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Analysis of Power Quality in a Hybrid Power System

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Abstract: Renewable energy sources (RES) play a significant role to tack a climate change, reduce an energy cost, improve a power reliability. However, they will be effect on the power quality (PQ) of production energy when it is connected with utilized grid because of their randomness generations, resulting in, voltage instability, fluctuations in frequency, harmonic distortion and low power factor. In this paper, PQ issues and their improvement methods, including; filters, Flexible Alternate Current transmission system devices, and classifying the control techniques; traditional, intelligent, and hybrid, are reviewed. In addition, a preliminary investigation on a Dynamic Static Compensator (DSTATCOM) device with a Proportional-Integral (PI), is conducted using a 25kV distribution networks of households and verified its capacity to correct PQ issues and provide voltage stabilization. The motivation of this review article was to allow research customers to understand PQ issues and solutions but also a starting part whereby comparison can be made on whether or not PI control was beneficial in the DSTATCOM, and sets a regulatory limit to conduct more intense and feasible solutions based on intelligent and hybrid systems.

Keywords: Adaptive/Hybrid Control; Conventional control Artificial intelligence; Distribution Network; DSTATCOM; Power Quality; Renewable Energy Sources;

1. Introduction

The increasing energy demand today has resulted in few significant issues, including instability within networks and loss of power supply. One of the solutions could be utilizing Clean Renewable Energy Sources such as solar and wind energy alongside traditional electrical grids. The main problem faced by this integration is the degradation of PQ due to the stochastic and non-linear nature of reliance on renewable energy sources [1]. Power quality is important for ensuring that electric networks operate in a stable manner as PQ problems are manifested as non-sinusoidal waveforms of voltage, current, or frequency. Voltage sag, harmonics, frequency deviation, and poor power factor are all examples of power quality problems that need more efficient and flexible solutions in control [2]. Different control strategies have emerged over the years, which can be grouped into three main directions, to effectively deal with power quality issues and achieve appropriate performance of modern compensation devices. The first direction is Conventional Controllers (PI and PID), which is commonly preferred due to their ease of understanding and ease of design. Conventional Controllers can often be found in compensation devices which often include D-STATCOM, STATCOM, and UPQC, and they fundamentally rely on Vector Reference Control within VSC inverters, which allows for the accurate tracking of reactive current reference and a rapid response to a household or single circuit change between cycles. Here, total response time is rarely well beyond one cycle duration. The second direction being used is Intelligent Controllers (ANN and FLC), producing a more accurate approach and fantastic capability to address nonlinearity and noise. These models enhance the performance of D-STATCOM in highly variable environments or simply dealing with THD better than conventional models. Finally, the third direction is Hybrid and Optimized Models; often applies an acceptable speed of a conventional controller plus adaptation capabilities. Hybrid and Optimized Models are the best option when dealing with devices that

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account for multiple different power quality issues at the same time (ex. Voltage sag/harmonics). Even with this degree of research effort and research studies, however, there remains a significant gap in the standardization and analysis of these techniques as they relate to hybrid energy systems, particularly regarding the issues of the computational burden of hybrid methods and their high performance. For this reason, this paper provides a comprehensive analytical study of power quality problems and control techniques in hybrid systems, and future developments for designing better performing and reliable control systems. The paper is organized as follows: Section 2 discusses the literature reviews of conventional, intelligent and hybrid controllers applied in past research studies; Section 3 identifies the power quality problems that need to be addressed; Section 4 identifies the power quality improvement techniques and devices that have been used (e.g., FACTS devices); Section 5 identifies the control techniques inside these devices, including traditional, intelligent, and hybrid controllers; and Section 6 presents the reviewed findings and a discussion, and Section 7 concludes and summarizes the study and future directions.

2. State of Art

2.1 Conventional Controllers

The review of existing literature has been primarily dedicated to developing premium solutions to address serious concerns powering quality issues, specifically total harmonic distortion , voltage imbalance, and low power factor, associated with grid connected PV systems. With regard to the context of device designs, an interesting approach in [3] has pioneered a multilevel inverter (MLI) design consisting of 10 IGBT switches with 127 voltage levels per cycle, utilizing Square Wave Switching to eliminate switching losses that ultimately resulted in a THD of 2.33% in current. Additionally, a substantial amount of research has been focused on advanced filtering and control strategies. For example, a comparative study in [4] was conducted on a 5.5 kW PV system, and measurements indicated that the performance of the HAPF sourced current THD to 1.5%. Conversely, another supporting study in [5] effectively utilized a SHAPF controlled by synchronous reference frame theory to reduce the current THD in the same fashion, which ultimately improved the source current THD from 27.32% to 3.94%, which was compliant according to IEEE 519. Additionally, the effectiveness of HAPFs was improved in [6] through the use of the Recursive Least Square algorithm to eliminate current harmonics associated with non-linear loads, exhibiting better performance than standard p-q and d-q control by improving the THD from 28.38% to 1.76% in shunt connection and 0.37% for the series connection. With grid level compensation, the D-STATCOM performed well in hybrid wind-solar systems in [7] also reduced the current THD value to 1.64% from 15.4% when not control was present. The ability of synchronous compensators was improved in [8] using a PV-based STATCOM performing a new control approach called the MDNESOGI. The MDNESOGI demonstrated better performance than the standard SOGI for rejecting a DC offset while effectively alleviating harmonic distortion, reactive power compensation, power factor correction, and load balancing while maintaining IEEE standards. In addressing complex microgrid issues, a hybrid control scheme reported in [9], combining Active Resonance Damping and dual d-q control, is found to decrease the current THD from 9.33% to 3.1%, and also the Voltage Unbalance Factor from 10% to 2.47%. Lastly, field measurements reveal an operational issue: one study, reported in [10], finds PV inverters at low power levels with high THD, while another study, found in [11], finds solar irradiance to play an important role, with current THD values as high as 14.10% on cloudy days, which is well above the IEEE 519 limits, and this framework emphasizes a need for dynamic control.

Conventional controllers are regarded as the first line of defense for controlling power quality. These controllers are easy to implement, simple to apply, and have low computational cost (Low Computing Cost). They have shown their usefulness effectiveness in large part for simple power quality improvements such as harmonics reductions and power factor corrections. However, there are still limitations and their effectiveness is often only marginal at best: the provision for stability is only good in steady-state conditions when the system parameters are known. For instance, even well-known controls have their limitations in dynamic, complex and variable conditions, such as would arise in a hybrid system where renewable energy is present. This is because conventional controllers, such as PI controllers and others, require the application of specific mathematical models, which ultimately requires manual tuning of their parameters.

2.2 AI-Based Controllers

The recent development of power quality research represents a strong drift toward applying AI and machine learning (ML) to address the complex and dynamic challenges posed by grids interconnected with renewable energy systems and therefore improve upon the performance of traditional controllers. An initial study in [12] presented a method driven by AI for harmonics detection in microgrids using Machine Learning Regression Analysis (MLRA) and ANNs. Simulations of an IEEE 34 bus system illustrated that the MLRA model outperformed the other approaches in accuracy for predicting harmonic components with negligible error (approximately 3.7127e-15%). Additionally, a complete AI framework in [13] demonstrated the integration of machine learning, deep learning (CNN, RNN) and signal processing (WT, FT) approaches to improve power quality, resulting in a THD reduction from 7.5% to 2.1% while also raising the Power Quality Index from 65% to 92%.

Research on compensation devices has focused on the use of intelligent controllers with the D-STATCOM. In [14] investigated the relative performance of the ANN and ANFIS for controlling the D-STATCOM and the ANFIS technique was identified as having better performance achieving an accuracy of 1.5% THD for current. Supporting this assertion, in [15] utilized an ANFIS controller and obtained a source current THD of 1.51%, compared to the ANN learning technique (1.65%) and SRFT (1.74%), while offering faster learning. When the context was changed to the UPQC, there was a hybrid ANFIS-ANN approach in [16] that also produced excellent results with the THD stabilized to 4.26% for load voltage, and just 0.08% for source current. Additionally, a PV-UPQC analyzed with an ANN and Lyapunov optimization in [17] reduced voltage unbalance from 1.5% (initial condition) to 0.8% while also achieving a THD of less than 1%.

In the control of microgrid systems, recent work has shown that different neural network topologies can be beneficial. In an isolated study [18], an upgraded Nonlinear Autoregressive Neural Network with Exogenous Input (NARX) model was utilized to provide power quality in AC microgrids that are connected to a PV and BESS. By employing this NARX controller, the voltage THD dropped to 1.27%, while the current THD dropped to 1.69% (compared to PI results, 8.97% and 9.67% respectively), while also reducing dip/swells of the voltage. The performance of the NARX-NN was also upheld with a larger comparative study [19] that tested this controller against PID and Fuzzy-PID controllers for hybrid microgrids. Going forward, In [58] introduced a controller that uses an ANN and showed exceptional and stable performance over PI-type and Fuzzy-PI-type controllers while dealing with multi-faceted power quality issues that occur in AC microgrids.

