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# Fault Detection and Protection Schemes for Distributed Generation Integrated to Distribution Network: Challenges and Suggestions

**YOUNIS M. NSAIF[1], M. S. HOSSAIN LIPU[1,2], AFIDA AYOB[1,2], YUSHAIZAD YUSOF[1], AND AINI HUSSAIN[1]**

[1]Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia
[2]Centre for Automotive Research (CAR), Universiti Kebangsaan Malaysia, Bangi 43600, Selangor, Malaysia

Corresponding author: M. S. Hossain Lipu (lipu@ukm.edu.my)

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**ABSTRACT** The use of distributed generation has received wide attention due to low maintenance costs, reduced transmission line losses and network congestion, as well as minimal impact on climate change and global warming. However, the distributed generation integrated to the distribution network introduces various protection problems that cannot be solved by conventional protection systems. These obstacles include the bi-directional power flow and the variation in the fault current level during the topology change. Thus, appropriate fault detection and protection scheme are strongly recommended to increase safety and reliability of the distributed network. This paper presents a comprehensive overview of the distributed network fault detection and protection strategies incorporated with distributed generation. This review also investigates the various fault detection approaches concerning types, communication methods, operation mode, constraints and benefits. Additionally, numerous island detection techniques are explored, focusing on generation types, parameters, cost and advantages. Moreover, the review outlines the various protection schemes highlighting categories, operation, constraints, strength and shortcomings. The key issues and challenges are discussed along with selective proposals for future research. All the highlighted viewpoints of this research will hopefully be beneficial to power system engineers and researchers for the advancement of distributed network fault and protection strategies for suitable operation and management of future distributed generation systems.

**INDEX TERMS** Distributed network, distributed generation, fault detection, island detection, protection scheme, protection coordination, protection strategy.

## NOMENCLATURE

| | |
|---|---|
| ARU | - Auto reclosing unit. |
| CMs | - Communication-based Methods. |
| CPR | - Central Protection Regulator. |
| CTI | - Coordination Time Interval. |
| CTs | - Current Transformers. |
| DBN | - Deep Belief Network. |
| DC | - Direct current. |
| DG | - Distributed Generation. |
| DN | - Distributed Network. |
| DOCR | - Directional Over-Current Relaying. |
| DSST | - Distributed Solid-State Transformer. |
| ELM | - Extreme Learning Machine. |
| FCL | - Fault-Current Limiter. |
| FIS | - Fuzzy Inference System. |
| FRT | - Fault Ride Through. |
| GA | - Genetic Algorithm. |
| HHT | - Hilbert-Huang Transform. |
| HIF | - High Impedance Fault. |
| HIFDS | - High Impedance Fault Detection Signal. |
| HT | - Hilbert transform. |
| IIDGs | - Inverter interfaced distributed generations. |
| ISM | - Island Mode. |
| LC | - Local Control. |
| LIF | - Low Impedance Fault. |
| LMs | - Local Methods. |

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| | |
|---|---|
| LP | - Linear Programming. |
| NBC | - Naive Bayes Classifier. |
| NCM | - Network-Connected Mode. |
| NDZ | - Non-Detection Zone. |
| OCR | - Over Current Relay. |
| PCC | - Point of Common Coupling. |
| PMU | - Phasor Measurement Unit. |
| PSO | - Particle Swarm Optimization. |
| PV | - Photovoltaic. |
| RA | - Relay Agent. |
| RMS | - Root Mean Square. |
| ROCOF | - Rate of Change of Frequency. |
| ROCOP | - Rate of Change of Power. |
| ROCOV | - Rate of Change of Voltage. |
| SDG | - Synchronous Distributed Generation. |
| SFDC | - Solid Fault Detection Signal. |
| SNOP | - Soft Normally Open Point. |
| SSST | - Sub-Station Solid-State Transformer. |
| SST | - Solid-State Transformer. |
| SVM | - Support Vector Machine. |
| THD | - Total Harmonic Distortion. |
| TIV | - Transient Index Value. |
| TMS | - Time Multiplier Setting. |
| TT-transform | - Time to Time transform. |
| VTs | - Voltage Transformers. |
| WTT | - Wavelet Transformation Technique. |

## I. INTRODUCTION

Nowadays, the incorporation of distributed generation (DG) in a distributed network (DN) has increased dramatically due to numerous benefits, including adjacent installation to the load, cost-effectiveness, reduction in transmission line losses, transmission and distribution of network congestion and minimisation of the influence of the network on global warming and other types of emissions [1]–[3]. However, the integration of DGs into the DN results in various protection problems that can affect the existing protection relay efficiency [4]. Once any fault takes place in the DN, DG will produce a fault current in the DN on the basis of a generator type, size, position and network structure [5]. Hence, this fault current can lead to relay malfunction.

One of the biggest challenges in DN is the identification of the faults and the detection strategies. Given the dynamic behaviour of DNs, current directions and magnitude changes lead to significant problems in the fault detection process. Moreover, the inverter interfaced distributed generations (IIDGs) are sensitive to DN voltage disturbances, such as switching devices in inverters that can directly influence high current strains during a voltage drop. In the DN of the industrial systems, approximately 92% of all defects occurs due to voltage drops [6]. IIDG, such as photovoltaic (PV) systems exacerbate the protection problem because of their low fault ride through (FRT) abilities [7]. Furthermore, high impedance fault (HIF) causes severe damage to DN protection due to low fault current magnitudes. Consequently, the detection of faults in the DN is essential to avoid harmful impact to the network.

The DN can operate independently in the island mode (ISM), including the network-connected mode (NCM). The ISM causes malfunctions in the power system and the DG unit as well as problems with protection [8]. Consequently, the islanding condition must be identified quickly within appropriate durations, and the DG must be isolated immediately from the network [9], [10] within 2 s (100 cycles), according to 1547-2003 IEEE standard [11], [12]. Island detection methods can be categorised into local and communication-based detection methods. Local detection methods are generally classified as passive and active-based detection schemes [13]. Therefore, the development of an accurate island detection method is important for the smooth operation of protection and control systems in microgrids.

The unfavourable influence on the conventional protection scheme can be tackled in two ways. One approach is to preserve static coordination with old protective equipment but with some limits on the levels of DG penetration. The other approach involves updating the components of the protection system or modifying the overall protection scheme as necessary [5]. Recently, several methods have been created to protect a DN and mitigate the effects of DG. These methods include the adjustment of the over current relay (OCR) coordination, the phasor measurement unit (PMU) [14], the fault-current limiter (FCL).))[15], smart transformers [16], [17], adaptive protection devices [18], directional over-current relaying (DOCR) [19] and other protection techniques. However, the development of appropriate protection schemes in the DN is challenging due to the bi-directional power flow, operation mode change, and the system being complex and expensive.

This study presents a detailed survey on various fault detection and protection schemes for DG connected to a DN. The review offers the following contributions:

- The various fault detection methods of DG integrated with a DN are explored in detail. The classification of fault detection methods in terms of their advantages, parameters, types, communication methods, operation modes and constraints are discussed.
- The categories of island detection techniques, including active, passive, hybrid, and communication-based methods CMs) are reported. In addition, the advantages, parameters, DN types, costs, and detection time, are discussed thoroughly.
- The DN protection schemes with respect to categories, operations, constraints, strength and shortcomings are highlighted.
- The key issues and limitations of fault detection and protection are outlined, including operation mode, bi-directional power flow, operating cost, selectivity and sensitivity of relays are outlined.

- The selective future suggestions for the development of advanced fault detection and protection of DGs are provided.

This paper is organised into six sections. The survey methods and classification are outlined in section 2. Then, the fault detection strategies for a DN, including data analysis and island detection techniques are highlighted in section 3. In section 4, protection schemes in a distribution network system are described. Then, issues and challenges are explained in section 5. Finally, the paper ends with the conclusion and suggestions in section 6.

## II. SURVEY METHODS, OVERVIEW AND CLASSIFICATION OF DISTRIBUTED NETWORK PROTECTION

The aim of this survey is to conduct a critical discussion and analysis by collecting all the recent information related to fault detection and protection schemes in DG integrated to a DN. Firstly, the authors carried out a thorough literature review of DG fault detection and protection strategies using various databases, such as Scopus and Web of Science. Several platforms, including Google Scholar, IEEE Xplore, ScienceDirect, MDPI and ResearchGate were used to select suitable studies. Accordingly, a sum of 469 articles were found after the initial search. Secondly, suitable keywords were used to explore the relevant papers within the scope and target, including *distributed network, distributed generation, fault detection, island detection and protection scheme.* In addition, the title, abstract, subject, novelty and contributions of each paper were considered when exploring the relevant articles. Consequently, 272 articles were identified and analysed. Finally, the journal's quartile, citation, impact factor and review process were adopted to finalise the number of articles. A total of 150 references were chosen for this review paper at this stage.

The outcomes of the surveying approach are divided into five groups. Firstly, fault detection for DGs is comprehensively reviewed. Secondly, the various island detection approaches are described. Thirdly, several protection schemes for DGs are explained. Fourthly, key issues and challenges are highlighted. Finally, the conclusion, along with selective prospects for further enhancement of the DN fault and protection strategies, are provided. The reviewing methodology is arranged into two stages as depicted in Fig. 1.

The distribution network protection can be classified into two main categories, as illustrated in Fig. 2. In this section, various fault detection strategies are classified and discussed. Then, island detection techniques are highlighted. Subsequently, various ways to protect the DN and their benefits and disadvantages are discussed. The developed protection scheme occurs by using one or two techniques, such as the adjustment of the relay coordination, PMU, FCL, smart transformer, adaptive protection devices, DOCR and other protection techniques. An adaptive protection technique with PMU shows high reliability and security in all network topologies. Nevertheless, cost, system complexity and difficulty to implement are the limitations of the adaptive protection scheme. In contrast, dual-setting DOCRs are capable of working in both modes of NCM and ISM. In addition, the scheme has difficulty setting all the scenarios of contingencies. Therefore, this review is conducted to highlight various fault/island detection methods and protection techniques used in a DN to develop a protection scheme.

## III. FAULT DETECTION STRATEGIES FOR DISTRIBUTED NETWORK

### A. VOLTAGE ANALYSIS TECHNIQUE

The majority of studies that have been carried out in this field focus on the DG output voltage monitoring. These three-phase voltage signals taken from the point of common coupling (PCC) are required to convert from natural reference ABC to stationary reference. Consecutively, the stationary reference $\alpha\beta$ is converted to synchronously rotating reference $dq$ to simplify calculations. The two output voltage signals are direct current (DC) values. These DC voltage variables are contrasted to the desired reference variables and passed through a low pass filter. The final output signals are used to identify the fault. If the error value crosses the threshold value over a simulation period of 0.02 s, a trip signal is produced to open the side circuit breaker of the grid. At the same time, the phase-locked-loop is disconnected from the grid and attached to a reference signal [20]. Initially, the inverter is allowed to run in open-loop mode. After one operating cycle, the modem signal becomes '1', and the inverter is switched from open-loop mode to the ISM. This signal arrangement is needed to allow transients occurring from the insulation of the voltage source inverter from the grid to be set up before synchronising the operation of the inverter in ISM with the phase-locked-loop and the control loop. Accordingly, the period of open-loop free operation of the inverter is simplified. Manditereza and Bansal [21] proposed a voltage-based protection relay in Microgrid applications. Power-voltage sensitivity computations are used in the proposed relay algorithm to identify faults in specified protection zones. This relay detects single- and double-line faults in the DN under both NCM and ISM.

### B. HARMONIC ANALYSIS TECHNIQUE

The main concept of detecting faults by this technique is to monitor total harmonic distortion (THD) of the grid parameters, i.e. voltage and frequency. The technique compares this value with a reference value. A fault is detected if the threshold value exceeds the reference value. To detect voltage dips, Stanisavljevic *et al.* [6] monitored the third, fifth and seventh harmonics of the signal. The limits are set as 5%, and a fault is detected whenever the differences between the threshold and the reference value is over 5%.

