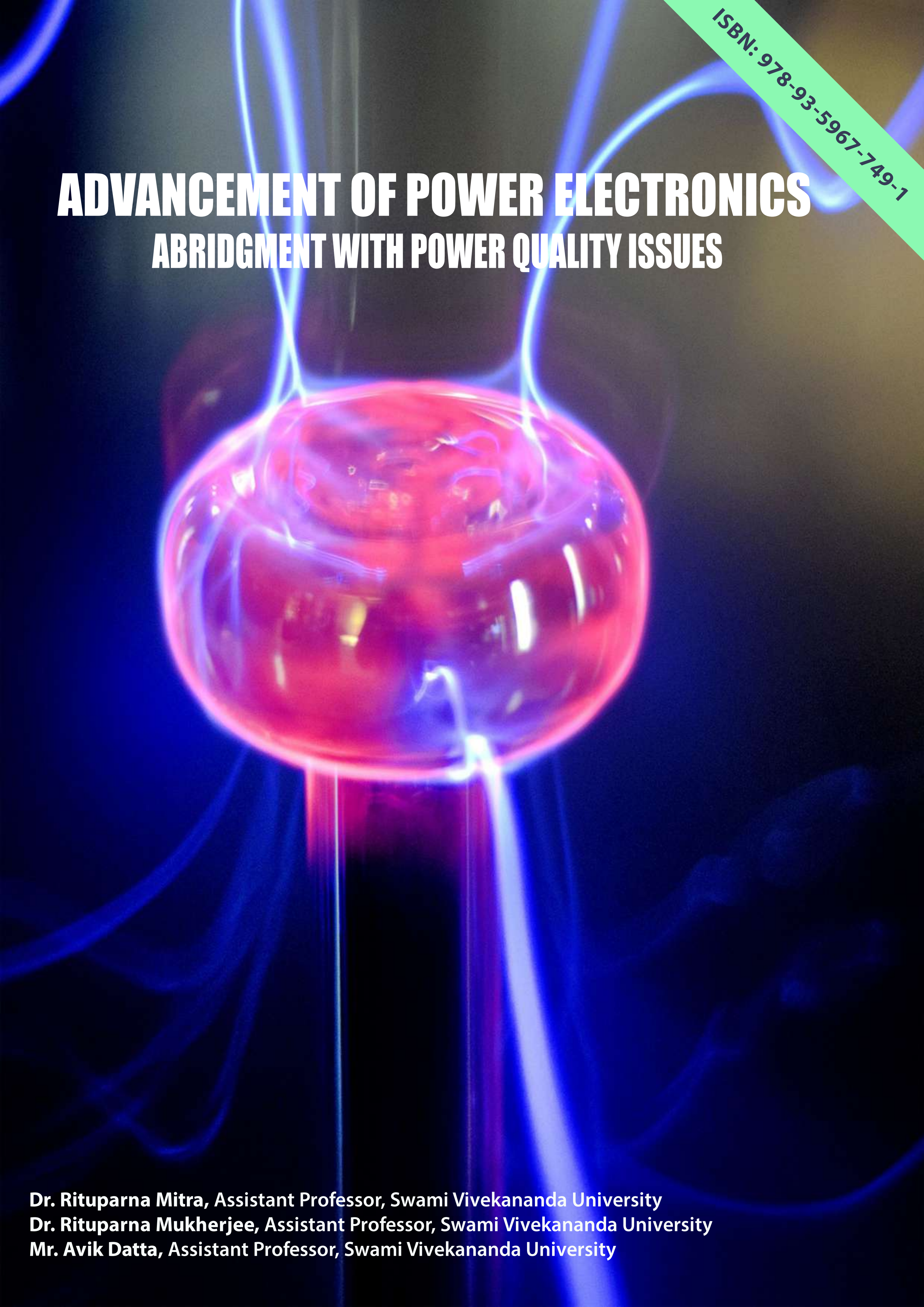

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ADVANCEMENT OF POWER ELECTRONICS

ABRIDGMENT WITH POWER QUALITY ISSUES

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Preface

Power quality is the measurement of how close to perfect an electrical voltage is at any given time or point. High quality electrical voltage is a sine wave that measures exactly what is expected in both voltage and frequency. A high quality electrical source is one that can deliver all the electrical energy needed without any change in the voltage. In the past, responsibility for power quality was thought to be the power companies' problem but that isn't really true. In almost every case, the circumstances that impact power quality are outside of the power companies control. Historically, most power quality problems were considered to be those things that affected the distribution of power. Lightning, line or transformer failures and/or very high electrical demands (brown outs) on the electrical network are just a few. However, most power quality problems are due to technology changes and the way the electricity is now being used by people. With each decade, the manufacturers of Power Conditioning and Power Quality equipment are faced with a new set of challenges. As technology changes in all industries, so does the need for ensuring the new technology does not impact the older systems and causing electrical problems. Power quality problems caused by this continued equipment improvement and cost reduction have forced large critical power protection systems to look into the reasons for this change in equipment and their function. There are several facts that will force changes in the technology/topology of power protection systems.

The role of power conditioning systems in the past was to protect the customer's equipment from power quality problems that occurred external to their facility. Today we must also deal with power quality problems caused by their own equipment. While power requirements are decreasing for individual pieces of equipment, the electrical distortion caused by the newer, more efficient power supplies degrade the performance of the electrical system both inside and outside the facility. Utilities are unable to provide the high quality and reliability in electrical power required to meet the ever increasing power quality standards of newer equipment. In the 1970's and 1980's, the problems were most felt in large data centers using sensitive computers. Power quality problems were addressed with Uninterruptible Power Systems, Power Distribution Units, and on site Power Generation. In the 1990's, these problems have increased and moved into factories, offices and anywhere solid-state devices are used. The question now is "Can these systems deal with the new types of critical load?" In many cases the answer is, "Not without minor, and in some cases, major design changes." The issues are becoming more technical and much harder to explain to the design Engineers as they are not aware of changes that will occur after the original build. This document will explain the problems associated with harmonics.

Power quality is a very important issue that should be addressed as poor power quality costs money and in some cases downtime. We will look at some direct and indirect costs attributed to power quality. Direct cost is the loss of production due to a voltage problem, which trips motor and control devices that stop the manufacturing process. It is the loss of products not produced and the labor charges for removing any damaged materials as well as employee wages paid while waiting for the process to restart. Indirect cost is the replacement of other equipment that becomes stressed by changing electrical voltages. As an example, a solid-state motor drive fails due to voltage spikes over time. These are commonly caused by power factor capacitors switching on and off line to correct varying power factors. However, the failure and subsequent damage to the machine will be untimely because is not caused by any one spike but by numerous spikes occurring and over a period of time. With this type of power quality damage, it is impossible to avoid the outage.

This book aims to bridge the gap between technology enthusiasts, researchers, and practitioners by providing a comprehensive overview of these diverse topics. Each chapter is written by experts in their respective fields, offering valuable insights and up-to-date information. We hope that this book will serve as a valuable resource for those seeking to explore the frontiers of emerging technologies and their applications in our ever-evolving world.

Thank you for embarking on this journey with us, and we hope you find this book both informative and inspiring.

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Acknowledgement

I am writing to express my heartfelt gratitude for the support and encouragement to Swami Vivekananda University, Kolkata, India provided in the creation of this book, "Advancement of Power Electronics Abridgement with Power Quality Issues". The commitment from university to fostering education and research has played a pivotal role in shaping the content and direction of this publication. We are deeply appreciative of the collaborative spirit and resources offered by Swami Vivekananda University, Kolkata which have allowed us to explore and share the latest innovations and technologies across various fields. We hope that this book serves as a valuable resource for this esteemed institution and the broader academic community, reflecting our shared dedication to knowledge, progress, and the pursuit of excellence.

With sincere appreciation,

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Chapter 1

1.1 Importance of Power Quality in Power System

Around the world, electrical power is shipped and distributed to homes, companies, and across borders and oceans. Numerous pieces of machinery and gadgetry are powered by this electricity, frequently without giving it a second thought. Most people only think about how we use power when something breaks down, and developed nations take for granted our ability to connect into a dependable and secure electrical infrastructure at any time.

Have you ever given any thought to the question, "How good is the "quality" of the power I am using to drive my electrical devices?" Few business owners ask this question, yet it holds the potential to lower your energy expenditures, increase productivity, lower maintenance costs, and lengthen the lifespan of your equipment.It is frequently possible and advisable to improve the power quality being delivered to a facility in order to provide more dependable, stable, and secure energy.

Reducing the frequency of incidents like breakdowns, overheating, and maintenance can save firms money. The benefits of high-quality power go beyond financial savings. It's also about getting paid. Manufacturing productivity rises when power is of higher quality, and plants may maximize their distribution capacities. The quality of your power is ultimately an investment in the success of your company.

There are various ways to detect poor power quality. The most prevalent and simple to spot are problems with service continuity. However, there are numerous other electrical issues that are more difficult to detect. Any of the following signs may indicate a problem with your power quality at your company:

Brief or prolonged electricity outages

1. Electrical machinery that is noisy
2. Voltage drops.
3. Voltage peaks
4. Harmonic asymmetry
5. Accelerated transients
6. Damage caused by lightning

A power quality audit is intended to show how a structure or installation may use electricity more efficiently. Usually, this is brought on by plainly visible problems like equipment failures or power outages. A more thorough audit will find hidden issues, and the solutions that follow will, over time, significantly reduce an organization's energy use and costs.

Installation of a meter that will continuously provide reliable measurements of the Power Quality is frequently included in audits. This enables energy professionals to continuously enhance and optimize the Power Quality of the system. Systems in place should be created to maximize Power Quality as enterprises grow and when equipment is replaced or improved.

We advise businesses looking to improve both the reliability of their energy supply and the efficiency of their energy use to conduct periodic Power Quality Audits. Quality Energy has done Power Quality Audits on a variety of organizations, including industrial facilities, commercial facilities, mining facilities, shopping centers, construction projects, governmental structures, and oil platforms and drilling rigs all over the world.

There are several reasons why the type of power used in our electrical appliances matters. First off, superior power is more effective. It enables the machinery to operate with optimal energy usage. This lowers your overall energy use and, as a result, your carbon footprint while also saving you money on your electricity bill. By minimizing the 'wear and tear' on machinery, using optimized power lowers the danger of equipment failure or overheating and lowers the frequency at which maintenance work will be needed.

Poor-quality electricity is risky and expensive for both the utility and the consumer. A lot of attention must be paid to the calibre of the power being delivered to the loads. Continue reading as we discuss the causes of bad power quality, numerous measuring factors, power quality standards, and different ways to improve power quality.

Power quality represents an equipment's capacity to use the power being supplied to it as well as the ability of a power grid to supply power to consumers efficiently. Technically, sinusoidal waveform measurement, analysis, and improvement at the rated voltage and frequency constitute power quality.

A power system's efficiency and cost can be significantly impacted by power quality. Therefore, it is crucial to ensure that the system is compatible with the power given to it and that the power it consumes is of the appropriate quality. Consumer awareness of power quality has increased recently, which is why many governments have amended their regulations to require electric utilities to ensure that the power quality is up to design standards. Modern machinery is also more susceptible to fluctuations in power quality. Power quality is a problem for utilities, manufacturers, and consumers, and this issue is growing daily.

1.2 Causes of Poor Power Quality

It's important to pinpoint the causes of a power system's poor power quality.
Uncertain occurrences, utilities, consumers, and manufacturers are some of these potential sources.

1.2.1 Event Uncertainties:

Random occurrences like faults, resonance, lightning surges, etc. are to blame for the majority of power quality issues. These kinds of problems are connected to electric utilities.

1.2.2 Poor power quality is caused by utility on three ends:

Power quality problems at the generating end are brought on by load shifting, outages, maintenance, and scheduling.

1.2.3 Transmission end:

Power quality is impacted in transmission lines by wind-related power interruptions, voltage changes, lightning, malfunctioning voltage regulation equipment, and other factors.

Poor power quality in the distribution system is caused by voltage dips, interruptions, transients, spikes, transformer energization, and other factors.

1.3 Consumer

A sizable portion of power quality problems are caused by consumers. Consumers' non-linear loads cause harmonics to be generated in the power system, which results in poor power quality. A load is considered non-linear if its impedance changes as a function of the applied voltage. Even though the system has sinusoidal voltage, the shifting impedance indicates that the non-linear load is drawing non-sinusoidal current. Harmonic current, which interacts with the system's impedance and causes voltage distortion, is present in non-sinusoidal current and may impact the power system and the loads attached to it.

1.4 Manufacturer

Manufacturers may be impacted by power quality issues in one of two ways:

1.4.1 Standards:

Poor power quality may be caused by a lack of standards for the installation, testing, certification, procurement, sale, or use of any device.

1.4.2 Equipment sensitivity:

If an item of equipment is too sensitive for the electrical environment, it may result in problems with power quality.

1.5 Common Power Quality Issues and Parameters

1.5.1 Transients

Transients are short-lived, highly intense pulses that appear in a sinusoidal waveform. Transients can originate from both internal and external sources, or from both inside and outside of the institution. The wind, lightning, and transformer switching are examples of external sources. Arcing, load switching, and system errors are examples of internal sources. These waveform distortions are undesirable because they put equipment at risk for damage from overloading, dielectric breakdown, fracture, and other factors. The transients lead to low quality in this way.

1.5.2 Voltage Variations

Voltage variation is the word used to describe the situation where a system's voltage deviates from its nominal value. Voltage interruption is one of the factors causing voltage variance and may be brought on by equipment failure, control issue, or fuse/circuit breaker actuation. Another factor that results from starting large motors, single line to ground faults, load shifting, or energizing heavy loads is sag or voltage dip, which is a fall in RMS voltage. Additionally, voltage changes are caused by under or over voltages. When a system is overloaded, undervoltages result, and when a system is equipped with lighter loads than the utility's recommended voltage level, overvoltages result.

1.5.3 Unbalanced Voltages

Unbalanced voltages are defined as voltages in a three-phase system that differ in either magnitude or in the phase difference (other than 120 degrees) between each of the two phases. The main reasons of voltage imbalance in power networks include blown fuses in any of the three phases, an uneven load distribution in a three-phase system, and no transposition in overhead transmission lines. The electrical equipment may be harmed or damaged by such uneven voltages, leading to poor power quality.

1.5.4 Flickers

Continuous changes in the voltage of the electricity being provided result in quick changes in the load currents, which make vision unstable. A lamp's brightness changes quickly and visibly, which is bad for the human eye. The common reasons of the flickering effect are sudden variations in load, motor drives, arc furnaces, welding equipment, etc. Therefore, the flickers raise concerns about the quality of the power.

1.5.5 Distorted Waveforms

Waveform distortion is the term for a waveform's departure from the steady state sinusoidal waveform. These distortions may take the form of harmonics, DC offset, or electric noise, among others. The term "DC offset" refers to the presence of a DC current or voltage component in an AC system. Switching devices, leakage inductance of inductor loads, etc. are the principal causes of DC offset. DC offsets can cause equipment to overheat and shorten its lifespan, which is bad for the power system. Harmonics are sinusoidal waveforms with frequencies that are an integral multiple of the fundamental frequency. The major causes of harmonics in the power system include non-linear loads, switching equipment, etc. These harmonics can cause equipment losses, control device malfunction, increased noise, etc.

Electric noise, which is characterized as unwanted electric signals superimposed on the voltage or current waveform of a power system, is another sort of waveform distortion. Electronic equipment, the corona effect, and faulty power supply connections are some common causes of electrical noise. Since each of these distortions has a negative effect on the power quality, they must all be reduced.

The measurement of the harmonic distortion present in a waveform is known as total harmonic distortion (THD). The relationship between a power system's power quality and THD is inverse. The power quality will be lower in a system with more harmonic distortion, and vice versa. The RMS harmonic content to the fundamental ratio, or THD, is equal to:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V^{2}_{n\text{-}rms}}}{V_{fund\text{-}rms}} \qquad (1)$$

Where $V_{fund\text{-}rms}$ is the RMS voltage of the fundamental frequency and $V_{n\text{-}rms}$ is the RMS voltage of the signal's nth harmonic.

1.5.6 Power Factor

Power quality and power factor are directly related. High power quality is indicated by a power factor value that is closer to 1. The lower the power factor value, the worse the quality of the power will be, and the more expensive it will be.

1.5.7 Varying Frequency

Frequency variations are described as changes in the frequency's magnitude from its nominal value (50 or 60 Hz). Frequency of power system deviates from the fundamental value if there is an imbalance between generation and demand.

Frequency changes can also be brought on by transmission system flaws.

Because all electrical devices are built in accordance with the rated frequency and any variations in this value may have a negative impact on them, these fluctuations lead to poor power quality.

1.6 Temporary interruptions

It is also possible to stop or disrupt the flow of electricity to customers, which results in a localized area experiencing total power loss and voltage zero for a brief or extended length of time.

Your utility may have planned for this interruption, but it could also be due to one of the following reasons:

Short term power outages typically result from insulator breakdown, lightning, insulation flashovers, and other factors. Equipment failure in the power system network, human error, severe weather, a lack of coordination amongst protective devices, etc, can all result in long-term disruptions.

1.6.1 Voltage notching

When current commutates from one phase to another during the regular functioning of power electronic equipment (rectifiers, SCRs, etc.), this is known as notching. The electrical system's inherent frequencies are excited by the abrupt voltage change caused by the notch. This causes more non-typical harmonics to show up in the system voltage. Sensitive logic and communication electrical circuits in the facility may be harmed as a result of the high frequency harmonics produced by notching, and radio interference may develop.

1.7 Effects of Poor Power Quality on Power System

Poor power quality has negative effects on both the utility and the customer. Following are some of the main consequences of poor power quality in the power system:

Equipment may be exposed to high peak waveforms due to harmonics, which can damage the equipment. Additionally, high voltages may cause equipment to run in a saturated state, resulting in additional disruptions.

Equipment lifespan is shortened as a result of overheating, noise, etc.

The effectiveness or performance of the system is significantly reduced by poor power quality.

Important data may be lost or distorted as a result of a power outage or other interruption, which could result in a significant loss.

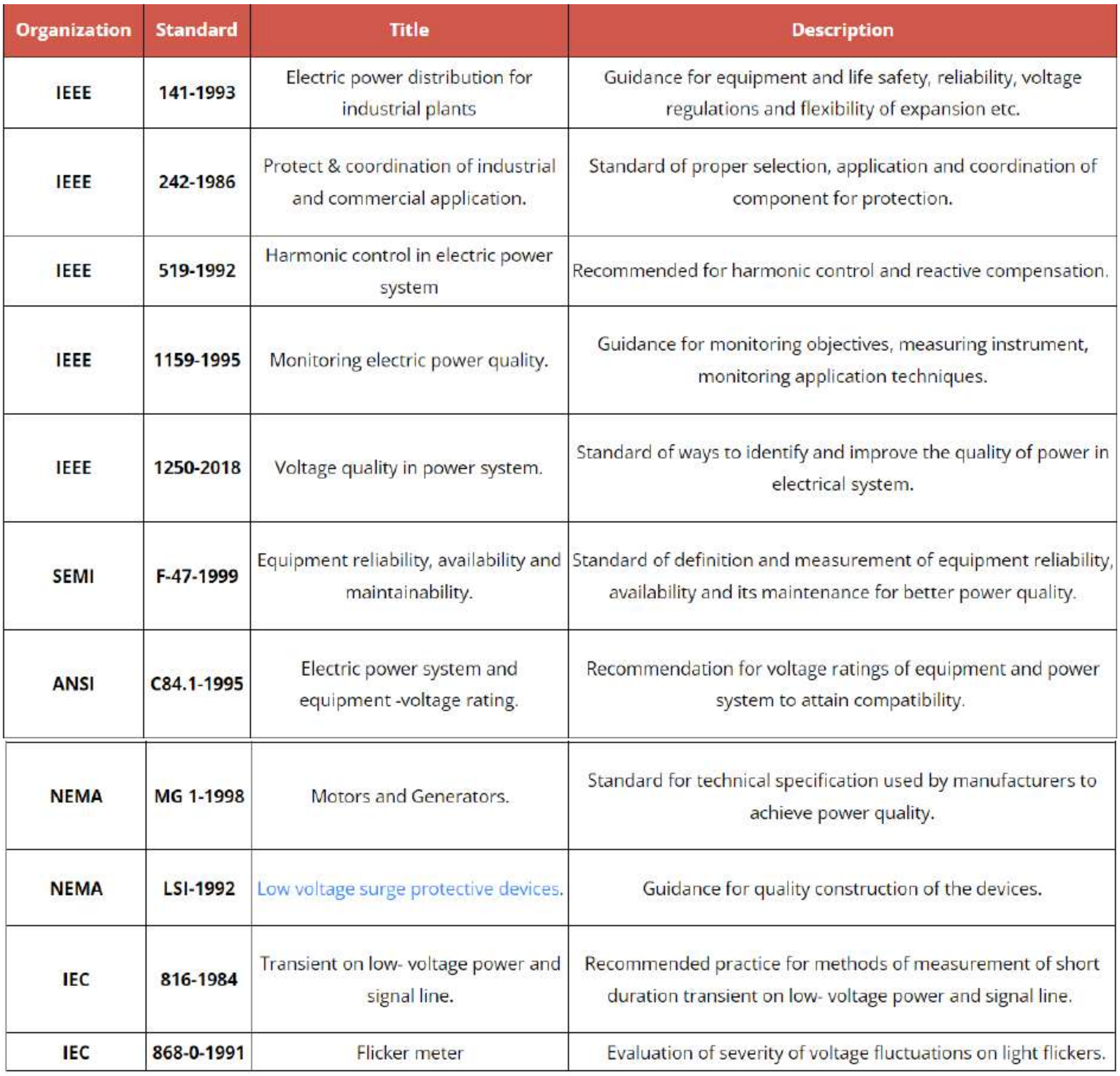
Poor power quality significantly raises the cost of a power system.

Due to the lack of power, consumers may experience a variety of issues, which has an impact on their utility costs as well.

Power quality problems severely influence or even harm consumer loads.

Due to the added strain that poor power quality causes, it is occasionally necessary to oversize the power system. High installation expenses are a result of this expansion.

1.8 Power Quality Standards



Organization	Standard	Title	Description
IEEE	141-1993	Electric power distribution for industrial plants	Guidance for equipment and life safety, reliability, voltage regulations and flexibility of expansion etc.
IEEE	242-1986	Protect & coordination of industrial and commercial application.	Standard of proper selection, application and coordination of component for protection.
IEEE	519-1992	Harmonic control in electric power system	Recommended for harmonic control and reactive compensation.
IEEE	1159-1995	Monitoring electric power quality.	Guidance for monitoring objectives, measuring instrument, monitoring application techniques.
IEEE	1250-2018	Voltage quality in power system.	Standard of ways to identify and improve the quality of power in electrical system.
SEMI	F-47-1999	Equipment reliability, availability and maintainability.	Standard of definition and measurement of equipment reliability, availability and its maintenance for better power quality.
ANSI	C84.1-1995	Electric power system and equipment -voltage rating.	Recommendation for voltage ratings of equipment and power system to attain compatibility.
NEMA	MG 1-1998	Motors and Generators.	Standard for technical specification used by manufacturers to achieve power quality.
NEMA	LSI-1992	Low voltage surge protective devices.	Guidance for quality construction of the devices.
IEC	816-1984	Transient on low- voltage power and signal line.	Recommended practice for methods of measurement of short duration transient on low- voltage power and signal line.
IEC	868-0-1991	Flicker meter	Evaluation of severity of voltage fluctuations on light flickers.

Table 1. Power quality standards

1.9 Power Quality Improvement Techniques

Numerous strategies have been proposed and put into practice to lessen the impact of bad power quality on the power system. Numerous solutions have been developed to lessen or eliminate the negative effects of poor power quality. In addition, extensive investigation and monitoring of the power quality are done to improve or keep it at the required level.

1.9.1 Power System Studies

A power system study is defined as a series of engineering examinations to guarantee a facility's electrical system is secure, competent, and reliable under both normal and abnormal circumstances. To conduct power system studies, engineers with extensive knowledge and comprehension of power systems are required. Power system studies come in a variety of forms, each with their own purpose and approach. Short circuit, coordination, arc-flash, load flow, harmonic analysis, and stability study are among the studies. To conduct power system studies, a power system must have complete and accurate data. Utilizing a variety of software tools, these studies are conducted. The efficiency of the system is improved and the risk level of continuous operations is decreased upon completion of power system studies.

1.9.2 Power Conditioning Devices

Equipment in a power system is supplied with higher-quality power thanks to the usage of power conditioning devices. Numerous gadgets function as power conditioners in various ways.

1.9.3 Power protectors

Surge protectors or surge suppressors are devices that shield electrical equipment from voltage peaks. Surge protectors are designed to detect sudden increases in voltage and divert any excessive current flow to the ground in order to limit the voltage level to a level that the system can sustain.

1.9.4 Filters

The tools used to remove the harmonics produced by the system's non-linear loads are called filters. When filters are positioned close to non-linear loads, harmonic currents are either bypassed or prevented from entering the power system.

1.9.5 Voltage Regulators

Voltage regulators are devices that automatically maintain a steady voltage level. Regardless of the input or connected load, it generates a fixed output voltage.

1.9.6 UPS

When there is an emergency or a main power outage, the UPS (Uninterrupted Power Supply) electrical device acts as a backup and supplies the system with power.

1.10 Power Quality Monitoring

Power quality monitoring (PQM) is the process of gathering, analyzing, and using electrical data to enhance the performance of the system and the quality of the electricity. It guarantees cost savings overall, quality control, energy management, and preventative maintenance. Consumers today are well aware of power quality issues and need effective electrical services. Electrical facilities utilize digital fault recorders, smart relays, and other specialized power quality equipment because they are concerned about power quality monitoring. To improve the quality of the power, modern power plants routinely check the voltage and current supplied to the user. Every power system should enhance its functionality, efficacy, and equipment lifetime.

1.11 Recent Scenario of Power Electronics Devices

Modern power systems rely heavily on power devices since they can invert and change voltages, buffer data, and switch. These devices are facing difficulties due to the complexity of power systems, which is rising along with distributed renewable generation. Wide bandgap devices are among the new innovations that have developed in recent years; each has pros and cons depending on the situation and application.

A method called "custom power" was created largely to satisfy the needs of business and industrial clients. The use of power is what custom power refers to medium voltage static or electronic controllers methods of distribution designed to deliver a dependable and higher Sensitive users require dependable power sources. These customised power systems are built on power electronic valves. Devices like active filters and state transfer switches and devices that use converters. Custom conversion-based power tools that reduce voltage fluctuations and Devices that are connected in series and shunt fashion are the two primary categories of interrupts. specific power In the sections that follow, devices are described.

1.11.1 Static transfer switch

There are two thyristor blocks that make up the static transfer switch (STS). Each thyristor block is made up of three thyristor modules, which correspond to the system's three phases.

Fig.1 depicts the typical STS layout found in industrial distribution systems. under typical circumstances. Switch 1 is how the principal supply feeds the load. The load is fed from the backup source switch in the event of a fault or voltage dip affecting the primary supply. The fundamental frequency's fourth to hr cycle is the range of the STS transfer time. As a result, the voltage dip's duration is cut down to this transfer time, which most loads can withstand.

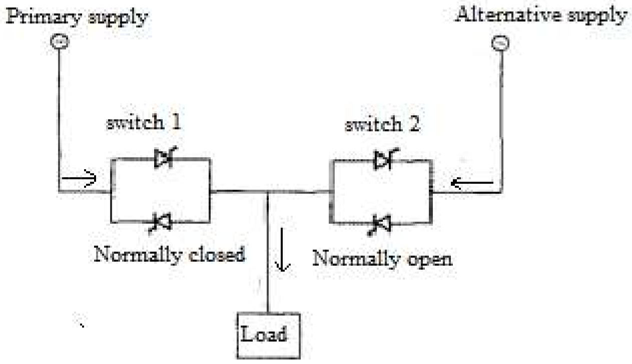


Figure 1. Static Transfer Switch

The STS's main flaw is that the load current is continuously carried by it, which causes significant conducting losses, especially in high power applications. The conducting losses range from 1% to 2% of the power of the load.

In [1], a hybrid static transfer switch (HSTS) was suggested. The theory states that under normal operating conditions, a typical mechanical circuit breaker (MCB), coupled in parallel with the thyristors, conducts the current. Less than a half-cycle is required for the current to commutate from the primary to the alternative source, although the total transfer time also depends on how quickly the voltage dip detecting reacts. To ensure a quick switchover of the load from the primary to the backup supply, the voltage dip detecting technique needs to be very quick.

1.11.2 Active Filters

Due to the growth of nonlinear, interest in active filters has grown recently. Traditionally, passive filters have been used to reduce harmonics. Harmonics are given a low-impedance path or a high-impedance block via passive filters.

Passive filter use has several drawbacks, including slow dynamic response, reliance on source impedance, resonance between the passive filter and source impedance, and inability to adjust to changing load conditions. The active filters have been suggested as a solution to the passive filters' drawbacks. Active filters inject the same amount of the harmonic current produced by the load with the opposite direction in order to cancel the harmonics at the point of common coupling, as opposed to providing impedance routes for current harmonics.

According to Fig.2(up), the shunt active filter serves as a non-sinusoidal current source when it is shunt linked to the distribution system. The shunt active filters should inject a current -& to achieve sinusoidal current flowing in the distribution system if the load current is $I_L + I_h$ where I_L is the fundamental component and I_h, is the harmonic load current. As shown in Fig.2(below), the series active filter is linked in series with the distribution system. In order to prevent the flow of harmonic currents, it functions as a non-sinusoidal voltage source, injecting voltage U_i with the same magnitude and opposite phase as load voltage harmonics.

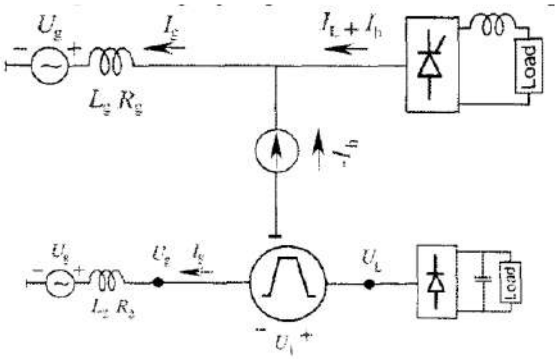


Figure 2. Active Filters: up) shunt active filter, down) series active filter

A voltage-fed pulse width modulated (PWM) inverter using gate turn-off thyristors (GTOs) or insulated-gate bipolar transistors (IGBTs) is the main component of an active filter. Fig.3 shows the single-phase complete bridge topology of a shunt active filter.

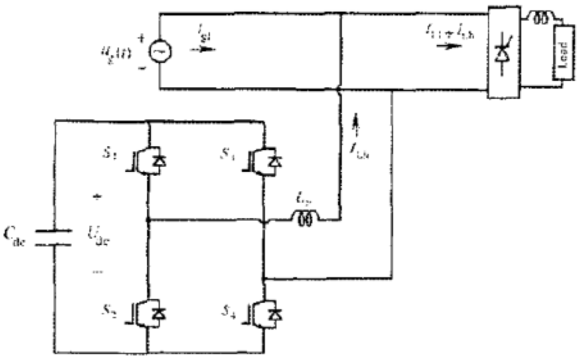


Figure3: Full bridge topology of single phase shunt active filter

The high frequency harmonics of the injected current are restricted using the inductance L_F. A dc voltage with no ripples is supported by the capacitance C_{dc}. The shunt active filter injects the necessary current thanks to the operation of the switches S_1 to S_4. The only variation in the configuration of the series active filter is that it is connected in series. Extracting voltage or current harmonics from the correspondingly distorted voltage or current to be filtered is what it means to regulate active filters. There are two basic approaches that can be used to accomplish this: one is based on instantaneous reactive power theory (p-q theory), and the other is based on Fourier analysis in the frequency domain[2].The following is a summary of the p-q theory. Voltages and currents from the phase are changed to stationary as a reference frame

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \tag{2}$$

The definition of the instantaneous active power is:

$$p = u_1 i_1 + u_2 i_2 + u_3 i_3 = u_\alpha i_\alpha + u_\beta i_\beta = \mathrm{Real}(u\, i^*) \tag{3}$$

Where

$u = u_\alpha + j u_\beta$, $i = i_\alpha + j i_\beta$, i^* is the complex conjugate of i. The instantaneous reactive power is s:

$$q = -u_\alpha i_\beta + u_\beta i_\alpha = \mathrm{Imaginary}(u\, i) \tag{4}$$

From (2.7) and (2.8), the current components in the αβ frame can be obtained as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \left\{ \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ q \end{bmatrix} \right\} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} \begin{bmatrix} i_{\alpha q} \\ i_{\alpha q} \end{bmatrix} \tag{5}$$

Where

$i_{\alpha p}, i_{\beta p}$ are the instantaneous active components of i_α, i_β while $i_{\alpha q}, i_{\beta q}$ are the instantaneous reactive components of i_α, i_β Using (7). the following equations can be deduced:

$$i_p = i_{\alpha p} + j i_{\beta p} = \frac{1}{u_\alpha^2 + u_\beta^2}(u_\alpha + j u_\beta) p = \frac{u}{|u|^2} p \tag{6}$$

$$i_q = i_{\alpha q} + j i_{\beta q} = \frac{1}{u_\alpha^2 + u_\beta^2}(u_\beta - j u_\alpha) p = -\frac{ju}{|u|^2} q \tag{7}$$

If the average active power P and average reactive power Q are substituted in (8), the dc current component are obtained:

$$i_{\bar{p}} = P u / |u|^2 , \quad i_{\bar{q}} = -jQ u / |u|^2 \tag{8}$$

The difference between i_{p^-} and i_p,I_{q^-} and i_q respectively are then ac components, which they are compensated by shunt active filters. It is worth to mention here that shunt active filters in a range of 50 kVA up to 60 MVA been installed in Japan. Series active filters are still under field-testing.

1.11.3 Uninterruptible power supply

The uninterruptible power supply (UPS) has traditionally been used as a solution to prevent production interruption and outage expenses. Through a two-stage process of conversion (AC/DC) and inversion (DCIAC), the load power is drawn from the primary power source. The energy provided by the battery keeps the load voltage stable during a voltage drop or interruption. Fig. 4 displays a single-line diagram of the UPS. It can power the load for minutes or even hours, depending on the battery's storage capacity.

