Proceedings Paper:

Rezaei Jegarluei, M, Sanchez Cortes, J, Azizi, S orcid.org/0000-0002-9274-1177 et al. (1 more author) (2022) Wide-Area Event Identification in Power Systems: A Review of the State-of-the-Art. In: 2022 International Conference on Smart Grid Synchronized Measurements and Analytics (SGSMA). 2022 International Conference on Smart Grid Synchronized Measurements and Analytics (SGSMA), 24-26 May 2022, Split, Croatia. IEEE . ISBN 978-1-6654-9824-1

https://doi.org/10.1109/SGSMA51733.2022.9805846

Wide-Area Event Identification in Power Systems: A Review of the State-of-the-Art

Mohammad Rezaei Jegarluei, Jesús Sánchez Cortés, and Sadegh Azizi
School of EEE, University of Leeds, Leeds, UK

Vladimir Terzija
Center for Energy Science and Technology
Skolkovo Institute of Science and Technology, Russia

***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 power systems. Wide-area event identification (WAEI) is deemed 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 situational awareness on complex power 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 these methods in dealing 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 research gaps that need to be addressed to fulfill the needs of power system operators, thus facilitating the uptake of WAEI methods in practice.**

***Index Terms*— Communication latency, phasor measurement unit (PMU), superimposed circuits, wide-area event identification.**

I. 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 complimenting 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 1990s, 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 into 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 response-based and model-based approaches:

Response-based: 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 response-based approaches, which means training quality plays a key role in the success rate of a response-based 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.

Response-based approaches prove advantageous to dealing with systems 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 response-based 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 approaches for WEAI, 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 response-based 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 approaches could be classified into four groups regarding their operating principles as below:

- High-frequency contents of signals [8]-[10],
- Rotor angle variations [11],
- Unbalanced current location [12], [13],
- Impedance analysis of the grid [14]-[22].

A WAEI method would be advantageous to system operators provided that it can make swift yet reliable decisions and cope with practical challenges such as [1]:

- Measurement errors and bad data,
- Sparse PMU coverage,
- PMU malfunction and communication failures,
- Unacceptably long communication latencies,
- Loss of the time-synchronization signal.

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 for the presence of RESs in the system.

Mitigating the impacts of major events such as short-circuit faults, line outages, and generation outages are fundamental to securing the operation of the power system. Thus, we focus on wide-area fault location (WAFL), wide-area generation outage identification (WAGOI), and wide-area line outage identification (WALOI) in the remainder of this paper. Recent WAEI methods concentrating on resolving practical challenges are investigated, and their pros and cons are discussed. The paper also recommends directions for future research and suggests priorities to focus on.

II. 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 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).

A. 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 maloperations.

Table I
Performance Comparison between Different WABP Methods

Comparison aspect	[25]-[31]	[14],[16] [32],[33]	[22]	[18]
Single/Multiple Loss of PMUs	Intolerant	Tolerant	Tolerant	Tolerant
Need Time-Synch Signal?	Yes	Yes	No	No
Involve Iterative Solution?	No	No	Yes	No
Need Specific PMU Placement?	Yes	No	No	No
Tolerate PMU losses?	No	Yes	Yes	Yes
Identify 1-ph-g faults?	No	No	No	Yes
Accurate over time?	No	No	No	Yes
Computation time	Low	Low	High	Low
Need statuses of CBs /relays?	No	No	No	No
Valid for non-sim. CB opening?	No	No	No	Yes
Valid for 1-p CB opening?	No	No	No	Yes
Sensitivity to fault resistance	Low	Low	Low	Low
Identify faults in substations?	No	No	No	No
Identify faults in transformers?	No	No	No	Yes
Address the presence of RESs?	No	No	No	No

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 almost never occur simultaneously. Instead, one- or three-pole of the CB at one end of the faulted line might be opened shortly after the fault onset. 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 I.

B. 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 maloperations. WABP methods presented in [25]-[27] need specific PMU locations and suffer from one or more of the challenges pointed out in Introduction.

