Location Identification of Distribution Network Events Using Synchrophasor Data

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***Abstract*—This paper proposes a novel method to identify the location of events in power distribution systems. An event is defined broadly here to include a change in state of a switch, a change in voltage, in form of a sag or swell, etc. The proposed method is developed based on the *compensation theorem* in circuit theory to generate an equivalent circuit according to the pre-event and post-event feeder states. To such aim, the post-event voltage deviations from pre-event values are assumed to be measured by distribution-level phasor measurement units, a.k.a, micro-PMUs. Importantly, we consider the fact that it is neither economic nor necessary to measure every node's voltage deviation along the feeder to find the source and location of the event. In fact, we utilize data from as few as *only two* micro-PMUs, that are installed at the beginning and at the end of the feeder, to identify the location of an event. The rest of the information collected from the feeder is in form of pseudo-measurements. Despite the natural inaccuracy in pseudo-measurements, the proposed hybrid method is robust against the pseudo-measurements error. The effectiveness of the developed method is demonstrated through simulating the IEEE 33 bus test system in PSCAD.**

***Keywords*: Distribution feeder events, micro-PMUs, data-driven method, location identification, compensation theorem.**

I. INTRODUCTION

The events at distribution grid are often categorized into two main groups; power quality (PQ) events, such as voltage sag and swell due to capacitor bank or load switching, and emergency events, such as interruption in service due to fuse blowing or relay and recloser tripping [1]. Historically, the detection and location identification of emergency events, such as permanent fault events, have been of greater interest to electric utilities than the PQ events, because of the need to accelerate the isolation and service restoration processes in case of emergency events. However, in recent years, electric utilities have increasingly become interested in location identification of not only emergency events but also PQ events due to proliferation of customer devices that are sensitive to the power quality.

Broadly speaking, the existing methods to identify event locations at distribution grid, whether of PQ type or emergency type, can be categorized into two main groups: *impedance-based* and *wide-area monitoring* methods [2]. The former class of methods work based on calculating the line impedance between the fault location and the sensor location. Such methods work well only for permanent faults [3], [4]. The main problem with the impedance calculation methods is that the results are rarely precise, i.e., they identify multiple possible locations for the event. These methods are also highly prone to errors related to measurements and the fault impedance.

As for the wide-area monitoring methods, they work based on the fact that voltages and currents along the feeders fluctuate due to either PQ events or emergency events. In this regard, these methods use the pre-event and post-event states of the grid to identify the exact location of the fault. It is worth mentioning that voltage and current fluctuations along the distribution feeder greatly depend on the type of the event as well as the location of the event. In [5], the pre-event and post-event grid states are used to track the location of the source of disturbance for voltage sags and shunt capacitor switching in a power distribution system. The proposed method was based on analyzing the transient behavior of current and voltage waveforms captured by power quality sensors.

Thanks to the recent development of the distribution-level phasor measurement units, a.k.a, micro-PMUs [6], wide-area monitoring methods can now be implemented in practice. In [7], the authors proposed state estimation based on micro-PMU data to identify the location of permanent faults, while assuming that *all* nodes are equipped with micro-PMUs, i.e., the grid is beyond fully observable. Subsequent to a fault, several parallel state estimation tasks are conducted based on different hypothesis on fault on different lines. The location of the fault is then deemed identified at the line where the related state estimation residual has the minimum value.

Another example to conduct event location identification based on micro-PMU data was presented in [8]. The focus is on identifying PQ events related to the operation of a capacitor bank. In [9]-[10], the authors proposed a voltage measurement-based approach to track the network modifications and to locate islanding events. In [11], the authors developed an algorithm to identify frequent dynamic events. Also, the role of supervisory control for events detection in microgrids was investigated in [12].

In this paper, we propose a method to make use of voltage and current synchrophasor data to identify the location of PQ events as well as emergency events. The essence of the proposed method is based on the analysis of the equivalent-circuit for feeder, obtained by applying *compensation theorem* from circuit theory [13], according to the pre-event and post-event feeder states. Our approach is highly practical because it requires using only two phasor measurement devices to identify the location of an event. The two micro-PMUs are proposed to be installed at the beginning and at the end of the

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feeder. The effectiveness of the developed method is examined on the IEEE 33 bus test system in PSCAD, followed by sensitivity analysis and discussions on the results.