Multiple artificial intelligence architectures have been investigated in filtering applications. A paper [20] examined a Radial Basis Function Neural Network (RBFNN) compared to p-q theory for a SHAPF against a conventional ANN controller; the RBFNN reduced the THD from 34.80% down to 2.24%, showing better performance than the ANN controller, which had a THD of 2.53%. Additionally, an ANN-based controller for a SHAPF study [21] was able to reduce the source current THD down to 0.98%, a THD that was reduced to 2.74% using a PI controller, once again demonstrating significant improvement. Other specific AI-based controllers included an Adaptive Linear Neuron (ADALINE) study in [22] assigned as an APF for a WECS, where the ANN reduced THD down to 3.8%, an improvement over a 6.2% using a PI controller. A further specialized AI controller for hybrid solar-wind-fuel cell systems, utilized a Fuzzy Logic based controller study in [23] to obtain THD on the current that was lower than 1.80% for balanced loads.

Finally, within dynamic and specialized systems, the Deep Reinforcement Learning (DRL) agent proposed in [24] was adapted to tune VSC parameters smoothly to improve frequency performance in microgrids. The Scaled Conjugate-ANN, developed in [25], had superior performance stability of power indicators in microgrids when compared to conventional FLC and PI controllers. Research with rail systems in [26] and hybrid power in [27] affirmed ANN controllers have improved stability with UPQC and DSTATCOM devices. The ANN controller in [26] reduced the source current THD to 1.46% in a UPQC, and the ANN-BP controller reduced current THD in a DSTATCOM to 3.9% in [27]. The controller employed in [28] for a DVR, in off-grid systems, performed quickly and effectively correcting voltage disturbances with survey purposes than conventional PI controllers.

The changeover from traditional controllers to AI-based controllers signifies a quantum leap in the enhancement of Power Quality improvement. these methodologies, including Artificial Neural Networks and Fuzzy Logic, have demonstrated the capability of managing complicated and non-linear systems, especially while using renewable energy sources appended to the grid. In addition to these capabilities, AI controllers are capable of detecting Power Quality problems and eliminating it with ultra-high precision, without the complexity of providing extensive mathematical computations. However, one of the main complications they will face is the complexity of design and training. Their performance is significantly affected and influenced by the accuracy and size of the training data that potentially can be quite large relative to the complexity of the system. In addition to the fore-mentioned issues, often they can take a long computation time using traditional neural networks and there is the potential they could converge to a Local Minimum during training.

2.3 Hybrid and Optimized Controllers

In the field of AI optimization, a detailed investigation in [29] to classifying the hybrid models of ANN and optimization algorithms, including GA, PSO, MVO, and ALO, for hybrid renewable energy sources integration. The authors revealed that the ANN-PSO model displayed the best performance, exhibiting the minimum Normalized Mean Square Error (NMSE) of 1.10% for the least computational time (=3367.50 seconds). In similar studies, for power quality enhancement a two-stage AI procedure is presented [30], using an Enhanced Kalman Filter for distortion identification followed by a Hybrid Artificial Neural Network with Fuzzy Intelligence (HANFI) controlling model which is very efficient in hybrid solar-wind systems. Optimization algorithms have been commonly applied to tune controllers in existing systems. A paper [31] applied a Fractional Order Proportional Integral Derivative (O-FOPID) controller in a UPQC (unified power quality conditioner), with parameters being optimized by the Crow-Tunicate Swarm Optimization (CT-SOA) algorithm. This control technique was noted to have superior behavior compared to proportional-integral (PI), FOPID, crow swarm optimization (CSA), and traditional swarm optimization algorithms (TSA), with THD values reported at 0.6131% under sag, and 0.9407% under swell. Limitations of the optimization technique such as parameter sensitivity were, however, noted. Additionally, research on Load Frequency Control (LFC) study in [32] was conducted around the use of the Equilibrium Optimizer (EO) algorithm to tune PI and FLC; results indicated that EO had improved results over FLC, regarding Area Control Error (ACE) and frequency deviation.
Enhancing synchronous compensators was another significant area of focus. A research study [33] enhanced the functioning of a STATCOM for hybrid energy systems with tuned controllers using the GWO algorithm, and was useful for reducing THD and voltage issues. A comparison of compensation devices study in [34] optimized the PI controller for the D-STATCOM using PSO and Political Optimization (PO) algorithms and found that it was more effective to control THD to 3.2% with the D-STATCOM, than with the SVC with a reduced THD of 5.9%.

Several hybrid configurations utilized control methodologies that are tailored for the problem. A hybrid control approach ([35]) for microgrids that incorporates a control of ANFIS+FOPIDC was introduced with THD values reduced to values between 2.23% and 2.44%. In a different study [36], a STATCOM using a quasi-Z-Source Inverter (qZSI) was presented using the AFF-SOGI approach and specifically the PI controller was tuned through FLC which experimentally yielded decreases in source current THD from 25.5% to 1.3%. A particular hybrid variation was also employed in [37] which was a HSAPF that used a Fractional Order Proportional Integral (FOPI) controller with optimization through the GWO algorithm which reduced THD to 1.74% (27.43% without a filter). An intelligent HSAPF was also able to decrease voltage THD such as the battery charger referenced in [38] where the THD load voltage was reduced from 21.83% to 3.99%. Here the PI controller was tuned through the PSO method.

The combination of PV and active filters was also optimized [39]. This investigation implemented a Fuzzy Logic-based MPPT method for the PV unit, as well as Adaptive Filters (ANF) through the RLS algorithm for harmonics compensation. The ANF-RLS technique performed considerably better than ANF-LMS technique for harmonics elimination and reactive power control. It indicated a high level of efficiency of optimization algorithms in the complexity of managing microgrid devices. The research on a DVR technique study in [40] incorporated an artificially neural network controlled by the Ant Lion Optimization (ALO) algorithm. The ALO-ANN approach was superior to the PSO-based controller and reached a THD of 2.32% (34.31% with PSO) along with a faster response time. In addition, an alternative hybrid control algorithm and HBMO-ANN ([41]) managed distributed renewable energy integrating and reached a reduction in the grid current THD of 3.60% and 3.80%, for both grid-connected and islanded modes, respectively, while the PI managed a THD of 10% and 12%.

A new controller for multi-microgrid stability study in [42] that integrates a GA into an ANN showed an 18% reduction in THD when compared to Model Predictive Control (MPC). For UPQC applications in WECS, an IALO-ANFIS model study in [43] to optimize the parameters of PI controller improved the power loss reduction performance relative to GA and IALO in combining them for power loss reduction. A hybrid predictor model study in [44] that implemented tables with ALO and a Multilayer Perceptron (MLP) neural network to control a DVR demonstrated good reference signal extraction performance, as well as utility in overcoming the controls of an ANN.

A methodology study in [45] for a hybrid system (solar, wind, batteries) was used in energy management that employed a GWO-optimized PI controller on the solar side, a PI controller on the wind side, and a RNN controller for the battery management, effectively making the transient performance much better in the whole hybrid system. An improved PI controller optimized by PSO study in [46] was also constructed on Hybrid Energy Storage System (HESS) in DC microgrids. The proposed capability with ANN and simple FL equation study in [47] was validated in the independent hybrid power system (battery and super capacitor HESS) for better power quality improvement and flow management, whereby the ANN-UPQC system study in [48] used in electrified railway systems outperformed PI control, reducing source current THD performance on source current THD down to performance of 25.16% down to 1.12%.

The Hybrid and Optimized Controllers suggest the future trend of power quality enhancement in multi-source systems. These techniques provide a way to tune the parameters of the primary controllers and improve performance through a faster response, improvement on the local min problem, and better performance on multi-objective compensation like the regulation of voltage and frequency and reduction of THD levels, etc. They have a better adaptation level to these variable conditions. However, with this enhanced performance, there is a sacrifice for increased implementation complexity and computational burden posed as one of the challenges for its implementation in Real-Time operation. Therefore, this challenge implies an additional investigation to make a contribution in developing and reducing the computational burden to realization as fast and practical work in power systems.

Table 1 Summary of Literature Review

Ref.	Device Type	Controller/Algorithm Typ	Key Quantitative & Functional Results
[3]	Novel Solar Multilevel Inverter	Square Wave Switching	Current THD: 2.33% (127-level design Eliminates switching losses.

