Chapter 1

INTRODUCTION AND LITERATURE REVIEW

This chapter presents a brief overview of the importance of the problem associated with the increasing penetration of renewable energy resources in the power grid. It motivates the foundation for the research conducted and reported in this thesis. This chapter, starting from a background and prevailing situation, furthers by delineating the literature review, research gap, motivation, thesis organization, and concluding remark.

1.1 BACKGROUND OVERVIEW

In its commitment to sustainability, the World has pledged to expand infrastructure and upgrade technology for supplying clean and green energy. India is the third-largest country in the world in terms of energy consumption [1]. The great emphasis and environmental concern have globally driven Renewable Energy (RE) integration into the power grid. The Energy supply by RE generation is shown in Figure 1.1. Worldwide, and RE-based energy supply in India is shown in Figure 1.2. The penetration of RE at the lower level of the grid does not pose any challenge. However, the RE integration at the higher level may pose additional challenges to grid operation because of the intermittency and variability of RE. The total 160 GW of variable RE would meet 22% of India's demand by 2022, including 11% from solar and 12% from wind.

Renewable energy accounts for around 22% of global power generation. Still, this share is expected to double in the next 15 years, partly due to the rapid growth of variable renewable energy from solar photovoltaics and wind. India is on the path toward achieving 175 GW of renewables by 2022 and has announced an ambition to reach 450 GW by 2030.

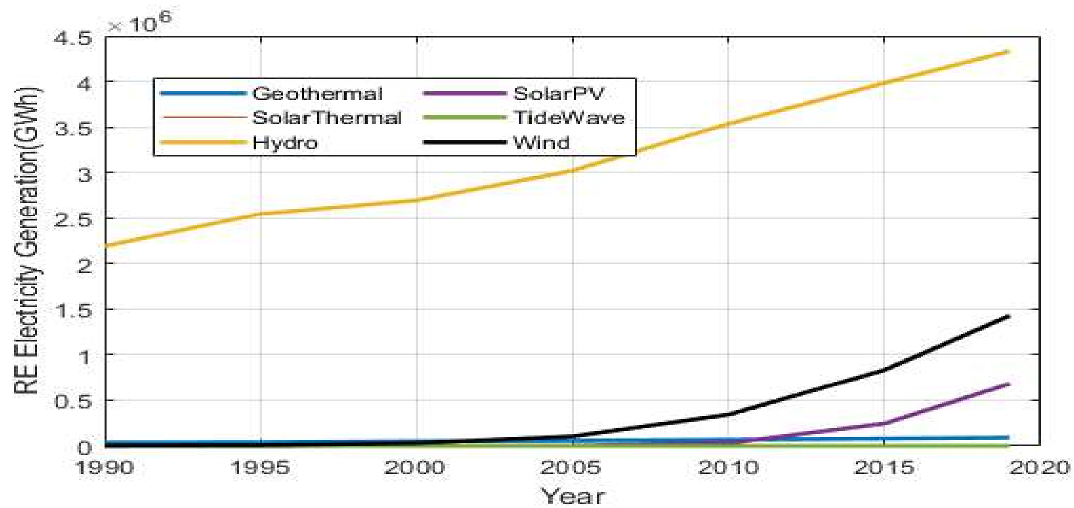

Figure 1.1 Renewable electricity generation, World [1]

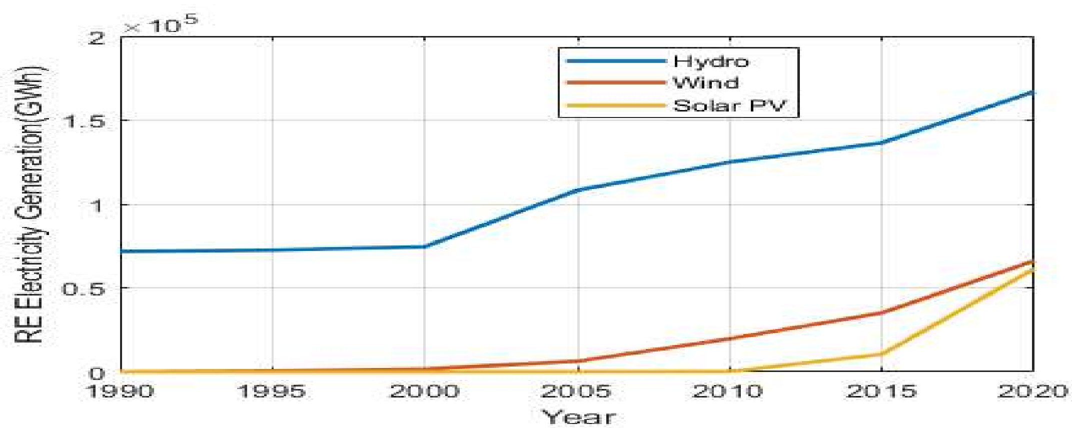

Figure 1.2 Renewable electricity generation, India [1]

