

**A REVIEW ON DETECTION AND CLASSIFICATION OF POWER QUALITY
DISTURBANCES IN EMERGING POWER SYSTEM WITH DISTRIBUTED
GENERATION****¹Ravishankar S. Kankale, ²Sudhir R. Paraskar, ³Saurabh S. Jadhao**Assistant Professor^{1,3}, Professor & Head², Department of Electrical Engineering, SSGMCE, Shegaon
ravi_kankale@rediffmail.com¹, srparaskar@gmail.com², ssjadhao@gmail.com³**ABSTRACT**

Nowadays, the ever-increasing power demand is fed by using renewable energy-based distributed generation (DG). Most of the renewable energy sourced distributed generation is based on power electronic converters. The integration of such distributed generation in a conventional distribution network becomes a major source of power quality disturbances (PQDs). In an emerging power system, the power electronic converters in the DG system, non-linear loads, switching events, and various power system faults are the major causes of power quality disturbances. These disturbances causing problems such as malfunctioning or failure of end-user equipment. Hence, it is necessary to monitor the power quality disturbances. The ongoing research is now focused on this area. A lot of research literature is available in the area of power quality. Due to the high penetration of renewable energy-based DG, the classification of power quality disturbances in the emerging power system becomes an important issue. This paper presents a review of signal processing, feature extraction, and classification techniques used for the detection and classification of power quality disturbances in emerging power system with distributed generation. This information will help researchers working in this field. A comparison of various signal processing and artificial intelligence techniques used for monitoring of PQDs has been tabulated. Major issues and major challenges in classifying power quality disturbances are analyzed in-depth and presented. This review further explores the opportunities for new researchers in the field of power quality disturbances detection and classification.

Keywords: Distributed Generation, Power Quality Disturbances, Signal Processing Techniques, Artificial Intelligence Techniques.

1.INTRODUCTION

The ever-increasing power demand in most of the developing countries is fed by centralized generating plants. These power plants are sufficiently large to feed the power demands of the consumers. During the peak hours the power generated by the centralized power plants may be insufficient to feed the complete power demand. Hence DG system are which to feed the load demand in the peak and off-peak period. Due to the advancement in power electronic technology and DG technology the use of renewable energy-based DG gets increased nowadays. The integration of DG brings new challenges in the power quality domain [1].

In the emerging power system, the occurrence of faults, switching of load, capacitor banks, solid-state devices, power electronics converters-based DG system, arc furnaces, reactor, and transformer energization are the major causes of power quality disturbances. These factors are responsible for the formation of voltage sag, voltage swell, voltage interruption, transients, harmonics, voltage notch, voltage flicker, and spikes. The quality of electric supply degrades mainly due to these PQDs. These power quality disturbances lead to the malfunction or failure of sensitive equipment of the end-user. The voltage sag and the momentary interruption occur due to faults whereas the voltage swell occurs due to switching off the heavy load. Nonlinear loads and power electronics component-based devices such as rectifiers and inverters are the major source of harmonic distortion and notching. Flickers are produced by the use of an arc furnace. Transients are formed by the energization of the transformer, switching of capacitor banks. In order to reduce the PQDs occurring in the

power system and to develop some corrective and preventive measures, one needs efficient power quality disturbance detection and classification techniques. Power quality monitoring becomes an important issue in the emerging power system in order to protect the sensitive equipment of end-user and to identify the exact cause of the power quality disturbance [2]. Both utilities and customers are now concern about power quality. As a result, most of the research is now focused on power quality studies. Power quality monitoring based on simple visual inspection of waveforms found to be laborious and time-consuming. Hence, an automatic power quality monitoring system is required [3].