[4]	Comparison of 4 techniques (HAPF best	PI	HAPF achieved the best performance, reducing current THD to 1.5%.
[5]	SAPF	SRFT	Reduced current THD from 27.32% to 3.94% (IEEE 519 compliant).
[6]	HAPF	RLS Algorithm	Reduced THD from 28.38% to 1.76% (Shunt) and 0.37% (Series).
[8]	STATCOM	MDNESOGI	Superior to SOGI in eliminating DC offset.
[13]	PQ Monitoring/Control Framework	ML/DL(CNN, RNN), Predictive Control	Reduced THD from 7.5% to 2.1%. Improved Voltage Stability by 20%
[49]	DSTATCOM	Comparison: ANFIS vs. ANN	ANFIS superior: Current THD reduced to 1.51%.
[19]		NARX-NN	NARX-NN outperformed PID and Fuzzy-PID in handling Sag/Swell and THD.
[23]		FLC	THD reduced to 1.80% (Balanced) and 3.90% (Unbalanced).
[24]	Frequency Control System	Deep Reinforcement Learning (DRL) Agent	Effective in improving frequency control via VSC tuning.
[50]	Microgrids Energy Management	Inverter Control and ANN	Reliable and effective in improving power quality.
[25]	DVR	Scaled Conjugate -ANN	Outperformed FLC and PI in stability and ripple reduction.
[16]	UPQC	Hybrid ANFIS-ANN	Lowest THD: Source current 0.08%.
[17]	UPQC	ANN	THD less than 1%.
[15]	DSTATCOM	Comparison: ANFIS vs. ANN vs. SRFT	ANFIS best: THD 1.51%.
[18]	AC Microgrid Systems (PV+BESS)	Enhanced ANN: NARX model	NARX superior to PI: Voltage THD 1.27%.
[51]	AC Microgrid Systems (PV)	Comparison: ANN vs. P vs. Fuzzy-PI	ANN achieved fast and stable performance.
[20]	SHAF	RBFNN + p-q theory	RBFNN superior to ANN: THD from 34.80% to 2.24%.
[21]	SHAPF	ANN vs. Traditional PI	ANN superior to PI: Current THD 0.9
[22]	APF	Adaptive Linear Neuron (ADALINE)	ADALINE superior to PI: THD 3.8%.
[27]	DSTATCOM	ANN-BP	ANN-BP superior to PI: THD 3.9%.
[26]	UPQC	Comparison: ANN vs. NARMA-L2 vs. Optimiz PI	ANN best: Source current THD 1.46%
[28]	DVR	ANN	ANN superior to PI in voltage disturbance correction (faster and more accurate).
[30]	PQ Enhancement (Two-Stage AI)	EKF + HANFI Control Model	High efficiency in distortion detection and PQ improvement.
[31]	UPQC	O-FOPID optimized	Ultra-low THD: 0.6131% (Sag)

		by CT-SOA	, 0.9407% (Swell).
[39]	SHAF	Fuzzy Logic MPPT + Adaptive Filters (ANF-RLS)	ANF-RLS superior to ANF-LMS in harmonic elimination.
[33]	STATCOM	PI-GWO	Effective in improving voltage/current and reducing THD.
[34]	D-STATCOM vs. SVC Comparison	PI optimized by PSO and PO	D-STATCOM achieved THD 3.2% (better than SVC at 5.9%).
[32]	Load Frequency Contro	Equilibrium Optimizer for I, PI, FLC tuning	EO outperformed FLC in reducing Area Control Error (ACE).
[36]	STATCOM	AFF-SOGI + PI optimiz FLC	Source current THD reduced from 25.5% to 1.3% (Experimental).
[37]	HSHAPF	FOPI optimized by GWO	THD reduced to 1.74%.
[38]	HSAPF	PI optimized by PSO	Load voltage THD reduced from 21.8 9%.
[45]	SEPIC	GWO-optimized PI + PI + RNN	Improved transient response.
[46]	Hybrid Energy Storage System	PI optimized by PSO	Improved performance of the hybrid energy storage system.
[40]	DVR	ANN optimized by Ant Lion Optimization	THD: 2.32% (34.31% better than PSO
[41]	Inverter	Hybrid Control: HBMO-ANN	Grid current THD: 3.60% (Grid-Connected).
[42]		ANN + GA	Outperformed MPC: 18% reduction in THD.
[43]	UPQC	IALO-ANFIS for PI tuning	Outperformed GA and ALO in power loss reduction.
[44]	DVR	ALO-MLP NN + ANFIS-GA	Overcomes drawbacks of traditional neural networks (premature convergenc
[48]	UPQC	ANN	Superior to PI: Source current THD from 25.16% to 1.12%.

3. Power quality issues

Power quality refers to the degree of stability and variation of the voltage, current, frequency of the electrical power system. Therefore, any changes or variation in these characteristics, either in the value or the sinusoidal nature of the waveforms of voltage or current waves, represents an electrical power quality challenge [14]. The power quality is one of the important issues in renewable energy systems, especially via photovoltaic systems at the PCC. Since the power output of photovoltaic solar panels is dependent on solar irradiance, temperature, and weather, the output will continuously be intermittent and unstable. Additionally, advanced electronic appliances with non-linear loads are the main contributor to power quality issues [4].

3.1 Voltage sag

Voltage sag is classified as one of the most serious power quality disturbances, where the Root Mean Square (RMS) voltage is reduced to anywhere between 10% and 90% of its nominal value. The main concern arises due to the effects of voltage sag on the stability of the power grid. For example, grid-connected PV systems will inject significant levels of current into the grid when connected, and this will cause the voltage to drop. This can lead to negative effects such as damage or reduced lifecycle of electrical equipment, and in some cases total shutdown of the system, along with reduced efficiency and stability of the electrical system [52].

3.2 Voltage swell

Voltage Swell is a type of power quality disturbance in grid-connected renewable energy systems, which is considered less severe. It can be defined as a short duration increase (typically less than one minute in duration) in the voltage's RMS value above the fundamental operating value. Voltage swell arise when the load rapidly decreases or capacitor bands have been switched in. The swell can be recognized and measured when the voltage magnitude increases to levels from 110% to 180% of the nominal system voltage[53].

3.3. Voltage flicker

Flicker is understood as a periodic variation in the effective RMS voltage value. Flicker usually occurs because of quick fluctuations occurring in the power supply sources or dynamic loads causing a perceivable flicker in alteration of voltage at the point of common coupling with the grid. The frequency content (representing the signal's magnitude) is the relevant consideration in assessing the severity of flicker. In the case of Distributed Energy Resources, the magnitude for unwanted flicker emission shall not exceed 0.6 per unit (for short-term severity) and 0.9 per unit (for long-term severity) as required in IEEE 1547 standards [52].

3.4. Total harmonics distortion

The Total Harmonic Distortion is regarded as one of the most significant parameters for assessing power quality. It occurs mainly due to switches and the operation of inverters in grid-connected renewable energy systems, such as photovoltaic solar energy systems, and also due to nonlinear loads. THD is defined as the ratio of the harmonic power to the fundamental waveform of a signal, which can be either voltage or current. IEEE 519-1992 clearly states that to ensure quality of supply, the Total Harmonic Distortion value must be less than 5% [53]. The THD is mathematically determined as a percentage according to the following equations:

$$THDv = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V1} \times 100\% \tag{1}$$

$$THDi = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I1} \times 100\% \tag{2}$$

where $I1$ and $V1$ represent the current and voltage of the primary frequency component (50 Hz), respectively, and In and Vn represent the nth order harmonic for the current and voltage, respectively.

3.5. Poor power factor

The occurrence of a Poor Power Factor among grid-connected renewable energy systems represents an important issue with respect to the stability of the grid and our power transfer efficiency. Grid-connected Photovoltaic systems are often designed to operate at a PF level close to unity. Nevertheless, the power factor does vary continuously due to the variability of solar irradiation in the system as well as the actual operational characteristics of power or grid inverters, which can lead to a flow of non-active (i.e. reactive) components into the grid. This flow eventually leads to a poor power factor, which does have direct negative effects that must be considered in regards to grid performance it increases the current on transmission and distribution lines, which thus leads to more active power losses in conductors and transformers. The lower power factor may cause Voltage Drop along the lines, as additional current and losses will reduce the power transfer efficiency and awkwardly consume grid capacity. Beyond these direct technical issues, this leading to a reduced power factor violation or offset from the strict standards of legitimacy of levels imposed by Grid Codes' strict limitations on distributed generation. Thus, achieving the desired high and stable power factor at the Point of Common Coupling often remains an ongoing challenge that requires significant research and development in control[54]. The PF is defined as the ratio between the active power (P) and the apparent power (S), and this fundamental relationship is given in Equation (3):

$$PF = \frac{\mathrm{P}}{\mathrm{S}} \tag{3}$$

3.6. Frequency variation

Frequency variation are an operational challenge for power systems, defined as the departure of the frequency from its nominal value, which is usually 50 or 60 Hertz. Deviations primarily result from imbalance power generated versus consumed. Frequency deviations introduce undesired consequences for both equipment operation and the stability of the grid, but these will only come to light if not accounted for. Oscillations are increasingly pronounced in systems where there is high penetration of intermittent renewable energy sources (e.g., wind and solar) because of the variable and uncertain nature of this type of power generation. The application of new advanced control devices, such as D-FACTS, and appropriate control algorithms can be employed to mitigate fluctuating frequency and provide resiliency to the system[53][52]. Table 2 summarizes the problems most associated with each of the different DREG techniques.