The system integration of the renewables framework has been divided into six phases to be successfully managed in each phase by the International Energy Agency (IEA), as shown in Figure 1.3. Most countries globally are in Phases 1 and 2 of system integration of renewables and experience minor system integration challenges. India is in Phase 2 alongside the United States, China, and Mexico. Portugal, Germany, Spain, the United Kingdom, Italy, and the Indian states of Karnataka, Rajasthan, Tamil Nadu, Gujarat, and Telangana are in Phase 3 and are already facing challenges related to integrating high shares of RE. In Phase 3, RE determines the operating pattern of the power system. Karnataka, Tamil Nadu, and Rajasthan are fast approaching Phase 4. Very few countries and regions globally have entered Phase 4; they include Denmark, Ireland, and South Australia. These countries/regions and the Indian states of Karnataka and Tamil Nadu are at the forefront of global integration experiences and already see periods (minutes, hours, or days) when solar and wind constitute almost all power generation. Phase 4 focuses on ultrashort-term flexibility capabilities that will be required to provide flexibility within seconds, with additional focus on flexibility on a timescale from days to weeks. Then in Phases 5 and 6, the focus on flexibility shifts to months and years, often referred to as seasonal flexibility, due to the structural imbalances of solar and wind generation over the seasons[3].

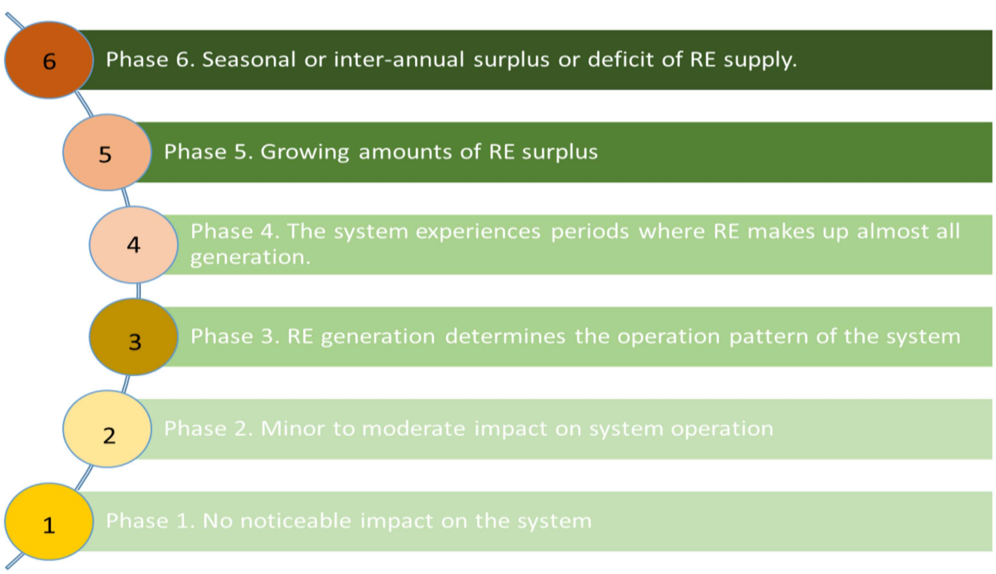

Figure 1.3 Phase of system Integration of renewables [2]

However, this large-scale integration of RE based DERs repeatedly poses a technical challenge to the system operator, such as stability, protection, islanding, and power quality. This is because of the nature of variability and uncertainty of RE sources.

This extensive integration of RE has been supported by smart grid technology and the capability of the flexibility of operation of ADN in a centralized and de-centralized approach.

1.2 MOTIVATION AND PROBLEM STATEMENT

In order to meet the increasing load demand of future electricity grids, the integration of RE in distribution networks is anticipated to play an increasingly important role. Figure 1.4 shows the increase in load demand and RE generation over the Years. There has been a growing interest in the penetration of renewable energy sources in the electric grid due to their potential merits, such as lower CO_2 emission, which reduces the dependability on conventional power sources. However, the inclusion of renewable sources poses additional significant challenges such as bidirectional power flow in the network that may cause malfunctioning of the relays, relay coordination, voltage/frequency control, and islanding detection issues.