II. EVENT LOCATION IDENTIFICATION METHOD

This section describes the proposed method for identifying the location of an event in a distribution feeder. First, a basic circuit theorem is introduced. The proposed method, then, is developed based on the theorem. Finally, the proposed algorithm for event location identification is presented.

A. Compensation Theorem

An event in a circuit can change all or a subset of nodal voltages and branch currents along the circuit. According to the compensation theorem [13, pp. 177], once an element changes in a circuit, the amount of changes in the nodal voltages and branch currents can be obtained through an equivalent circuit, in which the changed element is replaced with a current source that injects current at a level equal to the amount of change in the current going through the element; and all sources are *replaced* with their internal impedances. The importance of the compensation theorem is in the fact that the analysis of an event through the analysis of such equivalent circuit is easier than through the analysis of the original circuit.

As an illustrative example, consider an element with impedance Z^{pre}, as shown in Fig. 1(a). Suppose Z^{post} denotes the element impedance after a change occurs in the element, shown in Fig. 1(b). Let I^{pre} and I^{post} denote the currents that are drawn by the element before and after the change, respectively. According to the compensation theorem, the equivalent circuit of this network can be obtained by replacing the changed impedance element with current source

$$\Delta I = I^{post} - I^{pre}, \tag{1}$$

and all sources with their internal impedances. The equivalent network, shown in Fig. 1(c), can be used to analyze the changes of the nodal voltages and branch currents, i.e.,

$$\Delta V_s = V_s^{post} - V_s^{pre} \tag{2}$$

and

$$\Delta I_{sr} = I_{sr}^{post} - I_{sr}^{pre}. \tag{3}$$

The proposed application of the compensation theorem in distribution systems is to identify the location of an event, of PQ or emergency type, as we next describe in details.

B. Proposed Methodology

Consider a distribution feeder, such as the one shown in Fig. 2. Suppose two micro-PMUs are installed on this feeder, one at the substation and one at the end of the feeder. The micro-PMUs record the voltage and current flowing at the downstream and upstream of the feeder. There are n buses across the feeder, i.e., between the two micro-PMUs. All loads are assumed to have constant impedances. In case of a lateral, the lateral is replaced with its equivalent admittance.

Suppose the feeder experiences an event, whether a PQ event or an emergency event, at bus k, where $k \in \{1, ...n\}$. Based on the compensation theorem, a current source with current ΔI_k can be replaced at bus k in order to create an equivalent circuit. The nodal voltages and branch currents in the presence of current source ΔI_k are equal to the changes in nodal voltages and branch currents, obtained from subtracting pre-event and post-event states. Therefore, we conclude that the voltage and current at the beginning and at the end of the equivalent feeder are essentially equal to the changes in voltages and currents that are recorded by the micro-PMUs.

1) Forward Nodal Voltages Calculation: The changes in nodal voltages along the feeder can be calculated by using the measurements from the micro-PMU at the *beginning* of the feeder, together with pseudo-measurements, as follows:

$$\begin{aligned} &\Delta V_1^f = \Delta V_u \\ &\Delta V_2^f = \Delta V_1^f + (\Delta I_u + \Delta I_1^f) Z_1 \\ &\vdots \\ &\Delta V_n^f = \Delta V_{n-1}^f + (\Delta I_u + \Delta I_1^f + \cdots + \Delta I_{n-1}^f) Z_{n-1} \end{aligned} \tag{4}$$

where ΔV_i^f denotes the forward calculated nodal voltage of bus i by starting from the beginning of the feeder, and ΔI_i^f denotes the current injection at bus i. Note that, ΔI_i^f is equal to $Y_i \Delta V_i^f$, where Y_i indicates the equivalent admittance of the lateral i, and can be obtained based on the pseudo-measurements and system voltage. Notations ΔV_u and ΔI_u indicate the difference between the pre-event and post-event voltage and current, captured by the micro-PMU installed at the beginning of the feeder. Given the measurement precision of micro-PMUs and since bus 1 is where the micro-PMU at the beginning of the feeder is installed, we set ΔV_1^f equal to the change in voltage recorded by the micro-PMU at the beginning of the feeder. In addition, considering the voltage drop made by the current flowing through the line with impedance Z_1 leads to calculating ΔV_2^f. Similarly, all the nodal voltages across the feeder can be obtained from the previous buses' voltage and laterals' current hierarchically.

