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State of the art, challenges and prospects of wide-area event identification on transmission systems

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ABSTRACT

The proliferation of advanced metering devices such as phasor measurement units (PMUs) along with communication systems readiness has opened new horizons for centralized protection and control of transmission systems. Wide-area event identification (WAEI) is considered an indispensable enabling block to these advanced applications. This paper is aimed at scrutinizing existing WAEI methods and discussing their prospects and shortcomings in improving the situational awareness of complex transmission systems. The disturbances of interest are those that significantly impact system operation and stability, namely short-circuit faults, line outages, and generation outages. The reluctance of system operators to entrust WAEI methods is discussed and linked to the inability of existing methods to deal with real-world challenges such as communication latencies, temporarily incomplete network observability, and the loss of the time synchronization signal. The superimposed-circuit concept is detailed and promoted as a powerful methodology with great unleashed potential for addressing these problems. The paper ends with remarks on the remaining research gaps that need to be addressed to fulfill the needs of power system operators, thus facilitating the uptake of WAEI methods in practice.

1. Introduction

The advent and increasing proliferation of PMUs have opened a promising avenue to wide-area monitoring, protection, and control in power systems [1]. Such applications present great potential for overcoming the growing complexity of power systems by complementing local protection/control practices and covering for their insufficiencies. In this context, wide-area event identification (WAEI) is defined as the application of available phasors in the control center to detect and locate severe events such as short-circuit faults, line outages, and generation outages in near real-time. Providing a dynamic picture of the system state [2], WAEI helps to detect high-impact failures and prevent widespread disturbances by taking timely remedial/preventive actions [3]. This is far beyond what the traditional supervisory control and data acquisition (SCADA) system or other legacy monitoring practices could offer [4].

Since the early PMU prototype was built in the early 1990 s, numerous endeavors have been made to develop WAEI methods using PMU data [1]. However, despite many theoretical advancements in the field, there has not been much tangible progress in the practical domain yet. This paper is aimed at scrutinizing, comparing, and contrasting existing WAEI methods as well as characterizing research directions that can facilitate the uptake of such solutions by the industry.

WAEI attempts so far can be categorized into model-free and model-based approaches:

Model-free: In general, these are artificial intelligence (AI)-based approaches requiring no to very little physical knowledge of the system under study, while in operation [5–7]. The objective here is to develop a function that maps the input of measurements to the output of event identity based on extensive input–output examples provided by offline simulations. Learning is indispensable to model-free approaches, which means training quality plays a key role in the success rate of a model-free method. The power system, however, is a dynamic system whose state and topology are constantly changing/evolving over time. Such continuous changes could void the validity of the previous learning shortly, thus necessitating the repetition of time-consuming simulations to create a new training data set. It will not come as a surprise if the power system has hugely changed by the time the new training is complete and ready to use.

Model-free approaches prove advantageous in dealing with systems

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where the equations governing the system's behavior are partly or entirely *unknown*, *highly complicated,* or *inaccessible* in the time frame of interest. There are many engineering problems where one can use AI as a better alternative to traditional solutions, which justifies the huge wave of research interest in such approaches. However, this is not the case when one can easily find low-demanding analytical solutions to a problem.

The foregoing shortcomings should not be interpreted as a NO to using model-free approaches for wide-area applications but more of a motivational call for more profound research to address practical challenges. This is necessary to facilitate the adoption of AI-based techniques for WAEI, as they are increasingly expanding in popularity in academia.

Model-based: In model-based approaches, measurements taken and collected in the control center are interpreted with reference to the static/dynamic models of the power system. The differential swing equation, algebraic circuit equations, or the wave propagation principle can be used, individually or together, to express frequency, voltage, and current measurements as functions of the event characteristics and/or inception time. These may result in straightforward closed-form solutions that could be evaluated with little computation, making communication latencies the dominant factor determining the decision time. Compared to model-free approaches, model-based ones can be considered better suited to WAEI as the governing equations are known, and the associated measurements are readily available thanks to the wide-area monitoring system (WAMS).

Existing model-based WAEI approaches may be classified into four groups (based on their operating principles and the information they need) as below:

- High-frequency contents of signals [8–10]: Methods of this category utilize frequency measurements as indicators of different events and their locations. These methods take advantage of the fact that different events have different impacts on frequency variations, rate of change of frequency (RoCoF) and propagation properties of frequency dynamics.
- Rotor angle variations [11]: In these methods, machines' rotor angles are measured following a disturbance. The largest oscillation could lead to the event location. This can be achieved through different techniques based on PMU measurements, speeds of generators, and active and reactive power at generator terminals.
- Unbalanced currents [12,13]: These methods take advantage of current measurements to detect changes at the terminals of transmission lines. These changes can help identify the faulted line.
- Bus impedance matrix [14–22]: These methods make use of the bus impedance matrix. A system of equations is built based on available measurements. Then, a transfer function is developed to relate changes in the nodal currents to the faulted element.

