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Active Power Quality Improvement Techniques in Modern Electrical Systems

Urmila S. Patil[1], Naved A. Khan[2], Prerna Kulshrestha[3]
Associate Professor, Assistant Professor
Department of Renewable Energy Drives and Power Electronics
Sree Narayana College, Kollam, India
Email: *Urmilapatil5s@yahoo.com, navedakan099@gmail.com, prerna10kulshrestha@rediffmail.com*

Abstract

Power quality has become a major concern in modern electrical power systems due to increased use of nonlinear loads, renewable energy integration, power electronic converters, and sensitive industrial equipment. Disturbances such as voltage sag, swell, harmonics, flicker, transients, and unbalance affects the reliability and performance of electrical devices. Traditional passive techniques are no longer sufficient to mitigate these issues effectively. Hence, active power quality improvement techniques using advanced power electronic devices and intelligent control strategies are widely adopted. This paper reviews different active power quality improvement methods including Active Power Filters (APF), Unified Power Quality Conditioner (UPQC), Dynamic Voltage Restorer (DVR), Distribution STATCOM (DSTATCOM), and hybrid filtering methods. Control strategies, comparison of techniques, advantages, limitations, and recent developments are discussed. The paper also highlights future trends toward smart grid and AI-based control for power quality enhancement.

Keywords: *Power quality, Active power filter, UPQC, DVR, DSTATCOM, Harmonics mitigation, Voltage sag compensation.*

INTRODUCTION

Power quality problems are increasing day by day due to rapid industrialization and use of power electronic based loads such as rectifiers, adjustable speed drives, computers, and LED lighting. These loads inject harmonics and cause voltage distortions in the distribution network.

Also, integration of solar PV, wind energy, and electric vehicles is changing the behavior of traditional grids. As a result, utilities and consumers both are facing issues like equipment overheating, malfunctioning of relays, false tripping, and reduced efficiency.

Earlier, passive filters and capacitor banks were used to solve some of these issues. However, passive devices have limitations such as fixed compensation, resonance problem, bulky size and poor dynamic response. To overcome these limitations, active power quality improvement devices based on power electronics and fast control algorithms are developed.

Active techniques can dynamically respond to disturbances and provide real-time compensation. These devices can detect distortions and inject suitable compensating signals to maintain desired voltage and current waveforms.

2. POWER QUALITY ISSUES IN DISTRIBUTION SYSTEMS (ELABORATED)

Power quality problems mainly arise in distribution systems because this is the point where power electronic loads, renewable sources, and consumer equipment are directly connected. Unlike transmission systems which are relatively stable, distribution networks face frequent disturbances due to switching operations, nonlinear loads, unbalanced loading, and environmental conditions. These disturbances degrade the voltage and current waveforms from their ideal sinusoidal shape and affect the performance, efficiency, and lifetime of connected equipment.

The most common power quality issues observed in distribution systems are explained below in detail.

2.1 Voltage Sag (Dip)

Voltage sag is a short duration reduction in RMS voltage, typically between **10% to 90%** of nominal voltage, lasting from **0.5 cycles to 1 minute**.

Causes:

- Short circuit faults in nearby feeders
- Starting of large induction motors
- Transformer energization
- Sudden increase in load

Effects:

- Tripping of contactors and relays
- Shutdown of sensitive loads such as PLCs and computers
- Malfunction of variable speed drives

Voltage sag is one of the most serious issues for industrial consumers because even a small dip can stop an entire production line.

2.2 Voltage Swell

Voltage swell is the opposite of sag. It is an increase in RMS voltage to **110%–180%** of nominal value for short duration.

Causes:

- Sudden load removal
- Switching off large loads
- Fault in neutral connection
- Capacitor bank switching

Effects:

- Insulation stress on equipment
- Damage to electronic devices
- Overheating of loads

2.3 Harmonics

Harmonics are voltage or current components at frequencies that are integer multiples of the fundamental frequency (50/60 Hz). They distort the waveform from sinusoidal to non-sinusoidal.

