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Practical limits and future perspectives

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REVIEW

Power system coherency recognition and islanding: Practical limits and future perspectives

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Abstract

Electrical power systems are continuously upgrading into networks with a higher degree of automation capable of identifying and reacting to different events that may trigger undesirable situations. In power systems with decreasing inertia and damping levels, poorly damped oscillations with sustained or growing amplitudes following a disturbance may eventually lead to instability and provoke a major event such as a blackout. Additionally, with the increasing and considerable share of renewable power generation, unprecedented operational challenges shall be considered when proposing protection schemes against unstable electro-mechanical (e.g. ringdown) oscillations. In an emergency situation, islanding operations enable splitting a power network into separate smaller networks to prevent a total blackout. Due to such changes, identifying the underlying types of oscillatory coherency and the islanding protocols are necessary for a continuously updating process to be incorporated into the existing power system monitoring and control tasks. This paper examines the existing evaluation methods and the islanding protocols as well as proposes an updated operational guideline based on the latest data-analytic technologies.

1 | INTRODUCTION

The shifting energy landscape and the increasing electricity demand are driving fundamental changes in how power networks operate. However, increasing the renewable energy share, which results in a noticeable reduction of the system inertia and more variable power exchanges, is a complicated challenge for transmission system operators (TSOs) [1]. Although electric power systems are designed to be robust to withstand such contingencies, they are still susceptible, mainly when they are operated near their stability limits [2]. Such conditions cause the power networks to operate under high stress. Additionally, limited capabilities of supervision and diagnosis can compromise the partial or total integrity of the network, as evidenced by the numerous blackouts reported within the past decades, unleashing subsequent chain events [3–6]. Under such circumstances, it is logical to resort to the activation of protective measures to separate the power system

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into islands and preserve most of the system integrity. These islands will be self-sustainable in the best scenario. However, a considerable part of the network would still stop operating and affect thousands of users [7, 8].

Given that the island formation can provoke instability challenges, safety and power quality issues in the formed subnetworks underlying the fragile power response of the remaining synchronous generators may undergo voltage and frequency variations [9]. Then, it is essential to identify the generator's grouping to ensure the correct operation in the formed electric islands and evaluate the island's conditions for proposing further control actions that retain the reliable operation of the network as much as possible. Nonetheless, identifying and forming intentional islands is not an easy task in low-inertia systems, since the non-synchronous generation contributes neither to the rotational inertia nor effective primary frequency control to the electrical system [10]. Besides, time constants are on different scales than those of traditional synchronous generation, making the system weak and vulnerable to disturbances. Based on the dynamic information (in variables or data components) that allows featuring the system's dynamic behaviour, the identification of coherent groups is also key to evaluate the operating conditions of the island after a disturbance [11, 12] since the island formation analysis guides the electrical network's survival and restoration.

The first step is to detect the intentional or unintentional islanding condition. Here, the island detection methods, whether passive or active, can be utilised. [12, 13]. The second step is to determine the two possible scenarios: the presence of either large amounts of generation or large amounts of loads. This step leads to actions to disconnect (shed) either the loads or generation to maintain the generation-load balance and achieve the survival of the electrical island. After this, restoration techniques are needed to evaluate the re-connection of the island to the main network or other islands, raising the need for re-synchronisation evaluation. These tasks have to be evaluated step-by-step. Although individually, these can be seen as feasible tasks, the time and impact on the network users depend on them, and the major challenge is that they can have time-varying parameters [2]. In this context, several partitioning and controlled islanding methodologies have been proposed. For instance, in Ref. [14, 15], an islanding scheme system is proposed based on the non-linear Koopman mode analysis for obtaining the dynamics from voltage angles to identify the coherent groups and dividing the system into islands. In Ref. [16], the authors explore the critical time of island formation as a safety index for creating intentional islands. They use the concept of slow coherency of generators to determine the boundaries of the islands. They define the maximum time allowed to isolate the system into islands before a blackout takes place due to a critical contingency. Also, in Ref. [17], the authors locate the optimal firing lines once the coherent groups are calculated. Then, they complement it by analysing the balance between generation and load. This methodology obtains the optimal cutting sets employing topological requirement criteria and the load balance requirement. Finally, a grid restoration after a blackout protocol is proposed in Ref. [18], where a switching sequence development is proposed.

These contributions exhibit a consistent path of developing data-driven methods (DDMs) instead of model-based methods (MBMs) for coherency identification and islanding [19]. This new paradigm requires re-evaluating the procedures to achieve adequate generator recognition and envisioning new approaches for secure and operative islands. However, a few contributions have focussed on this aspect. Moreover, the standard definitions of short-term prediction (real-time) and long-term prediction (off-line) [20] require to be re-examined considering existing power system security and control advancements. Thus, this paper examines the existing coherency identification and islanding analysis and proposes protocols to achieve a realistic assessment. Additionally, it discusses the present and possible low-inertia scenarios involving coherent recognition and splitting networks.

The rest of the paper is organised as follows: Section 2 summarises the existing methods and proposes an updated coherency point-of-view analysis classification. Section 3 presents the operational challenges involved in an islanding protocol. In Section 4, the future considerations in systems with low inertia are analysed, and Section 5 presents a general discussion. Finally, Section 6 concludes the paper.

2 | COHERENCY IDENTIFICATION AND ISLANDING: ANALYSIS METHODS

This section discusses possible options to analyse coherency identification groups and island formation. Although both analyses have been extensively studied with multiple methods, they can generally be classified according to the general analysis and how they process information from the system.

2.1 | Motivation

Evaluating the coherence among generators allows defining the groups of generators that oscillate together or with relative values according to a tolerance when they are subjected to a disturbance. This coherency enables analysing the behaviour and grouping of the generators in the event of a disturbance and, based on this, taking control actions or general analysis of the network. The coherency phenomenon is presented when a set of generators form a coherent group when they behave at similar angular velocities given a tolerance over a specific time interval.

One of the most significant events in power systems history was the 1996 Western Systems Coordinating Council blackout (10 August 1996) [21]. In this event, a series of disturbances occurred that resulted in the division and formation of four electric islands, highlighted in Figure 1; this specifies the regions where the islands were formed: North (1), Northern California (2), Southern (3) and Alberta islands (4). Besides this event, other events have occurred in that same system [21, 22]. Also, other cases of widespread blackouts have been reported worldwide [23].

