_{k,\text{post}}^f - V_{k,\text{pre}}^f \tag{9}$$

$$V_{\Delta k}^b = V_{k,\text{post}}^b - V_{k,\text{pre}}^b. \tag{10}$$

As in (7), we can obtain the following relationship:

$$V_{\Delta k}^f = V_{\Delta k}^b e^{j\delta}. \tag{11}$$

Therefore, for each bus k, we can use the forward sweep, the backward sweep, and the relationship in (11) to derive:

$$e^{j\delta} = \frac{V_{\Delta k}^f}{V_{\Delta k}^b} = \frac{V_{\Delta k-1}^f + Z_{k-1} I_{\Delta k-1}^f}{V_{\Delta k+1}^b + Z_k I_{\Delta k+1}^b}, \tag{12}$$

where we use the forward sweep to iteratively obtain $V_{\Delta k-1}^f$ and $I_{\Delta k-1}^f$ from the differential measurements at micro-PMU 1; and the backward sweep to iteratively obtain $V_{\Delta k+1}^b$ and $I_{\Delta k+1}^b$ from the differential measurements at micro-PMU 2.

3) Minimizing Mismatch: From Compensation Theorem in Circuit Theory, one can model the event at bus k with a current source [16]. If the location and amount of the current source are known, then the relationships in (8) and (12) result in the same δ at any bus in the system. However, when it comes to the event location identification problem, neither the location nor the amount of the current source is known. As a result, when we conduct the forward sweep, our analysis is correct from bus 1 to bus k; but it is incorrect from bus $k+1$ to bus n. Similarly, when we conduct the backward sweep, our analysis is correct from bus n to bus k; but it is incorrect from bus $k-1$ to bus 1. Accordingly, the synchronization operators that are obtained in (8) and (12) are generally different, *except* at the bus where the event occurs. Thus, we can use the *mismatch* between the calculation of δ in (8) and the calculation of δ in (12) as the metric to obtain the unknowns:

$$\Phi_k = \left| \frac{V_k^b}{V_k^f} - \frac{V_{\Delta k}^b}{V_{\Delta k}^f} \right|. \tag{13}$$

We can obtain the location of the event as

$$k = \underset{k}{\text{argmin}}\, \Phi_k. \tag{14}$$

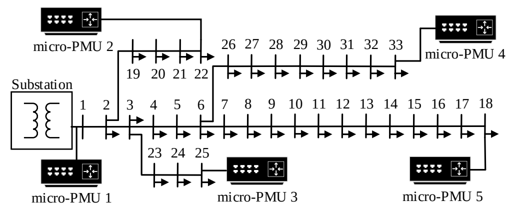

Fig. 2. The IEEE 33-bus system with five micro-PMUs.

Once k is obtained, we can use (8) or (12) to obtain δ. The above analysis identifies the location of the event *despite* the fact that the micro-PMUs have lost time synchronization.

An implicit assumption in the above analysis is that parameter δ is the *same* in (7) and (11), i.e., the unknown shift in the phase angle does *not* change *during* the event. This is a valid assumption; because, in practice, an event takes only a short period of time, often only fraction of a second [8], [19].

B. Extension to Multiple Phasor Measurement Units

Consider a distribution feeder with m laterals. Suppose $m+1$ micro-PMUs are available, one at the substation, and one at the end of each lateral (here we count the main itself as a lateral). An example with five micro-PMUs is shown in Fig. 2 based on the IEEE 33-bus test system, where $m = 4$.

Suppose all or a subset of micro-PMUs lose time synchronization. As in Section III.A, suppose we take micro-PMU 1 as the reference for the calculation of phase angles. We can repeat the analysis in Section III.A between micro-PMU 1 and each of the other four micro-PMUs. We can obtain the *mismatch* between micro-PMU 1 and micro-PMU i as

$$\Phi_{k,1i} = \left| \frac{V_k^{f(1)}}{V_k^{b(i)}} - \frac{V_{\Delta k}^{f(1)}}{V_{\Delta k}^{b(i)}} \right|, \tag{15}$$

where $i = 2, \ldots, m+1$. Superscript $f(1)$ means that the forward sweep starts from micro-PMU 1; and superscript $b(i)$ means that the backward sweep starts from micro-PMU i.