Sources:

- Rectifiers and inverters
- SMPS, computers, LED drivers
- Adjustable speed drives
- EV chargers

Effects:

- Overheating of transformers and motors
- Increased losses in cables

- False operation of protective devices
- Reduced power factor

Harmonics are measured using Total Harmonic Distortion (THD).

2.4 Voltage Flicker

Voltage flicker is rapid and repetitive variation in voltage magnitude.

Causes:

- Arc furnaces
- Welding machines
- Fluctuating industrial loads

Effects:

- Visible fluctuation in lighting
- Annoyance to consumers
- Reduced lamp life

Table 1: Power Quality Problems

Problem	Cause	Effect on System
Voltage Sag	Short circuits, motor starting	Equipment shutdown
Voltage Swell	Sudden load removal	Insulation damage
Harmonics	Nonlinear loads	Heating, losses
Flicker	Arc furnaces, welding	Light fluctuation
Transients	Switching operations	Damage to electronics
Unbalance	Unequal loading	Motor vibration

These issues require dynamic and intelligent compensation rather than static solutions.

3. NEED FOR ACTIVE POWER QUALITY IMPROVEMENT (ELABORATED)

The nature of electrical loads connected to modern distribution systems has changed significantly in the last two decades. Earlier, most loads were linear and predictable such as heaters, incandescent lamps, and induction motors operating at constant speed. Today, the system is dominated by **power electronic converters**, renewable energy interfaces, electric vehicle chargers, data centers, and automation equipment. These devices behave as **nonlinear and time-varying loads**, continuously injecting disturbances into the network.

Traditional passive solutions such as LC filters, capacitor banks, and reactors were designed for fixed operating conditions. They provide compensation only at specific frequencies and loading levels. When load conditions change, passive devices either become ineffective or create new problems such as resonance and overcompensation. Therefore, modern distribution systems require **dynamic, intelligent, and adaptive** compensation methods, which leads to the need for active power quality improvement techniques.

Active techniques are based on power electronic converters controlled by fast digital processors. These devices can sense disturbances in real time and inject the exact compensating current or voltage required to maintain desired power quality.

3.1 Fast Response to Disturbances

Power quality problems such as voltage sag, swell, and transients occur within milliseconds. Passive components cannot react quickly to such rapid changes. Active compensators, on the other hand, use high-speed switching devices (IGBT, MOSFET, SiC) and digital controllers (DSP, FPGA) to respond almost instantly.
For example:

- A DVR can inject compensating voltage within a few cycles during a sag.
- A shunt APF can cancel harmonic currents in real time as soon as they are detected.

This fast dynamic response is very important for sensitive loads like PLC systems, robotics, and medical equipment.

3.2 Flexible and Adaptive Control

Active devices are controlled using advanced algorithms such as p-q theory, d-q theory, fuzzy logic, and neural networks. These controllers continuously monitor system parameters and adjust compensation accordingly.

This flexibility allows:

- Compensation under varying load conditions
- Selective harmonic elimination

- Adjustable reactive power support
- Operation under balanced and unbalanced conditions

Passive filters cannot provide such adaptive control because their parameters are fixed.

3.3 Compact Size and Reduced Resonance Problems

Passive filters require large inductors and capacitors, making them bulky and heavy. They also introduce resonance issues with system impedance, which can amplify harmonics instead of reducing them.

Active filters use semiconductor devices and small DC link capacitors, resulting in:

- Smaller size
- Lighter weight
- Elimination of resonance problems
- Easy installation in existing systems

3.4 Multi-Functional Operation

One of the biggest advantages of active compensators is their ability to solve multiple power quality issues simultaneously.

For instance:

- A Shunt APF can perform harmonic filtering, reactive power compensation, and power factor correction.
- A UPQC can mitigate voltage sag/swell, harmonics, unbalance, and reactive power issues at the same time.

This multi-function capability reduces the need for multiple separate devices.

