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A Brief Review on Identification, Categorization and Elimination of Power Quality Issues in a Microgrid Using Artificial Intelligent Techniques

Amrit Pattnaik[1], Meera Viswavandya[2], Prakash Kumar Hota[3]
[1]Department of Electrical Engineering, Odisha University of Technology and Research, Bhubaneswar, Odisha, India (pattnaikamrit10@gmail.com) ORCID 0000-0002-5195-6083
[2]Department of Electrical Engineering, Odisha University of Technology and Research, Bhubaneswar, Odisha, India (mviswavandya@outr.ac.in)
[3]Department of Electrical Engineering, Veer Surendra Sai University of Technology, Burla, Odisha, India (pkhota_ee@vssut.ac.in)

Abstract
Power quality is the manifestation of a disruption in the supply voltage, current, or frequency that damages the utility equipment and has become an important issue with the introduction of more sophisticated and sensitive devices. So, the supply power quality issue still remains a major challenge as its degradation can cause huge destabilization of electrical networks. As renewable energy sources have irregular nature, a microgrid essentially needs an energy storage system containing advanced power electronic converters, which is the root cause of the majority of power quality disturbances. Also, the integration of non-linear and unbalanced loads into the grid adds to its power quality problems. This article gives a compact overview of the identification, categorization, and mitigation of these power quality events in a microgrid by using various Artificial Intelligence-based techniques like Optimization techniques, Adaptive Learning techniques, Signal Processing and Pattern Recognition, Neural Networks, and Fuzzy Logic.

Author Keywords. Power Quality, Microgrids, Artificial Intelligence, Identification and categorization, Renewable Energy Sources, Energy Storage System, Power Electronic Converters, Distributed Generation.

Type: Review Article

1. Introduction

A microgrid is a miniature and compact version of the conventional supply system that works either in low voltage or medium voltage networks and comprises a combination of micro-sources, energy storage systems, and various non-linear loads (García Vera, Dufo-López, and Bernal-Agustín 2019). The concept of microgrid first came into the picture in 1882 with Thomas Edison building his first power plant.

A micro-source also called distributed generation (DG) is mainly made up of various modern technologies such as fuel cell, wind turbine, photovoltaic (PV) module, etc. These are combined to form various units, each unit having only a small capacity, then integrated with power electronic devices and finally, they are kept at the utility sites. The main purpose of these power electronic devices is to give control and flexibility as needed by the microgrid system. The energy storage system in a microgrid comprises batteries, flywheels, super-capacitors, etc. which stores the additional power produced by the microgrid system for use at a later time.

The burning of fossil fuels emits a lot of poisonous gases such as carbon dioxide, carbon monoxide, methane, etc. into the atmosphere causing an increase in the level of global warming. The high level of Carbon dioxide in the atmosphere has a very high potential to increase the level of global warming to an intolerable level. Further, fossil fuels are categorized as non-renewable energy sources whose stocks are diminishing day by day because of their high rate of usage. Due to the above-mentioned reasons, there has been a high concern to reduce the use of fossil fuels. One of the ways is not to use fossil fuels but instead use renewable energy sources (RES). The production of RES is from the natural sources present and available on earth such as solar power, wind, water, nuclear energy, and biomass energy. The good thing about these sources of RES is that they are non-depleting and replenishable in nature (Badal et al. 2019). Also, they emit no or very less amount of carbon dioxide to the atmosphere when compared with fossil fuels.

Power Quality (PQ) issue arises in a microgrid due to the integration of the intermittent nature of RES with advanced power electronic converter technology and also due to the presence of non-linear and unbalancing loads connected to it (Vinayagam et al. 2015). PQ can be defined as the net deviation of voltage, current, or frequency from their ideal characteristics that result in failure or maloperation of consumer equipment. The various PQ issues that can occur in a microgrid are transients, voltage imbalance, frequency deviations, and harmonic distortions.

A microgrid can be operated either independently called the islanded mode of operation or can be operated by connecting it to the main grid at the point of common coupling (PCC) (Parhizi et al. 2015). When the microgrid is in an islanded mode of operation, the loads can be supplied by a microturbine. As RES like wind and solar power are highly intermittent in nature, their capacity for producing power is very unstable. Also, they can cause unexpected variations in the real power as well as alterations in the system frequency that can result in the appearance of harmonics. Moreover, if too many voltage variations occur in the system, then it can lead to an increase in the reactive power demand of the system which ultimately is an inconvenience for the customers as it can cause an increase in their electricity bills. If there is an imbalance in the voltage-frequency behavior, it can cause an increase in transmission line losses.

There are various techniques to mitigate the above-mentioned power quality problems some of which are (Natesan et al. 2014):

1. Droop Control Method to boost active and reactive power of the grid
2. Implementation of Active Power Filters (APF) and Static VAR Compensators (SVC) to maintain the grid voltage and frequency.
3. Active Power Conditioners for power quality enhancement
4. Various energy storage systems such as Battery Energy Storage System (BESS), supercapacitors-based energy storage system, etc. for mitigation of power quality problems
5. Employment of flexible AC transmission system devices for boosting power quality.

Today's world has an ever-increasing interest in electricity generation from clean and self-renewing sources which has given rise to the microgrid concept and has inspired its development in recent times. The successful and efficient integration of a microgrid with the conventional grid can entirely change the electricity infrastructure of the world. However, the supply power quality problems, being the major disadvantage of a microgrid system, pose a considerable challenge in its establishment. For a long time, researchers from all over the world have been trying to predict, analyze and mitigate various power quality events in a microgrid by using different conventional as well as advanced techniques. But the current evolution and application of artificial intelligence-based techniques for prediction, analysis, and mitigation of such events have shown that they have higher efficacy in comparison to other methods. These reasons motivated us to write a comprehensive review containing an extensive compilation of a number of intelligent techniques for identification, elimination, and categorization of power quality events, that have been put in one place which will be immensely helpful for the researchers to build upon many research ideas as well as help them in developing a foundation for their research work.

Various artificial intelligence and machine learning techniques adopted by authors to mitigate different power quality issues and reviewed in this paper can be seen in a quick glance in (Table 1) given below.

Citations	Issues Mitigated	Technique Applied
(Babu, Srinivas, and Ram 2018; de AL Rabêlo, Lemos, and Barbosa 2012; Vinod and Singh 2019)	Voltage and Frequency Fluctuations, Voltage and Current Harmonics	Particle Swarm Optimization
(Jumani et al. 2018; Jumani et al. 2019)	Voltage and Frequency Fluctuations, Transient Behavior and Harmonics	Grasshopper Optimization
(Jumani et al. 2019; Jumani et al. 2019; Naderipour et al. 2021)	Voltage and Frequency Fluctuations, Transient Behavior, Harmonics and Switching Loss	Salp Swarm Optimization
(Sedhom et al. 2019; Sedhom et al. 2020)	Voltage and Frequency Fluctuation	Harmony Search Optimization
(Choudhary et al. 2020)	Frequency Fluctuation	Grasshopper Optimization + Fuzzy Logic
(Latif et al. 2020)	Frequency Fluctuation	Butterfly Optimization
(Othman and Gabbar 2017)	Reactive Power Compensation and Harmonics	Enhanced Bacterial Foraging Optimization
(Teekaraman, Kuppusamy, and Nikolovski 2019)	Voltage and Frequency Oscillations	Multi-Objective Symbiotic Organism Search Algorithm
(Prabaakaran et al. 2019; Mahmoud, Abouheaf, and Sharaf 2019; Bagheri et al. 2018; Younesi, Shayeghi, and Siano 2020; Radhakrishnan et al. 2020)	Voltage and Frequency Fluctuations, Unbalancing Load, Harmonics and Reactive Power Compensation	Reinforcement Learning
(Yalcin and Ozdemir 2016)	Voltage Sag	Decision Tree
(Moreira et al. 2018)	Power Factor Correction and Current Harmonics	k-Nearest Neighbors
(Rupal et al. 2017)	Detection of Voltage Sag, Capacitor Switching, Harmonics, Isolated and Non-Isolated Microgrid Modes	Ensemble Empirical Mode Decomposition-Support Vector Machine
(Wang, Pulgar-Painemal, and Sun 2017)	Voltage Instability	Convolutional Neural Network
(Alshehri and Khalid 2019)	Voltage and Frequency Fluctuations	Artificial Neural Network + Differential Evolution Optimization
(Ab-BelKhair, Rahebi, and Abdulhamed Mohamed Nureddin 2020; Nureddin, Rahebi, and Ab-BelKhair 2020)	Voltage and Current Harmonics	Deep Neural Network
(Raya-Armenta, Lozano-Garcia, and Avina-Cervantes 2018)	Voltage Fluctuation and Power Flow Imbalance	Artificial Neural Network
(Kwan et al. 2007; Prabhakar and Charles 2019; Garcia-Torres et al. 2021;	Voltage and Frequency Fluctuations, Voltage and Current Harmonics,	Model Predictive Control

Golsorkhi and Lu 2016; Shan et al. 2019; Zhao et al. 2020; Tamrakar et al. 2021)	Reactive Power Compensation, Transient Behavior and Unbalancing Condition	
(B. Rao and A Rao 2013; Nalini and Raja 2019; Tephiruk et al. 2018)	Voltage and Frequency Deviations and Harmonics	Fuzzy Logic
(Kamal et al. 2020)	Power Transfer Problem, Frequency Fluctuation and Harmonics	Adaptive Neuro-Fuzzy Jacobi Wavelet
(Das et al. 2021)	Reactive Power Compensation, Voltage Fluctuation and Harmonics	Adaptive Fuzzy-Neural Network
(Kaushal and Basak 2019)	Voltage and Frequency Fluctuations, Harmonics and Power Factor Deviation	Fuzzy Inference System

Table 1: Articles Reviewed in this Work

The rest of the paper is arranged into the following sections. Section 2 talks about the usefulness of the various optimization techniques in raising the power quality of a microgrid. Section 3 provides the applicability of Reinforcement Learning in improving the power quality. Section 4 describes the usage of Signal Processing and Pattern Recognition techniques in the detection and classification of power quality disturbances. Section 5 discusses the role of Neural Networks and Deep Learning (DL) in enhancing the power quality of microgrids. Section 6 gives a brief idea about the importance of intelligent controllers in dealing with power quality issues of a microgrid. Finally, section 7 gives the conclusion to this paper.

