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DETECTION AND CLASSIFICATION OF POWER QUALITY DISTURBANCES IN EMERGING POWER SYSTEM USING SOFT COMPUTING TECHNIQUES: A REVIEW

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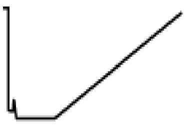
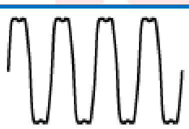
ABSTRACT: The penetration of renewable energy (RE) sources to meet energy demands and meet de-carbonization targets is growing global concern over power quality. Because of the changing outputs and interface converters, power quality (PQ) disruptions are increasingly prevalent with RE penetration. To provide clean electricity to the consumer, it is necessary to recognize and mitigate PQ disruptions. The strategies for detecting and classifying PQ disturbances in the electrical system with renewable energy penetration are reviewed in this article. The overall goal of this review paper is to present alternative methods for extracting features in order to detect and categorize PQ disturbances in noisy environments. The overall goal of this review paper is to present alternative methods for extracting features in order to detect and categorize PQ disturbances in noisy environments. Several research papers have been critically examined, categorized, and listed for engineers, scientists, and academics working in the field of power quality.

INDEX TERMS: Artificial intelligence, power quality disturbances, international standards of power quality monitoring, signal processing, renewable energy sources, noise.

1. Introduction

Nowadays, the word "power quality" refers to a broad concept. Power quality is becoming a problem for both electric companies and customers. Poor power quality is also caused by the increased usage of solid-state switching devices, nonlinear and power electronically controlled loads, unbalanced power systems, lightning control, computer, and data processing equipment, as well as industrial plant rectifiers and inverters. Non-linear loads, switching events, and network failures are the main causes of power quality disruptions in growing power systems with power electronic converters (PQDs). Poor power quality causes customer-sensitive equipment to malfunction system of power. As a result, power quality monitoring is becoming increasingly necessary in the evolving power system in order to protect electrical and electronic equipment while also determining the source of the disturbance. As a result, current research is concentrating on detecting and classifying power quality issues in future power systems. Table 1 shows the waveform representation of various power quality disturbances generated using the mathematical models of respective power quality disturbances

Table 1: Power Quality Disturbances

Wave shape or RMS variation	**Causes**	**Sources**	**Effects**	**Power conditioning solutions**
	Impulsive transients (Transient disturbance)	-Lightning -Electrostatic discharge -Load switching -Capacitor switching	Destroys electronic chips and regulators	-Surge arresters -Filters -Isolation -Transformers
	Oscillatory transients (Transient disturbance)	-Line/cable switching -Capacitor switching -Load switching	Destroys electronic chips and regulators	-Surge arresters -Filters -Isolation -Transformers
	Sags/swells (RMS Disturbance)	Remote system faults	Motors stalling and overheating Computer failures ASDs shutting down	Ferro resonant transformers Energy storage technologies Uninterruptible power supply (UPS)
	Interruptions (RMS disturbance)	-System protection -Breakers -Fuses -Maintenance	Loss production Shutting down of equipment	Energy storage technologies UPS backup generators
	Under voltages/ over voltages (steady-state variation)	-Motor starting -Load variations -Load dropping	Shorten lives of motors and lightning filaments	Voltage regulators Ferroresonant transformers
	Harmonic distortion (steady-state variation)	-Nonlinear loads -System resonance	Overheating transformers and motors Fuses blow Relays trip Meters mis-operation	Active or passive filters Transformers with cancellation of zero sequence components
	Voltage flicker (steady-state variation)	-Intermittent loads -Motor starting -Arc furnaces	Lights flicker Imitation	Static VAR systems

2. POWER QUALITY

Today's common word for describing the interference of power electronics devices is "power quality." Power quality refers to any issue with a power source that causes a change in voltage, current, or frequency that causes end-user sensitive equipment to malfunction or fail. Power quality is a crucial problem in terms of the equipment which is user-sensitive is a major concern. Customers and utilities alike are now worried about power efficiency. Table 2 displays the types of power quality events based on time span and voltage strength/magnitude. The growing research interest in the field of power quality can be seen immediately in Fig. 1, which depicts the statistics of articles published per year that were indexed by the Google Scholar database by using the exact search phrase power quality in the title of each article. Since 2001, there has been a surge in interest in the field of PQ. Power electronic technology is used in the integration of renewable energy sources and distributed generation into power grids, which can cause numerous PQ disturbances in electric power systems. As a result of the increased applications of power electronic converters in distributed generation and renewable energy sources, the future research trend in the area of PQ analysis will be increased. [13].