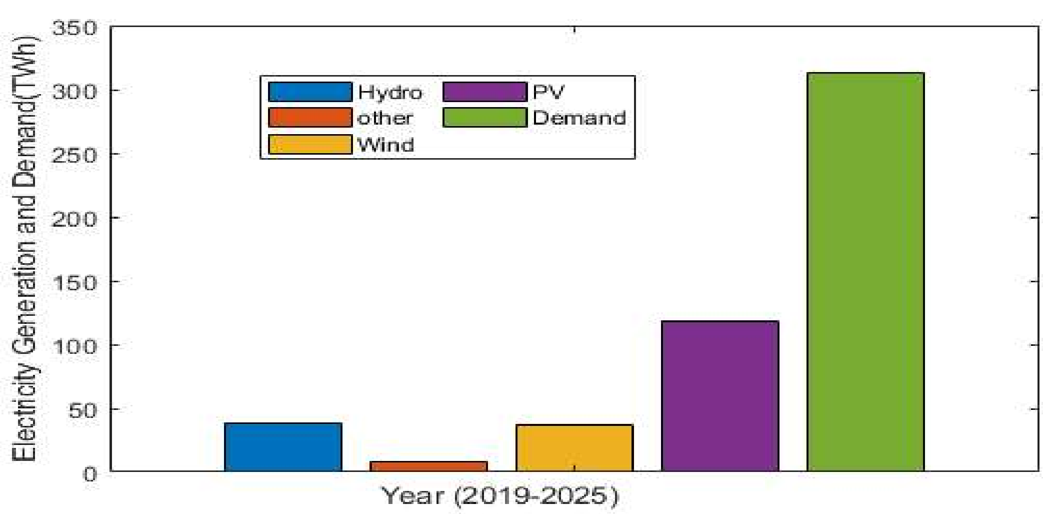

Figure 1.4 RE generation growth and Electricity demand Increment in India [1]

Massive emphasis on integrating renewable sources leads to higher penetration of distributed energy resources (DER) at transmission and distribution levels [3]. Increased

DER integration enjoys the advantage of lower CO_2 emission and reduced dependency on conventional power generation. However, the primary issue with distributed renewable generation is its intermittent nature and variability. Therefore, uncertain power output from renewable sources raises difficulties in operation and control. Fluctuations arising from the intermittencies, apart from affecting the power quality, also affect the system dynamics and possess problems in integrating DER's to the grid. The significant challenges encountered in islanded systems are: (i) significant frequency and voltage variations are observed in the absence of a primary grid (if not regulated adequately), (ii) islanding may create an insecure working environment for utility employees (working personnel) while energization of the line during maintenance, (iii) out-of-phase reclosures may cause significant damage, and (iv) islanding may affect the automatic restoration of service for the nearby consumers. Further, it brings challenges such as the relay's mal-operation due to bidirectional power flow and islanding protection [4]. The severity and sensitivity of the problems arising due to the islanding phenomenon make mitigation of these issues critical, which needs to be analyzed in systems with distributed generation (DG).

1.2.1 Issues of High penetration RE

- Grid Side effect
  - Voltage variation (under-voltage , over-voltage, flicker) Voltage events (sag - swell)
  - Frequency variation (under-frequency or over-frequency)
  - Transients (switching)
  - Harmonic distortion (due to non-linear loads)
- DER side effect

- Injection of fluctuating power
- Islanding detection issues
- Relays co-ordination
- Voltage/ frequency control

1.3 LITERATURE SURVEY

This section gives a literature review on unintentional islanding and power quality disturbance detection and its classification methods. The review contains the advantages, disadvantages, and limitations of the methods reported by researchers.

1.3.1 Islanding detection in Active Distribution Network

When a portion of an area electric power system (EPS) is energized solely by one or more local EPSs through the associated PCCs, that portion of the area EPS is electrically separated from the rest of the area EPS on all phases to which the DER is connected as shown in Figure 1.5. This situation is called an island, and the phenomenon in which the DER energizes the island is called "islanding"[5].

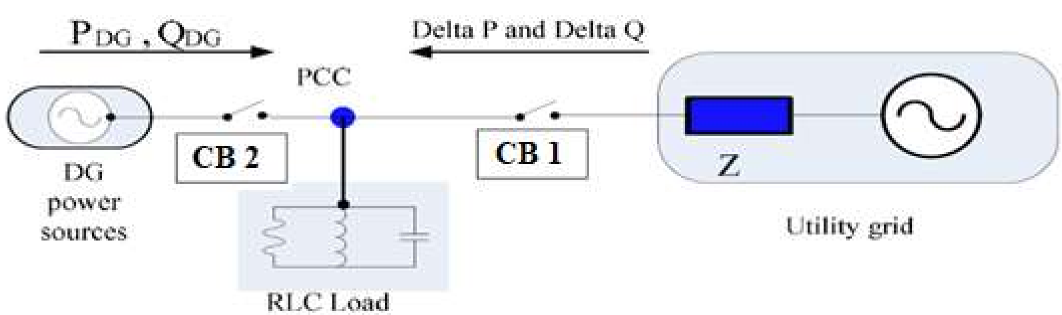

Figure 1.5 Block Diagram of representation of EPS

Islanding has been categorized into two types: intentional islanding and unintentional islanding.