2. Usefulness of Optimization Algorithms in Power Quality Improvement

Under this section, the authors Ahmed Jumani et al. (Jumani et al. 2020) have discussed the usage of the Particle Swarm Optimization (PSO) technique to improve the PQ of an AC microgrid. They have come to the conclusion that PSO-based controllers have been highly useful in leading new and intelligent ways to optimize the dynamic response and PQ of a microgrid.

Another method used by the authors Mahesh Babu et al. (Babu, Srinivas, and Ram 2018) to deal with power quality issues is by integration of Unified Power Quality Conditioner (UPQC) into the grid. In this, optimal tuned synchronous reference frame theory is used for generation and control of reference voltage and current and the voltage source converter in UPQC requires gating pulses which are generated by using pulse-width modulation (PWM) current controller and hysteresis band current controller.

In order to enhance the gain of the proportional-integral (PI) controller, the authors (Babu, Srinivas, and Ram 2018) have made use of the PSO algorithm and the evaluation of its performance has demonstrated to decrease harmonics and voltage sags when switching on large loads. The PSO-based UPQC was shown to be able to better compensate voltage dips and reduce harmonics as compared to conventional PI-controlled UPQC. The authors conducted simulations in MATLAB and SIMULINK environments to check the effectiveness of the proposed method. This method may also be used in grid-tied microgrids to enhance their PQ parameters.

A different approach was taken by Rabêlo et al. (de AL Rabêlo, Lemos, and Barbosa 2012) to formulate and estimate the harmonic components present in voltage or current waveforms of a three-phase source based on the PSO technique. Since the waveforms of voltage and current are not purely sinusoidal so, this method can identify exactly which harmonic components are present in the contorted waveforms. The authors saw the behavior of variable harmonics by simulating a fault condition in the transmission line using Alternative Transients Program (ATP) software.

In the end, the authors in (de AL Rabêlo, Lemos, and Barbosa 2012) compared the results obtained from the PSO algorithm with that obtained by using the conventional Discrete Fourier Transform (DFT) method and observed the following:

1. There were vast improvements in the precision in estimating the DC and other harmonic components.
2. The average error in the estimation of the magnitude of harmonics of voltage and current signals done by the PSO method was seen to be constant and practically zero.
3. On the other hand, the average error in the estimation done by using discrete Fourier transform (DFT) came out to be greater than 7%.

This approach can also be extended further to include a grid-connected microgrid so as to reduce its PQ issues like harmonic distortion and voltage fluctuations.

With the aim to achieve voltage and frequency stability in a combination of Photovoltaic-Solid Oxide Fuel Cell (PV-SOFC) microgrid working in the islanding mode having highly sporadic load profile, the authors V. P. Vinod et al. (Vinod and Singh 2019) suggested a Voltage Source Inverter (VSI)-based PI control mechanism for the grid whose efficiency was enhanced by Improved PSO algorithm. They did a performance evaluation of the suggested control mechanism with that of a benchmark PI control technique by modeling and simulating both the controllers in MATLAB and SIMULINK environments. Then, they made the following remarks:

1. Due to the sudden change of the microgrid network to its islanding operation, unexpected voltage fluctuations occurred at the output side. Lesser ridges in the output waveforms were seen with the Improved PSO-based control than with the conventional PI control. Also, the proposed technique brought the voltage and frequency to their steady-state in a lesser time of 0.03 seconds as compared to the traditional control.
2. During islanding operational mode, lesser THD values of output-side voltage (1.00%) and current (1.27%) were obtained with the proposed control than their corresponding values of 1.23% (output voltage) and 1.43% (output current) with the conventional PI control.

A new type of control approach method was used by the authors Ahmed Jumani et al. (Jumani et al. 2018) for regulating voltage and frequency fluctuations as well as the transient behavior of an autonomously operating solar-integrated microgrid network by making use of the Grasshopper Optimization (GO) technique. They incorporated the grid's PI control system with the Grasshopper algorithm along with a droop control mechanism. Then, they made an in-depth functioning investigation of the presented control technique with that of PSO and Whales Optimization (WO) methods; by designing it in MATLAB and Simulink platforms. They obtained the following results:

1. During the islanding event, the GO-tuned PI control mechanism obtained quicker and superior paradigmatic solutions for its controller parameters than WO or PSO because of its lowest fitness function value and fastest convergence in the least number of iterations.
2. When the load fluctuated during the autonomous operation of the microgrid, the proposed control method was able to bring the system voltage and frequency to their rated values in the least possible time thereby, satisfactorily suppressing the system's transient behavior.

3. During the isolated grid operation, the load current THD values after PV introduction and after the load variation in the case of different control schemes are tabulated in (Table 2) (Jumani et al. 2018) below.

Optimization-Based Control Scheme	THD Values (in %)	
	After PV Placement	After Load Variation
Grasshopper	0.08	0.21
Whales	0.15	0.26
Particle Swarm	0.18	0.37

Table 2: THD Comparison with Different Control Methods

Therefore, the authors concluded that the GO-tuned PI control technique had superior paradigmatic feedback along with the lowest THD values than the WO or PSO control mechanisms.

With the focus to achieve smooth transient behavior along with the lowest possible harmonic contents in a grid-tied microgrid system, the authors Ahmed Jumani et al. (Jumani et al. 2019) came up with the Grasshopper Optimization (GO)-based prototypical power flow control strategy so as to enhance its quality of power supply. In order to substantiate the efficacy of the suggested controller, they made a performance comparison of it with a PSO-tuned control technique by designing and simulating the network in MATLAB and SIMULINK software. They made the following observations:

1. Managing the power exchange between the microgrid system and utility during sudden load variation by using the GOA-tuned control outperformed that of the PSO-based controller in having the least overshoot and faster settling time.
2. The harmonic contents in the system output current with the GO controller after connecting the microgrid and after the load variations were 0.07% and 0.09% respectively which was lesser as compared to the PSO-based control.
3. Also, the suggested control method obtained a quicker and superior paradigmatic solution for its controller specifications due to its lowest fitness function value and faster convergence in the least number of iterations.

With the purpose of achieving a leveled transient response as well as the least number of harmonics in a grid-integrated solar microgrid system, the authors Ahmed Jumani et al. (Jumani et al. 2019) devised a paradigmatic control method utilizing the intuitive algorithm of the Salp Swarm Optimization (SSO) technique. They merged the SSO algorithm with the DG controller so as to enhance its efficiency by reducing the fitness function value. Then, they compared and contrasted the effectiveness of the suggested control mechanism with that of the GO-based control technique by modeling and simulating the networks in the MATLAB-SIMULINK platform. They made the following interpretations:

1. In the environment of undetermined PV integration and sudden load variation, the controller based on the SSO technique was able to bring the power fluctuation back to their set reference values in the least amount of time without allowing much overshoot in their values i.e., the overshoots were 31.7333% after PV integration and 12.0% due to sudden load variation.
2. During the grid-integrated operation, the quantities of harmonic contents observed in the load current after microgrid introduction and load variation for different control schemes are tabulated in (Table 3) (Jumani et al. 2019) below.

Control Method	Harmonic Contents (in %)	
	Microgrid Introduction	Load Variation
Salp Swarm	0.05	0.26
Grasshopper	0.06	0.53

Table 3: Comparison of Harmonic Contents with Different Control Schemes

3. Moreover, the proposed control method obtained the controller optimal solutions in the least number of iterations in addition to having the lowest fitness function value as compared to GO-based control.

From the above interpretations, the authors concluded that the SSO-tuned controller performed better in terms of transient behavior and harmonic suppression.

With the focus on dealing with voltage and frequency variations, transient behavior as well as system harmonics in an autonomous microgrid network, the authors Ahmed Jumani et al. (Jumani et al. 2019) developed a microgrid control system working in isolated mode by making use of the smart algorithm of the SSO technique. They used droop control along with successive PI-tuned voltage and current controls in the suggested grid control system. They modeled and simulated the suggested microgrid network in MATLAB and SIMULINK environment. Then, they drew an efficiency-based comparison of the suggested control technique with that of PSO and GO-based methods. The following were their interpretations:

1. The voltage transients obtained with the SSO control had lesser overshoots for the cases when DG was introduced (1.45%) as well as when the load was reduced (14.77%); it also had the least undershoot extent for the case when the load was increased (15.04%).
2. The SSO control gave better frequency transients too; the overshoot and undershoot values being 0.46% for all three cases.
3. The SSO control was also able to bring the fluctuating voltage and frequency back to their rated values for all the three cases in the least amount of time i.e., 26.36, 94.19, and 77.40 milliseconds respectively in contrast with the PSO and GO controls.
4. The lowest fitness function value in the least number of iterations was also accomplished by the SSO as compared to PSO and GO techniques.
5. The DG-side current harmonic contents in cases of DG introduction, load addition, and load reduction were 0.84%, 0.65%, and 0.13% respectively.