For timely mitigation of PQDs, detection and classification are essential. In the detection process, the time-frequency analysis of the PQDs is carried by using signal processing techniques. Prediction of type of power quality disturbances using the classifiers which are trained with signal features can be termed as power quality disturbance classification. A voltage or current signal is analyzed preliminarily for the diagnosis of the PQDs using signal processing techniques such as short-time Fourier transform (STFT), discrete wavelet transform (DWT), wavelet packet transform (WPT), Stockwell transform (ST), empirical mode decomposition (EMD), and Kalman filter (KF) [26]. The processed signal contains significant information about the disturbances. Hence, features are extracted from this signal. These extracted features are given as an input to the classifier. Decision tree (DT), fuzzy logic (FL), artificial neural network (ANN), and support vector machines (SVM) are the commonly used classifiers for the classification of PQDs. Various methodologies are proposed based on different signal processing and artificial intelligence techniques in order to enhance classification accuracy. The complexity, inefficiency, and computational time of the existing PQDs detection and classification techniques provide enough scope for researchers to strive for better alternatives [4-6].

The organization of this paper is as follows. Section 1 presents the introduction. The distributed generation is discussed in section 2. The power quality is briefly discussed in section 3. The automatic power quality monitoring system is described in section 4. Finally, the conclusion of the paper and future scope is covered in sections 5 and 6 respectively.

1. DISTRIBUTED GENERATION (DG)

2.1 DG TECHNOLOGIES

Distributed generation is not a new concept but due to the advancement of DG technology, the use of it is increasing in recent years. Distributed Generation is used in the emerging power system to support the ever-increasing power demand. It is also called as Embedded Generation, Dispersed Generation, or Decentralized Generation. It is defined as the Generation of electricity by the means of smaller facilities as compare to central generating stations in order to have interconnection with the grid at any point. There are various technologies available for a distributed generation [3]. These technologies can be broadly classified on the basis of the energy resources used for the generation. Table 1 shows the commonly used DG technologies available in the market along with their typical module size.

Table 1: DG technologies with their typical available module size

No.	Technology	Typical available size power module
1	Combined Cycle Gas Turbine	35-400 MW
2	Internal Combustion Engines	5 kW -10 MW
3	Combustion Turbine	1-250 MW
4	Micro-Turbines	35 kW-1 MW
5	Fuel Cells, Phosphoric Acid	200 kW -2 MW
6	Fuel Cells, Molten Carbonate	250 kW -2 MW
7	Fuel Cells, Proton Exchange	1-250 kW
8	Fuel Cells, Solid Oxide	250 kW-5 MW
9	Battery Storage	0.5-5 MW
10	Small Hydro	1-100 MW
11	Micro Hydro	25 kW -1 MW
12	Wind Turbine	200 W -3 MW
13	Photovoltaic Arrays (PV Arrays)	20 W-100 kW
14	Solar Thermal, Central Receiver	1-10 MW
15	Solar Thermal, Lutz System	10-80 MW
16	Biomass Gasification	100 kW-20 MW
17	Geothermal	5-100 MW
18	Ocean Energy	0.1-1 MW

2.2 GRID INTEGRATION OF DG

Distributed generation is integrated with the grid at the point of interconnection in order to include the distributed generation in the power system. The reliability of the power system gets increased by Grid integration of the DG system. This will also lead to the inclusion of renewable energy resources in the main framework of the power system. DG systems can have positive and negative impacts on the power system due to the occurrence of various technical and economic issues in grid integration. In order to reduce the negative impacts at high penetrations, appropriate measures have to be implemented. Different DG systems have different integration issues. Effective planning is required for the successful integration of the DG system with the grid. This can be achieved by introducing the concept of smart grid and microgrid in the emerging power system [8].