We can take into account all possible choices of calculating the mismatch and obtain an overall mismatch as follows:

$$\Phi_k = \sum_{i=2}^{m+1} \Phi_{k,1i} = \sum_{i=2}^{m+1} \left| \frac{V_k^{f(1)}}{V_k^{b(i)}} - \frac{V_{\Delta k}^{f(1)}}{V_{\Delta k}^{b(i)}} \right|. \tag{16}$$

We can use the above overall mismatch to obtain the unknown event bus by conducting the same minimization as in (14).

The above method defines a potentially different synchronization operator δ_{1i} between micro-PMU 1 and any micro-PMU i. Thus, any combination of such synchronization operators could be zero (if the two micro-PMUs are synchronized) or non-zero (if the two micro-PMUs are not synchronized).

IV. Case Studies

In this section, we study two cases based on two different distribution systems, a 10-bus system with no laterals and two micro-PMUs, and the IEEE 33-bus system, with four laterals and five micro-PMUs. The parameters for the 10-bus system are given in Table I. The single-line diagram for the 10-bus system is the same as in Fig. 1. All the case studies in this Section are done in Simulink by simulating there-phase power systems using the power system simulation package in [18].

TABLE I
PARAMETERS OF THE 10-BUS TEST SYSTEM

Item	Setting	Item	Setting
Length	50 km	Load	40kW + 80kVAR
Voltage	6 kV	Frequency	60 Hz
R_+	0.0321 Ω/km	R_0	0.3479 Ω/km
L_+	0.473*10^{-3} H/km	L_0	1.370*10^{-3} H/km
C_+	0.038*10^{-6} F/km	C_0	0.038*10^{-6} F/km

*Subscripts + and 0 indicate positive- and zero-sequence, respectively.

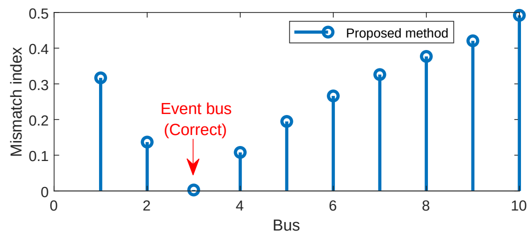

Fig. 3. The result of proposed method when a high-impedance fault occurs at bus 3 in the 10-bus system while time synchronization is lost.

A. An Illustrative Example

In this case study, a single phase to ground high-impedance fault (100 Ω) occurs at bus 3 at the 10-bus test system. Suppose losing GPS satellite signals causes a 2,314 micro-second drift between micro-PMU 1 and micro-PMU 2, which causes 50° drift in measuring their phase angles. The mismatch Φ_k, at each bus is plotted in Fig. 3. Notice that the minimum mismatch is at bus 3, which is the *correct* event bus.

B. Performance Comparison

Next, suppose a load switching event occurs at bus 7. The performance of the proposed method and the method in [2] are compared in Fig. 4. Discrepancy is a term that is defined in [2]. Here we minimize the mismatch. The method in [2] minimizes the discrepancy to identify the location of the event. The definitions of mismatch and discrepancy are very different.

Both the proposed method and the method in [2] can correctly identify the event location when the measurements are time synchronized, see Fig. 4(a) and (b). However, if the measurements are *not* time synchronized, then only the proposed method can identify the event bus correctly, see Fig. 4(c) and (d). The method in [2] identifies an incorrect bus.