Table 2: Types of Power Quality Events

Power Quality Events		**Time Span**	**Voltage Strength/Magnitude**
Short Span Variation			
Sag	Instantaneous	0.5-30 cycle	0.1-0.9 pu
	Momentary	30 cycles-3sec	0.1-0.9 pu
	Temporary	3sec-1min	0.1-0.9 pu
Swell	Instantaneous	0.5-30 cycle	1.1-1.8 pu
	Momentary	30 cycles-3sec	1.1-1.4 pu
	Temporary	3sec-1min	1.1-1.2 pu
Interruption	Momentary	0.5cycle-3sec	<0.1 pu
	Temporary	3sec-1min	<0.1 pu
Long Span Variation			
Interruption(sustained)		>1min	0.0 pu
Overvoltage (OV)		>1min	0.8-0.9 pu
Undervoltage (UV)		>1min	1.1-1.2 pu
Transients			
Impulsive	Nanosecond	<50 nsec	
	Microsecond	50-1 msec	
	Millisecond	>1 msec	
Oscillatory	Low frequency	0.3–50 msec	
	Medium frequency	20 μsec	
	High frequency	5 μsec	
Voltage Unbalance(VU)		Steady State	0.5-2%
Waveform Distortion			
Dc offset		Steady State	0-0.1%
Harmonics		Steady State	0-20%
Interharmonics		Steady State	0-2%
Notching		Steady State	
Noise		Steady State	0-1%

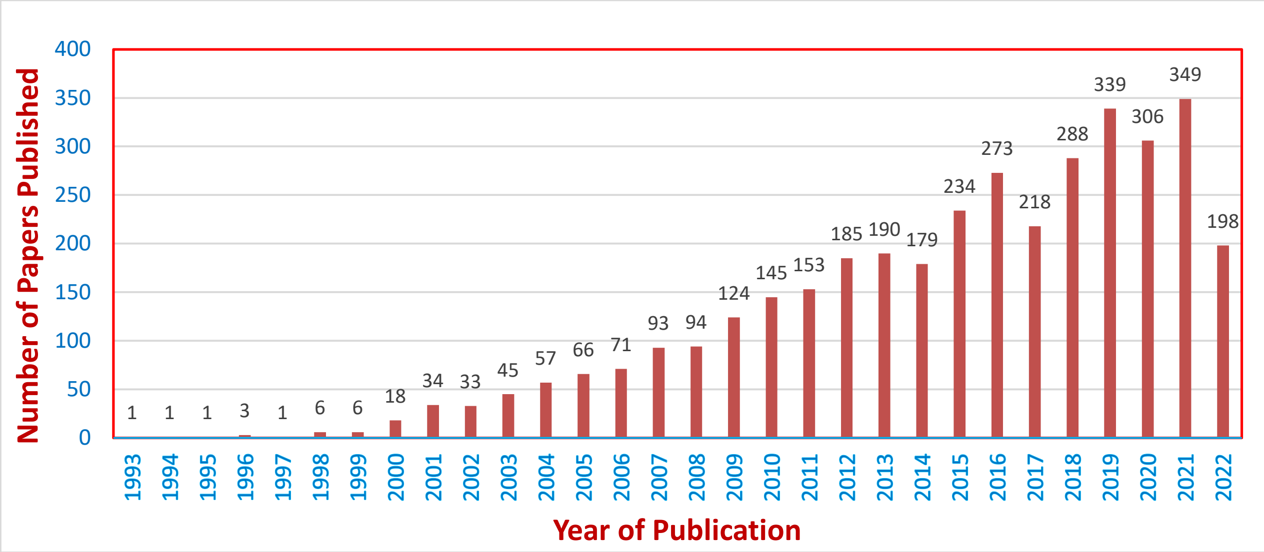


Fig1: Number of Papers Published each year in the field of Power Quality (Indexed by Google Scholar)

In recent years, research on PQ issues and its detection principle has been increased. Several authors have proposed various power quality detection and classification technique.