The performance of this technique depends on the threshold selection. A small threshold reduces the accuracy of the technique, whereas a large threshold increases the detection time. Hence, the threshold for detecting faults and the waiting

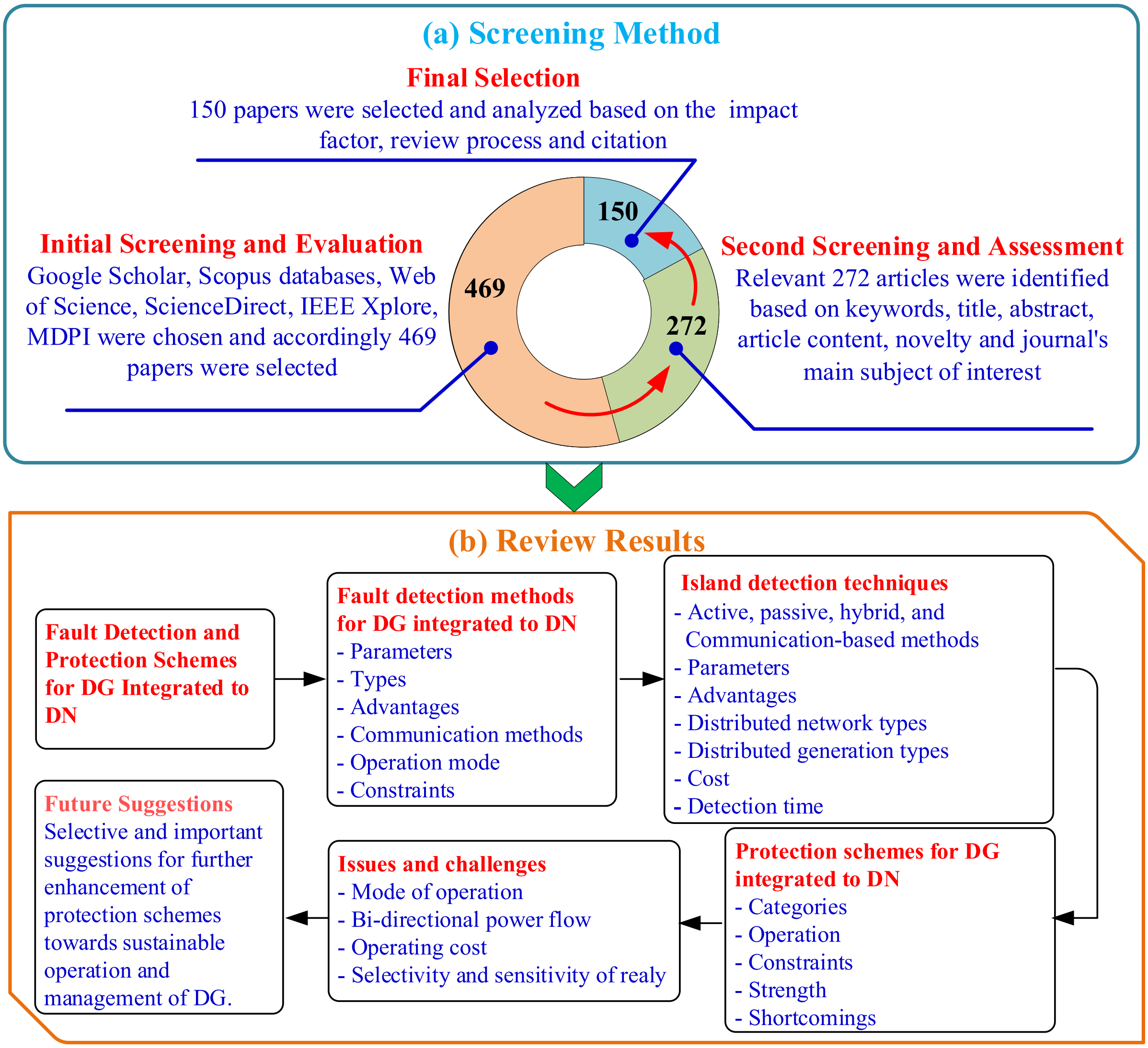


**FIGURE 1.** Schematic illustration of the survey methods.

time can be determined as follows:

$$\xi_{th} = SF_{\xi} \times \xi_{normal}, \tag{1}$$

$$t_w = SF_t \times t_{w,normal}, \tag{2}$$

where $\xi_{normal}$ represents the maximum values of the detecting index in a normal DN condition. $t_{w,normal}$ is the maximum duration time of $\xi > \xi_{th}$ for switching actions. Meanwhile, $SF_{\xi}$ and $SF_t$ are the safety factors to preserve the reliability of the technique for unexpected normal situations [22]. Morello *et al.* [23] used second harmonic magnitudes of voltage and current to build relay protection. Firstly, fast Fourier transform is applied on the magnitude of the input. Then, transformation output of current and voltage is compared with the threshold separately. This relay detected fault in the upstream side of DN without the need of communication channels. Meanwhile, Sadeghkhani *et al.* [24] employed transient observation function on inverter current signal to detect symmetrical and asymmetrical fault.

### C. TRAVELLING WAVE TECHNIQUE

The travelling wave technique is based on the signal polarity and receiving time information to both lines during fault occurrences. It can be clarified by a lattice diagram, as demonstrated in Fig. 3.

In the figure, + and – represent the signal polarity. The travelling wave technique can be categorised in two forms, namely, the single-end and double-end or multi-end approach. In the single-end approach, the polarity and time information are obtained by extracting two wavefronts. In contrast, the initial wavefronts are detected by units located at both sides of the line in the double-end approach [24]. The fault location is identified by comparing the travelling wave energy of the input current signal with the threshold value.

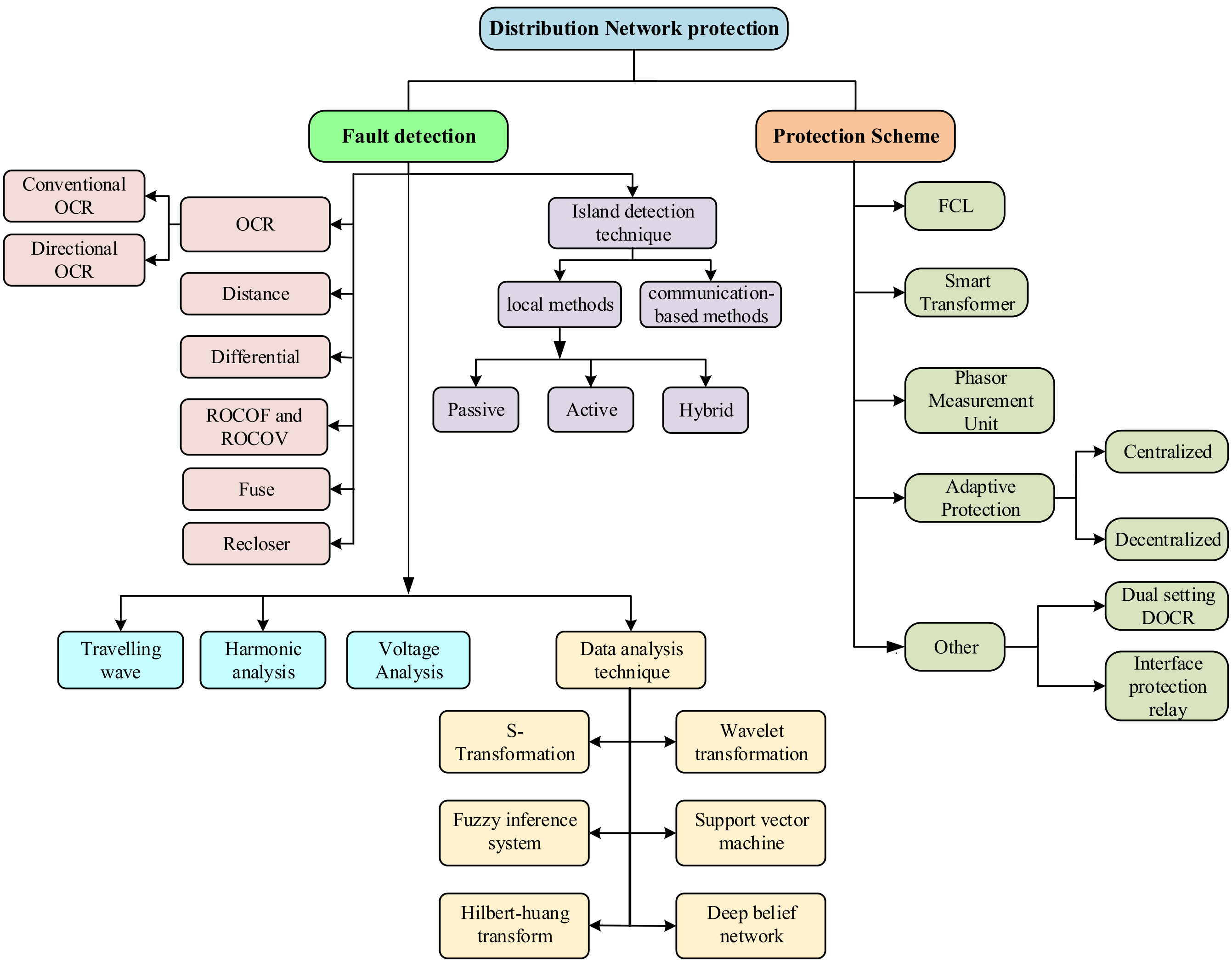


**FIGURE 2. Classification of distributed network protection.**

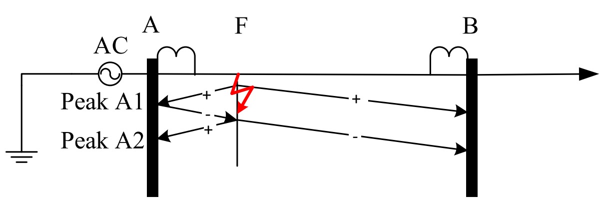


**FIGURE 3. Lattice diagram [24].**

Therefore, the travelling wave energy must be known [25]. Saleh *et al.* [26] used the first localised travelling wave when a fault occured in DC microgrid. This work focused mainly on the travelling waveform characteristics and polarity, instead of its arrival time. This method offers benefits such as being faster than conventional techniques and no requirement for communication channel.

### D. DATA ANALYSIS TECHNIQUES

Fault detection in a DN with DG aims to detect islanding, identify the faulty zone and achieve protective action [27]. The fault current magnitude in the ISM is smaller than the fault current in the NCM, which causes the conventional OCR to malfunction. In mesh DN with a significant penetration of the conventional protection of DGs, i.e. OCR, fuse, distance relay and reclosers have no ability to isolate the fault; and therefore, they should be reset after any change in DN topology [28]. In addition, differential protection depends on an expensive communication link, which can be affected by a fault. For a safe and stable DN operation, a fast and precise fault detection technique combined with a protection scheme is highly required [29].

The detection technique should preserve FRT, which means the DGs will remain interconnected with the DN even when the voltage drops to 30 percent of the nominal PCC voltage for 0.15 s. During this process, the DG inverter is compelled to boost the reactive power supply to maintain the stability [30]. Furthermore, the technique must continue to reclose the circuit breaker after the temporary faults occur. In this section, data analysis techniques are highlighted.