Table 2 PQ issues related to different DREG units

PQ concerns	Solar PV	Wind Power	Mini Hydro Power	Diesel Generator
Voltage Sag and Swell	Yes	Yes	Yes	Yes
(Under/Over) Voltage	No	Yes	No	Yes
Voltage Unbalance	Yes	No	No	No
Voltage Transient	No	Yes	No	No
Voltage Harmonics	Yes	Yes	Yes	No
Flicker	Yes	Yes	No	Yes
Current Harmonics	Yes	Yes	Yes	No
Power Fluctuation	Yes	Yes	No	No
Interruption	Yes	Yes	No	No

4. Power quality enhancement techniques

For the power grid to obtain clean and stable electric flow, the power variables, like voltage and current, must have a sinusoidal waveform. Power quality issues, previously described, are harmful to the electric power system unless appropriately addressed. This is why power quality issues need to be dealt with according to sophisticated and specialized techniques to reduce the magnitude of these issues and constrain them within a safety envelope. In the literature review presented, there are many sophisticated and integrated thoughts on diverse addressing techniques for power quality issues, including: Filtering, Inverters such as FACTS devices, and others. The fig.1 depicts many common addressing techniques for power quality issues.

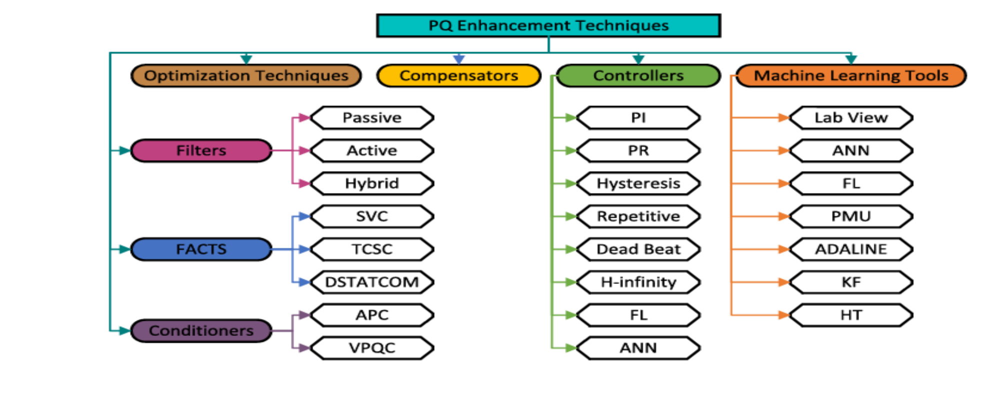

Fig. 1 Overall techniques for PQ issues[55].

4.1 Filters

Harmonics caused by power transformers and non-linear loading, among others, can be counted as important power quality issues that need to be addressed. Filters are considered one of the main solutions to help not only with the harmonic issue but also compensating for reactive power and neutral current, reducing voltage fluctuations and voltage imbalance, load balancing, and alleviating voltage distortions, sags, and swells; and there are several types of filters available that can be used effectively[55].
Filters can be categorized into three primary types: Passive Filters, Active Filters, and Hybrid Filters.

4.1.1 Passive power filters

A Passive Filter is considered the most basic filter; As shown in Fig. 2 it consists of a combination of inductors and capacitors tuned at the frequency assigned to them. Passive filters (e.g., LCL filter) can potentially enhance power quality and reduce THD in grid-connected renewable energy systems [4]. However, despite its simplicity, cost-effectiveness, and reliability, studies have shown that utilizing passive filters to address Power Quality issues in renewable energy systems has the potential for Harmonic Resonance. As well, the design of a first order (L) filter is complicated and often does not meet the IEEE 1574 standard. In addition, while LCL filter is effective for grid-connected inverters, it may induce current irregularities, both dynamically and in steady-state operation [53]. For these reasons, the disadvantages of passive filters, their usage of is less in a complex microgrid configuration that connects multiple Distributed Generators (DG), [55]. As a result, many researchers instead prefer the alternative of using an APF in the electrical power system network.

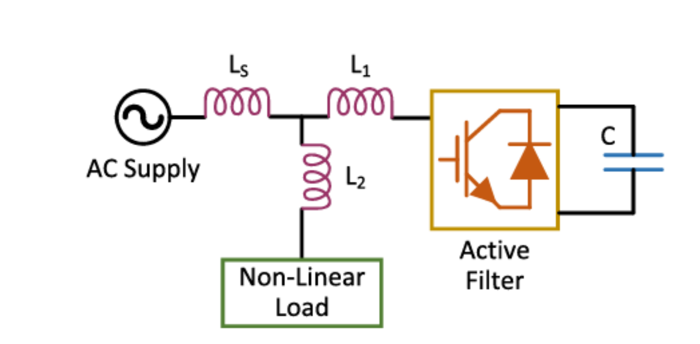

Fig. 2 Schematic structure of Passive Power Filter[55].

4.1.2 Active power filters

Due to the limitations of passive filters, Active Filters (APFs) can provide an appropriate alternative to mitigate harmonic-related issues. They are a better option than passive filters since they can inject real power at the source frequency with a 180° phase shift. APFs can be setup as shunt (parallel) or series devices. APFs require power electronic components and complicated control systems to monitor and compensation for harmonic currents, and for time-varying harmonics emulated by non-linear loads. In spite of their benefits, APFs need a complicated control algorithm, which makes them impractical for low scale applications. Additionally, they need high power capacity to mitigate voltage harmonics, thus they become expensive in high power applications[56]. These associated deficiencies can be handle by Hybrid Filters. The structure of the active power filter is shown in Fig.3.

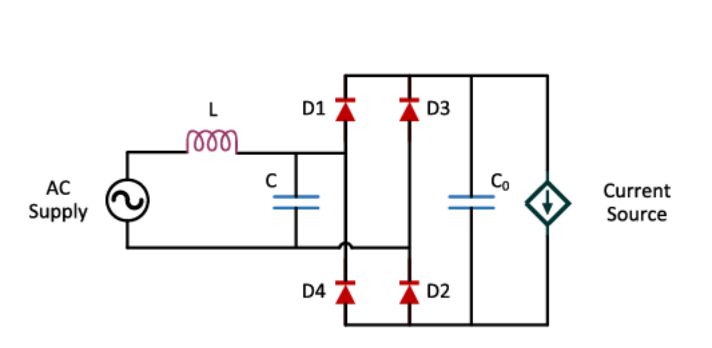

Fig. 3 Schematic structure of Active Power Filter[55].

4.1.3 Hybrid power filters

Hybrid Power Filters integrate the benefits found in Passive Power Filters (cost-effective and simplicity), and crucial advantages from Active Filters (such as effective mitigation of electromagnetic interference / disasters, regulation of the voltage, and use of electrical power electronics for harmonic control in a dynamic mode) as shown in Fig.4. The major benefit is that it costs no more than the full cost of an Active Filter and responds faster than a passive filter, operating alone. Overall, the hybrid filter is a strong alternative in high power quality systems[57].

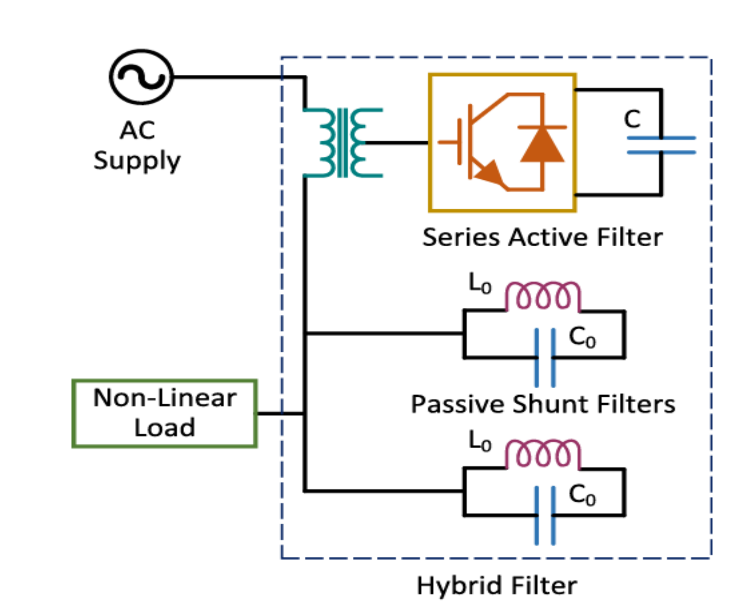

Fig. 4 Schematic structure of Hybrid Power Filter[55].