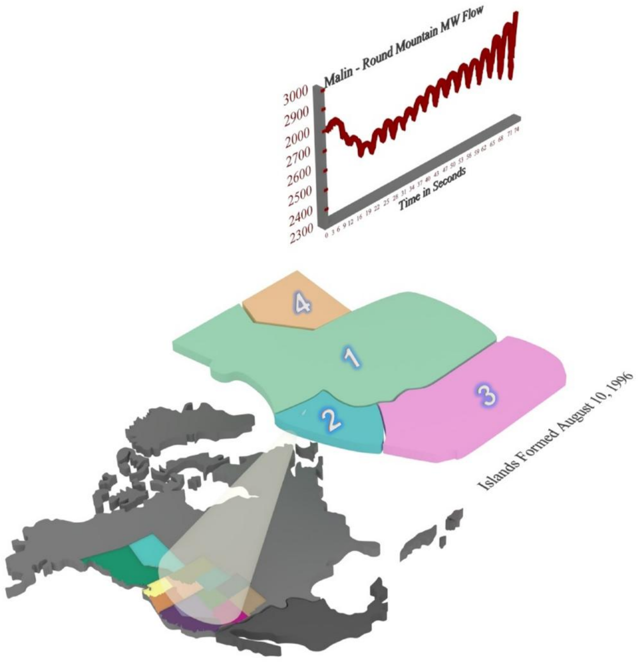

FIGURE 1 Western System Coordinating Council 1996 blackout

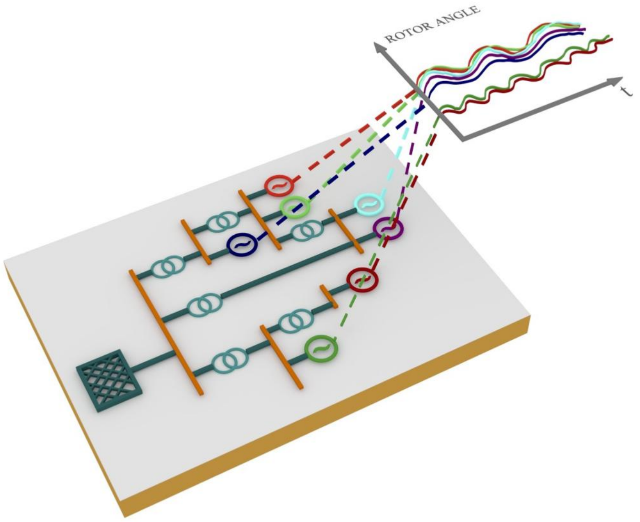

FIGURE 2 Coherent generators

2.2 | Slow coherency

Coherent analysis has been approached from various perspectives for network analysis, applying various methodologies. Slow coherency analysis is the most reported in the literature; it is typically performed offline and is used to find weak connections between groups. This method arises from the analysis of electrical systems. It is observed that groups of strongly connected machines are formed during a disturbance, presenting a similar dynamic concerning low-frequency inter-area modes [24].

The slow coherency analysis is focussed on the evaluation of the coherent properties of the system, independent of the perturbation, based on the theory of singular perturbations. It was developed primarily to build dynamic equivalents and coherent machines [25, 26].

When a disturbance takes place in the system, the electrical machines begin to oscillate naturally, responding to the changes present due to the disturbance and the state of the network. Later, each machine will oscillate according to a natural frequency, which can be slow or fast, as seen in the example in Figure 2. It is observed that certain machines oscillate at slower frequencies than the other ones, resulting in the formation of coherent groups. In this case, two groups are clearly seen to be formed.

As indicated in Ref. [25], this method analyses the slow angular oscillations present in the rotors of the generators, which are produced due to a strong interconnection of generators through a weak link, known as inter-area modes. Specifically, it is about determining the slowest oscillation modes of the system by calculating the eigenvalues associated with the generators [27]. Small eigenvalues indicate slow natural frequencies, translating to a mode between areas.

The concept of slow coherency starts from the analysis of m modes observed in the system response to a disturbance, where two machines i and j are deemed to be slowly coherent, that is, if the difference between their angles δ_i and δ_j responds to:

$$\delta_i(t) - \delta_j(t) = d_{ij}(t) \tag{1}$$

where d is a small value.

Consequently, this methodology can be applied to study the grouping of machines in a system with n areas, such that the angle difference d does not involve the n response's modes [28].

Figure 2 illustrates the visualisation of the difference in the generators' angles in a power network group. This difference in each group is slight, representing the grouping of the general network and the number of sub-areas that can be formed. Likewise, by averaging the modes of each area, we can reduce the system to an equivalent generator, representing the dynamics of the area in question, as seen in Figure 3. It is observed how from an n-machines system, we can obtain equivalents that help us synthesise the information and reduce it. In this specific case, a system of seven machines (according to the configuration) can be reduced to two equivalent machines and three equivalent impedances, where each machine represents the dynamics of each area. These dynamic equivalents have become an essential tool for studies in electrical power systems since they also reduce the system parameters that participate in the dynamic behaviour and consequently achieve a significant reduction in computational time and data processing costs with acceptable precision margins [29, 30].

2.3 | Model-based methods

One of the main challenges is the need to deal with a large amount of data related to stability studies of these highly interconnected and extensive electrical systems without considering each of the controls present in the electrical

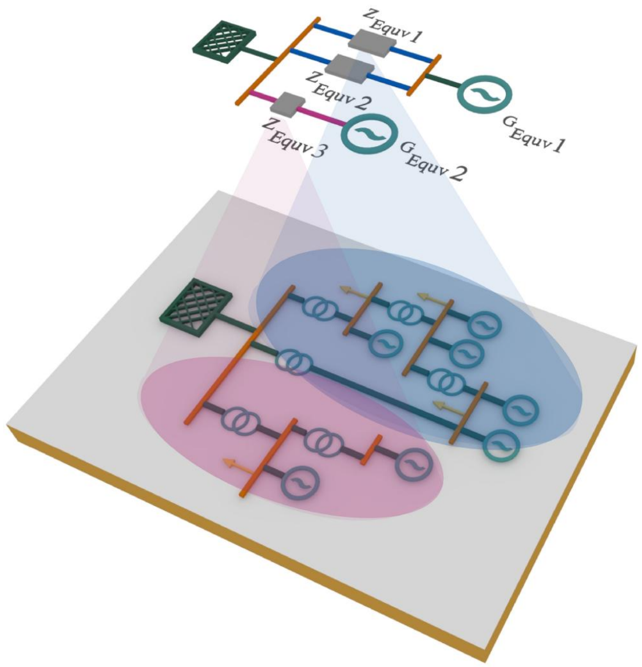

FIGURE 3 Network reduction representation

network. Due to this complexity, for stability studies and specifically electrical coherency, the typical analysis is based on simplified models of a reduced order of the network. A smaller number of algebraic-differential equations are used to represent the areas of the network. Therefore, the system will comprise one or more equivalent generators and an equivalent network (Figure 3).