A WAEI method will be advantageous to the system operators if it can make swift reliable decisions in the face of practical challenges such as [1]:

- Measurement errors and bad data: Random measurement errors are attached to numerical estimation algorithms, misconfiguration, and noise. Larger errors can be attributed to biased or wrongly connected meters and cyberattacks that might lead operators to bad decision-making.
- Sparse PMU coverage: It may not be possible to equip all substations with PMUs due to infrastructure and budget limitations. To guarantee reliable continuous service, therefore, full network observability should not be a prerequisite of WAEI methods.
- PMU malfunction and communication failures: Power systems are subject to the misoperation of metering devices and failures in the communication infrastructure. WAEI methods should be robust against these unpredictable and unavoidable problems.
- Unacceptably long communication latencies: Even if the power system was fully observable, it could not be guaranteed that all measurements would be received in time. Loss of data and communication latencies occur quite often in different operating scenarios.
- Loss of the time-synchronization signal: The phasors estimated by a PMU are expressed w.r.t its local time reference, which is aligned with a common time reference. If a PMU temporarily stops receiving the time-synchronization signal (e.g. GPS), its phasors might start drifting away from phasors calculated by other PMUs, which are time-synchronized [22].

High penetration of renewable energy sources (RESs) is introducing huge changes into well-established operational and control paradigms of power systems. This is because RESs demonstrate distinguished dynamic behaviors that significantly differ from those of synchronous generators. Appropriate adjustments to almost all existing WAEI methods or the development of new ones are deemed necessary if we are to accommodate the presence of RESs in the system. This paper is an extension of the author's conference article presented at the 2022 International Conference on Smart Grid Synchronized Measurements and Analytics (SGSMA) [2], and is aimed at scrutinizing the state of the art, challenges and prospects of WAEI on transmission systems in more detail.

The remainder of this paper is organized as follows. Recent WAEI methods for short-circuit faults, line outages, and generation outages concentrating on resolving practical challenges are investigated, and their strengths and weaknesses are discussed in Section 2, Section 3, and Section 4, respectively. Section 5 describes the superimposed-circuit methodology, which is a potential solution to real-time WAEI applications as it can readily address practical challenges and nonidealities. Section 6 highlights future research directions. Finally, the paper is concluded in Section 7.

2. Wide-Area fault location and backup protection

Timely and accurate fault location is beneficial to power system stability and operation. Voltage and current signals taken slightly farther away from the fault location might be more accurate than those taken from the faulted line terminals. This is because the transient response of an instrument transformer will be smaller and less disturbing when the sudden change it undergoes is smaller [1]. In this context, wide-area fault location (WAFL) is one of the numerous applications of PMU data. Although there is a close link between fault location and protection, WAFL cannot be employed for primary protection due to corresponding communication latencies. Nevertheless, WAFL can serve the purpose of backup protection in the form of wide-area backup protection (WABP).

2.1. WABP: Desired characteristics

To be considered for WABP, an appealing WAFL method would need to possess the following characteristics:

1. *Independence from the operation statuses of circuit breakers* (*CBs*) *and protective relays*: This is necessary as otherwise, the WABP method will not function properly in cases of CB failures and relay malfunction/misoperation.

2 *Ability to detect the fault type and faulted phases:* This is to enable single-pole tripping of CBs following single-phase-to-ground faults.

3. *Remaining valid after non-simultaneous tripping of CBs*: The openings of the CBs at the two line-ends rarely occur simultaneously. Instead, one- or three-pole of the CB at one end of the faulted line might be opened shortly after the fault inception. Therefore, the WAFL formulations are to remain reliable after single-end, one- or three-pole disconnection of lines.

4. *Low sensitivity to fault resistance*: Fault resistance is of a random magnitude and highly nonlinear by nature. To ensure the security and

dependability of WABP, the underlying WAFL is to be robust against the magnitude of fault resistance.

5. *Ability to identify faults at substations and transformers*: A powerful WABP is expected to identify faults at substations and also infer CB failures if we are to provide comprehensive centralized backup protection to the system.

These five are in addition to the general requirements of WAEI methods described in Section 1.

2.2. Pros and cons of existing WABP methods

Many WAFL methods are only suited to offline purposes [13,15,20–22], as they suffer from technical difficulties introduced by iterative solving processes. They cannot be easily employed for protection purposes due to the rigid requirements of WABP. In [23,24], the operation statuses of CBs and protective relays are used to identify the faulted line. However, the performance of these methods may be impaired in the case of CB failures and relay malfunction. WABP methods presented in [25–27,35–39] need specific PMU locations and suffer from one or more of the challenges pointed out in the Introduction Section. It is worth mentioning that methods presented in [35–41] can only identify the faulted line, and do not provide the exact location of the fault on the faulted line.