4.2 Invertors

Inverters are considered as key components for integrating renewable energy sources to either electrical grids and other stand-alone coil sources. Inverters provide controlled ac voltage by converting dc voltage using control devices (such as FACTS devices and UPQC). It is critical for active power and reactive power compensation at PCC requiring appropriate elected voltage, while establishing power quality in ac circuits.

a) Static var compensator

The Static Var Compensator is an electrical controller that is shunt-connected and was developed in the 1970s. The SVC is considered to be the first generation of FACTS (Flexible AC Transmission Systems) controllers, and is controlled with the use of thyristors. The SVC will inject reactive power into the system, but will also control various parameters of the electrical network. The fig.5 demonstrates a typical SVC circuit diagram. The SVC controls the voltage at its point of connection by controlling the amount of voltage injected into or consumed from the power system: when the voltage of the system is low, it will generate reactive power (capacitive SVC) and when the voltage of the system is high (positive pressure) it absorbs reactive power (inductive SVC), thereby controlling the voltage in order to maintain voltage against drops caused due to loss of reactive power, which causes system instability[58]. The structure of the Static var compensator is shown in Fig.5. Equation 4 is used to express the theoretical basis of this methodology.

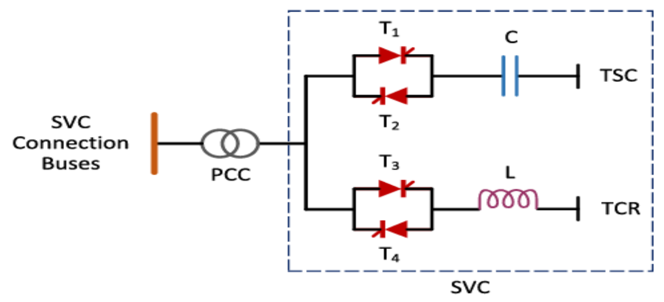

Fig. 5 Typical circuit diagram of Static var compensator[55].

$$Q_{SVC} = \frac{V^2}{X_{SVC}} \tag{4}$$

where Q_{SVC} refers to the Reactive Power that the SVC is supplying to the system. V is the RMS value of the system voltage at the PCC. The reactive power is controlled dynamically by changing the equivalent reactance X_{SVC} of the compensator.

b) Dynamic voltage restorer

The Dynamic Voltage Restorer is categorized as a D-FACTS device. As shown in Fig.6 It normally consists of a VSI, which could be either a GTO or IGBT type, an energy storage element, an injection transformer and a capacitor bank. The DVR can be used to compensate voltage on the system upon experiencing a voltage sag. The DVR operates when voltage is injected into the distribution line allowing to preserve the voltage profile and provide stability of load voltage by synchronizing the voltage between the load and source[59].

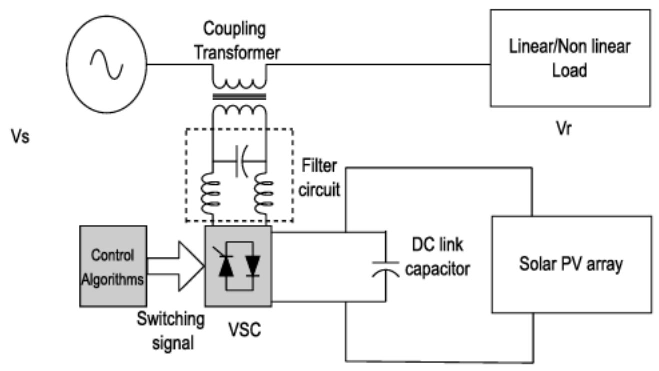

Fig. 6 Typical circuit diagram of Dynamic voltage restorer[52].

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \tag{5}$$

$$S_{DVR} = V_{DVR} I_L^* \tag{6}$$

Equations (5) and (6) describe the basic operation of the DVR. The component definitions are: $V_{DVR}$is the injected voltage in series supplied by the DVR, which acts as the corrective term that is working to maintain the loading voltage magnitude, or voltage magnitude at the load (V_L). The correction is based on the electrical properties of the system, where Z_{th} represents the equivalent Thévenin impedance and $I_L$is the load current. V_{th} represents the system voltage value measured during the fault or sag condition. Finally, the term S_{DVR} in equation (6) represents the complex apparent power that the DVR either injects or absorbs for the purposes of voltage correction.

c) Distributed static synchronous compensator

The Distribution Static Synchronous Compensator is regarded as a robust FACTS device that can compensate for currents associated with power quality events. The device operates on a VSI that is supplied from a DC voltage source. As shown in Fig.7 the D-STATCOM can solve several power quality problems including voltage sag and swell, flicker, oscillation, current distortion, source current balancing, and voltage control at the Point of Common Coupling. The D-STATCOM is also used for harmonic compensation in the source current and to supply reactive power to maintain the Power Factor. The D-STATCOM has a faster dynamic response than the first generation of FACTS, such as the SVC, and it can also provide independent and accurate reactive power control, making it the best FACTS device for solving multiple power quality problems in modern distribution systems[34]. The mathematical basis for the function mentioned above is defined in Equation (7,8).

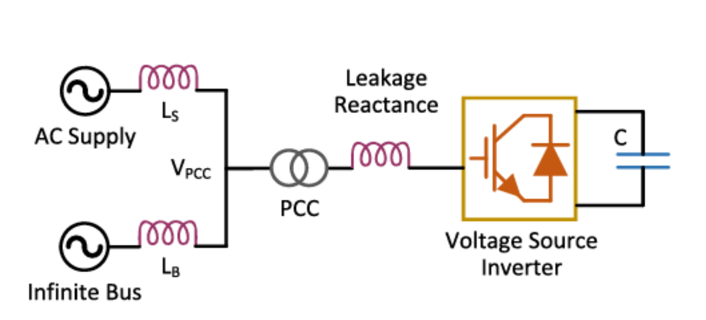

Fig. 7 Schematic diagram of DSTATCOM[55].

$$I_{sh} = I_L - I_S = I_L - \frac{V_{th} - V_L}{Z_{th}} \tag{7}$$

$$S_{sh} = V_L I_{sh}^{\,*} \tag{8}$$

Equations (7) and (8) express the functional behaviour of shunt compensation devices. In Equation (7), the shunt injected current (I_{sh}) is represented to be the difference between the load current (I_L), and the source current (I_s). This current is expressed in terms of the Thévenin equivalent voltage (V_{th}), the load reference voltage (V_L), and the system impedance (Z_{th}). Equation (8) defines (S_{sh}) as the complex apparent power that the compensator has to supply or absorb, which depends on both the load reference voltage and the complex conjugate of the current I_{sh}^*.

d) Unified Power Quality Conditioner devices

The UPQC is considered the most integrated device in the family of D-FACTS. as shown in Fig.7 the UPQC consists of two active power filters, namely a shunt active filter and a series active filter, which are connected through a common DC-link capacitor. A UPQC system can be used to solve various power quality issues such as voltage sag and swell, harmonics and flicker, as well as power quality issues concerning load current quality. The objective of a UPQC system is to control both the current and voltage action of the load or duty, to the appropriate amplitude at PCC. The manipulation of current and voltage across the PCC is through the series active filter (control voltage and frequency values on the source side) and the shunt active filter (reduce harmonics, to improve the quality of the load current)[31].

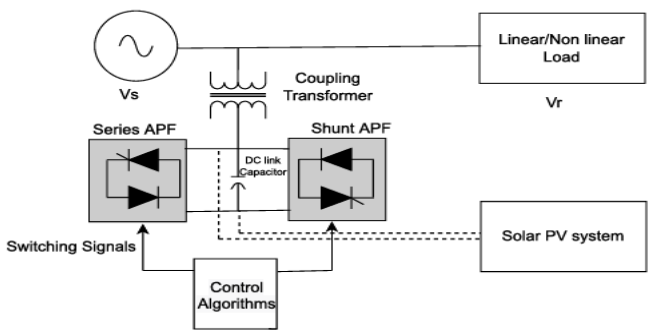

Fig. 8 Schematic diagram of UPQC[52].

In order to evaluate the applicability of each Custom Power Device for specific power quality problems, a comparative analysis of the mitigation abilities is presented in Table (3) of DVR,D-STATCOM, and SVC against the various problems described below:

Table 3 Comparative Analysis of Different Custom Power Devices for Power Quality Mitigation[60].