The studies of coherent generators have their origins in the analysis of unwanted oscillations present in the power system operation. These electro-mechanical oscillations are primarily addressed by modal analysis of the system. *Generator coherency* is a mathematical tool used to analyse the stability of a small signal based on the analysis of the oscillatory modes of the system, obtained from a linearisation of the non-linear system model around an equilibrium point representing a stable operating condition. From the linearised model, the oscillation damping is analysed using the system's natural modes (eigenvalues) [31]. These swing modes can be classified into electro-mechanical modes and control modes. The electro-mechanical modes define the nature of the oscillation modes, meanwhile, the control modes are used to evaluate voltage stability. The study of these oscillations mostly starts from linearised electro-mechanical models. In coherency studies, using linearisation is valid for small disturbances since severe disturbances can result in an erroneous analysis.

Mode-shape and participation factors allow identifying the generators grouping that oscillate against each other in one specific mode and the state variable that contributes the most to the oscillation. Such a linearisation can be considered as a snapshot [32].

2.4 | Measurement-based methods

These methods are associated with time-series data-stream with coherency representative data, from (mostly simulated) synthetic data, or obtained from recorded actual data from a past event (not highly reported in the literature or high-security clearance needed).

An inner classification of these methods can be split into two categories as follows.

(1) Off-line Coherency Identification: Power systems are investigated to analyse their behaviour and, above all, ensure their stability when subjected to disturbances. Throughout such a study, essential system characteristics are observed. One such characteristic is that one or more generators tend to oscillate together as a group with a similar and close speed and phase angle; such generators are classified as coherent generators. For coherent generators to be defined, the angular difference among them must remain quasi-constant within a range for a considerable time. This definition is used to reduce the system model's size, since the coherent generators can be effectively represented by a single generator, reducing simulation time and computational effort when analysing power systems [25].

Another possible option is to analyse the entire data stream with an analytical data method and use it for further decomposition. With this option, a combination of classical detection methods and time-domain simulations to extract system's information can be considered. For example, in Ref. [33], modal analysis is applied to obtain the main characteristics of the dominant modes of the Mexican electrical system and time-domain simulations are used to analyse the characteristics and interaction of these modes. The time-domain analysis is carried out by using simulations and obtaining signals from the most critical points that are supposed to have phasor measurement units (PMU).

(2) On-line Coherency Identification: Power system coherency has been addressed from different perspectives; most of them are with analyses carried out offline. Since electrical power systems are dynamic systems, during real-time operation, network conditions change and can modify the dynamics of the generators and, therefore, the correlation among them. With the inclusion of PMU technology, modern wide area monitoring systems (WAMS) and the application of machine learning (ML), novel methodologies provide a power system online analysis, especially in matters related to the monitoring and control of the network. That is why PMUs can be used to develop methodologies capable of determining changes in the composition of the generator sets of the system. Within these methodologies, we find the methods based on measurements. These methods use sliding windows and apply signal processing techniques (e.g. Prony, matrix pencil, principal component analysis (PCA), among others)

to provide an overview of the oscillatory modes of the system and thereby perform a grouping [10, 34].

On the other hand, since the size of power systems and the large amount of data associated, data mining-based techniques have been proposed for online evaluation. Such techniques aim to synthesise the information and detect relationships that provide patterns among variables and can be used for grouping the generators. Furthermore, developing sliding-window methods that split the time series into more suitable or realistic frames that emulate the TSO visualisation action provides enough information for the TSOs to understand the system dynamics. By this analysis, the information is obtained during a window span, which is updated regularly, allowing real-time representations of the network [35].

The difference between the offline and online consistency methods can be observed in Figure 4, where the offline methods in the top plot can provide an analysis over the entire disturbance, either once it has occurred or through a simulation using models. This analysis provides an overview of the system's behaviour that will depend on the analysis time and the models used. The longer the analysis time and the more complex the models are, the more accurate the results will be, and additional effort and computational time will be required. These results will help to control and propose protection actions against certain everyday events or for the tuning and adjustment of system controls. Likewise, the bottom plot shows how the online analysis works, where the system's dynamics can be captured through small time windows and take control and protection actions during disturbances, performing a real-time execution.

Following a parallel path to the already stated methods, multivariate statistical methods for coherency identification has been applied directly to process time-series or features. Principal component analysis use an orthogonal transformation [36] meanwhile singular value decomposition (SVD) use a matrix decomposition procedure [37]. Both methods find linear correlations between variables of the dataset to visualise the coherency groups using their spatial features. In both methods (PCA and SVD), coherency identification is not straightforward; therefore, a clustering algorithm is used in a complementary way to find the optimal number of groups. In this regard, the independent component analysis (ICA) allows to go farther because of process non-Gaussian and noise multivariate signal. The extraction of the dominant narrow-band peaks from the power spectra of the signal using the spectral ICA allows to identify the coherent groups in a single step; the robust procedure is described in Ref. [38].

With advanced methods, based on concepts, the infinite-dimensional information can be captured using Koopman Mode Decomposition [39] and its reduced approach, Dynamic Mode Decomposition [40]. Koopman operator modes (an extension of the mode linear oscillators) are obtained by these approaches. These modes provide information on system dynamics in terms of frequency and are used to identify oscillations and coherent groups of machines and determination of system stability margins. Recently, under this same type of study, a new method was presented based on the modification of the Koopman modal decomposition [41]. In addition, a sliding window was added, representing the online operation from the TSO viewpoint, demonstrating that this methodology could be used to analyse data in real-time. Moreover, the Koopman operator, in combination with other methodologies, has recently been used to enhance the stability of power networks [42], with a predictive controller of the Koopman model for the control of a power system stabiliser (PSS). This design ultimately excludes the equations that modelled the system since its main advantage is that they are based on the analysis of data obtained from system measurements. Furthermore, this data-based PSS control exhibits the advantage to damp out electro-mechanical oscillations and, therefore, the transient stability of the electrical network is improved.