**TABLE 1.** Summary of various existing fault detection methods.

| Ref. | Method | Advantage | Parameter used | HIF | Multi-DG and type | Communication use | Constraints | Operation Mode |
|---|---|---|---|---|---|---|---|---|
| [41] | -Wavelet individual entropy and fuzzy inference system | -Fast fault detection | Current | - | Diesel generator | - | Needs to test on complex conditions | NCM |
| [40] | -Fuzzy logic technique | -Detect the HIF | Current | Yes | No | - | DG | NCM |
| [47] | -Wavelet transform and support vector mechanism | -Detect different kinds of faults | Voltage | - | One DC source | - | Needs to test on complex conditions | NCM |
| [29] | -Statistical morphology, recursive least square methods and Butterworth filter | -Detect, classify and locate faults | Current | - | Two source Solar | - | HIF | NCM and ISM |
| [48] | -Differential phase angle criteria | -Fast fault detection | Voltage | - | Solar plant and wind generator | Yes, PMU | Costly | NCM and ISM |
| [35] | -S-transform | -Detect fault type and location at various topologies | Voltage and current | - | Four DGs are not specific | Yes, central server | Costly, test on mesh DN and FRT | NCM and ISM |
| [49] | -Power spectral density and wavelet transform | -Detect and classify HIF | Current | Yes | Yes | - | Mesh DN and ISM | NCM and ISM |
| [50] | -CIGRE benchmark parameters and theoretical fundamentals | -Detect LIF | Current and voltage | - | Yes | Yes | FRT, costly and mesh DN | NCM and ISM |
| [7] | -Deep belief network, time-time transform and PMU | -Detect the fault quickly and accurately | Current | - | Yes | Yes, central server | Costly | NCM and ISM |
| [51] | -Travelling wave and wavelet analysis | -Detect the fault quickly and accurately | Current | - | No | Yes, central server | Mesh DN, solar DG and costly | NCM |
| [46] | -Least square - Adaline algorithm and modified support vector mechanism | -Detect/classify HIF and section identification | Current | Yes | Yes, except wind turbine | - | Mesh DN, Low voltage DN and complex condition, near to zero active power mismatch | NCM and ISM |
| [52] | -Hilbert-Huang Transform and differential relay | -Detect fault on both radial and mesh DN | Current | Yes | Yes | Yes | Costly, solar DG and test on case of near-zero active power mismatch | NCM and ISM |

A summary of various existing fault detection methods is listed in Table 1.

As shown in the summary and analysis stated in Table 1, only four techniques are capable of HIF detection. Three of these techniques, which have been verified in multi-DGs and two techniques, do not require communication links. Meanwhile, only one technique can operate at both operation modes. In addition, this technique is successful in detecting a low impedance fault (LIF) based on a communication link that uses voltage and current parameters. Therefore, for DN protection a cost-effective fault detection technique must be developed, that can detect various types of faults (i.e. HIF, LIF, symmetrical and asymmetrical) at different operation, topology and noisy conditions.

### 1) WAVELET TRANSFORMATION TECHNIQUE

The wavelet transformation technique (WTT) is a technique based on time-frequency analysis. It is used to detect a fault with digital relays. The WTT procedure has some drawbacks, including the high sampling rate and equipment restrictions. In addition, it classifies data regardless of time and frequency. The WTT computational time is also often high [31]. Moreover, the WTT is a signal processing technique with the capability of processing data at several scales and resolutions. It can locally investigate discontinuities in high-order derivatives and sudden signal changes where other signal processing methods cannot inadequately identify power quality problems. The wavelet transformation of the transient signals is commonly implemented through a multi-resolution algorithm that uses the bases of the orthogonal wavelet to analyse signals into various scale components. The approximation of detailed components in the signal are obtained by filtering the signal through low- and high-pass filters. Once the signal is transmitted by low- and high- pass filters, the combination is used as a subsample, and the resolution is halved according to the number of measurements. The subsamples of the pair and precision are halved according to the sample number. The resolution of the frequency is doubled, as the frequency band created covers half of the above frequency band [32]. Som and Samantaray [33] employed discrete WTT to detect faults in low voltage DC microgrid. All DC faults can be detected using this methodology. In contrast, Kumar and Saxena [34] used the combination of discrete WTT and decision tree to classify faults in DN with the integration of multiple wind turbine DGs. This approach employed only current signal and achieved high accuracy.

### 2) S-TRANSFORMATION TECHNIQUE

S-transform is an expansion of the definition of wavelet transformation. It is one of the modified passive detection methods. The strategy is based on the use of standard deviation and energy signal acquired by the analysis of zero, positive and negative sequences. At the same time, the three-phase components of voltage and current signal detect fault, location, type of fault and commission phases [35]. Amiri and Vahidi [36] introduced the S-transform located protection scheme for the DN. The method is completely independent of the level of the short circuit and the network structure. Thus, it can work with precision in all DN operating modes. The operating procedure for this technique depends on the IEC 61850 series of standards for providing efficient communication protocols. Nevertheless, the S-transform can achieve multi-resolution analyses of preserving the information of frequency. The predefined Gaussian window cannot be considered suitable for all forms of signals. Moreover, time consumption of the S-transform is large in contrast with other methods based on time-frequency [37]. Lastly, one disadvantage of the S-transform approach is it requires added memory for data processing.

### 3) FUZZY INFERENCE SYSTEM

The fuzzy inference system (FIS) is used for detecting the island in the DN because it responds to sudden variations in signals. Moreover, it is capable of detecting various types of faults in different conditions. To detect the fault accurately and effectively by FIS, the fundamental elements of a fuzzy decision system, such as fuzzy sets and fuzzy rule base [38], [39] must be understood. Vyshnavi and Prasad [40] used a three-phase current to calculate the fuzzy inputs, as shown in Fig. 4. The membership functions are assigned as low, normal and high. In the next step, fuzzy outputs are achieved on the basis of the membership function rules. In the last step, fuzzy outputs are aggregated as an input to de-fuzzifier functions. De-fuzzifier outputs indicate whether HIF occurs. This technique needs an expert to set the fuzzy rule correctly. Dehghani et al. [41] used wavelet singular entropy to retrieve the detailed coefficient of the three-phase positive component and current signals. Then, these signals are used as an input of FIS. The indexes of FIS are obtained by fuzzy sets and rules. Consecutively, the indexes are converted to perceived variables to detect and classify faults. Chaitanya and Yadav [50] used teager energy operator and FIS. Primarily, teager energy operator is employed to extract features from current signals. Then, FIS is applied to detect and classify fault in distribution line incorporated with DG. This approach can detect HIF and shunt fault.

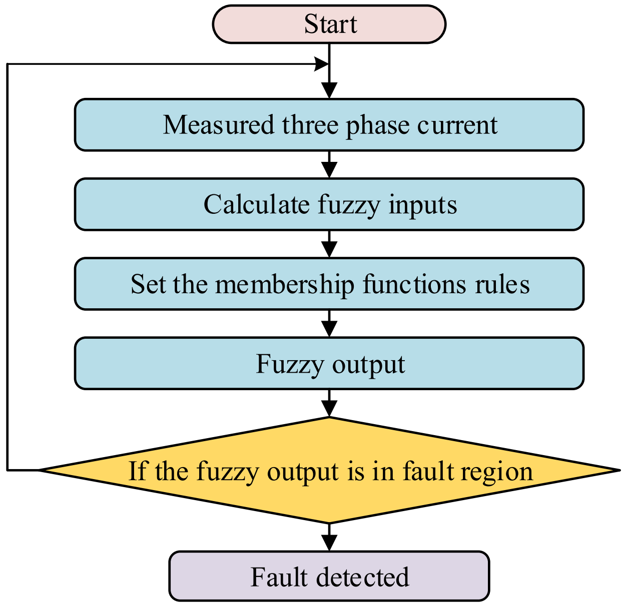


**FIGURE 4.** Flowchart of fault detection based on FIS [40].

### 4) SUPPORT VECTOR MACHINE

The support vector machine (SVM) is a widely used classifier to detect faults [42], [43]. The authors in [44] used the SVM classifier to detect fault/islanding in an active DN. Additionally, to minimise non-detection zone (NDZ), the authors increased the input parameters of the SVM classifier and used seven measurements, namely, f, P, Q, $RMS_V$, $RMS_I$, $THD_V$ and $THD_I$. In contrast, Forouzesh et al. [45] proposed an SVM classifier that depends on root mean square (RMS) voltage from PCC. Meanwhile, Manohar et al. [46]. proposed the HIF fault detection, classification and section identification approach based on least squares-Adaline algorithm and modified SVM. In this approach, the least squares-Adaline algorithm acts as the feature extraction of the essential and harmonic elements of current signals. The sine cosine algorithm is then used to drive the optimal hyperparameter for the SVM classifier. This algorithm is applied to detect/classify the fault and identify the section.

Chaitanya et al. [55] used variational mode decomposition and SVM to detect HIF and LIF in distribution lines with incorporation of DGs. The variational mode decomposition acted as features extraction. Then, the SVM detects and classifies the fault.

### 5) DEEP BELIEF NETWORK

The deep belief network (DBN) is a powerful computational method that uses a deep architecture comprising multiple layers of restricted Boltzmann machines [53]. Gashteroodkhani et al. [54] used S-transform and DBN to detect faults in a DN. The differential current features are extracted by Clark and S-transform.The differential features are trained by the DBN to detect faults during different operation modes and topologies. Another study by Gashteroodkhani *et al.* [7] used a combination of time-to-time transform (TT-transform) and DBN to detect and classify faults under different cases and DN topologies in both operation modes. In this approach, a three-phase current from both ends of the line are measured. Clark and TT-transform are used to extract differential features. These features are used to train the DBN. TT-transform and the DBN approach demonstrated high accuracy in detecting and classifying faults compared with various methods.

#### 6) HILBERT–HUANG TRANSFORM

Hilbert-Huang Transform (HHT) is a time-frequency-analysis-based technique that consists of empirical mode decomposition and Hilbert transform (HT) [55]. HHT is a very powerful, adaptable and accurate technique for signal feature extraction. In addition, The HHT is capable of analysing non-stationary power signals. Mishra and Rout in 2018 proposed HHT to extract the differential features of current signals. Here, the authors applied EMD on the phasor current signals and their zero components to convert them to a group of intrinsic mode function.HT and machine learning approaches, i.e. SVM, naive Bayes classifier (NBC) and extreme learning machine (ELM), are applied to detect and classify faults [52]. Mishra and Rout found that the HHT-ELM-based technique is better than HHT-SVM- and HHT-NBC-based techniques. Baloch and Muhammad [56] employed HHT to extract features from voltage and current signals. Then, logistic regression and AdaBoost classification are applied to detect and classify faults. This approach provides high accuracy and detects all types of faults except the HIF and LIF.

### E. ISLAND DETECTION TECHNIQUES

The ISM occurs when the DN is disconnected from the main power grid. DG is faced with an operational matter, such as unintentional or unplanned islanding. This issue could cause damage to the electrical instruments and system equipment in the isolated section [57], [58]. The DG device should be disconnected (or turned OFF) as soon as the island occurs to prevent any potential danger. As per IEEE 1547-2003, the disconnection duration needs to be less than 2 s [59]. The main concept of detecting the island entails monitoring system parameters, such as voltage, frequency and harmonic distortion according to variable changes considerably throughout an island condition [60]. Two methods are used for detecting the island including local methods (LMs) and CMs. The LMs are broadly classified as passive, active-based detection schemes [37], [61]. The passive detection methods have easy implementations, improved power quality and faster fault detection ability for all types of DG configurations. A larger NDZ and improper threshold setting are the main disadvantages of the passive method. Conversely, active-local approaches have smaller NDZ. However, it produces disturbances to the distribution system, which becomes a major problem as the number of DG units increases. Thus, modern research has focused on hybrid methods [62] through the combination of two methods to achieve superior results and reduced cost. On the other hand, the CMs use advanced communication substructure and signal analysing techniques. CMs have a small NDZ and is extremely effective compared with LMs. Nevertheless, it requires high-speed communication [63].

A summary of numerous island detection techniques is listed in Table 2. Table 2 demonstrates that some passive approaches have smaller NDZ. In addition, only one hybrid technique [64] can be applied on radial and mesh DN. Furthermore, some techniques in articles [65], [66] and [67] tested on a near-to-zero active power mismatch situation. In contrast, only one article [68] considered zero active/reactive power mismatch conditions. A number of articles [69], [70], [71], [72], [73], [66], and [74] delivered comparative analysis techniques between island and non-island events, while articles [75], [66], [67], [76] provided zero NDZ. For the duration time aspect, the CM in article [66] required only 14 ms to detect island. However, the technique in [66] had different type of DGs that were not tested on DN. In addition, it requires high cost to implement. Therefore, an island detection technique with null NDZ needs to be developed. Moreover, the proposed technique must be tested on both radial and mesh DNs and near-to-zero active power mismatch situations. The proposed technique must also discriminate island events from non-island cases as per IEC 61727 standard.