i) Intentional islanding: A planned electrical islanding that is capable of being energized by one or more local EPSs.

ii) Unintentional islanding: A unplanned island where the DER energizes a portion of the area EPS through the PCC.

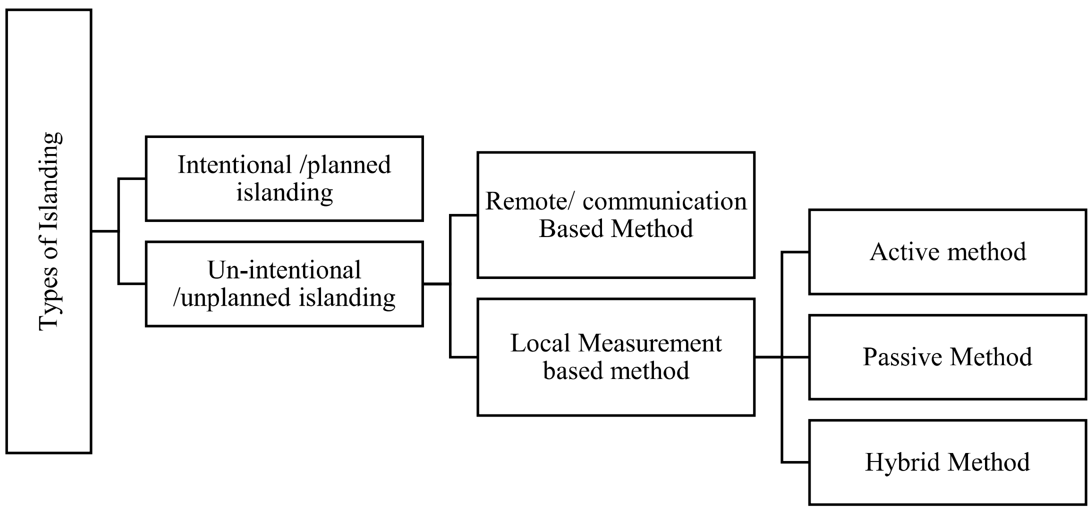

Figure 1.6 Classification of Islanding Detection Technique

The intentional islanding does not threaten the system as the control strategies for such a case are predefined. However, unintentional islanding threatens the system as the primary grid no longer regulates voltage and frequency. As per the IEEE standards, i.e., IEEE 1547 [5], the DG systems' islanding events must be ascertained within two seconds of their inception. Hence, the requirement of a suitable islanding detection technique (IDT) is inevitable for ADN with DER systems. The extensive literature survey of islanding detection has been reported in [6]–[13]. The classification is based on the types of islanding shown in Figure 1.6.

The available IDTs have been categorized into three foremost sets: i). Communication-based IDT, ii) Active IDT, and iii) Passive IDT.

1.3.1.1 *Communication-based IDT*

Communication-based IDTs require additional communication infrastructures such as Phasor Measurement Units (PMUs), Supervisory Control and Data Acquisition (SCADA), and Power Line Carrier Communication (PLCC) in widespread power distribution systems with multiple DGs, laterals, and feeders [14]–[20]. The classification of communication-based IDT is shown in Figure 1.7. The micro-PMU (μPMU) based method utilizing Pearson's correlation coefficient has been discussed in [21]. In [14], principal component analysis and extended mathematical morphological filter have been utilized to process the data set of phasors of voltages, frequency, and rate of change of frequency from different sites in grid-connected MG operation. Due to the expensive and complicated nature of communication, active and passive IDT are preferred over communication type IDT.