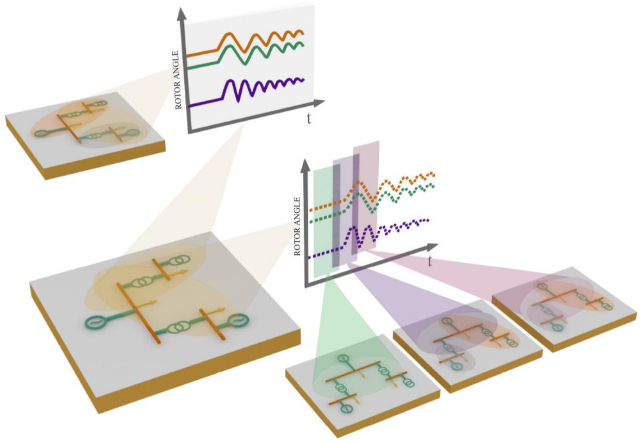

FIGURE 4 Offline versus online coherent analysis

Likewise, learning machines have proposed other methodologies, applying self-organisation maps to identify coherent groups in the electrical power systems [43]. Due to the ability to identify the grouping of generators, these described techniques aim to determine the best formation of intentional islands. Online unsupervised data mining techniques, such as SVD and K-means, have also been applied to coherent group identification focussing on the frequency measurements for clustering slopes in Ref. [44] from the ENTSO-E dynamic models. A robust measurement noise and low computing approach is proposed in Ref. [28]. The model-free approach is based on largest Lyapunov exponent (LLE) method, which establishes the mathematical relationship between the LLE and the angular velocity difference to design an online generator coherency identification (CGI) scheme for power systems.

2.5 | Forecast coherency identification

With the recent advancements in ML and deep learning methods, a much anticipated next step for both coherency recognition and islanding protocols is the possibility of forecasting future time-series steps in combination with clustering. However, the computational cost of this strategy is still high.

AI monitoring, optimisation and control technologies will help to foresee instability situations that a human operator might not be able to accomplish in time [45]. An example of this concept has been developed in Ref. [46], where a data-fusion-based self-correction algorithm aids in identifying load shedding areas and predicting intervals of the projected blackout magnitude. This strategy allows an operator or automatic controller to respond more effectively to the cascading failure situation. Wide area blackouts can be prevented using sophisticated state estimation and angle prediction algorithms that use data collected by PMUs as a precursor of instability mitigation and protection schemes [47, 48]. Additionally, wind speed forecast has been incorporated in the system survivability network splitting in Ref. [49] to model storm-related cascading failures accurately [50].

2.6 | Real-time coherency identification

Recent advances in hardware-in-the-loop (HIL) technologies have opened up the possibility of creating scalable test systems that guarantee complete test coverage. This technology produces the closest approximation to a real-time simulation time and the most effective approach to evaluate large power systems by testing protection and controlling devices. An example of coherency identification and power systems reduction in HIL is given in Ref. [51]. It is known that events related to widespread blackouts of electrical power systems can be of different nature, which may (or may not) be contemplated. Some of these that are contemplated have an action protocol; however, some scenarios are not considered. These are tested in minimal models without considering the actual dynamics of the event. Due to this, HIL has become a handy tool for analysing electrical systems, specifically for events where the actual dynamics can give different results, either to generate reaction protocols or for network control aspects.

2.7 | On-line and real-time partitioning

To maintain safe operating conditions and to be able to quickly and effectively react to contingencies originating from transient instabilities, TSOs continuously monitor power systems. Typically, operational management samples real- and near real-time data on power flows at critical locations. Results are incorporated into network simulations to update power system dynamic security assessments and compare actual operating circumstances to critical technological restrictions [52]. Up-to-date, system operators have employed a variety of technical or operating reserves and services, re-dispatch, and load shedding to manage the security of the power system. In addition, the specific products or support services offered to assist in managing system security are often described in terms of how they work and how long it takes to implement them.

Frequency control, network management, and the provision of black start services—those services restored after a blackout—are essential activities [53]. Furthermore, as a defence mechanism when cascading events take place in the system that may compromise system operation, Ref. [54] proposes a methodology based on tree partitioning. It intends to perform the least number of line cuts and the formation of the least number of division groups of the system through spectral grouping to divide the electrical system through the formation of connected tree groups. Recently, in Ref. [2], the transient stability is analysed as a function of the transfer impedance between the coherent generators once the island operation has been determined. It is observed that with this relationship variable when the system is in island mode, the transient stability can be improved as long as this impedance is moving in the right direction. Finally, as a security measure to separate a failure area of the power system and protect the primary sub-network of the power system, a remedial action scheme is proposed in Ref. [55], including load shedding schemes.

Controlled islanding acts as the last resource mechanism to prevent blackouts. One possible strategy proposed in Ref. [56] uses local generator out-of-step protection and generator coherency using fault location through status flags embedded into the protection relays. Similarly, in Ref. [57], the spectral clustering analysis is applied to form intentional islands aiming to achieve the minimum interruption of the power flow in the network. This methodology is hinged on the generators' coherent grouping, which can be implemented as a real-time prevention method to prevent system degradation when cascading events take place.

Some proposals for separating the system contemplate conventional generation. However, in the electrical system, there is rapid growth and interconnection of renewable energy sources, which influence and modify the system parameters. For this reason, a realistic analysis must consider systems with high penetration of renewable sources. In this regard, Ref. [58] combines the fuzzy *C*-means (FCM) clustering methodology and tunable robust optimisation programing (OCI-AROP). The FCM method identifies the coherent generators; in this case, it is used with frequency data obtained from PMUs. The OCI-ARIOP is responsible for keeping all the restrictions related to coherent groups, connectivity restrictions and robustness restrictions concerning renewable energy sources. With the combination of these two methodologies, the load pull in the system is minimised, considering conventional generation and renewable sources. Other optimisation strategies as in Ref. [59], where a noise robust multiflock-based technique is used to rapidly identify coherency within a short observation window, are proposed. Meanwhile in Ref. [60], a coherency measure matrix is formulated using the generator rotor measurements to cluster the coherent generators. This approach is validated in terms of indicator and statistical measurements.

2.8 | Island detection

In previous sections, we have discussed the methods for grouping generators and splitting the system into islands when cascading events occur that can compromise the operation of the network. Within these cascading events is the intentional formation of islands; for this specific aspect, crucial techniques have also been developed to detect the formation of these islands in time. Local techniques, whether active, passive or hybrid, are about monitoring specific parameters of the network at the common connection point, where island separation can occur. In contrast, remote techniques are based on the communication of the electrical network elements, especially at the points susceptible to the formation of islands [61]. With the development of neural networks, we also find in the literature methods that use Recurrent Neural Networks or adaptive techniques for the early detection of islands.