2) Backward Nodal Voltages Calculation: In a similar manner, the nodal voltages along the feeder can be calculated by using the measurements of the micro-PMU at the *end* of the feeder, together with pseudo-measurements, as follows:

$$\begin{aligned} &\Delta V_n^b = \Delta V_d \\ &\Delta V_{n-1}^b = \Delta V_n^b + (\Delta I_d + \Delta I_n^b) Z_{n-1} \\ &\vdots \\ &\Delta V_1^b = \Delta V_2^b + (\Delta I_d + \Delta I_n^b + \cdots + \Delta I_2^b) Z_1 \end{aligned} \tag{5}$$

where ΔV_i^b represents the backward calculated nodal voltage of bus i by starting from the end of the feeder. Here, ΔI_i^b denotes the current injection at bus i, which is equal to $Y_i \Delta V_i^b$. Notations ΔV_d and ΔI_d indicate the difference between pre-event and post-event voltage and current, captured by the micro-PMU installed at the end of the feeder. Since a micro-PMU is at bus n, we set ΔV_n^b equal to the change in the voltage recorded by the micro-PMU at the end of the feeder.

3) Voltage Comparison: In the two sets of equations that we obtained in (4) and (5), it is assumed that for all the laterals the current can be obtained from the production of

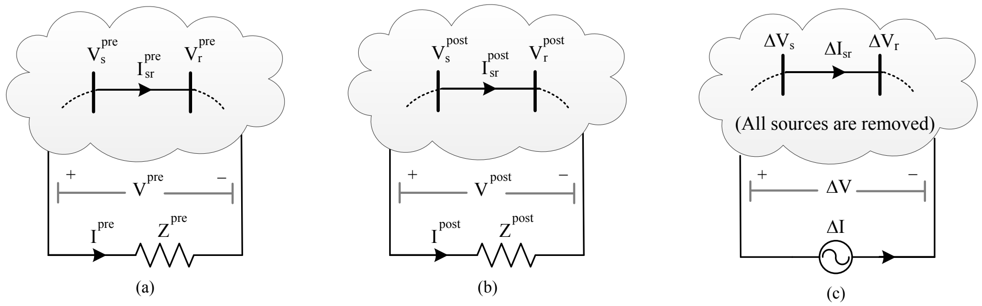

Fig. 1. An illustration of compensation theorem: (a) pre-event network; (b) post-event network; (c) equivalent circuit based on compensation theorem.

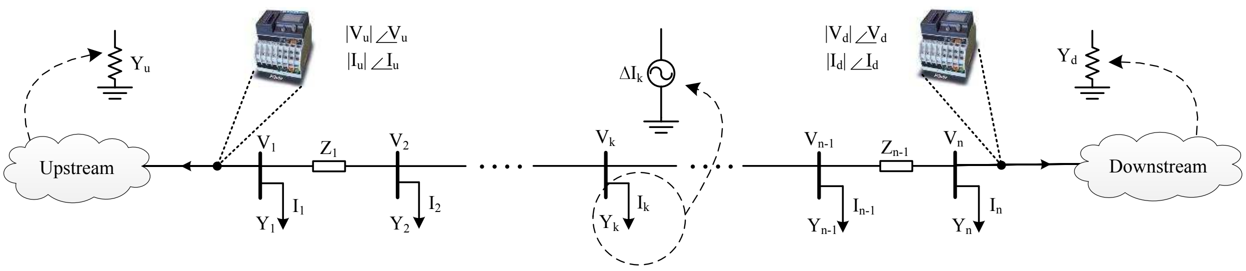

Fig. 2. Representation of a distribution feeder based on compensation theorem equivalent circuit. Measurements are done by two micro-PMUs.

nodal voltage and bus admittance. The calculation based on such product is valid for all the buses, *except for* bus k in which the event occurs. At this bus, current source ΔI_k injects current into the equivalent feeder and the production of voltage and lateral admittance is *no longer correct* for this bus current. Therefore, the downstream voltages of bus k calculated in equation (4), i.e., $\{\Delta V_{k+1}^f,\cdots,\Delta V_n^f\}$, and the upstream voltages of bus k calculated in equation (5), i.e., $\{\Delta V_1^b,\cdots,\Delta V_{K-1}^b\}$, are not correct, and they cannot be considered correct nodal voltages. In other words, we can make the following distinctions across the calculated voltages:

$$\begin{gathered}\underbrace{\{\Delta V_1^f,\cdots,\Delta V_k^f}_{\text{correct}},\underbrace{\Delta V_{k+1}^f,\cdots,\Delta V_n^f\}}_{\text{incorrect}}\\ \underbrace{\{\Delta V_1^b,\cdots,\Delta V_{k-1}^b}_{\text{incorrect}},\underbrace{\Delta V_k^b,\cdots,\Delta V_n^b\}}_{\text{correct}}\end{gathered}\tag{6}$$