Where a power outage could result in losses higher than the cost of the UPS, a UPS is required [3]. This technique no longer seems to be economically viable for higher-power loads due to the costs associated with losses resulting from the two additional conversions and battery maintenance [4].

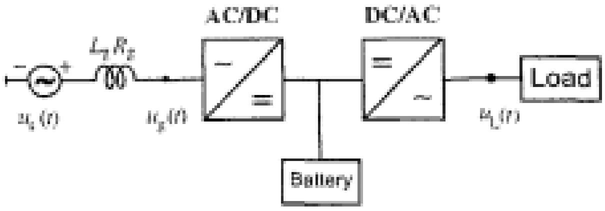


Figure 4. The single line diagram of UPS

1.11.4 A voltage source converter with a shunt connection (DSTATCOM)

By supplying or absorbing reactive power, shunt-connected bespoke power devices, such the Distribution Static Compensator (DSTATCOM), are coupled in shunt with the distribution system to maintain the voltage of the distribution feeder at the desired level. As shown in Fig. 5, the DSTATCOM comprises of an output filter, a tiny dc energy store, and a voltage source converter (VSC). The foundation of the DSTATCOM is the idea that the VSC generates a programmable AC voltage source behind the transformer leaking reactance, which results in a reactive power flow between the DSTATCOM and the distribution system when the voltage difference across the reactance[5] is increased. A Canadian lumber mill in British Columbia installed the first DSTATCOM, which is utilised for reactive power adjustment to prevent voltage flicker[6]. A k 2MVAr DSTATCOM with a typical power factor of about 0.85 has been fitted for a 2.6 MVA load. The DSTATCOM may also interchange active power with the distribution system by selecting energy storage with sufficient capacity, which enables the DSTATCOM to compensate for voltage dips as well[7]. However, because it would be required to inject a very big current in that scenario, the DSTATCOM cannot be utilised to correct for deep drops.

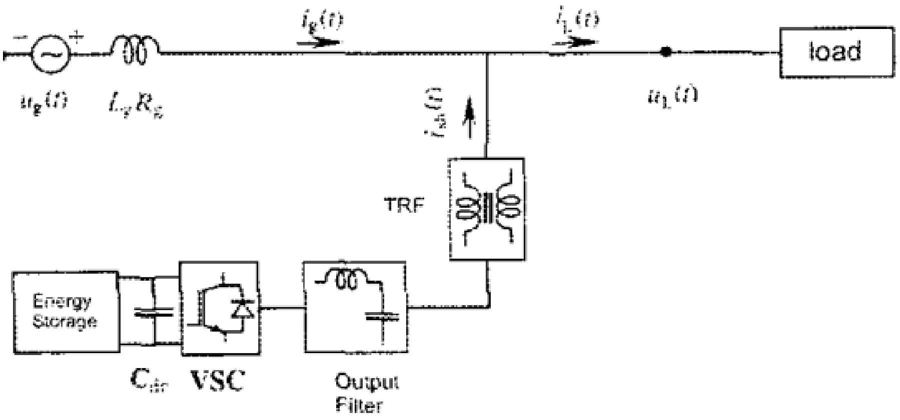


Figure 5. Single line diagram of DSTATCOM

1.12 Implementation of power electronics in the power quality scenario

Solutions for power quality that rely on Active Power Filters (APF) and UPSs are presented in this section. APFs are shunt- or series-type power quality compensators that are based on power electronics. In contrast to the series active power filter (SeAPF), which is connected in series with the power grid and thus compensates for voltage-related power quality issues, the shunt active power filter (ShAPF) is connected in parallel with the power grid.Additionally, the association of the SeAPF and ShAPF results in the UPQC, which is also covered in this part. The UPQC naturally has the ability to correct the same power quality issues as the SeAPF and ShAPF combined, namely in terms of voltages and currents. Additionally, in this section, power quality solutions based on UPSs are presented. Three basic types of UPSs are taken into consideration: line-interactive, online, and offline. Each of these types can address varying degrees of power quality issues.

1.12.1 Shunt Active Power Filters

The ShAPF is an APF that connects to the power grid in parallel while compensating the loads that are downstream of the ones that cause the power quality issues.

As a result, the ShAPF is a piece of machinery that can correct for power quality issues caused by currents, namely harmonic currents, reactive power, and unbalanced currents in three-phase power networks. The way a ShAPF works is to measure the load currents downstream and absorb currents with a specific waveform that, when added to the load currents upstream of the ShAPF, produces sinusoidal, balanced currents that are in phase with the corresponding phase-toneutral power grid voltages (see Figure 6).

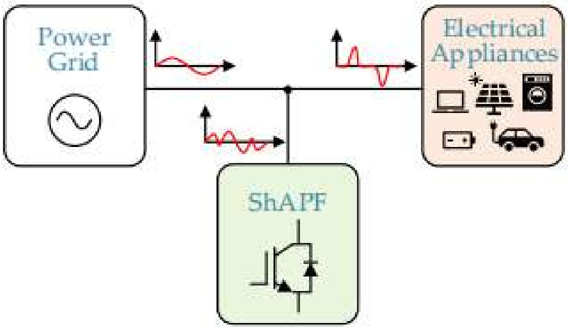


Figure 6.Operation principle of a shunt active power filter

A transformer core's magnetic flux compensation theory served as the foundation for the harmonic current cancellation idea employed in ShAPFs, which was first suggested in 1971 [8]. Gyugyi and Strycula introduced the idea of an active ac power filter using PWM converters in 1976. However, because this ShAPF was based on a line-commutated converter made up of thyristors, its practical application was restricted to compensating for fundamental reactive power [9]. The works of Gyugyi and Strycula were made feasible by Akagi, Kanazawa, and Nabae's ShAPF in 1984, which is composed of a three-phase, three-leg ac-dc converter based on bipolar junction transistors operating with PWM. This ShAPF is not only capable of compensating fundamental reactive power but also harmonic currents [10]. ShAPFs have received a lot of research attention since they were first developed, and multiple topologies have been proposed for single-phase or three-phase (three-wire or four-wire) power systems, based on various ac-dc converter topologies [11]. The subsections that follow analyse these various classification groupings.

1.12.2 ShAPFs Based on Voltage Source/Current Source Converters

A ShAPF can be based on either a voltage source converter or a current source converter, depending on the ESS utilised in the dc-link, as is the case with any ac-dc or dc-ac converter topology. With the dc-link having a fixed polarity voltage and the current being able to flow in both directions, voltage source converters use capacitors to transform the converter into a voltage source (Figure 7a). Contrarily, current source converters use inductors in the dc-link to transform the converter into a current source. As a result, the voltage can accept both polarities and the dc-link has a fixed direction current (Figure 7b).

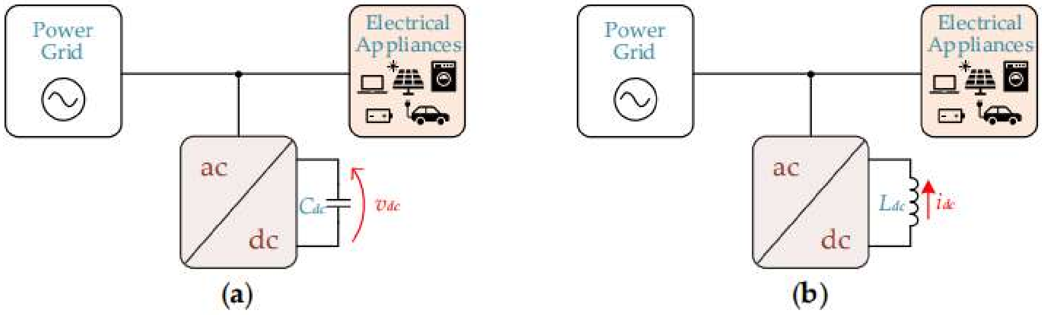


Figure 7. Basic structure of a ShAPF based on a:(a) Voltage source converter;(b) Current source converter

The performance of voltage source and current source converters is examined in [12,13] with regard to their use in ShAPFs; each technique has advantages and disadvantages of its own. For instance, while operating under light load conditions, voltage source ShAPFs exhibit reduced efficiency and larger switching ripple in their output currents. On the other hand, in order to safeguard the power semiconductors from overvoltages, current source ShAPFs require the employment of a large, heavy dc-link inductor.

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1.12.3 ShAPFs for Three-Phase Systems

Depending on whether the neutral wire is present or not, three-phase systems can either have three or four wires. As a result, three-phase ShAPFs can also be built on three-wire or four-wire topologies, with the latter also being able to compensate for neutral currents in addition to the other power quality issues (harmonic currents, reactive power, and unbalanced currents) that were previously mentioned. Despite the fact that the earliest ShAPFs to be described in the literature were of the three-wire, three-phase kind, as seen in Figure 8a's architecture. Due to the connection of single-phase loads in three-phase systems, four-wire layouts have drawn more attention [14].

Three-phase four-wire ShAPFs can have three legs or four legs; the former has a split dc-link [15] with its midpoint connected to the neutral wire (Figure 8b) [16], and the latter has a common dc-link and an additional semiconductor leg [17] with its midpoint connected to the neutral wire (Figure 8c) [18]. Current source SAPFs can be used in three- and four-wire systems, as discussed in [19,20], even though the cited papers focus on voltage source topologies.

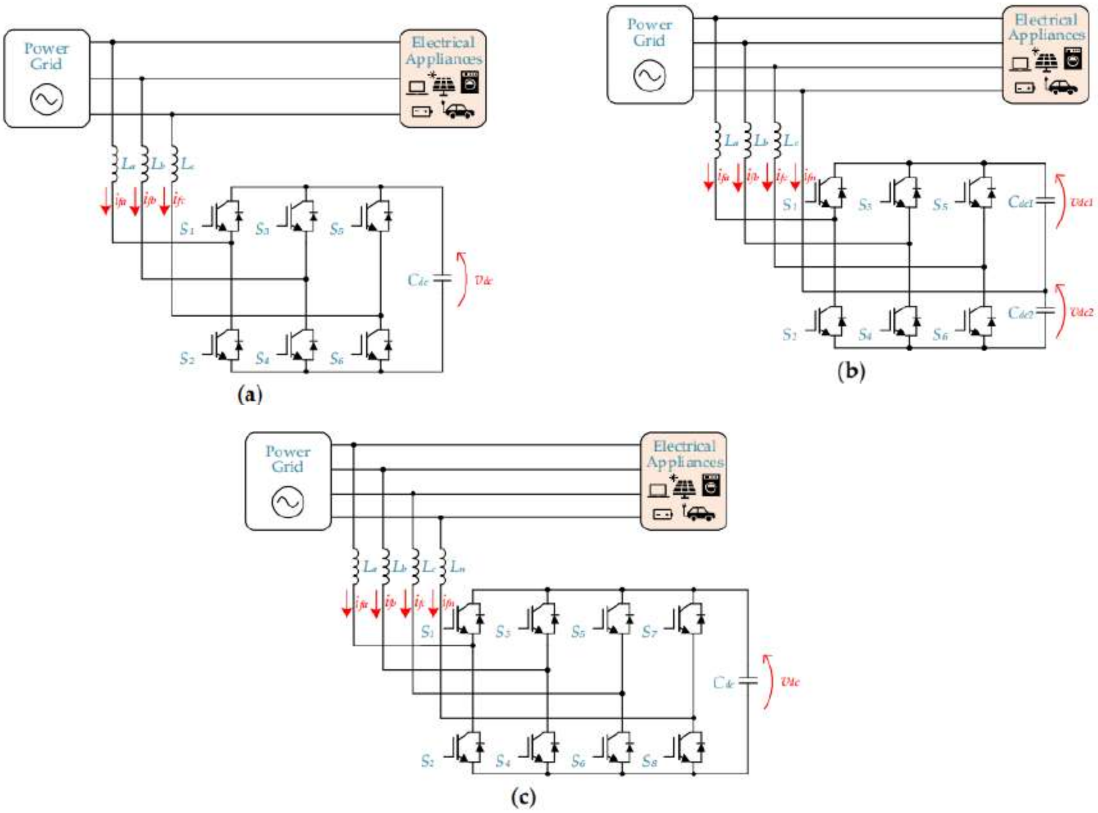
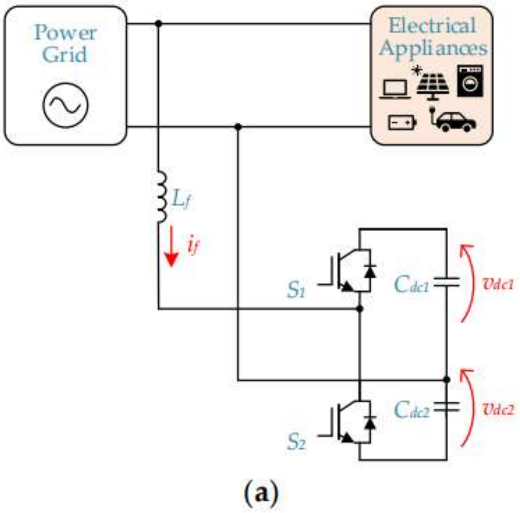


Figure 8. Three-phase ShAPFs using ac–dc converters based on: (a) Three-wire three-leg; (b) Four- wire three-leg; (c) Four-wire four-leg.

1.12.4 ShAPFs for Single-Phase Systems

ShAPFs were first created for three-phase systems since industrial installations had a higher prevalence of power quality issues including current harmonics and reactive power, which were also more costly. However, single-phase ShAPFs were developed as a result of the expanding use of nonlinear loads in dynamic installations [21]. Although the majority of papers on single-phase ShAPFs focus on the usage of full-bridge converters, single-phase ShAPFs based on the half-bridge topology and a two-quadrant topology were also proposed [22,23]. Figure 9 depicts the half-bridge (Figure 9a) and full-bridge (Figure 9b) topologies-based structure of single-phase ShAPFs.

The fundamental disadvantage of these topologies is that they require a larger dc-link inductor than three-phase topologies due to the lower dc-link ripple frequency in single-phase systems. In [24], a single-phase current source ShAPF topology is given that enables the dc-link inductor's inductance value to be decreased while still retaining a minimal ripple in the dc-link current.



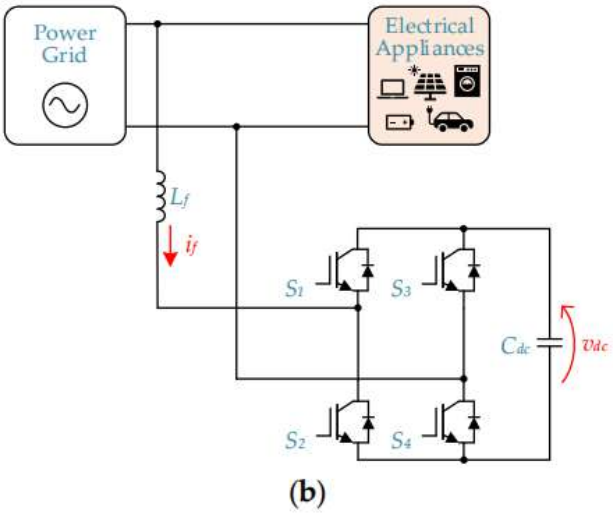


Figure 9. Single-phase ShAPFs using ac–dc converters based on: (**a**) Half-bridge topology; (**b**) Full-bridge topology.

1.12.5 ShAPFs Based on Multilevel Topologies

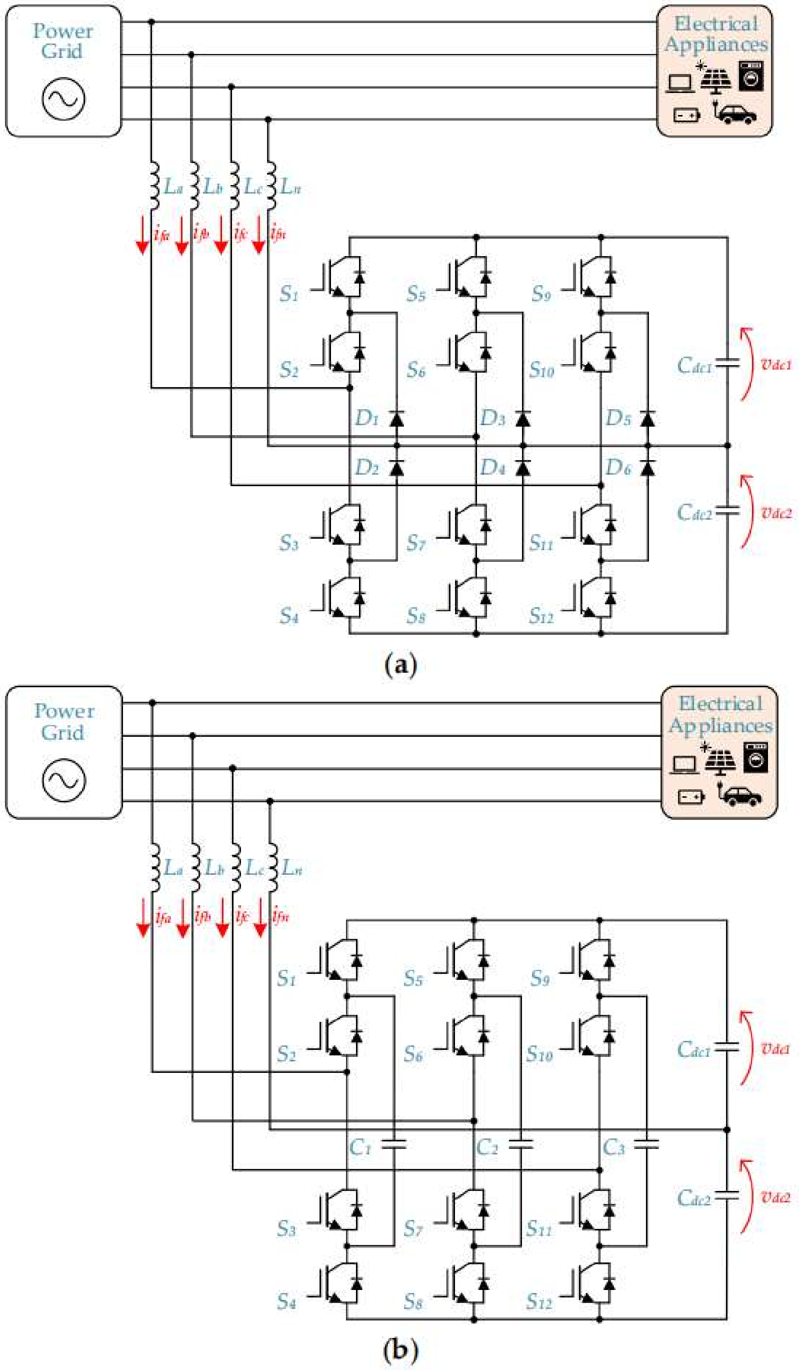
The half-bridge and full-bridge converters used in the aforementioned ShAPF topologies can only create two voltage levels per converter leg. Multilevel converters, on the other hand, can generate three or more voltage levels per converter leg. These converters, which can be utilised with either single-phase or three-phase topologies, can be used to lower the voltage stress on power semiconductors and to enhance the waveform quality of the ac-side current.

A three-phase, three-leg NPC ac-dc converter [25] is the first instance of a multilevel converter in the literature, and it originally appeared in 1981. Given that the dc-link midpoint and the midpoints of each diode leg are connected to the neutral, this converter by definition has a four-wire topology. In Figure 10a, this topology's schematic is depicted. A variant of this converter with four legs instead of three is presented in[27], with the midpoint of the fourth leg being linked to the neutral. In [26], the performance of this converter working as ShAPF in both three-wire and four-wire systems is evaluated. The dc-link is still split in this topology, but its midpoint and the midpoints of the diode legs are connected to one another but not to the neutral.

The three-level half-bridge NPC, consisting of a single semiconductor leg whose midpoint is connected to the power grid phase and with the midpoint of the split dc-link being connected to the neutral[28], is the most traditional implementation of the NPC topology for single-phase ShAPFs. In contrast to the traditional full-bridge ac-dc converter, which can create three voltage levels, this converter's power semiconductors only need to tolerate half as much voltage for the same dc-link voltage. It should be noted that adding more power semiconductors (including switches and diodes) and dc-link capacitors connected in series might increase the number of levels.

The full-bridge NPC architecture is an alternative to the half-bridge NPC topology, where the converter is made up of two semiconductor legs, the midpoints of which are linked to phase and neutral[29]. The midpoints of the split dc-link and the legs of the diode, similar to the three-phase four-leg NPC, are linked to one another but not to the neutral. As with the half-bridge NPC, the number of switches, diodes, and dc-link capacitors connected in series can be raised to produce more voltage levels. This full-bridge NPC topology can provide five voltage levels. However, the full-bridge NPC topology can be made simpler while retaining all of the voltage levels by utilising an NPC structure in one leg and a straightforward half-bridge leg in the other. This converter is typically built as an asymmetric NPC that can also generate five voltage levels. The operation of this converter as a ShAPF is suggested in[30].

The flying capacitor topology is a different family of multilevel converters that is widely used. As shown in Figure10b, these topologies are similar to the NPC except that capacitors are used in place of diodes. The flying capacitor topologies are also known as "capacitor clamped" as a result of this. With single-phase flying capacitor ShAPF being proposed in [31], based on a half-bridge configuration, and [32], based on a full-bridge configuration, the variants of the flying capacitor topology obey a similar structure to the NPC variants. The half-bridge type generates three voltage levels, but the full-bridge model generates five voltage levels, similar to NPC topologies. In contrast to its NPC counterpart, the full-bridge flying capacitor topology does not require a split dc-link.Regarding three-phase systems,[33] presents a ShAPF based on a three-leg flying capacitor topology, while [34] presents a structure very similar to [33], but with four legs as opposed to three. In [35,36], flying capacitor and NPC-based non-traditional multilevel converters for the ShAPF are presented.



(a)

(b)

Figure10. Three-phase ShPF using multilevel ac-dc converters based on: (a)NPC;(b) Flying capacitor

The cascaded multilevel topology is the third family of traditional multilevel converters. This architecture is based on the series connection of traditional full-bridge converters, where the quantity of voltage levels can be raised with the quantity of converter cells. The cascaded multilevel topology, in contrast to the NPC and flying capacitor topologies, uses separated dc sources. Because of this, it is also known as the cascaded H-bridge topology.The initial cascaded multilevel topology was used with a three-phase converter, much like the multilevel topologies that were previously demonstrated. A three-phase, five-level cascaded multilevel ShAPF with two full-bridge converter cells in each phase is presented in [37], while an eleven-level structure with five full-bridge converter cells in each phase is presented in[38]. In[39,40], five-level and nine-level cascaded multilevel topologies for single-phase ShAPF are presented, respectively.

1.12.6 Hybrid ShAPF

To lower its power rating, ShAPF can also be used in conjunction with passive filters. Due to this combination, the idea of hybrid APF was created. In this design, the passive filters are set to correct for the most noticeable current harmonic orders (like the 5th and 7th), while the ShAPF only has to do so for higher-order harmonic currents. Depending on the connection between the active and passive filters, hybrid ShAPF can be either parallel hybrid or series hybrid. While the parallel connection, shown in Figure 11b, provides for reducing the ShAPF's current rating, the series connection, shown in Figure 11a, allows for decreasing the ShAPF's voltage rating, namely the dc-link voltage.

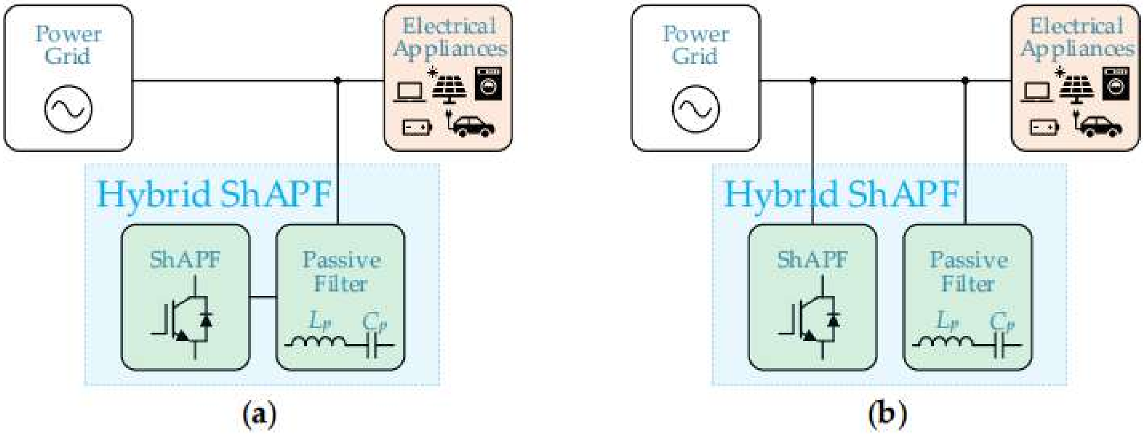


Figure 11. Basic structures of hybrid ShAPF using: (a) Series connection; (b) Parallel connection.

According to [41,42], the series connection is the one that is most frequently employed in hybrid ShAPF in the literature. The cited articles deal with three-phase, three-wire systems, however it is also possible to find references in the literature that apply hybrid ShAPF to three-phase, four-wire systems as well as single-phase systems (e.g.,[43,44] and [45,46]). In [47], a concept known as "smart impedance" applied to hybrid ShAPF is proposed, which does away with the tuning of the passive filters in favour of electronic tuning, or tuning by the ShAPF acting as a distinct equivalent impedance for each harmonic frequency. The parallel operation of two hybrid ShAPFs using various switching frequencies while sharing the same dc-link is proposed in [48].Additionally, as suggested in [49], hybrid ShAPF can be utilised to reduce harmonic resonances in power systems.

1.12.7 Series Active Power Filters

Series APF (SeAPF) are voltage sources that are wired in series with the electrical power grid. They are capable of reducing harmonics, notches, sags, swells, and flicker, which are all voltage-related issues [50]. In addition to compensating for voltage imbalances, three-phase SeAPF may also do so for reactive power [51]. Similar to a controlled voltage source, the SeAPF generates a voltage that is combined with the grid voltage to provide the required load voltage. For instance, the SeAPF generates a voltage in phase opposition to the harmonic content of the power grid voltage to correct for voltage harmonics, making the resulting load voltage sinusoidal [52].Despite the existence of different topologies, a SeAPF is typically constructed from a voltage source inverter (VSI) and a capacitor in the dc-link [53] and connected in series with the electrical power grid using coupling transformers [54]. A three-phase SeAPF based on a VSI converter is schematically depicted in Figure 12 in a simplified form.

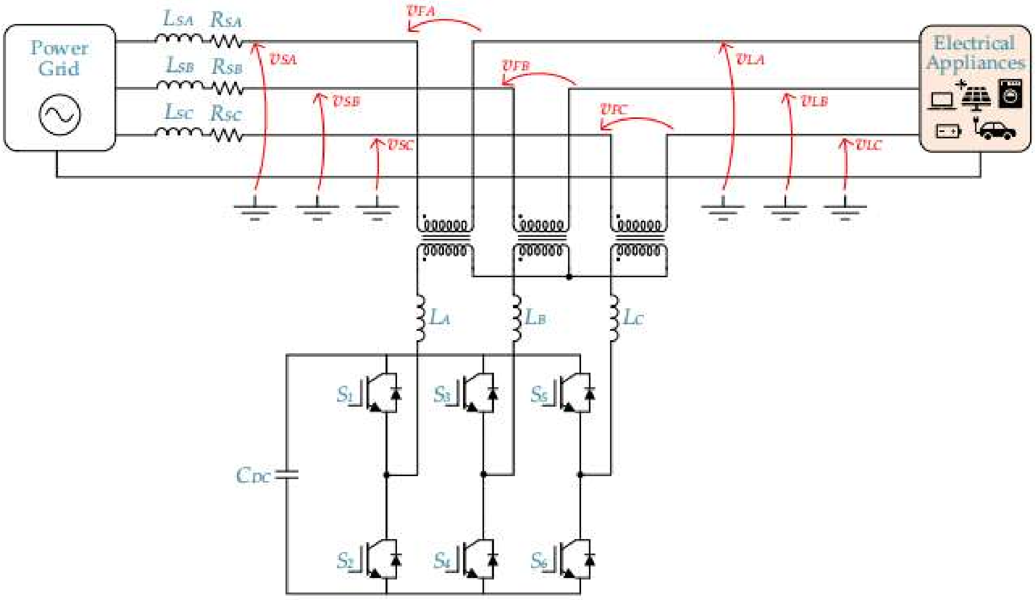


Figure 12. Simplified schematic of a three-phase SeAPF based on a voltage source inverter.

The SeAPF's compensation capabilities are increased if the converter's dc-link comprises energy sources, enabling the compensation of steady-state power grid under- or overvoltages [55]. The employment of bidirectional converters coupled back-to-back to keep the dc-link voltage controlled is one potential method for extending the SeAPF's compensatory capabilities [56]. The simplified schematic SeAPF with enhanced adjustment capability is shown in Figure 13.

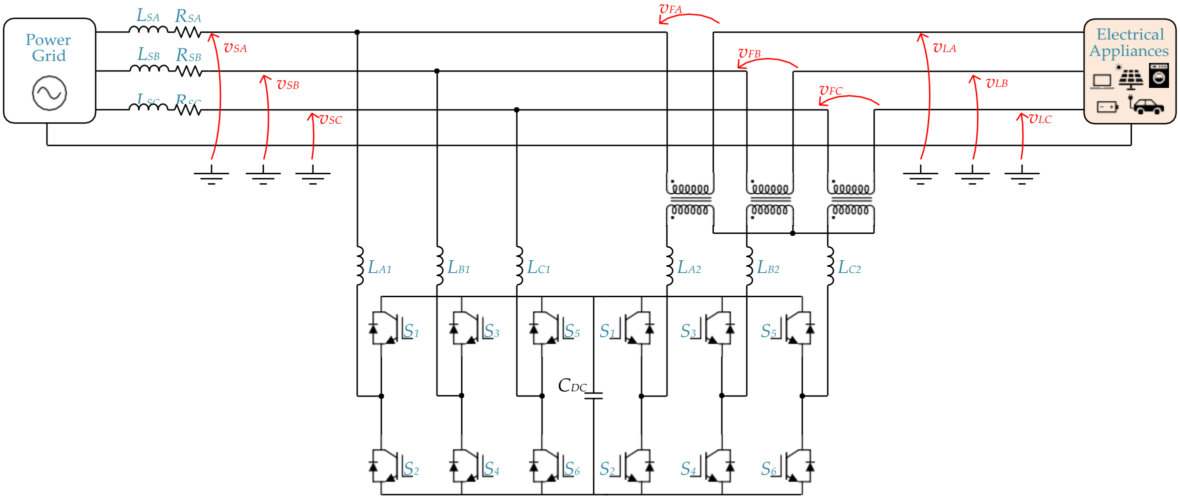


Figure 13. Simplified schematic of a three-phase back-to-back power converter to extend the compensation capabilities of the SeAPF.

The ability to exchange energy with the power grid through the bidirectional ac-dc converter that supplies the SeAPF dc-link, allowing the adjustment of steady-state power grid under- or overvoltages, is the main benefit of this more advanced topology. For instance, the SeAPF generates a voltage with the same frequency and phase angle of the power grid voltage to obtain a load voltage with nominal amplitude in order to correct for an undervoltage while ignoring other potential power quality issues. To make up for the undervoltage in this situation, the SeAPF injects energy into the power grid (the active power supplied by the SeAPF may be calculated using the average value of the product of the SeAPF voltage by the load current).In this way, and neglecting the losses, the bidirectional ac–dc converter needs to absorb the same amount of active power as produced by the SeAPF to maintain the dc-link voltage regulated. That is, the energy injected by the SeAPF is absorbed by the bidirectional ac–dc converter, making the system neutral in terms of active power exchanged with the power grid. However, despite its advantages, this enhanced topology requires an additional power converter, increasing the cost of the SeAPF.

1.12.8 Hybrid Series Active Power Filters

Although the potential of the SeAPF to compensate for power quality issues caused by the power grid voltages by creating sinusoidal and balanced load voltages is very intriguing, there has not been a significant uptake of this technology in actual applications. The SeAPF gains a number of benefits when used in conjunction with shunt passive filters, raising its appeal. The term Hybrid Series APF (HySeAPF) is frequently used in the literature to describe this setup [57].On the other hand, the passive filters correct the harmonic currents and the power factor, resulting in more sinusoidal and reduced-amplitude currents flowing through the SeAPF. As a result, the HySeAPF power converter's Volt-Ampere rating is lower than that of the SeAPF as is customary. The reduction of harmonic currents flowing through the coupling transformer, which increases losses and stresses these components, is another benefit of the HySeAPF topology [58].

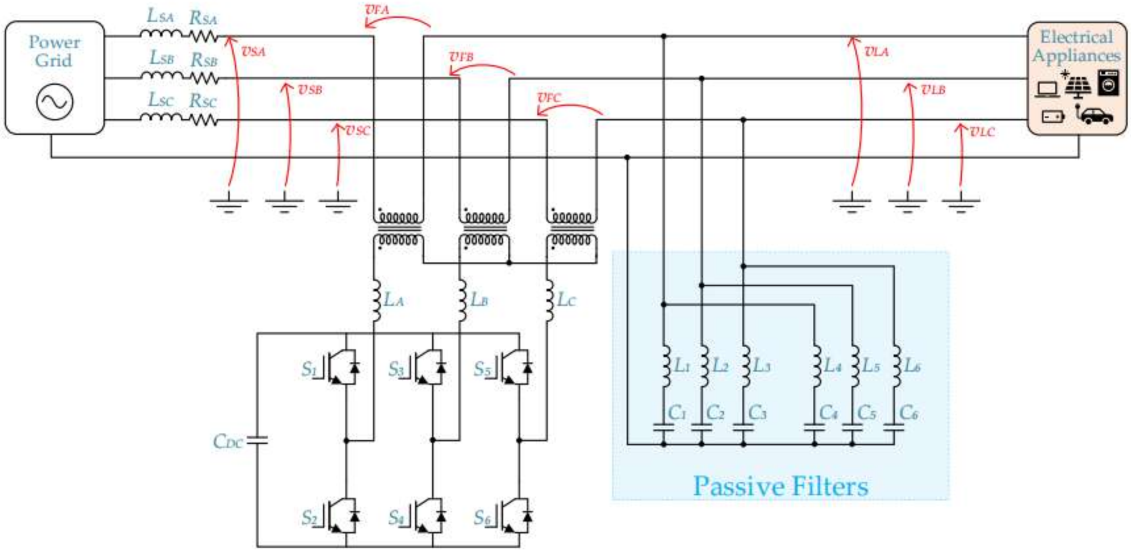


Figure 14. Simplified schematic of a three-phase hybrid series active power filter (HySeAPF)

1.12.9 Transformerless Series Active Power Filters

Transformers used to link the SeAPF in series with the electric grid may jeopardise the device's functionality. Transformers are not made to handle distorted voltages and currents, which leads to this issue. Some topologies known as Transformerless Series APF (TlSeAPF) were researched and proposed in the literature [59] to address the issues with the low-frequency transformers employed in the traditional architecture of SeAPFs. A TlSeAPF made up of three separate H-bridges with a voltage source at the dc-link is presented in [60].