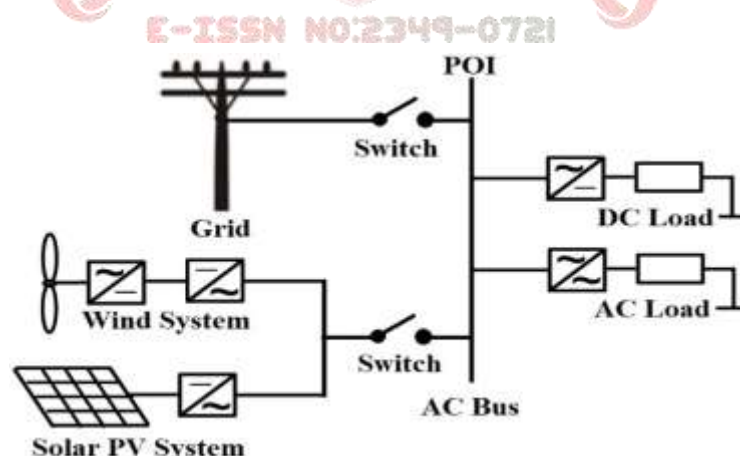


Figure 1: Integration of DG with Distribution Network

2.3 DG INTERFACING TECHNIQUES

Synchronous generators and induction generators are used in small hydro-power and wind power generation, these generators can be directly interfaced with the grid. Due to power quality and starting transients' issues, they sometimes require power electronic converters for interfacing with the grid. Renewable energy resources-based distributed generation systems such as solar PV generation, wind generation requires

power electronics converters like DC-to-DC converter and DC-to-AC converter (inverter) for interconnection with grid [9]. There are three basic interfacing technologies available for DGs.

1. Synchronous Generator
2. Induction Generator
3. Power Electronics Converter

Figure 2 shows the block diagram of hydro or wind energy resources-based DG interfacing with grid and figure 3 shows the block diagram representation of solar energy-based DG interfacing with the grid.

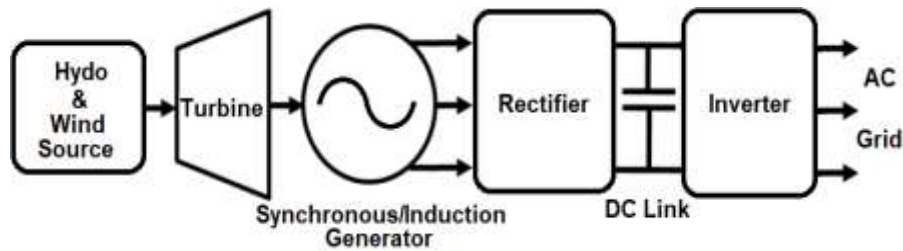


Figure 2: Synchronous/Induction Generator based DG interfacing with grid

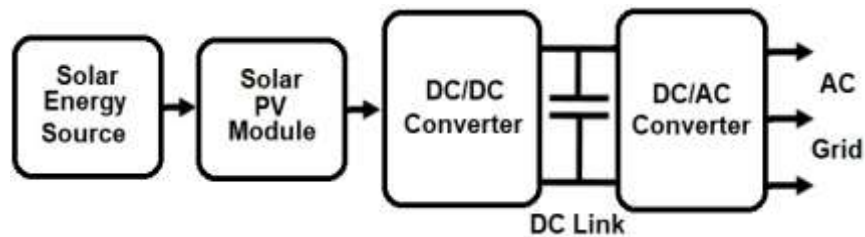


Figure 3: Power Electronics Converter based DG interfacing with grid

2.4 RENEWABLE ENERGY MARKET IN INDIA

India was ranked fourth in the world for the renewable energy installed capacity. The government of India has made a special amendment in the budget for the promotion of renewable energy-based generation. They are giving subsidies for the installation of solar and wind energy projects. They have prepared the action plan to achieve the target of 227 GW renewable energy installed capacity out of which 114 GW will be solar power installed capacity and 67 GW will be wind power installed capacity by 2022. As of January 31, 2021, the installed capacity of renewable energy is 92.55 GW out of which solar comprises 38.79 GW and wind comprise 34.4 GW and 38.68 GW respectively. The Biomass constitutes 10.31 GW and small hydropower constitutes 4.75 GW.