In [1], Kamarulazhar Daud and et. al. proposed a novel algorithm to detect voltage sags and transient detection and classification using half/one-cycle windowing techniques based on continuous s-transform with neural network. The system using 14 bus bars based on IEEE standards had been designed using MATLAB©/Simulink to provide PQD data. The data of PQD is analyzed by using WT based on CST to extract features and its characteristics. Besides, the study focused on an important issue concerning the identification of PQD selection and detection, the feature and characteristics of two types of signals such as voltage sag and transient signal are obtained. After the feature extraction, the classified process had been done using NN to show the percentage of classification PQD either voltage sags or transients. The analysis show which selection of cycle for windowing technique can provide the smooth detection of PQD and the suitable characteristic to provide the highest percentage of classification of PQD [1].

In [2], CagrıArikanet and et. al proposed Classification of Power Quality Disturbances at Power System Frequency and Out of Power System Frequency Using Support Vector Machines. In this paper, author tried to classify pure sine and power quality disturbances (PQD) such as voltage sag, voltage swell, voltage with harmonics, transients and flicker at power system frequency (50 Hz). Wavelet transform (WT) is used to extract distinctive features. Wavelet energy criterion is applied to wavelet detail coefficients. It is seen that classification performance of support vector machine (SVM) used as classifier is well. Then pure sine and PQD that are out of power system frequency are classified. Curve fitting approach is used for estimating frequency. It is observed that SVM classifies PQD signals well when frequency of pure sine is updated with the frequency of PQD even if they deviate from 50 Hz.

In [3], Prakash K. Ray and et al. present the classification of PQ disturbances by extracting ten different statistical features through S-transform. Classification of PQ disturbances is done by using modular probabilistic neural network (MPNN), support vector machines (SVMs), and least square support vector machines (LS-SVMs) techniques.

In [4], Swarnabala Upadhyaya and et. al suggest Automatic Classification of Power Quality Disturbances Using Hidden Markov Models In this paper, the Discrete Wavelet Transform is implemented for detection of ten types of the power quality (PQ) disturbance signals. Further, four features of the single as well as the combined PQ signals disturbances are extracted from these wavelet transforms coefficients. The features are plotted with reference to their decomposition levels in order to distinguish the disturbances with their feature value. The Discrete Wavelet Transform is implemented for detection of ten types of the power quality (PQ) disturbance signals.

In [5], Okelola and et. al. suggests Detection and Classification of Power Quality Event using Discrete Wavelet Transform and Support Vector Machine. To detect power quality disturbances, discrete wavelet transform was adopted in the feature extraction process. For the classification of the power disturbances support vector machine was used. Synthetic power quality signals were used in this paper. The synthetic signal was generated using synthetic parametric equations; the signal was filtered to remove unwanted noise. Events such as dip, swell and interruption were introduced to the signal. Discrete Wavelet Transform is then used for the detection of the events and change points, the signals of each event were trained using Support Vector Machine. The results obtained from the developed system show a high degree of classification rate.

In [6], Sharmistha Sarkar , suggests the Power Quality Disturbance Detection and Classification using Signal Processing and Soft Computing Techniques. In this work a hybrid technique is used for characterizing PQ disturbances using wavelet transform and fuzzy logic. Various PQ events are generated and decomposed using wavelet decomposition algorithm of wavelet transform for accurate detection of disturbances. It is also observed that when the PQ disturbances are contaminated with noise the detection becomes difficult and the feature vectors to be extracted will contain a high percentage of noise which may degrade the classification accuracy. Hence a Wavelet based denoising technique is proposed in this work before feature extraction process. Two very distinct features common to all PQ disturbances like Energy and Total Harmonic Distortion (THD) are extracted using discrete wavelet transform and are fed as inputs to the fuzzy expert system for accurate detection and classification of various PQ disturbances. The fuzzy expert system not only classifies the PQ disturbances but also indicates whether the disturbance is pure or contains harmonics. A neural network-based Power Quality Disturbance (PQD) detection system is also modeled by implementing Multilayer Feed forward Neural Network (MFNN).