In [61], a topology and control algorithm for a single-phase SeAPF that links in series with the power grid without coupling transformers is presented with respect to single-phase topologies of TlSeAPF. By employing an algorithm to effectively regulate the voltage in the dc-link capacitor, this design also avoids the requirement of an external power source (Figure 15).

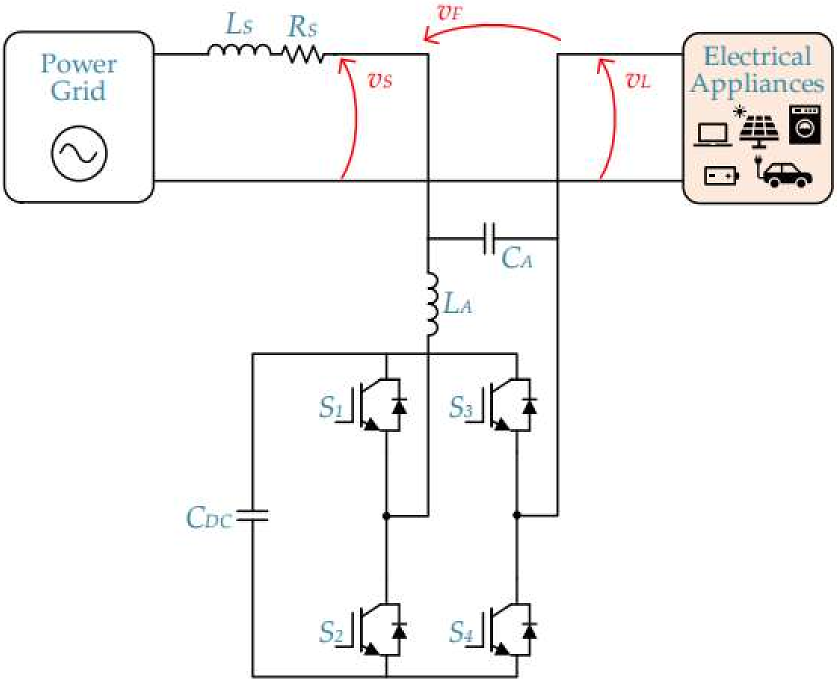
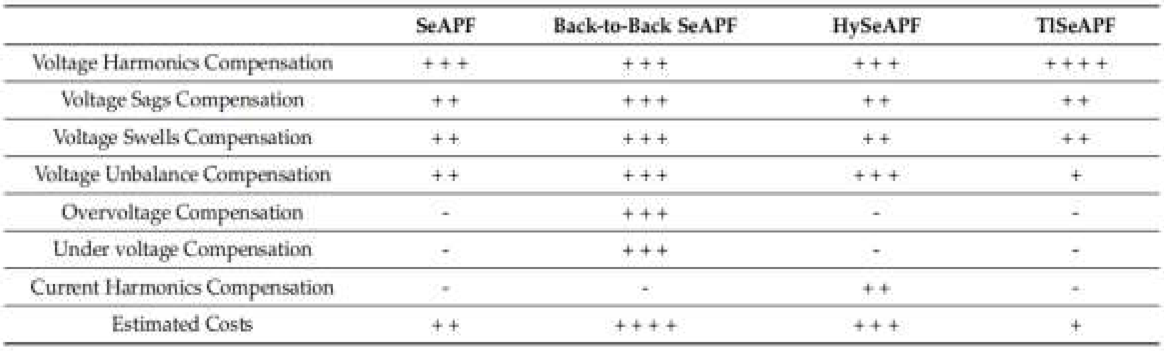


Figure15 Simplified schematic of a transformerless single-phase series APF (TISeAPF)

The investigation, development, and dissemination of this kind of power quality conditioner should continue despite the SeAPF's lack of popularity in industrial applications compared to other methods of compensating for power quality issues. This equipment has some interesting characteristics, particularly in its hybrid version when combined with passive filters. A comparison of the primary SeAPF's compensating properties is shown in Table 2.



	SeAPF	Back-to-Back SeAPF	HySeAPF	TISeAPF
Voltage Harmonics Compensation	+ + +	+ + +	+ + +	+ + + +
Voltage Sags Compensation	+ +	+ + +	+ +	+ +
Voltage Swells Compensation	+ +	+ + +	+ +	+ +
Voltage Unbalance Compensation	+ +	+ + +	+ + +	+
Overvoltage Compensation	-	+ + +	-	-
Under voltage Compensation	-	+ + +	-	-
Current Harmonics Compensation	-	-	+ +	-
Estimated Costs	+ +	+ + + +	+ + +	+

Table 2. Comparisons between SeAPF devices for power quality improvement

1.12.10 Unified Power Quality Conditioner

The SeAPF and ShAPF working together on the same dc-link leads to the UPQC. This integration enhances the performance of both APF when they work in concert [62]. The SeAPF was thought of as a voltage-controlled voltage source, providing the compensating voltage (V_F), while the ShAPF was considered a current-controlled voltage source, producing the compensating current (i_F). The primary concept is that the power-factor compensation and dc-link voltage regulation of the load current, i_L, as well as the distorted and unbalanced components of the load current, i_L, are compensated by the ShAPF. The SeAPF, on the other hand, is in charge of making up for the distorted and imbalanced load voltage components. Along with compensating for transient voltage oscillations (voltage sags/swells), the SeAPF also offers active damping[63].Figure16 serves as an illustration of the concept of correcting harmonic components from the load current (i_L) and grid voltage (V_S) using active filters. It is also usual to refer to the SeAPF as the series converter and the ShAPF as the shunt converter when discussing the UPQC topology.

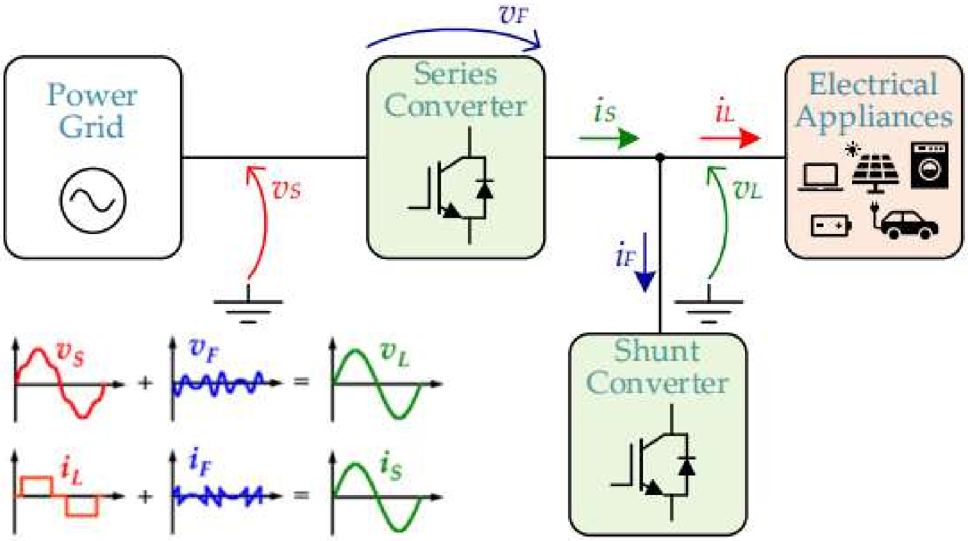


Figure16 Basic principle of both active filters compensating harmonics components.

Figure 17. shows a condensed representation of the UPQC, where the SeAPF is situated before the ShAPF. Control algorithms that take i_{Sx} and V_{Sx} as inputs determine the compensating voltage of the SeAPF, V_{Fx}, for x = a, b, and c. Based on the load current (i_{Lx}) and dc-link voltage (V_{DC}), the compensating current (i_{Fx}) to the ShAPF is computed. It is significant to note that

the fundamental positive-sequence components of V_{Sx} are synchronised with the fundamental components of V_{Fx}, i_{Fx}, and both. The phase-locked loop (PLL) [64], whose output signals are employed in the control algorithms of both converters, can be used to accomplish this.Additionally, both active filters' modulation methods frequently use i_{Fx} andV_{Fx} in their feedback loops.

As they provide galvanic isolation and enable lowering of the dc-link voltage, power transformers that connect SeAPF with the power grid should also be taken into consideration. The fact that ordinary transformers were not made to handle high-frequency voltages and currents must be kept in mind, too. Small passive filters, designated Z_{Sx} and Z_{Px} in Figure 24, are thus employed to reduce the flow of these high-frequency components.

The voltage loss of power transformers is another disadvantage. The load voltage (V_{Lx}), whose amplitude is reduced by the voltage drop on the series transformer, makes this aspect more obvious. To get around it, there are a few options. One of them is having the series-converter controller accept V_{Lx} as an input, with the SeAPF being solely in charge of maintaining V_{Lx} regulation. Since it is similar to adjusting transitory voltage fluctuations, it initially shouldn't be a problem. Nevertheless, this approach has several drawbacks. The series converter is compelled to create a fundamental voltage in phase with i_{Sx} in order to counteract transient voltage oscillations, which causes energy to flow from the series converter to the power grid.As a result, the dc-link voltage drops, forcing the ShAPF to create a necessary component to maintain the dc-link voltage's regulation. The generation of such a current raises i_{Sx}, which in turn raises the voltage drop in the series transformer.

One of the primary UPQC restrictions for mitigating transient voltage oscillations is this circulating power between the series and shunt APF. Consider the ability of both APF to provide reactive power in a coordinated manner for balancing transient voltage oscillations as an alternative to reducing it. Since both APF create the regulated reactive power based on the same variable, namely the amplitude of the load voltage, coordination is required [65].

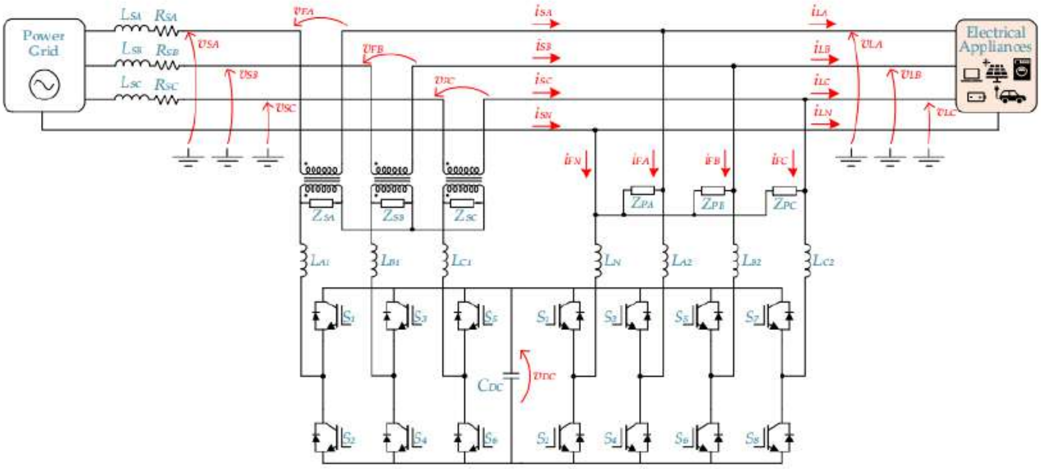
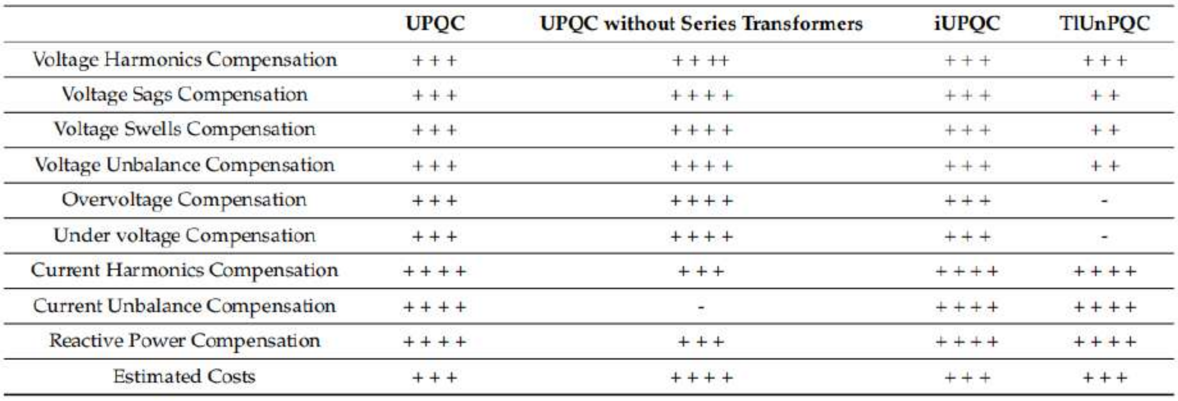


Figure17. Simplified diagram of the UPQC

Other methods exist for getting rid of the series and shunt transformers. One of the suggestions eliminated the series power transformer by using three single-phase UPQCs in a three-phase circuit[66]. The shunt transformers were still connected to the circuit, though. This concept has limitations because imbalanced voltages or currents can be compensated for [67]. A topology linking a single-phase full-bridge series converter to a three-phase shunt converter was proposed in [68] as a solution to this issue. The proposed topology in [68], however, was coupled to a three-phase, four-wire circuit and contained 36 power switches.

Recurring to high frequency isolated bidirectional converters to connect the series and shunt converters' dc-links is another way to get around the low frequency series and shunt power transformers, permitting the energy transfer between both converters that is necessary for UPQC operation [69]. High-frequency transformers can be used to implement the isolated bidirectional converters, which enables for equipment that is smaller, lighter, and less expensive. Since the non-linearity and losses of the low-frequency transformers are eliminated from the system, it is also anticipated that the UPQC will perform better in compensating the power quality issues and have a higher efficiency as its series and shunt converters connect to the power grid without transformers [70].When the circulating power between the series and shunt converters is low and there is little power loss in the isolated bidirectional dc-dc converters, the efficiency enhancement is most apparent[71].

It can be advantageous to use a hybrid UPQC topology [72], composed of a voltage source inverter in the series converter and a current source inverter in the shunt converter, since in the conventional UPQC the series converter is controlled as a controlled voltage source and the shunt converter is controlled as a current source. High-frequency isolated bidirectional current-source to voltage-source converters are utilized to enable the energy transfer between the series and shunt converters.The main benefits of the hybrid UPQC resulted from the simplicity with which the series and shunt power converters could be controlled. This ease of control allowed for open-loop voltage control of the series converter and open-loop current control of the shunt converter, resulting in high bandwidth and an inherently stable architecture that gave the UPQC superior performance compensation characteristics. A significantly modified UPQC known as the transformer-less universal power quality conditioner (TlUnPQC) is provided in[73]. The TlUnPQC lacks a common dc-link and is made up of shunt and series APF, which limits its ability to compensate compared to the UPQC.There are some plans for the UPQC to be used in MV levels instead of distribution power grids based on LV levels, with multilevel converters taking the place of the traditional three-phase full-bridge converter. The internal dc-link voltages of both multilevel converters may be easily managed considering their redundancy states to create the controllable voltages and currents because the UPQC is built on a back-to-back architecture [74]. A comparison of the primary SeAPF's compensating properties is shown in Table 3.



	UPQC	UPQC without Series Transformers	iUPQC	TIUnPQC
Voltage Harmonics Compensation	+ + +	+ + ++	+ + +	+ + +
Voltage Sags Compensation	+ + +	+ + + +	+ + +	+ +
Voltage Swells Compensation	+ + +	+ + + +	+ + +	+ +
Voltage Unbalance Compensation	+ + +	+ + + +	+ + +	+ +
Overvoltage Compensation	+ + +	+ + + +	+ + +	-
Under voltage Compensation	+ + +	+ + + +	+ + +	-
Current Harmonics Compensation	+ + + +	+ + +	+ + + +	+ + + +
Current Unbalance Compensation	+ + + +	-	+ + + +	+ + + +
Reactive Power Compensation	+ + + +	+ + +	+ + + +	+ + + +
Estimated Costs	+ + +	+ + + +	+ + +	+ + +

Table 3. Comparison between UPQC devices for power quality improvement

1.13 Uninterruptible Power Supply

A UPS is a piece of power electronics-based hardware whose purpose is to guarantee a constant power supply to a particular load or group of loads. A UPS is a piece of equipment that can make up for power outages. There are several types of UPS depending on how they link to the power grid and the loads. Some UPS systems can also make up for power quality issues such voltage sags, voltage swells, overvoltages, undervoltages, flicker, harmonic voltages, and, in the case of three-phase systems, insufficient power.

Unbalanced voltages and power grids [75]. Some UPSs, depending on their nature, can also make up for the same power quality issues as a ShAPF, a SeAPF, or a UPQC can [76].

UPSs fall into one of three categories according on their physical make-up: static, rotary, or hybrid. Rotary (or dynamic) UPS are based on rotating elements, such as electrical machines and/or flywheels, as opposed to static UPS, which are based on power electronics converters. Hybrid UPS naturally include components from both static and rotating versions[77]. Only static UPS are discussed in this review, though, as the focus of the research is power electronics. ESS, which are primarily battery-based, are essential regardless of the physical makeup of the UPS type.

The way that UPSs are connected to the power grid and to the loads can also be used to classify them. The protection level and features that a specific UPS is capable of are tied to this classification [77]. UPS can be categorised as offline, line-interactive, or online in this manner [78]. Following that, a detailed description of each of these types' features and the amount of security afforded to the loads is provided.

1.13.1 Offline Uninterruptible Power Supply

The simplest UPS type is an offline UPS, often known as a passive standby UPS or a line-preferred UPS. In this method, the loads and UPS are connected in parallel to the power grid, meaning that the loads are fed directly from the power grid, thus the term "line-preferred." The IEC 62040-3 standard's definition of the offline UPS as "voltage and frequency dependent" means that it does not provide voltage conditioning to the loads. A static switch is installed upstream of the UPS so that, in backup mode, in the event of a power failure, the loads can be removed from the upstream power grid and powered solely by the UPS.

As shown in Figure 18, an offline UPS normally consists of two power converters: an ac-dc converter for charging the batteries from the power grid and a dc-ac converter for supplying the loads. The batteries are connected to the same dc-link that is shared by both converters. The ac-dc converter only works in regular mode in this construction, but the dc-ac converter only works in backup mode. As an alternative, an offline UPS can be made up of two bidirectional converters: an ac-dc converter that connects to the power grid via a dc-link and a dc-dc converter that connects to the batteries via the same dc-link.The ac-dc converter powers the dc-link in normal mode so that the dc-dc converter can regulate the battery charge. In backup mode, the ac-dc converter functions as a dc-ac converter to power the loads by discharging the batteries and powering the dc-link.

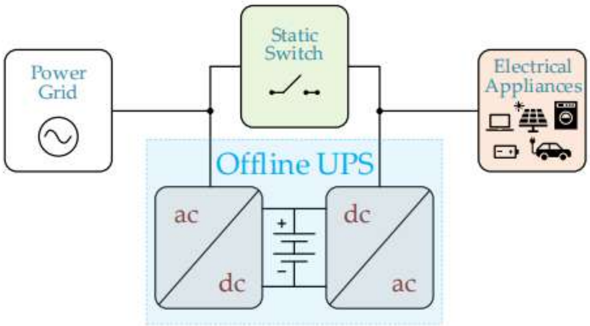


Figure 18. Basic structure of an offline UPS

An offline UPS has the drawback of not enabling a smooth transition from regular mode to backup mode, regardless of its topology. This is mostly because of the time it takes to detect a power failure and the mechanical transfer switch's inertia.

The literature lacks a sufficient amount of recent research on offline UPS. In [80] an offline UPS with zero transfer time employing integrated magnetics, for example, It was suggested to connect the electrical grid, the UPS output, and the loads using a three-port transformer. Additionally to the null transfer time, this idea offers short-circuit safety.

[81] makes a suggestion for an offline UPS based on a bidirectional cycloconverter with a high-frequency transformer. While in backup mode, the cycloconverter is used to control the voltage supplied to the loads, standard mode controls the cycloconverter to charge the batteries, i.e., with power flowing from the power grid to the batteries. Using only five completely regulated power semiconductors, including the inverter and battery charger, and their corresponding antiparallel diodes, [82] proposes an offline UPS.

According to [83], an offline UPS based on a high-frequency transformer and a bidirectional dc-dc converter is proposed. In this converter, one side of the converter is made up of a full-bridge topology and the other side is made up of a half-bridge topology.

1.13.2 Line-Interactive Uninterruptible Power Supply

Some traits of offline and online UPS are combined in the line-interactive UPS. The IEC 62040-3 standard classifies this sort of UPS as "voltage independent" since it may offer voltage management to the loads during normal power grid operation[79]. Similar to the offline UPS, the line-interactive UPS has a static switch upstream that can be used to disconnect the loads from the upstream power grid and instead provide them with power from the UPS in backup mode.With the exception of an additional inductor connected in series between the upstream power grid and the point of common coupling for the UPS and the loads [84], one common type of line-interactive UPS was presented in 1994. This type is depicted in Figure 19. The ac-dc converter produces or consumes reactive power to provide voltage regulation to the loads depending on whether there is an under-voltage or an over-voltage, with the inductor withstanding the voltage difference between the power grid and the loads.

Additionally, the power grid can be used to supply active power to charge the batteries. The bidirectional ac-dc converter acts as a dc-ac converter in backup mode, using the energy stored in the batteries to supply the loads with sinusoidal voltage. The static switch is opened to disconnect the UPS and the loads from the upstream power grid.

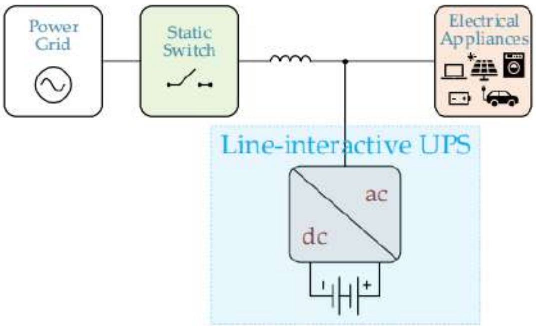


Figure 19. Basic structure of the line-interactive UPS with series inductor.

The delta conversion line-interactive UPS is a type of line-interactive UPS that may correct voltage and current power quality issues (Figure 20). Two bidirectional ac-dc power converters make up the power grid interface of this form of UPS, which was proposed in 1996 [85]. The main converter, also known as one of the converters, is linked to the power grid in parallel, while the delta converter, also known as the other converter, is connected to the power grid in series (often using low-frequency transformers). Both converters share the same dc-link. This type of UPS is also known as a series-parallel line-interactive UPS because of its structure.

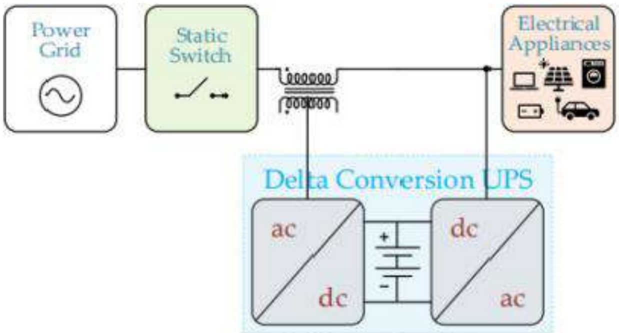


Figure 20. Basic structure of the delta conversion line-interactive UPS

As can be seen, its structure is very similar to that of a UPQC, and in addition to its primary function of compensating power outages, this UPS is capable of compensating power quality issues in terms of voltage (sags, swells, undervoltages, overvoltages, notches, harmonics) and in terms of current (power factor, harmonics, unbalances). Additionally, the series (or delta) converter, which is normally rated for 20% of the UPS output power, does not have to be rated for the same power as the parallel (or main) converter.In this UPS, the series converter ensures a sinusoidal power grid current while the parallel converter regulates the voltage supplied to the loads. The parallel converter also regulates battery charging and provides or absorbs the voltage difference between the power grid and the loads in the event of undervoltage or overvoltage, respectively.

Since the parallel converter continuously regulates the voltage of the loads, another benefit of this UPS is that it enables a smooth transition from normal to backup mode. Since the whole load power does not pass through both power converters, the delta conversion line-interactive UPS exhibits characteristics comparable to those of an online UPS without experiencing the same lack of efficiency. Although this sort of UPS is designated as "voltage independent" by the IEC 62040-3 standard[79], it is not able to regulate frequency, as is the case with any line-interactive UPS, because the loads are not entirely cut off from the power grid.

[86] makes a proposal for a single-phase delta conversion UPS based on push-pull converters, with galvanic isolation achieved in both the series and parallel converters. This allows for the use of a low voltage battery while also lowering the cost of the overall system. A single-phase line-interactive UPS is presented in [87] that has a similar design to an offline UPS, i.e., one that includes a rectifier, battery charger, and bidirectional dc-dc and dc-ac converters for connecting the power grid and loads. Despite the authors' definition of the proposed UPS as offline, it can regulate voltage, giving it the functionality of a line-interactive UPS.

Using a bidirectional isolated three-port dc-dc converter to interface fuel cells and ultracapacitors with the dc-link of the grid interfacing dc-ac converter, a single-phase line-interactive UPS whose main ESS is based on fuel cells is presented in[89]. [88] presents the application of a line-interactive UPS for three-phase microgrids that can operate in both grid-connected and islanded modes. [90] presents a three-phase four-leg ac-dc converter-based delta conversion UPS for three-phase four-wire systems.

Regarding transformerless topologies, [91] presents a single-phase line-interactive UPS that uses a bidirectional switch operating at line frequency to reduce the ground leakage current, and [92] proposes a single-phase delta conversion UPS that does not use transformers or a dedicated dc-dc converter to charge the batteries.

1.13.3 Online Uninterruptible Power Supply

The UPS type that provides the maximum level of load protection is the online UPS. Since this type is connected in series between the power grid and the loads, it is also known as a double-conversion UPS or an inverter-preferred UPS. As a result, the UPS constantly supply the loads whether the operation is in backup or normal mode. Since the load voltages are already being produced by the UPS, there is no change or transition when a power outage occurs, which is an advantage in that it enables a smooth transition from normal mode to backup mode. Additionally, because it has the ability to control the amplitude, frequency, and phase angle of the generated voltage, the online UPS offers voltage conditioning to the loads.The IEC 62040-3 standard thus identifies online UPSs as "voltage and frequency independent"[79].

As shown in Figure 21, an online UPS is made up of at least two power converters: an ac-dc converter to connect to the upstream power grid and a dc-ac converter to connect to the downstream loads. The batteries are connected to the same dc-link that is shared by both converters. To regulate battery charging or discharging instead, a bidirectional dc-dc converter can be inserted between the dc-link and the batteries.Additionally, there is a static switch that is only used for UPS maintenance and is typically open in both normal and backup modes. The ac-dc and dc-ac converters operate continuously, whether the operation mode is regular or backup, and both need to manage the full operational power in each case, thus despite its practical advantages, the online UPS has poorer efficiency than the aforementioned types.In [93], a bridgeless boost PFC converter, a non-conventional bidirectional dc-dc converter employing a linked inductor, and a full-bridge dc-ac converter are presented for a single-phase transformerless online UPS using a low voltage battery (24 V). A system based on fuel cells is provided in [94] for online UPS employing alternative ESS, and a system based on a battery and ultracapacitor combination is published in [95]. A proposal for an online UPS with a PV solar module equipped with a maximum power point tracking converter (a boost dc-dc converter), coupled to the dc-link of the ac-dc and dc-ac converters that make up the UPS, was made in [96]. This is another application for RES outside of ESS.

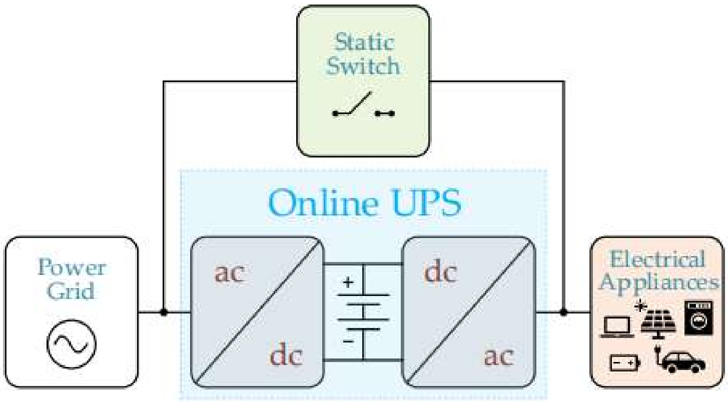
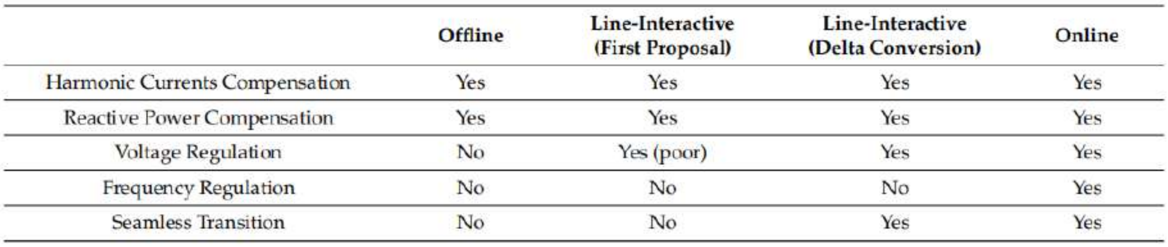


Figure 21. Basic structure of an online UPS

[97] proposes an online UPS that can supply emergency power to both voltage-frequency independent loads and voltage-frequency dependent loads. Using a three-phase four-leg dc-ac converter, [98] presents an online UPS for three-phase four-wire systems. In [99], a cascaded structure of boost dc-dc converters that interface the dc-link of a full-bridge dc-ac converter for single-phase systems and can produce seven voltage levels is presented. However, two step-down grid-frequency transformers are required to supply the inputs of the boost dc-dc converters.

It is suggested in [100] to use an NPC topology for the front-end ac-dc and back-end dc-ac converters, with the batteries connected in the dc-link of both converters, to create an online UPS for three-phase four-wire systems. A similar arrangement is suggested in [101], but with an extra dc-dc converter—a bidirectional three-level buck-boost dc-dc converter—to connect the batteries with the dc-link.[102] presents a family of three-phase online UPSs with galvanic isolation achieved using high-frequency transformers, and various studies have looked at the parallel operation of dc-ac converters in online UPSs.

publications like [103], [104], and [105], which propose a regeneration protection method due to unequal power distribution among parallel-connected online UPSs and a dc-link protection scheme for parallel-connected online UPSs, respectively. The features of each UPS type mentioned in this section are summarised in Table 4.



	Offline	**Line-Interactive (First Proposal)**	**Line-Interactive (Delta Conversion)**	**Online**
Harmonic Currents Compensation	Yes	Yes	Yes	Yes
Reactive Power Compensation	Yes	Yes	Yes	Yes
Voltage Regulation	No	Yes (poor)	Yes	Yes
Frequency Regulation	No	No	No	Yes
Seamless Transition	No	No	Yes	Yes

Table 4. Comparison between the different types of UPSs

Chapter 2

2.1 Recent Advancements in FACTS Devices

It is accurate to say that, in recent years, the security of transport networks has grown to be one of the biggest issues facing society and the economy going forward. Operators are progressively striving to optimize their infrastructure and architectural equipment, as well as to improve the management of energy transfers, real-time monitoring, and control [106-109]. This is due to the competitive element associated with deregulation and the difficulties of creating new structures.

One approach to achieving these objectives is the employment of FACTS devices built on power electronics. FACTS devices can contribute to safer and more efficient electrical network operation.FACTS devices can enhance the stability and dependability of power systems, resulting in fewer disruptions and incidents, by managing voltage and power flow.

Additionally, a distinct separation of duties between various entities will be necessary for the liberalization of transport networks. As they provide more precise control over power flows and can help to minimize overloading or other issues that could come from competing demands, FACTS devices can help to guarantee that this division is specified and enforced [110-113].

Overall, the employment of FACTS devices is a significant advancement in assuring the security and effectiveness of transport networks, and they are expected to become more and more significant over time.

While it is true that FACTS devices are most frequently utilized in the gearbox system, D-FACTS devices can also be used in the distribution system. The type, location, and size of FACTS devices affect how well they operate, thus it's critical to identify the best way to combine these elements to obtain the needed performance improvements [114].

The FACTS allocation problem entails determining the best FACTS device type, placement, and size for electrical power systems. This is a challenging optimization problem that necessitates a thorough examination of the power system as well as the potential advantages and disadvantages of various FACTS configurations.

FACTS devices have been essential to the growth of the integration of power electronics into the electrical network over the past few years. FACTS devices have the benefits of stabilizing voltage, suppressing oscillations in the electrical system, and improving power transfer capabilities by managing the flow of active and reactive power. These advantages may result in increased power systems' dependability, stability, and efficiency, all of which are necessary to fulfil the rising demand for electricity in a sustainable and economical way.

Overall, the most effective FACTS device deployment can assist in addressing many of the issues that contemporary power systems must deal with, such as the requirement for higher capacity, improved dependability, and improved stability.

The following are the main sources of innovation and inspiration for this survey study:

The factors or constraints that should be regarded as the optimum execution in terms of the solution's precision, speed of convergence, and efficacy, with the highest success rate, while supporting the FACTS device optimization problem, are investigated.

In order to address the FACTS device optimization issue, a summary of numerous enhancement strategies that have been widely applied is provided in this study. These strategies include traditional optimization techniques, meta-heuristic methods, sensitive index methods, and hybrid methods.

This also outlines the advantages and disadvantages of various innovation techniques that have been applied to resolve FACTS device optimization problems.

The methodologies used, the test systems used, the types of FACTS devices investigated, and the beneficial objectives of each amended document are listed in tables. The strengths and weaknesses of the many enhancement techniques that have been applied to address FACTS device optimization difficulties are discussed near the end of the paper.