Based on the above interpretations, the authors concluded that the SSO-tuned autonomous microgrid control was far more superior in controlling voltage and frequency fluctuations, harmonic reduction and gave a better transient response than PSO or GO-based controls.

In order to control voltage and frequency fluctuations in an autonomously operating microgrid system when exposed to a variable loading environment, the authors Sedhom et al. (Sedhom et al. 2019) suggested a DG droop control mechanism incorporating H-infinity control as well as the Harmony Search Optimization (HSO) method so as to enhance its capabilities. They designed the suggested control system as a multi-level control loop such that the droop control was the first level, voltage control was the second level, current control was the third level and finally, the filter and coupling circuit control was the fourth level. They implemented the HSO algorithm in the H-infinity control model in order to properly calibrate its weighted parameters μ and ζ for the system stability enhancement. Then, they compared and contrasted the efficiency of the suggested control mechanism with that of the droop control method by modeling and simulating them in MATLAB and SIMULINK software. They made the following observations:

1. Under variable load conditions with different types of loads, the droop control was unable to regulate the system voltage and frequency to their rated values after every load change whereas, the suggested control mechanism was successful in regulating them.
2. Also, the output voltage and current harmonics were greatly reduced with the application of suggested control as compared to that of droop control.
3. Moreover, the system had the least settling and rise times of 0.217 milliseconds and 0.169 milliseconds respectively as well as a higher gain margin of 96.5 dB and a phase margin of 80.6° with the proposed HSO control.

Control Scheme	Type of Loads Connected	Current THD (in %)	Voltage THD (in %)	Voltage Deviation (in Volts)
Droop Control	Linear	0.93	1.93	95.56
	Non-Linear	2.03	2.30	105.25
	Unbalancing	1.02	2.11	102.10
Harmony Search Optimization	Linear	0.44	0.92	13.14
	Non-Linear	0.68	0.92	5.31
	Unbalancing	0.46	0.96	59.86

Table 4: Performance Comparison of the Control Methods

Based on the observations and interpretations from (Table 4) (Sedhom et al. 2019), the authors concluded that the HSO-tuned controller had a better control performance than the droop control method.

In order to regulate voltage and frequency as well as minimize the harmonic contents in an autonomously operating intelligent microgrid system, the authors Sedhom et al. (Sedhom et al. 2020) suggested a three-level control mechanism fed with the HSO algorithm as a means to enhance the controller parameters. They devised the three-level controller such that the primary droop controller kept the grid voltage and frequency overshoots within the tolerance limits during load changes, the secondary multi-stage H-infinity controller brought the system voltage and frequency back to their reference values after load variation whereas the final tertiary level was inputted with the Harmony Search technique to provide the best H-infinity control parameter values. They made a performance comparison between the suggested control mechanism and a Model Predictive Control (MPC)-based control mechanism to analyze their respective efficiencies by designing and simulating them in MATLAB-SIMULINK software. They got the following observations:

1. During the load variation environment, implementation of the HSO control technique effectively reduced the voltage and frequency overshoots as compared to the MPC control.
2. After the load change scenario, the HSO-tuned controller efficiently minimized the max frequency deviation and voltage harmonics to 0.27% and 0.42% respectively from their respective values of 0.90% and 0.78% with the MPC technique. Also, the suggested method brought down the response time of the controller from 0.025 milliseconds to 0.008 milliseconds.
3. The stability of the microgrid network following a load disturbance was better handled by the suggested control mechanism as it significantly diminished the settling and rise times to 2.44 milliseconds and 1.37 milliseconds respectively.

Based on these observations, the authors concluded that their HSO-based control method was better suitable to handle the voltage and frequency changes, mitigate harmonics as well as maintain system stability.

With the aim to achieve harmonic elimination in the output voltage of microgrid inverter as well as to minimize losses resulting from its switching action, the authors A. Naderipour et al. (Naderipour et al. 2021) devised a five-level CH-MLI cascaded H-bridge inverter by integrating it with an SSO-based Sinusoidal Pulse Width Modulation (SPWM) technique. The smart algorithm of the SSO enhanced the parameters of the SPWM carrier wave so as to be able to detect and eliminate the lower order harmonics. They drew out an efficiency-based comparison of the suggested technique with that of the conventional SPWM technique by modeling and simulating them in the MATLAB-SIMULINK platform. They got the observation that for a given modulation index, the harmonic distortions in the inverter output voltage were lesser with the SSO-based SPWM technique rather than with the traditional SPWM method, and hence, they concluded that the suggested technique was more effective in harmonic mitigation as compared to the traditional one.

In order to achieve a proper load-frequency control in a marine Wind-PV integrated microgrid system operating in autonomous mode, the authors A. K. Choudhary et al. (Choudhary et al. 2020) devised a Proportional Integral Derivative (PID) with filter control strategy incorporating fuzzy logic along with the intelligent algorithm of GO technique. They designed and simulated the proposed network in the MATLAB-SIMULINK platform. Then, they made a compare and contrast between the effectiveness of the suggested GO-Fuzzy-PID method with that of traditional PID, Artificial Neuro-fuzzy Inference System (ANFIS), PSO-PID, and GO-PID methods in regulating the frequency. They made the following observations listed in a tabular form in (Table 5) (Choudhary et al. 2020).

Disturbances	Control Method	Undershoot (in Hz)	Overshoot (in Hz)
Step Load Variations	GO-Fuzzy-PID	-0.018977	0.0054644
	GO-PID	-0.041463	0.015101
	PSO-PID	-0.19752	0.084753
	ANFIS	-0.42651	0.14745
Arbitrary Load Changes	GO-Fuzzy-PID	-0.0047048	0.0046
	GO-PID	-0.022266	0.02153
	PSO-PID	-0.047847	0.041594
	ANFIS	-0.37421	0.29393
Change in Grid Parameters	GO-Fuzzy-PID	-0.0047199	0.0045385
	GO-PID	-0.022408	0.0213
	PSO-PID	-0.040573	0.035657
	ANFIS	-0.38681	0.31035
Absence of Solar Power	GO-Fuzzy-PID	-0.0047487	0.0041742
	GO-PID	-0.022454	0.020153
	PSO-PID	-0.048548	0.042578
	ANFIS	-0.44853	0.29099

Table 5: Comparison of Control Methods Under Different Disturbance Events

From all the above event cases, they observed that the system frequency variation was minimal with the suggested GO-Fuzzy-PID control strategy and hence, they concluded that the suggested technique performed better in controlling system frequency under different system disturbances as compared to the other methods.

In order to make an in-depth analysis on the dynamic performance and system frequency enhancement of a hybrid Wind- PV microgrid network operating in the islanding mode, the authors Abdul Latif et al. (Latif et al. 2020) suggested an unconventional grid control system designed with the Butterfly Optimization Algorithm (BOA)-tuned two-phased Proportional-Integral-one plus Integral-Derivative (PI-(1+ID)) control mechanism. They made an efficiency-based comparison of the suggested method with that of PSO and GO-based PI-(1+ID) control methods by modeling and simulating them in MATLAB and SIMULINK environments. They also made a comparative study on frequency regulation with BOA-based PI, PID, and PI-(1+ID) controllers. They got the following observations:

1. During the condition of inaccessible renewable energy sources, the magnitude of system frequency oscillations, as well as the time taken to bring the system to its steady-state were the least with the suggested control in comparison to other control methods as given in (Table 6) (Latif et al. 2020) below.

Control Methods	Undershoot (Hz)	Overshoot (Hz)	Settling Time (sec)
PI	-0.0669	0.0544	3.976
PID	-0.0389	0.0136	4.097
PI-(1+ID)	-0.0190	0.0006	2.581

Table 6: Comparison of Frequency Response with Different Control Techniques

2. During the condition of arbitrary fluctuation in the load demand, the change in the system frequency was minimal with the BOA-tuned parameters rather than with the PSO or GO methods.

Based on the above observations, the authors concluded that the suggested BOA control technique was the most suitable method to regulate the rapid frequency transients in a microgrid.

In order to achieve better system dynamic feedback, reactive power, and harmonic compensation along with system voltage and power factor enhancement in a Wind-PV-Fuel Cell (FC) integrated microgrid network, the authors Ahmed Othman et al. (Othman and Gabbar 2017) suggested an innovative Modulated Power Filter (MPF) incorporated with the intuitive algorithm of Enhanced Bacterial Foraging Optimization (EBFO) technique. They made use of the EBFO for performance maximization of the MPF parameters. Then, they made a compare and contrast of the system response with and without the MPF control by modeling and simulating the network on MATLAB/SIMULINK platform. They made the following observations:

1. The voltage and current harmonic contents at different network terminals (i.e., VS, V1, VL, and Vg) were significantly lesser with the MPF controller than without it as shown in (Table 7) (Othman and Gabbar 2017) below.