#### 1) PASSIVE APPROACH

Generally, passive island detection method is based on continuous monitoring and measuring of local data from DG terminals or PCC, such as voltage, current, power, frequency, harmonic distortion and phase angle. The variation of these parameters is then systematically compared with pre-defined threshold values to detect the island [77]. The preferred threshold value is important because it determines the precision and detection time of islanding [78]. The advantages of passive methods include easy implementation, economical cost and speed. However, there are large NDZ and low differentiation between island and non-island cases. Bakhshi *et al.* [65] used the adapted frequency of the common coupling point as an input signal to the forced Helmholtz oscillator. The dramatic change between chaotic and standard motions defined the identification index threshold. This method is capable to detect islanding under active power mismatch is nearly zero. Shahryari *et al.* [79] used island detection relay based on neural network. Additionally, wavelet transform and mean-square error are used to select appropriate input signals to the relay. The advantage of this technique is that it does not need a threshold value. Moreover, it has a small NDZ of approximately 6%. Nevertheless, it cannot deal with network reconfiguration and multi-distribution generations, as the algorithm depends on the state space matrix.

**TABLE 2. Summary of a numerous island detection techniques.**

| Island detection types | Approach | Advantages | Parameter used | Distributed network types | Multi-distribution generation and types | Cost | Detection time (second) | Ref. |
|---|---|---|---|---|---|---|---|---|
| Passive | -S-transform and ELM | -ELM has better precision and execution time than SVM or other commonly used classifiers under different noisy conditions | Negative sequence component of voltage and current | Radial | Yes, except solar | Reasonable | N/A (meets island condition) | [77] |
| | -Harmonic analysis, output voltage distortion | -Minimises NDZ | Voltage and frequency | Small-scale radial | NO, Solar | Reasonable | N/A (meets island condition) | [78] |
| | -Voltage relay, power imbalance application region and application region | -Detects island and eliminates false operation of relay | Voltage | Radial | Two synchronous distributed generation (SDGs) | Reasonable | 0.5 | [81] |
| | -Auto-correlation function and HT | -Accurate island detection<br>-Smaller NDZ | Three-phase current | Radial | Yes, Solar | Reasonable | 0.5 | [31] |
| | -Signal trajectory pattern recognition and smart relays | - Accurate island detection | Voltage and frequency | Small-scale radial | No, only SDG | Reasonable | N/A (meets island condition) | [80] |
| | -Forced Helmholtz oscillator | -Identifies the islanding status of near-zero real power mismatch<br>-Smaller NDZ | Frequency | Radial | Yes | Reasonable | 0.214 - 0.454 | [65] |
| | -Wavelet transform and neural network | -Reduces NDZ to less than 6%<br>-Needless threshold value | Voltage and current | Small-scale radial | No | Reasonable | 0.05 | [79] |
| | -Multi-gene genetic programmed | -Detects and classifies island correctly | Voltage waveform | Radial | No, only SDG | Reasonable | N/A (meets island condition) | [82] |
| | - ROCOF and particles swarm optimisation | -Detects island quickly and discriminates between island and non-island events | Voltage waveform | Radial | No, only SDG | Reasonable | 0.3 | [70] |
| | -SVM | -Minimises false tripping and achieves selectivity and accuracy<br>-It has NDZ below 10%. | Voltage and current | Radial | Yes, only solar | Reasonable | 0.04 | [83] |
| Active | -Irregular current injection technique and dynamic impedance | -Discriminates island events from DG unit cut-in events in multi-DG operation | Voltage | Radial | Yes | Reasonable | 0.5 | [84] |
| | -Second harmonic current injection | -Discriminates island events from non-island cases that temporarily exceed the second harmonic of PCC voltage | Second harmonic voltage | Radial | Yes, only IBDG | Reasonable | N/A (meets island condition) | [69] |
| | -Least square technique, transient index value and three-phase current injection at PCC | -Fast island detection in case of zero active/reactive power mismatch conditions and transient events caused by nonlinear loads | Voltage and current | Radial | Yes | Reasonable | 0.2 | [68] |

**TABLE 2.** ***(Continued.)*** **Summary of a numerous island detection techniques.**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | D-axis current injection | Discriminates island events from non-island cases. | Voltage, and active power output | Radial | Yes, only IIDG (Solar) | Reasonable | 0.1 | [71] |
| | Pattern detection, Gps, Active Power difference | Zero NDZ, Power quality of the system is not degraded | Voltage and current | Radial | Yes, IIDG | Costly | N/A (meets island condition) | [75] |
| | Inject low frequency current, ROCOF relay | Discriminates island events from non-island cases | Voltage and current | Radial | No | Reasonable | 0.1-0.2 | [72] |
| | Impedance measurement, frequency band-width | Detects island under zero and non-zero power flow condition | Voltage and current | Radial | No | Reasonable | <0.16 | [85] |
| Hybrid | -Continuous wavelet transform and power quality estimation | -Discriminates island events from other fault instances<br>-Minimises NDZ error and avoids threshold selection | Voltage and current | Radial | Yes | Reasonable | N/A (meets island condition) | [86] |
| | -Genetic algorithm; SVM as classification technique | -Minimises time and maximise the accuracy of detection technique<br>-Smaller NDZ | Voltage and current | Radial and mesh | Yes | Reasonable | N/A (meets island condition) | [64] |
| | Unbalance voltage, and frequency disturbance method | Detects multiple islanding situations | Voltage, and DG frequency | Mesh | Yes | Reasonable | N/A (meets island condition) | [87] |
| | Estimate of high frequency impedance, centralized injection technique, Over and under frequency | Maintains good island detection accuracy and decreases disturbances to the system | Voltage and current | Radial | Yes, IIDG (wind turbine) | Reasonable | N/A (meets island condition) | [88] |
| | Frequency shift, THD and RMS | Smaller NDZ, decreases the effect of Active approach | Voltage | Radial | Yes, IIDG (Solar) | Reasonable | <0.4 | [89] |
| | Rate of change of the voltage (ROCOV), rate of change of power (ROCOP) | -Discriminates island events from non-island cases,<br>-near to zero NDZ, | Voltage, and active power output | Radial | Yes, only IIDG (Solar) | Reasonable | 0.51 | [73] |
| | Active power estimation, predefined disturbance injection into direct axis reference current | Discriminates island events from non-island cases.<br>-Smaller NDZ | Voltage and current | Radial | Yes, IIDG | Reasonable | 0.3 | [74] |
| CMs | Micro-PMU, phase angle difference of voltage signals. | Discriminates island events from non-island cases, Identifies the islanding status of near-zero real power mismatch, zero NDZ, high reliability | Voltage , frequency, and phase angle | Radial | Yes, IIDG | Costly | 0.014 | [66] |
| | PMU, wireless communication, voltage stability, phase angle jump | Anti-island protection | Voltage, and current | Radial | No | Costly | N/A (meets island condition) | [90] |
| | PMU, GPS | Detects island conditions | Voltage and current | Mesh | Yes | Costly | N/A (meets island condition) | [91] |
| | Micro-PMU, Fortescue Transform, phase angle difference | -Zero NDZ,<br>-Decreases the risk of cyber-attacks | Voltage | Radial | No | Reasonable | 0.01 | [76] |
| | PMU, moving-window principal component analysis, and mathematical morphological filter | -Zero NDZ<br>-Identifies the islanding status of near-zero real power mismatch | Magnitude and phase angle of voltage, frequency, ROCOF | Mesh | Yes | Costly | 0.27 -1.27 | [67] |

### 2) ACTIVE APPROACH

Active approaches are able to distinguish between islanding and non-islanding cases quickly [80]. Recently, Emadi *et al.* [69] presented an active islanding detection approach based on a second harmonic current injection into the system. This approach is deactivated after the islanding is identified and the voltage/frequency stays within the expected limits under power balance conditions. In contrast with other active island detection approaches, this approach reduces the second harmonic PCC voltage of the NCM as well as enhances the system performance. Nale *et al.* [68] proposed two criteria for detecting the island based on the transient index value (TIV) and superimposed current angles in positive sequence at PCC. Three-phase voltage signals at the PCC are used to determine the TIV. As illustrated in Fig. 5, the detection of the islanding occurs when the threshold of the TIV exceeds the limit and the superimposed current angles in a positive sequence is positive. This method has the ability to discriminate between island and non-island events, such as capacitor switching, switching of large load, DG turn off and fault conditions in hybrid DN [68].

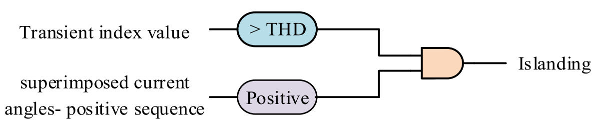


**FIGURE 5.** Island detection method based on transient index value and superimposed current angles in positive sequence [68].

Murugesan & Murali [71] proposed an active islanding detection approach based on direct-axis current injection combined with mean of absolute direct-axis voltage variation and mean of absolute rate of change of direct-axis voltage variation analysis technique. Gupta *et al.* [72] presented an active relay based on low-frequency current injection and rate of change of frequency (ROCOF) on the converter side. The ROCOF relay function depends on the dynamic frequency change during islanding owing to the power inequality between the production and the load. The dynamic frequency change at PCC after islanding is directly proportional to the power mismatch and can be calculated by,

$$\frac{df}{dt} = \frac{(P_{DG} - P_l)}{2 \times S_{DG} \times H_{SG}} \times f_o, \tag{3}$$

where $P_{DG}$ and $P_l$ represent the output power of DG and load power, respectively. $f_o$ refers to rated fundamental frequency, while $S_{DG}$ and $H_{SG}$ represent power rating and inertia constant of DG, respectively. The islanding remains unobserved when $P_{DG}$ is equal to $P_l$. The benefits of both [72] and [71] approaches are that they discriminate island events from non-island cases. However, Gupta *et al.* [72] did not test on multi-DGs system. Furthermore, Sivadas and Vasudevan [75] presented an active approach based on the ratio of d-axis component of PCC voltage and injected current into PCC. The presence of islanding is detected when this ratio remained constant. Additionally, GPS is employed to coordinate the patterns when several inverters are running in parallel. DN power quality is not degraded by this technique, which has null NDZ. Llonch-Masachs *et al.* [85] presented island approach dependent on impedance measurement and frequency bandwidth detection. This method detects island under zero and non-zero power flow condition.

### 3) HYBRID APPROACH

The combination of passive and active detection approaches is used to detect islanding. This hybrid approach possesses the advantages of both approaches and overcomes their disadvantages. Paiva *et al.* used the real-time continuous wavelet transform to develop a non-stationary signal analysis for producing the power quality index [86]. The evaluation of a data set comprising power quality indexes is used to identify the islanding phenomena. This power quality indexes include the voltage amplitude, frequency, event duration time, unbalanced degree, DN impedance and power angle. A transient detection system is used to mitigate the power quality issues related to signal injection by restricting the period of interharmonic injection and enabling it only when a transient occurs. The power quality indexes are then compared with threshold values to detect island events. Mlakic *et al.* [89] presented hybrid island detection approach based on the identification of Gibbs phenomenon and PCC voltage combined with $THD_V$. This method improves power quality by limiting the use of active detection methods without compromising their benefits. Sirige *et al.* [87] proposed a hybrid approach based on unbalance voltage and frequency disturbance technique. When the voltage imbalance threshold is reached, the frequency disturbance approach is applied. Island detects if the frequency level is less than a specified threshold. The disadvantage of this approach is that it fails to detect island when frequency level goes above the threshold value. Bakhshi-Jafarabadi and Popov [74] proposed a hybrid approach based on the drop of absolute PCC voltage and active power output. The islanding occurs when absolute voltage and DG active power exceed the threshold. This approach discriminates island events from non-island cases. Further, the power quality is unchanged during NCM and short duration disturbance takes place during the island situation. Jia *et al.* [88] employed high-frequency impedance estimation with external centralised transient injections for detecting island. This method obtains good island detection accuracy while reducing system disturbances. Bakhshi-Jafarabadi *et al.* [73] proposed hybrid method based on ROCOV while the disturbance was induced into the duty cycle of a DC/DC converter, and ROCOP. The mathematical expessions for ROCOV and ROCOP can be written as follows,

$$ROCOV = \frac{\Delta V'_{PCC}}{V_{po}} \times 0.1 \times f, \tag{4}$$

$$ROCOP = \frac{\Delta P_{DIS}}{P_{DG}} \times 0.1 \times f, \tag{5}$$

where $\frac{\Delta V'_{PCC}}{V_{po}}$ refers to the change in the relative output voltage, $f$ represents system frequency, and $\frac{\Delta P_{DIS}}{P_{DG}}$ refers to changes in relative active power disturbance. This method exibits near-zero NDZ and small power quality deterioration.