Since they provide a number of advantages, such as an enhanced voltage profile, lower power losses, increased system dependability, and increased safety, flexible AC transmission system (FACTS) devices have grown in popularity in recent years. However, because it has mixed integer, nonlinear, and non convex restrictions, deciding on the best kind, position, and size of FACTS devices can be a difficult optimization task.

Researchers have created a number of optimization strategies for the use of FACTS devices in electrical power systems in order to overcome this issue. The following are a few recent examples of innovative optimization techniques:

Multi-objective optimization: This method takes into account several competing goals at once, like reducing power losses and enhancing voltage stability. Decision-makers can select the best option from a variety of optimal solutions that represent a trade-off between the various objectives thanks to multi-objective optimization.

Robust optimization: This method takes the optimization problem's uncertainties into account, such as shifting load demand or the production of renewable energy. Robust optimisation can deliver solutions that are less susceptible to modifications in the system parameters by incorporating uncertainty into the optimisation model.

Machine learning-based optimisation: Using machine learning algorithms, this technique predicts the ideal configuration of FACTS devices based on the state of the system right now. Fast and precise solutions can be obtained via machine learning-based optimisation, particularly in large-scale systems.

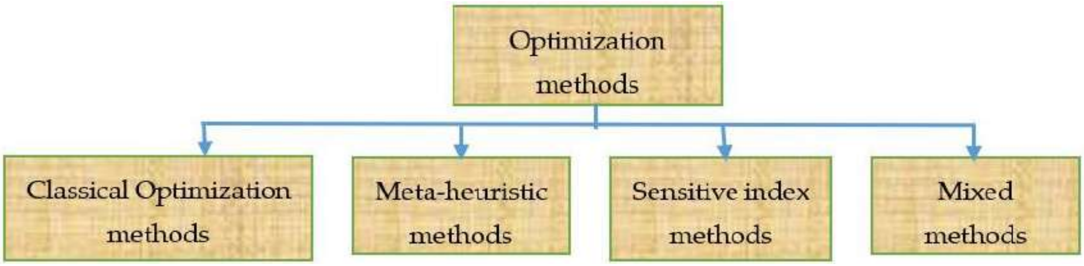
Hybrid optimisation: To increase the quality of the solution and the rate of convergence, this strategy integrates various optimisation techniques, such as gradient-based methods and metaheuristic algorithms. In order to overcome the shortcomings of several strategies, hybrid optimisation might combine their strengths.

By offering more precise and effective solutions, these cutting-edge optimisation techniques have the potential to greatly enhance the performance of FACTS devices in electrical power systems. However, more study is required to assess how well these methods work in real-world settings and to create fresh methods that can manage the complexity of the optimisation problem.

These days, power electronics-based FACTS devices enable tighter continuous control of power flows with the following advantages: maintaining a voltage that is within acceptable ranges at load buses, controlling the flow of active and reactive electrical power in thermally constrained lines, improving safety measures, and operating electrical systems close to their capacity limits, among other improvements. For all of these reasons, it is essential to create solutions, including the usage of FACTS controllers, that allow us to successfully manage electrical networks. In order to address this FACTS device optimisation challenge, numerous strategies based on evolutionary algorithms (EA), swarm intelligence (SI), sensitivity index, and their combinations have been used.

The four major categories of FACTS optimization problem-solving strategies—classical optimization techniques, meta heuristic methods, sensitive index methods, and mixed techniques—are depicted in Figure 22 and are often utilized in the literature.

Figure 22. Classification of FACTS optimization problem-solving techniques.



Traditional optimisation techniques for system problems are based on mathematical equations and are typically iterative. These techniques include linear programming (LP), nonlinear programming (NLP), integer programming (IP), mixed integer linear programming (MILP), mixed integer nonlinear programming (MINLP), mixed discrete continuous programming (MDCP), dynamic programming (DP), and sequential quadratic programming.

The ideal location, kind, and size for FACTS units are now determined using metaheuristic optimisation approaches. Compared to conventional methods, these strategies make it simpler to find the best solutions to problems. Four categories can be used to classify this group [115]: (i) evolutionary algorithms such as genetic algorithms (GA) [116], evolution strategy (ES) [117], evolutionary programming (EP) [118], genetic programming (GP) [119]; (ii) physics-based algorithms such as the ant lion optimization (ALO) technique [120], bio geography-based optimizer (BBO) [121], curved space optimization (CuSO) [122], flower pollination algorithm (FPA) [123], galaxy-based search algorithm (GBSA) [124], gravitational search algorithm (GSA) [125], harmony search algorithm (HAS) [126], multiverse optimization (MVO) algorithm[127], simulated annealing (SA) [128], atom search optimization (ASO) algorithm [129]; (iii) swarm-based algorithms such as particle swarm optimization (PSO) [130], whale optimization algorithm (WOA) [131], artificial bee colony (ABC) [132], chemical reaction optimization (CRO) algorithm [133], crow search algorithm (CSA) [134], cat swarm optimization (CaSO) algorithm [135], cuckoo search (CS) [136], dragonfly algorithm (DA) [137], bats algorithm (BA)[138], firefly algo- rithm (FFA) [139], grasshopper optimization algorithm (GOA) [140], gray wolf optimizer (GWO) [141], honey-bee mating optimization (HBMO) [142], moth–flame optimization (MFO) algorithm [143], bacterial swarm optimization (BSO) [144], immune algorithm (IA) [145], symbiotic organism search (SOS) algorithm [146], etc.; and (iv) other population-based algorithms such as the black hole (BH) algorithm[147], parallel seeker optimization algorithm (PSOA)[148], imperialistic competitive algorithm (ICA) [149], sine cosine algorithm (SCA) [150], teaching–learning-based optimization (TLBO) algorithm[151], water cycle algorithm (WCA) [152], bacterial foraging algorithm (BFA) [153], coyote optimization algorithm (COA) [154], and the tabu search (TS) algorithm [155-156].

2.2 FACTS Devices

2.2.1 Classification of FACTS Devices

Three categories of FACTS systems are listed [157-158]. The first class is composed of traditional thyristor-controlled control systems (bank of capacitors or inductors, phase-shifting transformer, transformer with load-adjustable tap). The static converters used by the other two classes are powered semiconductors that the GTO can regulate. The alternating current dimmer or reactance controlled by a thyristor valve, such as SVC and TCSC, and the voltage source converters, which can supply an alternating voltage with adjustable amplitude, frequency, and phase, such as series compensation SSSC, shunt compensation STATCOM, hybrid compensation (series-parallel) UPFC, and (series-series) IPFC, are examples of how they differ structurally. OUPFC, a different hybrid FACTS device configuration combining UPFC and the phase-shifting transformer (PST), was created in ref. [159] addressing the optimal power flow (OPF) issue. The minimising of fuel expenditures and overall system losses was taken into account in this setup.The general algebraic modelling system (GAMS) and MATLAB were used to solve this problem, with the locations, settings, and number of OUPFCs serving as the decision variables. A generalised UPFC (GUPFC), also known as a multi-line UPFC, was proposed by Kavuturu et al.[160] to regulate the bus voltage and power flows of numerous lines in a power grid. Power utilities face a variety of issues in a competitive environment, and the GUPFC's powerful control capacity with bus voltage and multi-line power control offers considerable potential to address many of these issues. Actually, the incorporation of these devices increased voltage stability, reactive power loss, reactive power generation, and reactive power flow in lines.To boost gearbox capacity, stability, and efficiency in power systems, FACTS (flexible AC gearbox system) devices are used.

2.3 Utility of FACTS Devices for Power System Enhancement

The main fundamental rules [157] for the proper operation of the electrical network include permanently ensuring equality between production and consumption to maintain the frequency at a constant value, respecting the admissible limits of the lines, the stability limit for the power, the thermal limit for heating the conductors, and keeping the voltages of all nodes within acceptable limits.

2.3.1 line Power flow regulation

A line's main purpose is to carry active power. Reactive power must be relatively small in relation to active power if it is being transferred. These requirements must be verified via the transmission line[158]: Regardless of the load, the voltage should remain relatively constant down the length of the line. Low losses are necessary for the line to function well. The conductors shouldn't get too hot from joule losses. These requirements must all be met by extra equipment if the gearbox line does not meet these criteria.

2.3.2 Voltage drop regulation

For power systems to operate effectively and reliably, voltage must be kept at a reasonable level and voltage loss must be minimized. Reactive power can be produced locally instead of being transported, which is one approach to accomplish this. Reactive power compensation is another application for FACTS devices, as was previously indicated.

They can also increase power transfer efficiency and voltage stability, among other advantages, and can offer quick and precise control of reactive power compensation [158].

Overall, by minimizing voltage drop and transmission losses, the use of compensation devices for reactive power compensation can help to increase the efficiency and reliability of power systems. These devices can also aid in reducing the requirement for the pricey and ineffective long-distance transfer of reactive power by producing reactive power at the site of consumption.

2.3.3 FACTS compensation for shunt devices

Shunt compensation is used to use or generate reactive power at the connecting point. The shunt compensators allow for the maintenance of the node tensions in the steady state. They enhance transient stability and reduce power oscillations under dynamic situations [161]. The voltage at the midpoints of a lengthy transmission line must first be adjusted by installing shunt compensators before the power delivered via the line may be increased. The centre of the gearbox line is the optimal location for the shunt compensating device [157,162].

2.3.4 FACTS series device compensation

The network connects these compensators in sequence. These devices typically work by adding a variable voltage source, such as an inductive or capacitive variable impedance source, to alter the transmission line impedance [163].

2.4 Power Transfer Capability Improvement

The system can operate extremely close to its temperature and stability limits thanks to the installation of the best FACTS devices in the transmission network. Because the power flow across the lines depends on the voltages at the transmitting and receiving ends, the AC power system provides built-in power stability. In the case of a lossless line with sending end voltage V_k and receiving end voltage V_m, δ_k and δ_m are the sending and receiving end's respective phase angles, and X is the line's reactance. The employment of each FACTS controller type will follow clearly specified control objectives. The potential actions for regulating the transited active power in a transmission line are shown in Figure 23 below.

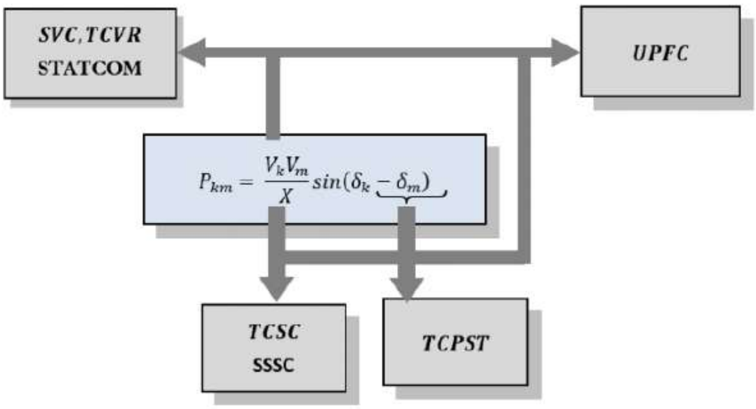


Figure 23. Adjustment of the power transmitted for the different FACTS.

2.5 Static Var Compensator

SVC, or static var compensator, is a device used in railway power supplies to provide compensation. Fig. 24 illustrates the SVC's common structure. A thyristor linked in series or parallel with a capacitor or an inductor makes up the device.

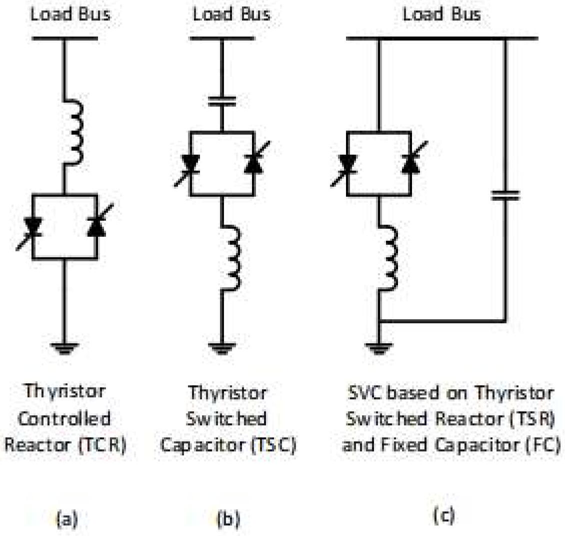


Fig. 24: Typical circuit structure of Static VAR compensator (SVC).

SVC has historically been applied to offer traction power adjustment. For instance, a commuting SVC with a system capacity of 48 MVA was suggested for the 77kV line in the Japanese Tokaido Shinkansen railway in [164], which was published in 1995. Additionally, it was stated to be the original SVC utilised for railway power delivery. The use of SVC to increase the power factor of the traction train supply was investigated in 2009 [165].

Additionally, simulations based on measured data from the Beijing-Shanghai electrified railway's two 110/27.5 kV V/V transformers, having a combined capacity of 31.5+25 MVA, were carried out. The SVC parameters are quite sensitive and can affect its performance, according to this study's findings. The use of SVC for traction power in Indian railways was investigated in 2014 [166].

The outcomes of the research listed above demonstrate that SVC can successfully assist in managing the load voltage. Due to incomplete reactive power correction, the power factor improvement is not perfect. The restricted flexibility of the reactive power produced by SVC is to blame for this. Additionally, SVC cannot compensate for system imbalance and harmonics on its own. SVC is frequently used in conjunction with a passive harmonic filter, although it is also capable of injecting harmonics into the system on occasion.

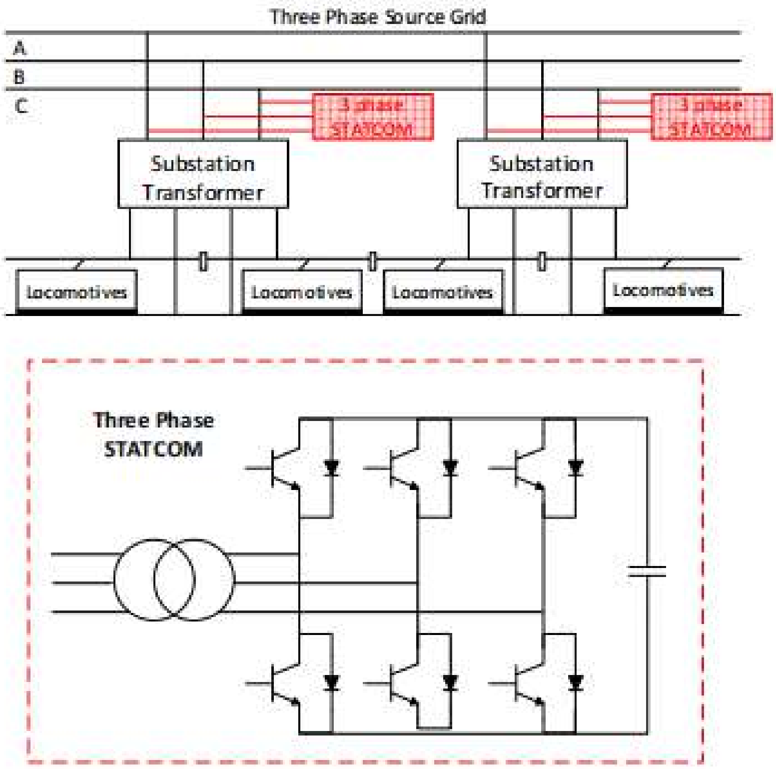


Fig. 25: Illustrative idea of the circuit schematics of 3 phase STATCOM for compensation in railway traction power supply.

2.6 Static Synchronous Compensator

The abbreviation STATCOM stands for static synchronous compensator. STATCOM is often a three phase voltage source converter in railway traction power supplies, as depicted in Fig. 25.

Traction loads are typically single-phase loads, and a substation transformer converts the three-source grid into two single-phase outputs. These imbalanced locomotive loads subsequently cause the source grid to produce unbalanced current. Phase shift between the primary and secondary sides of a substation transformer is possible. Therefore, active and reactive power transfer across the three source phases is necessary to address the system unbalance issue.

The three phase source grid is connected to STATCOM to offer compensation.[167] suggested and studied a three phase STATCOM with a system capacity of 60 MVA for a high speed railway at 225kV in Tangier-Kenitra, Morocco. Although STATCOM has the capacity to give reactive power compensation as well, the study's research was primarily focused on imbalance compensation.

The control complexity of three phase STATCOM is considerable because three phase balancing, reactive power, and harmonic compensation are required simultaneously. Consequently, although having greater dynamic compensation performance, it is still not frequently used in railway traction power.

2.7 TRENDS IN OPERATION OF FACTS DEVICES

2.7.1 Operation Voltage Reduction using Different Coupling Structure

The operation voltage of STATCOM and RPC is high, as mentioned in the preceding section, which causes high operation voltage and loss. Since the majority of locomotive loads are inductive, STATCOM and RPC are connected to a system with an inductive coupling structure, which increases the voltage drop across the coupled structure and necessitates a high DC link voltage.

The use of a capacitive coupled structure, such as a series LC branch, can lower the DC link operation voltage during inductive reactive power compensation, as is well known in the field of power converter research. Additionally, the operation voltage need for harmonics compensation may be reduced by using a series LC branch with a certain parameter design.

2.7.2 Various Converter Structure to Reduce Operation Loss

Various converter structures have also been suggested in addition to variations in coupled impedance to enhance compensatory performance or lessen operating loss. Here, a few of them are introduced.

By suggesting an RPC based on a half bridge converter in [168], the total number of components was cut in half in order to reduce operating loss. A 60 kV, 5.5 MVA two phase, three wire converter was also suggested in [169] in order to reduce the number of components compared to RPC by one branch. The results demonstrate that harmonics and system unbalance in traction power systems can both be corrected. However, the control is more intricate than RPC, which could increase the computation's error.

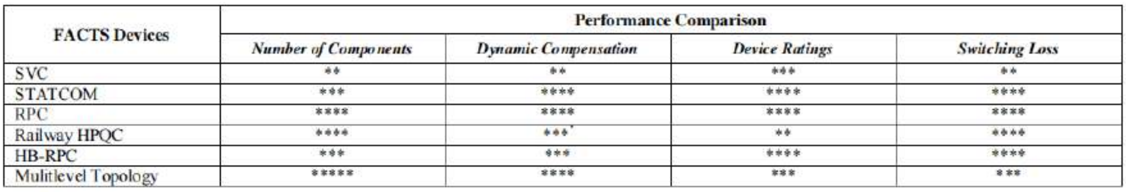
2.8 Combination of different FACTS technologies

Passive components are less expensive than active components. As a result, the cost of installation is decreased by combining different technologies.

For railway power compensation at 25 kV, a hybrid construction that combines active power filters and passive damping filters was developed in 2004 [170]. The combination now includes modern technology. For instance, a combination of RPC and magnetic static var compensator (MSVC) is suggested in [171] and [172], which were published in 2016. While the MSVC is in charge of reactive power compensation and harmonic suppression at a specific frequency, the RPC is primarily used in the structure to handle active power transfer and harmonic compensation**.**The construction helps to lower the device rating and RPC's DC operation voltage. Through the use of simulation at 220/27.5 kV at 20 MVA and experimental data at 220/220 V at 5 kVA, its efficacy and validity were confirmed. Due to the addition of MSVC, there are now more components, which could result in greater installation costs.

2.8.1 Modular Multilevel Converters for Lowering Switching Frequency and Increasing Efficiency

High switching loss caused by high switching frequency is another issue with FACTS devices in train power supplies. Then, to address this issue, there is a topology known as the modular multilevel converter (MMC). In recent years, there has been a clear research trend towards the use of multi-level technology for railway power compensators.



FACTS Devices	Performance Comparison			
	Number of Components	*Dynamic Compensation*	*Device Ratings*	*Switching Loss*
SVC	**	**	***	**
STATCOM	***	****	****	****
RPC	****	****	****	****
Railway HPQC	****	***	**	****
HB-RPC	***	***	****	****
Mulitlevel Topology	*****	****	***	***

TABLE 4. COMPARISONS OF DIFFERENT RAILWAY FACTS DEVICES

Along with the benefit of a lower switching frequency, a multi-layer design allows for a reduction in device ratings for each component. The following are recent two-year publications on relevant topics. In [173], comparisons of various multilevel converter topologies were displayed. The comparison takes into account the quantity of components and power loss in order to serve as a guide for choosing a multi-level structure for railway applications. A delta-connected modular multilevel converter-based RPC is suggested in [174]. By balancing the three phase harmonic reference current, the multilayer structure can reduce device ratings. The half bridge converter topology is sometimes applied in studies involving multilevel technology, as in [175]. Additionally, experimental RPC MMC findings are shown in [176]. In [177], the modelling and control of MMC-based RPC are also covered in detail. [178] also includes more comparisons between the MMC structure and the two level ones for railway converters. The minimal rating need of the device is almost the same under symmetric conditions, which is a significant discovery of the work. However, in a symmetrically unbalanced environment like a railway, the minimum rating required might rise to three times the square root. You can also find additional pertinent research in [179] and [180].

2.9 FUTURE OUTLOOK

The IEEE, the World Bank, and other organizations have published numerous assessments indicating that there would be an increase in both the need for and production of energy in the future. It is anticipated that traditional diesel and gasoline-powered vehicles will eventually be replaced by electric vehicles (EVs). Numerous studies are being conducted right now to improve the interface between EV batteries and the power grid in order to facilitate fast battery charging and the use of batteries as energy sources during times of high demand. The future is predicted to see a growth in this trend. Rooftop solar panel utilization is a different concept that is already gaining popularity; a sharp increase in its use is anticipated in the future.The production of renewable energy is anticipated to increase significantly in the upcoming decades, and numerous projections have been produced to reduce global warming through zero carbon emission. In this way, a paradigm shift in the connection of dispersed energy resources and the usage of renewable energy is being foreshadowed.

Because of their enhanced efficacy, versatility, and ability to act quickly on a variety of issues, non-dominated sorting multi-objective optimization approaches and hybrid techniques are predicted to become increasingly prevalent in the future of optimization techniques. Because of their versatility in automatically and selectively managing a number of power system characteristics, more generic FACTS devices like UPFC and other versions are anticipated to see an increase in use in the future decades.[181] estimates that in 2020, renewable energy sectors will contribute close to 27.8% of the world's energy. The predicted growth rates are as follows: 30.2% in 2025; 32.8% in 2030; 35.4% in 2035; and 37.1% in 2040. Around 3,398 TWh of energy will be consumed in Europe, 10,410 TWh in Asia, 709 TWh in Africa, and 22,536 TWh worldwide in 2020. It is anticipated that in 2025, it will reach 3,528 TWh in Europe, 12,488 TWh in Asia, 867 TWh in Africa, and 25,307 TWh worldwide.

The predicted increase in electricity consumption to 3,648 kWh in 2030 28,513 TWh worldwide, 14,826 TWh in Asia, 1,095 TWh in Africa, and TWh in Europe. Until it reaches 3,793 TWh in Europe, 17,120 TWh in Asia, 1,392 TWh in Africa, and 31,907 TWh globally in 2035, the trend will continue to rise. The total amount of power needed by 2040 will be 35,407 TWh, with 3,985 TWh needed in Europe, 19,254 TWh in Asia, 1,789 TWh needed in Africa, and 1,789 TWh needed elsewhere in the world [181]. By 2050, the world's population is predicted to reach 9.7 billion people, and there will be an estimated 48,800 TWh of electricity demand, according to projections made by [182].

The usage of solar PV and battery storage is anticipated to increase dramatically in the majority of the major power-consuming sectors as they are more likely to become more affordable in the future. In 2050, it is predicted that solar PVs would make up more than two thirds of all energy used, wind energy will account for approximately a fifth of the total energy, and hydropower and bioenergy will make up around 10% of the entire energy [182]. Solar PVs are anticipated to become extremely competitive after 2030 and increase in generation from 37% in 2030 to roughly 69% in 2050 [182]. Total losses in the 100% renewable electricity system are anticipated to decrease by half as compared to the current electrical systems with large energy input losses.

Chapter 3

Vehicle-to-Grid (V2G) Operations of Electric Vehicles

Electric vehicles (EVs) have undergone a remarkable transformation over the past decade, evolving from niche products into mainstream transportation options. The push for cleaner and more sustainable mobility solutions, coupled with advancements in battery technology and charging infrastructure, has accelerated the adoption of EVs worldwide. However, the potential of these vehicles extends beyond emissions reduction and improved energy efficiency. One of the most promising innovations in the realm of electric mobility is Vehicle-to-Grid (V2G) technology.

V2G represents a paradigm shift in how we perceive and utilize electric vehicles. It transforms these mobile assets into dynamic, bidirectional energy resources, capable of not only drawing electricity from the grid but also feeding excess energy back into it. This groundbreaking concept holds the key to addressing critical challenges in the energy sector, from grid stability and renewable energy integration to demand response and emergency backup power. As we delve into this extensive topic, this comprehensive 3000-word introduction aims to provide a thorough understanding of V2G operations, exploring its principles, benefits, challenges, and the evolving landscape of V2G technology.

3.1 Backdrop of the Study

3.1.1. Electric Vehicles (EVs) in Transition

The electrification of the transportation sector has been on the horizon for several decades, driven by concerns about climate change, air quality, and energy security. As gasoline-powered vehicles continue to contribute to greenhouse gas emissions and dependence on fossil fuels, EVs emerged as a compelling alternative. Innovations in battery technology have allowed for longer driving ranges, faster charging, and more affordable EVs, fostering widespread consumer acceptance[183].

3.1.2. The Evolution of EV Batteries

Central to the rise of EVs are their lithium-ion batteries. These energy storage devices have become increasingly efficient, lightweight, and cost-effective, enabling EVs to compete with their internal combustion engine counterparts. Advances in battery chemistry and manufacturing have spurred the development of EV models with extended ranges, making them suitable for various applications, from daily commuting to long-distance travel.

3.1.3. Charging Infrastructure Expansion

To support the growing EV market, an extensive network of charging infrastructure has been established worldwide. This infrastructure includes Level 1 and Level 2 chargers for residential and public use, as well as fast-charging stations that significantly reduce charging times. These developments have alleviated concerns about range anxiety, making EV ownership more practical and convenient.

3.2 Understanding Vehicle-to-Grid (V2G) Technology

3.2.1. What Is V2G?

Vehicle-to-Grid (V2G) is a trans formative concept that redefines the role of electric vehicles in the broader energy ecosystem. At its core, V2G enables EVs to serve as both consumers and producers of electricity. When plugged in, an EV can draw power from the grid for charging, just like a conventional appliance. However, when the vehicle is stationary or connected to a charging station, it can also act as a source of electricity supply back to the grid.

3.2.2. Bidirectional Energy Flow

V2G technology facilitates bidirectional energy flow between electric vehicles and the grid. This means that an EV's battery can discharge electricity back to the grid when needed, in addition to the typical function of storing energy for driving. This bidirectional capability distinguishes V2G[184] from conventional electric vehicles, which primarily serve as energy consumers.

3.2.3. Key Components of V2G Systems

V2G systems consist of several key components, including the electric vehicle, a bi-directional charging station, and software and communication protocols that enable the vehicle and the grid to interact seamlessly. These components work in concert to enable V2G operations.

3.3 Benefits of V2G

3.3.1. Grid Stabilization

One of the primary advantages of V2G is its potential to enhance grid stability. Electric vehicles can act as grid resources, providing or absorbing electricity as needed. This capability is particularly valuable during peak demand periods when the grid may be strained, reducing the risk of blackouts and ensuring a reliable supply of electricity.

3.3.2. Renewable Energy Integration

V2G plays a crucial role in the integration of renewable energy sources, such as wind and solar, into the grid. EVs can store excess electricity generated during periods of high renewable energy production, effectively acting as mobile batteries. This stored energy can be discharged back into the grid when renewable generation is low, mitigating the intermittency challenges of renewables[183].

3.3.3. Demand Response

V2G technology enables demand response programs, allowing utilities to manage electricity consumption during peak periods. By incentivizing EV owners to discharge energy back into the grid during times of high demand, utilities can reduce the need for costly infrastructure upgrades and stabilize electricity prices for consumers.

3.3.4. Income Generation

EV owners can generate income through V2G operations. By selling excess energy from their vehicle's battery back to the grid or participating in grid services programs, EV owners can offset the cost of EV ownership and potentially turn their vehicles into revenue-generating assets.

3.3.5. Emergency Backup Power

In emergency situations, such as power outages or natural disasters, V2G-capable EVs can serve as reliable backup power sources for homes and critical infrastructure. This added resilience can enhance community preparedness and response to unforeseen events.

3.3.6. Reduced Infrastructure Costs

V2G has the potential to reduce the need for large-scale stationary battery storage facilities. By leveraging the distributed energy storage capacity of a fleet[187] of EVs, utilities can optimize grid operations without the high costs associated with building and maintaining stationary battery installations.

3.4. Challenges and Considerations

3.4.1. Battery Degradation

One of the primary concerns associated with V2G operations is battery degradation. Frequent charging and discharging cycles can accelerate the wear and tear on EV batteries, potentially reducing their lifespan. Researchers and manufacturers are actively working to mitigate this issue through advanced battery management systems and improved battery chemistry.

3.4.2. Standardization

The successful implementation of V2G technology requires standardization of communication protocols and hardware interfaces. Achieving interoperability among different EV models, charging stations, and grid systems is crucial to the widespread adoption of V2G.

3.4.3. Regulatory and Policy Barriers

V2G faces regulatory and policy challenges, including issues related to grid access, compensation for EV owners, and liability considerations. Governments and regulatory bodies are actively working to establish frameworks that support V2G[191] deployment and incentivize participation.

3.4.4. Consumer Adoption and Awareness

To fully realize the benefits of V2G, widespread consumer adoption is essential. Increasing awareness and educating consumers about the advantages of V2G, along with providing incentives and support for EV owners, can drive greater participation in V2G programs.

3.4.5. Technological Advancements

The continued advancement of V2G technology is necessary to overcome technical challenges and enhance system efficiency. This includes improving charging and discharging speeds, optimizing energy management algorithms, and exploring new battery technologies.

3.5. The Evolving Landscape of V2G

3.5.1. Global Adoption

V2G technology is not confined to a single region; it is gaining traction worldwide. Various countries and regions are piloting V2G projects and initiatives to explore its potential benefits and challenges. Prominent examples include the United States, Europe, and parts of Asia.

3.5.2. Industry Initiatives

Industry stakeholders, including automakers, utilities, and technology companies, are actively investing in V2G research and development. Collaborative efforts between these entities are crucial for advancing V2G technology and infrastructure.

3.5.3. Research and Innovation

Ongoing research efforts are focused on addressing the technical and operational aspects of V2G. Innovations in battery technology, grid management, and communication protocols continue to shape the evolution of V2G systems.

3.6. Voltage and Frequency Regulation by Electric Vehicles in V2G Operating Mode

Electric vehicles (EVs) equipped with Vehicle-to-Grid (V2G) capabilities play a pivotal role in enhancing grid power quality by contributing to voltage and frequency regulation. This section delves into the mechanisms through which EVs help maintain stable voltage[190] and frequency levels on the grid and the implications of their involvement in these aspects.

The stability of an electrical grid relies heavily on maintaining consistent voltage and frequency levels. Deviations from these standard parameters can lead to power quality issues, equipment damage, and even power outages. Electric vehicles (EVs) with V2G capabilities are emerging as dynamic assets that can assist in voltage and frequency regulation, bolstering grid power quality and reliability.

3.6.1 Voltage Regulation

Voltage regulation is a critical aspect of grid power quality, ensuring that consumers receive electricity at the prescribed voltage levels. Voltage fluctuations, whether too high or too low, can damage sensitive electronic equipment and disrupt daily operations. EVs, when connected to the grid for V2G operations, offer a solution to voltage regulation challenges.

Voltage Boost: During periods of low voltage on the grid, EVs can inject power back into the grid, effectively boosting voltage levels to within the desired range. This capacity to act as distributed voltage stabilizers helps mitigate voltage sags and ensures a consistent power supply.

Voltage Absorption: Conversely, when the grid experiences excess voltage, EVs can absorb surplus power by charging their batteries. This action prevents over-voltage conditions, safeguarding electrical appliances and equipment from potential damage.

Dynamic Response: EVs equipped with V2G technology can respond rapidly to voltage fluctuations, providing grid operators with a flexible resource for voltage control. Advanced algorithms and real-time communication enable EVs to adjust their charging and discharging rates to maintain grid voltage within acceptable limits.

3.6.2 Frequency Regulation

Grid frequency stability is equally crucial for power quality and reliability. Deviations in grid frequency can disrupt the operation of electric equipment and lead to power imbalances. Here, EVs in V2G operations have a significant role to play.

Frequency Support: EVs can support grid frequency by responding to frequency deviations in real time. When the grid frequency drops below the standard level, indicating excess demand, EVs can discharge stored energy to supply power to the grid and help restore the frequency to the desired range.

Frequency Absorption: Conversely, if the grid frequency rises above the standard level, indicating an oversupply of electricity, EVs can absorb excess power by increasing their charging rates. This action helps prevent frequency spikes and maintains grid stability.

Grid Ancillary Services: In regions where grid operators offer ancillary services like frequency regulation, V2G-enabled EVs can participate in these programs, providing valuable support for grid stability. This participation can also generate revenue for EV owners, further incentivizing V2G adoption.

3.7. Benefits of Voltage and Frequency Regulation by EVs in V2G Operations

The contribution of EVs to voltage and frequency regulation in V2G operations offers several noteworthy benefits:

Enhanced Grid Reliability:

EVs act as distributed resources for voltage and frequency control, contributing to a more stable and reliable grid. This improved reliability benefits both residential and commercial consumers.

Reduced Grid Strain:

During peak demand periods or when the grid is under stress, EVs can alleviate strain by providing additional power or absorbing excess energy. This can reduce the risk of blackouts and enhance the grid's capacity to handle fluctuations in demand.

Optimized Grid Resources:

V2G-enabled EVs help grid operators optimize their resources, reducing the need for costly grid infrastructure upgrades. This efficiency leads to cost savings[189] for utilities and, potentially, lower electricity costs for consumers.

Support for Renewable Energy Integration:

The flexibility of EVs in responding to grid conditions aligns with the intermittent nature of renewable energy sources. EVs can store excess renewable energy during periods of high generation and release it when renewable output is low, promoting the integration of clean energy into the grid.