As stated in previous sections, we can find both model and measurement-based techniques that can perform online or offline islanding detection. For example, in Ref. [62], the authors propose a non-linear adaptive linear approach based on the moving-window kernel PCA of voltage-angle signals. The PCA Kernel was also combined with affinity propagation to find correlations among multiple indexes using an AP-based clustering algorithm and Prony to identify the coherent groups and low-frequency modes [63]. The method detects the formation of electrical islands in the system, benefiting from a real-time implementation. More recent methodologies, such as Ref. [12], implement the analysis of the participation factors for detecting islands by using measurements of the phasor angle obtained from PMUs—a methodology that, in addition to detecting the island, presents information on the formed groups and their elements.

In general, unintended islands are constantly exposed to unsustainability caused by insufficient generation capacities to supply local loads, overloading of components and other phenomena derived from the initial disturbances that caused them. Control actions are also needed to mitigate power outages and network interruptions. These challenges lead to evaluating the islanding detection accuracy and timing in the methodologies proposed in the literature, notably when there is distributed generation (DG) in the system. The IEEE 1547 standard stipulates a maximum delay of two seconds for detecting an unintentional island [64]. Further, according to the IEEE 929 standard, the DG must be disconnected as soon as it is islanded [65]. Therefore, the detection time of the island plays a critical role since it will determine the reaction time of the system and its controls, as well as the amount of damage that the system will suffer, which will be essential for the restoration.

Underfrequency Load Shedding (UFLS) schemes, as part of the last resources of the islanding process, require adaptable and balanceable mechanisms that help the subnetworks for maintaining the frequency at the nominal level [66]. Counting with enough information at the frequency nadir in an early stage after a disturbance will enable the UFLS quicker [67]. Mapping the nadir response and forecasting its behaviour through ML models is a potential capability that can be added to the islanding sequence. Power grid cascading failures are mainly characterised by loading levels, load-shedding constraints, and line-tripping thresholds [68]. Thanks to the sensitivity of the blackout size distribution that is provided by those features, there are operational margins that may be exploited to protect power systems by lowering the chance of large blackouts. The cascade outage analysis can be split into four checkers: transient stability, frequency outage, line outage, and the voltage outage [69]. Such analysis contemplates the accurate modelling and activation of the corresponding relays employed in the network.

The repair or reconnecting of islands becomes difficult as the number of needed islands increases. Then, effective algorithms need to be devised to identify coherency using PMU data. The configuration of coherent generators relies on the system characteristics [70]. Most of the proposed methods that consider the use of PMU employ measurements of voltage angles. However, this approach is limited: if these angles do not coincide or are not synchronised with the rest of the system, or if there is a discontinuity in data reception, it can give a wrong reading or false operation of the protocols. In addition, many of them lack robustness because the sensitivity of the noise present in the signals.

All the above-mentioned approaches possess advantages and disadvantages, but combining them can give adequate results. However, these combinations of methods may also give erroneous results. For example, in Ref. [71], some topological methods are analysed, such as the case of graph theory, which according to the literature, is famous for forming electric islands. This analysis shows that if this type of topological methodology is applied in isolation from the physical models of the system, erroneous analyses can be obtained. Therefore, it is recommended to have backup methodologies that can corroborate what is obtained through the topological approaches.

3 | OPERATIONAL CHALLENGES AND PROPOSED ISLANDING PROTOCOL

When a power system is subjected to a significant disturbance, control actions must be taken to minimise the impact of the disturbance. Unfortunately, these corrective control actions are mostly passive under frequency load-shedding devices that operate utilising pre-established settings, leaving the system vulnerable to cascading events and outages. Islanding is usually the last line of defence against disastrous cascading events [72]. In the last decade, the literature has focussed on answering two critical aspects regarding islanding in a power system: *where* and *when* to island. Also, the emphasis is on *where* rather than *when*. The approach for identifying suitable islands consists of two stages:

1. Defining groups of generators that swing together, and
2. Splitting the power system into islands containing groups of generators that swing together and satisfy some other criteria, for example, generation-load power balance or lines.

These two stages are executed sequentially.

The former stage identifies coherent groups of generators based on the dynamic characteristics of the synchronous machines but it does not determine if these groups of generators will be stable. As noted in previous sections, slow coherency is the traditional method used for finding coherent groups; it is typically performed off-line and is also used for finding weak connections among groups.

The latter stage determines the island boundaries, and various methods have achieved this, among them graph theory stands out. Different criteria are employed to find the island partitions requiring the minimum post-islanding load shedding. Some investigations have attempted to include constraints that reflect the dynamic behaviour during the post-islanding process; however, these are still far to reach maturity. Solving graph partitioning problems implies high computational burdens. Although graph simplification is applied to reduce the computational burden, this also narrows the solution search space. Several considerations are not acknowledged in current approaches:

- Implications of the disturbance type/size on the oscillation modes: Slow coherency theory does not consider the type or size of the disturbance even though they affect the generator's grouping, for example, the tripping of a transmission line changes the network's topology and, therefore, the weak connections among groups, and the system's coherency.
- The actual state of the disturbed network at the moment of island creation: The islanding procedure is not instantaneous, so the system's electro-mechanical variables, loading and topology may undergo changes since the initial state was determined. Graph partitioning methods do not attempt to reflect these state changes in their solutions. Instead, they operate taking into consideration a single snapshot of the system state.

Islanding formation is a complex process that implies many aspects such as the characteristics of the electrical system, the state of operation, and the type of contingency. These aspects are decisive for the formation of islands, since they will determine the islands' successful formation and their restoration. From start to finish, the process is globally represented in Figures 5–8, where four fundamental stages can be observed. Each one plays an essential role in adequately functioning the electrical system during the islanding formation process.