Terminals	Methods	Voltage Harmonics (%)	Current Harmonics (%)
V_S	With MPF	0.10	4.55
	Without MPF	0.62	7.25
V_1	With MPF	4.82	4.56
	Without MPF	35.5	21.0
V_L	With MPF	4.40	4.92
	Without MPF	29.3	36.8
V_g	With MPF	4.61	4.20
	Without MPF	26.7	18.5

Table 7: Performance Comparison with and without MPF

2. Due to the grid implementation with the MPF control, the terminal voltages attained a steady value of 1 per unit without much deviation, the reactive powers at the VS and Vg terminals were well-compensated and an enhanced power factor was obtained at the terminals.

From these observations, the authors concluded that the EBFO-based MPF microgrid control strategy had better performance in mitigating the voltage transients, harmonics, and compensating reactive power.

In order for quick damping of system voltage and frequency oscillations due to load variation in an autonomously operating Wind-PV integrated microgrid system, the authors Y. Teekaraman et al. (Teekaraman, Kuppusamy, and Nikolovski 2019) suggested a hybrid Multiple Objective Symbiotic Organism Search (MOSOS)-based PI control mechanism so as to enhance its performance by optimal tuning of its control parameters. They designed this PI control mechanism in such a way that the space vector pulse width modulated signals generated by this PI controller were fed to a three-leg-three-phase inverter. They modeled and simulated the microgrid network with the suggested control strategy using the MATLAB/SIMULINK platform. They made the following observations:

1. The suggested MOSOS-tuned PI control method was able to maintain a steady control signal obtained from the power controller whereas, without PI calibration, unstable signals were obtained.
2. With the optimal PI parameters adjusted by the MOSOS algorithm, the values of the system response parameters i.e., rise time (0.17 sec), settling time (1.5 sec), and overshoot (14.9%) were reduced to their minimum limits during load variation.

3. Role of Reinforcement Learning in Enhancing Power Quality

In (Prabaakaran et al. 2019; Mahmoud, Abouheaf, and Sharaf 2019; Bagheri et al. 2018; Younesi, Shayeghi, and Siano 2020; Radhakrishnan et al. 2020), the authors have made use of the Reinforcement Learning algorithm to control different power quality issues occurring in a microgrid.

In (Prabaakaran et al. 2019), the authors Prabaakaran et al. formulated a new method to compensate for various problems related to the quality of power in a microgrid such as harmonics, reactive power compensation, voltage dips, and momentary overvoltage by making use of a modified version of the Reinforcement Learning mechanism. They have used a voltage controller to control voltage imbalance and a current controller to control any current variations.

The paper (Prabaakaran et al. 2019) made some modifications in the Reinforced Learning technique and has also used Distribution Static Compensator (DSTATCOM) so as to utilize them appropriately in compensating the feeble AC supply which is the result of unbalanced load connected to a microgrid. By using this modified algorithm, the authors made some improvements to the system so that it responds quickly to any power quality problems in the grid. The following were the observations made from this work:

1. The improvised version of the Reinforcement Learning along with the DSTATCOM quickly compensated the voltage sag that occurred in the grid by compensating reactive power as well as voltage injection to the grid.
2. Without any compensation, the level of THD was found to be 36.95% which indicated a very high number of harmonics in the system that could cause grid disruptions.
3. By using proper DSTATCOM control in conjunction with the modified algorithm, the THD level in the grid came down to 0.1%.

A different method was adopted by the authors Mahmoud et al. (Mahmoud, Abouheaf, and Sharaf 2019) to control the output side voltage of a distributed generator operating in autonomous mode by using the adaptive learning method. In this, the control problem of the distributed generator is optimized by the Reinforced Learning approach and solved by using the method of adaptive critics that finds an iterative solution for the fundamental equation of Bellman optimality. The authors have developed a control method by using the Reinforcement Learning mechanism which is implemented into the grid to rough out any power quality disturbances and they have also compared the competitiveness of this controller with that of a standard Riccati controller when subjected to an environment with the undetermined dynamic condition. The following were observations from this paper:

1. When subjected to disturbances, the system with an adaptive learning controller was robust and was better able to withstand the uncertain behavior of the system's dynamic parameters than the conventional Riccati controller.
2. The control signals were smaller with the adaptive controller as compared to using the Riccati controller.
3. The total accumulated cost was also found to be lesser when using the controller with Reinforced Learning than the traditional Riccati controller.
4. When the microgrid operating in islanded mode was subjected to an additional RLC load, the adaptive control technique was able to bring down the voltage at the PCC to its nominal value within a few cycles.

In order to alleviate the various power quality disturbances in a microgrid like harmonic distortions, unbalanced load, and reactive power compensation, the authors M. Bagheri et al. (Bagheri et al. 2018) designed a DSTATCOM integrating the adaptive learning method by using voltage and current controllers. The reactive power setpoint is adjusted using the voltage controller whereas the grid's unbalancing load current was compensated by the current controller through the quadrature and zero axes.

The authors in (Bagheri et al. 2018) applied this control mechanism to an islanded grid with a weak AC source and simulated this system under different load conditions along with three-phase faults. They made the following observations:

1. When the islanded grid was subjected to load changes, the proposed mechanism was able to control the PCC voltage by escalating the reactive power generation capacity of DSTATCOM.
2. During the condition of unbalanced load on the grid, the suggested control scheme maintained the source current in a balanced condition even when load current became unbalanced.
3. When the microgrid was treated to a non-linear load condition, the suggested scheme along with the DSTATCOM balanced the distributed generation current by mitigating harmonic distortions of the load.

In order to achieve proper voltage regulation and enhancement of the system frequency in a wind turbine-integrated AC microgrid system, the authors Abdollah Younesi et al. (Younesi, Shayeghi, and Siano 2020) suggested a control mechanism incorporated with the smart algorithm of Reinforcement Learning (RL) technique for its performance enhancement. They devised the Markov Decision Process (MDP) by quantizing the continuous signals into a finite number of states and this devised quantized problem was solved using the iterative Q-learning method. Then, they brought out an effectiveness-based comparison of the suggested technique with that of conventional PID and Fuzzy-based PID control methods by designing and simulating them in the MATLAB-SIMULINK environment. They made the following observations:

1. During the case of a three-phase symmetrical fault on the system, the suggested RL-tuned PID control mechanism was better able to suppress the voltage and frequency transients with the least number of overshoots and undershoots as well as took lesser time to bring the system back to its steady-state.

2. During the case of unexpected load changes in the system, the proposed control method showed excellent dynamic performance as compared to the other controls in a way that it overcame the system voltage and frequency disturbances with the least amount of deviation along with faster settling time.
3. For both the cases, the intuitive RL-based control strategy gave the minimum values of the two time-domain performance indices i.e., Integral Time Absolute Error (ITAE) and Integral of Square Error (ISE) in comparison with that of conventional and fuzzy-based PID control.

From the above observations, the authors concluded that the RL-tuned PID technique performed better in mitigating voltage and frequency oscillations in the microgrid system.

In order to establish a quicker frequency response to mitigate large frequency disturbances due to switching actions in a multiple interconnected microgrid network, the authors Nikita Radhakrishnan et al. (Radhakrishnan et al. 2020), formulated a control mechanism based on the RL algorithm for generator control refinement when subjected to large disturbances. They designed and simulated the network by using GridLAB-D simulation software and used the HELICS platform for controller communication. They observed that with the RL-based control, the values of performance parameters of the system frequency response i.e., rise time, peak time, peak overshoot, settling time and steady-state error were much better as compared to that without any control mechanism. Hence, they concluded that the RL-tuned microgrid control enhanced the grid's ability to handle large frequency variations.

4. Signal Processing and Pattern Recognition Techniques in Mitigating Power Quality Disturbances

A different approach was undertaken by T. Yalcin et al. (Yalcin and Ozdemir 2016), A. C. Moreira et al. (Moreira et al. 2018), and Rupal H. et al. (Rupal et al. 2017) where they used Pattern Recognition and Signal Processing techniques respectively to solve the problem of power quality disturbances in microgrids.

In (Yalcin and Ozdemir 2016), the authors have used the Hilbert Huang Transform which is a Signal Processing technique (SPT) along with other Machine Learning methods like Support Vector Machine (SVM), C4.5 Decision tree algorithm in order to automatically detect and classify voltage sags in the electricity grid. The power signal to identify voltage dips in the system was explored by using the Pattern Recognition technique (PRT) based on Hilbert Huang Transform. The Ensemble Empirical Mode Decomposition (EEMD) method was used for grid voltage sag classification after which Hilbert Huang transform was used to generate instantaneous amplitude and instantaneous frequency. Here, the authors have made a comparison between the C4.5 Decision tree and SVM in terms of the error in calculation and their respective computational time to produce the best solution. They made an observation of the following things:

1. As compared to SVM-polynomial degree 2 having a CPU time of 17.879 seconds, the SVM-RBF sigma 1 had a better computational time of 17.784 seconds. However, the error in computation was the same for both which was 0.1%.
2. When SVM was compared with the Decision tree, the latter had an accuracy of 100% (i.e., zero error in computation) with a computational time of 20.064 seconds.

Thus, they concluded that the C4.5 Decision tree algorithm had superior performance when compared with the SVM technique.