Factors	SVC	DVR	DSTATCOM	UPQC
Rating	Low	High Capacity	Low	Higher
Operational Speed	Below DVR	Fast	Blow DVR	Faster
Method of Compensation	Shunt	Series	Shunt	Series and shunt
Active Power/ Reactive power	Reactive power	Active Power/ Reactive power	Reactive power	Both
Harmonics	Less	Significantly Less	Less	Least
Problem Solved	Sag/ Swell	• Sag/Swell • Harmonics • Fluctuation	Sag/ Swell	• Sag/Swell • Harmonics • Transients • Unbalance • Flicker
Cost	Average	High	Normal	Higher
Complexity	High	High	High	Higher

5. Control Technology

In power quality enhancement devices, such as D-STATCOM and UPQC, the control system is regarded as one of the main components that is most important in the overall system performance effectiveness, as it assures effective compensation to numerous voltage and/or current disturbances or

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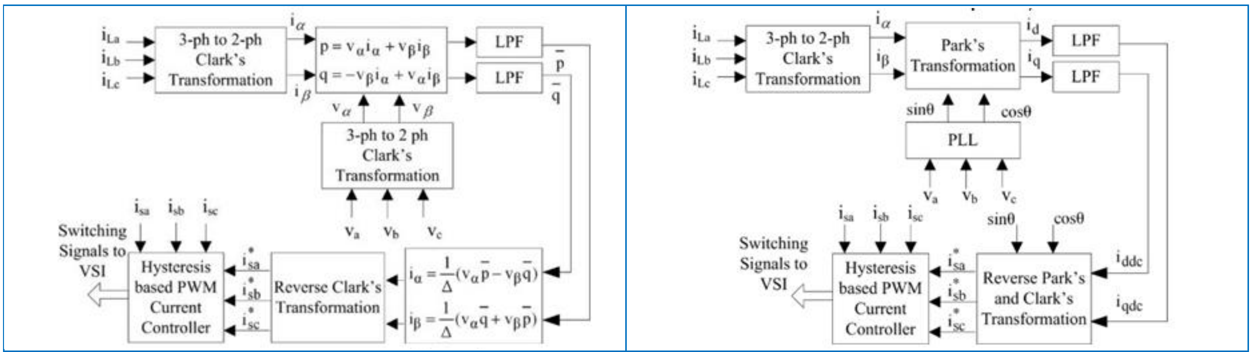
interruptions in a fast and very accurate way. Selecting the specific control algorithm is contingent upon the characteristics and complexity of the issue as well as the requirements of the system. Hence, the main algorithms that we review in the literature are based on three general classes: Conventional Control Algorithms, Optimized Techniques, and Artificial Intelligence.

5.1 Conventional control algorithms

Classical control approaches present various functions to understand and resolve power quality issues. These approaches are primarily based on reference current extraction, using a PLL circuit to provide an accurate reference of the grid. After extracting the reference, Closed-Loop Regulators (such as PI controller), provide switching pulses to the VSI to track the reference currents and mitigate disruption in the system[33].

a) Reference Current Generation Methods

Present extraction algorithms determine the magnitude of the required current compensation. These extractions are conducted using sophisticated theories, such as Synchronous Reference Frame Theory or (SRF/d-q theory) or Instantaneous Reactive Power Theory (p-q theory), that consider the active and reactive power component of the system. These theories are able to utilize Clarke and Park Transformations to convert the three-phase components of voltage and current (a-b-c) to (d-q) two-axis component representation as shown fig. 9. The (d-q) components will act as a DC signal in, while steady-state conditions are being balanced, therefore providing a much easier platform to analyze and control. Then, by using the transform components, three-phase active and reactive power can be calculated determining the Reference Source Current signals for controlling the inverters used for compensation[61]. The mathematical basis for the function mentioned above is defined in Equation (10,11).



(a) Basic IRBT control algorithm | (b) Basic SRF control algorithm

Fig. 9 Reference Current Generation Methods[61].

$$I^{*}_{d} = K_{pv}(V^{*}_{dc} - V_{dc}) + K_{iv}\int (V^{*}_{dc} - V_{dc})dt \tag{10}$$

$$V^{*}_{cd} = V_{d} + L\frac{di_{q}}{dt} + Ri_{d} - wLi_{q} + K_{pd}(i^{*}_{d} - i_{d}) + K_{id}\int (i^{*}_{d} - i_{d}) \tag{11}$$

The two equations refer to the Double-Loop Control system in the dq frame. V^{*}_{dc} refers to the desired DC-link reference voltage, whereas V_{dc} refers to the measured actual DC-link voltage. K_{pv} and K_{iv} are proportional and integral gains used for the outer voltage loop, which outputs the d-axis reference current, I_{d}. The inner current loop uses K_{pd} and K_{id} as the proportional and integral gains to minimize the error of the current I_d^* and I_d (actual current), which then generates the controller output reference voltage for the d-axis V_{cd}^*. The equation includes also includes V_d (the system voltage along the d and the system components) L and R, in addition to the cross-coupling term $(wL\ iq)$, which decouples the control of the q-axis.

b) Closed-Loop Regulation Controllers

A closed-loop regulator (PI or PID controller) is crucial for stabilization of the system and compensator internal power. After transforming the three-phase electric current voltage into d-q or p-q frame. The Controller is to maintain the voltage across the DC Link capacitor constant and equal to the reference value. The controller takes the error between the reference (desired) voltage and the measured voltage across the capacitor to produce an active current that is added to the reference current to counteract internal losses in the VSI. While these controllers are conceptually simple, they depend on the proper tuning of the parameters to have dynamic performance with a fast response and high compensation speed[33]. The mathematical principle governing this methodology can be expressed as follows:

$$u(t) = K_p \cdot e(t) + K_i \int e(t)dt \tag{12}$$

where u(t) is the Control Output Signal that ultimately controls the inverter, which is generated based on the instantaneous error signal (e(t)), being the difference between the reference value and the measured value. Proportional Gain (K_P) controls the immediate speed of response to the error, while Integral Gain (K_i) is responsible for eliminating the Steady-State Error in the long run, as it keeps track of the error signal forever.

5.2 Optimization techniques

The dynamic efficiency of traditional controllers (such as PI and PID) strictly relies upon accurate tuning of their parameters. The literature review indicates that manual or classical tuning procedures seldom generate the optimal response of the system with rapid load changes and unbalance conditions. Hence, optimization techniques are deemed valuable to determine the optimal set of the parameters of conventional controllers with the goal of reducing system error and improving dynamic performance. For example, meta-heuristic optimization algorithms (e.g., PSO, GA, GWO, ...) are based on mathematical concepts leveraged to solve complex optimization problems. The literature review has indicated that their characteristics allow these algorithms to solve power quality problems through the optimal solutions of the controller parameters[62]. Figure (10) illustrates the proposed control system structure, showing the application of the PSO algorithm to tune the optimal parameters of the PI controller in the closed-loop control scheme:

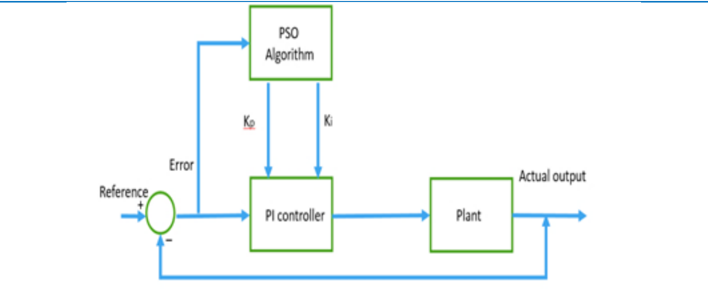


Fig. 10 Typical PI controller[34].

5.3 Artificial intelligence

Due to the increasing complexity of the networks, AI is considered one of the most promising contemporary technologies in power grids. When it introduced before, AI provided an opportunity to bypass the computational complexity related to mathematical modeling that is required by traditional control algorithms to manage complex problems. AI applications can relate selected variables and utilize high amounts of information, and therefore enhance the prediction and alarming accuracies. AI applications may extend to many areas. Applications may extend from renewable energy forecasting to producing the switching pulse for the converter, which can alleviate power quality related problems. Two main AI-based control methods will be provided in this article (Fuzzy Logic and Artificial Neural Networks)[63].

a) Fuzzy Logic

Fuzzy Logic Control algorithms are advantageous in uncertain environments, because it allows you to distribute the parameter states across a range from zero to one, instead of being solely reliant on binary Boolean logic (zero or one). Unlike traditional controllers relying on linear models as a basis, FLC provides an intelligent dynamic control solution that adjusts to time varying conditions. Its decision making process is similar to human decision making, so it can handle data that is inaccurate and distorted to yield an effective response to power quality issues. Although, to get accurate results, the Fuzzy Rules need to be developed with high certainty either based on good knowledge of the systems behavior or by using other statistical optimization methods[64]. Figure 11 illustrates the general structure and basic working theory of a FLC.