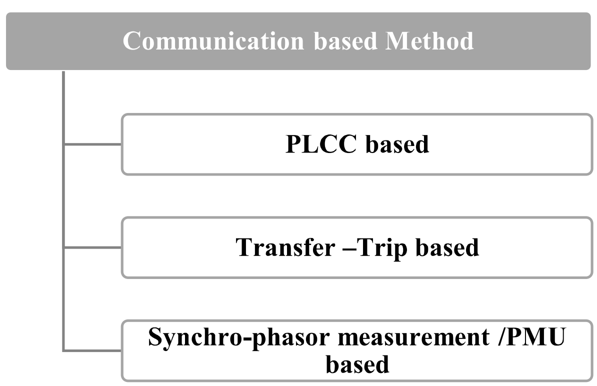

Figure 1.7 Classification of Remote/communication-based IDT

1.3.1.2 *Active IDT*

Active and passive IDTs are based on local information monitored at the DG interconnection point [22]–[31]. Among active IDTs, impedance measurement method [32], phase jump method, active frequency shift (AFS) [33], and Sandia frequency shift (SFS)[34] methodologies have been commonly used for inverter type DGs. Further, different combinations with variations of the above-mentioned IDTs have also been utilized for inverter type DERs. However, the existence of a minor Non-detection Zone (NDZ) in active IDTs reduces its accuracy and capability of islanding detection because it is continuously injecting the disturbance signal at the point of common coupling (PCC), and degrades the power quality, and injects harmonics in the voltage signal. Further, it increases the complication during fine-tuning of the control loop in the inverter type DERs operation. Figure 1.8 has shown some critical active IDT classification.

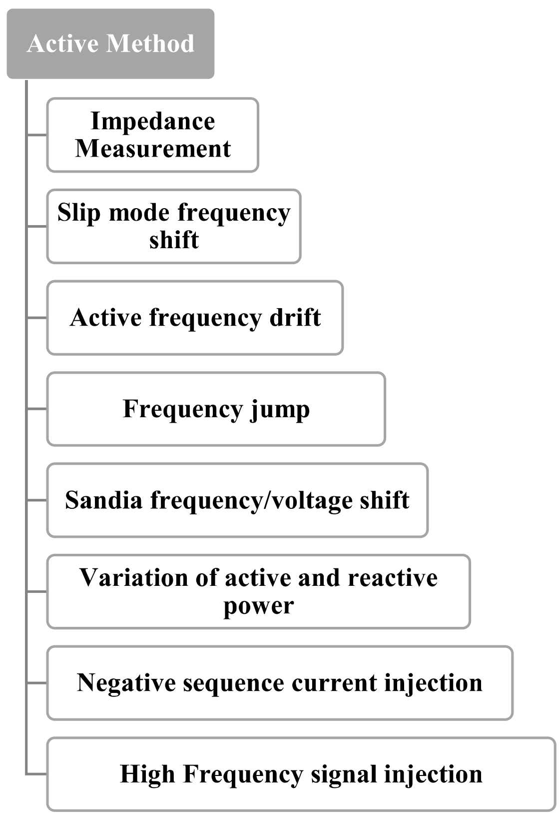

Figure 1.8 classification of active IDT

1.3.1.3 *Passive IDT*

Passive IDTs based on under-voltage/frequency and over-voltage/frequency relays, ROCOF relay, is widely used for Islanding protection schemes [35]–[47]. The passive IDTs have been performed remarkably when the power deficit between load and generation exists, but it fails to detect islanding events if power mismatch is insignificant.

With the use of advanced signal processing tools, the passive method overcomes its limitation of large NDZ.

In recent years, several advanced signal processing-based IDTs have been developed. These methods are classified into frequency and time domains. Discrete Fourier Transform (DFT), Short-time Fourier transforms (STFT), Wavelet transforms (WT) [48], S-transform (ST), Mathematical Morphology (MM) [48], and Empirical Mode Decomposition (EMD)[49] are some examples of signal processing based passive IDT. However, STFT uses a fixed windowing approach for transient signal analysis; hence, the technique is not commonly employed. S-transform has a modified form of STFT with variable window size. WT is a significantly used signal processing tool that extracts the signal feature, but it has limitations in selecting mother wavelets and noise signal sensitivity. In various time-frequency based decompositions, EMD has been used. It is affected by external noise presented in the system.