The method in [16] is a pioneer superimposed-circuit-based WABP method based upon voltage measurements. The work is further developed in [17] 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 I summarizes the features of the most effective WAFL/WABP methods. As can be seen, the linear method of [18] outperforms other methods for they are all sensitive to the loss of the time synchronization signal. 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]-[31] 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]. It is worth noting that none of the existing WAFL/WABP methods takes account of renewable generations, which makes them less attractive to system operators given the increasing penetration of RESs in power systems.

III. Wide-Area Line Outage Identification

Prompt line outage identification is critical to system operators to prevent cascading outages and alleviate the consequent impacts. The slowness of the SCADA system to update topology-related signals has contributed to many blackouts [34]. The knowledge of the most recent network topology is also vital to centralized control and protection applications [35]. 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 [36]. Other solutions that do not rely on a specific set of data have gained much attention, recently.

A. *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 heavily loaded and stressed transmission lines, where we are in most need of successful line outage identification. 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 disturbances*: Following a line outage event, CBs at the opposite ends of transmission lines 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 from the triggering cause, *e.g.*, a short-circuit fault or intentional tripping, to complete and can be fulfilled 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 challenging as much as it is beneficial to situational awareness.

Table II
Performance Comparison between Different WALOI Methods

Reference	[37]	[38]-[40]	[41], [42]	[43]	[44]
Need offline/expensive computations?	No	No	No	Yes	Yes
Specific nodal power injections?	No	Yes	No	No	No
DC power flow assumptions?	Yes	Yes	Yes	No	No
Based on steady-state response?	Yes	Yes	Yes	Yes	Yes
Need time-synch signal?	Yes	Yes	Yes	Yes	Yes
Sensitive to light-loaded line outages?	No	No	No	No	Yes
Valid for 1-p CB opening?	No	No	No	No	No
Capture the disturbance from the onset?	No	No	No	No	No
Address the presence of RESs?	No	No	No	No	No

B. *Pros and Cons of Existing WALOI Methods*

Many WALOI methods have been proposed over the last two decades. Reference [37] 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 [38]-[40] 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 [41] to expedite the calculation of power transfer distribution factors. In [42], 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 the DC power flow approximations, making them unreliable when the approximation is inaccurate. The fast-decoupled load flow principle is employed in [43] 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, authors in [44] 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 is manifest 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 II 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 [43] and [44] need extensive simulation studies, which is a barrier to their implementation in practice. The existing methods cannot capture the cascade of disturbances resulting in the line outage and 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 WABP methods accounts for the presence of RESs in the power system.

The authors believe that the superimposed-circuit methodology has a great potential to address this challenge. Unlike fast-decoupled or DC-power-flow-based methods, the superimposed-circuit methodology makes it possible to capture the dynamic response of the system in transient conditions. To this end, the tripped line can be treated the same way as the faulted line in [17]. This helps to deal with delayed or missing data of PMUs without having to resort to uncertain statistical models to characterize the power system behavior.

IV. Wide-Area Generation Outage Identification

Active power deficit 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 [46]. 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 [46]. 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 systems. In this context, WAGOI could pave the way for the development of centralized UFLS methods.

A. *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 [46]. This can also enhance the impact of remedial actions by quickly shedding an appropriate amount of load at the vicinity of the event. This type of load shedding proves to be mandatory when it comes to combinational frequency and voltage instabilities [45].

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 restricted by shedding the same or even less amount of load.

3. *Not relying on the statuses of generator CBs (GCBs)*: Monitoring GCB 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 is highly appreciated 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 rate of change of frequencies (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.

B. *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 [46]-[48]. 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 [49]. 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 [50]-[51] 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]. RoCoF measurements are avoided in [52] using synchronizing power coefficients that relate the remaining active power generations to the generation imbalance. However, this method demands some generator terminals to be equipped with PMUs. 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 III 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 while the linear WAGOI method proposed in [19] can function with any set of data. It should be noted that none of the existing WAGOI methods address the presence of RESs, which can be an interesting research direction for the future.