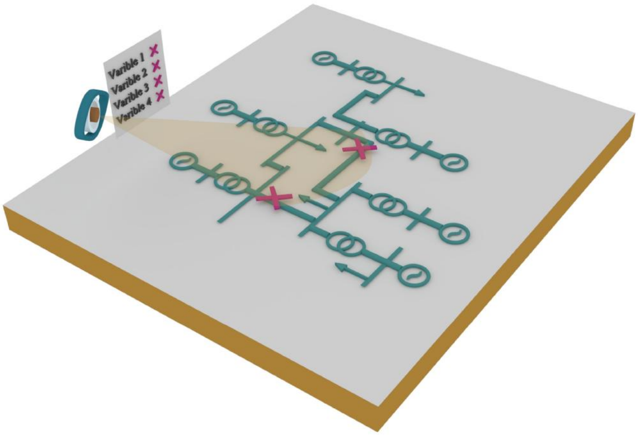

FIGURE 5 Stage I: Identification of the event

(a) Stage I: The first stage is depicted in Figure 5. It corresponds to the confirmation or determination of the system's collapse, which will depend on its conditions, that is, the current state when the contingencies take place. In this image, the eye represents the network's surveillance and its variables to monitor the specific point, that is, where is the event or events (denoted as cross-outs in the image). This point is critical since the faster the system's collapse is detected, the faster control actions can be taken for the island formation, which in turn will depend on the contingencies' sequence. Its determination is achieved by analysing the system, the variables, and power flows through the network. This stage allows the identification of the type of collapse of the network, which can be voltage, frequency or angular collapse—even one of these can give way to another. Besides, within this point and with system analyses, the key idea is to identify the elements causing the collapse to isolate them and move on to stage two. The main objective of this stage is to ensure, as much as possible, service continuity and, if possible, to prevent islanding. Within this stage, we can also find the formation of unintentional islands, which can form in any system and are considered in the second stage.

(b) Stage II: After identifying either the collapse of the network or the formation of unintentional islands, the best network partition configuration is examined to safeguard the most significant part of the system, as displayed in Figure 6, where it evidences how the original system in Figure 5 is split into two islands and the problem is recognised. At this stage, it is decided which lines will be tripped to assemble the grouping and island formation to ensure the secure operation of the system. The objective is to form the minimum number of islands and disconnect the least number of lines and elements possible. This aims to fulfil the methods described above, either before the collapse or with real-time analysis to find the best configuration. At this stage, even part of the system can be shed to safeguard the more significant part. The electrical islands are formed in this stage to find a balance between generation and load.

    This stage is crucial, since it is not only dealt with splitting the system for the sake of dividing, but it is about creating islands, that is, this stage tries to guarantee that most of the islands can survive and preserve the service continuity. Even though the possibility that not all the islands survive is something that must also be considered in island formation planning that is why it is said that the formation of islands is critical. Moreover, an island solution must be found in a short time to prevent system's degradation in general. An indispensable aspect of the transition process towards island mode is the knowledge of system's

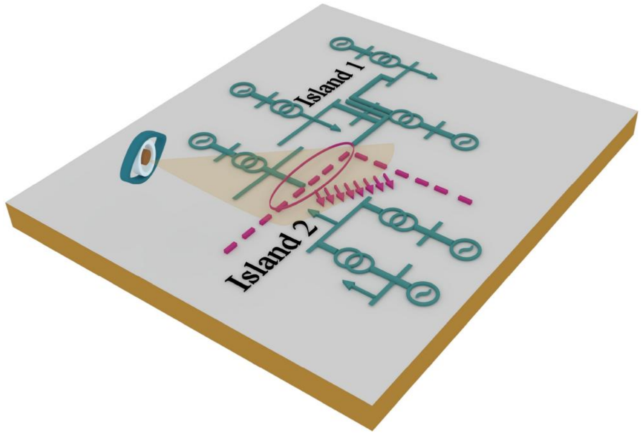

FIGURE 6 Stage II: Islanding cut-sets

operating conditions before the island is formed to have control of these situations and therefore facilitate this transition. During this process, there must be a grouping planning of generators and loads based on the pre-island conditions, even more so when there is DG since these have to participate in this planning to support the voltage and frequency control of the network or shutdown and blackout if needed for post-island control.

(c) Stage III: Once the best configuration of the islands is found, each island is analysed verifying its correct operation, corresponding to the third stage (see Figure 3).

As soon as the island condition is detected or activated, control actions must be carried out to control the stability of the island and its correct operation. Thus, Figure 3 represents the analysis and observation of the main electrical network and the islands formed, examining the variations in the variables such as the phase angle and magnitude of voltages, as well as the active and reactive power. The balance or imbalance between generation and load, a product of the separation into islands, is represented by means of the balance. Unbalances between generation and load occur when island formation occurs, whether voluntary or involuntary. Therefore, in this stage, the first action that is analysed is the balance between generation and load; if this is not met, it is a matter of ensuring it by regulating generation or load shedding. Techniques such as Automatic Load Tripping (ALT), Load Rejection by Frequency (LRF) and Automatic Generation Tripping (AGT) are applied according to the system's operating conditions and mainly the island's condition. At this stage, it is about achieving island's stability regardless synchronisation with other islands. Here all available tools are employed to achieve it.

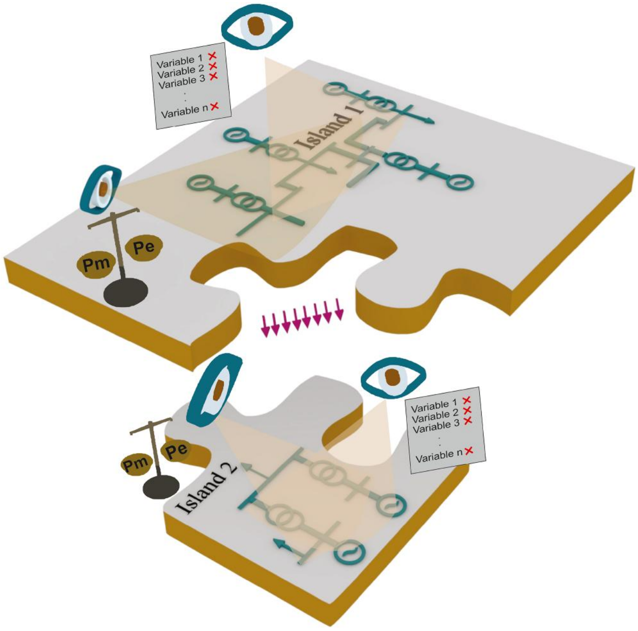

FIGURE 7 Stage III: Island monitoring and control

On the other hand, when the system is operating in island mode, and even more so if there is DG penetration, it must be capable of actively regulating voltage and frequency to maintain the established parameters. To this end, there must be an adequate reserve margin, which will depend on the operating conditions in terms of demand. For this, it must have techniques capable of monitoring the load, that is, a scheme that automatically adjusts the generation power with the demand. These schemes become essential when you have DG sources since you need to provide a dynamic response from the DGs to work in parallel. With regard to frequency control, generators must have this type of control and have a power margin available to absorb any surplus of load or generation that may occur on the island. In general, synchronous machines are the ones that absorb these variations; however, when there is a non-conventional generation, they must have some strategies to support control frequency and must be combined with load shedding schemes.