The method in [16] is a pioneer superimposed-circuit-based WABP method based on voltage measurements. The work is further developed in [17] and [28] by incorporating both voltage and current measurements. Similar to many other WALF methods, these two methods are sensitive to the temporary loss of the time synchronization signal. In response, research works such as [18] tackle the possibility of unsynchronized input phasors.

Table 1 summarizes the features of the most effective WAFL/WABP methods. As can be seen, the linear method of [18] outperforms most of the other methods as they are all sensitive to the loss of the time synchronization signal. This method ensures a low computation burden. The effective technique in [29] can also be used to further reduce the computation time. The nonlinear method presented in [22] is another method that can function with unsynchronized measurements but at the expense of an iterative solving process. The method is thus computationally demanding and prone to the multiplicity of solutions. The WABP methods proposed in [25–33] place certain constraints on PMU numbers and locations to be operative.

Single- or three-pole disconnection of the faulted line from one end will not affect the validity of the superimposed-based-WABP formulations [18]. The reason is that the faulted line is modeled by two current sources at its two ends, with no limitation on the amount of current injected by each source. Under asymmetrical faults, the negative-sequence circuit is the circuit of choice for WAFL analysis. This helps to avoid the impact of time-variant behaviors of synchronous machines, thus providing higher accuracy [18].

Most of the existing WAFL/WABP methods do not take renewable generations into account, which makes them less attractive to system operators given the increasing penetration of RESs in power systems. The presence of RESs has been incorporated in only a few WABP methods over recent years. An integrated WABP method is presented in [42] as a supplementary algorithm for distance protection, which requires a specific PMU placement. The superimposed-circuit methodology has proved to be flexible enough to account for the presence of RESs in the power system. In [43], a superimposed-circuit-based WABP method is presented against asymmetrical faults on transmission systems with high penetration of RESs. In this method, a few appropriately selected RESs are substituted by equivalent current sources, while the remaining RESs are replaced by their equivalent impedances accounting for the control strategies and overcurrent limits. A drawback of this method is that it is only applicable to asymmetrical faults. On the other hand, further research seems necessary to reduce the impact of or completely remove the iterative nature of this method.

3. Wide-area line outage identification

Wide-area line outage identification (WALOI) is critical to system operators to prevent cascading outages and alleviate the consequent impacts. The slowness of the SCADA system in updating topology-related signals has contributed to many blackouts [44]. The knowledge of the most recent network topology is also vital to centralized control and protection applications [45]. Continuous monitoring of CB statuses at all line terminals would be a trivial solution to line outage identification. However, communication latencies and sensor failures might introduce long delays or make timely line outage detection impossible [46]. Other solutions that do not rely on a specific set of data have gained much attention recently.

3.1. WALOI: Desired characteristics

The high refresh rate data provided by PMUs can offer a solution for WALOI [1]. In addition to the general requirements of WAEI methods described before, an appealing WALOI method is characterized by:

1. *Functioning under realistic scenarios*: For instance, DC power flow assumptions are not remotely valid in the case of heavily loaded and stressed transmission lines, where the system operators are in urgent need of successful line outage identification following such events. On the other hand, the derivations of power flow-based methods are based on the quasi-steady-state response of the system, which is why these methods cannot be integrated into real-time applications.

2. *Ability to capture the cascade of events on the line causing the line outage*: Over the course of a line outage event, the CBs at the opposite ends of the transmission line rarely open simultaneously because of the uncertainties in the actuation time of CBs and the protection system's nonidealities. A line outage event may take hundreds of milliseconds

Table 1
Performance Comparison between Different WAFL/WABP Methods.

Reference	[25–33]	[14,1634]	[22]	[18]	[35]	[36]	[37]	[38]	[39]	[40]	[41]	[43]
Tolerate Loss of PMUs?	No	Yes	Yes	Yes	No	No	No	No	No	No	Yes	Yes
Need Time-Synch Signal?	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Involve Iterative Solution?	No	No	Yes	No	No	No	Yes	No	Yes	No	No	Yes
Need Specific PMU Placement?	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No
Identify 1-ph-g faults?	No	No	No	Yes	No	No	No	No	No	Yes	No	Yes
Accurate over time?	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes
Computationally expensive?	No	No	Yes	No	No	No	Yes	Yes	No	No	Yes	No
Need statuses of CBs /relays?	No	No	No	No	No	No	No	No	No	No	No	No
Valid for non-sim. CB opening?	No	No	No	Yes	No	No	No	No	No	No	No	Yes
Valid for 1-p CB opening?	No	No	No	Yes	No	No	No	No	No	No	No	Yes
Sensitivity to fault resistance	Low	Low	Low	Low	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Low
Identify faults in substations?	No	No	No	No	No	Yes	No	No	No	Yes	No	No
Identify faults in transformers?	No	No	No	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
Address the presence of RESs?	No	No	No	No	No	No	No	No	No	No	No	Yes

from the triggering cause, e.g., a short-circuit fault or intentional tripping, to completion. An effective WALOI method should be able to capture the fault inception (if any), the sequential tripping of the line CBs and the completion of the disconnection of the line from the grid (which can be single- or three-pole).