Table III
Performance Comparison between Different WAGOI Methods

Reference	[48]	[50], [51]	[10]	[52]	[3]	[19]
Need offline studies?	No	No	Yes	No	Yes	No
Need specific PMU placement?	Yes	No	Yes	Yes	Yes	No
Need time-synch signal?	Yes	Yes	Yes	Yes	Yes	No
Tolerate PMU losses?	No	Yes	No	Yes	Yes	Yes
Estimate both size and location?	No	Yes	No	Yes	No	Yes
Need operating status of GCBs?	No	No	No	No	No	No
Identify partial outage?	No	No	No	No	Yes	Yes
Identify multiple outage?	No	No	No	No	No	Yes
Computational burden	Low	Low	High	High	High	Low
Address the presence of RESs?	No	No	No	No	No	No

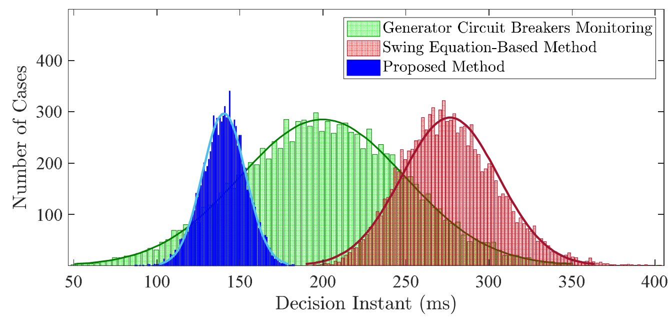

Fig. 1. Comparison between the proposed, direct GCB monitoring and swing equation-based LoG size estimation methods in terms of execution time [19].

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 GCBs monitoring and swing-equation-based methods. In this study, system-wide communication latencies are not definite and are assumed to have a 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 GCBs 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 GCBs monitoring method together with the superimposed-circuit method could reduce the average decision time by 35%.

V. Superimposed-Circuit Methodology for WAEI

In this section, the superimposed circuit concept and derivations are put forward. The following methodology lays the foundation 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 replaced for 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. Figs 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 Figs 2(a) and 2(b) have the same bus impedance matrix denoted by $\boldsymbol{Z}$. The circuit nodes are indexed 1 to N. Let $\boldsymbol{V}^{pre}$ and $\boldsymbol{V}^{post}$ represent the vector of node voltages before and after the disturbance, respectively. Then, 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 equation can be derived:

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

Equation (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:

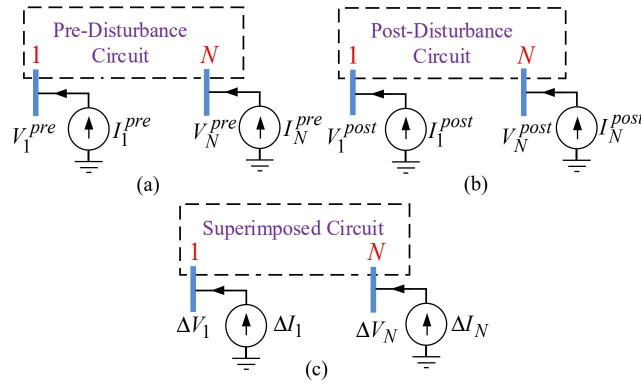

Fig. 2. (a) Pre-disturbance, (b) Post-disturbance and (c) Superimposed circuits for a disturbance [19].

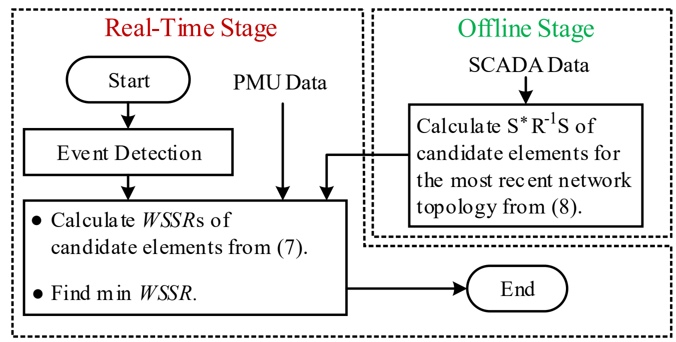

Fig. 3. Flowchart of a superimposed-circuit-based method.

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

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:

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

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.

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 *WSSR*s by (7). Some other advantages of the superimposed-circuit methodology are explained in the following subsections.