To compare the robustness between the two methods, we use a *robustness index*, which is defined as:

$$\text{Robustness} = \frac{\text{2nd smallest } \Phi_k - \text{smallest } \Phi_k}{\text{2nd smallest } \Phi_k}. \tag{17}$$

The above index is particularly helpful in scenarios where both methods identify the location correctly. The robustness index shows the ability to maintain the correct results. In this regard, we compare the smallest ϕ_k, i.e., the current solution, with the second smallest ϕ_k, i.e., the closest ϕ_k which could result in altering the selection of our current solution.

The comparison of robustness index between the two methods is plotted versus δ at increments of every 5°. While robustness stays at 1 for the proposed method, see Fig. 5 (a), it drops quickly for the method in [2], see Fig. 5 (b). Moreover, the proposed method continues to identify the correct event bus

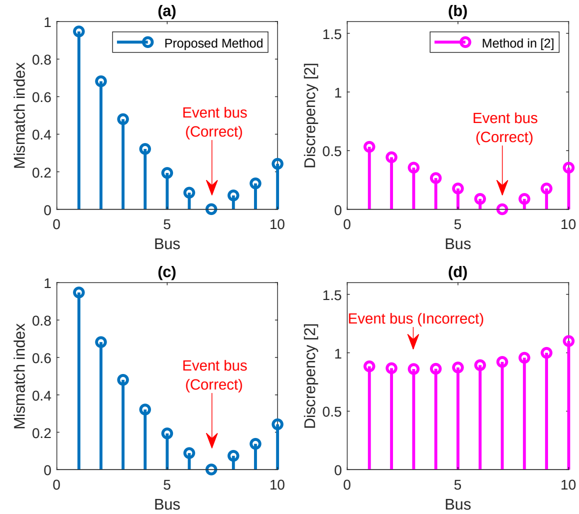

Fig. 4. Comparison between the proposed method and the method in [2] under different time synchronization scenarios: (a)(b) time synchronization is exact; (c)(d) time synchronization is drifted by 2,314 microseconds.

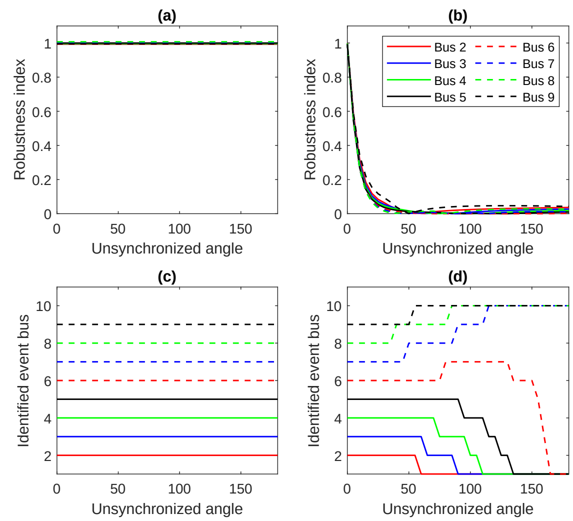

Fig. 5. Robustness index and identified bus (the true event bus indicates in the legend for each case) for every 5° of phase angle shift from 0° to 180° under scenarios: (a) robustness index for proposed method (b) robustness index for [2] (c) identified bus for proposed method, (d) identified bus for [2].

under various unsynchronized angles, see Fig. 5 (c); however, the method in [2] gradually starts identifying incorrect buses as the drift increases in the time synchronization, see Fig. 5(d).

C. Examples in IEEE 33-Bus Test System

The above satisfactory results are observed also in a larger network with laterals, namely the IEEE 33-bus test system.

Fig. 6 shows the results of applying our proposed method under different event location scenarios and different amount for the drift in time synchronization. We see that the proposed method can identify the correct event bus in all these various scenarios. Here, we assume that the amount of the drift when losing time synchronization is the same across micro-PMUs 2 to 5, when compared with micro-PMU 1 as the reference.