3. *Sensitivity to the outage of light-loaded lines*: The outage of light-loaded lines does not noticeably alter power flows in the power system. Identifying such events might be extremely challenging yet necessary to situational awareness.

3.2. Pros and cons of existing WALOI methods

Many WALOI methods have been proposed over the last two decades. Reference [47] puts forward a WALOI method based on the DC power flow assumptions and quasi-steady-state variations of voltage phase angles across the grid. The authors in [48]-[50] take advantage of the theory of quickest change detection. These methods assume incremental active power injections after line outages can be characterized by Gaussian distribution models. A graph theory-based formulation is employed in [51] to expedite the calculation of power transfer distribution factors. In [52], the DC power flow model is reformulated so that effective techniques in compressive sampling and variable selection can be employed. The foregoing WALOI methods rely on power transfer distribution factors obtained using DC power flow approximations, making them unreliable when the approximation is inaccurate. The fast-decoupled load flow principle is employed in [53] to alleviate this deficiency. Nonetheless, the accuracy of this method declines as the dependency between active and reactive power flows increases.

To improve the identification accuracy, the authors in [54] apply AC power flow calculations for every possible line outage, which considerably increases the computational burden. It is important to note that the derivations of power flow-based methods are all based on the quasi-steady-state response of the system. It follows that such methods are not fit for purpose when it comes to dynamic situational awareness and thus do not stand a chance to be integrated into near real-time applications.

Table 2 compares different aspects of existing WALOI methods. As can be seen, all these methods would suffer if the time synchronization signal is lost. The methods proposed in [53] and [54] need extensive simulation studies, which can impede their implementation in practice. The methods presented in [35] and [55] combine model-free and model-based approaches. The authors in [35] propose a method for multiple event identification. This is achieved by subtracting the impact of the first event from the measurements obtained when the second event occurs. Nonetheless, both methods require a database of recorded events to function properly. This is in addition to the inherent shortcomings of model-free methods, as is the case in [37] and [41]. The method set forth in [40] distinguishes between wide-area events and cyberattacks by processing PMU data. This method requires full network observability, which may not be guaranteed in real power systems, given the unperdictability of communication systems (even if we can assume that all buses are PMU-equipped).

None of the existing methods can deal with non-simultaneous tripping of the CBs at the line opposite ends. This is because the derivations of these methods are based on approximate static relations between voltage phase angles and power injections. Long-time delays will be inevitable (to reach the quasi steady-state response of the system) if a certain level of accuracy is sought by these methods. None of the existing WALOI methods accounts for the presence of RESs in the power system.

Contrary to fast-decoupled or DC-power-flow-based methods, the superimposed-circuit methodology makes it possible to capture the dynamic response of the power system in transient conditions. In [56], a superimposed-circuit-based method is presented for line outage monitoring and identifying the sequence of events on a transmission line before it gets disconnected from both ends. Network observability is not needed for this method to work, nor does the method rely on the reception of any fixed set of data. This is advantageous in dealing with delayed or missing data of PMUs without having to resort to uncertain statistical models describing power system behaviors. A core achievement of this method is that it does not need approximate DC power flow derivations to characterize dynamic events. This feature highly reduces the method's decision time and success rate. Overall, the method of [56] proves suitable for real-time applications for its robustness against partial failures of communication network and losses of the time synchronization signal.

4. Wide-area generation outage identification

Active power deficits caused by sudden generator outages could compromise the frequency stability of power systems. These events are traditionally counteracted by conducting under-frequency load shedding (UFLS) [19]. UFLS prevents further frequency decline by disconnecting an appropriate amount of load from the system to regain the generation and consumption balance. A predetermined amount of load will be shed if the local frequency at the relay location drops below a certain frequency threshold [57]. The next load-shedding steps will be sequentially triggered if the frequency keeps declining and violates the next frequency thresholds. This process continues until the sum of the load shed becomes sufficient to regain the active power balance. However, conventional UFLS methods are slow in handling large loss of generation (LoG) events when the power system requires faster remedial actions [57]. This is an operational challenge, especially with high penetration of renewable generations, which provide little or no inertia to the power system. The slowness of conventional UFLS may lead to unacceptably large frequency deviations in such power systems. In this context, wide-area generation outage identification (WAGOI) could pave the way for the development of centralized UFLS methods.

4.1. WAGOI: Desired characteristics

Along with the general requirements of WAEI methods, WAGOI is expected to possess the following features:

1. *Agility in LoG detection and localization*: Fast detection and localization of LoG events can effectively improve the performance of UFLS [57]. This can also enhance the impact of remedial actions by quickly shedding an appropriate amount of load in the vicinity of the event. This type of load shedding proves to be mandatory when it comes to

Table 2
Performance Comparison between Different WALOI Methods.