In the superimposed-circuit methodology, each sequence circuit may be analyzed individually, as explained in [16]-[19]. To model the impact of the loss of time synchronization signal, phasors provided by PMU_1 to PMU_{Np} are multiplied by unknown phase angle operators, $e^{j\theta_1}$, …, $e^{j\theta_{Np}}$, respectively, which make the formulation nonlinear. Reformulating the system of equations (6) as a linear combination of nodal current sources and angle drifts makes the problem linear again [18]-[19]. In doing so, the unknown angle drifts operators are moved from the measurement vectors to the vector $\boldsymbol{x}$, while their coefficients will be added to the $\boldsymbol{H}$ matrix.

PMUs are normally placed in the power system as per the availability of infrastructure rather than the requirements of particular functionality [53]. WAEI methods that need specific PMU measurements are essentially vulnerable to losses of PMU data and long communication latencies. This is while superimposed-circuit-based methods do not impose rigid constraints on the number or the PMU locations. It follows that the loss of PMU data or long communication latencies will not render superimposed-circuit-based methods unserviceable. The system of equations (6) is highly overdetermined in virtue of the multitude of measurements provided by PMUs. Thanks to the linearity of the developed system of equations, well-known bad data identification approaches such as the largest normalized residual test (LNRT) can be deployed to identify and exclude erroneous measurements [54].

VI. Remarks on Future Research Directions

Despite huge efforts conducted on WAEI methods, many practical challenges and requirements are yet to be addressed. This section puts forward some suggestions as to future research directions.

- With reference to increasing penetration of renewables, WAEI methods should take account of 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 [54]. 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 that are chronologically close to each other. These include but are not limited to multiple generation outages or the outage of an overloaded line following an LoG.
- It will be beneficial if WAEI is extended to monitoring and identifying system separation into a few islands.

Cutting-edge research is needed to address 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.

VII. 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 way 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.

References

[1] V. Terzija *et al.*, "Wide-area monitoring, protection, and control of future electric power networks," *Proc. IEEE*, vol. 99, no. 1, pp. 80–93, Jan. 2011.

[2] A. S. Dobakhshari, S. Azizi, M. Paolone, and V. Terzija, "Ultra-fast linear state estimation utilizing SCADA measurements," *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 2622–2631, Jul. 2019.

[3] D. Kim, A. White and Y. Shin, "PMU-based event localization technique for wide-area power system," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 5875–5883, Nov. 2018.

[4] S. G. Ghiocel *et al.*, "Phasor-measurement-based state estimation for synchrophasor data quality improvement and power transfer interface monitoring," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 881–888, Mar. 2014.

[5] L. Xie, Y. Chen, and P. R. Kumar, "Dimensionality reduction of synchrophasor data for early event detection: Linearized analysis," *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 2784–2794, 2014.

[6] M. Rafferty, X. Liu, D. M. Laverty, and S. McLoone, "Real-time multiple event detection and classification using moving window PCA," *IEEE Trans. Smart Grid*, vol. 7, no. 5, pp. 2537–2548, 2016.

[7] S. Hosur and D. Duan, "Subspace-driven output-only based change-point detection in power systems," *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 1068–1076, 2019.

[8] W. Gao and J. Ning, "Wavelet-based disturbance analysis for power system wide-area monitoring," *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 121–130, Mar. 2011.

[9] D.-I. Kim, T. Y. Chun, S.-H Yoon, G. Lee, and Y.-J. Shin, "Wavelet-based event detection method using PMU data," *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 1154–1162, May 2017.

[10] H. X. Zhang, F. Shi, Y. T. Liu, and V. Terzija, "Adaptive online disturbance location considering anisotropy of frequency propagation speeds," *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 931–941, Mar. 2016.

[11] K. Mei, S. M. Rovnyak, and C.-M. Ong, "Clustering-based dynamic event location using wide-area phasor measurements," *IEEE Trans. Power Syst*., vol. 23, no. 2, pp. 673–679, May 2008.

[12] Q. Jiang, B. Wang, and X. Li, "An efficient PMU-based fault-location technique for multiterminal transmission lines," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1675–1682, Aug. 2014.

[13] G. Feng and A. Abur, "Fault location using wide-area measurements and sparse estimation," *IEEE Trans. Power Syst*., vol. 31, no. 4, pp. 2938–2945, Jul. 2016.

[14] Y. Liao, "Fault location for single-circuit line based on bus-impedance matrix utilizing voltage measurements," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 609–617, Apr. 2008.