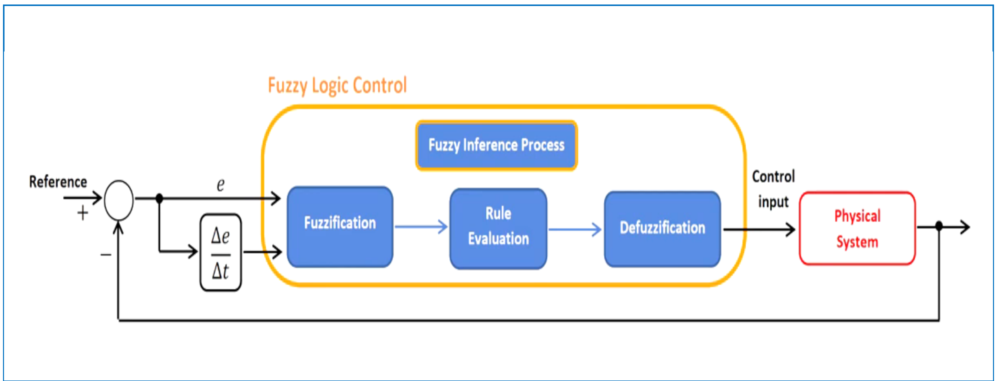


Fig. 11 Block diagram of FLC.

b) Artificial Neural Networks

The Artificial Neural Network is a powerful data modeling approach on the biological brain, enabling more reliable and efficient solutions to address system problems and make timely judgments. ANNs use a network of artificial neurons (artificial neurons perform the specific function, establishing relations between a set of input and output data) as depicted in fig.12. These networks are capable of dealing with complicated behavior due to the combination of neurons in the network and Corresponding weighting factor parameters. Multiple inputs are received, summed up with the weights as determined from the training (Weighted Summation), and the results are derived through an Activation Function. Due to their capabilities for Non-Linearity and Self-Learning, ANNs are acknowledged as important intelligent control algorithms for addressing power quality issues. As it was reviewed in previous works from literature they are acknowledged as capable of achieving desired results when accurate data and proper training are utilized[29].

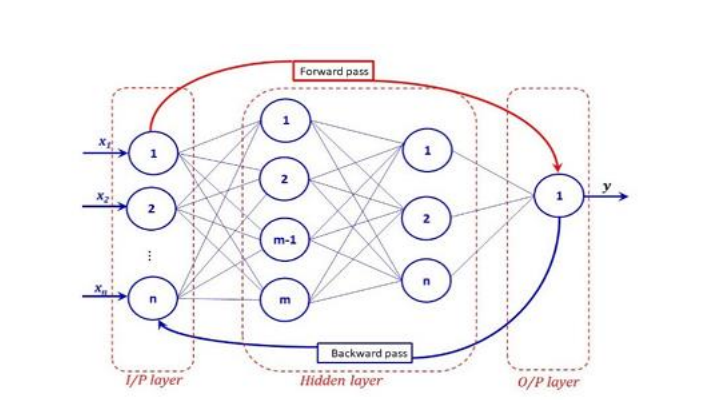


Fig. 12 Block diagram of an ANN System[12].

5.4 hybrid model

The Hybrid Technique uses more than one way of doing things so to take advantage of both strategies at once while minimizing the disadvantages of a single strategy. It is in the forefront of research like a combination of intelligent algorithms (ANN or FLC) with optimization algorithms (PSO or GWO) which provides an even more effective outcome. As was indicated before in the literature review, these models exhibited a significant ability to adapt to changes and reduce power quality disturbances more accurately. These models are also a step toward making Adaptive Intelligent Control which can operate in a nonlinear and unstable environment which is the next phase of control systems in smart grids[29].

6. Results and discussion

This study intends to present a holistic review of power quality issues and assess mitigation approaches, with an emphasis on implementation of the DSTATCOM as a preliminary intervention to mitigate power quality disturbances in a 25KV distribution by the stages of variation of load. Although systems like the UPQC have more advanced control systems that provide simultaneous compensation for both voltage and current disturbances, the choice of DSTATCOM with a PI controller for this phase of study was based on very specific practical and academic reasoning - from a practicality perspective, the DSTATCOM provides simplicity in design and implementation, flexibility, and efficiency when compared with traditional compensators; along with achieving a rapid dynamic response that is needed in mitigating transient deviations. The DSTATCOM is also effective at reducing the most significant power quality issues such as voltage sags and swells, and harmonic distortion when successfully integrated with suitable control strategies. From an academic perspective, the recommendation of the PI controller is very significant because it provides effective voltage regulation and smooth response, reduced steady-state errors. The combined effort of DSTATCOM with a PI controller simply acts as a practical performance benchmark for assessment within the context of conventional, simple control of the system. Doing this allows the researcher to examine the effects of traditional control before transitioning to more advanced solutions such as intelligent and hybrid systems. It is important to note that next-generation systems such as the UPQC provide a higher level of performance; however, advanced systems like the UPQC are significantly more complicated and costly, and may not be possible to implement in some cases that would prefer a balance of the performance needed and the economic feasibility. Where Table (4) presents the detailed system specifications and electrical parameters used to build the D-STATCOM module and the distribution system in the Simulink test environment:

Table 4 Specifications of the Simulink DSTATCOM module test.

Characteristics	Values
DC Link(Battery)	10000e-6 F
L	800e-6 H
RC	0.0007854 ohm , 100e-6 F
Vdc	2400 V
Kp	0.55
Ki	2500

6.1. Analysis of Dynamic Response and Source Voltage Fluctuations

The DSTATCOM system was evaluated for dynamic response by applying extreme and abrupt disturbance tests for evaluating the responsiveness of the DSTATCOM in Matlab/Simulink. The tests included an abrupt change in the equivalent source voltage (25 KV). For testing the voltage disturbance at t=0.2s, the operating point of the source was increased by 6%, and for disturbance at t=0.3s, the source voltage was decreased by 6%. Simultaneously with a disturbance in the source, loads were applied at t=0.2s in order to increase reactive power (demand), and tested the response behavior for two disturbances simultaneously in voltage and load perturbation.

The results shown in Fig.13 demonstrated that the inner control loop (PI controller) effectively tracked the measured reactive current (Iq) to the reference current ($Iqref$) under all disturbance conditions. The effective tracking under all disturbance conditions verifies the exceptional tracking abilities and overall performance of the PI controller, and subsequently establishes the accuracy to generate the needed reference signal for varying inputs. The most meaningful aspect of the dynamic response was DSTATCOM's capability to switch its reactive power characteristics (from absorption to generation, or vice versa). Notably, the reactive power switching occurred in less than one electrical cycle. This capability provides the DSTATCOM with an effective solution to supplying voltage support and trans-controlling voltage transients.

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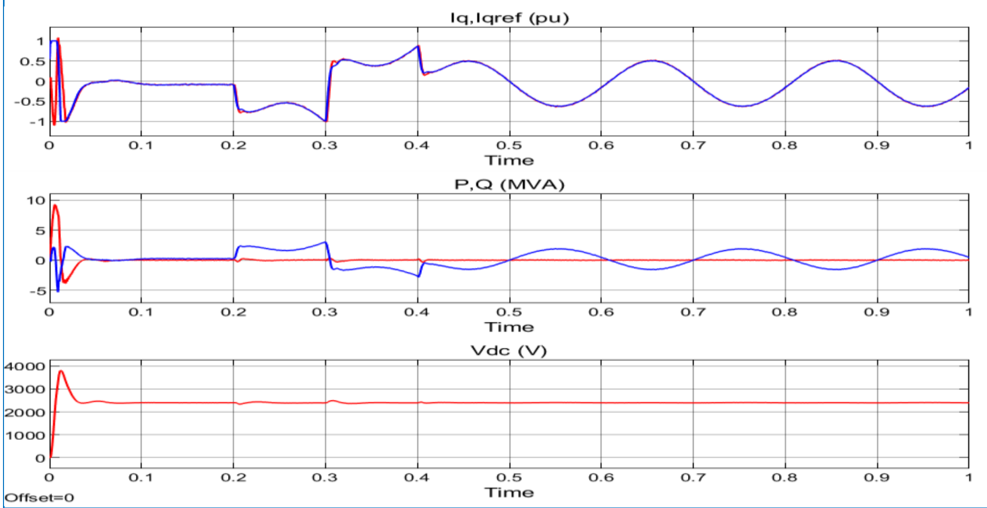

Fig. 13 D-STATCOM Dynamic Response.

6.2. Voltage sag,swell and Voltage Flicker

The DSTATCOM device was thoroughly evaluated based on its performance in stabilizing the voltage at the PCC during the previous dynamic disturbances (6% source voltage increase and decrease, and sudden load change) that were applied to the system.

From the results in Fig. 14, the voltage at the PCC was successfully stabilized. The DSTATCOM was able to mitigate the voltage variations at the source voltage and improve the speed of recovery back to its reference value with minor overshoot/undershoot and fast transient recovery time. Further the device demonstrated a notable performance in significantly reducing the Voltage Flicker due to the sudden operation of the variable load. The DSTATCOM performed effectively to stabilize the voltage sufficiently to keep the DSTATCOM/PI performance within acceptable power quality levels indicating this is an effective fast and reliable stabilizing device for support grid stability.