In [7], Ghada S. Elbasuony and et al. proposed a unified index for power quality assessment in different distributed generation system. The proposed index can facilitate overall power quality evaluation. Based on the values of the index it was found that the hybrid energy system shows better power quality performance compared to the other systems.

In [8], Moises V. Ribeiro and et. al. suggests a “Emerging Signal Processing Techniques for Power Quality Applications By looking into the development offered by signal processing techniques to the analysis of other well-known signals, such as speech and image, we speculate that we are just at the beginning of a challenge revolution in the power quality field. In fact, the use of signal processing techniques can impact the way that voltage and current signals are measured and analyzed in power system field. In the regard, we point out that power quality analysis is a new research area for the signal processing community as it requires the development of powerful and efficient methods dedicated to emerging power quality problems, for example, pattern classification, multi resolution analysis, statistical estimation, adaptive and nonlinear signal processing, and techniques that can be implemented on power quality (PQ) monitoring equipment.

In this contribution, the authors address the algorithm for identifying power frequency variations and integer harmonics by using a wavelet-based transform.

In [9] Shouxiang Wang and et al. proposed a novel full closed-loop approach to detect and classify power quality disturbances based on a deep convolutional neural network. In the proposed deep convolutional neural network, multiple units are stacked to extract features from massive disturbance samples automatically. The proposed method can overcome defects of the traditional signal processing and artificial feature selection. Simulation and field data from a multi-micro grid system are used to prove the validity of the proposed method.

In [10] Lin and et al. proposed power quality disturbance (PQD) recognition method based on image enhancement techniques and feature importance analysis. They converted PQD signals into gray images, disturbance features are extracted from the binary images using the sequence forward search method. Random forest classifier is used to identify the PQD signals. Results of simulation and experiments shows the efficacy of new method. A detailed analysis of PQ classification techniques along with related accuracies is done and shown in table 3.

Table 3: Recognition accuracies of the PQ classification techniques.

Reference	**Feature Extraction**	**Classifier**	**Feature Selection**	**Classification Accuracy %**	
				Without Noise	With Noise(30dB)
Liao(2004)(17)	FT–WT	FES	-	99	-
Wang(2011)[29]	DWT	-	EGA	96	-
Eristi(2012) [28]	DWT	SVM	-	98.51	-
Eristi (2013) [15]	DWT	LS-SVM-KMA	-	98.88	98.14
Zhang (2012) [19]	WPT	MSVM	-	97.7	92.25
Hashemine jad(2012) [21]	ST	HMM	-	98.14	95.05
Shunfan(2013[24]	ST	DT	-	99.27	97.91
Biswal(2009) [20]	HST	FCM	GA	95.75	-
Biswal(2013) [22]	FDST	FDT	-	98.66	97.948
Eristi (2014) [23]	S	ELM	-	99.50	99.67
Ray (2014) [30]	HST	SVM-DT	GA	99.5	96.1
Biswal(2011)[31]	TTT	FCM	ACO	95.97	-
Lee (2011) [27]	ST–TTT	PNN	PSO	96.3	96.1
Jashfar(2013)[26]	ST–TTT	FFNN	-	92.083	-
Abdelsalam (2012) [18]	KF–DWT	FES	-	98.7197	97
Saxena(2014)[25]	HHT	PNN-SVM	-	100	-
Daud(2017)[1]	WT	CST-NN	-	95	97
Arikan(2013)[2]	WT	SVM	-	97.905	91.12
P.K.Ray(2013)[3]	ST	LS-SVM	-	98.21	94.66
Swarnabala(2015)[4]	WT	HMM	-	72.92	64.35
Okelola(2015)[5]	DWT	SVM	-	89.33	-
Sarkar(2014)[6]	WT	FES	-	97	-
Wang(2019)[9]	WT	DNN		100	-
Lin(2019)[10]	ST-EMD	RF	Gini importance-SFS	96.22	99.44