In [50], a Grey Wolf Optimized Artificial Neural Network (GWO-ANN) amalgamated with Intrinsic Mode Function (IMF) has been proposed as an intelligent islanding detection method. Here variational mode decomposition and Hilbert transform have been utilized to obtain the IMF for the modal voltage signal, the standard deviation, and the energy of IMFs are employed for training/testing the GWO-ANN model; the developed model has been used for identifying the islanding operations from other non-islanding events. In [51], islanding detection in the distribution system for synchronous generator type DGs has been proposed to utilize the dynamic equations of three electrical variables islanding situations. The variables' have been transformed using the space vector domain in three parameters: semi-major/minor axis and inclination angle. The parameters have been used to yield a decision boundary used to classify islanding or non-islanding events. In [52], a parallel inductive impedance (PII) switching-based IDT has been proposed. In this IDT, switching the PII at the DG location produces a minimal variation in the dv/dt in the case when DG runs analogous with the main grid. However, the variations will be very large during the occurrence of islanding. The variation of the dv/dt has been processed by fast Fourier transform (FFT) for better resolution. All type of impedances has been tested but purely inductive impedance has better performance than other impedance types. In [53], impedance monitoring through injecting low-frequency current parameter at the terminal of DG has been proposed for inverter type DG. In [54], six features such as zero, negative and positive components are extracted from the second harmonic component of voltage and current signals through Discrete Fourier Transform (DFT). These extracted features are used for deep learning classifiers using the Long Short-Term Memory (LSTM) network for fast detection of islanding events in a microgrid (MG). In [55], the energy preserving ensemble empirical mode decomposition technique and least square support vector machine (LSSVM) have been used to detect evolving disturbances in the system. It has been implemented in real-time in Field-Programmable Gate Array (FPGA) blocks to detect changing disturbances.

In [56], time-varying filter-based empirical mode decomposition has been utilized to decompose the measured voltage signal at the distributed generation into various intrinsic mode functions (IMF). Further, the Teager energy operator has been utilized to extract the IMF's energy to classify the islanding scenario. In [57], the amalgamation of a time-varying filter and time domain decomposition has been used to decompose the signal and extract the features. Further, the machine learning Ensemble k-Nearest Neighbor (EkNN) classifier has been used for the islanding condition by applying the feature vector generated using signal decomposition processes to make the final decision. A discrimination factor based method for islanding detection has been proposed in [58]. The discrimination factor is determined using the autocorrelation factor of the voltage signals, which are fetched from the terminal of the DG system. In [59], periodic maxima of superimposed voltage components based IDT have been proposed and implemented on the digital platform using Verilog hardware description language targeted on the field-programmable gate array. In [60], a mode singular entropy-based IDT has been proposed for integrated microgrids. The voltage signal has been decomposed into four modes by variational mode decomposition. Further, these four modes have been processed through singular value decomposition to determine the mode singular entropy used to classify islanding events. In [61], selected harmonic distortion has been utilized for detecting islanding from measured voltage signals using the Kalman filter. Hybrid and intelligent IDTs [51]-[62] have been reported by researchers exploring Artificial intelligence (AI) based, soft computing techniques such as SVM and pattern recognition for Islanding detection. However, the requirement of a large amount of training and testing data is a major drawback of these IDTs. The classification of passive IDT has been shown in Figure 1.9 from the extensive literature review.

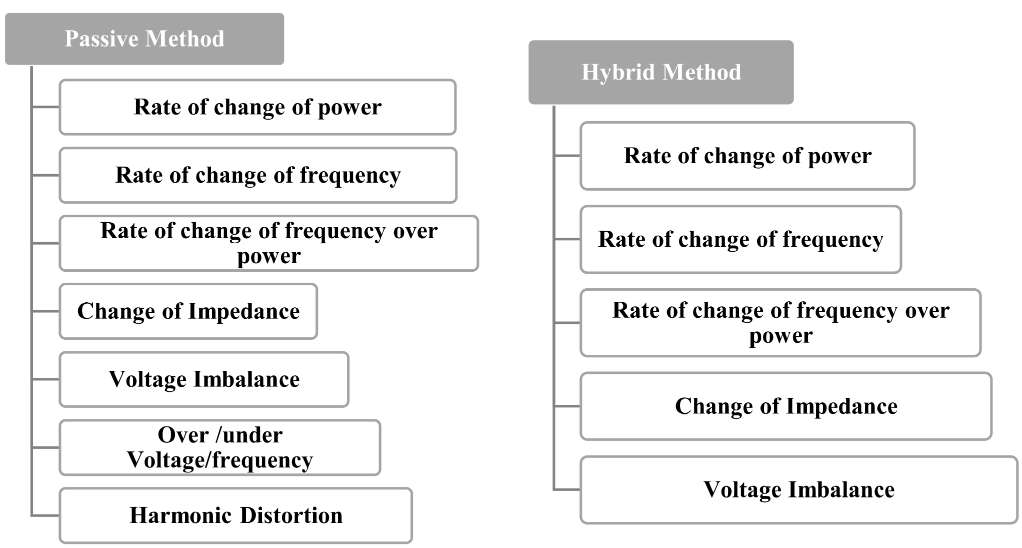

Figure 1.9 Classification of Passive IDT methods

Table 1-1 Differences in Active and Passive IDTs

	PASSIVE METHOD	ACTIVE METHOD
Principle	**Monitoring changes in voltage, current, frequency, harmonics**	**Apply disturbances from distributed resources**
Detection Time	**Short**	**Long**
Dead Zone	**Required**	**Not required**
Mal-operation	**Possible**	**Not so possible**
Influence on system	**No**	**Possible such as voltage fluctuation**

1.3.2 Power Quality Disturbance classification and detection

The operation of the electric power system ensures the continuous supply of undistorted sinusoidal rated voltage and current at the rated frequency to the load centers. However, disturbances and faults in electricity networks may create abnormal events. Detection, classification, and characterization of these abnormal events are essential, as it finds their application for protection and mitigation issues and post-mortem analysis.