Another important aspect is the protections' coordination. Usually, when an island condition happens, it is because an event occurred and activated the protection, provoking the formation of islands, whether intentional or not. However, when the system already has the island operation, the coordination of protection devices must be maintained to safeguard the integrity of the network. This is where the part of having dynamic or adaptable protections also becomes crucial. Islanding operation requires readjustment of the protection devices or setting schemes that switch when there are island conditions. Specifically, when operating in island mode, there must be sufficient monitoring and control to understand and operate in this mode. Just as there are DG sources, their operation must be managed and coordinated with the rest of the system to help the proper functioning of the island.

(d) Stage IV: Once the correct functioning of the islands is achieved, the process of restoration or interconnection is analysed. This stage is represented in Figure 8, where it is observed that the island formed requires reconnection to the system for restoring the original system, implying a

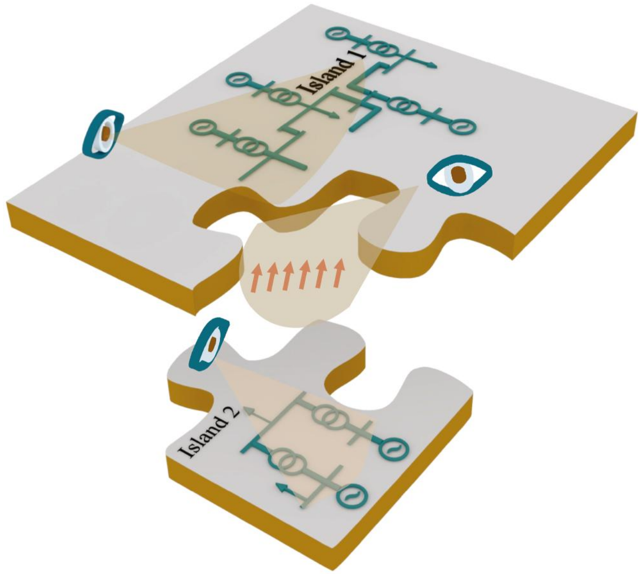

FIGURE 8 Stage IV: Island reconnection and restoration of the main network

parallel analysis of the island and the main network. For this, it is necessary to examine the synchronism between the islands, reconnect island by island, and analyse the correct function and balance between generation and load. Additionally, a black start is required in islands that could not be maintained or in generators and loads that were disconnected to maintain the islands' operation. This stage depends a lot on *Stage II* since the fewer islands and disconnected machines, the fewer operations are performed, and the faster and easier the reconnection will be.

During the previous stage, the correct operation of the islands was ensured. However, in this stage, machines belonging to each island are in synchronism, but nothing ensures that they are also in synchronism with the machines in other islands. This part can be seen in Figure 9, where three islands represented by an equivalent machine are observed; each island rotates at a different speed, maintaining the island's stability. For the reconnection of the islands, a resynchronisation process is advocated. First, in the image represented by a switch, it is necessary to wait for each island to be synchronised (Position 0). Then, the reconnection process is carried out when the islands turn at the same speed and synchronisation conditions are fulfiled. In the image, this is represented by the closing of switches (Position 1), where all the islands rotate synchronously to restore the main network, monitoring all the network parameters and ensuring load balancing and generation. In general, a strategy must be established to deliberately stagger the reconnection of the islands to the main system, which will depend on the number of islands and the general balance of generation and load. When islands possess DG, monitoring the variables should indicate the appropriate conditions to resynchronise the island with the main network. Specifically, the voltage, frequency, and phase sequence between the island and the primary system must be within the acceptable limits described in the IEEE Std 1547–2003 standard to allow reconnection.

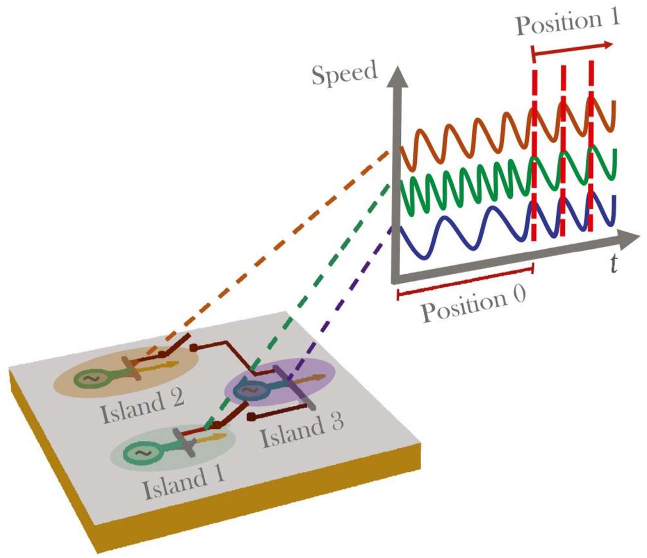

FIGURE 9 Switching control for reconnection of islands

4 | FUTURE CONSIDERATIONS OF LOW-INERTIA POWER SYSTEMS

The current large deployment of aggregated inverter-based resources (IBR) is considerably reducing the inertia in the system, making it less resilient to unexpected events that are consistently being increased, presenting a challenge for reacting-time decisions on the planning and the TSO operation [73]. Furthermore, with the inertia shrinking, blackout risk with high penetration increases [74]. Thus, innovative mechanisms that help to improve the damping control in the power grid are necessary. One possible mechanism arising with the grid-forming control technologies is the supplementary control added to the doubly fed induction generators [75, 76], coordinated with the PSS spread through the system [77]. Another short-coming technology being deployed is the battery energy storage systems, which with the WAMS, could provide a wide-area damping control [78]. Similarly, supplementary controllers, such as the power oscillation damper, can also enhance the reaction to the undesired low-frequency oscillations with the High Voltage Direct Current networks embedded in the AC networks [79, 80]. Figure 10 represents the technologies mentioned above involved in low-frequency oscillation improvement.