Table 2: Installed Capacity (In MW) of Power Stations in All India (As on 31.01.2021)

Mode of Generation		Installed Capacity in MW	% of Total Installed Capacity
Thermal	Coal	200284.50	53.08
	Lignite	6120.00	1.62
	Gas	24956.51	6.61
	Diesel	509.71	0.13
Nuclear		6780.00	1.79
Hydro		46059.22	11.94
RES*(MNRE)		92550.74	24.53
Total		377260.67	100.00

*Break up of RES based Power Generation as on 31.01.2021 is given below (in MW):

Small Hydro Power	Wind Power	Bio-Power		Solar Power	Total Capacity in MW
		BM Power/ Cogen.	Waste to Energy		
4758.46	38683.65	10145.92	168.64	38794.07	92550.74

2. POWER QUALITY

Power Quality is the general term used nowadays to show the interference of power electronics devices. Any power problem that leads to the variation in the voltage, current, or frequency which results in the failure or maloperation of end-user sensitive equipment called power quality. Power quality is an important issue as far as the end-user-sensitive equipment's are concerned. Nowadays, both utility and customers are now concern about power quality. Table 3 shows the categorization of power quality events on the basis of time duration and voltage magnitude.

Table 3: Classification of power quality events

Power Quality Events		Time Duration	Voltage Magnitude
Short duration variation:			
Sag	Instantaneous	0.5-30 cycle	0.1-0.9 pu
	Momentary	30 cycles-3 s.	0.1-0.9 pu
	Temporary	3 sec-1 min.	0.1-0.9 pu
Swell	Instantaneous	0.5-30 cycle	1.1-1.8 pu
	Momentary	30 cycles-3 s.	1.1-1.4 pu
	Temporary	3 sec-1 min.	1.1-1.2 pu
Interruption	Momentary	0.5 cycles-3 s.	<0.1 pu
	Temporary	3 sec-1 min.	<0.1 pu
Long duration variation:			
Interruption (sustained)		>1 min.	0.0 pu
Undervoltage (UV)		>1 min.	0.8-0.9 pu
Overvoltage (OV)		>1 min.	1.1-1.2 pu
Transients:			
Impulsive	Nanosecond	<50 nsec.	
	Microsecond	50-1 msec.	
	Millisecond	>1 msec.	
Oscillatory	Low freq.	0.3-50 msec.	0-4 pu.
	Medium freq.	20 μ sec.	0-8 pu.
	High freq.	5 μ sec.	0-4 pu.
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%
Voltage unbalance (VU)		Steady state	0.5-2%

3.1 POWER QUALITY ISSUES RELATED TO DG

Power quality is a general term used to describe the influence of power electronic converters on the power and voltage quality of the grid [27]. Interconnection of DG with the grid causes power quality issues like instability of voltage profile, distortion of the voltage waveform, voltage fluctuation, and unbalance in the grid. These issues further lead to mal-operation of sensitive equipment and protection devices, faulty metering, and operation of loads, heating and aging of equipment connected in power system like transformers, cables and motors, interference with the communication system, etc [60]. Harmonics are generated by the DG system

which will lead to a reduction of power factor and capacity of the system. End-user-sensitive equipment needs to be protected from adverse effects caused by the fluctuation of voltages. Hence, a power quality monitoring system is the need of an hour in the emerging power system so as to protect sensitive equipment and to identify the cause of power quality disturbance [42]. A specific power quality disturbance arises due to the specific DG operating condition. Grid synchronization of DG causes voltage sag in the case of wind generation. Voltage rise occurs at the point of interconnection due to load tripping. The frequency deviation occurs with the increase in DG penetration. The outages of a DG cause voltage variation, transients, and frequency variation., Islanding is responsible for voltage variation and sudden increase in the frequency. Variations of solar insolation led to the variation of voltage causing voltage sag or swell and variation in wind speed causes voltage fluctuations which leads to the formation of low magnitude flickers [60]. Figure 4 shows the waveform representation of various power quality disturbances generated using the mathematical models of respective power quality disturbances.