Reference	[47]	[48–50]	[51,52]	[37,41,53]	[36,54]	[35,55]	[40]	[56]
Need offline/expensive computations?	No	No	No	Yes	Yes	Yes	Yes	No
Specific nodal power injections?	No	Yes	No	No	No	No	No	No
DC power flow assumptions?	Yes	Yes	Yes	No	No	No	No	No
Based on steady-state response?	Yes	Yes	Yes	Yes	Yes	No	No	No
Need time-synch signal?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Sensitive to light-loaded line outages?	No	No	No	No	Yes	No	Yes	Yes
Valid for 1-p CB opening?	No	No	No	No	No	No	No	Yes
Capture the disturbance from the onset?	No	No	No	No	No	No	No	Yes
Address the presence of RESs?	No	No	No	No	No	No	No	No

combinational frequency and voltage instabilities [58].

2 *Accuracy in LoG size estimation*: The sooner the size of the tripped active power is obtained, the more quickly the frequency decline can be arrested by shedding the same or even less amount of load.

3. *Not relying on the statuses of generator CBs (GCBs)*: Monitoring GCBs statuses is a trivial solution but is prone to failure due to communication latencies and sensor failures. Thus, a complementary approach with a different philosophy will be highly advantageous in practice.

4. *Ability to identify partial generation outages at a substation and multiple outages at different substations*: It is plausible that only a few and not all of the generating units at a substation are tripped. System transients such as voltage deviations and large RoCoFs may cause an LoG to be followed by other generation outages at different locations. WAGOI is expected to be able to monitor and follow this course of events.

4.2. Pros and cons of existing WAGOI methods

Several adaptive methods have been proposed so far to expedite the UFLS operation. Most adaptive UFLS methods use the swing equation of the center-of-inertia to estimate the size of LoG events [57,59,60]. However, system inertia is becoming volatile with more renewables and can hardly be assumed constant. Besides, it defeats the purpose of LoG size estimation if the approach relies on high-speed communication with all generators [61]. If such communication between all generators and the control center was available, the LoG size could have been directly obtained by monitoring GCB statuses.

Due to the shortcomings of direct monitoring of GCBs, several approaches have been proposed based on PMU data [1]. Methods presented in [62–64] locate the LoG event with an accuracy of around 100 miles using local frequency measurements by GPS-synchronized frequency disturbance recorders. In a similar approach, the arrival times of frequency waves recorded by PMUs are used in [10] and [36]. The combination of frequency and voltage measurements is employed in [39] and [65] for better identification of the event characteristics. RoCoF measurements are avoided in [66] using synchronizing power coefficients that relate the remaining active power generations to the generation imbalance. However, this method demands some generator terminals be equipped with PMUs. References [35,36,41], and [55] tackle the shortcomings of RoCoF measurements by resorting to machine learning approaches. However, training makes these methods less attractive to system operators. A superimposed-circuit-based WAGOI method is presented in [19] for identifying the location and size of LoG events. LoG identification and size estimation provided by this method can improve the performance of centralized UFLS methods.

Table 3 compares the existing WAGOI methods from different perspectives. As can be seen, most of the existing methods require synchronized measurements and would be vulnerable to the loss of the time synchronization signal. Some of these methods require specific PMU numbers and locations or need extensive offline studies. This is the case while linear WAGOI method proposed in [19] can function with any set of data. It should be noted that none of the existing WAGOI methods addresses the presence of RESs, which can be an interesting research direction for the future.

A large number of simulations on the IEEE 39-bus test system are carried out in [19] to compare the speed of the superimposed-circuit-based WAGOI method with the direct GCB monitoring and swing-equation-based methods. In this study, system-wide communication latencies are not definite and are assumed to have normal distribution with mean 200 ms and standard deviation 50 ms. The superimposed method operates once a few PMU data (five in that study) are collected in the control center. Fig. 1 shows the distributions of decision time instants by the preceding methods. The superiority of the superimposed-circuit-based method over the swing-equation-based method can be easily inferred as the latter needs all measurements to be received, contrary to the former. Although the direct GCB monitoring method is faster than the superimposed-circuit-based method in some cases, it is slower when the data of the tripped generator is delayed. Using the direct GCB monitoring method together with the superimposed-circuit method could reduce the average decision time by 35 %.

5. Superimposed-circuit methodology for WAEI

In this section, the superimposed circuit methodology and derivations are put forward. This lays the foundations for WAEI that can account for practical challenges and pertinent nonidealities. Based upon the Substitution Theorem, any element can be replaced by proper nodal current sources. It is possible to do this such that the pre-disturbance and post-disturbance bus impedance matrices remain the same [18]. This will result in a system of linear equations relating the superimposed voltage and current phasors to unknown nodal current sources that replace the disturbed element. Applying the weighted least-squares method to the developed system of equations would enable the identification of the disconnected element.