Grid Ancillary Services:

V2G-enabled EVs can participate in grid ancillary services markets, offering a potential source of income for EV owners. This financial incentive encourages more people to adopt EVs and participate in V2G programs.

3.8. Challenges and Considerations

While the benefits of voltage and frequency regulation by EVs in V2G operations are substantial, several challenges and considerations must be addressed:

Battery Degradation: Frequent charge and discharge cycles can accelerate battery degradation. Effective battery management systems and optimized V2G algorithms are essential to mitigate this issue and prolong battery lifespan.

Standardization: Achieving interoperability and standardization of V2G communication protocols and hardware interfaces is critical to ensure seamless integration of V2G-enabled EVs into the grid.

Regulatory Framework: Clear and supportive regulatory frameworks are necessary to enable widespread V2G adoption and participation in grid services programs. These regulations should address grid access, compensation for EV owners, and liability considerations.

Consumer Education: Increasing awareness and educating consumers about the advantages of V2G participation is essential to drive widespread adoption and ensure that EV owners understand how their vehicles can contribute to grid power quality.

EVs equipped with V2G capabilities have the potential to significantly enhance grid power quality by actively participating in voltage and frequency regulation. Their ability to respond dynamically to grid conditions, coupled with their distributed nature, makes them valuable assets in maintaining a stable and reliable electrical grid. While challenges exist, the benefits of V2G-enabled EVs in voltage and frequency regulation are substantial, paving the way for a more resilient and efficient energy future.

3.9. Reduction of Voltage Sags and Surges through V2G Operations

Voltage sags and surges are common power quality issues that can disrupt electrical systems, damage equipment, and lead to downtime. In this section, we explore how electric vehicles (EVs) with Vehicle-to-Grid (V2G) capabilities contribute to reducing voltage sags and surges, thus enhancing grid power quality and reliability.

Voltage sags, characterized by a momentary decrease in voltage levels below the standard range, and voltage surges, marked by sudden voltage spikes above the norm, are prevalent grid disturbances. These events can result from various factors, including equipment faults, lightning strikes, and sudden changes in load. Voltage sags[185] and surges can lead to malfunction or damage of sensitive electronic equipment, affecting industrial processes, data centers, and residential appliances. V2G-enabled EVs offer a solution to mitigate these issues through their ability to absorb or inject power as needed.

3.9.1 Voltage Sag Mitigation

Voltage sags, also known as voltage dips, occur when the grid voltage momentarily falls below the acceptable range. This can disrupt operations in industrial facilities, data centers, and manufacturing plants. V2G-enabled EVs can play a crucial role in mitigating voltage sags:

Immediate Response: EVs equipped with V2G technology can detect voltage sags almost instantly. When a sag is detected, the EV can inject power into the grid to support voltage levels, effectively minimizing the impact of the sag on connected equipment.

Continuous Monitoring: V2G systems continuously monitor grid voltage levels and are programmed to respond when voltage deviations occur. This proactive approach ensures that voltage sags are addressed promptly, preventing disruptions.

Localized Support: Since V2G-enabled EVs are distributed throughout the grid, they can provide localized support during voltage sags, reducing the need for costly grid infrastructure upgrades to address these disturbances.

3.9.2 Voltage Surge Suppression

Voltage surges, or transients, can occur due to lightning strikes, switching events, or other sudden changes in electrical conditions. These surges can damage electrical equipment and pose safety risks. V2G operations can help suppress voltage surges:

Absorption of Surplus Energy: When a voltage surge occurs, V2G-enabled EVs can absorb excess energy by increasing their charging rate. This action prevents the surge from propagating further into the grid and protects connected equipment from damage.

Grid Resilience: By acting as distributed energy absorbers during voltage surges, V2G-enabled EVs contribute to grid resilience. This added resilience ensures that the grid can withstand unexpected disturbances without widespread outages.

3.9.3 Benefits of Voltage Sag and Surge Mitigation by EVs in V2G Operations

The reduction of voltage sags and surges through V2G operations offers several significant advantages:

Protection of Sensitive Equipment: V2G-enabled EVs safeguard[183] sensitive electronic equipment, such as computers, servers, and industrial machinery, from voltage-related damage. This protection is crucial for businesses and organizations that rely on uninterrupted operations.

Minimized Downtime: Voltage sags and surges can lead to downtime and costly equipment repairs. By mitigating these disturbances, V2G-enabled EVs help minimize downtime and associated financial losses.

Improved Power Quality: V2G technology enhances overall power quality by preventing voltage deviations. This improved power quality benefits both residential and commercial consumers.

Grid Reliability: V2G-enabled EVs contribute to grid reliability by actively addressing voltage sags and surges. Their distributed nature means that they can assist in mitigating disturbances at various points in the grid.

Cost Savings: The protection of equipment and reduction in downtime translate into cost savings for businesses and industries. Additionally, the avoidance of equipment damage reduces the need for frequent replacements.

3.10. Limitations of V2G Mode

While V2G-enabled EVs offer substantial benefits in reducing voltage sags and surges, several challenges and considerations must be addressed:

Battery Management: The frequent charge and discharge cycles required for voltage regulation can impact battery lifespan. Robust battery management systems[183] and optimization algorithms are essential to minimize battery degradation.

Standardization: Ensuring interoperability and standardization of V2G communication protocols and hardware interfaces is critical for seamless integration into the grid.

Regulatory Framework: Clear and supportive regulations are necessary to incentivize V2G adoption and participation in voltage regulation programs. These regulations should address grid access, compensation for EV owners, and liability considerations.

Consumer Education: Raising awareness among consumers about the benefits of V2G participation in voltage regulation is essential to drive adoption and ensure that EV owners understand the role their vehicles play in power quality enhancement.

In conclusion, V2G-enabled EVs offer a promising solution to the reduction of voltage sags and surges in the electrical grid, significantly enhancing power quality and reliability. Their ability to detect and respond to grid disturbances in real-time makes them valuable assets for protecting sensitive equipment and minimizing downtime. While challenges exist, the benefits of V2G-enabled EVs in voltage sag and surge mitigation underscore their potential as contributors to a more resilient and high-quality electrical grid.

3.11. Grid Resilience and Electric Vehicles with V2G Technology

Grid resilience, the ability of an electrical grid to withstand and recover from disruptions, is a critical aspect of ensuring reliable power supply. In this section, we explore how electric vehicles (EVs) with Vehicle-to-Grid (V2G) capabilities contribute to grid resilience and enhance overall power quality.

Grid resilience is paramount in ensuring that electrical power is available consistently and reliably to consumers. Various factors, including extreme weather events, natural disasters, and equipment failures, can disrupt the grid and lead to power outages. Electric vehicles (EVs) with V2G capabilities have the potential to significantly enhance grid resilience by serving as distributed energy resources during emergencies and disturbances.

3.11.1 Grid Resilience through V2G Operations

Electric vehicles with V2G technology offer several mechanisms through which they contribute to grid resilience:

Emergency Backup Power: During power outages caused by storms, grid failures, or other emergencies, V2G-enabled EVs can serve as emergency[184] backup power sources. These EVs can supply electricity to homes, critical infrastructure, and essential services, ensuring that essential functions continue even when the grid is down.

Distributed Energy Resources: V2G-enabled EVs are distributed throughout the grid, serving as decentralized energy resources. This distribution reduces the risk of widespread power outages by providing localized energy sources during emergencies.

Load Shedding: In scenarios where the grid faces extreme stress or overload, V2G-enabled EVs can assist in load shedding. They can temporarily disconnect from the grid, reducing demand and preventing grid instability during critical moments.

Enhanced Grid Recovery: After a power outage or disturbance, V2G-enabled EVs can assist in grid recovery efforts by supplying electricity to critical infrastructure, such as hospitals and emergency response centers. This support accelerates the restoration of power to affected areas.

3.11.2 Benefits of Grid Resilience through V2G-Enabled EVs

Enhancing grid resilience through V2G-enabled EVs offers numerous benefits:

Improved Reliability: V2G-enabled EVs contribute to grid reliability during emergencies, reducing the duration and impact of power outages. This reliability is especially critical for healthcare facilities, emergency services, and critical infrastructure.

Faster Recovery: The use of V2G-enabled EVs in grid recovery efforts accelerates the restoration of power to affected areas, minimizing disruptions and inconvenience for consumers.

Reduced Vulnerability: Distributed energy resources provided by V2G-enabled EVs reduce the vulnerability of the grid to single points of failure. This increased resilience makes the grid more robust and less susceptible to catastrophic failures.

Enhanced Disaster Preparedness: V2G-enabled EVs are valuable assets for disaster preparedness, allowing communities to maintain essential services and communication even in the face of extreme events.

Cost Savings: The ability of V2G-enabled EVs to supply emergency backup power can result in cost savings for both consumers and utilities by reducing the economic impact of power outages.

3.11.3 Challenges and Considerations

Despite the significant advantages of grid resilience through V2G-enabled EVs, several challenges and considerations should be addressed:

Battery Degradation: Frequent use of EV batteries for grid resilience purposes can accelerate battery degradation. Effective battery management systems and optimization algorithms are essential to mitigate this issue.

Infrastructure and Accessibility: Ensuring that V2G infrastructure is readily accessible and available to all communities, including underserved areas, is crucial for equitable grid resilience.

Regulatory Framework: Clear and supportive regulations are necessary to incentivize V2G adoption for grid resilience. These regulations should address grid access, compensation for EV owners, and liability considerations during emergencies.

Consumer Education: Raising awareness among consumers about the role of V2G-enabled EVs in grid resilience and emergency preparedness is essential to drive adoption and community resilience.

In conclusion, V2G-enabled EVs have the potential to significantly enhance grid resilience by serving as distributed energy resources during emergencies and disruptions. Their contribution to grid recovery, load shedding, and emergency backup power supply makes them valuable assets in ensuring reliable power supply, even in the face of extreme events. While challenges exist, the benefits of V2G-enabled EVs in enhancing grid resilience underscore their importance in building a more robust and dependable electrical grid.

3.12. Optimizing Grid Resources and Electric Vehicles in V2G Operations

Optimizing grid resources is essential for maintaining grid stability and ensuring reliable power supply. In this section, we explore how electric vehicles (EVs) with Vehicle-to-Grid (V2G) capabilities[185] contribute to resource optimization, ultimately enhancing grid power quality.

Optimizing grid resources involves efficiently managing electricity supply and demand to maintain grid stability. Electric vehicles (EVs) equipped with V2G technology play a vital role in this optimization process by dynamically adjusting their charging and discharging rates in response to grid conditions.

3.12.1 Load Balancing and Grid Optimization

EVs with V2G capabilities contribute to load balancing and grid optimization through several mechanisms:

Peak Demand Management: During peak demand periods, when electricity consumption is at its highest, EVs can collectively provide additional power to the grid[186]. This reduces the strain on the grid infrastructure and prevents overloading, ultimately enhancing grid stability.

Load Shifting: EVs can engage in load shifting by charging during off-peak hours when electricity is abundant and less expensive. This helps balance the grid by redistributing energy consumption to times when demand is lower.

Demand Response Programs: Utilities can leverage V2G-enabled EVs to participate in demand response programs[187]. EV owners can receive incentives for allowing their vehicles to discharge energy back into the grid during high-demand periods, effectively reducing the need for additional generation capacity.

Grid Ancillary Services: V2G-enabled EVs can provide grid ancillary services, such as frequency regulation and voltage support, enhancing grid stability and reliability. These services can be monetized, creating economic incentives for EV owners to participate.

3.12.2 Benefits of Grid Optimization through V2G Enabled EVs

Optimizing grid resources through V2G-enabled EVs offers a range of benefits:

Reduced Grid Strain: By participating in load balancing and demand response programs, V2G-enabled EVs reduce the strain on the grid during peak demand periods, minimizing the risk of blackouts and ensuring reliable power supply.

Cost Savings: Load shifting and participation in demand response programs can result in cost savings for both utilities and consumers[188]. Off-peak charging and grid optimization help lower electricity costs during high-demand periods.

Efficient Resource Utilization: V2G-enabled EVs contribute to the efficient utilization of existing grid resources, reducing the need for costly grid infrastructure upgrades and new power generation capacity[189].

Enhanced Grid Stability: The dynamic response of V2G-enabled EVs to grid conditions[190], such as frequency and voltage fluctuations, enhances grid stability and reliability.

Support for Renewable Energy Integration: Grid optimization through V2G enables smoother integration of renewable energy sources, as EVs can store excess renewable energy during high generation periods and release it when renewable output is low.

3.13 Grid Power Quality Enhancement through V2G Operations

Voltage and frequency regulation lie at the core of grid power quality. Electric vehicles equipped with V2G technology[195] have demonstrated their ability to act as dynamic voltage stabilizers, responding to voltage fluctuations in real-time. Whether injecting power to boost voltage during sag conditions or absorbing excess power to prevent overvoltage, V2G-enabled EVs offer a reliable and distributed solution to grid voltage regulation challenges. Similarly, these vehicles play an integral role in maintaining grid frequency stability. By adjusting their charging and discharging rates in response to frequency deviations, EVs contribute to frequency regulation, ensuring a consistent power supply and preventing grid imbalances.

Furthermore, V2G-enabled EVs contribute to the reduction of voltage sags and surges, providing essential protection for sensitive electronic equipment and minimizing downtime. Their capacity to absorb excess energy[196] during voltage surges and supply power during sags has a profound impact on power quality, benefiting industries, businesses, and households alike. As voltage-related disturbances become more prevalent, the role of V2G-enabled EVs in safeguarding power quality cannot be overstated.

In times of crisis and grid disturbances, V2G-enabled EVs emerge as invaluable assets for enhancing grid resilience[197]. Their ability to serve as emergency backup power sources during power outages ensures the continuity of critical infrastructure, healthcare facilities, and essential services. By functioning as distributed energy resources, V2G-enabled EVs [198] reduce the vulnerability of the grid to catastrophic failures, offering localized energy sources that can aid in grid recovery efforts. The rapid response and load-shedding capabilities of these vehicles contribute to grid stability during extreme events, further solidifying their role in grid resilience.

Grid optimization, achieved through load balancing, peak demand management, and demand response programs, represents another significant contribution of V2G-enabled EVs to grid power quality. These vehicles assist in distributing energy consumption to off-peak hours, reducing strain on the grid during peak demand periods, and potentially lowering electricity costs for consumers. Participation in demand[199] response programs enables EV owners to monetize their vehicles' energy storage capacity, offering economic incentives for V2G adoption. Furthermore, V2G-enabled EVs enhance grid stability and facilitate the integration of renewable energy sources, as they can store excess renewable energy and release it when needed.

3.14 V2G as a Pillar of Grid Transformation

As we conclude this comprehensive exploration of the impact of electric vehicles on V2G operations and grid power quality, it becomes evident that V2G technology represents a pivotal pillar of grid transformation and modernization[202]. V2G-enabled EVs are not mere modes of transportation; they are intelligent, responsive, and distributed energy resources that hold the potential to reshape the energy landscape.

The journey from voltage and frequency regulation to grid resilience, and from voltage sag mitigation to grid optimization, illustrates the multifaceted contributions of V2G-enabled EVs to power quality enhancement. These vehicles are the bridge between the transportation and energy sectors, offering a symbiotic relationship that benefits consumers, utilities, and the environment.

3.15 Several critical areas of focus will shape the future of V2G operations

Technological Advancements: Continued innovation in battery technology, advanced control systems, and smart grid infrastructure will drive the efficiency and effectiveness of V2G operations.

Policy and Regulation: Governments and regulatory bodies must play a proactive role in creating a conducive environment for V2G adoption. Clear policies, incentives, and standards will foster growth in this sector.

Infrastructure Expansion: The expansion of V2G infrastructure, including charging stations and communication networks, is crucial to support the widespread adoption of V2G technology.

Consumer Engagement: Educating and engaging consumers in V2G initiatives will be vital for achieving broad acceptance and participation. Consumers need to understand the benefits and incentives associated with V2G-enabled EVs.

Grid Modernization: Utilities and grid operators must modernize their infrastructure and adapt to the changing energy landscape. This includes integrating V2G capabilities[203] into grid management systems.

In closing, the transformative potential of V2G-enabled EVs in enhancing grid power quality cannot be overstated. These vehicles are poised to play a pivotal role in creating a more resilient, efficient, and sustainable energy future. By actively participating in voltage and frequency regulation, mitigating voltage sags and surges, bolstering grid resilience, and optimizing grid resources, V2G-enabled EVs are leading the way toward a grid that is not only smarter but also more responsive to the evolving needs of our society. As we stand at the intersection of transportation and energy[204], V2G operations represent a beacon of hope, offering a path toward a more reliable, cleaner, and sustainable energy ecosystem—one where electric vehicles are not just consumers of power, but active contributors to its quality and resilience.

The road ahead is filled with challenges and opportunities, but the promise of V2G technology remains undiminished. It is a promise of a future where our vehicles not only take us places but also help power our world, one where our grid is not just a passive provider of electricity, but a dynamic and adaptable system that responds to our needs. It is a future where electric vehicles, equipped with V2G capabilities, are not just a part of the solution; they are the embodiment of a brighter and more sustainable energy future.

Chapter 4

4.1 Power quality improvement

We can now employ renewable resources in a variety of ways thanks to advancements in power electronics. Renewable energy sources can be interconnected with the distribution grid or with other renewable and non-renewable generators, storage systems, and loads in microgrids via power electronics interfaces [205]. The main grid system can be thought of as having unlimited power, which means that changes in load do not influence the stability of the system. A microgrid is distinct from this. On the other hand, in a microgrid, significant and abrupt changes in the load could cause a voltage transient in the AC bus of significant magnitudes. Additionally, the widespread use of switching power converters and other non-linear loads, particularly in microgrids, might lower power quality indicators.Nonlinear loads have an impact on the power quality on the grid as well, but in microgrids they can have particularly negative effects.

Utilising the APC as a power interface between renewable energy sources and the microgrids' AC bus could be one way to get around the aforementioned limitation, as shown in Fig. 26.

Current and voltage fluctuations in power distribution systems have proven to be successfully compensated by APC [206], [207]. In the technical literature, a variety of APC topologies have been published[208], but the majority of them are not suitable for use in microgrid applications.

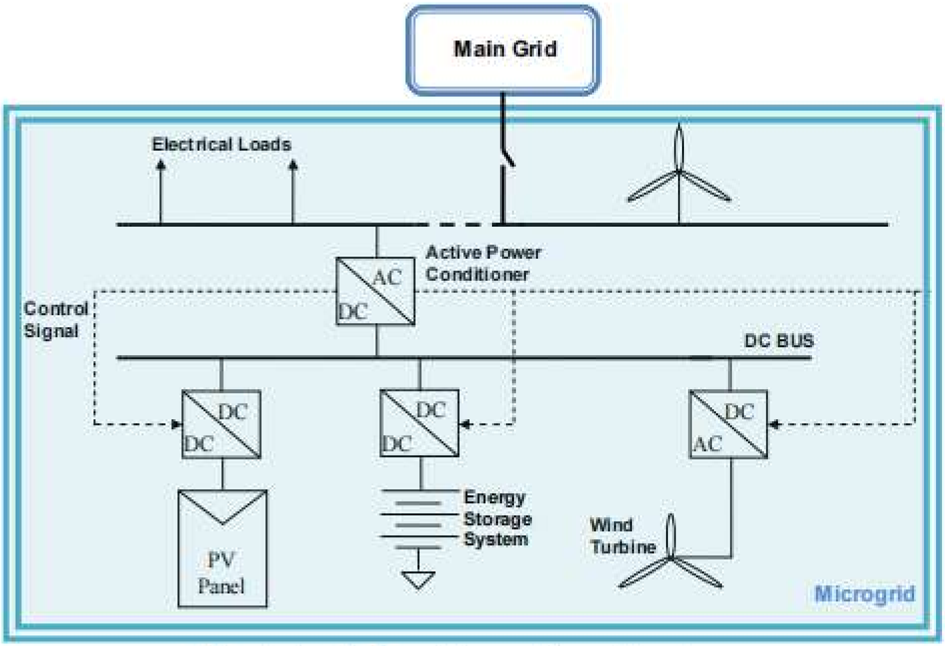


Figure 26. APC for microgrid applications

In this research, an APC that helps a microgrid's power quality is shown. The revolutionary control technique that enables energy injection into the microgrid, compensating for current harmonics, correcting the power factor, and balancing the supply voltage at the PCC (Point of Common Coupling) will be the main emphasis of the discussion. SimPowerSystems from MATLAB has been used in numerous simulation studies to demonstrate the viability of the control method.

4.2 Active Power Conditioner Topology

Four-leg converters are the most used topology for managing four currents[209]. Though the conventional three-leg four-wire converter has demonstrated higher controllability [210], the former is chosen due to the latter's use of fewer power semiconductor devices. In this study, it is demonstrated that disturbances such voltage imbalance, THD, and others may be reduced using an appropriate control method, even with a straightforward three-leg, four-wire system. Fig. 27 displays the topology of the examined APC and how it connects to the microgrid. It comprises of a voltage source inverter with three legs and four wires. The VSI functions as a voltage source with current control in these kinds of applications.Two capacitors are used to divide the DC link voltage and connect the neutral point to the midpoint of the two capacitors in order to supply the neutral point. This topology enables current to pass through the switches and capacitors in both directions, resulting in voltage variation between the DC capacitors.

$$i_{fa} + i_{fb} + i_{fc} = i_{fN} \tag{9}$$

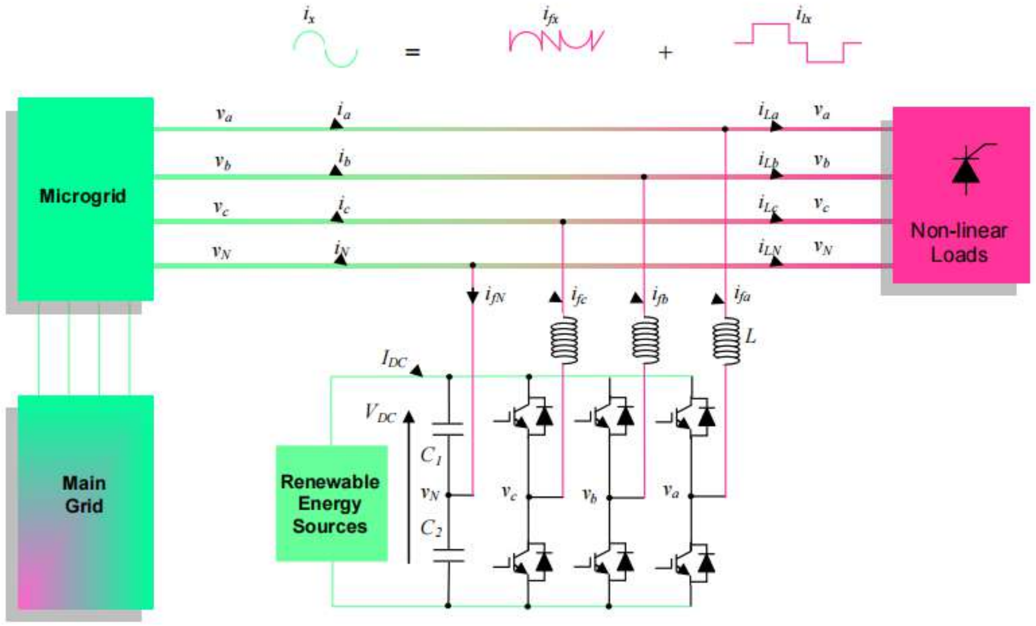


Figure 27. APF topology

Phase APC currents are i_{fa}, i_{fb}, and i_{fc}, while the APC neutral current is i_{fN}.

As a result, the total DC voltage will fluctuate at both the neutral current's frequency and the switching frequency in addition to the switching frequency. As seen in[206], if the current control is achieved using hysteresis, the aforementioned disadvantage can be mitigated by adding a dynamic offset level to both of the hysteresis band's bounds.
The current at (PCC) for the explored topology shown in Fig. 27 is as follows:

$$i_x = i_{lx} + i_{fx} \qquad (10)$$

Where i_x, i_{lx}, and i_{fx} are the microgrid side current, load current, and APC current, respectively, for the examined topology provided. The current phases a, b, and c are indicated by the x index.

The current of the immediate load is: The current at (PCC) in Fig. 27 is:

$$i_{lx} = i^1_{lx} + i_{lxk} + i_{lxq} \qquad (11)$$

i^1_{lx} the fundamental active current component;
i_{lxk} the addition of current harmonics;
i_{lxq} the reactive current component.

The three-phase APC current is given by:

$$i_{fx} = i^1_{fx} + i_{fx} \qquad (12)$$

i^1_{fx} - the fundamental conditioner current component;
I_{fx}- the deforming component of the current.

The current obtained from the grid must be sinusoidal and, moreover, in phase with the voltage at PCC, as shown in Fig. 27. In order to guarantee a sinusoidal wave for the grid current, the control strategy for the APC must be created (i_x):

$$i^1_{lx} + i_{lxk} + i_{lxq} + i^1_{fx} + i_{fx} = i_x \qquad (13)$$

Unwanted current harmonics are produced by APC switches around the switching frequency and its multiples. These undesired current harmonics can be filtered with the LR passive filter if the APC's switching frequency is high enough.

4.3 Control of APC

A. Control Strategy

A control algorithm for an APC can be created in a variety of methods [211]. Typically, the balanced grid voltage at the PCC is taken into account when designing the controller. The supply voltage in a microgrid itself may be distorted and/or imbalanced. As a result, the controller of an APC used to enhance the power quality in the microgrid must be built in accordance with this type of grid's weaknesses.

The suggested control algorithm is a compensation approach that causes the microgrid side current to become sinusoidal and balanced in order to force the APC to compensate the current of a non-linear load (Fig. 3). The three-phase grid current (i_a, i_b, i_c), three-phase voltage at the PCC (V_a, V_b, V_c), and DC-link voltage (VDC) are all needed by the controller.The error signal between the DC-link voltage (VDC) and a reference voltage (* VDC) is passed through a PI controller to determine the magnitude of the same current.

The reference three-phase grid currents i*, i*, and i* can be represented as follows using these magnitude and phase displacement values of 120° and 240°, respectively:

$$i^*_a = \varepsilon \cdot \sin(\omega t) \qquad (14)$$

$$i_b^* = \varepsilon \cdot \sin\left(\omega t - \frac{2\pi}{3}\right) \tag{15}$$

$$i_c^* = \varepsilon \cdot \sin\left(\omega t - \frac{4\pi}{3}\right) \tag{16}$$

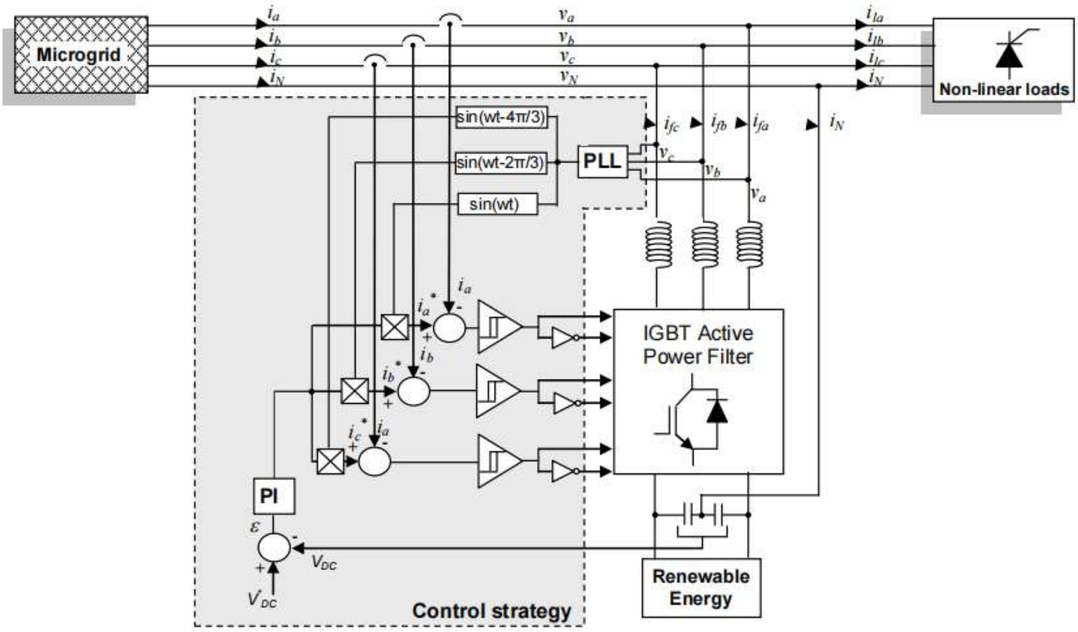


Figure 28. APC control strategy

B. Switching control

The controlled current has been kept within a specified band surrounding the references, as can be shown in Fig.28. Depending on the fault, the switches' state is decided. The state of the switches changes when the current is increasing and the error surpasses a specific positive value; at that point, the current starts to decrease until the error reaches a specific negative value. The switch's state then changes once again.

The non-linear controllers based on hysteresis techniques enable faster dynamic response and improved robustness with respect to the modification of the non-linear load when compared to linear ones.The switching frequency, which is not constant and can produce a significant side harmonics band around the switching frequency, is a disadvantage of hysteresis techniques.

The switching frequency can be fixed using several methods, such as modulated hysteresis or variable hysteresis bandwidth, to get over this issue. But this is not what this essay is about.

4.4 Control Circuit Analysis and Design of Grid-Interfacing Inverter

Assuming that the load current and PCC voltage both contain a set of harmonic components n, where n = 1 ,2, 3…..N the PCC voltage vector $V_s(t)$ will be created. present-day vector $I_L(t)$ one can write I_L (t) as:

$$v_s(t)=\begin{bmatrix}v_{sa}\\v_{sb}\\v_{sc}\end{bmatrix}=\begin{bmatrix}\sum_{n=1}^{N}V_{sna}\sin(n\omega t)\\\sum_{n=1}^{N}V_{snb}\sin\left(n(\omega t-120°)\right)\\\sum_{n=1}^{N}V_{snc}\sin\left(n(\omega t+120°)\right)\end{bmatrix}\tag{17}$$

$$i_L(t)=\begin{bmatrix}i_{La}\\i_{Lb}\\i_{Lc}\end{bmatrix}=\begin{bmatrix}\sum_{n=1}^{N}I_{Lna}\sin(n\omega t-\varnothing_{na})\\\sum_{n=1}^{N}I_{Lnb}\sin\left(n(\omega t-120°)-\varnothing_{nb}\right)\\\sum_{n=1}^{N}I_{Lnb}\sin\left(n(\omega t+120°)-\varnothing_{nc}\right)\end{bmatrix}\tag{18}$$

$(V_{sna},V_{snb},V_{snc})$ are the peak values of PCC voltages, $(I_{lna},I_{lnb},I_{lnc})$ are the peak values of load currents, and $(\phi_{na},\phi_{nb},\phi_{nc})$ are the phase angles corresponding to nth order harmonics.