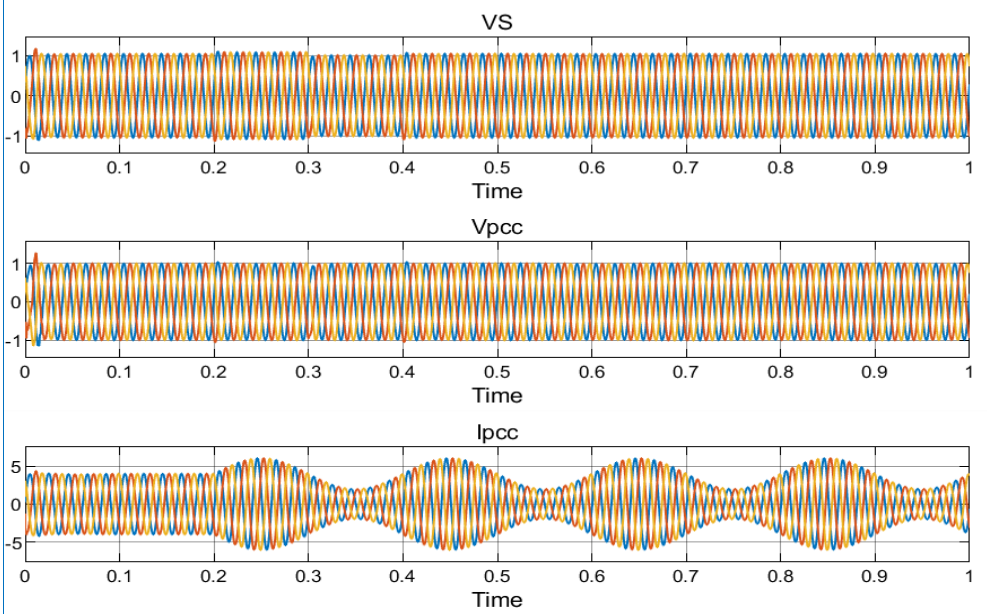

Fig. 14 Voltage and Current Waveforms (VS, VPCC, IPCC).

6.3.Power Factor

Analysis of the power factor at the PCC produced oscillation between 0.86 and unity that is efficiently as shown in fig. 15, and effectively, controlled. Furthermore, this oscillation serves as explicit technical evidence that the DSTATCOM device is utilizing reactive power on a continuous basis, and effectively, with the grid. This is critical to counteract the reactive component of the fluctuating load. The overall sustained value of the power factor oscillating in proximity to unity reiterates the basic function of the DSTATCOM device and is a significant milestone towards the improvement of power quality. This is honestly effective evidence of the DSTATCOM/PI systems effectiveness in improving power transfer efficiency and minimizing losses in the supply network.

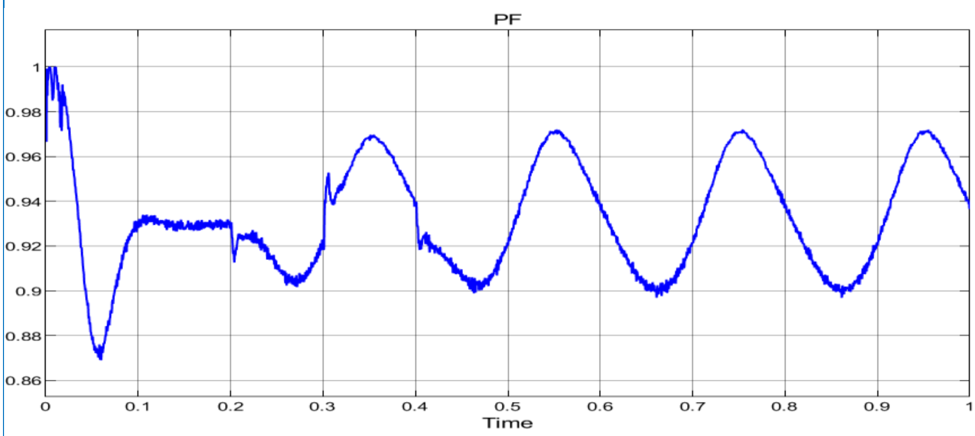

Fig. 15 Power Factor at PCC.

6.4.THD

Total Harmonic Distortion is considered one of the most important parameters used to assess power quality in electrical power systems. A high THD value indicates that current or voltage contains unwanted components of additional frequencies that would impact the electric system performance both directly and negatively. The consequences would be evident due to increased electrical losses in the lines and transformers, an increase in the temperature of devices and equipment, shorten their estimated life, and increase the possibility of failure.

The last performance of the DSTATCOM/PI system in terms of harmonic performance was assessed by examining THD at the PCC, utilizing the Fast Fourier Transform (FFT) analysis. The THD of the current after compensation is 3.99% as shown in fig. 16. This value is lower than the maximum value of 5% allowed by the international power quality standard IEEE 519. This performance demonstrates the capability of the PI controller to successfully preserve waveform purity and meet codes and standards in accordance with the respective standards.

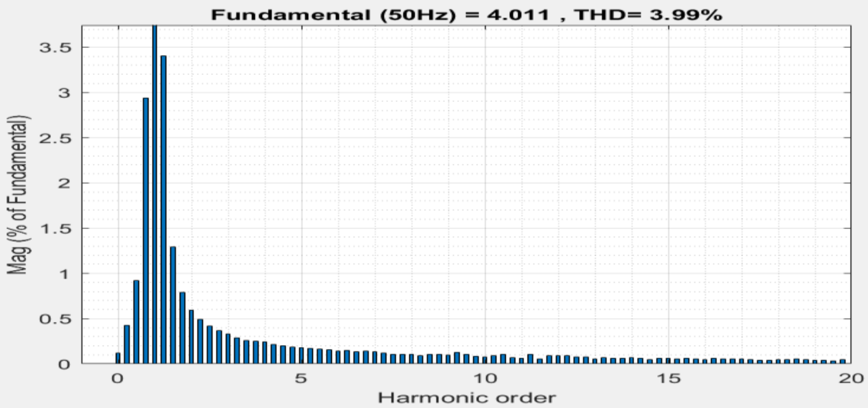

Fig. 16 Total Harmonic Distortion Analysis of PCC Current.

7. Conclusions

The study presented here is a full analytical review, responding to issues of power quality and challenges encountered through a full literature review, and surveying various devices for mitigating technical issues related to power quality. Several of these reviewed devices are classified as filters, FACTS devices, and control techniques including traditional control techniques, intelligent control techniques and hybrid control strategies. The DVR was shown to perform unimposing for the voltage disturbances compared to the SVC and DSTATCOM, and the UPQC was an effective means of protecting sensitive loads from power problems while hybrid controllers have a larger role in mitigating the more complex power quality issues that encompass all power quality issues. In order to improve upon these conclusions and obtain a reference benchmark, the DSTATCOM system with a PI controller was used and evaluated in a 25 KV distribution network. The simulation results confirmed that this configuration was effective at minimizing performance requirements; the system had a high dynamic response, was able to stabilize the PCC voltage effectively, and improve the power factor and the current total harmonic distortion was approximately 3.99%, which meets expected value requirements according to the IEEE 519 standard. Nevertheless, it is evident that the performance achieved is completely limited by the assumption of a steady-state DC link voltage supply (for example, via battery supply), indicating the PI controller's inability to successfully incorporate the required flexibility and adaptability to operate with the intermittent characteristic of renewable energy sources. As a result of this methodological limitation, future studies should highlight the need to move beyond the limits imposed by traditional control. This must be done either by utilizing intelligent algorithms for adaptive tuning of PI controller parameters, or by using Intelligent Controllers directly, to cope with renewable source much-desired instability and for adaptively obtaining an accuracy that can radically reduce THD to globally competitive levels.

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Conflicts of Interest: This research received no external funding.

List of abbreviations of this work	
Full From	Abbreviation
Active pass filter	APF
American national standard institute	ANFIS
Artificial intelligence	AI
Artificial neural network	ANN
Distributed flexible AC transmission system	DFACTS
Dynamic Static Compensator	DSTATCOM
Dynamic voltage restorer	DVR
Flexible AC Transmission Systems	FACTS
Fuzzy logic	FL
Genetic Algorithm	GA
Grey Wolf Optimization	GWO
hybrid active-passive filter	HAPF
Hybrid Shunt Active Power Filter	HSAPF
Instantaneous reactive power theory	IRPT
Low pass filter	LPF
Particle Swarm Optimization	PSO
Passive power filters	PPF
Phase locked loop	PLL
Photovoltaic	PV
Point of common coupling	PCC
Power quality	PQ
Proportional-Integral	PI
Root Mean Square	RMS
Shunt Active Power Filter	SHAPF
Static var compensator	SVC
Synchronous Reference Frame Theory	SRFT
Total Harmonic Distortion	THD
Unified power quality conditioner	UPQC
Voltage Source Inverter	VSI

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