3. SYSTEM FOR DETECTION AND CLASSIFICATION OF POWER QUALITY DISTURBANCES

Power systems can be simulated in MATLAB Simulink environment. Various power quality disturbances will be simulated and monitoring of voltage and current signal can be done. Figure 2 shows PQ Disturbances Detection and Classification System.

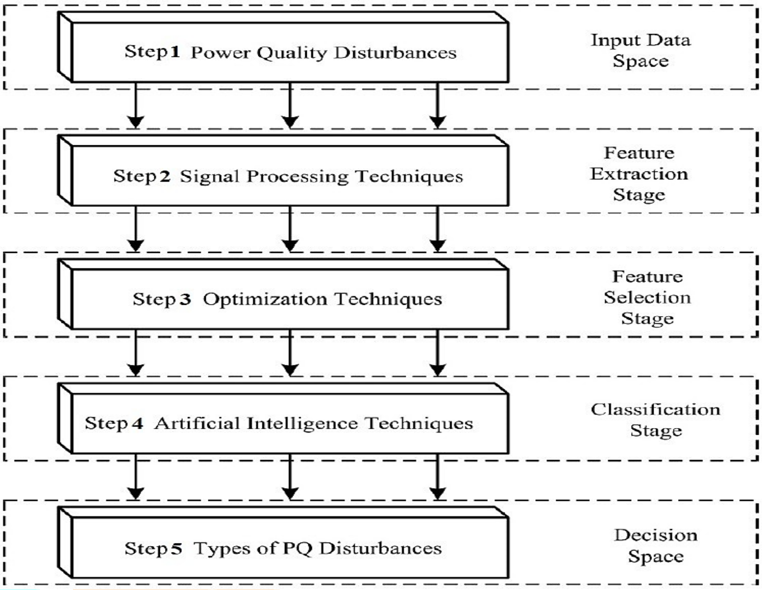


Fig 2: Block diagram of PQ Disturbances Detection and Classification System

In step 1, the data required for the analysis of power quality disturbances will be captured in the form of voltage and current signals under both simulation and experimental case. The experimental data of voltage and current signals from the laboratory test bench system will be captured with the help of sensors (CT and PT), digital storage oscillator and data acquisition system. In step 2, the appropriate signal processing technique will be selected from the available literature and implementation of the same will be done in MATLAB for processing the captured voltage and current signals for the feature extraction.. The feature extraction process is the most important part of the pattern recognition system because it is used to find distinguishing features from the obtained transform coefficients of the original signals. Using a feature extraction technique, PQ disturbances can be detected and classified. Following that, the extracted features can be used to classify PQ disturbances. Features can be extracted from the original signal or by using frequency transformation techniques. Various signal processing techniques, such as Fourier transforms, Wavelet transforms, Stockwell transforms, Hilbert transforms, Kalman filters, Gabor transforms, and their hybrids, can be used for feature extraction. Figure 3 depicts a state-of-the-art taxonomy of signal processing techniques used for feature extraction of PQ disturbances. These transformations are used to obtain data in the time and frequency domains.

The selection of the most suitable features of the PQ events is critical in order to achieve the highest classification accuracy [14]. However, the performance of a classifier is dependent on the extracted feature vector [15]. As a result, rather than designing a complicated classifier, the distinctive features of the patterns are the primary focus of pattern recognition systems. The statistical parameters of the transformed coefficients of the PQ disturbances can be calculated to reduce data size and obtain distinct features of the PQ disturbances. The most commonly used statistical parameters for classifying PQ disturbances are energy, entropy, minimum, maximum, standard deviation, mean, rms value, and their combinations.