The PCC output from the inverter can be used to determine the active power P and reactive power Q flow by using

$$P=\frac{V_sV_c}{X_c}\sin\delta_c=\frac{m_aV_{fc}V_s}{X_c}\sin\delta_c\tag{19}$$

$$Q=\frac{V_s}{X_c}(V_c\cos\delta_c-V_s)=\frac{V_s}{X_c(m_aV_{fc}\cos\delta_c-V_s)}\tag{20}$$

where $V_s<0$ is the PCC voltage, ma is the inverter modulation index, $Xc = Rc + j\omega L_c$ is the inductive filter impedance, and $V_c<\delta_c$ is the inverter output. The grid-interfacing inverter's control circuit is designed in accordance with Figure 30. In order to achieve compensation at unity power factor, the grid P_s's active power output should match that of the grid's apparent power as calculated by:

$$P_s=P_L+P_l-P=\frac{3}{2}V_{s1}I_{s1}^{*}\tag{21}$$

where P is the active power supplied by the RES, P_L is the active power of the load, P_l is the active loss power of the inverter, V_{s1} is the peak value of the PCC voltage's basic component, and I_{s1} * is the peak value of the required source current for compensation.

$$I_{s1}^{*}=\frac{2P_s}{3V_{s1}}\tag{22}$$

The reference instantaneous source currents (i_{sa}*, i_{sb}*, and i_{sc}*) are calculated from detected source voltages using the required peak value and unit current vectors (u_{sa}, u_{sb}, and u_{sc}).

$$i_{sa}^*(t) = I_{s1}^* u_{sa}$$

$$i_{sb}^*(t) = I_{s1}^* u_{sb}$$

$$i_{sc}^*(t) = I_{s1}^* u_{sc}$$

(23)

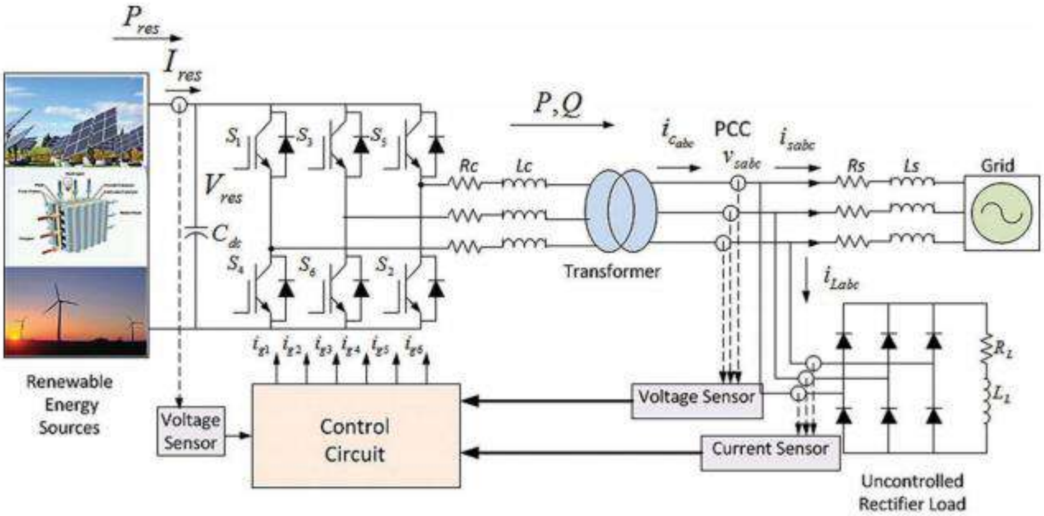


Figure 29. Proposed renewable based distributed generation system

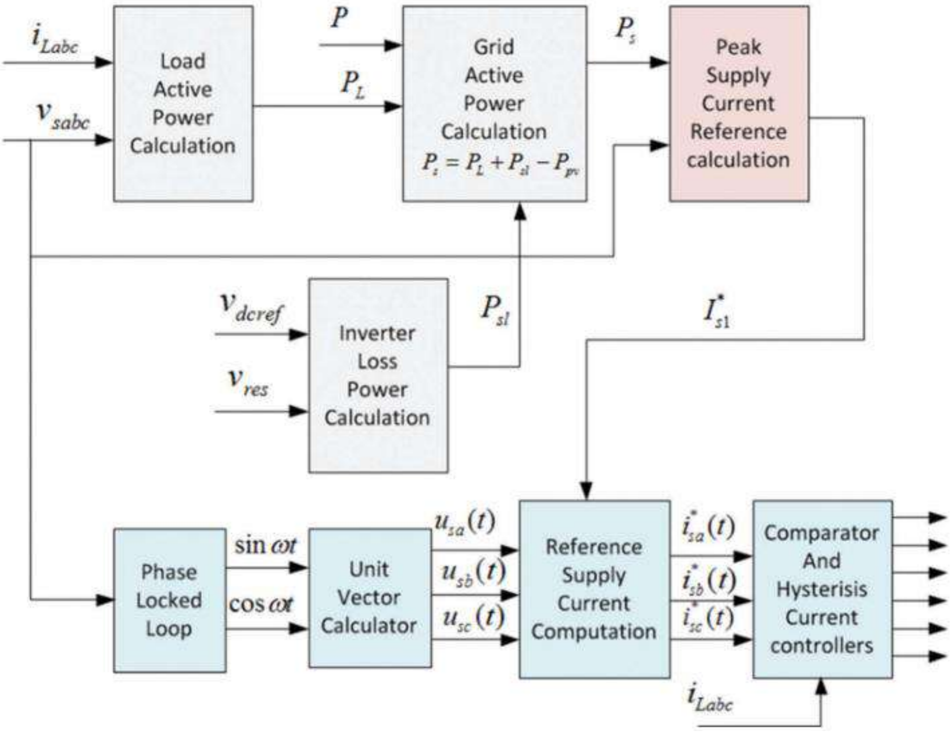


Figure 30. Control circuit of grid-interfacing inverter

The instantaneous source voltage of any one phase is used to create the unit sine vectors in a phase-locked loop. The expression for the unit sine templates is:

$$u_{sa}(t) = u_1(t)$$

$$u_{sb}(t) = -\frac{1}{2}u_1(t) + \frac{\sqrt{3}}{2}u_2(t)$$

$$u_{sc}(t) = -\frac{1}{2}u_1(t) - \frac{\sqrt{3}}{2}u_2(t) \qquad (24)$$

$u_1(t) = \sin(\omega t)$, and $u_2(t) = \cos(\omega t)$. By subtracting the instantaneous source reference currents from the detected load currents, the reference inverter currents are calculated.

$$\begin{aligned} i^*_{ca}(t) &= i^*_{sa}(t) - i_{La}(t) \\ i^*_{cb}(t) &= i^*_{sb}(t) - i_{Lb}(t) \\ i^*_{cc}(t) &= i^*_{sc}(t) - i_{Lc}(t) \end{aligned} \qquad (25)$$

The hysteresis current controller, which controls the PWM inverter's duty cycle, is provided the error ($\Delta i_{ca}, \Delta i_{cb}, \Delta i_{cc}$) between the reference inverter current and the actual inverter current.

$$\Delta i_{ca} = i^*_{ca} - i_{ca}$$

$$\Delta i_{cb} = i^*_{cb} - i_{cb}$$

$$\Delta i_{cc} = i^*_{cc} - i_{cc} \qquad (26)$$

Based on the discrepancy between the inverter's actual and reference current, the hysteresis controller creates switching pulses for the gate drives of grid-interfacing inverters. In the phase-a leg of the inverter, upper switch S_1 is on and lower switch S_4 is off if $i_{ca} > H_b$, and the opposite is true if $i_{ca} < H_b$. The hysteresis band's width, H_b, is indicated here. The similar idea underlies the operation of the switching pulses for the other two legs[212].

4.5 Active power quality enhancement for a single renewable energy system using PEKF controllers and a multilevel inverter

There are a few studies available, some of which are reviewed below. Using a large-scale decomposition coordination methodology, Huifeng et al. (2016)[213] devised a distributed model predictive control (DMPC) method for a hybrid energy resources system of dynamic economic optimal dispatch. Initially, a rolling optimisation mechanism was offered to handle the optimisation of intermittent energy resources.

This was achieved by transforming the hybrid energy resources' dynamic economic emission dispatch (DEED) model into a predictive control model. Subsequently, the computational complexity of the predictive control model was reduced by breaking it down into multiple subsystems, each of which was coordinated using Lagrangian multipliers.Using rolling optimisation mechanisms,[214] the model predictive control dynamically optimised random or uncertainty problem. Additionally, those subsystem optimisation issues were resolved through the use of adaptive dynamic programming (ADP). During the optimisation phase, the probability constraint was transformed into a deterministic constraint with its probability density function[215], and the linked coarse-fine constraint-handling technique was used to appropriately handle the system load balance.
The DMPC effectively combined with the large-scale decomposition-coordination approach to optimise the DEED of hybrid energy resources with less optimisation complexity and computational time, as demonstrated by the case study results. This indicated that the method offered an alternate means of resolving the DEED problem of hybrid energy resources. It is necessary to improve the power quality.A standalone hybrid photovoltaic (PV) array-excited wind-driven induction generator (IG) with simplified control has been described by Lenin et al. (2015)[221]. It takes into account a three-phase variable load with or

devoid of imbalance. This plan took advantage of the robustness and affordability of permanent magnet synchronous generators, which were often utilised in freestanding tiny wind turbines but are expensive.Instagram is a good substitute. All independent systems use batteries to store energy, although this method was designed to provide electricity even in the event that the battery ran out. A broad field Weather stations, 2.2-kW wind turbine emulators, and 2.4-kW PV panels were used in the testing for assessing performance. The validation of the control scheme indicates that it was anticipated to serve as a remote application solution in situations when utility grid integration is impractical. The values of the performance measures are not entirely sufficient[217].

Flywheel energy storage systems (FESS) with wind farms have been used by Abdeltawab and Yasser Abdel-Rady (2016)[213] to integrate renewable energy resources in transmission systems. Although FESS has several benefits, such great efficiency and a long lifespan, its lifetime is exponentially diminished as the rotation speed increases, and it has noticeable standby losses. In order to supply power to the main grid[218], FESS is hybridised with a wind farm. Wind curtailment has decreased and the excess wind energy has been sent to the grid codes by the FESS.The Energy Management System increased the FESS standby losses and extended its lifetime by using the anticipated wind power data. There were two controllers in the EMS. The long-term FESS power set-point was first controlled by a linear model predictive controller, and the wind power prediction error was corrected by a real-time adaptive hysteresis controller in the second controller. The efficiency of the EMS in lowering FESS losses while adhering to grid integration code restrictions was confirmed by comparative simulation tests[219]. Losses in distribution and transmission do occur.For a hybrid ac/dc micro-grid, Mehdi Hosseinzadeh and Farzad Rajaei Salmasi (Hosseinzadeh and Salmasi 2016)[220] have used a fault-tolerant supervisory controller. The main dc bus in the hybrid microgrid is linked to the loads, energy storage, and dc sources. On the other hand, the main ac bus is linked to the ac sources and sinks. An inverter or converter that operates in both directions switched the power between them. A main controller oversaw it, and the controller supervised the power flow by resolving an optimisation problem. The highest powers that could be used for wind, solar, and energy storage subsystems that were both error-free and fault-prone were considered. It was demonstrated that the maximum power available from solar and wind resources is impacted by subsystem faults.In order to meet demand for power while making the best use of renewable resources, the supervisory controller takes into account its tolerance for shading and converter failures in the solar system, as well as lubricating system failure and converter faults in the wind system. Furthermore, the power management system's tolerance for energy storage failure in each micro-gird was included in the overall control scheme. Based on dynamical models of the power resources, numerous simulation runs were used to assess the effectiveness of the supervisory controller. Enhancing system robustness is necessary. Baghaee et al. (2017)[216] have introduced a novel decentralised robust technique that enhances hybrid AC/DC MGs' performance for nonlinear and unbalanced loads while also improving small- and large-signal stability and power-sharing. DC/DC converters are equipped with a sliding mode controller to regulate the flow of power. Based on sliding mode control and Lyapunov function theory, two distinct controllers were devised for positive sequence power control and negative sequence current control. In the case of nonlinear and unbalanced loads, this controller enhanced power sharing and regulated the active and reactive powers injected by distributed energy resources. It also controlled harmonic and negative-sequence current. The paper outlined the core theorems, controller design process, robustness, closed loop stability analysis, and the theoretical idea of robust control as well as the mathematical modelling of MG components. Additionally, a novel hybrid AC/DC hierarchical control system that made use of a voltage compensation plan and harmonic virtual impedance loop oversaw this direct control approach.The system's energy efficiency needs to be raised.The power quality, performance metrics, transmission and distribution losses, system robustness, and energy efficiency degradation are shown to be drawbacks in the aforementioned related works. These drawbacks are taken into account and addressed in this framework by the BSHE-PWM control system for effective power management[222].

These days, there is a greater focus on grid-connected systems due to the integration of renewable energy systems into the grid. This results in higher energy efficiency, system robustness, voltage support, diversification of energy sources, transmission and distribution losses, and system reliability. A low-voltage network that addresses local energy problems and improves flexibility, MG is a small-scale power grid that can function in both grid-connected and islanded modes. One of the most promising approaches to meet the electrification needs is through standalone hybrid systems.A suitable set of software tools, similar to those used for large interconnected power systems, is needed for systematic analysis, the design of control and protection systems, and the optimal operation of a distribution system when DER penetration is high. This is because the power system will produce low output voltage and variable due to its eratic condition[223]. Numerous booster converters with a single switch can function in both boost and buck modes. These include Cuckoo-based converters, buck-boost converters, etc. Nevertheless, compared to traditional boost converters, its switching components experience a far higher voltage stress[224].

The suggested model, depicted in Figure 31, uses fuel cells, wind turbines, and solar cells to create power for the load and create an AC MG.

A steady-state voltage and frequency are supplied to the grid via ac-ac converters, which are used to convert the ac that wind turbines produce.

Figure 31. Wind-PV-fuel hybrid connected to the grid.

With the new dc-dc boost converter boost converter, the solar cell's voltage is increased and the maximum power is harvested.
Fuel cells produce direct current (dc), which is then used to increase voltage. This dc-ac is then transformed into electrical current to power the alternating grid.

As it runs at high voltage with stress per switching at lower voltage, higher efficiency, and less electromagnetic interferences, the cascaded H-bridge inverter is used to convert dc-to-ac. Controlling the voltage and current is necessary for steady state operations in order to affect circulating currents, balance power cell stress, and minimise switching losses[225].A constant dc-bus voltage booster converter is needed because of the power system's changing output voltage and low output voltage. A new boost converter is used when a high voltage is needed to feed the load in order to increase the voltage gain[226]. The dual switch dc-dc converter in this innovative dc-dc boost converter allows for a large boost voltage gain at a low duty cycle. In addition to reducing the voltage stress on IGBT, diodes, and the conduction loss on power switches, this converter is used to rectify power factor.
Fuzzy control predictive exogenous Kalman filter (PEKFC) is used to increase system stability.PEK is used to identify the system's steady state and transient state behaviour[227]. Fuzzy control is then used to diagnose the error and restore system stability. The cascaded H-bridge converter uses BSHE-PWM control to lessen harmonic distortion (bumble bees selective harmonic elimination-pulse width modulation).
‘

4.6 Model of system

In this study, we take into account the use of loads and an MG system connected to the power grid. MG gets its power from renewable energy sources like solar, wind, and PEMFC stacks.

4.6.1 Mathematical model for wind energy

Wind turbine converts the kinetic energy of wind into mechanical energy by means of producing torque. The mechanical power that the wind turbine extracts from the wind is given by

$$P_w = 0.5\ C_P(\lambda, \beta)\rho A V_w^3 \tag{27}$$

where P_w is Power generated by the wind turbine, A is area swept out by the turbine blades, Vw is the wind speed, ρ is air density, λ is tip speed ratio, β is pitch angle, CP λ; β is the power coefficient. Tip speed ratio λ, is a variable that expresses the ratio between the linear velocity of the blade tip to rotational speed of the wind turbine, the tip speed ratio as expressed as,

$$\lambda = \frac{R_s.R_b}{V_w} \tag{28}$$

where Rs, is rotor angular speed (rad=s_n),R_b is rotor blade radius (m).

4.6.2 Model Number for Permanent Magnet Synchronous Generator (PMSG)

The PMSG has been proposed as a method to use the mechanical energy (P) from wind to generate electricity. Higher power density, improved fault-ride through and grid support capabilities, reduced maintenance costs, and increased efficiency are the benefits of PMSG. The dq-axis stator voltages' voltages are

$$V_d = -R_s I_d + \frac{df_d}{dt} - \omega f_d \tag{29}$$

$$V_q = -R_s I_q + \frac{df_q}{dt} + \omega f_q \tag{30}$$

where ω is the electrical angular velocity of the rotor, Rs is the resistance of the stator windings, f_d; f_q are the d axis and q axis flux connections, and Id; Iq are the d axis and q axis stator currents.

$$f_d = -L_d I_d + f_p \tag{31}$$

$$f_q = -L_q I_q \tag{32}$$

where f_m is the permanent magnet's flux linkages and L_d, L_q, and qaxis inductances are represented.

4.6.3 A mathematical model for photovoltaic systems

In order to produce electricity, solar panels use the energy they absorb from the sun. A PV module is a pre-assembled unit that usually consists of six solar cells arranged in a row. A photovoltaic system that produces and supplies solar electricity for use in homes and businesses is made up of photovoltaic modules, which make up the array. A single solar cell is represented in this module as a resistance R_s that is connected in series with an exponential diode, a parallel resistor R_p, and the current source in parallel.

The module's output current is

$$I = I_{ph} - I_s[(e^{(V_s+I_s*R_s)/(N*V_t)} - 1) - ((V_s + I_s * R_s)/R_p)] \tag{33}$$

Where

$$I_{ph} = I_{ph0} \times \frac{I_r}{I_{r0}} \tag{34}$$

where I_{ph0} is the measured solar-generated current for the irradiance I_{r0}, and Ir is the irradiance in W/m^2 falling on the cell.is the diode's saturation current, and N is its quality factor, or diode emission coefficient. The thermal voltage is V_t, and the voltage across the electrical ports of a solar cell is V_s.

$$V_t = \frac{kT}{q} \tag{35}$$

where k is the Boltzmann constant, T is the Device simulation temperature parameter value, q is the elementary charge on an electron.

4.7 Theoretical framework for PEMFC stack

FC immediately transforms the chemical energy of fuel (H_2 and O_2) into electrical energy in a static electromechanical device. In addition to converting hydrogen and oxygen energy into electrical energy, the proton exchange membrane fuel cell (PEMFC) generates heat and water on its catalytic surfaces. The H_2 flow rate and FC current are the two key variables that influence the FC control system. Figure 32 displays the PEMFC model, which is based on analogous circuits.
The characteristics that affect fuel and air flow rates are pressure, temperature, composition, and variation.

$$V_{fc} = V_c V_n \tag{36}$$

$$i_c = \frac{eFk(P_{H_2} + P_{O_2})}{Rh} e^{-\Delta G/RT} \tag{37}$$

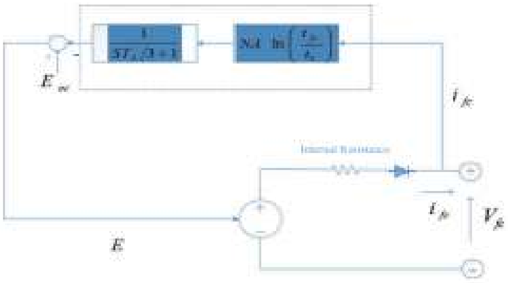


Figure 32: Fuel cell stack equivalent circuit.

$$T_a = \frac{RT}{e\alpha F} \tag{38}$$

where V_n is the Nernst voltage, the thermodynamic voltage of the cells and depends on the temperatures and partial pressures of reactants and products inside the stack (V), R is 8.3145 J/(mol K),Fis 96485 A s/mol, e is the number of moving electrons, V_c is the voltage constant at nominal condition of operation, and α is the charge transfer coefficient, which depends on the type of electrodes and catalysts used. The partial pressures of hydrogen (P_{H2}) and oxygen (P_{O2}) within the stack are measured in atmospheres; k is the Boltzmann's constant, which is 1.38 × 10–23 J/K; h is Planck's constant, which is 6.626 × 10–34 J s; and ΔG is the activation barrier's size, which is dependent on the kind of electrode and catalyst used. N is the number of cells, and T is the operation temperature (K).

4.8 Grid of utilities

The distribution grid is used to achieve the overall distribution system's power balance during grid-connected operation. Nonetheless, the distribution system's power balance is determined by the power balance equation that follows when the MG transits to function islanded from the distribution grid:

$$P_{we} + P_{spv} + P_{fc} = P_v \tag{39}$$

where P_{we}, P_{spv}, and P_{fc} stand for the power supplied by the fuel cell, solar PV array, and wind turbine, in that order.

4.9 A DC-DC converter proposal

The power factor function in a converter is used to raise the voltage. Because the output voltages of the various renewable energy sources—such as wind, solar, and fuel cells—are so low and variable, they are dependent on the weather. The low voltage is transformed into a continuous dc-bus voltage by this boost converter. Numerous booster converters with a single switch can function in both boost and buck modes. Thus, voltage gain will be provided with reduced voltage stress and conduction losses in the suggested dc-dc boost converter. The output from the hybrid wind, solar, and fuel cell serves as the input for the dc voltage. The suggested dc-dc boost converter for high voltage gain is depicted in Figure 33.

Mode I: Upon turning on the switches for S_a and S_b. The voltage output is

$$V_{out} = V_{dc} + V_{C_a} + V_{C_b} \tag{40}$$

This mode involves the discharge of the capacitors C_a and C_b and the charging of the inductor L. Based on the duty cycle χ and switching period S_b, the time interval is determined. Diodes D_b, D_c, D_d, and D_e are reverse biassed, while diode D_a is forward biassed.

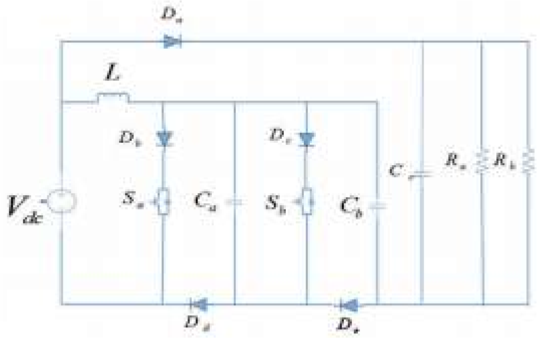


Figure 33. DC-DC boost converter.

Mode II: After the S_a and S_b is switch was switched OFF.

$$V_{C_a} = V_{C_b} \tag{41}$$

With an input voltage of between 15 and 20 V, the suggested dc-dc converter produced a high voltage gain output of 200 V. It is attached to the hybrid energy sources' output in order to give high power quality and high voltage gain output from low input voltage.

4.9.1 several-level converter

Multilevel power converters offer high voltage, minimal output voltage distortion, excellent quality, and great operational efficiency. By raising the voltage level, these benefits are realised. Four VDC, four MOSFET switches, and four diodes are linked with a single cell H-bridge in the nine-level converter seen in Figure 34. Four MOSFET switches are used to generate a nine-level output. There are eight MOSFET switches and four diodes needed for the nine-level dc-ac converter.The output voltage V_{out} from the dc-dc converter serves as the input for the multilayer inverter.
The computation of the highest voltage level attained is done by

$$N_l = 2d + 1 \tag{42}$$

where is the DC source count. The 9-level inverter's switching sequence, which produces a 9-level output voltage, is displayed in Table 6.

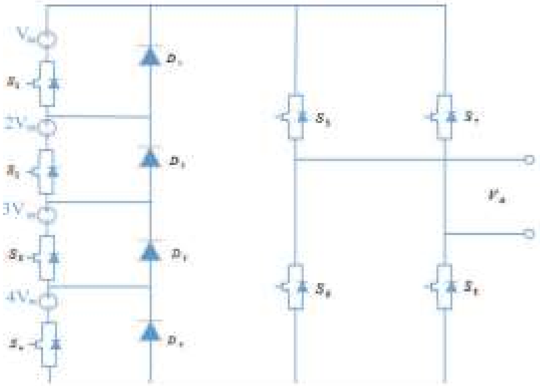


Figure 34: A cascaded H-bridge inverter with nine levels.

4.9.2 Controller for AC MG proposed

The suggested PEKFC offers fuzzy rules to function under notional circumstances and is used to forecast future errors. In Figure 35, the suggested PEKF controller is displayed. Using the output voltage Va from the 9-level cascaded H-bridge inverter, this controller calculates the system's current status and potential future errors. Fuzzy rules give the nominal conditions to operate the system in a steady state based on the prediction error.

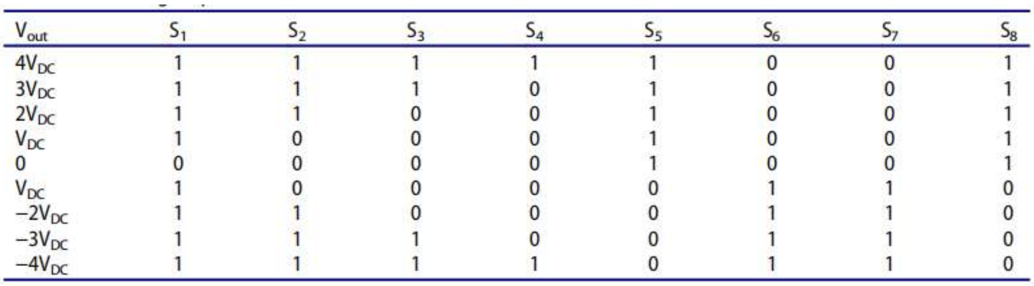
4.9.3 PEKFC for voltage control

The exogenous signal of the state is provided by the exogenous Kalman filter, and the nonlinear model of the system is linearized using the defined signal. The exogenous Kalman filter for state estimation is depicted in Figure 36. Although there is a transmission delay, this exogenous Kalman filter delivers the state estimation and update commands. It will estimate the state using the most recent updated state forecast during this delay.
The current system's nonlinear state space model is shown as

$$x_{k+1} = A_k x_k + V_a + ps_k \tag{43}$$

$$y_k = Cx_k + n_k \tag{44}$$

where T is the variable function of the Amplitude A_k, x_k is the system state, V_a is the voltage input, ps_k is the process noise, and n_k is the measurement noise.



V_{out}	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
$4V_{DC}$	1	1	1	1	1	0	0	1
$3V_{DC}$	1	1	1	0	1	0	0	1
$2V_{DC}$	1	1	0	0	1	0	0	1
V_{DC}	1	0	0	0	1	0	0	1
0	0	0	0	0	1	0	0	1
V_{DC}	1	0	0	0	0	1	1	0
$-2V_{DC}$	1	1	0	0	0	1	1	0
$-3V_{DC}$	1	1	1	0	0	1	1	0
$-4V_{DC}$	1	1	1	1	0	1	1	0

Table 6. Switching sequence of 9 level inverter

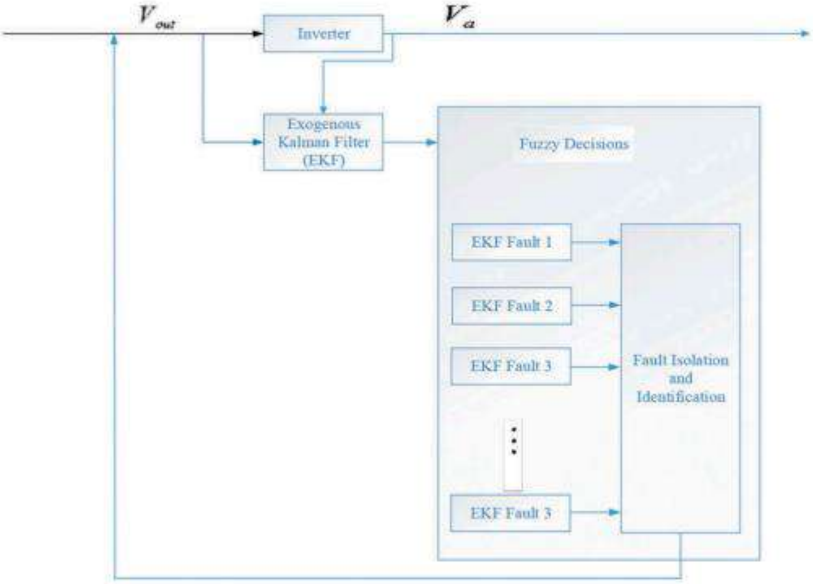


Figure 35: A suggested controller for PEKF.

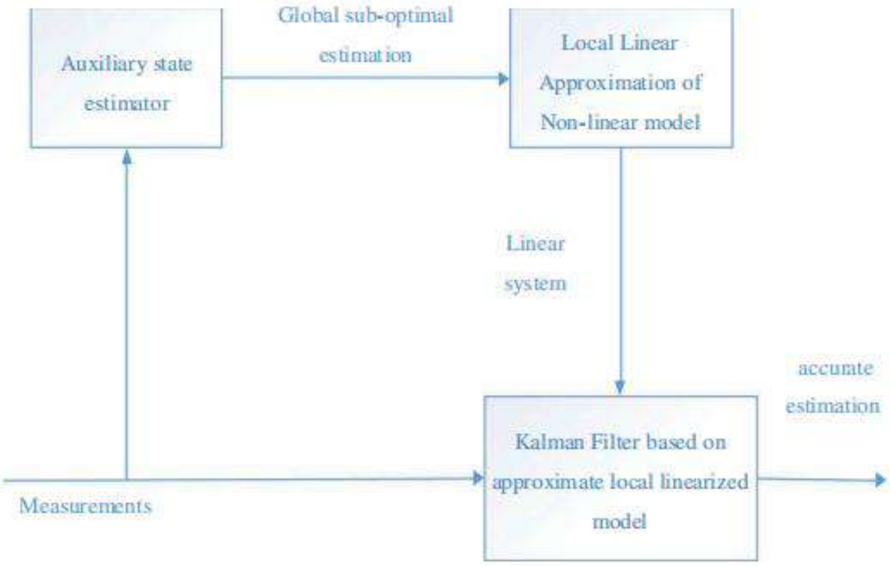


Figure 36. Exogenous Kalman filter.

$$A_k = \begin{bmatrix} \cos(\omega T) & \sin(\omega T) \\ -\sin(\omega T) & \cos(\omega T) \end{bmatrix} \tag{45}$$

$$C = [1 \quad 0] \tag{46}$$

The voltage's updated auxiliary state estimation is

$$\dot{x}_{k+1} = A_k \dot{x}_k + k(y_k - \dot{y}_k) \tag{47}$$

$$\dot{x}_k = \dot{x}_{k+1} = A_k \dot{x}_k - k_e(y_k - C_k \dot{x}_k) \tag{48}$$

The Kalman gain realised is

$$k_e = A_k P_{k-1} C_k^T (C_k P_{k-1} C_k^T + R_k)^{-1} \tag{49}$$

The estimation error's covariance matrix is described as

$$\hat{P}_k = P_{k+1} = A_k P_{k-1} A_k^T - k_e C_k P_{k-1} A_k^T + Q_k \tag{50}$$

A less-than-ideal reference voltage solution is provided by this estimate. Subsequently, the precise estimation of the state is acquired by utilising the auxiliary state estimation. The estimated expected state is

$$\hat{x}_{k+1} = f(\dot{x}_k) \tag{51}$$

$$\hat{y}_k = h(\dot{x}_k) + n_k \tag{52}$$

where

$$f(\dot{x}_k) = [2\cos\omega T \quad 2\cos\omega T \dot{x}_{k-1} - \dot{x}_{k-2} \quad \dot{x}_{k-1}]^T \tag{53}$$

$$h(\dot{x}_k) = 2\cos\omega T \dot{x}_{k-1} - \dot{x}_{k-2} \tag{54}$$

The single sinusoid estimation linearized system is

$$\hat{x}_k = \dot{\hat{x}}_{k+1} = f(\hat{x}_{k+1} + k_g(\hat{y}_k - h(\hat{x}_{k+1})) \tag{55}$$

The definition of the Kalman gain is

$$k_g = \hat{P}_k H_k^T [H_k \hat{P}_k H_k^T + R_k]^{-1} \tag{56}$$

The future error that the Kalman filter predicts to be is

$$\hat{P}_{k+1} = F_k[\hat{P}_k - k_g H_k \hat{P}_k] F_k^T \tag{57}$$

Where

$F_k = \frac{\partial f(\hat{x})}{\partial(\hat{x})}$ and $H_k = \frac{\partial h(\hat{x})}{\partial(\hat{x})}$

The fuzzy rule that provides voltage to lessen voltage deviation is derived based on the measurement inaccuracy. The fuzzy rule for the error derived from the state is displayed in Table 7. Fuzzy rules are used to control the voltage, adjusting the reference voltage in order to balance the MG voltage. The output voltage is balanced using the provided fuzzy rule based on the estimated state.

4.10 Elimination of harmonics

SHE-PWM is used to compare the reference signal at a fundamental frequency in order to generate the gate signal. However, the higher-order harmonics are not entirely eliminated in the current SHE-PWM. Additionally, there was no assurance of global optimisation and premature convergence when employing GA-based SHE-PWM. Thus, the suggested selective harmonic elimination pulse width modulation strategy for bumblebees offers global optimisation and excellent exploration. The single phase multilevel converter's multilayer PWM output waveform is

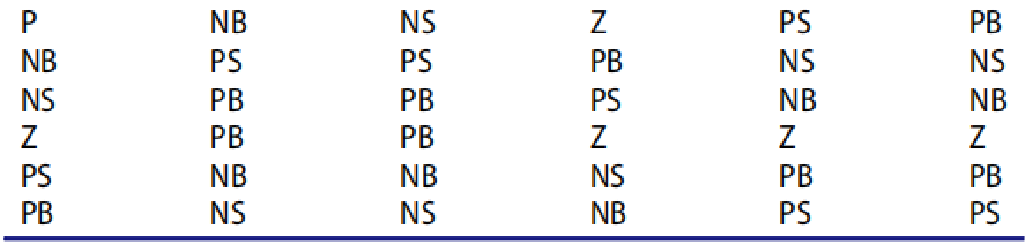
$$V_o = \sum_{x=1}^{\infty} a_x \cos x\theta + b_x \sin x\theta \tag{58}$$

The output voltage can be decreased to because of the half-wave symmetry and odd function symmetry of the PWM waveform.

$$V_o = \sum_{x=1,3,..}^{\infty} b_x \sin x\theta \tag{59}$$

The SHE method's nonlinear set equation is

$$\begin{aligned} V_{do} &= \frac{4V_{DC}}{\pi}(b_1\cos(\theta_1) + b_2\cos(\theta_2) + b_3\cos(\theta_3)\cdots b_x\cos(\theta_x)) \\ 0 &= \frac{4V_{DC}}{5\pi}(b_1\cos(5\theta_1) + b_2\cos(5\theta_2) + b_3\cos(5\theta_3)\cdots b_x\cos(5\theta_x)) \\ &\vdots \\ 0 &= \frac{4V_{DC}}{x\pi}(b_1\cos(x\theta_1) + b_2\cos(x\theta_2) + b_3\cos(x\theta_3)\cdots b_x\cos(x\theta_x)) \end{aligned} \tag{60}$$



P	NB	NS	Z	PS	PB
NB	PS	PS	PB	NS	NS
NS	PB	PB	PS	NB	NB
Z	PB	PB	Z	Z	Z
PS	NB	NB	NS	PB	PB
PB	NS	NS	NB	PS	PS

Table 7. Fuzzy rule base

where Z is the number of dc sources in the converter and the product of $V_Z V_{dc}$ is the value of the Z^{th} dc source for the single phase system, x=1; 3; 5;..........; 2N-1.

$$P_Z = N_1 + N_2 + \cdots + N_Z \tag{61}$$

where N_1; N_2;...;N_Z is the number of pulses at converter 1; 2;....;Z every quarter cycle.

The definition of the modulation index M_{index} is $M_{index} = V_{do}/ ZV_{dc}$, where $0 \leq M_{index} \leq 1$.

The normalised fundamental component (b_1) and the input DC voltage source (V_{dc}) for every converter cell are identified. The limitation is minimised to produce these optimal switching angles. The lookup tables include the obtained switching angles, which are used to regulate the converter at a specific operating point. Therefore, there are no longer any harmonics in the output voltage[228].

$$0 \leq \theta_1 \leq \theta_2 \leq \cdots \leq \theta_N \leq \frac{\pi}{2} \tag{62}$$

Chapter 5

5.1 Distributed Generation and Power Quality

Due to the significant overlap between distributed generation (DG) and power quality technologies, many people active in DG have also become involved in DG. Therefore, including a chapter on this subject is quite appropriate. DG, as its name suggests, employs smaller generators than the typical plant for a central station. They are dispersed across the closer to the loads is the power system. A smaller-sized thing can be described as several different generator sizes. Because the focus of this book is Considering the primary and secondary distribution systems' power quality, The topic of DG will only include generators with capacities under 10 MW. At transmission voltages, where the system is built to support numerous, larger generators are often coupled generators.

The typical distribution system uses cables to transport electric energy from a single power source to several loads. As a result, when there are several sources, several power quality problems occur. Will DG worsen the service end users have grown to anticipate, or will it improve the power quality? Both sides of this debate have valid points to make, and this article looks at a few of them.

5.2 Resurgence of DG

Power is typically produced in sizable, centrally located generating stations and distributed to end customers via transformers, transmission lines, and distribution lines in developed countries for more than seven decades.In DG literature, this is frequently referred to as the "wires" system. This book essentially explains what can go wrong when power is delivered through wires. The initial electrical power networks made use of DG and were built on remote islands using very tiny generators. Economies of scale allowed the current centralised system to replace that approach. Additionally, there was a need to place electrical producing facilities near the source of fuel and water, and to sequester them away from population centres for environmental reasons.