#### 4) COMMUNICATION-BASED METHODS

CMs do not depend primarily on local variable measurements to identify an island. CMs use advanced communication substructure for successful operation. CMs have advantageous features in comparison to LMs such as effectiveness and smaller NDZ. However, the only limitation in CMs is cost due to high-speed communication. Shukla *et al.* [76] used Fortescue transform to extract the voltage data acquired by micro-PMU. Island detection and appropriate procedures are carried out using angle difference between the negative and positive sequence components. This approach limits the use of communication channels and detects islands within 0.01 seconds. Nevertheless, it is not appropriate for multi-DG systems. Subramanian and Loganathan [66] proposed micro-PMU, phase angle difference and rate of change of phase angle difference of voltage signal to detect island. The advantage of this technique is that it discriminates island events from non-island cases. Moreover, it identifies the islanding status of near-zero real power mismatch. Radhakrishnan *et al.* [67] presented reliable island approach baed on PMU installed at all bus to monitor and acquire data such as voltage magnitude, phase angle, frequency and ROCOF.These data are sent to the DN control center by a communication channel.Moving-window principal component analysis and mathematical morphological filter are then applied to identify island conditions. Kumar and Bhowmik [91] employed PMU to detect island. Island is identified when the ratio of current and voltage phasors exceeds the thresholds. This method is appropriate for wide area DN. Katyara *et al.* [90] employed PMU, wireless communication, and voltage stability analysis to detect island. This method does not consider multi-DG conditions.

## IV. PROTECTION SCHEMES IN A DISTRIBUTION NETWORK SYSTEM

The operating scenarios of DN are more complex and irregular with an increasing number of DGs. Therefore, the protection conditions cannot be fulfilled by conventional protection, which considers the maximum and minimum fault current [92]. Furthermore, DN connected with DGs can continuously supply power (depending on demand load) to the grid when island happens and then isolate the faulty segment. This feature enhances reliability and efficiency of the system. Accordingly, various ways to protect a DN during the ISM and the NCM are illustrated below. A summary of protection schemes is listed in Table 3. The table demonstrates that few protection schemes can operate during the NCM and the ISM. Furthermore, only the protection scheme in article [93] has an auto reclosing unit. However, this does not indicate whether ISM and FRT are considered. A number of these schemes use communication links. However, these articles do not consider back up protection in case of communication failure.

### A. ADJUST RELAY CONFIGURATION

The OCR model was created to combine the inverse time current responses of the field OCRs [94]. The operating time of the OCR is driven from the inverse curve of the IEC 60255 standard, as shown in equation (6). The time multiplier setting (TMS) of relays is calculated by linear programming approach. In the NCM, TMS settings are constant in DNs which does not have DGs. However, the same relay configuration is not suitable for the ISM. The relay time characteristics can be calculated using the following formula,

$$t_r(I_{fault}) = TMS\left(\frac{0.14}{\left(\frac{I_{fault}}{I_{pick-up}}\right)^{0.02}-1}\right), \quad (6)$$

where $r$ is the number of relays, $I_{fault}$ is the magnitude of the fault current, and $I_{pick-up}$ is the pick-up current. Relay coordination problems with different operating modes of DG can be solved by coordination time interval (CTI), which can be expressed by,

$$CTI = t_p(I_{l-2}) - t_b(I_{i-2}), \quad (7)$$

where $I_{l-2}$ represents the current at the terminal of the relay during fault line 2. $t_p$ and $t_b$ represent the operating times of primary and back-up relays, respectively [95]. Relay settings and relay operating times have upper and lower constraints, which can be illustrated as follows:

$$I_{pick-up_{\min}} \le I_{pick-up} \le I_{pick-up_{\max}}, \quad (8)$$
$$TMS_{\min} \le TMS \le TMS_{\max}, \quad (9)$$

The main objective is to minimise the operating times of all relays (T) and maintain the protection coordination constraints at the same time [96].

$$MinimizeT = \sum_i^n \sum_j^m (t_{p_{ij}} + t_{b_{ij}}), \quad (10)$$

where $n$ is the total number of relays and $m$ is the total number of the fault position investigated. In addition, $t_{p_{ij}}$ and $t_{b_{ij}}$ represent the primary and back-up relay operating time, respectively. $i$ is the relay number, and $j$ is the fault location [96], [95].

### B. PHASOR MEASUREMENT UNIT

For a variety of factors, the PMU has become a significant utility in the distribution system, including the rapid development of DNs. Meanwhile, a higher penetration of DG and storage requires greater metering precision, faster rates of reporting and further communication susceptibility. PMUs can precisely measure the amplitudes of voltage, voltage-phase angles and harmonic components [97]. It could be used to monitor distribution system phenomena, such as voltage sag and high-impedance fault identification. The flow chart of the real-time monitoring of DN by the PMU is presented

**TABLE 3. Summary of various protection schemes For distributed generation.**

| Ref. | Method | Advantages | Constraints | Operation mode | Communication required |
|---|---|---|---|---|---|
| [102] | FCL<br>Combination of GA and LP | -Minimise processing time<br>-Reduce size of the FCL | -Does not consider mesh grid<br>-Did not study the effect of IIDG on this method<br>-Costly | NCM | Yes |
| [134] | FCL | -Limit fault current of IIDG<br>-Adjust the transition resistance of the fault | -Test system contains only one source of IIDG (wind turbine). | NCM | Yes |
| [135] | Dynamic state estimation, PMU, setting-less component protection and centralised communication | -Efficient for real-time operation and protection<br>-Monitor the total dynamic characteristics of equipment under protection | -If the communication system fails, the protection system would be miscoordinated.<br>-Need a backup protection in case of communication fail<br>-Optimal placement of PMU was not considered. | NCM | Yes |
| [136] | Differential protection | -Fast and reliable back-up protection approach | -IIDG<br>-High capital cost<br>-ISM does not take it into consideration. | NCM | Yes |
| [137] | Differential protection<br>Hilbert space and fuzzy logic technique | -The protection system operates in fewer than two cycles when a failure happens. | -ISM does not take it into consideration.<br>-High capital cost | NCM | Yes |
| [123] | Zero sequence parameter, fast Fourier transform, Z score, fuzzy c-means, historical data, space relative distance and RA | -Enhance protection profitability of conventional techniques with DGs in single-phase ground fault protection of radial grid | -Loss of communication signal between RA is not considered.<br>-Back-up protection scheme in case of communication failure<br>-ISM does not take it into consideration.<br>-Large amounts of memory storage for processing | NCM | Yes |
| [138] | Impedance estimation methods and distance relays | -Enhance relay trip efficiency and ensure protection coordination among traditional power systems and distributed wind generation systems | -Validate the scheme on different DG (SG and solar photovoltaic)<br>-ISM and mesh DN are not considered.<br>-Need a voltage transformer with extra costs | NCM | No |
| [139] | Positive sequence component of impedance and current and central monitoring system (wide area) | -Identify the fault area under different fault conditions<br>-Satisfy FRT consideration | -Mesh DN<br>-This technique only suitable for wind DG.<br>-Tested on medium voltage DN<br>-Costly | NCM | No |
| [140] | Impedance estimation method | -No need for a communication line in backup protection<br>-Detect high impedance fault quick response time | -Mesh DN<br>-FRT<br>-Costly | Both | Yes |
| [141] | Inverse-time OCR and Beetle antennae search algorithm | -Enhance speed of OCR<br>-Maintain coordination between adjoining relay | -Mesh DN<br>-Bi-directional power flow<br>IIDG | Both | No |
| [36] | Intelligent electronic device, S-transform and decentralised scheme | -HIF detection<br>-It can operate in both models.<br>-It does not use the central server. | -Large time consumption for the S-transform | Both | Yes |
| [126] | Adaptive OCR, PSO, Integer -LP, adaptive coordination, optimal TSM, protection time, proper setting group and central computer | -Reduce the average operating duration of OCRs<br>-Determine the appropriate setting group to activate for every relay in each network state, taking into consideration the coordination constraints | -ISM<br>-IIDG, i.e. solar and wind turbine<br>-Expensive<br>-If the communication system fails, the protection system would be mis-coordinated. | NCM | Yes |
| [119] | GA and central units | -Perform the optimal coordination of DOCR | -ISM<br>-IIDG, i.e. solar and wind turbine<br>-Costly<br>-If the communication system fails, the protection system would be miscoordinated. | NCM | Yes |
| [142] | GA and central units | -Minimise the number and size of FCLs<br>-Adaptive protection manages the operation of FCL to restore the coordination of DOCRs. | -ISM<br>-If the communication system fails, the protection system would be miscoordinated.<br>-Back-up protection scheme in case of communication failure<br>-Expensive | NCM | Yes |

**TABLE 3.** ***(Continued.)*** **Summary of various protection schemes For distributed generation.**

| | | | | | |
|---|---|---|---|---|---|
| [143] | Dual-setting DOCR, GA, PSO, Rosen's gradient projection and Zoutendijk's technique and Mesh DN | -Perform the optimal coordination of DOCR<br>-Minimum communication link required | -IIDG<br>-The scheme needed manual tunings.<br>-Low Voltage DN | Both | Yes |
| [144] | Artificial neural network, PMU, Fourier transform to place PMU and centralised control (wide area) | -Identify and classify the defect precisely without affecting the relays in the healthy section | -Expensive<br>-If the communication system fails, the protection system would be miscoordinated. | Both | Yes |
| [145] | PMU, positive sequence component of voltage and current, centralised control (wide area) and impedance angle | -Develop main protection of DN<br>-Detect various type of fault and location<br>-Response time of two to three cycles | -FRT<br>-Expensive<br>-The protective scheme will collapse in the occurrence of a communication breakdown. | Both | Yes |
| [129] | Dual-setting DOCR and optimal protection coordination | -Minimise the overall relay operating time<br>-It does not need installing fault current limiters or adaptive features. | -Studied the effect of solar photo voltaic and wind turbine on this method<br>-The method depends on low bandwidth communication for effective discrimination in backup operations, which may suffer from problem and delay.<br>-Difficult to set all scenarios of contingencies | Both | Yes |
| [93] | Digital relay, Park transformation, wavelet transform and auto reclosing unit | -Detect small fault current<br>-Detect HIF by discrete wavelet transform | -Optimum coordination of relays<br>-ISM<br>-FRT | NCM | Yes |
| [133] | Digital relay, hybrid tripping characteristic (OCR and under voltage relay) and linear program | -It does not need any communication link.<br>-Minimise the operation of the relay | -FRT<br>-Optimal coordination of relay<br>-Ensure coordination between pairs<br>-Low voltage grid | Both | No |
| [146] | Digital relays, auto-cosine similarity and three-phase current | -Fast/accurate fault detection and localisation<br>-It does not require any communication link. | -ISM<br>-Mesh DN<br>-Maintain coordination between relays<br>-SDG<br>-HIF | NCM | NO |

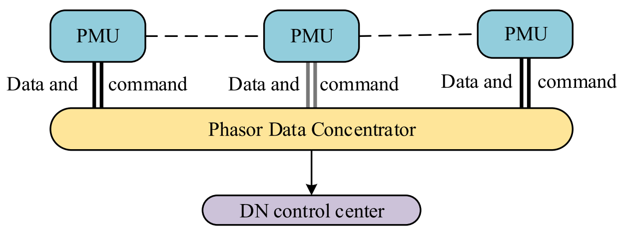


**FIGURE 6.** **Flowchart of real-time monitoring of DN by PMU.**

in Fig. 6. The phasor data concentrator collects data from the PMU and sends it to the DN control centre. Furthermore, PMUs could be used to identify tap changer malfunctions on a sub-station transformer. Consequently, relay malfunction and power system black-outs can be avoided [98].