The fundamental observation in (6) is that the calculated voltage at bus k in both backward and forward nodal voltage calculations is a correct value. In other words, ΔV_k^f and ΔV_k^b are essentially equal, because if they are not equal then at least one of them must be incorrect, which is a contradiction.

Next, we define the discrepancy of the nodal voltages obtained from both calculations across all buses as:

$$\Delta V_i^{f-b}=|\Delta V_i^f-\Delta V_i^b|,\quad \forall i,\tag{7}$$

where V_i^{f-b} is designated as the difference between ΔV_i^f and ΔV_i^b, defined in (4) and (5), respectively. According to (6), among all buses, the voltage of bus k in the two calculated nodal voltages sets are most similar; therefore, it is expected that ΔV_k^{f-b} has the *minimum* value among all buses:

$$k^\star=\arg\min_k\ \Delta V_k^{f-b}.\tag{8}$$

4) Validity of the Method: The proposed method is based on the implicit assumption that the event occurs in the area *between* the two micro-PMUs. Therefore, before using the proposed method, we should first determine whether the event has indeed occurred in such area. This can be done by checking the equivalent upstream and downstream admittances calculated by the two micro-PMUs. The equivalent admittances seen by the micro-PMUs can be calculated as:

$$Y_u=\frac{\Delta I_u}{\Delta V_u}\tag{9}$$

and

$$Y_d=\frac{\Delta I_d}{\Delta V_d},\tag{10}$$

where Y_u and Y_d indicate the equivalent admittances of the upstream and downstream of the feeder in the equivalent circuit, respectively. If the real parts of Y_u and Y_d are both *positive*, then the event is initiated from a point within the area restricted by micro-PMUs [14]. Otherwise, the event occurred outside this area, e.g., somewhere at the transmission level or at the downstream feeder.

C. Proposed Algorithm

Once we confirmed that the event has indeed occurred in the area between the two micro-PMUs, the next step is to calculate the nodal voltages along the feeder through forward calculation by starting from the beginning of the feeder, as well as backward calculation by starting from the end of the feeder. The exact location of the event is then determined to be at the bus where the two calculated nodal voltages by the forward and backward methods have the most least discrepancy among all buses. The proposed method is summarized in Algorithm 1.

Algorithm 1 Event Location Identification

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Input: Micro-PMUs measurements, pseudo-measurements.
Output: The location of an event.
Obtain $Y_u$ and $Y_d$, as in (9) and (10), respectively.
if $\mathbf{R}\{Y_u\} < 0$ or $\mathbf{R}\{Y_d\} < 0$. then
    The change is not between the two micro-PMUs.
else
    Obtain vector $\Delta V^f$ using (4).
    Obtain vector $\Delta V^b$ using (5).
    Obtain vector $\Delta V^{f-b}$ using (7).
    Obtain the event location $k^\star$ using (8).
    return $k^\star$
end if
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III. CASE STUDIES

This section demonstrates the effectiveness of the proposed event location identification method by applying it to the IEEE 33 bus test system. The single line diagram of the feeder is shown in Fig. 3, and the relevant technical data can be found in [15]. In below, following a brief description over the implementation of the developed method on this test system, simulations results for different types of events and various under-contingency sensitivity analyses to examine the effect of different parameters on the method robustness are presented.

A. Implementation of the Method on IEEE 33 bus

The IEEE 33 bus test feeder is simulated in *PSCAD* [16], and the voltages and currents of bus 1 and bus 18 are read as pre-event measurements at the beginning and at the end of the feeder, which are deemed to be provided by micro-PMU 1 and micro-PMU 2. By applying an event at a defined bus, the feeder is again simulated and similar to the original feeder, the post-event measurements are obtained. The discrepancy of pre-event and post-event measurements is recorded to be used by the proposed method, according to the equivalent-circuit that is formed based on the compensation theorem. This equivalent-circuit consists of a main feeder with 18 buses, in which the laterals are deemed equivalent admittances connected to the main feeder buses. The task here is to identify the location of an event on the main feeder by using Algorithm 1.