In order to achieve the proper classification of the power quality issues and to adopt the right alleviation techniques in a three-phase, grid-tied AC microgrid working under unbalanced voltage and current conditions, the authors A. C. Moreira et al. (Moreira et al. 2018) devised an intelligent Expert System (ES) using the k-Nearest Neighbor (KNN) as well as the decoupled power-current decomposition methods. They designed and simulated an IEEE 13-Bus grid network along with the suggested classification technique in MATLAB-Simulink and PSCAD-EMTDC platforms. They made the following observations:

1. When one of the nodes i.e., Node 632 of the 13-bus system had a power factor around 0.90 (which was less than the lower limit of 0.92) and lesser current distortions, the suggested ES classifier recommended using a three-phase capacitor bank as the compensation means at this node because of which the node power factor increased to 0.93.
2. When Node 634 of the 13-bus system had a lower power factor around 0.897 and higher current distortion, the proposed ES classifier recommended connecting a passive filter in series with the non-linear load along with a fixed capacitor bank for 5th harmonic frequency mitigation.
3. When the Node 680 of the 13-bus system had the least power factor of 0.754 as well as a high current imbalance, the suggested KNN classifier recommended utilizing a Static VAR Compensator (SVC) due to which the node power factor increased to 0.95 along with phase balancing of the unbalanced circuit.

From these observations, the authors concluded that the suggested KNN-based ES classifier correctly classified the quality problems with 99.98% accuracy along with their proper mitigation techniques.

Rupal H. et al. (Rupal et al. 2017) made an excellent and critical analysis of the limitations of Empirical Mode Decomposition (EMD) over the EEMD method in the detection of power quality issues in the case of islanding and non-islanding modes of a microgrid. They made a performance analysis of the two methods by modeling and simulating a 13-bus photovoltaic system in the PSCAD platform. The classification of the disturbances was done by a non-linear classifier based on the SVM method. Their study gave the following results:

1. Signal containing both voltage sag and harmonics:
   a) A mode mixing was observed when applying the EMD method i.e., it was unable to differentiate between the two events as its Intrinsic Mode Function (IMF) contained both the events.
   b) This mode mixing problem was solved when the EEMD method was applied as its IMF1 contained only harmonics whereas its IMF2 contained only voltage dip. Also, the duration of the voltage sag got corrected by the EEMD method.
2. Signal with a mix of capacitor switching and harmonics:
   a) The EMD method mixed the properties of both the events as was given by its IMF.
   b) The IMF1 of the EEMD technique contained only harmonics and its IMF2 contained only the capacitor switching event.
3. Non-Islanded Operational Mode of Microgrid:
   a) When the load on bus 6 was disconnected, it was seen that the EEMD method identified this event 10 samples earlier than the EMD method.
   b) When the capacitor bank was switched on at bus 5, the EEMD method identified this event 13 samples earlier than the EMD method.
4. Islanded Operational Mode of Microgrid:
   a) When there was a small (2%) mismatch in active power, the EEMD method detected this event 12 samples faster than the EMD method.

b) When there were zero mismatches in active power, the EEMD method detected this event 8 samples faster than the EMD method.

From the above results, the authors in [28] concluded that the EEMD technique is far more superior to the EMD method in detecting the different power quality problems in a microgrid.

5. Neural Networks and Deep Learning Methodologies in Power Quality Augmentation

The authors Yajun Wang et al. (Wang, Pulgar-Painemal, and Sun 2017) developed an advanced method to solve the problem of voltage instability occurring in microgrids by using the Convolutional Neural Network (CNN) algorithm and made a comparative performance analysis of this method with those of Back Propagation Neural Network (BPNN), SVM and Decision Tree techniques. They performed a case study on the modified version of the IEEE 14-bus system in order to analyze and classify the unstable behavior of grid voltage; which was carried out in three steps:

I. Data sets was formed by making use of simulation results in offline mode.
II. The model was made compact to avoid computational complexity and then trained using CNN.
III. Performance assessment was done by online testing of data set.

Then they observed the performances of various techniques for the given number of data sets and finally concluded that CNN was the most accurate method to classify the instability problems with an accuracy of 97.59%, followed by SVM, BPNN, and Decision Tree with their respective accuracies of 95%, 91.3%, and 90.37%.

In order to ensure the supply of safe and reliable quality of power, a different style was adopted by the authors N. Mohan et al. (Mohan, Soman, and Vinayakumar 2017) who made an in-depth analysis of the performances of different Deep Learning (DL) techniques namely Convolutional Neural Network (CNN), Recurrent Neural Network (RNN), Identity-Recurrent Neural Network (I-RNN), Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), and Convolutional Neural Network-Long Short-Term Memory (CNN-LSTM) in categorizing the various power quality problems in real-time. They performed various tests so as to come up with a prototypical DL design having particular topologies and network parameters. Then performance evaluation was done based on a set of real-time, artificially induced individual and combined power quality phenomena.

The authors (Mohan, Soman, and Vinayakumar 2017) chose the TensorFlow platform along with Keras to carry out the performance evaluation work. They observed that when the framework of the model was based on CNN only, its accuracy and precision were 98%; so, in order to further improvise the model, they combined the characteristics of CNN with that of LSTM and got a much better accuracy of 98.4%. The accuracies, in the increasing order, of different DL models that were obtained are given in (Table 8) (Mohan, Soman, and Vinayakumar 2017) below.

Deep Learning Classes	Accuracy (in %)
RNN	91.5
I-RNN	93.6
GRU	96.4
LSTM	96.7
CNN	98.0
CNN-LSTM	98.4

Table 8: Accuracy of Deep Learning Models

Therefore, the authors concluded that the hybrid model i.e., CNN-LSTM combining the features of both CNN and LSTM was able to categorize the power quality events highly accurately with 98.4% accuracy.

With the aim to detect and categorize the different power quality problems in a microgrid, the authors S. Wang et al. (Wang and Chen 2019) brought forward an innovative method of closed-loop feedback based-Deep CNN which is a sub-part of the DL technique. In the suggested deep CNN procedure, automatic feature extraction from huge perturbation samples was done by piling numerous units together. The authors compared this method with other advanced DL techniques such as LSTM, GRU, ResNet50, and Stacked Auto Encoder (SAE) all of them having automated feature selection so as to prove the supremacy of the former method in tackling the limitations of the latter ones. In order to carry out the analytical experimentation on power quality issues, they designed and simulated a multi-microgrid system. Then they trained the models and tested their performance with a test set of 1000 samples along with noise signals of 20 dB, 30 dB, and 40 dB strengths. The following observations were made given in a tabulated format in (Table 9) and (Table 10) (Wang and Chen 2019).

Model Type	Number of Parameters	Training Time (in mins)	Accuracy (in %)
Deep CNN	166,420	191	99.5
LSTM	25,488	1164	99.4
GRU	19,248	1069	99.3
ResNet50	23,603,979	2232	98.9
SAE	99,200	254	96.5

Table 9: Training Efficiency of the Models

Type of Neural Network	Noise Strength (in dB)	Average Accuracy (in %)
Deep CNN	No Noise	99.96
	20	98.13
	30	99.66
	40	99.95
ResNet50	No Noise	99.84
	20	96.94
	30	99.06
	40	99.83
GRU	No Noise	99.98
	20	97.71
	30	99.56
	40	99.96
LSTM	No Noise	99.94
	20	97.79
	30	99.58
	40	99.93
SAE	No Noise	99.14
	20	92.39
	30	96.36
	40	98.82

Table 10: Performance of Neural Networks with Noise Signals

From the above observations, the authors concluded that the suggested deep CNN-based model is the paradigmatic option for the categorization of microgrid power quality issues.

In order to regulate and reinstate the PCC voltage and frequency of a microgrid in case of power quality disturbances, the authors J. Alshehri et al. (Alshehri and Khalid 2019) took a different approach by developing an advanced hybrid controller for a Battery Energy Storage System (BESS) on the basis of combined Artificial Neural Network (ANN) and Differential Evolution Optimization (DEO) techniques. They calibrated the parameters of the controller by training the ANN model with input data sets and enhanced the controllers by feeding them with low and high magnitude disturbances by making use of the DEO method. The authors corroborated the efficiency of the suggested control mechanism by conducting simulations on a PV network having a BESS and an alternator. They drew a comparison of this strategy with that of a conventional PID controller. Their experiment gave the following results:

1. For High Magnitude (3.287 per unit) Disturbance:
    a) Without any controller, the grid voltage and frequency kept oscillating for longer than 10 seconds.
    b) But when the suggested control strategy was applied, the oscillations died out in fewer than 2 seconds and the grid was restored to its steady-state. Also, the overshoot and settling time was better in comparison with the PID controller.
2. For Low Magnitude (0.512 per unit) Disturbance:
    a) Without any control action, the grid voltage and frequency kept oscillating for a longer period of time.
    b) The oscillations died out in fewer than 2 seconds and steady-state stability was achieved when the suggested DEO-ANN controller was used. It had a better performance than the traditional PID controller in controlling overshoot and recovering the grid's steady-state condition.

The authors Ab-BelKhair et al. (Ab-BelKhair, Rahebi, and Abdulhamed Mohamed Nureddin 2020) adopted a new approach to studying the power quality problems and their alleviation in a hybrid Wind-Photo-Voltaic (PV) microgrid network under unforeseeable weather conditions by developing an algorithmic program for control strategy which is based on the combination of Maximum Power Point Tracking (MPPT) and Deep Neural Network (DNN) techniques. They did an experiment to come up with a state-of-the-art DNN control method that would increase the quality of supply as well as decrease the THD of the grid system. Then, they performed an in-depth analysis of the harmonic distortions under various conditions such as individual wind network, individual PV network, and finally the complete hybrid microgrid network and compared the results with that of a traditional PI control mechanism. These networks were designed, simulated, and studied in MATLAB and SIMULINK platforms. The results obtained by the authors are tabulated in (Table 11) (Ab-BelKhair, Rahebi, and Abdulhamed Mohamed Nureddin 2020) as follows.