The disturbance of interest in this paper is defined as sudden changes in nodal current injections in the circuit. Fig. 2(a) and 2(b) show the corresponding pre- and post-disturbance circuits with the same topology but with nodal current sources of different values. Having the same topology and elements, the circuits of Fig. 2(a) and 2(b) have the same bus impedance matrix denoted by $\boldsymbol{Z}$. The circuit nodes are indexed 1 to N.

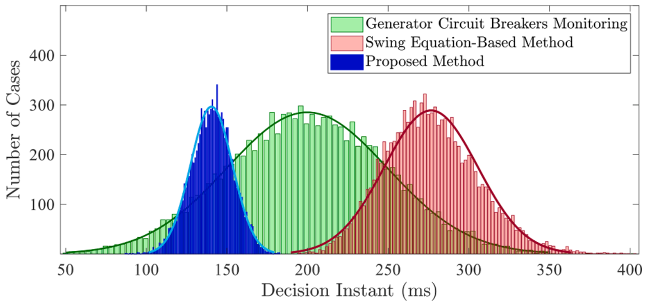

Fig. 1. Comparison between the proposed, direct GCB monitoring and swing equation-based LoG size estimation methods in terms of execution time [19].

Table 3
Performance Comparison between Different WAGOI Methods.

Reference	[39,60,65]	[62,63]	[10,37,55]	[66]	[3]	[35]	[36]	[40]	[41]	[64]	[19]
Need offline studies?	No	No	Yes	No	Yes	Yes	No	Yes	Yes	No	No
Need specific PMU placement?	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Need time-synch signal?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Tolerate PMU losses?	No	Yes	No	Yes	Yes	No	No	No	Yes	Yes	Yes
Estimate both size and location?	No	Yes	No	Yes	No	No	No	No	No	No	Yes
Need operating status of GCBs?	No	No	No	No	No	No	No	No	No	No	No
Identify partial outage?	No	No	No	No	Yes	No	No	Yes	No	No	Yes
Identify multiple outage?	No	No	No	No	No	Yes	No	No	No	No	Yes
Computationally expensive?	No	No	Yes	Yes	Yes	No	Yes	No	Yes	No	No
Address the presence of RESs?	No	No	No	No	No	No	No	No	No	No	No

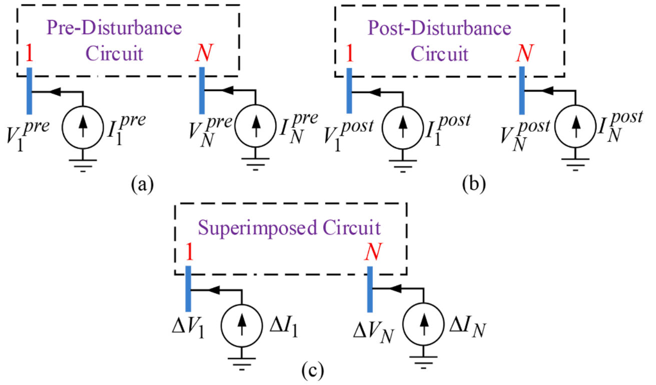

Fig. 2. (a) Pre-disturbance, (b) Post-disturbance and (c) Superimposed circuits for a disturbance [19].

Let $\boldsymbol{V}^{pre}$ and $\boldsymbol{V}^{post}$ represent the vectors of node voltages before and after the disturbance, respectively. Therefore, the nodal equations for the two circuits satisfy the following equations [17]:

$$\boldsymbol{V}^{pre} = \boldsymbol{Z}\boldsymbol{I}^{pre} \tag{1}$$

$$\boldsymbol{V}^{post} = \boldsymbol{Z}\boldsymbol{I}^{post} \tag{2}$$

where, $\boldsymbol{I}^{pre}$ and $\boldsymbol{I}^{post}$ represent the vectors of nodal currents before and after the disturbance, respectively. By subtracting (1) from (2), the following matrix equation can be derived:

$$\Delta \boldsymbol{V} = \boldsymbol{Z}\Delta \boldsymbol{I} \tag{3}$$

Eq. (3) can be attributed to a hypothetical superimposed circuit, as shown in Fig. 2(c), in which all quantities are indicated by the Δ symbol.

The letters I and J are used for nodal current injections and branch currents, respectively, to distinguish between them. If ΔI_j refers to the superimposed nodal injection at a node j, the superimposed voltage at any node i can be obtained from:

$$\Delta V_i = \sum_{j=1}^{N} Z_{i,j} \Delta I_j \tag{4}$$

where $Z_{i,j}$ denote the element in the i-th row and j-th column of the bus impedance matrix of the superimposed circuit with N nodes. Let $\Delta J_{u,v}^{s}$ denote the superimposed current of the sending-end of a healthy line u-v, which satisfies the following equation:

$$\Delta J_{uv}^{s} = \sum_{q=1}^{N} C_{uv,q}^{s} \Delta I_q^{s} \tag{5}$$

where the coefficient $C_{uv,q}^{s}$ is detailed in [17].