B. Case I: PQ Event

The PQ event in this case study is in form of a typical load switching action. A 60 *kVA* load, with power factor 0.95, is switched on at a certain bus on the main feeder. Note that the total loading of the feeder is 4.5 MVA. The switching of such a small load does not cause major disturbance, since the connected load is only 1.33% of total loading.

Table I shows the results for the case where the PQ event happens at bus 9. We can see that, ΔV^{f-b} has its minimum value, 0.2 *V*, at bus 9, i.e., the forward and backward voltage calculations have their smallest mismatch at bus 9. Accordingly, Algorithm 1 identifies bus 9 as the location of the event, *which is correct*. The second smallest voltage mismatch occurs at bus 10 with value 8.9 *V*, which is considerably greater than the mismatch at bus 9. Such large difference between the first and the second largest voltage mismatches provides a reliable margin to accurately distinguish the location of the event.

Next, the same type of PQ event is simulated to occur at two other locations., i.e., buses 3 and 15. The results are shown in Figure 4, and the curves are related to mismatch vectors. According to the curve associated with the event at bus 3, the mismatch vector has the minimum value at bus 3. It means that the two nodal voltage vectors at bus 3 have the most similarity, which results in Algorithm 1 to correctly identify bus 3 as the location of the event. Similarly, for the curve associated with the event at buses 9 and 15, the mismatch vectors carry their minimum at the bus where the event occurs. We can see that, as we move away from the bus undergoing the event, the values of mismatch increase. Thus, Algorithm 1 accurately identifies the location of the PQ event in all three cases.

C. Case II: Emergency Event

In this study, an emergency event is defined as a fault occurrence which significantly changes the value of currents and voltages along the feeder. Here, a fault with the resistance of 1 Ω is considered as an emergency event. The value of the fault current varies from roughly 800 to 3000 A with respect to the location of fault along the feeder. This high level of current magnitude makes sure that the fault current would be enough to be qualified as an emergency event.

Again, three different locations are examined as the location of the event, i.e., including bus 3, 9, and 15. Fig. 5 depicts the curves associated with the mismatch vectors. As shown, for each event, the curve has its minimum value at the bus in which the fault occurs. It is also obvious that by going far from the location of the fault, the values of mismatch vectors increase.

It is interesting to compare the amount of voltage mismatch ΔV^{f-b} in Figures 4 and 5. Clearly, the voltage mismatch is much larger for the emergency event than for the PQ event. That means, there is a much greater margin of accuracy in identifying the correct location for emergency events; therefore, it is very unlikely for the location of an emergency event to be identified incorrectly.

D. Under-Contingency Sensitivity Analysis

In practice, the utility's knowledge about system parameters is not perfect. The range of uncertainty varies for different types of parameters; nevertheless, for a defined level of parameters accuracy, the robustness of the proposed method against the parameter variations should be determined. In order to do so, this section conducts some under-contingency sensitivity analyses to investigate the impact of different parameters uncertainty on the proposed method's effectiveness.

Recall that the proposed method makes use of four principal parameters: impedances of the distribution lines, pseudo-measurements, current synchrophasor measurements, and voltage synchrophasor measurements. For each system parameter, Mont Carlo approach is used to generate different scenarios based on the errors in the system parameter.

Table II shows the results obtained from the lines impedance variations. As shown, for lines impedance error with 10%

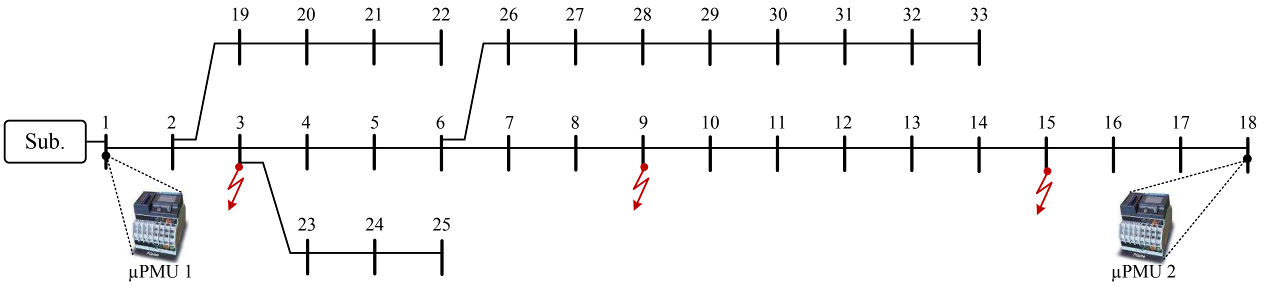

Fig. 3. The under-study feeder that is simulated in PSCAD. Three different event scenarios are simulated at buses 3, 9, and 15.