Type of Network	PI Control Mechanism		DNN Control Mechanism	
	V_L THD (%)	I_L THD (%)	V_L THD (%)	I_L THD (%)
Wind	0.17	29.9	0.12	2.28
PV	0.17	0.35	0.12	0.02
Hybrid	0.17	3.62	0.12	0.10

Table 11: DNN and PI Performance Comparison

From the above results, the authors concluded that the hybrid system integrated with the suggested DNN control strategy performed superiorly to that of the PI controller in every aspect.

With the aim to achieve a superior power flow control as well as a better voltage regulation in a wind turbine-integrated microgrid system working in a grid-connected mode, the authors Raya-Armenta et al. (Raya-Armenta, Lozano-Garcia, and Avina-Cervantes 2018) suggested a wind control system whose performance was enhanced by the ANN algorithm in conjunction with the B-Spline functions. They used the least mean square error algorithm to train these B-Splines and designed the network by using the respective differential equations of the system components. Then, they analyzed the system under two test cases which were designated as constant and variable mechanical torque reference respectively. During the analysis, they observed that the error between the obtained and reference reactive powers were less than 2% and 6% for former and latter cases respectively; whereas the voltage fluctuation with respect to reference voltage was at most 1% for both the cases. From these observations, they concluded that the addition of the proposed technique increased the efficiency of the wind controller to control power exchange between the microgrid network and utility.

In order to maximize the output power of the PV unit, to increase the efficiency of the fuel cell unit as well as to reduce the system harmonics in a hybrid PV-Fuel Cell integrated microgrid system, the authors Mohamed Nureddin et al. (Nureddin, Rahebi, and Ab-BelKhair 2020) devised a control mechanism for controlling and obtaining the maximum power output from PV and fuel cell units by incorporating the Maximum Power Point Tracker with the smart algorithm of the DNN. They made an in-depth analysis of the voltage and current harmonics present in the network output by modeling and simulating both the units in the MATLAB-Simulink platform. They made a compare and contrast on the performance of the units with DNN as compared to when Fuzzy Logic was used. They made the following observations:

1. The maximum output power achieved by the PV unit equipped with the DNN technique was more (i.e., 18080 Watts) as compared to that with the fuzzy logic (i.e., 17820 Watts).
2. Also, the efficiency of the DNN-tuned fuel cell was higher (i.e., 57.09 %) than the fuzzy-based fuel cell (i.e., 57.01 %).
3. Moreover, the output harmonic contents of the system obtained with the suggested technique were lesser than the standard value of 5 % as set by the IEEE; which is tabulated in (Table 12) (Nureddin, Rahebi, and Ab-BelKhair 2020) as given below.

Parameters	PV	FC	Hybrid Microgrid
Voltage Harmonics (%)	3.55	3.55	3.55
Current Harmonics (%)	0.90	4.46	0.40

Table 12: Harmonic Comparison in Different System Models

From the above observations, the authors concluded that the suggested DNN-based DG controller had superior performance than fuzzy logic and was also able to reduce the harmonics below the IEEE standard value.

6. Contribution of Intelligent Controllers in Power Quality Enhancement

This section provides a context to the part played by AI-powered controllers in dealing with grid power quality issues that are introduced by the authors K. H. Kwan et al. (Kwan et al. 2007), P. Prabhakar et al. (Prabhakar and Charles 2019), Garcia-Torres et al. (Garcia-Torres et al. 2021), S. Golsorkhi et al. (Golsorkhi and Lu 2016), Y. Shan et al. (Shan et al. 2019), Zhuoli Zhao et al. (Zhao et al. 2020), U. Tamrakar et al. (Tamrakar et al. 2021), B. Dharma Rao et al. (B. Rao and A. Rao 2013), S. Nalini et al. (Nalini and Raja 2019), N. Tephiruk et al. (Tephiruk et al. 2018), Tariq Kamal et al. (Kamal et al. 2020), Soumya Das et al. (Das et al. 2021) and Jitender Kaushal et al. (Kaushal and Basak 2019).

Owing to a large number of grid disturbances like input voltage and output current harmonics, voltage dips, or momentary overvoltage as well as input side power factor problem, the authors Kwan et al. (Kwan et al. 2007) suggested an MPC algorithm in conjunction with UPQC. In order to squeeze out the fundamental and other harmonic components to set up required references, they utilized Kalman filters. To substantiate the potential of MPC-based UPQC, they designed and simulated this system in the MATLAB environment and obtained the following results:

1. Non-Linear Load Harmonic Compensation:

   When harmonic compensation was done for source voltage and load current, they got the following THD values given in (Table 13) (Kwan et al. 2007); which shows that they achieved harmonic reduction with the suggested method.

Parameters	Before Compensation	After Compensation
Voltage THD	13.96%	1.9%
Current THD	42.5%	4.5%

Table 13: THD Before and After Compensation

2. Source Voltage Disruptions:

   When sag and swell events were given to the source voltage from 0.1-0.2 seconds and from 0.3-0.4 seconds respectively, the MPC-based UPQC brushed off these events so that load voltage was in accordance with the reference voltage.

3. Load Variations:

   In this case, the proposed technique rejected the harmonic disturbances so that the source current was in accordance with the reference current and they obtained the following THD values for different loads shown in (Table 14) (Kwan et al. 2007).

Load Type	I_S THD	I_L THD
Dimmer	< 5%	41.5%
Fluorescent Lamp	< 5%	23.2%
Dimmer + Lamp	< 5%	21.0%

Table 14: Current THD Under Various Loads

From the above observations, the authors concluded that the MPC strategy was able to get rid of harmonics, voltage events as well as load demand variation.

Another prediction-based control approach was followed by the authors P. Prabhakar et al. (Prabhakar and Charles 2019) in improving the microgrid power quality issues. They made use of the MPC technique in designing DSTATCOM and UPQC appliances along with filters in order to reduce harmonics as well as compensate reactive power for grid-connected and autonomous microgrid modes. Then, they compared and contrast the effectiveness of both devices in different modes of operation by using MATLAB and SIMULINK platforms. They came to the following conclusions:

1. THD in the case of UPQC control was better (3.5%) as compared to that in DSTATCOM control (4.9%) but an easier realization of DSTATCOM than UPQC.
2. During grid-connected microgrid operation, the MPC-based UPQC controller minimized the reactive power more effectively than the DSTATCOM controller.
3. In the presence of non-linear load in the autonomous microgrid operation, reactive power was completely minimized with the DSTATCOM control than with UPQC control.

With the aim to perform a rigorous analysis of the transient behavior and harmonic response in the grid-tied and autonomous operation of a single and interconnected microgrid system, the authors Garcia-Torres et al. (Garcia-Torres et al. 2021) put forward a method of MPC-controlled microgrid converters. They made a differentiation between the suggested control technique with that of classical PI-based PWM (PI-PWM) control. They used SimPowerSystems present in the SIMULINK of MATLAB software to design and simulate this system. They recorded the following observations:

1. Single Microgrid System:
    a. In grid-tied operation, the transient behavior of the system was longer with the classical control whereas the system reaches steady-state in only two cycles with MPC control. Even with non-linear and unbalancing loads, the system had a lesser current THD with MPC control than with PI-PWM control
    b. During autonomous operation, superior transient behavior and lower voltage THD occurred with the proposed control strategy.
2. In an interconnected microgrid network, individual microgrids governed their own loads without being a burden on their adjacent microgrids. Also, non-linear and unbalancing loads did not affect the network's THD values.

In order to minimize voltage unbalancing, reduction of output current harmonics, and to prevent DG overloading condition in a 5-bus CIGRE benchmark microgrid system, the authors S. Golsorkhi et al. (Golsorkhi and Lu 2016) devised a localized grid droop control mechanism integrated with the intuitive algorithm of the MPC technique. They designed and simulated the suggested control technique in the MATLAB-SIMULINK platform and compared its performance with that of a traditional droop control technique. Then, they realized the MPC method in SIMULINK via the qpOASES software. They made the following observations:

1. During the case of step-load increment at bus-2, the magnitude of unbalance in the voltage at different buses was lesser with the suggested control mechanism than with the traditional control as given in (Table 15) (Golsorkhi and Lu 2016) below.

Bus Number	**Voltage Unbalance (in %)**	
	With MPC	**With Droop Control**
1	0.55	2.6
2	1.76	3.1
3	0.45	2.6
4	0.60	2.6
5	0.68	2.7

Table 15: Comparison of Bus Voltage Imbalance

2. During the case of unbalanced load switching at bus-2, the unbalancing in the bus voltage with the MPC control was around 0.1-0.2% whereas, it was nearly 0.6% with the traditional droop control method.
3. When the load at bus-2 was made up of a single-phase and a three-phase load, the magnitude of the bus voltage unbalance with the MPC method was very less (i.e., 0.1-0.2%) than with the traditional method.
4. The current harmonic contents at different buses too were greatly minimized with the help of the MPC technique as given in (Table 16) (Golsorkhi and Lu 2016) below.