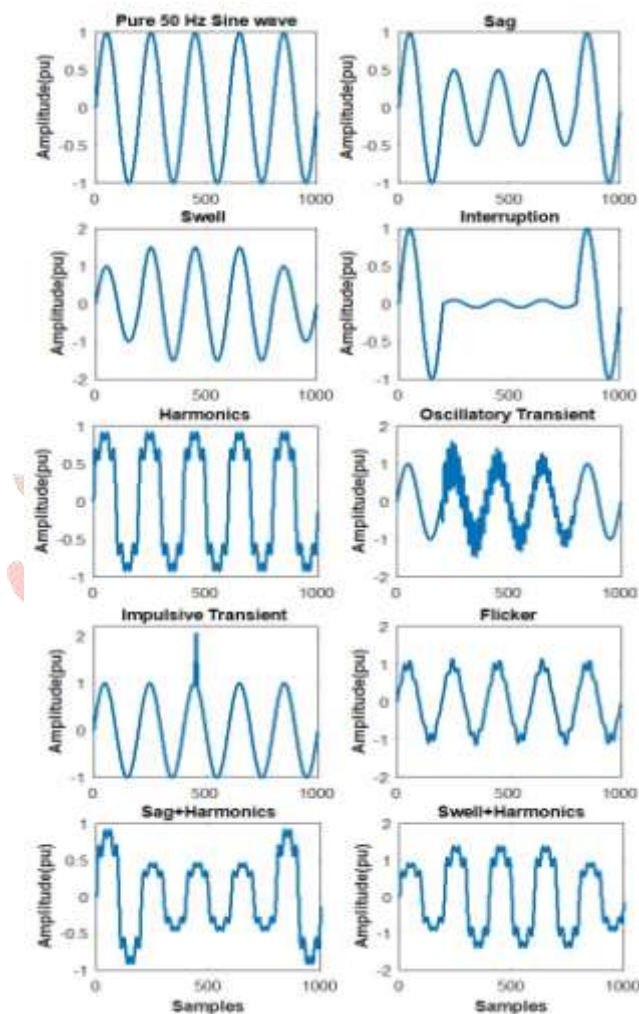


Figure 4: Power Quality Disturbances.

3. POWER QUALITY MONITORING SYSTEM

The power quality monitoring system continuously monitors the power system for disturbances if any. The power quality disturbance if occurs in the system then the power quality monitoring system automatically detects the occurrence of disturbance and classifies the power quality disturbance. The basic operating principle of this automatic power quality monitoring system can be well described with the help of the block diagram shown in figure 5. This system consists of five units. A first unit is a monitoring unit that consists of devices like

sensors, transducers, and a data acquisition system that will continuously monitor the voltage and current signals for power quality disturbances. This unit is also called an input unit because here both voltage and current signals are captured by the data acquisition system and are given as input to the feature extraction unit. In the feature extraction unit, the input signal is preprocessed for time-frequency analysis by the application of appropriate signal processing techniques available in the literature which are shown in figure 6. The coefficients obtained after time-frequency analysis are further used to calculate statistical parameters for feature extraction. The vector of extracted features is then processed in the feature selection unit by the appropriate optimization technique available in the literature as shown in figure 7 for optimal feature selection. These optimal features are further processed in the classification unit by the application of appropriate artificial intelligence technique-based classifiers available in the literature as shown in figure 8. The output of the classification unit is given to the decision unit to make the final decision about the type of power quality disturbances and display the same as a result. The implementation of a complete system can be done in real-time using both hardware and software [40].