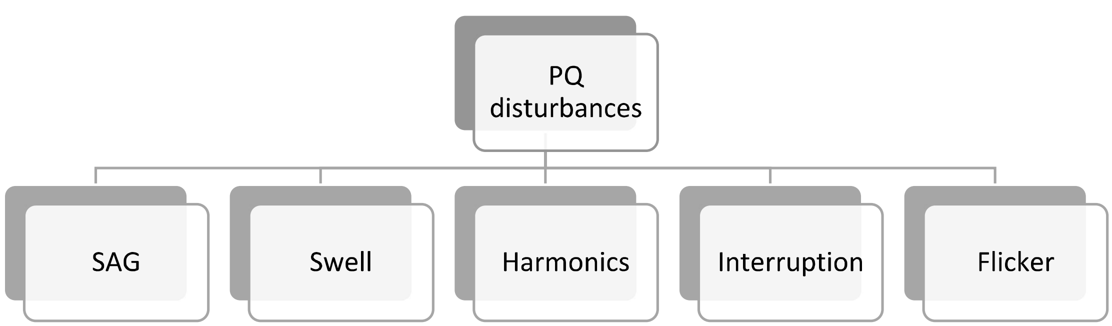

Figure 1.10 Classification of PQ disturbances

In [63]–[66], a comprehensive review of PQD detection techniques has been reported. It provides various concepts utilized for extraction of the features to detect and classify the PQ disturbances even in a noisy environment. A critical review of the state-of-the-art techniques based on Digital Signal Processing (DSP), Artificial Intelligence, Machine Learning, and optimization techniques for automatic recognition of PQ events. It is aimed to present extensive information on the status of detection and classification of PQ events to academics following a line of investigation on a similar domain. In [67], symmetrical components-based detection and classification of various power-quality (PQ) disturbances have been proposed. Triggering points for PQ disturbances have been detected from the negative sequence component of the disturbance phase and have been classified from the signatures of the waveforms using the summation of the positive and negative sequence components. In [68], a Discrete Wavelet Transform (DWT) based method has been proposed to determine the deviation from the weighted sum of percentage energy deviation of the DWT.

In [69], two-stage feature extraction using the wavelet transform method was used to obtain the distinctive features of event signals. In the first stage, power quality event types are determined using a support vector machine classifier, and in the second stage of the intelligent recognition system, types of power quality disturbances regarding each fault event are identified by further analysis. In [70], Wavelet Transforms (WT) and Support Vector Machines (SVM) based method on a combination of binary classifiers which are optimized for those special cases where the real signals contain a multitude of events within the analyzed temporal window. In [71], a PQ monitoring system based on wavelet packet decomposition (WPD) has been proposed to detect five different types of disturbances in the presence of noise. In [72], tunable-Q wavelet transform (TQWT) and dual multiclass support vector machines (MSVM) have been proposed for the detection of power quality disturbances. The proposed approach first investigates the presence of low-frequency inter harmonics and then tunes the wavelet to decompose the signal into fundamental and harmonic components. In [73], wavelet and random forest-based feature extortion and classifier have been used to implement it in real-time on myRIO-1900 using the LabVIEW interface of an optimized power quality events classifier for the detection and classification of 21 classes of single and combined disturbances. The classifier is the real-time implementation of optimal feature extraction, optimized classification, accurate zero-crossing detection, and efficient handling of different noise levels present in the voltage signal.

In [74], Stockwell's transform (ST) based voltage signal decomposition and features are extracted for power quality disturbances assessment. In [75], a modified optimal fast discrete Stockwell transform (ST) with random forests (RF) classifier-based PQ detection framework has been proposed. In modified ST, a single signal-dependent window is introduced, with optimally selected window parameters via energy concentration maximization-based constraint optimization. In [76], a Histogram of Oriented Gradients (HOG) and Support Vector Machine (SVM) has been proposed to distinguish power quality events. In [77], Stockwell's transform and Fuzzy C-means (FCM) clustering initialized by a decision tree have been proposed for the detection and classification of power quality (PQ) disturbances. In [78], ST and Extreme Learning Machine (ST–ELM) based approach to classify power quality (PQ) event signals has been proposed. In this approach, the distinctive features of the PQ event signals have been obtained with the S-Transform-based feature extraction. The feature vector obtained with feature extraction has been applied as input to the ELM classifier.