3.5 Integration with Digital Controllers and Smart Grid

Active compensators can be easily integrated with:

- Digital signal processors (DSP)
- Microcontrollers and FPGA
- IoT-based monitoring systems
- Smart grid communication networks

This allows remote monitoring, real-time data analysis, and intelligent decision-making. Such integration is not possible with conventional passive devices.

4. ACTIVE POWER FILTERS (APF) – DETAILED DISCUSSION

Active Power Filters (APF) are widely used custom power devices designed to eliminate harmonics, compensate reactive power, and improve overall power quality in distribution systems. Unlike passive filters that are tuned for specific harmonic frequencies, APFs dynamically sense distortion in the system and generate an equal but opposite compensating signal using power electronic converters.

An APF mainly consists of:

- Voltage Source Inverter (VSI)
- DC link capacitor
- Coupling inductor/transformer
- Sensors for voltage and current
- Digital controller (DSP/FPGA)

Based on the connection method, APFs are classified as **Shunt APF** and **Series APF**.

4.1 Shunt Active Power Filter

The shunt APF is connected in parallel with the nonlinear load at the point of common coupling (PCC). Its main purpose is to inject compensating current into the system to cancel harmonic and reactive components drawn by the load.

Working Principle

Nonlinear loads draw distorted current from the supply. The shunt APF senses this current, extracts the harmonic and reactive components using control algorithms, and injects a current of the same magnitude but opposite phase. As a result, the source current becomes sinusoidal and in phase with the supply voltage.

Isource=Iload−IAPFI_{source} = I_{load} - I_{APF}Isource=Iload−IAPF

Main Features

- Harmonic current mitigation
- Reactive power compensation

- Power factor correction
- Balancing of three-phase currents
- Reduction of neutral current in 3-phase 4-wire systems

Advantages

- Suitable for current-related problems
- Simple structure
- Effective for nonlinear loads like rectifiers, SMPS, drives

Typical Applications

- Industrial plants
- Data centers
- Commercial buildings with heavy electronic loads

4.2 Series Active Power Filter

The series APF is connected in series with the supply line through a matching transformer. It is mainly used to correct voltage-related problems such as voltage harmonics, sag, swell, and unbalance.

Working Principle

When the supply voltage is distorted, the series APF injects a compensating voltage in series so that the load receives a pure sinusoidal voltage.

Vload=Vsource+VAPFV_{load} = V_{source} + V_{APF}Vload=Vsource+VAPF

If there is a voltage sag, the APF injects missing voltage. If harmonics are present, it injects harmonic voltage components to cancel them.

Functions

- Voltage harmonic elimination
- Voltage sag and swell compensation
- Voltage unbalance correction
- Voltage regulation for sensitive loads

Advantages

- Protects sensitive equipment from supply disturbances
- Effective for voltage-related issues

4.3 Control Strategies Used in APF

The performance of an APF depends heavily on the control algorithm used to detect distortions and generate reference compensating signals.

a) Instantaneous p-q Theory (Akagi Theory)

This method transforms three-phase quantities into α-β stationary reference frame and calculates instantaneous real and reactive power. From these values, harmonic components are separated.

Merits:

- Simple mathematical implementation
- Suitable for balanced and unbalanced loads
- Fast dynamic response

b) Synchronous Reference Frame (d-q Theory)

In this method, three-phase currents are transformed into rotating d-q frame synchronized with supply voltage using Park transformation. Harmonic and reactive components appear as AC quantities and can be filtered easily.

Merits:

- Accurate harmonic detection
- Good for steady-state performance
- Widely used in DSP-based control

c) Hysteresis Current Control

This is a current tracking method where the actual filter current is forced to follow the reference current within a hysteresis band.

Merits:

- Simple implementation
- Very fast response
- No need for complex modulation

Demerit:

- Variable switching frequency

d) PWM Based Control

In PWM control, reference signals are compared with high-frequency carrier waves to generate switching pulses for VSI.

Merits:

- Constant switching frequency
- Better harmonic performance
- Suitable for digital implementation

DYNAMIC VOLTAGE RESTORER (DVR)

DVR is used to mitigate voltage sag and swell by injecting compensating voltage in series with the supply.