Bus Number	**Current Harmonics (%)**
1	0.4
2	0.5
3	0.4
4	0.5
5	0.5

Table 16: Bus Harmonic Levels

From the above observations, the authors concluded that the MPC-based droop control technique showed superior performance in dealing with the system voltage deviation and current harmonic issues.

In order to achieve a reduction of voltage fluctuation and voltage harmonic contents in the output waveforms in a Wind-PV-Battery integrated microgrid system, the authors Y. Shan et al. (Shan et al. 2019) suggested an MPC-based current-power (MPCP) and voltage-power (MPVP) control techniques without using any PI controller. They utilized MPCP-tuned BESS to take control of its bidirectional DC-DC converter whereas, the AC-DC converter was directed by the MPVP mechanism. Then, they made a compare and contrast of this MPC-based technique with that of a conventional cascaded PI control method by modeling and simulating the suggested method in MATLAB and Simulink environment. They made the following observations:

1. During the grid-tied operational mode of the microgrid, the suggested control mechanism was better able to flatten the output DC voltage waveform of the bus thereby, resulting in a steadier output voltage as compared to that with the conventional PI control.
2. During the autonomous mode of the microgrid, when load switching was done, a smooth output DC voltage with a low harmonic content of 1.05% was obtained with the MPC-based control whereas the PI method showed voltage oscillations with high harmonic contents of 3.20%.
3. During the case of synchronizing and connecting the microgrid with the power grid, the microgrid voltage wave coincided almost perfectly with the utility voltage without any significant voltage deviation.

From these observations, the authors concluded that the proposed MPC method without PI control was better in mitigating voltage transients and reducing output harmonics.

In order to deal with the increase in system transients and harmonics caused due to rapid switching action in an AC microgrid operating in the autonomous mode, the authors Zhuoli Zhao et al. (Zhao et al. 2020) devised a localized droop control mechanism based on the intelligent algorithm of the modified Finite Control Set-Model Predictive Control (FCS-MPC) technique. They successfully minimized the switching frequency and voltage harmonics by employing the feedback correction mechanism. Then, they brought out a performance comparison of the suggested control technique with that of traditional cascade PI and Proportional Resonant (PR) control mechanism by designing and simulating the suggested grid network in the MATLAB-SIMULINK platform. They made the following observations:

1. During the case of non-linear load connection to the PCC, drastic contortion in the output voltage and current occurred with the traditional PI as well as PR controllers. Moreover, there was a large amount of odd harmonic contents with a distortion magnitude of 5.63% by using PR control; whereas, the harmonic content was minimized to just about 1.63% with the help of the suggested control mechanism.
2. During the case of non-linear and unbalanced load switching, oscillating voltage and current waveforms were obtained with the traditional PR control. But, applying the suggested control mechanism maintained a steady sinusoidal output voltage as well as compensated the reactive power.
3. During the case of step load variation in the grid, undulations in the voltage waveform were observed with the PR control which got mitigated by using the suggested FCS-MPC technique.

From the above observations, the authors concluded that the localized FCS-MPC control mechanism was able to give a better system transient response as well as destroy the output side In order to deal with a large rate of change of frequency (ROCOF) as well as high-frequency deviations in a low-inertia microgrid network, the authors U. Tamrakar et al. (Tamrakar et al. 2021) devised a fast frequency response-based control architecture using the Moving Horizon Estimation (MHE) technique which in turn is based on the smart algorithm of the Model Predictive Control (MPC) method. They measured the ROCOF and frequency deviation from the phase-locked loop (PLL) evaluation by making use of the MHE technique and these measurements were used by the MPC to interpret a finite-horizon, optimization problem so as to calculate the grid's control actions. Then, they made an efficiency comparison of the suggested MPC-based MHE method with that of a conventional low pass filter by designing and simulating the microgrid network with the proposed control mechanism in MATLAB and SIMULINK software. They got the following observations:

1. With the help of the MHE method, the ROCOF and frequency measurements were much better and more accurate along with minimum time delays as compared to that with a low pass filter, so that it improved dynamic stability of the system by reducing the fluctuations in the network.
2. With the help of the suggested control method, suitable weighting parameters were able to be chosen by the energy storage system operative that reduced large frequency overshoots as well as load shedding due to low system frequency.
3. Also, the longevity of the energy storage system was enhanced with the use of a regulated MPC-tuned MHE control mechanism.

From these observations, the authors concluded that the proposed MPC-based MHE control technique was able to improvise the dynamic performance of the system by limiting the ROCOF and frequency oscillations.

In order to achieve a higher quality of supply voltage by getting rid of harmonic distortions in a grid integrated Wind-PV microgrid network, the authors B. Dharma Rao et al. (B. Rao and A. Rao 2013) designed a PWM controller for the microgrid based on the Fuzzy Logic algorithm and compared the efficiency of the suggested control mechanism with that of a traditional PI-based PWM control method. They modeled and simulated these networks in MATLAB and SIMULINK environments. Their observations were recorded in a tabulated format as given in (Table 17) (B. Rao and A. Rao 2013) below.harmonics.

System Parameters	PI-PWM Method	Fuzzy PWM Method
Grid Voltage	7%	2%
Converter Output Voltage	10%	2%
Grid Current	10%	2%

Table 17: Comparison of Voltage Contortion

From the above observations, the authors concluded that the limitations of the classical PI-PWM controller in dealing with voltage quality were easily conquered with a fuzzy control technique.

The authors S. Nalini et al. (Nalini and Raja 2019) proposed a UPQC-based DC microgrid controller modeled with the fuzzy logic algorithm in order to indicate and control voltage disturbances and harmonics so as to maximize the power grid efficiency. They designed this microgrid network integrated with an energy management system and simulated it in MATLAB software. Then, they obtained the following results:

1. During the event of voltage dip at the source side, the addition of fuzzy-based UPQC attenuated this event thereby making the source voltage near sinusoidal.
2. Also, UPQC integration drastically reduced the harmonic contents in load voltage and current so that their THD values were 3.35% and 2.52% respectively.

Therefore, they concluded that UPQC with fuzzy control method was a faster and more efficient technique to enhance power quality rather than the benchmark control strategies.

In order to deal with voltage and frequency variation when an autonomous Hydro-PV microgrid system is put through random disturbance events, the authors Tephiruk et al. (Tephiruk et al. 2018) devised a Fuzzy Logic-based BESS control strategy. The fuzzy algorithm enhanced the BESS by feeding it with authentic dynamic parameters of the disturbance event. They designed and simulated the proposed strategy with the help of DIgSILENT PowerFactory platform. Then, they brought out a comparison between the effectiveness of the suggested strategy with that of a robust control mechanism in stabilizing the system. They made the following observations listed as cases I and II:

I. Low load Autonomous Operation:
    a. Without the BESS control mechanism, it was impossible to suppress the speedily changing voltage and frequency disturbances thereby, resulting in highly unstable microgrid operation.
    b. With the Fuzzy BESS strategy, the voltage and frequency changes were better regulated rather than with the robust BESS control. Also, the proposed strategy brought the system frequency to its steady-state in just about 1 second.

II. Escalated load Autonomous Operation with Undetermined PV Integration.

The performance comparisons for both the cases are tabulated in (Table 18) and (Table 19) (Tephiruk et al. 2018) as given below.

Control Method	Lowest Voltage (Per Unit)	Lowest Frequency (Hertz)
Fuzzy BESS	1.003	49.974
Robust BESS	1.001	49.953

Table 18: Performance Comparison for Case I-(b)

Control Method	Lowest Voltage (Per Unit)	Lowest Frequency (Hertz)
Fuzzy BESS	1.002	49.974
Robust BESS	1.000	49.966

Table 19: Performance Comparison for Case II

Based on the above observations, the authors concluded that the Fuzzy-aided BESS control technique had better performance than the robust BESS method in maintaining a stable grid operation.

In order to obtain better power transfer capabilities and system frequency regulation, higher efficiency of microgrid inverter output as well as lesser harmonic contents in a PV-integrated microgrid system, the authors Tariq Kamal et al. (Kamal et al. 2020) devised a microgrid control based on a combination of supervisory and Adaptive Neuro-Fuzzy Jacobi Wavelet (ANFJW) control methods. They divided the supervisory control into upper and lower-level positions such that the upper position produced control signals by taking into consideration the variation of load and weather conditions whereas the grid converters and energy sources were under the control of the lower position. They controlled and enhanced the operation of the grid inverter via the adaptive neuro-fuzzy algorithm. Then, they brought about a performance comparison of the suggested control with that of traditional PID, Fuzzy Logic, and Neuro-Fuzzy control techniques by designing and simulating the network in MATLAB software. They made the following interpretations:

1. Under a given load and weather condition, the system's active and reactive powers smoothly coincided with their respective reference waveforms using the suggested control method but power overshoots occurred with the other methods.

2. Also, by using the suggested controller, the harmonic contents (2.37%) and frequency variation (less than 0.02%) were way lesser, shown in (Table 20) (Kamal et al. 2020), than their respective standard limits of 5% and ±0.8% as set by the IEEE.

Control Method Used	Power Transfer Efficiency (in %)		Harmonic Distortions (in %)
	Active	Reactive	
Conventional PID	86.94	87.04	8.96
Fuzzy Logic	89.11	89.18	6.54
Neuro-Fuzzy	92.17	92.25	3.63
ANFJW	99.05	99.08	2.37

Table 20: Comparison of Control Methods Based on Various Parameters

Based on the above interpretations, the authors concluded that the suggested control technique had superior performance in handling power transfers, regulating grid frequency as well as minimizing system harmonics as compared to the other methods.