[15] A. S. Dobakhshari, "Fast accurate fault location on transmission system utilizing wide-area unsynchronized measurements," *Int. J. Electr. Power Energy Syst.*, vol. 101, pp. 234–242, Oct. 2018

[16] S. Azizi and M. Sanaye-Pasand, "A straightforward method for wide-area fault location on transmission networks," *IEEE Trans. Power Del*., vol. 30, no. 1, pp. 441–445, Feb. 2015.

[17] S. Azizi and M. Sanaye-Pasand, "From available synchrophasor data to short-circuit fault identity: Formulation and feasibility analysis," *IEEE Trans. Power Sys*t., vol. 32, no. 3, pp. 2062-2071, May 2017.

[18] S. Azizi, G. Liu, A. S. Dobakhshari, and V. Terzija "Wide-area backup protection against asymmetrical faults using available phasor measurements," *IEEE Trans. Power Del*., Dec 2019.

[19] S. Azizi, M. R. Jegarluei, A. S. Dobakhshari, G. Liu and V. Terzija, "Wide-Area Identification of the Size and Location of Loss of Generation Events by Sparse PMUs" *IEEE Trans. Power Del.*, vol. 36, no. 4, pp. 2397-2407, Aug. 2021.

[20] Q. Jiang, X. Li, B. Wang, and H. Wang, "PMU-based fault location using voltage measurements in large transmission networks," *IEEE Trans. Power Del*., vol. 27, no. 3, pp. 1644–1652, Jul. 2012.

[21] N. Kang and Y. Liao, "Double-circuit transmission-line fault location with the availability of limited voltage measurements," *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 325–336, 2012.

[22] A. S. Dobakhshari, "Wide-area fault location of transmission lines by hybrid synchronized/unsynchronized voltage measurements," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1869-1877, May 2018.

[23] X. Tong *et al.*, "The study of a regional decentralized peer-to-peer negotiation-based wide-area backup protection multi-agent system," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 1197–1206, Jun. 2013.

[24] M. Chen, H. Wang, S. Shen, and B. He, "Research on a distance relay-based wide-area backup protection algorithm for transmission lines," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 97–105, Feb. 2017.

[25] S. Mirhosseini and M. Akhbari, "Wide-area backup protection algorithm for transmission lines based on fault component complex power," *Int. J. Elect. Power Energy Syst.*, vol. 83, pp. 1–6, Dec. 2016.

[26] P. Kundu, A. K. Pradhan. "Synchrophasor-assisted zone-3 operation." *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 660–667, Apr. 2014.

[27] J. Ma *et al*., "A fault steady-state component-based wide-area backup protection algorithm," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 468–475, Sep. 2011.

[28] H. K. Zadeh and Z. Li, "Phasor measurement unit-based transmission line protection scheme design," *Elect. Power Syst. Res.,* vol. 81, no. 2, pp. 421–429, Feb. 2011.

[29] J. Zare, F. Aminifar, M. Sanaye-Pasand, "Synchrophasor-based wide-area backup protection scheme with data requirement analysis." *IEEE Trans. Power Del.,* vol. 30, no. 3, pp. 1410–1419, Jun. 2015.

[30] J. Ma *et al*., "A wide-area backup protection algorithm based on distance protection fitting factor." *IEEE Trans. Power Del.,* vol. 31, no. 5, pp. 2196–2205, Oct. 2016.

[31] M. K. Neyestanaki and A. M. Ranjbar, "An adaptive PMU-based wide area backup protection scheme for power transmission lines," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1550–1559, May 2015.

[32] M. Majidi, M. Etezadi-Amoli, M. S. Fadali, "A sparse-data-driven approach for fault location in transmission networks," *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 548-556, Mar. 2017.

[33] S. Azizi, M. Sanaye-Pasand, and M. Paolone, "Locating faults on untransposed, meshed transmission networks using a limited number of synchrophasor measurements," *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4462-4472, Nov. 2016.

[34] US-Canada Power System Outage Task Force, "Final report on the August 14th blackout in the United States and Canada: Causes and recommendations," Apr. 2004. [Online]. Available: http://energy.gov.