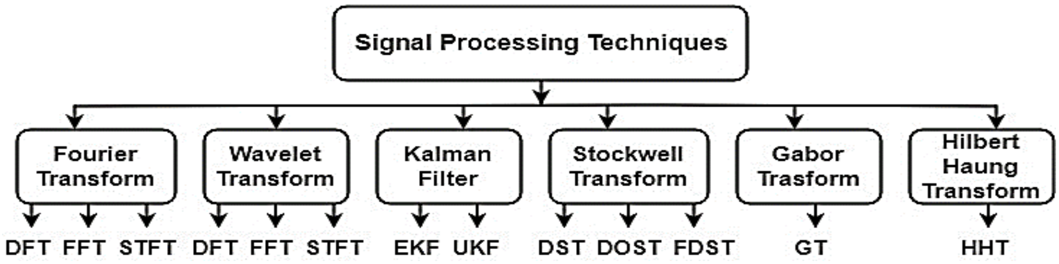


Fig 3: Taxonomy of Signal Processing Techniques

In step 3, the optimization techniques such as genetic algorithm and particle swarm optimization can be used for the optimal feature selection from the features extracted in previous step. Figure 4 shows some feature selection techniques.

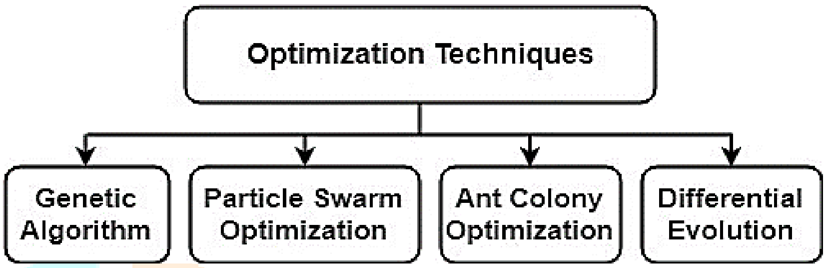


Figure 4: Feature Selection Techniques

In step 4, the appropriate artificial intelligence techniques will be selected from the available literature and implementation of the same as a classifier will be done in MATLAB to process the selected features for classification. Figure 5 shows various artificial intelligence techniques.

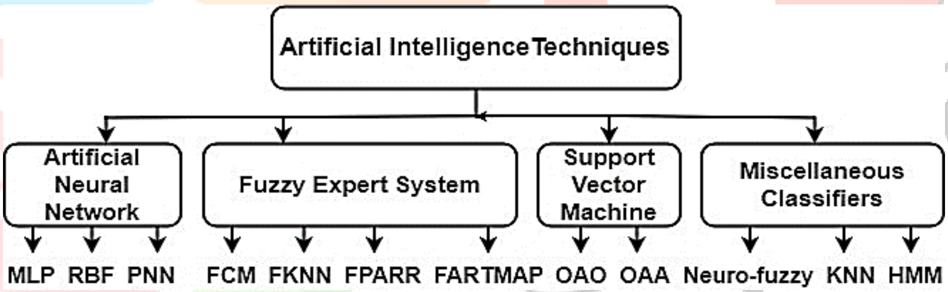


Figure 5: Taxonomy of Artificial Intelligence Techniques

In step 5, the decision pertaining to the type of power quality disturbance will be given by the selected classifier. The generalized classification strategy is shown in figure 6.