In order to achieve better reactive power compensation, superior voltage regulation as well as proper harmonic elimination in a grid-connected microgrid network, the authors Soumya Das et al. (Das et al. 2021) developed a microgrid control based on Shunt Hybrid Filters (SHF) incorporated with the Adaptive Fuzzy-Neural Network (AFNN) control algorithm so as to enhance its performance in handling the power quality problems. They made an efficiency-based comparison of the suggested control method with that of Adaptive Fuzzy Sliding (AFS) and Adaptive Fuzzy Back-Stepping (AFBS) techniques by designing and simulating the models in MATLAB and SIMULINK software. They made the following observations:

1. Connection of RL and RC Loads:

   Under this condition, all the performance parameters obtained by using the AFNN strategy were much better as compared to those obtained with the AFS and AFBS methods; which is tabulated in (Table 21) (Das et al. 2021) as given below.

Type of Load Connected	Performance Parameters	Control Schemes Employed		
		AFS	AFBS	AFNN
RL	Current Harmonics (%)	3.41	2.24	1.83
	Overshoot (%)	9.06	7.33	5.33
	Settling Time (sec)	0.10	0.12	0.05
	Reactive Power (VAR)	5.22	-5.53	-0.2904
RC	Current Harmonics (%)	3.22	2.25	2.10
	Overshoot (%)	4.00	7.33	5.33
	Settling Time (sec)	0.10	0.12	0.06
	Reactive Power (VAR)	24.67	6.958	31.44

Table 21: Performance Comparison under Different Loads

2. Dynamic Loading:

   During this process, the AFNN-based control mechanism was best able to minimize the voltage deviation as well as was able to bring the system back to its steady-state in the fastest possible time as compared to other control methods; which is given in (Table 22) (Das et al. 2021).

Control Schemes	Overshoot (%)	Settling Time (sec)
AFS	5.33	0.50
AFBS	5.06	0.45
AFNN	4.66	0.40

Table 22: Performance Comparison under Dynamic Loading

3. Resistive Load With Source Voltage Contortion:

In this environment, the AFNN-tuned SHF control performed superiorly in compensating the voltage ripples as well as in reducing the harmonic contents in the source current as compared to other methods; as tabulated in (Table 23) (Das et al. 2021).

Control Methods	Ripple Factor (%)	Harmonics (%)
AFS	0.200	4.86
AFBS	0.060	4.38
AFNN	0.026	3.87

Table 23: Performance Comparison with R-Load and Contorted Source Voltage

4. Unbalancing, Non-Linear RL Load:

   Under this situation, the suggested AFNN control strategy was highly effective than the other methods in handling the voltage ripples as well as in compensating the current harmonics as given in (Table 24) (Das et al. 2021) below.

Control Methods	Ripple Factor (%)	Harmonics (%)
AFS	0.85	3.12
AFBS	1.06	2.82
AFNN	0.53	2.89

Table 24: Performance Comparison with Non-linear and Unbalanced RL Load

From the above observations, the authors concluded that the suggested AFNN-based SHF control technique had the most superior performance in compensating the various power quality issues arising in a grid-tied microgrid system.

In order to quantitatively analyze the indistinct deviations in system voltage, frequency, power factor, and harmonic contents of an AC microgrid supplying to various types of loads, the authors Jitender Kaushal et al. (Kaushal and Basak 2019) devised an unorthodox monitoring technique based on the Fuzzy Inference System (FIS) i.e., the FIS-based Power Quality Monitoring Index (PQMI). They used this FIS-based method to evaluate the magnitude of the power quality events on the system. Then, they designed and simulated the grid network in MATLAB-Simulink platform and substantiated the suggested technique using Mamdani and Sugeno type FIS methods. They made the following observations:

1. In the case of a resistive load, the PQMI of the system was the best (i.e., 1.21) for grid-tied as well as autonomous operation modes. Also, the harmonic content and voltage deviations were 3.68% and 6.78% respectively during its autonomous operation which was well below the IEEE set standard values.
2. In the case of an inductive load, the PQMI values for both the modes of microgrid operation were good (i.e., 3.22) while low values of power factor (0.80) and harmonics (3.67%) were attained which were considered to be in the good ranges according to the IEEE standard limits. However, the voltage deviation was more (i.e., 9.12%) as compared to that in the resistive load case but was still below the IEC 60038 set standard range of ±10%.
3. Due to the connection of an asynchronous motor (rotational load) to the grid, the PQMI of the system during grid-tied mode was good (i.e., 3.20) but was average (i.e., 5.20) during autonomous mode because of the harmonic increment (5.54%).
4. Due to a three-phase bridge rectifier (non-linear load) connected to the grid, the values of PQMI during both the grid operation modes was 7.00 (i.e., poor) because of a large number of harmonics (17.02%) and voltage deviation.

5. In the case of a dynamic load connected to the grid, the PQMI during grid-tied mode was good (i.e., 3.21) because of low harmonic level (2.22%) and lesser voltage deviation; whereas, the PQMI during autonomous mode was average (i.e., 5.22) due to very high harmonic contents (22.7%) and low power factor.

Type of Load	**PQMI with Mamdani Type FIS**		**PQMI with Sugeno Type FIS**	
	Grid-tied Mode	**Autonomous Mode**	**Grid-tied Mode**	**Autonomous Mode**
Resistive	1.21 (Best)	1.21 (Best)	1.00 (Best)	1.00 (Best)
Inductive	3.22 (Good)	3.22 (Good)	3.00 (Good)	3.22 (Good)
Rotational	3.20 (Good)	5.20 (Average)	3.00 (Good)	5.00 (Average)
Non-Linear	7.00 (Poor)	7.00 (Poor)	7.00 (Poor)	7.00 (Poor)
Dynamic	3.21 (Good)	5.22 (Average)	3.00 (Good)	5.00 (Average)

Table 25: PQMI Indices for Different Operational Modes with Various Loads

From (Table 25) (Kaushal and Basak 2019), the authors concluded that the Mamdani type FIS gave more accurate and precise PQMI values than the Sugeno type which gave only the round-off values.

7. Conclusion

This paper has presented a comprehensive review of the importance of a variety of artificial intelligence and machine learning techniques that have been used by researchers over the recent years in the field of microgrid supply quality enhancement. Due to the embedment of power electronic equipment in a microgrid system, the irregular nature of renewable energy sources as well as the presence of loads of non-linear nature, maintaining steady power quality in the power network containing one or more microgrids poses a huge challenge. Different advanced techniques like Optimization methods, Reinforcement Learning, Pattern Recognition, neural networks, Deep Learning, and intelligent controllers to mitigate power quality issues are extensively explored and discussed in this work.

The papers reviewed in this work are focused mainly on the power quality aspects of a single microgrid system whose power supply capabilities are very limited during the stand-alone mode of operation. Hence, further research works can be done in the areas of identification, evaluation, and compensation of different power quality issues in interconnected microgrid systems so as to increase the reliability as well as power supply capabilities of electrical networks to a greater extent. Also, in this review work, a large number of literatures have been compiled in one place but still, there are a lot of literatures available in this area that we have not been able to put together in this work.

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NOMENCLATURE

DG	Distributed Generation
PV	Photovoltaic
RES	Renewable Energy Sources
PQ	Power Quality
PCC	Point of Common Coupling
PSO	Particle Swarm Optimization
UPQC	Unified Power Quality Conditioner
PI	Proportional Integral
PWM	Pulse-Width Modulation
GO	Grasshopper Optimization
WO	Whales Optimization

SSO	Salp Swarm Optimization
HSO	Harmony Search Optimization
MPC	Model Predictive Control
SPWM	Sinusoidal Pulse-Width Modulation
PID	Proportional Integral Derivative
ANFIS	Artificial Neuro-Fuzzy Inference System
BOA	Butterfly Optimization Algorithm
PI-(1+ID)	Proportional-Integral-one plus Integral-Derivative
EBFO	Enhanced Bacterial Foraging Optimization
MPF	Modulated Power Filter
MOSOS	Multiple Objective Symbiotic Organism Search
DSTATCOM	Distribution Static Compensator
RL	Reinforcement Learning
SVM	Support Vector Machine
EEMD	Ensemble Empirical Mode Decomposition
ES	Expert System
EMD	Empirical Mode Decomposition
IMF	Intrinsic Mode Function
CNN	Convolutional Neural Network
BPNN	Back Propagation Neural Network
DL	Deep Learning
RNN	Recurrent Neural Network
I-RNN	Identity Recurrent Neural Network
LSTM	Long Short-Term Memory
GRU	Gated Recurrent Unit
SAE	Stacked Auto Encoder
BESS	Battery Energy Storage System
ANN	Artificial Neural Network
DEO	Differential Evolution Optimization
DNN	Deep Neural Network
FCS-MPC	Finite Control Set-Model Predictive Control
PR	Proportional Resonant
MHE	Moving Horizon Estimation
ROCOF	Rate of Change of Frequency
ANFJW	Adaptive Neuro-Fuzzy Jacobi Wavelet
SHF	Shunt Hybrid Filter
AFNN	Adaptive Fuzzy Neural Network
AFS	Adaptive Fuzzy Sliding
AFBS	Adaptive Fuzzy Back-Stepping
FIS	Fuzzy Inference System
PQMI	Power Quality Monitoring Index