TABLE I
CALCULATED NODAL VOLTAGE VECTORS AND CORRESPONDING MISMATCH VECTOR

Bus #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
ΔV^f	4.3	4.8	7.9	10.4	12.9	19.2	22.6	27.1	35.5	44.0	45.3	47.9	60.5	66.4	72.0	78.6	93.6	100.5
ΔV^b	42.5	42.1	40.6	39.8	39.0	37.1	36.8	36.3	35.7	35.1	35.0	34.9	34.3	34.1	33.9	33.8	33.6	33.6
ΔV^{f-b}	38.2	37.3	32.7	29.4	26.1	17.9	14.2	9.2	0.2	8.9	10.3	13.0	26.2	32.3	38.1	44.8	60.0	66.9

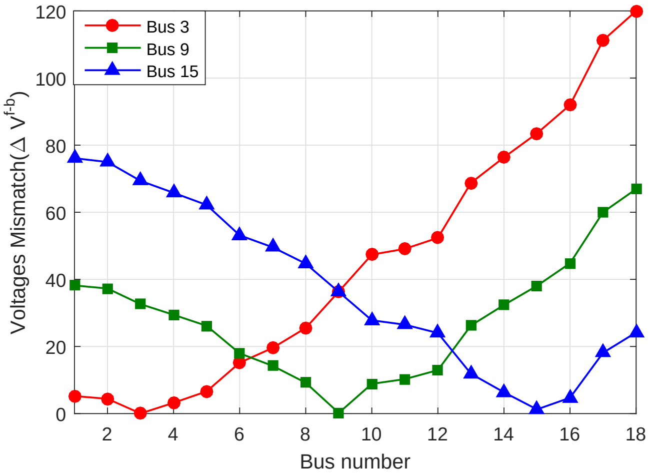

Fig. 4. Results associated with three different locations of PQ event.

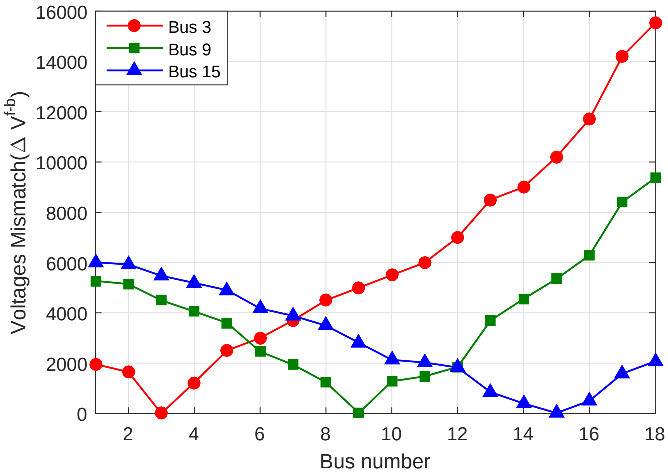

Fig. 5. Results associated with three different locations of emergency event.

standard deviation, nearly 95.5% of the event location identifications are done correctly, and just in 2.5% of the results, the location of events is wrongly identify, in which the neighboring buses are wrongly identified as the bus where the event occurs. Also, with this range of error, the location of the event is identified to be no more than one bus away form the true location of the event, implying that in the worst case, the event location might be identified at the neighboring buses.

By increasing the error in lines impedance, the results demonstrate a satisfying estimation of the event location identification. For instance, for lines impedance error with 50% standard deviation, roughly 50% of event locations are found correctly, and just 13% of the events location are wrongly identified at the buses beyond the neighboring buses. This indicates that even with a large range of errors in lines impedance, a great portion of wrong identifications are related to identifying the neighboring buses as the location of the event.