Zanjani *et al.* [99] proposed an algorithm for detection of uncertainties in the DN and integrated transmission that depends on the estimation of Thevenin impedance in the DN (in the NCM). The uncertainties on the network side have a completely different action. Although the Thevenin impedance is constant, the current path changes due to the reliability of renewable power generations or the separation of network lines. The algorithm is used to prevent the uncertainties by the indications sent by micro-PMUs. Consequently, the main relay and backup relay are readjusted automatically on the basis of the new situation.

PMUs' measurement precision can experience degradation when measurement noises occur [100]. To observe the impacts of measuring units, each calculated phasor value is combined with a complex Gaussian noise whose actual and imaginary components are created randomly with zero mean and standard derivation. Measuring noise levels are calculated using the measured voltage-signal-to-noise ratio. Generally, PMUs cannot be placed on all buses due to economic restrictions [97]. Meanwhile, measurement noise, as well as communication errors will induce protection failure. Placing PMU strategies with constraints of both operation modes to preserve low cost and full system observability need to be considered for future studies.

### *C. FAULT CURRENT LIMITER*

An FCL is used to reduce the noxious effect of DGs on the protection system. The FCL is installed in series besides the power line, and has low impedance. During NCM, an FCL does not affect the network [101]. However, it causes a rise in the impedance value, while a fault occurs and restricts the fault current. Mohammadi Chabanloo *et al.* [102] minimised the expense of an FCL by reducing the impedance aiming only at the partial limitation of the fault current of the DG rather than the maximum fault current limitation. In addition, genetic algorithm (GA) -linear programming (LP) optimisation algorithms are used to coordinate protective equipments. Meanwhile, Saad *et al.* determined the optimum unidirectional FCL impedance value between upstream and downstream networks to optimise the CTI between protection devices. It avoids expected failures of protection relays because of the consecutive incorporation of DGs. Applying the FCLs to the distribution system results in the malfunction or non-operation of the protecting relays and influences their protection coordination. Therefore, Lim and Lim [103] used voltage across the FCL and voltage proportional coefficient to calculate the OCR's trip time and then minimise the tripping-delay time due to FCL application. To prevent miscoordination of fuse cut-outs and re-closer fuse miscoordination, [104] Guarda *et al.* used a methodology for FCL placement. The objective is to minimise the difference between fault currents to which relays are subjected to without taking into account the integration of DGs and after the DG connection. The objective function equations are illustrated below.

$$f_1 = \sum_{n=1}^{n_{fuses}} \left| I_{protecting_{DG\_n}} - I_{protecting\_NoDG\_n} \right| + \sum_{p=1}^{n_{fuses}} \left| I_{protecting_{DG\_p}} - I_{protecting\_NoDG\_p} \right|, \quad (11)$$

$$f_2 = \sum_{k=1}^{n_{FCL}} (R_k + X_k), \quad (12)$$

where $n_{fuses}$ represents the number of fuse cut-outs. $I_{protecting_{DG\_n}}$ is the fault current on the $n^{th}$ protecting fuse cut-out with DG penetration, $I_{protecting\_NoDG\_n}$ is the fault current on the $n^{th}$ protecting fuse cut-out without the penetration of DG, and $I_{protecting_{DG\_p}}$ is the fault current on the $p^{th}$ protected fuse with DG penetration. $I_{protecting\_NoDG\_p}$ is the fault current on the $p^{th}$ protected fuse without the penetration of DG, $n_{FCL}$ is the number of FCLs, $R_k$ is the resistance of the $k^{th}$ FCL, and $X_k$ is the reactance of the $k^{th}$ FCL. These objective functions aim to evaluate FCL placement to minimise the existing fault difference between protecting fuse cut-outs with and without DG to preserve selectivity. Furthermore, the FCL size must be minimised to reduce costs, as the costs rely on their impedances [104]. In contrast, Alghamdi [105] proposed coyote optimization technique to obtain optimal location of DGs and FCLs for a single-phase DN. This technique reduces faulty current levels and power losses. The author [105] observed that raising the voltage profile reduces a significant amount of power losses. Meanwhile, Zarei and Khankalantary [106] used particle swarm optimization (PSO) to find optimum FCL impedance values for DN with SDGs. This technique is not restricted by type, size, location and number of DGs. New DG installations do not affect preceding FCL impedance calculations. However, the effect of ISM and mesh DN are not considered by both Alghamdi [105] and Zarei and Khankalantary [106] techniques. On the other hand, Farzinfar and Jazaeri [107] proposed directional FCL installed between the upstream and downstream network. Directional FCL is enabled only during upstream network faults and restricts the fault contribution on downstream DN. Moreover, Markov Chain Monte Carlo algorithm is applied to obtain optimum setting of directional FCL. This technique can restore the optimal coordination of existing relays considerably and at the same time protect the DN effectively.

### D. SMART TRANSFORMER

A solid-state transformer (SST) can be integrated with a distributed DC network, such as a PV generator, battery storage, DC load and charge station, due to its secondary multi-wind structure [108], [109]. The SST shows enormous potential in DC grid or renewable-energy integration. Single-stage medium voltage alternating current grid SST can prevent massive and costly DC OCRs and medium voltage direct current breakers [110]. A sub-station solid-state transformer (SSST) supplies a bus with a voltage range between 0.97 pu and 1.05 pu. This bus voltage changes marginally with fluctuating load. Meanwhile, it has normal operation if the load is lower than the maximum value of rating the SST power. The allowed maximum line voltage drop is 0.08 pu, depending on the number of connected loads and the length of the distribution line. Thus, when the voltage drop of the primary voltage of the distributed solid-state transformer (DSST) exceeds 0.08 pu, the supplied voltage by SSST increases. If the base voltage of the DSST goes below 0.92 pu, network malfunction occurs. Therefore, the insulated gate bipolar transistors of the SST block and disconnect the DN from the network. In this situation, the DN turns to ISM and is supplied by the DG [111]. The drawback of this method is that it omits the dynamic DN topology. Hence, it cannot stand alone to protect the DN, and it needs to mirage with the fault detection method to protect the DN.

When power electronic devices placed at a normally open node in DN, it is called soft normally open point (SNOP) that can significantly improve DN versatility and controllability [112]. The SNOP implementation in DN is shown in Fig. 7. These devices can perform active power flow management, reactive power compensation, voltage regulation, and fast-fault isolation [113].

Aithal and Wu [114] used local measurements at the SNOP grid connection in order to identify a fault index. This technique dependent on positive-sequence and negative-sequence of current values. Fault index value is determined as follows,

$$Faultindexvalue = \frac{(I^{+}_{ph-RMS} - I^{-}_{ph-RMS})}{(I^{+}_{ph-RMS} + I^{-}_{ph-RMS})}, \quad (13)$$

where *ph* refers to the phases *a*, *b*, and *c*. In addition, the + and – represent positive- sequence and negative-sequence values. The single line to ground fault is detected when fault index value reduces below 80%. The technique does not consider the effect of DGs and ISM.

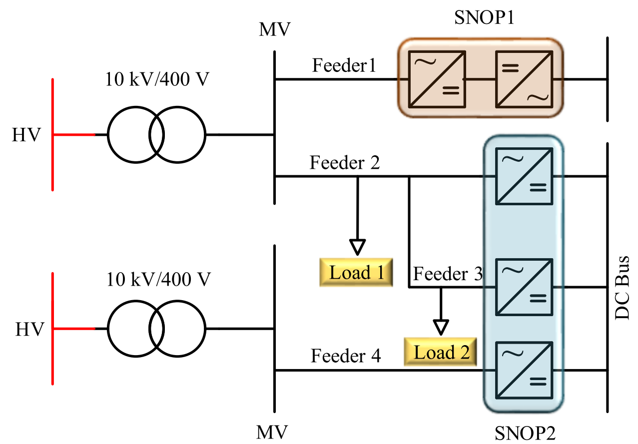


**FIGURE 7.** The SNOP implementation in DN [112].

## E. ADAPTIVE PROTECTION SYSTEM

In general, adaptive protection is an online protection technique aimed to modify the protection configurations to all conceivable situations of the power system and to maintain adequate operation, regardless of system topology [115]–[118]. The flowchart of the adaptive protection scheme is denoted in Fig. 8. The protection system tracks the DN topology and implements new relay coordination in the occurrence of some alteration in boundary operation conditions. Infrastructures that generally establish an adaptive protection system are centralised and decentralised.

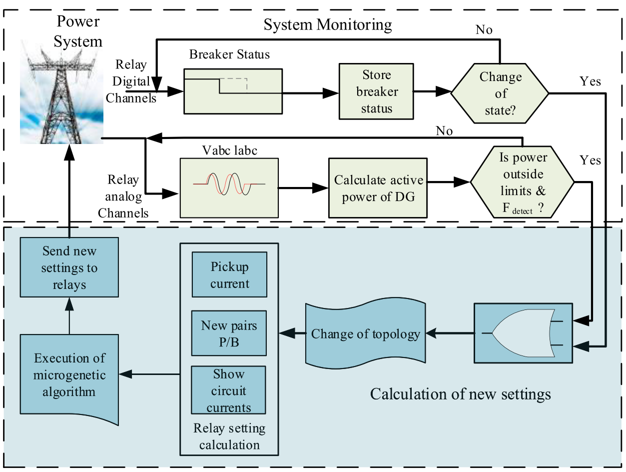


**FIGURE 8.** Flowchart of adaptive protection scheme [119].

## F. DECENTRALISED FRAMEWORK

A decentralised framework is made up of different autonomous control canters splitting the relays into portions or agents. Given their durability, decentralised approaches receive considerably more interest than centralised approaches. Agent-based decentralised approaches are capable of self-checking and respond accordingly to prevailing operating conditions [120], [121].

The framework presented in [122] considers all protection relays as smart agents. A relay agent (RA) consists of sub-agents for measuring current transformers (CTs) and voltage transformer (VTs), a sub-agent for connectivity and a sub-agent for operations. The communication sub-agent performs contact among various agents. The sub-agent calculation (VT and CT) continually monitors the voltage and current at the relay site, and it transmits signals to the operations sub-agent. Microgrid configuration is identified using the transmitted signals to the operations sub-agent from all sub-agents, i.e. relay, DG and PCC. Consequently, each relay becomes conscious of the remaining microgrid specification for fault circumstances and any variations in microgrid topology. An operation sub-agent consists of multiple sections, such as directional, memory and computing parts. The directional part detects the current direction that helps to distinguish microgrid faults. The memory component becomes the archive for saving protection settings. The processor portion is responsible for calculating TMS, computing the trip time delay, and processing other information for better coordination between the main and back-up relays [122]. Wang *et al.* [123] presente a decentralised scheme based on RAs to protect DNs from single-phase earth protection, as shown in Fig. 9. Fig. 9 demonstrates that every RA control has at least two relays and consists of four phases: fault detection, feature extraction, fault distinction and coordination of RA.