[35] A. J. Wood and B. F. Wollenberg, Power generation, operation, and control. *John Wiley & Sons*, 2012.

[36] *IEEE Standard for Synchrophasor Data Transfer for Power Systems*, IEEE Std. C37.118.2-2011, 2011.

[37] J. E. Tate, and T. J. Overbye, "Line outage detection using phasor angle measurements," *IEEE Trans. Power Syst.*, vol. 23, no. 4, pp. 1644–1652, Nov. 2008.

[38] Y. C. Chen, T. Banerjee, A. D. Domínguez-García, and V. V. Veeravalli, "Quickest line outage detection and identification," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 749–758, Jan. 2016.

[39] G. Rovatsos, X. Jiang, A. D. Domínguez-García, and V. V. Veeravalli, "Statistical power system line outage detection under transient dynamics," *IEEE Trans. on Signal Processing*, vol. 65, no. 11, pp. 2787-2797, 1 Jun. 2017.

[40] X. Jiang, Y. C. Chen, V. V. Veeravalli and A. D. Domínguez-García, "Quickest line outage detection and identification: Measurement placement and system partitioning," *2017 North American Power Symposium (NAPS)*, Morgantown, WV, 2017, pp. 1-6.

[41] H. Ronellenfitsch, D. Manik, J. Hörsch, T. Brown and D. Witthaut, "Dual theory of transmission line outages," *IEEE Trans. on Power Syst.*, vol. 32, no. 5, pp. 4060-4068, Sept. 2017.

[42] H. Zhu, and G. B. Giannakis, "Sparse overcomplete representations for efficient identification of power line outages," *IEEE Trans. Power Syst.*, vol. 27, no. 4, pp. 2215–2224, Nov. 2012.

[43] X. Yang, N. Chen and C. Zhai, "A control chart approach to power system line outage detection under transient dynamics," *IEEE Trans. Power Syst.*, vol. 36, no. 1, pp. 127–135, Jan. 2021.

[44] Z. Dai and J. E. Tate, "Line outage identification based on AC power flow and synchronized measurements," *2020 IEEE Power & Energy Society General Meeting (PESGM)*, 2020, pp. 1-5.

[45] M. Abedini, M. Sanaye-Pasand, and S. Azizi, "Adaptive load shedding scheme to preserve the power system stability following large disturbances," IET Gener. Transm. Distrib. 2014, 8, 2124–2133.

[46] V. Terzija, "Adaptive underfrequency load shedding based on the magnitude of the disturbance estimation," *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1260–1266, Aug. 2006.

[47] U. Rudez and R. Mihalic, "Monitoring the first frequency derivative to improve adaptive underfrequency load-shedding schemes," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 839–846, May 2011.

[48] R. Azizipanah-Abarghooee, M. Malekpour, M. Paolone, and V. Terzija, "A new approach to the online estimation of the loss of generation size in power systems," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2103–2113, May 2019.

[49] S. Azizi, M. Sun, G. Liu, and V. Terzija, "Local frequency-based estimation of the rate of change of frequency of the center of inertia," *IEEE Trans. Power Syst.*, vol. 35, no. 6, pp. 4948–4951, Nov. 2020.

[50] Y. Zhang, *et al.*, "Wide-area frequency monitoring network (FNET) architecture and applications," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 159–167, Sep. 2010.

[51] W. Li, J. Tang, J. Ma, and Y. Liu, "Online detection of start time and location for hypocenter in north America power grid*," IEEE Trans. on Smart Grid*, vol. 1, no. 3, pp. 253-260, Dec. 2010.

[52] N. Shams, P. Wall, V. Terzija, "Active power imbalance detection, size and location estimation using limited PMU measurements," *IEEE Trans. Power Syst*., vol. 34, no. 2, pp. 1260–1266, Mar. 2019.

[53] Z. H. Rather, Z. Chen, P. Thøgersen, P. Lund, and B. Kirby, "Realistic approach for phasor measurement unit placement: Consideration of practical hidden costs," *IEEE Trans. Power Del*., vol. 30, no. 1, pp. 3–15, Feb. 2015.

[54] A. Abur, and A. G. Exposito, *Power System State Estimation: Theory and Implementation*, Marcel Dekker, Inc., 2004.