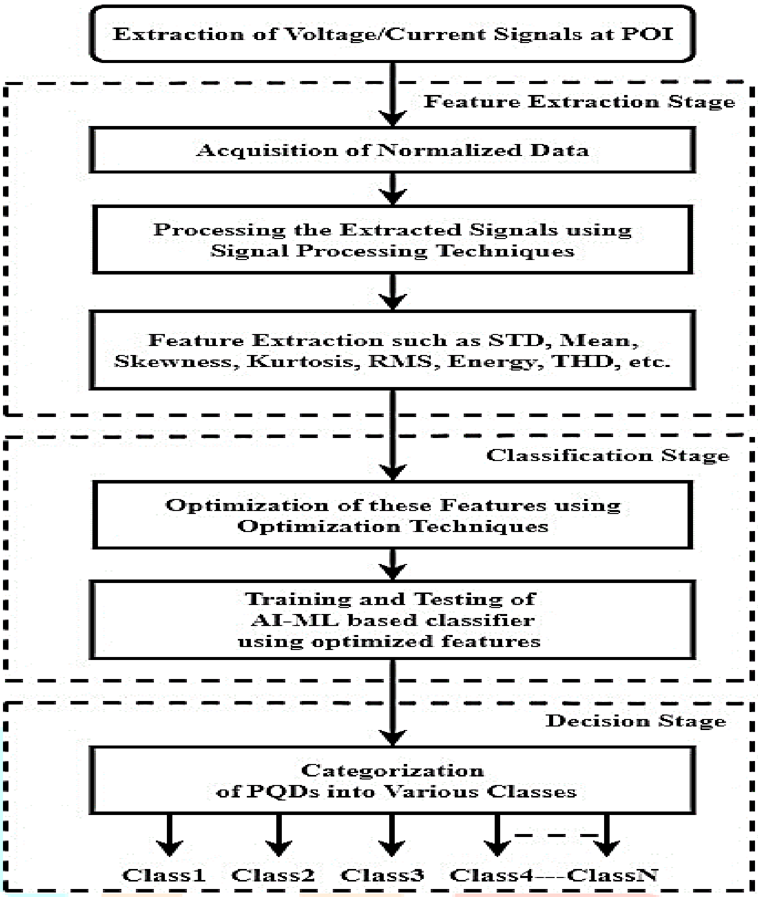


Figure 6: Generalized Classification Strategy

4. CONCLUSION

This study conducts an analytical and thorough evaluation on the identification and classification of power quality issues in developing distributed generation power systems. According to the review, the most widely used signal processing algorithms are the Fourier transform, Wavelet transform, Stockwell transform, Kalman filter, Gabor transform, and Hilbert-Haung transform. The researcher will be assisted in choosing a specific technique for the detection and classification of power quality issues by the comparative analysis of several signal processing techniques, optimization strategies, and artificial intelligence techniques. For the classification of data, it has been discovered that the majority of researchers like using ANN, FES, DT, RF, and SVM classifiers. From the extensive literature survey it is found that there is still scope to find better method to detect and classify PQ disturbances in terms of computational complexity. The challenging issues in automatic classification of PQ disturbances are detection of the causes of disturbances and detection of multiple disturbances. A lot of research is focused on the synthetic data for training and testing classifiers. The real-time data must be applied. De-noising is still a challenge for classification, the feature extraction and classification algorithms poorly perform in noisy environment. Most of the PQ disturbances classification methods are based on the 1-phase data. In practical, power system is a 3-phase system. Therefore, the research must be focused on real-time 3-phase power system disturbances.

5. FUTURE SCOPE

According to the thorough literature review, there is still room for improvement in detecting PQDs.PQDs are classified based on their accuracy, computational time, and complexity. The majority of the research is devoted to detecting and classifying power quality disturbances. The difficult issue is determining the source of the power quality disturbances. Because most research is focused on single power quality disturbances, there is opportunity to focus on multiple power quality disturbance detection. Researchers must create a universal algorithm capable of detecting both single and multiple power quality disturbances. The majority of research work employs synthetic data to test the algorithm. The algorithm's accuracy must be tested using real-time data. The majority of PQD detection and classification methods rely on single-phase data. In practice, because our electrical power system is three-phase, we must use a three-phase real-time system for PQD detection and classification. The data acquisition system records the ambient noise as well as the voltage and current signals. In a noisy environment, feature extraction and classification algorithms perform poorly. As a result, prior to applying the algorithm, the signal must be denoise.There is still room to create a new algorithm that works well in both noiseless and noisy environments. Real-time analysis and mitigation of PQDs is a focus of power quality research. The majority of the algorithms used for PQD detection and classification are specific to a particular power system and are not generalizable. As a result, there is an opportunity to develop a universal algorithm that can be applied to any power system, regardless of rating, with or without distributed generation.

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