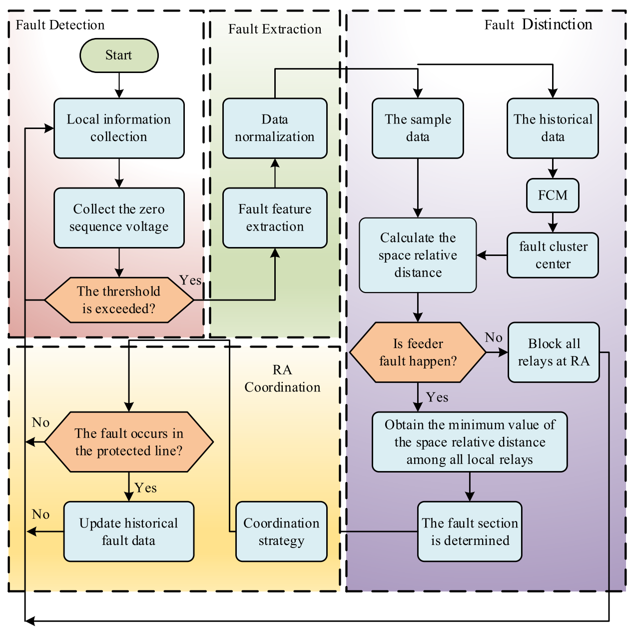


**FIGURE 9.** Flowchart of protection scheme based on RA [123].

The first process measures local parameters (voltage and current). Fault detection depends on zero sequence of the voltage. If it exceeds the threshold value, fast Fourier transform and z-score are used to extract and normalise all fault characteristics, respectively. Fault characteristics are separated into two-parts; real-time data and historical data in phase three. Historical data are considered as a fault cluster. The centre of the fault set is computed from historical error data in offline mode using fuzzy c-means algorithms. The fault set acts as the space distribution of the fault-data for each feeder under a specific fault condition. The space relative distance between the sample data and the fault cluster centre is computed by distance computation methods for every relay. The fault can be determined by the apparent differences in the value of the relative space distance between bus fault and feeder fault. Afterwards, the relay coordination strategy is adjusted to distinguish the line fault effectively [123].

The authors in [124] proposed a three-phase scheme using conventional and self-organising map cluster technique proposed on the basis of digital over-current relays and their configuration sets. The only restriction of this technique is the number of setting groups available for these OCRs and the clusters available for clustering. This characteristic creates challenges when the power grid faces numerous different operational scenarios.

To implement and deploy decentralised adaptive protection easily, Barik and Centeno [125] proposed storing flexible setting groups in relays that can imitate peer-to-peer communication scenarios without using vast communication links between different distribution system nodes. As a result, more studies are required in case of communication failure and its impact on decentralised protection. Additionally, the improvement of back-up protection must consider reducing the operation time and isolating the faulty area. Finally, future work could include adjusting low-voltage ride through curves for different DGs to ensure appropriate protection coordination without infringing IEEE1547 DG connectivity standards.

### G. CENTRALISED FRAMEWORK

In this framework, relays are connected to the central control unit, which monitors the electricity grid continuously and sends the related settings to each relay [124]. Therefore, a centralised framework can evaluate OCR coordination precisely. Samadi and Chabanloo [126] used a centralised framework with integer linear programming and particle swarm optimisation to determine the appropriate SG for each OCR in every network topology. Fani *et al.* [127] presented an adaptive protection framework consisting of offline and online stages. The offline approach was used to obtain a proper setting group compatible with the voltage profiles. In addition, an online technique is used to implement a predetermined setting group depending on existing voltage profiles. The fault current rises according to the voltage profile, thereby reducing the CTI. In such a situation, the CTI must be guaranteed to maintain accuracy throughout the fault duration. Accordingly, on the basis of each voltage profile, how the incremental current changes the CTI throughout the fault interval must be verified. In addition, the contingency fault must be identified. The contingency fault list contains most serious faults. By using an offline approach, it can identify whether the modified current curve runs inside the boundary region. From the voltage profiles, it can predict how the current varies during the fault depending on pre-voltage profiles before the fault occurs. In this way, the modified current curve can be tested.

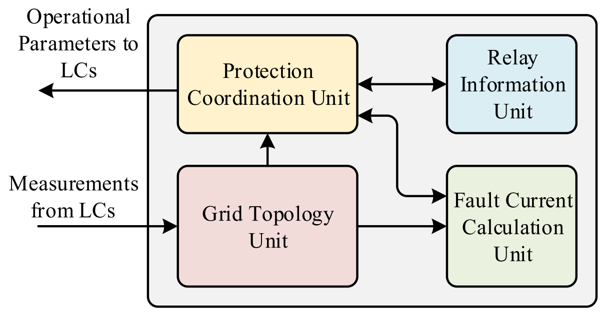


**FIGURE 10.** Flow chart of centralised protection regulator [118].

For a temporary fault, the falling voltage-profile has extra steps of current rise compared to the rising-profile. Meanwhile, the magnitude of this boost depends on the topology of the network, as well as the location of the fault and the resistance [127]. Nevertheless, an adaptive DOCR framework based on the analysis of the fault component is proposed by [128]. This scheme aggregates local measurements (fault current and voltage calculated at the point of the relay) with the NCM and the fault type to identify the online setting of the existing protection in the DG integration with the DN Maqbool and Khan analysed the transient component of the microgrid in the operations of NCM and ISM to determine the required changes in the OCR settings [118]. This scheme consists of local controls (LC) and a central protection regulator (CPR). Signalling and control data between CPR and LCs are conducted through a communication network. LCs are programmable communication-assisted instruments for calculating and evaluating grid parameters, e.g. current, voltage and frequency. The logic for detecting fault direction and fault isolation is established in the LC. The CPR operates as a processor device. Figure 10 illustrates the flow chart of the CPR.

The grid topology unit monitors the DN structure and operation mode. The protection coordination unit computes the relay coordination parameters and updates the LCs. The relay information unit preserves a relay database containing information about the location of relays and their operational configuration. The fault current calculation unit calculates the fault current at different locations in the DN.

Various tasks are assigned by CPR and LC to share the computational load and efficiently handle the distribution system protection strategy. CPR stores the microgrid setup and operating parameters. It is the duty of each LC to trace any alterations in its particular zone and update the CPR on all these changes. To share the burden of the CPR, the corresponding LC shall maintain a record of any changes in its section. Each LC and its operation parameters are monitored by the CPR. It also updates these variables for any variations in the microgrid specification. Whenever a microgrid shifts to an ISM, the CPR identifies and reports the switch to all LCs [118]. The drawback of the centralised adaptive protection technique is the actual cost of its execution. Furthermore, centralised communication systems suffer from a defect, which disturbs the whole protective system.

### H. OTHER PROTECTION METHODS

A dual-setting relay with limited bandwidth connectivity is used to avoid major shortcomings in the operation of these relays throughout backup protection while protection coordinating malfunction occurs [129]. This mechanism could tackle microgrids during both operation conditions without adaptive features. Thus, the transition of modes does not require an algorithm for the detection of FCL. The operating time of the dual-setting DOCR is determined as follows,

$$t_{rw}^{f} = TMS_{fr}\left(\frac{A}{\left(\frac{I_{fault_{frw}}}{I_{pick-up_{frw}}}\right)^{B}-1}\right), \tag{14}$$

$$t_{rw}^{B} = TMS_{Br}\left(\frac{A}{\left(\frac{I_{fault_{Brw}}}{I_{pick-up_{Brw}}}\right)^{B}-1}\right), \tag{15}$$

where $t_{rw}^{f}$, $TMS_{fr}$ and $I_{fault_{frw}}$ denote the operating time of relay $rw$, time multiplier setting and pick-up current forward settings while the relay operates as the primary protection, respectively. $t_{rw}^{B}$, $TMS_{Br}$ and $I_{fault_{Brw}}$ represent the operating time of relay $rw$, the time multiplier setting, and the pick-up current backward settings at the time relay, which takes the role of back-up protection. Optimally, relays coordinate with the dual configuration to reduce the total operating time of the relay for the primary and backup operations for both operating modes (NCM and ISM) given by,

$$t_{\min imize}=\sum_{ci=1}^{ci}\sum_{r=1}^{N}\sum_{w=1}^{L}\left(t_{rw-ci}^{fP}+\sum_{d=1}^{d}t_{rw-ci}^{Bb}\right), \tag{16}$$

where $ci$ is the setting identifier. In the NCM, $ci$ is equal to 1. Meanwhile, the $ci$ value is 2 in ISM. $N$ is the number of the entire relay. $L$ is the fault location number. $t_{rw-ci}^{fP}$ is the main relay $r$ operation time in the forward path, for fault at w and setting $ci$. $t_{rw-ci}^{Bb}$ is the back-up relay $r$ operation time in the reverse path, for fault location at $w$ and configuration $ci$. The minimised operation time in (16) should fulfil the constraints below,

$$t_{rw-ci}^{Bb}-t_{rw-ci}^{fP}\geq CTI, \tag{17}$$

$$I_{pick-up_{r}}{}^{min}\leq I_{pick-up_{fr}}, I_{pick-up_{Brw}}\leq I_{pick-up_{r}}{}^{max}, \tag{18}$$

$$TMS_{r}^{\min}\leq TMS_{fr}, TMS_{Br}\leq TMS_{r}^{\max}, \tag{19}$$

where $I_{pick-up_{r}}{}^{max}$ and $I_{pick-up_{r}}{}^{min}$ are the maximum and minimum pick-up current limits of relay $r$, respectively, in both forward and backward current settings. $TMS_{r}^{\max}$ and $TMS_{r}^{\min}$ are the maximum and minimum time multiplier settings of relay $r$, respectively, based on relay manufacture. Low bandwidth communication is used to ensure the appropriate coordination of back-up relay. Furthermore, the $f_{mincon}$ optimisation function with built-in MATLAB is used to solve equation (16) [129]. Darabi et al. [130] used the GA-PSO algorithm gathered with Rosen's gradient-projection approach and a few manual adjustments to maintain the coordination of dual-setting DOCRs. The total operation time of relays is reduced to 31.87 s compared with the operation time obtained by the $f_{mincon}$ optimisation function in [129]. Rosen's gradient projection and Zoutendijk's methodology are combined with the differential evolutionary algorithm, as proposed by authors in [131] to reduce the total operation time of the dual-setting DOCR. Consequently, the total operation time of the dual-setting DOCR dropped to 30 s. Therefore, the reduction in the total operation time of relays depends on the use of the powerful optimisation technique.

Eluvathingal and Swarup [132] proposed an interface relay dependent on an instantaneous variable sequence for the implementation of IIDG into the DN in NCM. The relay consists of three functional modules: the current module, the direction module and the voltage module. The current module distinguishes the fault condition by comparing current magnitude changes with the threshold. Moreover, the direction module is estimated depending on the difference in the phase angle between the positive sequence voltage and the current. Finally, the voltage module evaluates the voltage magnitude and defines the fault on the basis of the estimated voltage sag. Cui et al. [93] presented digital relay composed of five units: directional, solid fault detection, HIF detection, tripping and auto reclosing unit. Figure 11 illustrates the schematic diagram of the digital relay with five operational units. The directional unit identifies the direction of the fault current. The solid fault detection unit detects the fault by using the Park transformation of grid voltage.