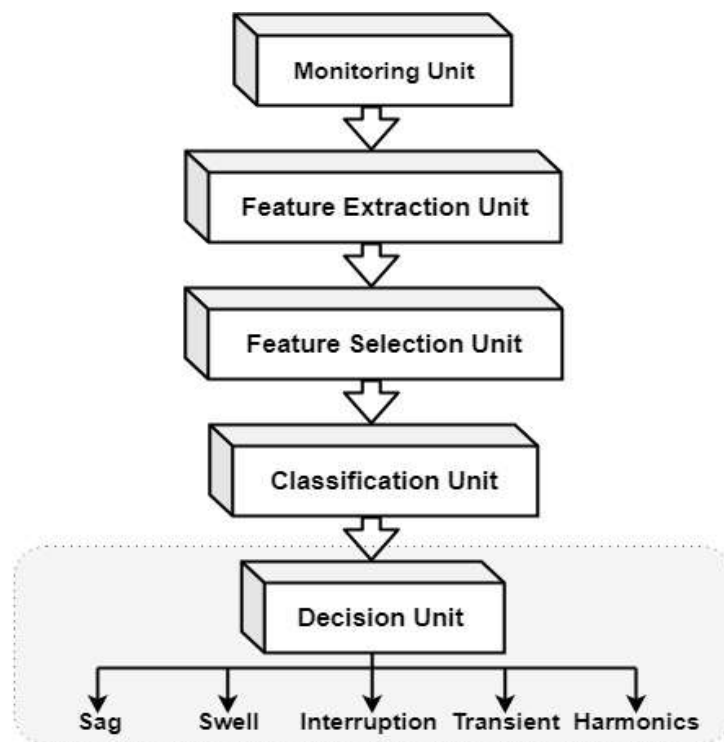


Figure 5: Block diagram of automatic Power Quality Monitoring System

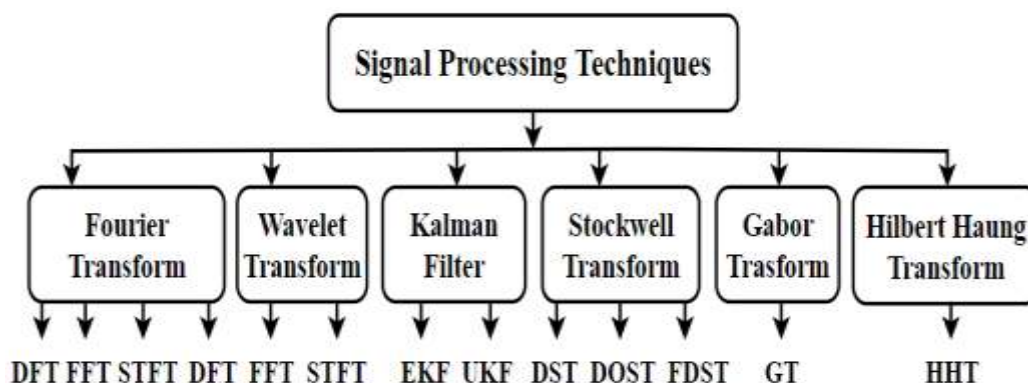


Figure 6: Taxonomy of Signal Processing Techniques

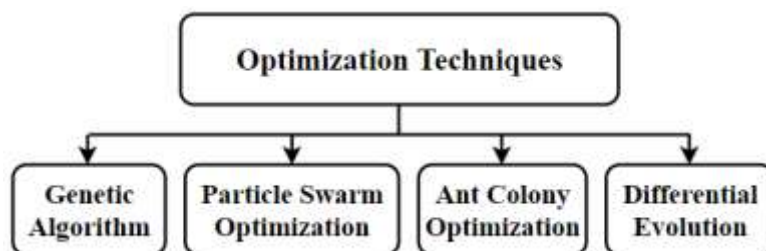


Figure 7: Taxonomy of Optimization Techniques

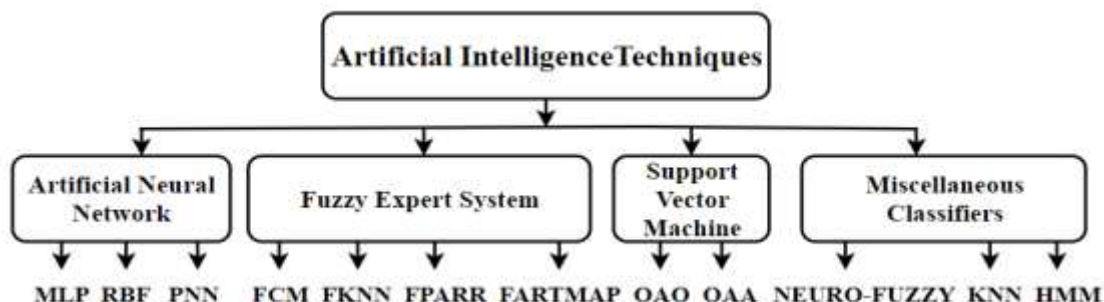


Figure 8: Taxonomy of Artificial Intelligence Techniques

A number of signal processing techniques are available in the literature but they have several advantages and disadvantages. Table 4 gives the comparative analysis of several signal processing techniques based on the accuracy, robustness, computational complexity, performance under the noisy condition, and real-time implementation. From the table, it is clear that modified ST has more advantages as compared to other techniques hence, this signal processing technique is widely used for the detection and classification of power quality disturbances in the emerging power system.