Table III provides the results corresponding to pseudo-measurements. In networks that are not fully observable, the exact values of power injections at buses are not defined. In this regard, the pseudo-measurements are defined as power injections at the buses which are mostly obtained via historical data and the capacity of distribution transformers installed at the beginning of laterals. Therefore, pseudo-measurements are prone to a large range of errors. As the results shown, errors with 20% standard deviation does not have any effect on the accuracy of the method, and for the errors with standard deviations up to 60%, the worst wrong identification is related to neighboring buses. Accordingly, the proposed method is highly robust against the pseudo-measurements error.

Table IV and V represents the results related to the errors in the current and voltage measurements, respectively. In this study, it is assumed that the micro-PMUs serve as the only measurement devices. These devices are highly accurate and the range of their error is even less than the commercial PMUs already used in transmission level. Here, the standard deviation of errors considered for micro-PMUs are related to

TABLE II
METHOD EFFECTIVENESS AGAINST LINES IMPEDANCE ERROR WITH DIFFERENT STANDARD DEVIATIONS

Error of Line Impedanec	Correct Location	One Bus Error	$>$ One Bus Error	Maximum Error
10%	97.42%	2.58%	0%	1 bus
20%	83.50%	16.29%	0.21%	2 buses
30%	69.98%	26.87%	3.15%	3 buses
40%	59.78%	32.67%	7.55%	4 buses
50%	49.73%	37.22%	13.05%	5 buses

TABLE III
METHOD EFFECTIVENESS AGAINST PSEUDO-MEASUREMENTS ERROR WITH DIFFERENT STANDARD DEVIATIONS

Error of Pseudo-Measurement	Correct Location	One Bus Error	$>$ One Bus Error	Maximum Error
20%	100%	0%	0%	0 bus
40%	99.55%	0.45%	0%	1 bus
60%	96.28%	3.72%	0%	1 bus
80%	91.1%	8.89%	0.01%	2 buses
100%	85.85%	13.97%	0.18%	2 buses

total vector error which includes both the magnitude and angle errors. We can clearly see that the error in voltage phasors has greater effect on the method's accuracy than the error in current phasors. This fact is so desired, because usually the currents phasors are perturbed by the noises which are difficult to get filtered, while the voltage measurements do not contain such level of noise, so they can be used with more confidence.

IV. CONCLUSIONS

This paper proposed a novel method, based on an innovative application of the compensation theorem in circuit theory combined with making effective use of data from micro-PMUs, to identify the location of events in distribution systems, whether of PQ type events or emergency type events. Based on the simulation results in PSCAD, if the network is correctly modeled and the pseudo-measurements are precisely obtained, the proposed method accurately estimate the exact location of the event. However, in practice, the network modeling and pseudo-measurements are prone to a level of inaccuracy. For a reasonable range of error in lines impedance, the proposed method confidently estimates the location of an event, or in the worst case scenario provides a satisfying estimation of neighboring buses of the bus that undergoes the event. Importantly, the proposed method is highly robust against error in pseudo-measurements, which is highly desired for networks with few number of micro-PMU installations. In addition, it was demonstrated that for a defined range of error in micro-PMUs measurement, the proposed method results in a reliable estimation of the event location.

TABLE IV
METHOD EFFECTIVENESS AGAINST CURRENT MEASUREMENTS ERROR WITH DIFFERENT STANDARD DEVIATIONS

Error of Current Phasor	Correct Location	One Bus Error	$>$ One Bus Error	Maximum Error
0.2%	99.79%	0.21%	0%	1 bus
0.4%	93.01%	6.99%	0%	1 bus
0.6%	82.64%	16.89%	0.47%	2 buses
0.8%	73.22%	24.05%	2.73%	3 buses
1.0%	57.87%	32.47%	9.66%	4 buses

TABLE V
METHOD EFFECTIVENESS AGAINST VOLTAGE MEASUREMENTS ERROR WITH DIFFERENT STANDARD DEVIATIONS

Error of Voltage Phasor	Correct Location	One Bus Error	$>$ One Bus Error	Maximum Error
0.2%	97.92%	2.08%	0%	1 bus
0.4%	83.29%	16.56%	0.15%	2 buses
0.6%	68.91%	28.83%	2.26%	3 buses
0.8%	56.72%	36.10%	7.18%	4 buses
1.0%	40.27%	39.36%	20.37%	5 buses

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