Meanwhile, the HIF detection unit detects HIF by $\alpha\beta$ transformation and discrete WTT. The tripping unit is used to decide when a trip signal will be issued. Lastly, the auto reclosing unit (ARU) is applied to ensure the seamless recoupling of the island section of the DN to the normal section after the clearance of the fault. Hybrid tripping characteristic is presented in [133] to develop a protection scheme. In this scheme, standard OCR and standard under-voltage protection are combined. The operation time of hybrid relay can be calculated by (20),

$$t_{hybrid}=TMS\left(\frac{A}{(M_{1})^{B}-1}+C\right)\left(\frac{\alpha}{1-(M_{V})^{\beta}}+\gamma\right), \tag{20}$$

where $M_1$ and $M_V$ are the multiples of the pick-up current, specifically $\left(\frac{I_{fault}}{I_{pick-up}}\right)$, and the multiples of the pick-up

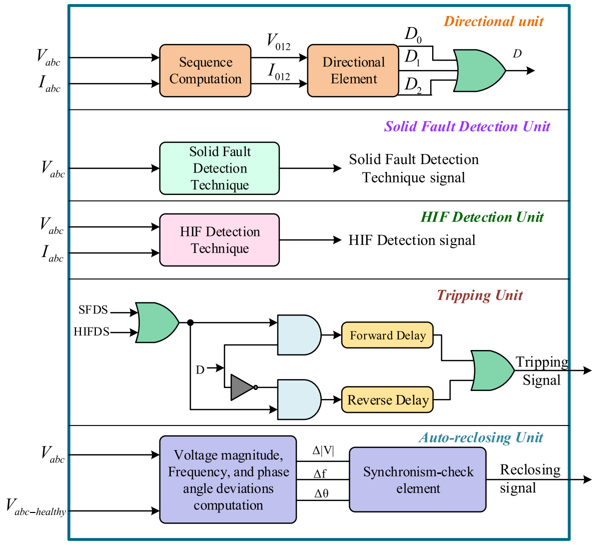


**FIGURE 11.** Schematic diagram of digital relay with five operational unit sections [93].

voltage, specifically $\left(\frac{V_{fault}}{V_S}\right)$, respectively. $I_{fault}$ and $V_{fault}$ are the fault current and voltage measured at the relay point, respectively. $I_{pick-up}$ and $V_S$ are the pick-up current and the relay setting voltage, respectively. $A, B, C, \alpha, \beta$ and $\gamma$ are the relay coefficients and are selected as 0.0515, 0.02, 0.114, 0.03, 0.5 and 0, respectively. The flow chart of the hybrid tripping characteristic scheme is depicted in Fig. 12. The scheme starts by measuring the voltage and current at the relay point. The voltage measurement is used to reduce the OCR pick-up current, to achieve high reliability and to distinguish low fault current circumstances from overloading. Voltage and current phasors are then calculated. When the voltage is below the setting value and the current is above the pick-up current, the directional element is picked up according to the impedance angle of the fault. Then, the operation time is calculated by equation (20), and a trip signal is issued.

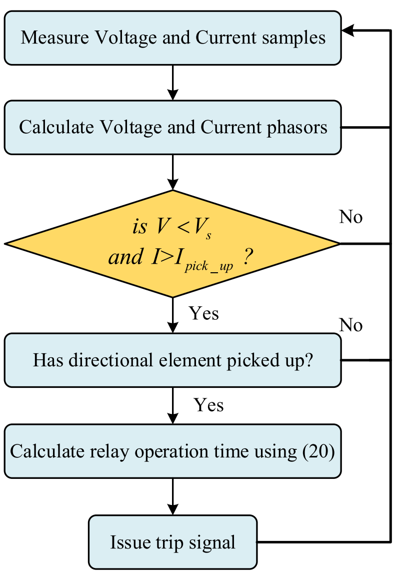


**FIGURE 12.** Flow chart of hybrid tripping characteristic scheme [133].

## V. ISSUES AND CHALLENGES

The incorporation of DGs into the network presents significant issues for implementation of conventional protection strategies, which requires modifications and advanced diagnosis. The functional obstacles that need to be addressed in the development of the DN protection system and its efficient implementation are discussed below.

### A. NON-DETECTION ZONE

The NDZ is known as an active zone when the phenomenon of islanding or fault cannot be identified on time in case of a slight mismatch of power between generation and consumption in this zone [79]. The NDZ depending on the island detection approach is installed, and the threshold values are set. For example, the ROCOV/ROCOF relay [147] has a large NDZ. The NDZ determines the effectiveness of an island detection approach. The negligible NDZ of the island detection approach can be carried out in three ways: signal processing, hybrid and communication- based approaches.

### B. OPERATION MODE OF THE DISTRIBUTION NETWORK

The microgrid has numerous merits and poses several protection issues due to both high and low short-circuit currents throughout the NCM and the ISM. Furthermore, microgrids with critical loads suffer from protection problems, such as delays in the relay operation time [148], due to low fault current magnitude during the ISM [149]. This issue contributes to the outage of critical loads and generators from the DN as a result of the voltage drop they face throughout the delay of the relay tripping time[150].

### C. BI-DIRECTIONAL POWER FLOW

The integration of multiple DGs is altering the conventional radial DN into the complex multisource one [136]. Consequently, conventional protection systems become unreliable or fail to identify faults due to a lack of coordination between relays [128]. Moreover, non-directional OCR are vulnerable to the loss of efficiency in networks, including unnecessary tripping (maloperation) [19]. Therefore, one of the challenges that the protection system encounters is the ability to maintain appropriate coordination under bi-directional power flow circumstances.

### D. THE NEED FOR ADDITIONAL DEVICES AND LOW OPERATING COSTS

When designing a protection system for the DN, several issues should be considered. The important matter is the need for an additional device. For instance, robust communication with a back-up system is required for online monitoring and computation of a short-circuit level for any small variation in the grid parameters [137]. Furthermore, PMUs are used for current and voltage phasors measurements with time reference in the distribution system [48]. In addition, FCLs are used to minimise the fault current in the coordination area [104]. The installation costs must be reduced as far as possible. Cost-effective criterion must be considered, and the costs must be compared with the profits and capability of installed devices [99]. The optimal location can be a cost-effective way for the installation and development of devices, i.e. FCLs, PMUs and communication system. A comprehensive feasibility study must be presented to propose a protection scheme for the DN.

### E. SELECTIVITY AND SENSITIVITY OF AN OVERCURRENT RELAY

The protection schemes may unexpectedly lose selectivity when the DN topology changes due to fault current level and direction changes [120]. In addition, the protection system must disconnect only the smallest faulty region when faults occur. Consequently, the protection system needs to be capable of working selectively for any faults or isolating the faulty area [137]. Additionally, the relay sensitivity should be regulated without impacting the protection scheme selectivity.

## VI. CONCLUSION AND SUGGESTIONS

Nowadays, DGs are highly integrated into DN because of their improved efficiency, reliability and stability. However, the incorporation of DGs in a DN leads to protection problems due to the bi-directional power flow and the change in the fault current level. Thus, the establishment of an efficient fault detection and protection scheme is an urgent necessity to ensure a stable and reliable operation of DG. Therefore, this review paper provides a discussion and an analysis of protection techniques for DGs highlighting classification, operation, parameters, constraints of fault detection, island detection techniques and protection schemes. As a first contribution, this review delivers a detailed insight into various fault detection techniques concentrating on the operational mode, communication methods, DG type, parameters, constraints and advantages. The analysis reveals that the SVM, FIS, DBN and travelling wave technique can detect the fault quickly and accurately. Wavelet transform, statistical morphology and recursive least square methods can detect, classify and locate faults. Furthermore, the HHT, differential relay, power spectral density and fuzzy logic technique can detect and classify the HIF. As a second contribution, this review investigates the various island detection techniques highlighting active, passive, hybrid, communication-based methods. The results indicate that active techniques can detect the islanding in 100 ms and discriminate island events from non-island cases that temporarily exceed the second harmonic of PCC voltage.

Passive techniques can identify the islanding status of near-zero real power mismatch with lower NDZ. The hybrid detection techniques illustrate high accuracy, decrease power system disturbances by limiting the use of active detection methods without compromising their advantages. The CMs provide the fastest island detection, null NDZ, and high reliability. However, CMs for island detection are costly compared to LMs. As a third contribution, this study describes the various protection schemes in a distribution network system concerning parameters, benefits, limitations, operational mode and communication requirement. The analysis demonstrates that differential protection is a fast and reliable backup protection approach. However, it exhibits high capital cost and does not take ISM into consideration. The S-transform can detect HIF, but it has large time consumption. The PMU is efficient for real-time operation and protection. However, it needs a backup protection in case of communication failure. The impedance estimation methods and distance relays improve the relay trip efficiency and ensure protection coordination among traditional power systems and distributed wind generation systems. However, a voltage transformer is required with extra costs, and these methods do not account for the ISM and mesh DN. Although the impedance protection technique is expensive, it brings benefits with regard to quick response time and HIF detection. The S-transform can detect HIF, but has large time consumption. As a fourth contribution, the current study explores the key issues, challenges and identifies the various shortcomings of DG fault detection and protection in terms of cost, bi-directional power flow, operation mode, selectivity and sensitivity of relays. As the fifth contribution, this review proposes some selective recommendations for the advancement of fault detection and the protection schemes of DGs, which are mentioned below.

- Further investigation is required to establish a quick and precise fault detection technique based on voltage protection to protect the DN in both operation modes against symmetrical, asymmetrical and HIF faults.
- Future research work should be conducted on the development of fast and accurate hybrid island detection method that can discriminate island from the non-island situation and operate with various types of DGs.
- Further exploration is necessary to achieve the minimum NDZ that can detect the island when active/reactive power mismatch reaches zero.
- Future examination should be carried out to mitigate distribution protection challenges, such as the bi-directional power flow, operation mode change, complex configuration and high capital cost.
- Further attention is required to develop a digital relay based on dual-setting OCR with under-voltage protection. In addition, the proposed digital relay must maintain the FRT and ARU after the temporary faults.
- The execution of the advanced optimisation technique is required to minimise the total operation time of the digital relay and ensure the proper coordination between the primary and backup relays.

The outcomes of this research towards the enhancement of fault detection and protection schemes in DGs are as follows:

- The critical discussion, analysis, issues and limitations would serve as valuable opportunities and directions for industries, power operator engineers and

decision-makers to encourage investments and carry out further research on DG fault diagnosis and protection connected to DN.
- The information provided may help researchers to select the appropriate fault detection and protection schemes that will improve reliable and stable operations of DGs towards reducing carbon emissions and achieving the global decarbonisation goal by 2050.
- The suggestions offered would be significant in developing an efficient fault detection and protection scheme that can obtain a pathway for future sustainable development goals (SDGs), specifically SDG7, by 2030.

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**YOUNIS M. NSAIF** received the B.S. degree in electrical engineering/power and machine from the University of Diyala, Iraq, in 2008, and the M.S. degree in electrical engineering/power and machine from the University of Baghdad, Iraq, in 2015. He is currently pursuing the Ph.D. degree with the Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, Malaysia. He has been serving as an Electrical Engineer at the Iraqi Ministry of Electricity, Iraq, since 2013. His research interest includes the development of power system protection.

**M. S. HOSSAIN LIPU** received the B.Sc. degree in electrical and electronic engineering from the Islamic University of Technology, Bangladesh, in 2008, the M.Sc. degree in energy from the Asian Institute of Technology, Thailand, in 2013, and the Ph.D. degree in electrical, electronic, and systems engineering from Universiti Kebangsaan Malaysia (UKM), Malaysia, in 2019. He is currently a Senior Lecturer with the Department of Electrical, Electronic and Systems Engineering, UKM. He is also a Coordinator with the Centre for Automotive Research (CAR), UKM. Prior to that, he worked as an Assistant Professor with the Department of Electrical and Electronic Engineering, University of Asia Pacific, Bangladesh. He is the Guest Editor of *Sustainability* (MDPI). His research interests include battery storage and management systems, electric vehicles, power electronics, intelligent controllers, artificial intelligence, and optimization in renewable systems.

**AFIDA AYOB** received the B.Sc. degree in electrical and electronic engineering from The University of Manchester, in 2000, and the Ph.D. degree from Newcastle University, in 2012. She is currently a Senior Lecturer with the Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia. Her research interests include power electronics, energy storage, and artificial intelligence.

**YUSHAIZAD YUSOF** received the B.Eng. degree in electrical and electronics engineering from Kagoshima University, Japan, the M.Eng. degree in electrical engineering from Universiti Teknologi Malaysia, Malaysia, and the Ph.D. degree in power electronics from the University of Malaya, Malaysia. He is currently a Senior Lecturer with the Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia. His research interests include power electronics, motor drive, engineering education.

**AINI HUSSAIN** received the B.Sc. degree in electrical engineering from Louisiana State University, Baton Rouge, LA, USA, the M.Sc. degree from UMIST, U.K., and the Ph.D. degree from Universiti Kebangsaan Malaysia. She is currently a Professor with the Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia. Her research interests include decision support systems, machine learning, pattern precognition, and signal and image processing.