Table 4. Comparison of various signal processing techniques

<i>Properties</i>	<i>STFT</i>	<i>WT</i>	<i>ST</i>	<i>Modified ST</i>
Size of Window	Fixed	Moving window	Adjustable	Adjustable
Measurements	Possible	Possible	Possible	Possible
Frequency accuracy	Not accurate	Not accurate	Accurate	Most Accurate
Execution of results	Easy	Little difficult	Little difficult	Little difficult
Frequency and time resolution	Marginally good	Good	Better time and frequency resolution	Better time and frequency resolution
Real-time implementation	Marginally possible	Possible with less accuracy	Possible with accuracy	Possible with accuracy
Robustness	Poor	Good	Very good	Excellent
Computational complexity	Complex	Marginally complex	Less complex	Less complex than ST
Flexibility	Not flexible	Marginally	Flexible	Flexible
Noisy signals	Fail	Affected	Not affected	Not affected
Non-stationary signals	Fail	Affected	Not affected	Not affected
Real time implementation	Poor	Good	Very Good	Excellent

4. CONCLUSION

In this paper, an analytical and extensive review on detection and classification of power quality disturbances in emerging power system with distributed generation is carried out. Broad information on the aspects of distributed generation and power quality has been covered. This paper presents a review on various signal processing techniques available in the literature such as Fourier transform, Wavelet transform, Kalman filter, Stockwell transform, Gabor transform and Hilbert-Huang transform which are used for feature extraction in power quality monitoring system. The optimization techniques such as Genetic algorithm, Particle swarm optimization, Ant colony optimization, and Differential evolution used for optimal feature selection are brief in this paper. The artificial intelligence techniques-based classifiers such as ANN, FES, and SVM have been

reviewed in detail. The effect of noise on various signal processing techniques used to detect and classify the PQDs is also outlined. As per the review, it can be concluded that the Fourier transform, Wavelet transform, Stockwell transform, Kalman filter, Gabor transform and Hilbert-Huang transform are the most commonly used signal processing techniques. The comparative study of several signal processing techniques, optimization techniques, and artificial intelligence techniques will help the researcher in the selection of specific technique for the detection and classification of power quality disturbances. It has been found that most of the researchers are inclined towards the use of ANN, FES, DT, RF, and SVM classifiers for the classification of power quality disturbances.

5. FUTURE SCOPE

From the rigorous literature review, it is found that there is still scope to find a better method to detect & classify PQDs on the basis of accuracy, computational time, and complexity. Most of the research work is focused on the detection and classification of power quality disturbances. The challenging issue is to detect the cause of the power quality disturbances. Most of the research work is carried out on single power quality disturbances so there is scope to carry the work on multiple power quality disturbance detection. The researchers need to develop a universal algorithm that can detect both single and multiple power quality disturbances. In most of the research work, synthetic data is used to test the algorithm. The real-time data must be applied to test the accuracy of the algorithm. Most of the PQDs detection and classification methods are based on single-phase data. In practice, our electrical power system is a three-phase system hence, is required to work on the three-phase real-time system for detection and classification of PQDs. The data acquisition system captures the surrounding noise along with the voltage and current signal. Feature extraction and classification algorithms poorly perform in a noisy environment. Hence it is required to denoise the signal before applying the algorithm. There is still scope to develop a new algorithm that can work effectively under both noiseless and noisy environments. In power quality research, real-time analysis and mitigation of PQDs is a thrust area. Most of the algorithms used for the detection and classification of PQDs are dedicated to a particular power system and are not generalized. Therefore, there is a scope to develop a universal algorithm that can be applied to any power system irrespective of the rating with or without distributed generation.

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