Now, let us assume PMUs provide N_p voltage and current measurements across the grid. By writing equations (4) and (5) based on these measurements, a system of linear equations can be obtained as below:

$$\boldsymbol{m} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{\varepsilon} \tag{6}$$

where $\boldsymbol{m}$, $\boldsymbol{H}$ and $\boldsymbol{\varepsilon}$ are the measurement vector, coefficient matrix, and error vector, respectively. Further, $\boldsymbol{x}$ is the vector of unknown nodal current injections.

The Weighted Sum of Squared Residuals (*WSSR*) is the objective function minimized for solving (6) and can be obtained from:

$$WSSR = \boldsymbol{m}^{*}\boldsymbol{S}^{*}\boldsymbol{R}^{-1}\boldsymbol{S}\boldsymbol{m} \tag{7}$$

where $\boldsymbol{R}$ denotes the covariance matrix of measurement errors, which is an N_p-by-N_p diagonal matrix whose i-th diagonal entry is the variance of the i-th measurement. The matrix $\boldsymbol{S}$ is called the residual sensitivity matrix and can be obtained from:

$$\boldsymbol{S} = \boldsymbol{I} - \boldsymbol{H}\left(\boldsymbol{H}^{*}\boldsymbol{R}^{-1}\boldsymbol{H}\right)^{-1}\boldsymbol{H}^{*}\boldsymbol{R}^{-1} \tag{8}$$

The *WSSR* of the actual disturbed element is theoretically zero and non-zero for healthy elements. Accordingly, (7) is evaluated for different suspected elements to identify the smallest *WSSR*, thus the disturbed element. The unknowns in the vector $\boldsymbol{x}$ of the system of (6) can also be readily estimated as follows

$$\hat{\boldsymbol{x}} = \left(\boldsymbol{H}^{*}\boldsymbol{R}^{-1}\boldsymbol{H}\right)^{-1}\boldsymbol{H}^{*}\boldsymbol{R}^{-1}\boldsymbol{m} \tag{9}$$

The estimated unknowns can be used to further investigate the identified disturbed element. For example, it can be used to calculate the fault distance on the faulted line and tripped active/reactive power following line outage or generation outage events.

A flowchart of the superimposed-circuit methodology for WAEI is shown in Fig. 3. The product $\boldsymbol{S}^{*}\boldsymbol{R}^{-1}\boldsymbol{S}$ can be calculated and saved in memory a-priory based on the bus impedance matrix of the system. Therefore, the real-time calculations are mainly limited to calculating WSSRs by (7). Some other advantages of the superimposed-circuit methodology are explained in the following subsections.

5.1. Individual analysis of the sequence circuits

Some events, such as asymmetrical faults and single-pole opening of CBs make the three-phase power system unbalanced. The method of symmetrical components replaces the solution of an unbalanced three-phase circuit with the solution of three balanced circuits connected to each other in a particular way satisfying the event constraints [67]. In the superimposed circuit methodology, each sequence circuit can be analyzed independently regardless of the event type. This is possible if other sequence circuits are replaced by proper current or voltage sources imitating the omitted circuits' behavior following the event [16–19].

5.2. PMU coverage and data loss

PMUs are normally placed in power systems w.r.t the availability of infrastructure and budget restrictions rather than the requirements of particular functionality [68]. WAEI schemes that need synchrophasor measurements from specific locations are essentially vulnerable to losses of PMU data and long communication latencies. This is while the superimposed-circuit-based based methods do not impose rigid limitations on the number and locations of PMUs.

An important implication of the foregoing feature is that the loss of PMU data or long communication latencies will not render superimposed-circuit-based methods unserviceable. Indeed, the system of (6) is normally overdetermined to a great extent, thanks to the multitude of measurements provided by PMUs. It follows that the solvability of (6) is not dependent on the availability of any specific single equation. Therefore, excluding the equations corresponding to a few PMUs whose data have not been received in the control center for any reason would not compromise the functionality of the WAEI method. It is an easy offline task to determine the simultaneous losses of

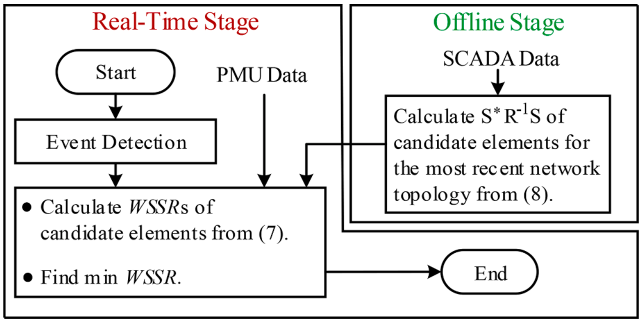

Fig. 3. Flowchart of a superimposed-circuit-based method.

which measurements can make (6) unsolvable [17]. Placing a few PMUs at strategic locations can practically remove such concerns.