Working:

- Detect sag using sensors
- Voltage source inverter injects required voltage
- Maintains load voltage constant

Applications: Sensitive industrial loads, hospitals, data centers.

DISTRIBUTION STATCOM (DSTATCOM)

DSTATCOM is shunt connected device used for reactive power compensation and voltage regulation.

Capabilities:

- Voltage stabilization
- Power factor improvement
- Harmonic reduction

It works similar to shunt APF but focuses more on reactive power control.

UNIFIED POWER QUALITY CONDITIONER (UPQC)

UPQC combines shunt and series APF to mitigate both current and voltage related issues simultaneously.

Component	Function
Series APF	Voltage compensation
Shunt APF	Current compensation

UPQC is considered most powerful device for power quality improvement.

HYBRID ACTIVE POWER FILTERS

Hybrid filters combine passive filters with active filters.

Advantages:

- Reduced cost
- Lower rating of active filter
- Better performance than passive filter alone

Used in high power applications.

CONTROL TECHNIQUES FOR ACTIVE COMPENSATORS

Different control algorithms are used:

- p-q theory
- d-q theory
- Artificial Neural Network (ANN)
- Fuzzy Logic Controller
- Sliding Mode Control

Intelligent controllers provide better dynamic response under varying load.

COMPARISON OF ACTIVE DEVICES

Device	Harmonics	Sag/Swell	Reactive Power	Cost	Complexity
Shunt APF	Yes	No	Yes	Medium	Medium
Series APF	No	Yes	No	Medium	Medium
DVR	No	Yes	No	High	Low
DSTATCOM	Yes	Limited	Yes	Medium	Medium
UPQC	Yes	Yes	Yes	High	High

APPLICATIONS

- Industrial plants
- Renewable energy systems
- Electric vehicle charging stations
- Data centers
- Smart grids

RECENT TRENDS

- AI based control of APF
- Integration with IoT sensors
- Use of multilevel inverters
- Digital twin based monitoring
- Wide bandgap devices (SiC, GaN)

CHALLENGES

- High initial cost
- Complex control design
- Requirement of fast processors
- Maintenance of power electronic components

FUTURE SCOPE

Future power systems will require intelligent and self-adaptive power quality devices integrated with smart grid communication.

CONCLUSION

Active power quality improvement techniques plays very important role in maintaining reliable and efficient power distribution. Devices such as APF, DVR, DSTATCOM, and UPQC provide dynamic and effective solutions to mitigate harmonics, voltage sag, swell, and reactive power problems. With advancement in power electronics and intelligent control, these devices are becoming more efficient and affordable. Future research is focusing on AI-based control and smart monitoring systems for better performance.

REFERENCES

1. H. Akagi, “Active harmonic filters,” Proc. IEEE, vol. 93, no. 12, pp. 2128-2141, 2005.
2. B. Singh, K. Al-Haddad, A. Chandra, “A review of active filters,” IEEE Trans. Ind. Electron., 1999.
3. M. El-Habrouk, M. Darwish, P. Mehta, “Active power filters: A review,” IEE Proc., 2000.
4. A. Ghosh, G. Ledwich, *Power Quality Enhancement Using Custom Power Devices*, Springer, 2002.
5. N. Hingorani, “Introducing custom power,” IEEE Spectrum, 1995.
6. S. Sankar, P. Venkatesh, “Performance of DVR for voltage sag mitigation,” Int. J. Electr. Power, 2012.
7. R. Gupta, A. Ghosh, “Control of shunt APF using p-q theory,” IEEE Trans., 2008.
8. J. Dixon, L. Moran, “Multilevel inverter for active filtering,” IEEE Trans. Ind. Electron., 2005.
9. M. Kale, E. Ozdemir, “Harmonic compensation with DSTATCOM,” Electr. Power Syst. Res., 2010.
10. V. Khadkikar, “Enhancing power quality using UPQC,” IEEE Trans. Power Delivery, 2012.