Next, suppose each micro-PMU operates on its own crystal oscillator with a *different* phase angle drift. An event occurs at

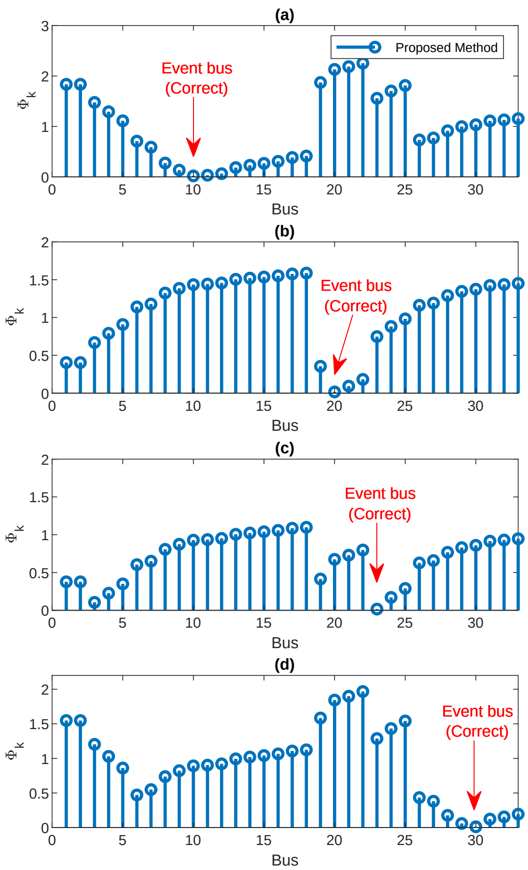

Fig. 6. The performance of the proposed method on the IEEE 33-bus system under different event location scenarios and different drifting in phase angle measurement due to loss of time synchronization: (a) bus 10 with 5° drift, (b) bus 20 with 10° drift, (c) bus 23 with 15° drift, (d) bus 30 with 20° drift.

bus 10. Taking angle drift as a normal distribution with every 0.2 Standard Deviation (S.D.) from 0 to 1, we generate 1,000 Monte Carlo scenarios. The results are shown in Fig. 7. Due to page limit, Fig. 7 only shows bus error, i.e., the difference between the number of the identified event bus and the true event bus. The notation "≥10" on the x-axis means that, the last bar is the *aggregation* of all the cases where the identified location of the event is off by 10 or higher number of buses.

When the proposed method is applied, the bus error is consistently zero, as we can see in Fig. 7(a), which means all the results are correct. On the contrary, when the method in [2] is applied, the bus error is significant and it can vary depending on the standard deviation in the drift in synchronization.

V. Conclusions

An event location identification method is proposed in a power distribution system when all or some micro-PMUs lose time synchronization. It is shown that, while a state-of-the-art method is highly capable of identifying the correct event location when the measurements are synchronized, it fails when time synchronization is lost among the micro-PMUs. However, the method that is proposed in this paper can obtain the event location correctly, despite the lack of time synchronization. The idea is to introduce new synchronization operators that can use physical concepts to capture the drift

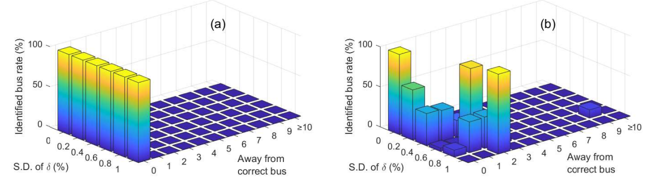

Fig. 7. Bus error versus standard deviation in synchronization drifting across 1,000 random scenarios that are generated by the Monte Carlo simulations: (a) the proposed method is used; (b) the method in [2] is used.

in the phase angle measurements in the absence of time synchronization. Multiple case studies confirm the accurate performance of the proposed method, including in the IEEE-33 bus test system, and for different types of events, including high impedance fault and load switching, are examined.

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