5.3. Considerations for loss of time-synchronizing signal

Synchrophasors reported by a PMU will be all time-stamped w.r.t the time reference of that device. The time drift of locally-measured phasors can be confined in the order of 1 μs over one second [69]. Therefore, the phase angles of phasors measured by a PMU at the same substation can be considered highly accurate with respect to each other [17]. To model the impact of the loss of time synchronization signal, phasors provided by PMU_1 to PMU_{Np} may be multiplied by unknown phase angle operators $e^{j\theta_1}, \ldots, e^{j\theta_{Np}}$. These multiplications make the formulation nonlinear in terms of the new unknowns. Rearranging the equations of (6) as a linear combination of nodal current sources and angle drifts can help maintain the system's linearity [18,19]. In doing so, the unknown angle drifts operators should be moved from the measurement vectors to the vector $\boldsymbol{x}$, while their coefficient will be added to the $\boldsymbol{H}$ matrix.

5.4. Bad data detection and identification

Due to the inclusion of bad data in the measurement set, the event identification results might become unreliable from time to time. This will be the case unless bad data is spotted and eliminated from the measurement set. The main contribution of [28] is the rigorous derivations of the mean and variance of superimposed errors, i.e. the differences between the errors of the corresponding pre- and post-fault synchrophasors. This enables a rigorous establishment of the covariance matrix. The elements of this matrix are used as measurement weights in (7)-(9). The superimposed errors are characterized based on the statistical distributions of the magnitude and phase-angle errors of pre- and post-fault synchrophasors. The linearity of the formulation, along with the derivations of superimposed errors, allows for the application of well-established bad data detection and identification methods. The largest normalized residual test (LNRT) [70,71] is a common technique that can be used to deal with erroneous measurements, e.g. current measurements of saturated CTs during close-in faults. Finally, thanks to the overdetermined nature of the system of equations (6), the detected bad data can be excluded from the vector of measurements.

6. Remarks on future research directions

Despite huge efforts and good progress made so far in presenting effective WAEI methods, there are many practical challenges and requirements to be addressed. This section puts forward some ideas for future research directions:

- With reference to the increasing penetration of renewables, WAEI methods should consider the presence of RESs in the power system.
- CB monitoring is the most trivial and easiest way of outage monitoring. WAEI methods should be able to take advantage of CB statuses along with PMU data to draw faster and more reliable conclusions.
- LNRT, as an effective tool for identifying bad data, might fail in the case of multiple interacting and conforming bad data, where measurement errors are in agreement so that circuit equations such as KCL and KVL still hold [70]. These hard-to-detect bad data might be intentionally fed into wide-area measurements in the form of cyberattacks. Indeed, devising more reliable encryption protocols and bad data identification methods are becoming increasingly integral to wide-area applications.
- Full network observability is not required for WAEI, but the reception of more data enhances accuracy. PMU data are prone to indefinite communication latencies and are not received simultaneously or even within a definite time period. Thus, formulating the required number of PMU data and the maximum waiting time before decision-making is a missing block in the context of WAEI.
- Existing WAEI methods focus on a single or a few types of events. An appealing WAEI method needs to be able to identify and distinguish between different events.
- Ideally, WAEI should be capable of identifying multiple events occurring almost at the same time. These include but are not limited to multiple generation outages, and the outage of an overloaded line following an LoG, or asymmetrical faults.
- It will be beneficial if WAEI is made capable of monitoring and identifying system separation into islands.

Cutting-edge research is needed to address the research gaps pointed out above. The superimposed-circuit methodology is a powerful tool with the potential to address many of the challenges associated with WAEI. The authors believe this research direction can open the door for advancing WAEI methods, thus facilitating their uptake by system operators.

7. Conclusion

Increasing penetration of renewables and resulting operational uncertainties and paradigm shifts put considerable emphasis on timely and reliable Wide-Area Event Identification (WAEI) to improve stability and resilience against high-impact events. This paper scrutinizes the advantages and shortcomings of existing WAEI methods proposed for the centralized monitoring of short-circuit faults, line outages, and generation outages. As discussed, most of these methods are unable to address practical challenges such as communication latencies/failures, temporary/permanent incompleteness of network observability, and the loss of the time synchronization signal. The paper also elaborates on the implications of overlooking realistic characteristics and interlinks between the events, such as the non-simultaneous opening of line CBs following faults. The authors believe that the superimposed-circuit-based methodology is the path forward to creating a unified platform for WAEI in the control center, given the practical challenges and real-time requirements associated with this centralized functionality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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