The impact of the low-inertia on the power systems coherency has been analysed lately. Coherency scenarios, including an inertia reduction, have been contemplated in Ref. [10], where the separation in the groups' conformation is evident when more non-synchronous generation is included. Subsequent analyses and contributions have found similar results on how the coherency groups change under high

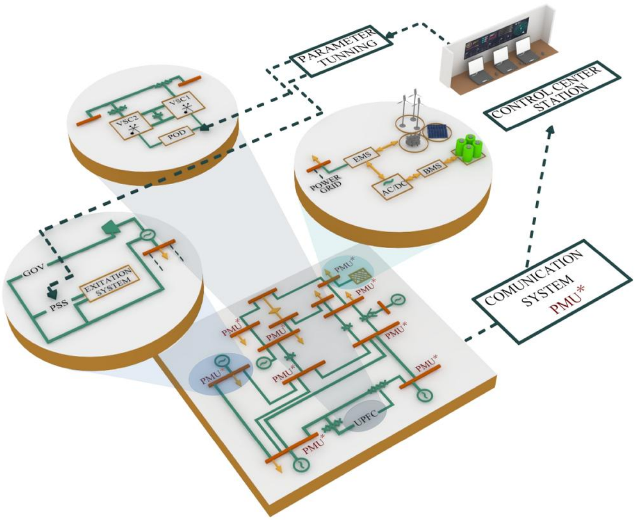

FIGURE 10 Representation of available technologies for damping control

penetration of non-synchronous generation [81, 82]. Coherent group patterns change associated with varying distribution and intermittencies in renewables [83]. An advantage of DDM methods is the independence of system structural and operating condition variations. Measurement- and model-based coherency identification techniques are combined to maximise mutual complementarity [84]. An environment of 100% grid-forming droop-controlled networks has been considered in the coherency analysis as well in Ref. [85], through the Generalised Eigenvalue Perturbation technique, for the feeder-aggregation of the inverters. Australia, an IBR operational integration system leader, is facing several challenges such as the potentially adverse interactions between IBRs provoking low-frequency oscillations [86]. Australia is now requiring to revise extensively the control tuning to mitigate these phenomena. Spatial variation in the Inertial Frequency Response (IFR), due to the non-homogeneity caused by the large deployment of IBR, requires adequate allocation of PMUs for IFR estimation [87]. Methods for identifying systems based on data are becoming more and more crucial, especially for systems for which physical models are difficult to come by such as IBRs [88]. Thanks to developments in power electronics, we now have better experimental gear than in the past century. The improvements in operations research, system identification, and ML have also led to improved computing tools. Restoration schemes after a blackout are also of consideration when having incorporated renewables [89]. Optimal black-start resource allocation with a vast deployment of non-synchronous generation means starting isolated power plants separately and progressively re-connecting them to one another to build an integrated system once more [90]. It is employed when a blackout necessitates a complete restart of the grid. Black start is therefore a key component of system operators' preparations for system restoration and recovery and is essential for preserving the electric power system's dependability and resilience.

5 | DISCUSSION

The latest events in power systems during 2019–2022 have taught us that power systems are still vulnerable to weather and power-related disturbances and human-caused events. During the latest political conflict between Ukraine and Russia, it has been evidenced that with the right protocols and precautions, Ukraine's power system could be disconnected, operate on its own, re-distribute power to neighbouring countries, and be reconnected to other systems in a stable and timely manner [91].

Cyberattacks are another human-caused extreme events that can provoke a cascade event involving uncontrolled islanding [92]. Since modern power systems have evolved into sophisticated cyber-physical systems, novel methods are required to isolate and protect the system. Cyberattacks using malicious injections in power networks can produce corrupted, sparse oscillation data that can trigger erroneous damping and modal frequencies. For protection from such eventualities requires robust algorithms that can detect, correct or recover from corrupted PMU signals [93]. A proposal for recovering clean signals from corrupted synchrophasor measurements is presented in Ref. [94]. It uses robust PCA to detect and differentiate event-induced outliers from spurious ones in data.

Recent electricity outages in Texas and California, caused by extreme weather, have also reminded us about the difficult circumstances and events that can affect large power systems. Not only regarding how to operate them accordingly [95] but, more importantly, warned us about the risks of operating a power system without the inertia necessary to maintain stability [96]. However, the existing deployment of IBR generation alleviates the high demand during the summer seasons. Furthermore, it helps to prevent grid collapses with the more advanced grid-forming controllers capable of reacting in parallel to conventional generation, bringing a headroom in case of a risky event [97]. Moreover, many large-scale grid components can be taken out of service over a short time when scenarios such as earthquakes are considered [98]. This approach uses transient electromechanical simulations that remove components affected by a regional hazard with stochastic scenarios as inputs. More methodologies involving geographic data in the WAMS are needed for improving the event location accuracy and proposing immediate remedial actions [99].

In most electrical systems, the TSO is already aware of the main points or weak elements of the system where an event, or more events, that could put the electrical network at risk is more likely to occur, mostly based on history of events that have taken place. Given this, protection and defence schemes are proposed based on this history of events; however, due to the growth of the network itself, climate change and new technologies, new events occur or may occur that were not contemplated. Such events can be due to natural, operational or human error causes and given this, the need arises to consider and design a new response scheme. The latter is an aspect that traditional schemes for forming islands do not contain. That is, the dynamic origin of island formation is not considered. Within all this, the adaptability of the protection schemes must be considered when operating on an island, since they play an essential role. When operating on an island, all the elements of the island must be protected in the first place to safeguard the operational ability of the network and second because it is not exempt from the occurrence of an event or a failure within the island. The importance lies in the fact that there must be a reconfiguration or adaptability of the scheme due to most are adjusted to operate when the entire network is connected. When operating in island mode, there are new conditions that lead to new protection settings. Besides when the island is reconnected, the operating conditions may vary, or initially, the settings are different as a result of the staggered interconnection of the islands.

6 | CONCLUSION

This paper has examined the existing coherency and islanding methods and has applied the latest advancements to formulate an adequate protocol for islanding operations. This protocol is envisioned to guarantee the secure operation of island formation in power systems after large disturbances take place. To achieve this, it comprises four consistent stages articulated symbiotically to attain from the event identification up to the complete system restoration. Its successful implementation by TSOs can improve the service continuity since it can reduce the restoration time, preventing long power outages.

This investigation also has provided an overview of possible options that future power systems might experiment under large-scale penetration of non-synchronous generation. Finally, it is noted that the next generation of transmission networks will require further development of data-driven and ML methods to be incorporated within the wide-area monitoring systems.

Data-driven methods for power systems dynamics are helpful to quantify predictability and extracting spatio-temporal patterns from collected datasets obtained from the grid monitoring or numerical simulations. Combining ML models with knowledge from strong mathematical frameworks is undoubtedly helping to understand the operating dynamics and propose more secure and robust power systems. Thus, both DDM and MBM are complementary and necessary for analysing the coherent identification and islanding power networks. Moreover, the existing advancements show that the effective combination of both grouping methods is important from both practical and theoretical standpoints.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

DATA AVAILABILITY STATEMENT

No data involved in this article.

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