In [79], proposes a novel decomposition and estimation method for instantaneous PQ indices (PQIs) monitoring in single- and three-phase systems with inter harmonics and transient disturbances. A new scaling filter and wavelet filter with narrow transition bands are designed for the Undecimated Wavelet Packet Transform (UWPT) to separate the inter harmonic components. In [80], proposes an integrated framework of an optimized S-transform (OST) and kernel SVM (KSVM) classifier for the classification and detection of various PQD signals. In [55], presents ensemble empirical mode decomposition (EPEEMD) and least square support vector machine (LSSVM) technique to detect evolving disturbances in succession and classify. In [81], proposes a universal approach for detecting power quality disturbances within large datasets regardless of the event's root causes. It is based on comparing the shapes of multiple cycles of waveform data through similarity scores. Pre-processing techniques to enhance the detector accuracy are presented. In [82], a new method for power quality disturbance identification and classification has been proposed by constructing a new deep convolutional network structure. The database established according to the power disturbance signal calibrated by an n-dimensional unit vector is first adopted to train the deep convolution network consisting of a five-layer 1D- MIR structure and a three-layer full-connection layer. Then, the network trained and optimized by the gradient descent method and adaptive moment estimation method (Adam) is applied to power quality disturbance identification and classification, thus improving the classification accuracy and speed.

In [83], proposes an Orthogonal Empirical Mode Decomposition (OEMD) implemented in Field-Programmable Gate Array (FPGA) to identify PQ and islanding events in real-time. In [84], Multiresolution S Transform (MST) and Decision Tree (DT) based PQ disturbance signal recognition method has been reported. A controllable time-frequency resolution has been obtained using adjustment factors to improve recognition accuracy. Five statistics features were obtained to quantitatively reflect the characteristics of the analyzed power quality disturbance signals, which is less than the traditional S-transform-based method. In [85], A new method of instantaneous feature extraction based on empirical wavelet decomposition and multi-scale fluctuation-based dispersion entropy (MFDE) has been proposed. In [86], Variational Mode Decomposition (VMD) and Detrended Fluctuation Analysis (DFA) based PQD for distribution networks with distributed generation have been proposed. The mode functions containing characteristic information are extracted as input signals to the DFA to detect and classify the nine types of power quality disturbances in the distribution network.

In [87], VMD and Weighted Online Sequential Extreme Learning Machine (WOSELM) has been integrated to detect and classify the power quality events. The Band-Limited Intrinsic Mode Functions (BLIMFs) indices' four effectual power quality indices were used to classify single and multiple PQEs using different advanced classifiers. In [88], VMD and decision tree-based detection and classification method of single and mixed power quality (PQ) disturbances in the grid-connected distributed generation system. In [89], utilize amplitude, disturbance duration, and total harmonic distortion from the captured waveform and long short-term memory (LSTM) network to recognize PQ events. This Artificial Intelligence is the long short-term memory (LSTM) network, which detects and classifies the PQ events in one step.

1.4 RESEARCH GAP AND MOTIVATION

The research gap has been identified during the literature review mainly divided into two critical problems i) islanding detection in an active distribution network and ii) Power quality disturbance detection in a highly RER penetrated active distribution system/Microgrid. In this thesis work, fast, accurate passive IDT has been developed for addressing the islanding detection in ADN, and simple online monitoring of power quality disturbance has been proposed.

1.5 THESIS ORGANIZATION

The thesis has been segregated into six different chapters, starting with a brief introduction, literature review, and research gap in the first chapter; the subsequent chapters to follow primarily discuss: -

- **Chapter 2:** Application Of Signal Processing Methods In Islanding And Power Quality Disturbance Detection
- **Chapter 3:** Passive Method For Islanding Detection Using Variational Mode Decomposition
- **Chapter 4:** Real-Time Simulation Of Variational Mode Decomposition Method For Islanding Detection
- **Chapter 5:** Detection And Classification Of Power Quality Disturbance Using Variational Mode Decomposition

Finally, the last chapter concludes the work and provides a brief overview for further research and future scope.

1.6 SUMMARY

This chapter introduces the problem and an in-depth literature review of various aspects touched through the work reported in this thesis, followed by the research gap and motivation. At the end of this chapter, a brief sequential organization of the various topics covered has been delineated. The next chapter will provide a basic understanding of signal processing techniques used for islanding and power quality application in power systems.