In order to promote energy independence, the Public Utilities Regulatory Act of 1978 (PURPA) was passed in the United States in 1978. To encourage the development of renewable and energy-efficient, low-emission technology, tax credits were offered and power was purchased at avoided-cost rates. As a result, the production of wind, solar, and geothermal energy as well as gas-fired cogeneration (combined heat and power) plants increased dramatically. With the advancement of better DG technologies and the liberalisation of the power industry, which allowed more power providers to compete in the market, interest in DG once again reached a height in the middle of the 1990s.Additionally, there is now a need for local generation and storage to cover the gap produced by the emergence of important high-technology loads that demand considerably greater reliability than can be provided by wire delivery alone.

Some futurists predict a return to the original power system model in a high-tech form. New technologies would enable interconnected power grids to be small (microgrids) and the generation to be distributed as broadly as the load. Renewable resources or clean-burning, high-efficiency technology would power the generation. The method of distributing energy will change from using wires to using pipes filled with fuel, most likely hydrogen in the end. If the industry can go from its current position to this future at all, it is unclear how.Recent initiatives to deregulate the electric power industry have focused on enabling innovative technologies as well as better electricity costs. The transition of the electricity sector to DG sources, however, is far from assured. Compared to generation methods, cables are relatively resilient, notwithstanding the challenges associated with wire-based delivery that are addressed in this book. Once built, they require very minimal care over the course of decades.

5.3 Perspectives on DG benefits

Understanding that there are various viewpoints on every pertinent issue is one essential to comprehending the DG issue. To demonstrate, we go over the advantages of DG from three different angles.

5.3.1 End-user viewpoint

The majority of the value in DG today is located here. End users who value electricity highly can typically gain significantly from having backup generation to increase reliability. Some people will gain significantly from high-efficiency applications like combined heat and power, where the overall energy bill is decreased. In places where there may be potential power shortages, end users may also be eligible for compensation for making their generation capacity available to the power system.

5.3.2 The utility of distribution

With the help of its current network of lines and substations, the distribution utility is interested in selling electricity to end users. Transmission and distribution (T&D) capacity alleviation is a possible application for DG. This application typically has a short lifespan until the load increases enough to warrant the construction of new T&D facilities. DG protects against unpredictable load growth as a result. If permitted by regulatory bodies, it can also act as a buffer against abrupt price increases in the power market.

5.3.3 The viewpoint of a commercial power producer

Those who approach DG from this angle are primarily focused on entering the local power market to offer power or ancillary services. In the context of DG, the majority of units are too small to participate in individual power market bids. Commercial aggregators will put up for bid the combined capacity of many units. The DG can either service the load off-grid or directly connect to the grid. The latter, while avoiding numerous interconnection-related issues, does not enable the full potential of the DG to be used.

5.4 The drawbacks of DG

The disadvantages of DG are seen from several angles as well. The remainder of this chapter is largely devoted to the worry that utilities have with power quality issues. Costs and maintenance should be the key concerns for end customers. Really, do end users want to run generators? Will electricity really be more affordable and dependable? Will DG continue to benefit from favourable power markets? There are a lot of unaddressed issues. But it appears likely that for the foreseeable future, the quantity of DG connected to the electric system will keep growing.

5.4.1 Interconnection perspectives

The question of how to link DG to the electric grid is likewise a contentious topic. In attempts to create industry standards for interconnection, this is the main source of much contention. Figures 38 and 39 show how the two main opposing positions are seen.

The perspective of end users and DG owners who desire to connect in order to reap one or more of the aforementioned benefits is shown in Figure 38. This kind of illustration can be found in numerous publications that promote the usage of DG.The DG is modest in comparison to the grid, which is the underlying message regarding electricity quality. This group frequently holds the belief that the grid is an enormous entity that is too big to be impacted by their comparatively tiny generator. Because of this, many people find it difficult to comprehend why utilities are reluctant to interconnect and just see their regulations as barriers intended to keep out competitors. The fact that the grid is perceived as unreliable and producing "dirty" power, despite its massive size, is another component of the end-user perspective that is not depicted in this illustration. The literature for DG advocates frequently portrays DG as enhancing system (including grid) reliability and supplying higher-quality power.Fig. 39 depicts the viewpoint on interconnected DG of typical utility distribution engineers, the majority of whom take a relatively cautious approach to planning and operations. Customer-owned DG produces dirty power and has a size that is enlarged to appear much greater than it actually is. Its design is also a tiny bit off-center, implying that it was not made and maintained with the same care as utility equipment.

Each of these viewpoints contains some components of reality. The goal of this book is to describe the topics as fairly as possible while highlighting solutions to power quality-related difficulties, without taking sides in the argument.

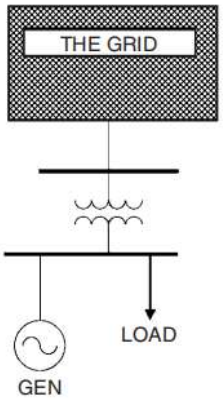


Figure 38. End user and generator perspectives on interconnections

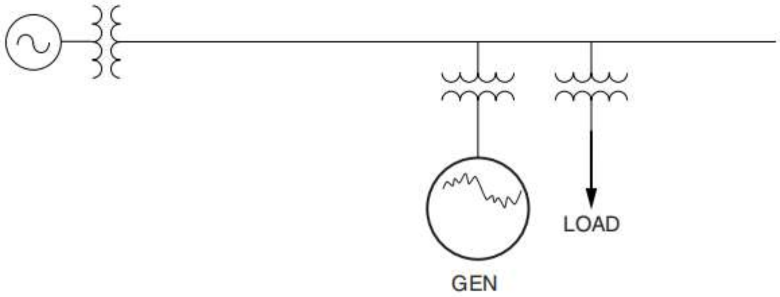


Figure 39 Distribution planner perspective on interconnection

5.5 DG Technologies

The focus of this chapter is on the power elements of DG, and the pertinent technological issue will only be briefly discussed. Particular technology proponents and marketers have a way of making things look highly alluring while failing to warn the reader of significant drawbacks.

5.5.1 Reciprocating engine genset

The reciprocating engine-generator set is the DG technology that is used the most frequently. In Fig. 40, a typical unit is displayed. Generally speaking, this technique is the least expensive DG technology, frequently by a factor of 2. Gas or diesel reciprocating engines are established technologies that are easily accessible.
Currently, mobile gensets that can be transported to the locations where they are needed are preferred by utilities. Supporting the transmission and distribution system during emergencies is a typical application. The substation-based units are connected to the grid by means of transformers, which normally increase the voltage from the 480 V generated by the generators.
The manufacture of these units has increased recently as a result of increased demand to relieve severe grid constraints that have developed in some regions. As a result, the price of the units has decreased, which has widened the price difference between this technology and the next-cheapest alternative, which is typically some type of combustion turbine.
End users like using diesel gensets for backup power. High NOx and SOx emissions are one of this technology's drawbacks. This drastically restricts the amount of time the units, especially diesels, may work, maybe to as few as 150 hours per year. Thus, peaking generating and emergency backup will be the key uses.
Less emissions are produced by natural gas-fired engines, which may often run for many thousand hours each year. Because they run at least during the workday, they are widely used in combined heat and power cogeneration applications in educational institutions, governmental agencies, and commercial buildings.

Synchronous alternators are the most typical configuration for standby and utility grid support applications, and this is what the unit in Fig. 40 possesses. Reciprocating engines with induction generators, however, are equally common. This is especially true for cogeneration applications under 300 kW because induction machines that are unlikely to sustain islands can frequently meet interconnection requirements more easily.
With efficiencies in the range of 35 to 40%, reciprocating engine generator sets exhibit consistent performance characteristics under a variety of environmental

situations. Compared to combustion turbines, which experience a significant reduction in power efficiency when the temperature outside rises, they are less susceptible to the environment.

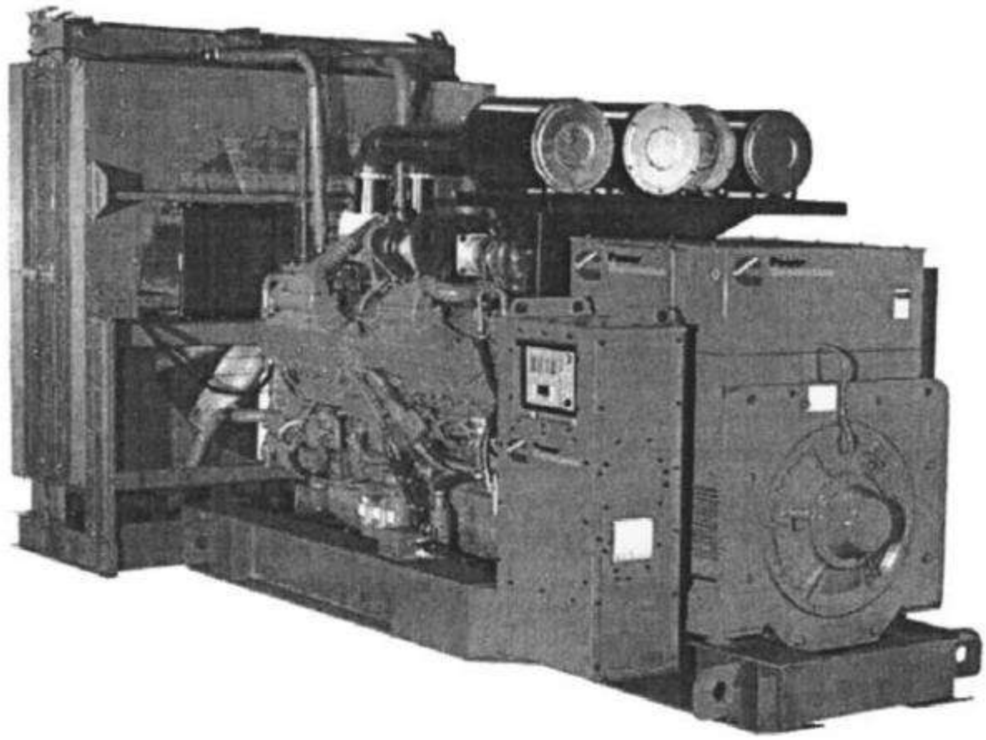


Figure 40. Diesel reciprocating engine genset.

However, compared to a reciprocating engine, the waste heat from a combustion turbine is substantially hotter. As a result, when a combined heat and power application calls for process steam, turbines are typically the preferred option.

5.5.2 Combustion (gas) turbines

The typical size range of combustion turbines utilised in cogeneration applications connected to the distribution system is 1 to 10 MW.The turbines are normally geared down to the synchronous alternator's needed speed, which is typically 1800 or 3600 rpm for 60-Hz systems. The turbines typically rotate between 8000 and 12,000 rpm. In either simple-cycle or combined-cycle configurations, units of 10 MW or more in size are frequently found connected to the transmission grid. Although different liquid fuels can also be used, natural gas is the most typical fuel.

The microturbine, a new type of combustion turbine, is what has sparked some of the resurgence in interest in DG. With the heat exchanger on the left, Figure 41 depicts a microturbine being used in a combined heat and power application. The clean and compact installations of this technology are one of its main benefits.This enables deployment close to places where people live and work, albeit in some settings the high-pitched turbine noise may cause some problems.

A microturbine's one-piece turbine with a permanent-magnet rotor is the only moving component. The assembly normally spins between 10,000 and 100,000 revolutions per minute (rpm).The output of the alternator is immediately rectified to direct current and supplied into an inverter that connects to the ac electrical power system. The inverter's reaction to system disturbances is thus the aspect of the micro-turbine that interests engineers interested in power quality.

The most typical applications for microturbines, which range in size from 30 to 75 kW, are modest commercial loads. To get better ratings, they might be mirrored in packs. Larger models, also referred to as mini-turbines, are also becoming available and range in power from 300 to 400 kW.The efficiency of microturbine energy generation is frequently stated to be as high as 30%, however 25% is a more likely figure. It is typically not cost-competitive for just producing power because to its low efficiency. However, net energy efficiency surpassing 60% can be attained when combined with an appropriate thermal load. The combined heat and power applications of this technology are best suited for small- to medium-sized commercial and industrial buildings.

Microturbines are sometimes utilised only for the production of energy in specialised applications. Microturbines make practical and eco-friendly standby and peaking generators due to their small size and minimal emissions.They can accept a broad variety of fuels, regardless of quality, and are a practical way to extract energy from bio-mass gas, flare gas, or natural gas that is not cost-effective to transport to pipelines. They are also utilised in some base-load applications.

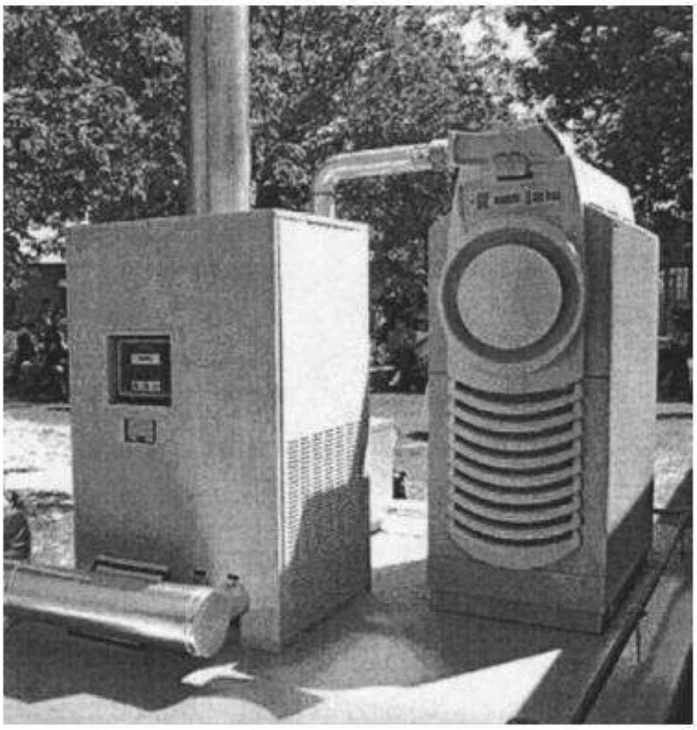


Figure 41. Microturbine in a combined heat and power installation.

5.5.3 Fuel cells

The fuel cell is another fascinating DG technology (Fig.42). Additionally, this technology has a tiny environmental impact, operates quietly, and produces almost no toxic pollutants. In order to attain one of the highest potential energy-conversion efficiencies, combined heat and power applications can make use of fuel cells, which are efficient electricity producers. The fuel cell is considered to be the key energy-conversion technology in those who envision a hydrogen-based energy economy in the future.

A fuel cell is essentially a battery that uses hydrogen to power an electrochemical process. It generates dc electricity, and connecting to the ac power system necessitates the use of an inverter.Currently, cost is fuel cells' main disadvantage. About ten times as expensive as reciprocating gensets are fuel cell technologies. This will confine the use of fuel cells for the generation of electricity to specialised applications until a price breakthrough. This innovation is anticipated to happen when the car industry switches to fuel cells.

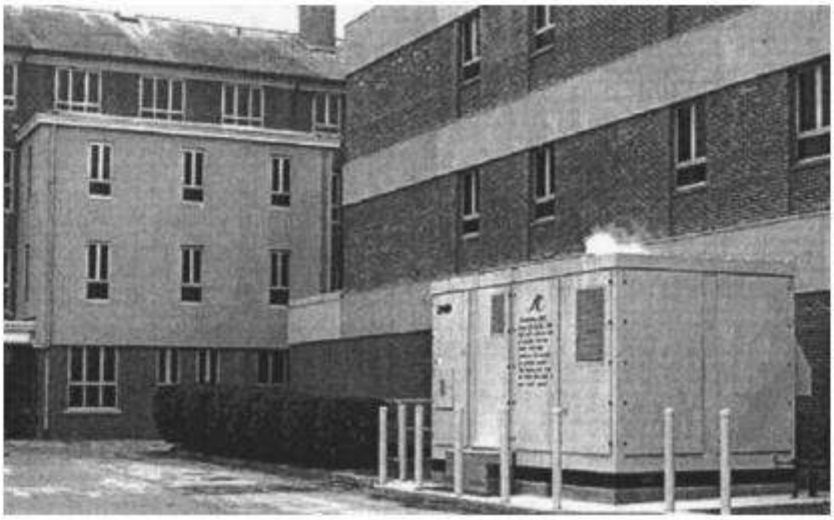


Figure 42 A fuel cell producing electricity and heat for a hospital

5.5.4 Wind turbines

Rapid growth in wind generation capacity has made it cost-competitive with conventional forms of energy in some areas. A typical application involves assembling several wind turbines with individual capacities ranging from 700 to 1200 kW into a "wind farm" with a combined maximum capacity of 200 to 500 MW. The example in Fig. 43 is just one. Instead of the distribution system, such huge farms are connected to the transmission system. For applications like ski resorts, smaller farms of 6 to 8 MW have been suggested; these farms would be directly connected to distribution feeders.Voltage regulation is the main problem with power quality in wind power. Wind power plants are frequently found in sparsely populated places where the electrical infrastructure is inadequate in comparison to the power they can provide. Voltage fluctuations that come from this are challenging to control. As a result, serving loads from the same feeder that also serves a wind farm is occasionally not practicable.

The electrical system interface for wind turbines uses three primary groups of generating technologies:

1.Traditional squirrel-cage or wound-rotor induction machines. To address the need for reactive power, switching capacitors are commonly added to these.

2.Wound-rotor induction machines with dual feeds that use power converters to regulate rotor current in order to regulate reactive power.

3. Non-power frequency generation requiring an interaction with an inverter.

Figure 43 Wind farm

5.5.5 Photovoltaic System

The installation of rooftop photovoltaic solar systems has been prompted by recent power shortages in several states and the passing of net metering legislation. A sizable system on a commercial building in California is depicted in Figure 44. A home unit should be between 2 and 6 kW in size. The cost of electricity after installation is relatively cheap, and the energy source is basically free while it is accessible. Even with buy-down incentives from government programmes, the upfront cost is relatively high. Currently, installed costs range from $5000 to $20,000/kW. Despite its high price, photovoltaic solar technology is favoured by many environmentalists, and it is anticipated that installed capacity will increase in the future.

Inverters are used to connect photovoltaic solar systems to the utility grid and generate dc power while the sun is shining on them. Some systems lack the ability to function independently; the inverters only function in the utility-interactive mode and depend on the grid's availability.

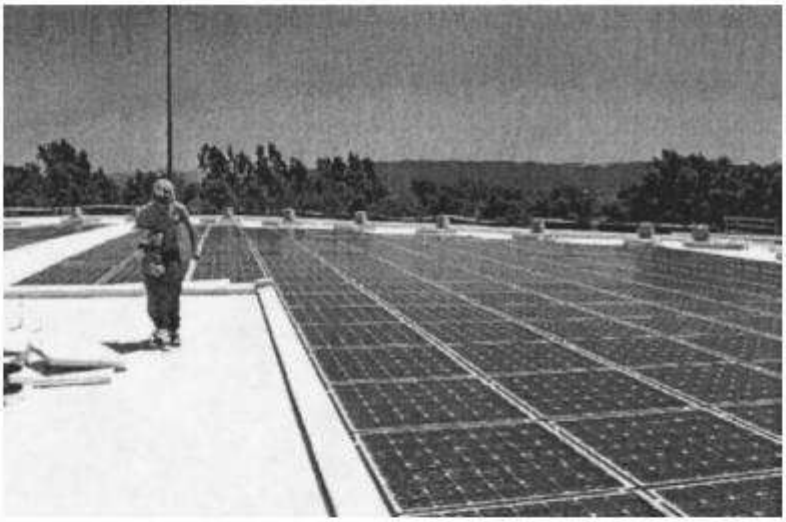


Figure 44 Rooftop photovoltaic solar system

5.5.6 Interface to the Utility System

The impact of DG on the distribution system's power quality is the main issue here. While the energy conversion technology may have some influence on power quality, the type of electrical system interface is usually the source of problems.
Several significant exclusions consist of:

1. Voltage variations may be brought on by the power fluctuation from renewable energy sources like wind and solar.

2. In order to attain the higher reliability anticipated from standby power applications, some fuel cells and microturbines do not respond well to step changes in demand and must be supplemented with battery or flywheel storage.

A persistent and annoying sort of flicker can result from reciprocating engine misfiring, especially if the power system reacts by amplifying it.

Types of Interfaces:
1. Synchronous machines are the major forms of electrical system interfaces.
2. Asynchronous machines (induction)
3. Power inverters for electronics

5.5.7 Synchronous machines

There are various issues when synchronous machines are used in grid parallel DG applications, despite the fact that they are an outdated technology, are widespread on power systems, and are well recognised. They are the most common kind of electric equipment utilised in applications involving backup generating. The machine has the capacity to follow any load within its design limits with adequate field and governor control. Because of its natural inertia, it can withstand fluctuations in step-load. Even though this is ideal for backup power, utility distribution engineers are quite concerned about it since this technology can readily support accidental islands that might emerge when the utility feeder breaker opens. Additionally, it has the ability to feed faults and may obstruct utility overcurrent protection.Interconnected synchronous generators on distribution systems are typically run with a constant power factor or constant variable exciter control, unless the machines are large in relation to the system capacity. For starters, a small DG lacks the capacity to control the voltage while connected. In most cases, doing so would cause the exciter to swing between the two extremes. Second, this prevents the utility voltage regulation system and the voltage controllers of several tiny equipment from conflicting with one another. The third reason for doing this is to lessen the likelihood that an accidental island will be sustained. To avoid being discovered, the island would need to be a nearly perfect match of the load at the time of separation.The utility system voltage can be controlled by a synchronous machine that is enormous compared to the PCC system's capacity. In some fragile systems, this may be an advantage in terms of power quality. The utility system protection and voltage control equipment should be coordinated with this type of system and properly analysed. Without adding complex controls, it would be possible to allow only one generator on each substation bus to run in this way. Voltage regulation will probably be taken over by the generation, which may cause voltage regulators to tap in the wrong places. However, utility voltage regulators have the potential to cause the generator exciter to operate at unfavourable set points. Many utilities will want a direct transfer trip between the utility breaker and the generation interconnection breaker in order to assure the detection of utility-side failures when the connected generator is being run under automatic voltage management.

The impedance of synchronous generators is one feature that is frequently disregarded.Generators sized for normal backup power applications have large impedances in comparison to the utility electrical power supply. Harmonics typically observe a subtransient reactance Xd that is around 15% of the machine's rated value. Around 25% may be the transient reactance, Xd, which controls the majority of the fault contribution. Typically, the synchronous reactance Xd is greater than 100%.As opposed to this, the power system's impedance as viewed from the main load bus is typically just 5 to 6 percent of the service transformer's rating, which is typically higher than the machine rating. End customers who anticipate a relatively painless transition from an integrated operation to an isolated backup operation are frequently let down. Here are some examples of unexpected effects in real life

1.When the generator tries to power adjustable-speed-drive loads, the harmonic voltage distortion rises to unbearable levels.
2. The fault current is insufficient to trip breakers or blow fuses that were sized for the contribution of the power supply.
3. Fluorescent lighting go out when lift motors are turned on because of a voltage drop.

To provide adequate power quality in isolated operation, generators must be sized far greater than the load.

The imperfection of a synchronous machine's voltage waveform is another issue that is frequently disregarded. There are significant third-harmonic currents in the voltage in some designs. This flaw may also exist in utility central station generation, but the unit step-up transformer's delta winding prevents the harmonic from moving. Because many possible end-user DG locations' service transformer connections are not set up to do this, a lot of third-harmonic currents will flow into the generator and possibly onto the utility system.

The end result is that, in order to reduce the third-harmonic component, synchronous generators for grid parallel DG applications should typically be constructed with a 2/3 winding pitch. If not, great care must be used when connecting the interface transformer, or other devices such a neutral reactor and shorting switch must be fitted.

5.5.8 Asynchronous machines

In many ways, connecting induction devices to the utility grid is straightforward. Induction motors are operated a little bit faster than synchronous speed to create induction generators. The likelihood of accidental islanding is significantly decreased because they need an additional source of stimulation. No specialised synchronising hardware is required. Induction generators can even be started across the line if the electrical power system's capacity allows for it. Before the machine is connected in weaker systems, the prime mover is started and brought to almost synchronous speed.After closure, there will be an inrush transient, but this will be minimal compared to beginning from a stop across the line.Operating an induction generator and an induction motor of the same size have essentially the same requirements. The main problem is that a simple induction generator needs reactive power (vars) from the power supply to which it is attached to excite the machine. This can be advantageous on rare occasions when there are high-voltage issues, but in most induction generator applications, low-voltage issues will prevail. In order to supply the reactive power locally, power factor correction capacitors are typically added as a repair. While it generally works well, there may be additional power quality issues as a result.One of the issues is that harmonics generated in the same facility will coincide with resonances created by the capacitor bank.Self-excitation is a different problem. A temporarily isolated induction generator mounted on a capacitor bank can keep producing for a while. Since this voltage is unregulated, it is likely to soon stray outside of the expected range and be noticed. However, this circumstance frequently leads to a ferroresonant state with harmful voltages.It is typically necessary to have instantaneous overvoltage relaying for induction generators that can get isolated on capacitor banks and loads that are less than three times the rated power.The idea that induction generators don't contribute to utility-side problems is one common misconception about them. Examples from textbooks often illustrate how an induction machine that dies after 1.5 cycles contributes current to a problem. However, there aren't many faults like this on a utility distribution system. This is true for three-phase faults close to the machine terminals that collapse the terminal phase voltages. The voltage on the affected phase does not drop to zero in the majority of SLG faults (see the examples in Chapter 3). In fact, very little voltage fluctuation may be noticed by generators connected to delta-wye transformers.A general rule of thumb is that if the voltage supplying the induction machine remains higher than 60%, assume that it will continue to feed into the fault as if it were a synchronous machine. This voltage level is sufficient to maintain excitation levels within the machine. There are many complex dynamics occurring within the machine during unbalanced faults, and a detailed electromagnetic transients analysis is needed to compute them precisely.

5.5.9 Electronic power inverters

To connect to the electrical power system, all DG technologies that produce either dc or non-power frequency ac must employ an electronic power inverter.Early line-commutated, thyristor-based inverters quickly gained a reputation for being bad for the power system. In reality, plans to build thousands of rooftop photovoltaic solar arrays with line-commutated inverters served as the impetus for the creation of a large portion of the harmonics analysis technology described in Chapters 5 and 6.4 These inverters generated harmonic currents in a manner that was comparable to that of loads driven by conventional thyristor-based converters. One concern was that this kind of DG would generate a substantial amount of power at the harmonic frequencies, in addition to adding to the distortion on the feeders. Wires are only heated by such power.The inverter technology has changed to switched, pulse-width modulated technologies in order to improve control and prevent harmonics issues. The electrical power system now has a friendlier user interface as a result of this.

The fundamental parts of a utility interactive inverter that complies with IEEE Standard 929-2000 are depicted in Figure 45. On the left side of the diagram, direct current is delivered either directly from a conversion technology or by rectifying the output of an ac generator. Many fuel cells, microturbines, photovoltaic solar systems, and certain wind turbines use variations of this type of inverter.To produce a sinusoid voltage or current of high frequency, an insulated gate bipolar transistor (IGBT) switch rapidly switches the dc voltage. Typically, the switching frequency is 50 to 100 times higher than the power frequency. These high-frequency components are typically inconsequential due to the filter on the output's attenuation. However, these high frequencies might occasionally be audible due to resonance circumstances in the power supply. The highest low-order harmonic, which is typically the fifth, is typically less than 3%, and the other harmonics are frequently insignificant. Based on the standards of IEEE Standard 519-1992, the overall harmonic distortion limit is set at 5%. Under certain circumstances, some inverters will occasionally surpass these limits.Manufacturers might cut corners with filtering or the switch control algorithm might contain a bug. However, compared to inverters based on previous technology, the harmonic problem with modern inverters is unquestionably much less of a concern.

Commonly used inverters primarily aim to produce a sine-wave current that mirrors the voltage waveform while connected to the utility. They would generate power at a unity power factor as a result. Although alternative strategies can be programmed into the switching control, the unity power factor strategy is the most straightforward and widely used. Additionally, it enables the switch's full current-carrying capacity to be employed for supplying active power (watts). The control goal would change to creating a sinusoidal voltage waveform at power frequency if the inverter had stand-alone capabilities, and the current would then follow the load.

One benefit of such an inverter for DG applications is that it may be immediately shut off when a problem is found. If there are synchronous machines with significant inertia maintaining the voltage on the system, there may be some delay in realising that something is wrong. The switching simply stops when a problem that requires disconnecting is found. Changes can occur in milliseconds thanks to the inertia that inverters typically display. Rotating machines could take a few cycles to react.As long as the current surge restrictions in the semiconductor switches are not exceeded, it would be possible to reclose out of phase on inverters without causing harm. Reconnection and resynchronization consequently present less of a challenge than in the case of synchronous machines.

The maximum current capacity of the IGBT switches is typically what restricts an inverter's ability to feed utility-side faults. Analysts frequently anticipate that the current will be restricted to two times the inverter's rated output. Naturally, the inverter will most likely presume a problem and stop working for a certain period of time once the current hits these numbers.Utility interactive operations may benefit from this, while applications that need a specific level of fault current to trigger relays may find it to be a drawback.

In accordance with IEEE Standard 929-2000, utility interactive inverters additionally feature a destabilising signal that persistently tries to modify the frequency of the control. The goal is to ensure that inaccurate islands are quickly found. Despite being tied to the utility, the electrical power system's strength outweighs this tendency towards instability. The frequency will soon deviate if the inverter system is suddenly isolated on load, allowing the control and external relays to notice it.

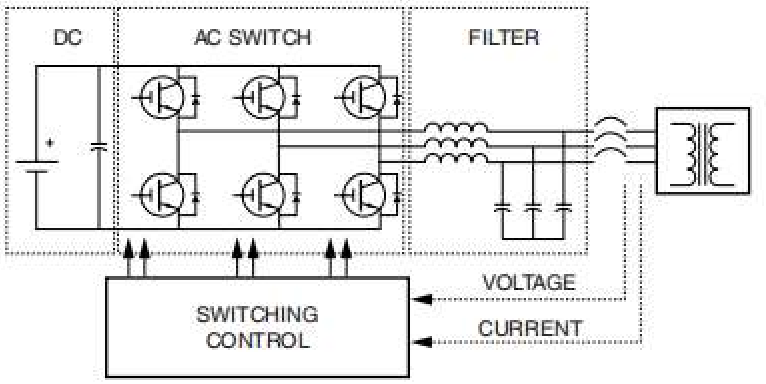


Figure 45. Simplified schematic diagram of a modern switching inverter

5.6 Power Quality Issues

One of the biggest power quality problems caused by DG is

1. Long interruptions. The usual reliability area is this. Many generators are built to supply backup power to the load in the event of a power outage. However, in some circumstances, DG might lead to more disruptions.
2. Regulation of voltage. When it comes to how much DG can be supported on a distribution feeder without requiring adjustments, this is frequently the biggest limiting element.
3.Harmonics. Both rotating machinery and inverters have harmonics issues, albeit the issue with inverters is less significant with contemporary technology.
4. Sag in voltage. This is a unique situation because DG might or might not be helpful.

These topics are covered one by one.

5.6.1 Long interruptions

A large portion of the existing DG was deployed as backup generation. Diesel gensets are the most often utilised technology for backup generation. Simply shifting the load to the backup system will realise the majority of this sort of DG's capability. Paralleling with the power system will allow for the extraction of more power, nevertheless. Due to its large capacity, the utility system will allow for many DG plants to run with better power quality. Not all backup DG, though, can be paralleled without incurring significant costs.

Not all DG technologies have the potential to significantly increase reliability. The DG must be able to handle the load when the utility system is unable to do so in order to achieve improvement.In order to survive rotating blackouts, a homeowner can, for instance, build a rooftop photovoltaic solar system. Unfortunately, the less expensive systems lack the necessary inverter and store capacity to function independently. As a result, reliability has not increased.

By using DG to cover emergencies when a portion of the delivery system is down, utilities may increase dependability. In this instance, the DG only serves a portion of the load—just enough to make up for the capacity that is not in use. This may enable deferring significant construction costs for a few years. The drawback is that overuse of this strategy can eventually result in lower reliability.If the load growth exceeds the system's base capacity, load shedding will be necessary during peak load periods or the system won't be able to maintain a safe voltage after a fault.

5.6.2 Regulation of Voltage

At first glance, it could appear that DG could enhance a feeder's voltage regulation. Compared to switched capacitor banks and typical tap-changing transformers, generator controls are substantially faster and more streamlined. This is possible with sufficiently huge DG with proper engineering. Voltage regulation, however, is not without its issues. Voltage regulation problems are frequently the most restricting for being able to handle the DG without alterations to the utility system in circumstances where the DG is placed relatively distance from the substation for the size of DG.

It is important to first acknowledge that some methods are inappropriate for controlling voltage. Simple induction machines and the majority of utility interactive inverters that don't generate reactive power fall into this category.Second, since doing so would interfere with utility voltage regulation equipment and increase the likelihood of sustaining an island, most utilities do not want the DG to try to regulate the voltage. Different DG would conflict with one another. Last but not least, a tiny DG simply lacks the power to control the voltage and will instead be dominated by the daily voltage fluctuations on the utility system. To interconnect with a fixed power factor or fixed reactive power regulation, small DG is nearly always necessary.

In order for large DG more than 30% of the feeder capacity that is set to regulate the voltage to function successfully with the utility voltage-regulating equipment, special communications and control are frequently needed. As the load cycles up and down, it's not uncommon for the DG to take over the voltage-regulating functions and push the substation load tap changer (LTC) into a considerable bucking position. When the DG abruptly disconnects, like it might due to a fault, this causes a difficulty. When this happens, the voltage is insufficient to support the load, and it takes a while for it to recover. Establishing a control system that locks the LTC at a predetermined tap while the generator is running and connected is one solution.

If there were a sufficient penetration of distributed, smaller DG producing a constant power factor, large voltage shifts are also possible.Shockingly attaching or unplugging such generation can cause a significant voltage change, which will last until the utility voltage-regulating system notices it. The adjustment should not be greater than 5% because this could take a few minutes. Fault clearing on the utility system is one circumstance that could result in this. When a fault occurs, all of the generation would disconnect, wait five minutes, and then reconnect. Customers would initially experience low voltage for around a minute before experiencing high voltages five minutes later. Faster tap-changing voltage regulators and the requirement that the load be disconnected anytime the DG is forced off are two solutions to this problem.When the DG is running at a power factor that is close to unity, there is less voltage excursion. However, there might be some circumstances when having the DG create reactive power will be helpful in everyday operation.

5.6.3 Harmonics

Many people still connect DG with unpleasant encounters with harmonics from electronic power converters. This would be a significant issue if thyristor-based, line-commutated inverters were still the standard. Fortunately, switching inverters like the one previously discussed in this chapter have been accepted by technologies that call for inverters. The majority of the harmonics issues with these technologies have been resolved as a result.

When a switching inverter is deployed in a system that resonates at frequencies created by the switching operation, one uncommon problem can develop. High-frequency hash typically appears on the voltage waveform as the symptom. The most common power quality issue, if there is one, is that clocks powered by this voltage can occasionally run too quickly.Adding a capacitor to the bus large enough to shunt off the high-frequency components while preventing new resonances usually resolves this issue.

In grid parallel operation, harmonics from rotating machines are not necessarily negligible. Zero-sequence triplen harmonics in the voltage are short-circuited by the utility power system, which can lead to surprisingly high currents. Only synchronous machines with a 2/3 pitch can be paralleled without special guidelines to control neutral current for grounded wye-wye or delta-wye service transformers. Nearly any type of three-phase alternator can be paralleled without this harmonic problem for service transformer connections with a delta-connected winding on the DG side.

5.6.4 Voltage sags

Voltage sags are the most typical power quality issue, however DG's ability to help with sags depends greatly on the type of generation technology and the interconnection location. A scenario where DG is coupled on the service transformer's load side is shown in Figure 46. A voltage sag may be countered by DG during the sag. The voltage magnitudes and phase correlations can be supported by large spinning machines. It is conceivable to operate an inverter to offset voltage excursions, despite this capability not being common.The impedance of the service transformer, which offers some isolation from the source of the sag on the utility system, aids the DG's influence on sags at its own load bus. However, because of this impedance, the DG is unable to offer any relief to other loads on the same feeder. DGs with capacities more than 1 MW frequently need to have their own service transformer. The primary distribution system serves as the point of common coupling with any load. Since other loads fed by the feeder experience voltage sag characteristics, it is unlikely that DG linked in this way will have any effect on those characteristics.

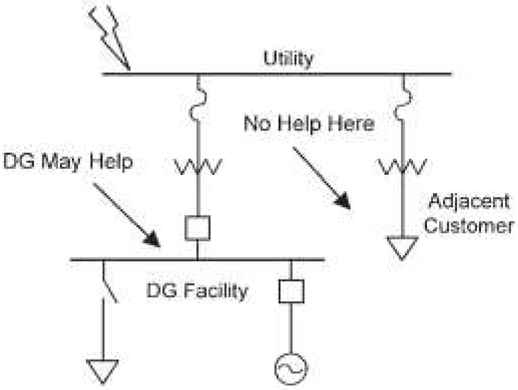


Figure 46. The impedance of the connections transformer prevents any effect on nearby utility customers, however distributed generation (DG) may help eliminate voltage sags on the local facility bus.

5.7 Power quality and reliability

The "Load Interruption Frequency" and the "Expected Duration of Load Interrupt Events" are indices in the power distribution system. These two fundamental indexes are utilised to create additional helpful indexes, such as [229]:

1. Total anticipated annual disruption time.
2. At the load supply point in question, availability or unavailability of the system is measured.
3. Energy is expected and requested but not provided annually.

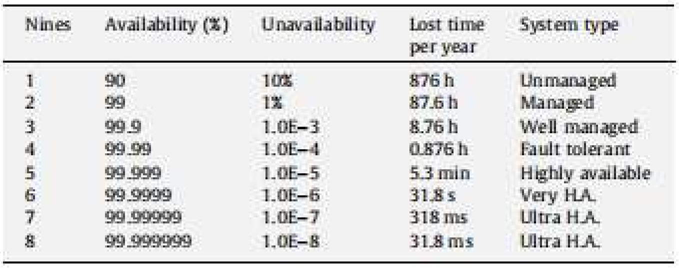
The average percentage of time over the long term that a system or component is successfully performing its intended function in service is known as availability. Typically, 365 days a year is used as the baseline maximum for measuring availability. It's common to refer to the availability, as indicated in Table 8, as the adopted reliability for high-value critical-process or computing programmes. A old, well-maintained grid provided power with a 99.9% reliability rate, or, in today's terminology, "three nines." Thus, for a total of 8,760 hours in a year, electricity customers face outages that last an average of 8 hours, which has historically been considered tolerable by the majority of utility subscribers.In terms of service interruptions, metropolitan power supply is currently given with a reliability of 5–6 nines, however rural electric customers often experience a low level of reliability, typically in the range of 2-3 nines.

It has been acknowledged, nonetheless, that this conventional dependability indicator is only marginally useful for comprehending the implications for digital technology [230]. For instance, a semiconductor fabrication factory may find frequent brief outages to be significantly more expensive and disruptive than a single 8-hour power outage. Measures of reliability should soon take into account some additional power quality issues (such voltage sag and swell disruptions), which are becoming more important as we go into the digital era.crucial process information services of high value Modern power system reliability refers more to [231], which is considerably different from earlier thinking on the subject.

Security. lowering the susceptibility of the infrastructures for power and information technology.

Quality. the provision of high-quality power for a huge number of digital devices.
Possibility and dependability. supporting 'five nines' (i.e., 99.999 availability),'six nines', or even higher bus voltage reliability.
redundant and self-healing. Increasing reliability through the use of distributed energy resources (DERs)

With the widespread use of PLCs, adjustable-speed drives (ASDs), computers, and other vulnerable equipment, the industry is growing more and more concerned about the issue of power quality and how it relates to the susceptibility of highly automated operations.The voltage sag (dip) and temporary interruption are the banes of automated industrial operations among all types of electrical disruptions [232].



Nines	Availability (%)	Unavailability	Lost time per year	System type
1	90	10%	876 h	Unmanaged
2	99	1%	87.6 h	Managed
3	99.9	1.0E−3	8.76 h	Well managed
4	99.99	1.0E−4	0.876 h	Fault tolerant
5	99.999	1.0E−5	5.3 min	Highly available
6	99.9999	1.0E−6	31.8 s	Very H.A.
7	99.99999	1.0E−7	318 ms	Ultra H.A.
8	99.999999	1.0E−8	31.8 ms	Ultra H.A.

Table 8. Comparative levels of availability

The term "voltage sag" refers to any low voltage event lasting 0.5 to 60 cycles that is between 10% and 90% of the nominal RMS voltage. A momentary voltage interruption is any low voltage event lasting between 0.5 cycles and 3 s that is less than 10% of the nominal RMS voltage. Power system breakdowns are the primary source of voltage sags in medium voltage distribution networks. According to where consumers are located in the electrical network, voltage sags caused by other faults might have varying effects on consumers. Although the load current is less than the fault current in comparison, variations in the load current during and after the fault have a significant impact on the voltage at the equipment terminals.According to research, voltage sags or interruptions of less than one second in length are to blame for 85% of power supply failures attributed to poor power quality [233].

Voltage sags can also be caused by starting large motors, though usually not to the same an extent. Voltage sags affect more customers than disruptions do, and for some of those customers, they may result in very serious issues. Sensitive equipment may experience issues if it is built to work within specific voltage ranges or if it lacks sufficient ride-through capabilities to filter out electrical supply fluctuations [234].Operations involving instruments and controls necessitate high-quality, ultra-reliable electricity in hitherto unseen amounts and time frames. Sags below 87% voltage and lasting longer than 8.3 milliseconds at the utility feed to the plant were predicted to cause production disruptions [235]. The issue is now worse, though, as more and more sensitive equipment is using more and more of the electricity that is now being provided by the utility providers [236].

DG is frequently utilised to boost on-site security [237]. Both the variety of primary energy sources and the dependability of the electrical supply are affected.There is currently no standard that outlines the obligations of the energy provider, the maker of the automation equipment, and the automated plant itself with regard to mitigating losses brought on by SQRA events [238]. High-tech customers are anticipated to demand a high level of security, quality, reliability, and availability (SQRA) power supply as modern economies enter the twenty-first century. This might be the most significant market opportunity for DG. In addition to enhancing the distribution grid's dependability, distributed generation (DG) can meet the needs of customers who need more SQRA electricity than the grid can typically supply, such as those who use continuous manufacturing processes or internet services and need to ensure a steady supply of power.This is creating new and exciting commercial prospects for acute energy providers in the deregulated electricity market [239].

5.8 Facility overview

A 25 kV feeder running from a remote substation supplies the Infrico complex. In order to step-down the 25 kV-230/400 V for the panel boards scattered throughout the building, the facility includes its own 630 kVA delta-wye transformer. Modern semi-automatic factory dedicated to manufacturing freezers and cool systems for the hospitality and pastry industries is the Infrico plant. A Flexible Manufacturing System (FSM) from one of the top suppliers in the world has recently been incorporated; it is a modular sheet metal FSM for the assembly of the stainless steel cabinet made for the various refrigerators listed in the Infrico catalogue.With the addition of a hydraulic or servo electric turret punch and its automatic loading/unloading function, the integrated FMS cells may perform integrated bending, right angle shearing, or laser cutting. Aside from that, it includes a automatic material handling module that can function as a skeleton handling system, automatic raw sheet storage, and buffer storage between two fabrication processes (perhaps even with the ability to sort by material type).

Chapter 6

The increased usage of sensitive electronics by industry and commercial customers is compelling utilities and consumers to pay more attention to the quality of the power they receive. Consumers, equipment manufacturers, and utilities are all currently worried about difficulties with power quality. The utility side feels under pressure to provide its consumers with high-quality power in order to meet their needs and draw in new customers. The consumer must receive adequate information from the utility side regarding electricity quality. If the utility side fails to provide high-quality power, they are penalized and are required to make up for the harmed customer. The manufacturers of equipment are attempting to create products that can withstand changes in power quality.Consumers also have high expectations for equipment and power that adheres to the standards in place. Voltage sag, voltage swell, transients, and steady state events like flicker and harmonics are the typical power quality problems. Voltage sag is the most common power quality phenomenon that affects end customers and causes significant financial loss. The device malfunctions and trips as a result of short-lived voltage sags. Additionally, the industrial customer experiences this occurrence with power quality the most frequently. Numerous techniques are used to lower the frequency of voltage sags, equipment trips, and process interruptions. The methodology for potential solutions either focused on lowering the amount of voltage sags or on reducing financial losses caused by the equipment malfunctioning or tripping in industrial or commercial processes.

6.1 Power Quality Monitoring

Gathering, analysing, and turning raw measurement data into information is the process of power quality monitoring. Data collection is often done by measuring voltage and current continuously over a lengthy period of time. Traditional analysis and interpretation were carried out manually, but recent developments in the fields of signal processing and artificial intelligence have made it possible to design and implement intelligent systems to automatically analyse and interpret raw data into useful information with little to no human involvement.

Programmes for power quality monitoring are frequently motivated by the need to enhance system-wide power quality performance.

6.1.1 Monitoring Points of Interest

One should distinctly establish the monitoring objectives before starting any power quality monitoring activity. The selection of monitoring tools, trigger thresholds, techniques for data collection and storage, and the demands for analysis and interpretation are frequently influenced by the monitoring objectives. Here is a list of a few typical goals for power quality monitoring.

monitoring to assess the performance of the system. The most general criterion is this. This purpose might be significant to a power producer if it wants to understand system performance and then match that performance to customer needs. A proactive method of power quality monitoring is system characterization. Understanding a system's typical power quality performance allows a provider to spot issues as soon as they arise and to supply its clients with knowledge that will enable them to match the features of their sensitive equipment with actual power quality characteristics.

6.1.2 Monitoring to Identify Specific Issues

Short-term monitoring is a common method used by power quality service departments or plant management to address issues at particular customer sites or with challenging loads. Although this technique of power quality monitoring is reactive, it frequently pinpoints the root of equipment incompatibility, which is the first step in a solution.

6.1.3 As Part of a Better Service for Power Quality Monitoring

Many energy providers are currently thinking about adding new services to their customer offerings. Offering varied degrees of electricity quality to meet the needs of various consumers would be one of these services. This objective can be met by a provider and a customer working jointly by putting equipment on the customer's property or changing the power system.In either scenario, monitoring is crucial to determining the standards for the differentiated service and ensuring that the utility meets the agreed-upon standards for power quality.

6.1.4 Monitoring as a Component of Preventative or Just-in-time Maintenance

Power quality data obtained over time can be examined to provide details on the performance of certain equipment. For instance, repeated capacitor-switching restrikes may indicate an impending failure of the capacitor-switching mechanism, just as repeated arcing faults from an underground cable may indicate an impending cable failure. Equipment upkeep can be swiftly requested to avoid catastrophic failure, hence averting significant power quality disruptions that will ultimately affect the performance of overall power quality.The monitoring programme must be created with the right objectives in mind and make the information accessible as soon as possible (i.e., immediately). A permanently installed monitoring system with automatic data gathering for both steady-state power quality conditions and energy use as well as disturbances will be the most comprehensive monitoring strategy.

6.1.5 Monitoring during a facility site inspection

Site surveys are carried out to assess issues with the functioning of the equipment and the quality of the power in a facility. The study will look at issues with wiring and grounding, equipment connections, and the facility's overall voltage and current characteristics. Infrared scans, ocular inspections, and power quality monitoring are crucial components of the total study.

The primary site survey ought to be planned to gather as much data as possible regarding the client facility. Particularly when the monitoring purpose is meant to address particular power quality issues, this information is crucial. The details are outlined here.

1. The nature of the issues (such as data loss, bothersome trips, component failures, control system issues, etc.)
2. The characteristics of the sensitive equipment that is having issues (at the very least, application guide information or equipment design information)

3. The moments that issues arise
4. Coincidence issues or known processes (like capacitor switching) that happen concurrently
5. Potential causes of power quality variations in the facility (such as arcing equipment, capacitor switching, motor starting, and power electronic equipment operation).
6. Using current power conditioning equipment
7. Information about electrical systems (such as cable data, one-line diagrams, transformer sizes and impedances, load data, and capacitor information).

6.1.6 Deciding what to watch

Power system conditions fall under the broad category of power quality. Important disturbances can include long-term overvoltages brought on by a regulator tap switching issue, current chopping during circuit interruptions, or extremely high frequency impulses brought on by lightning strikes. The variety of situations that must be characterised poses problems for the performance specifications of the monitoring equipment as well as the requirements for data collecting.

For the needs of monitoring, the techniques for describing ac power quality are crucial. For instance, high-frequency waveform sampling is necessary to characterise the majority of transients. A plot of the rms voltage against time can be used to identify voltage sags. A time frame is all that is needed to define an outage. Steady-state sampling is necessary for the monitoring of harmonic distortion levels and typical voltage changes, and the data must be analysed for trends over time. It may be expensive in terms of gear, communications costs, data administration, and report creation to conduct extensive monitoring of all the many sorts of power quality variations at numerous locations. As a result, the goals of the effort should be used to set the monitoring priority.Deciding where to monitor
Of course, in order to fully comprehend the system's total power quality, we would like to keep an eye on circumstances almost everywhere. However, the cost of such monitoring can be unaffordable, and there are difficulties in data administration, processing, and interpretation. Fortunately, since measurements gathered from a number of strategically placed points can be used to derive features of the overall system, taking measures from every conceivable position is typically not necessary. Therefore, it is crucial that the monitoring sites are properly chosen depending on the monitoring goals. Here are some illustrations of how to pick a monitoring location.
The EPRI DPQ project's monitoring experience1 provides a great illustration of how to pick monitoring sites.

The main goal of the DPQ project was to describe the power quality on the distribution feeders of U.S. electric utilities. Beginning in June 1992, actual feeder monitoring was finished in September 1995. Nearly 300 measuring locations and 24 different utilities took part in the data collection project. A statistically valid set of data on the numerous phenomena connected to power quality was to be provided by the project's monitoring.
The actual feeder circuits were monitored because it was the main goal, to characterise power quality on principal distribution feeders. Two other sites were chosen at random in addition to the monitor that was placed close to the substation.The main goal of the DPQ project was to describe the power quality on the

distribution feeders of U.S. electric utilities. Beginning in June 1992, actual feeder monitoring was finished in September 1995. Nearly 300 measuring locations and 24 different utilities took part in the data collection project. A statistically valid set of data on the numerous phenomena connected to power quality was to be provided by the project's monitoring.

The monitoring locations should be at actual customer service entrance locations when a monitoring project involves characterising specific power quality issues that are actually being experienced by customers on the distribution system because it includes the impact of step-down transformers supplying the customer. Data gathered at the service entrance can also be used to describe harmonic distortion levels and client load current variations. The added benefit of monitoring at customer service entrance sites is lower transducer expenses. Additionally, it offers clues as to where the disturbances originated, i.e., on the utility or customer side of the metre.Locating the monitors as close as feasible to the equipment affected by power quality changes is another crucial component of the monitoring site when characterising specific power quality issues. The monitor must display the same fluctuations as the sensitive equipment in order to function properly. If there is a large distance between the monitor and the afflicted equipment, high-frequency transients in particular may differ dramatically.Monitoring at the substation and specific customer service entrance sites is a suitable compromise strategy. Because it serves as the PCC for the majority of rms voltage changes, the substation is important. All consumers on other feeders supplied from the same substation bus experience the voltage sag experienced at the substation during a feeder malfunction. The service entrance sites for monitoring are determined by the sensitivity of the customer equipment and its location on a feeder.For instance, having a place directly downline from each protective device on the feeder is beneficial.

6.2 Options for devices to monitor power quality

The following are some of the equipment categories that can be used in an overall monitoring system:

6.2.1 DFRs, or digital fault recorders

The majority of substations may already have these in situ. The gadgets are not specifically made by DFR manufacturers for power quality monitoring. The voltage and current waveforms that characterise the fault event are often recorded by a DFR, which normally triggers on fault events.

1. As a result, they are useful for characterising rms disturbances during power system problems, such as voltage sags. For calculating harmonic distortion levels, DFRs can provide periodic waveform capture.
2. Wi-Fi-enabled relays and other IEDs. Many different kinds of substation equipment could be intelligent electronic devices (IEDs) with monitoring capabilities. Manufacturers are incorporating the capability to record disturbances and provide the information to an overall monitoring system controller in equipment like relays and reclosers that monitor the current anyhow. Both at the substation and on the feeder circuits are possible locations for these devices.

Recorders for voltage. To keep track of steady-state voltage changes in distribution systems, power companies employ a variety of voltage recorders. More and more complex models are appearing, fully able to describe transient voltage sags and even harmonic distortion levels. The maximum, minimum, and average voltage within a certain sampling window (for instance, 2 s) are often provided as a trend by the voltage recorder. The recorder can accurately characterise the magnitude of a voltage sag with this kind of sampling. It won't, however, offer the length with a resolution of less than 2 s.

4. Power monitoring inside the plant. Industrial facility monitoring systems now frequently contain some power quality features. These monitors can be utilised as a component of a utility monitoring programme, especially those situated near the service entry. Typical capabilities include triggered waveshape captures for voltage sag circumstances, voltage profiles for steady-state rms changes, and waveshape captures for harmonic distortion levels. Transient monitoring capabilities are uncommon for these sensors.

5. Power quality monitors with a specific purpose. The monitoring tool created for the EPRI DPQ project was especially made to track all variations in power quality. This device can measure voltage and current on all three phases in addition to the neutral. A 14-bit analog-to-digital (A/D) board can sample voltage and current at rates of 128 points per cycle and 256 points per cycle, respectively. Due to the high sampling rate, it was possible to detect voltage harmonics up to the hundredth and current harmonics up to the fifty-first. Most power quality measuring devices have the ability to record both triggered and sampled data. For rms and transient variations, respectively, triggers should be based on waveshape and rms thresholds. A critical capability of these instruments is simultaneous voltage and current monitoring with triggering of all channels during a disturbance. Substations, feeder locations, and customer service entrance locations have all shown to be good candidates for power quality monitors.

6. Receipt metres. Revenue metres already monitor voltage and current, thus it makes sense to include options for more sophisticated monitoring that might capture data on power quality. Almost all revenue metre manufacturers are headed in this way, and data from these metres can subsequently be integrated into a system for monitoring power quality as a whole.

6.2.2 Monitor connection disruptions

It is advised to power the monitor's input from a circuit other than the circuit being monitored. If the monitor is supplied from the same circuit that is being monitored, some manufacturers' input filters and/or surge suppressors on their power supplies may change the data that is being disturbed.

An important factor to consider is the power disturbance monitor's grounding. The disturbance monitor will include a ground connection for the instrument's power supply as well as a ground connection for the signal that will be monitored. The instrument chassis will be wired up to both of these grounds. Both of these ground terminals need to be linked to earth ground for safety reasons.

However, if multiple circuits are involved, this could result in ground loops.

Priority one is safety. Therefore, if there is a question about what to do, the two justifications should be related. It might be conceivable to power the instrument from the same line that is being monitored if ground loops are a serious issue and transient currents could harm the instruments or render the measurements invalid (just make sure there is no signal conditioning in the power supply first). As an alternative, connecting just one ground (the signal to be monitored) and setting the instrument on an insulating mat might be possible. However, this could lead to ground loops if several circuits are involved.

If it is conceivable for the instrument to become more potentially dangerous when compared to other equipment and ground references that the operator may come into touch with, appropriate safety precautions must be taken, such as employing insulated gloves when operating the instrument.

6.2.3 Setting monitor thresholds

Disturbance monitors are intended to find abnormal conditions. The range of conditions that can be regarded as normal must therefore be defined. As a place to start, several disturbance monitors feature pre-selected (default) thresholds.

The ideal method for choosing thresholds is to match them to the requirements of the affected equipment. Due to a lack of specifications or application rules, this could not always be practicable. A different strategy is to set the thresholds fairly tightly for a while (and gather a lot of disturbance data), and then utilise the information gathered to choose suitable thresholds for longer-duration monitoring. Some monitoring systems tout the benefit of requiring no installations or thresholds to be set. Naturally, there must be thresholds as no monitor (to date) has adequate storage space to record every cycle of the voltages and currents under observation. In these situations, the instruments' thresholds are largely set, and algorithms may be changed internally based on the disturbances being recorded. This kind of system is user-friendly because it is easy to set up, but it is still a compromise because you are unable to alter the thresholds based on the local circumstances at a certain site.

6.2.4 Measurement quantities and duration

Sometimes monitoring merely the voltage signals is enough to characterise system disturbances. For instance, the voltages characterise the transients and voltage sags that can impact client equipment and reveal information about the calibre of power being delivered to a facility. The currents connected to these disturbances, however, include a wealth of data that can be used to determine the source and whether or not equipment was harmed. Furthermore, if harmonics are a problem, current measurements are necessary because they capture the harmonic injection from the customer into the power system.

To describe how nonlinear loads on the system produce harmonics, current measurements are employed.

These harmonic generation properties can be determined by measuring the current at individual loads. A collection of loads or the entire facility can be identified as a source of harmonics by current measurements on feeder circuits or at the service entrance. Groups of consumers or a whole feeder can be described using the distribution system's current readings. Voltage measurements aid in describing how the system reacts to harmonic currents that are created. When resonance circumstances exist, high harmonic voltage distortion will be present at particular frequencies. Voltages and currents must be measured simultaneously in order to determine the features of a system's frequency response from measurements. The simultaneous sampling of all three phases is required to measure harmonic power flows.The monitoring's duration is determined by its goals. For instance, because utility system breakdowns are probably uncommon, monitoring may be necessary for a considerable amount of time if the goal is to resolve issues brought on by voltage sags during remote outages. It might be able to describe the conditions over a few days if the issue includes capacitor switching. To gain a sense of how the load fluctuates and how system variables may affect these levels, harmonic distortion problems and flicker difficulties should be characterised over a period of at least one week.The length of the monitoring is becoming less important as permanent power quality monitoring systems are increasingly being used, taking use of the vast range of equipment that may provide data as part of the system.

6.2.5 Tracking down the cause of an issue

Correlating a disturbance's waveform with potential causes is the initial step in determining its origin, as explained in Chapter 2. Identification is made easier if the reason has been classified (for example, as load switching, capacitor switching, remote fault state, or recloser action). The general principles listed below can be useful:

Only areas close to the disturbance's source will see high-frequency voltage changes. Due to circuit resistance, low-voltage (600 V and below) wiring frequently quickly dampens out high-frequency components, thus these frequency components only show up when the monitor is placed close to the source of the disturbance.

There will be a fairly dramatic change in voltage if there are any power outages near to where you are watching. Due to the stored energy in rotating machinery and capacitors, voltage will decay in the event of a power outage far from the monitoring location.

The capacitors that are creating resonance issues will be near by when the highest harmonic voltage distortion levels are present. In these circumstances, the voltage harmonic spectrum will typically be dominated by a single frequency.

6.3 Equipment for Measuring Power Quality

A large range of frequencies are covered by power quality phenomena. They range in duration from long-term outages (hours or days) to extremely quick transient overvoltages (microsecond time frame). In addition, intermittent phenomena like voltage flicker and steady-state phenomena like harmonic distortion are examples of power quality issues.

6.3.1 Instrument Types

Several different instruments may be employed, depending on the phenomenon being studied, even though devices that measure a wide variety of disturbances have been produced.

Wiring and grounding test devices
Multimeters
Oscilloscopes

Disturbance analyzers
Harmonic analyzers and spectrum analyzers
Combination disturbance and harmonic analyzers
Flicker meters
Energy monitors

Other devices that measure ambient conditions can be used to help solve power quality issues in addition to these, which measure steady-state signals or disturbances on the power system directly:

When it comes to identifying frayed connections and overheated wires, infrared metres can be extremely helpful. This kind of yearly system assessment can assist avoid power quality issues caused by arcing, loose connections, and overloaded conductors.

Electromagnetic radiation-related noise issues could necessitate measuring field strengths close to impacted equipment. For inductive coupling problems, magnetic gauss metres are employed to measure magnetic field strengths. When electrostatic coupling is a concern, electric field metres can be used to measure the strength of the electric fields.

Static electricity metres are specialised instruments intended to quantify static electricity in the proximity of equipment that is susceptible to damage. In some kinds of electronic equipment, electrostatic discharge, or ESD, can play a significant role in causing problems with power quality.

When choosing an instrument, a number of crucial aspects should be taken into account, regardless of the type of apparatus required for a certain test. Several crucial elements consist of:

The quantity of channels (for voltage and/or current);
The instrument's temperature parameters
The instrument's ruggedness, the input voltage range (e.g., 0 to 600 V), and the power requirements
Capacity to gauge voltages in three phases
Ability to measure currents; input isolation (isolation between input channels and from each input to ground).
Instrument housing (portable, rack-mount, etc.)
Usability (graphicals capabilities, user interface, etc.)
Communication capabilities (modem, network interface)
Documentation Analysis programmes

The instrument's versatility (comprehensibility) is also crucial. The fewer instruments used, the more functions that may be carried out with a single instrument.

6.4 Evaluation of Measured Power Quality Data

The data administration, analysis, and interpretation tasks have grown to be the most important issues in the total power quality monitoring endeavour as utilities and industrial customers have extended their power quality monitoring systems. Furthermore, the role of data administration and analysis has become even more crucial with the move in power quality monitoring from off-line benchmarking to online operation with automatic identification of issues and concerns.

Power quality data analysis is divided into two streams: offline and online analyses. As the name implies, the central processing centres conduct off-line power quality data analysis. However, for instantaneous information distribution, the online data processing is carried out within the instrument itself.

6.5 Evaluation of offline power quality data

The evaluation of offline power quality data is done independently of the monitoring devices. For this, specialised computer software is employed. Software designers and application programmers frequently face a difficult set of requirements while working on large-scale monitoring projects that require vast amounts of data to be analysed. First and foremost, the software needs to work well with both the many productivity tools that are now on the market and monitoring equipment. An effective and appropriate database is needed for the storage of enormous amounts of measurement data, both from disturbances and steady states. It is necessary to develop data management solutions that can swiftly load and characterise power quality data, as well as to combine analysis tools with the database. The architecture must allow for future growth and customization as well as facilitate automated data management and report production chores.

Data sharing between various types of monitoring devices is now considerably more feasible thanks to the Power Quality Data Interchange Format (PQDIF), a new standard format for exchanging power quality data. This implies that measurement data from a wide range of monitoring devices can be accessed by these systems, and that third parties may write apps for data management and analysis. One example of this kind of third-party programme is PQView.

The following tasks are typically performed by the off-line power quality data assessment software:

1.Examining specific disruptive incidents.

2.RMS variation analysis consists of tabulating voltage sags and swells, computing a variety of rms indices including SARFI, SIARFI, and CAIDI, and creating magnitude-duration scatter plots based on CBEMA, ITI, or user-specified magnitude-duration curves.

3.Steady-state analysis, encompassing trends in real-time voltages and currents as well as imbalances in the negative and zero sequences. Furthermore, a multitude of software systems offer statistical analysis for different probability levels, including minimum, average, maximum, standard deviation, count, and cumulative.

4.Users can do voltage and current harmonic spectra, statistical analysis of different harmonic indices, and trending over time with harmonic analysis.

5.Statistical study of maximum voltage, transient durations, and transient frequency is included in transient analysis.

6.Standardised power quality reports, such as executive summaries, monthly, daily, and customer power quality summaries, statistical performance reports, etc.

7.Examination of protective device performance (problem identification).

8.Examining how energy is used.

9.The relationship between energy consumption or power quality levels and significant characteristics (such as voltage sag performance versus lightning flash density).

10.The way in which equipment functions depends on the levels of power quality (reports on equipment sensitivity).

6.5.1 Evaluation of online power quality data

Data analysis done online during capture is done via online power quality data assessment. The analysis's findings are instantly available for quick distribution. Software design requirements for online assessments typically require a higher level of complexity than those for offline assessments. The majority of capabilities found in offline analysis software can also be added to an online system. Instant message delivery for alerting users to particular occurrences of interest is one of the main benefits of online data analysis. After receiving the notifications, users can then act right away.

6.5.2 Utilising Intelligent System Applications

Numerous sophisticated power quality monitoring systems come with intelligent off- or online systems to assess disturbances and system conditions in order to determine the root cause of the issue or even anticipate issues before they arise. Engineers can quickly ascertain the state of the system by using intelligent systems or autonomous expert systems in monitoring instruments.This is crucial for resuming service after significant disruptions.

A monitoring application's usefulness can be greatly increased by integrating intelligent systems into it so that it can produce information in addition to gathering data.Eleven The intelligent systems are bundled as separate, self-contained expert system modules, each of which carries out distinct tasks. Examples include an expert system module to identify the relative location of the defect causing a voltage sag and another expert system module to analyse capacitor- switching transients and establish the relative location of the capacitor bank.

6.5.3 Samples of expert system applications

An sophisticated power quality monitoring system can be built using one or more autonomous expert system modules. All modules will be triggered when capturing a power quality event. Each module will make an effort to find the particular knowledge that it is intended to look for. Users will be able to examine the unique knowledge as soon as it is discovered. The information can be forwarded as a fax, pager, or email message, or it can be seen in a typical browser. We offer several illustrations of autonomous expert systems.

6.5.4 Module for direction sag in voltage

One of the most significant disruptions to utility networks are voltage sags. Although they can sometimes be brought on by a failure inside end-user facilities, they are typically caused by a remote issue located someplace on the power system. Finding the source of the defect that caused the voltage sag can help prevent them in the future and help identify who is responsible for fixing the issue. For example, contracts with voltage sag performance standards must be implemented with an understanding of the fault site. Sags brought on by issues with the customer facility would not be the supplier's problem.This is crucial to consider when evaluating how well the distribution system performs in relation to the gearbox system since it might lead to voltage sag incidents that affect customer operations. The locations of the faults might be used to predict future issues or pinpoint areas that need maintenance or system adjustments. In any of these situations, an expert system that can locate the fault (at least upstream or downstream from the monitoring location) can be useful.

The voltage sag direction module is an autonomous expert system module that is specifically developed to detect and identify voltage sag events and then identify the voltage sag event's origin (either upstream or downstream from the monitoring point). The utility or the customer side of the metre will be the cause of the voltage sag if a data acquisition node is installed at a consumer PCC. The distribution system or the transmission system will be the cause of the voltage sag if the monitoring point is at a distribution substation transformer.

The current and voltage rms magnitudes before and after the sag event are compared by the voltage sag direction module to determine its operation. It monitors changes in phase angle between prefault and postfault.The source of the voltage sag event can be precisely identified by combining data from the phase angle behaviour and the rms magnitude comparison.Furthermore, the voltage sag direction module has algorithms to evaluate the quality of the information or solution found. The response will be transmitted as an output if it is found to be accurate; else, it will be ignored and no response will be sent. Erroneous or incorrect knowledge can be reduced in this way. There are several reasons why knowledge can be inaccurate, but the most common ones include incomplete information and unresolved conflicts between features.

The voltage sag direction module's outputs can be delivered as an email, printed on paper, sent to a pager, or shown on a computer screen via Web browser software.

6.5.5 Module for radial fault locators

It is possible for radial distribution feeders to have a variety of short-circuit occurrences, including symmetrical (three-phase) and unsymmetrical (single-, double-, and line-to-line) faults. These system flaws can be caused by a variety of factors, from human error and human intervention (such as equipment failure) to natural causes (such as extreme weather and animal encounters). Rapid fault location and source identification is essential for economical system restoration. Sending a lineperson to patrol the suspected feeders is the current procedure used to locate the problems. Although this approach has been tested, it is unquestionably not the most economical technique to restore power.To determine the distance from the position of the measurements to a fault location, an expert system module known as the radial fault locator is created. This module's distinctive characteristic is that it just needs the sequence impedance data from the primary distribution feeder together with a set of three-phase voltages and currents from a single measurement point. In order for the module to function, a permanent fault event must first be identified using the ground fault and phase fault pickup current thresholds.The apparent impedance approach is used to estimate the distance to the fault once a permanent fault occurrence has been recognised[13].After then, an estimate of the fault's distance is shown on a computer screen using a Web browser or paged and delivered to a queue person. The lineperson is able to locate the fault promptly. This example shows how smart power quality monitoring is becoming more popular. The idea is to gather data on power quality, extract relevant information, and then formulate it so users can take the appropriate action.Direction module for switching capacitors. On the power system, capacitor-switching operations are the most frequent source of transient occurrences. Oscillatory transients are produced when a capacitor bank is energised and interacts with the system inductance. In an uncontrolled switching, the transient overvoltage ranges from 1.0 to 2.0 pu, while the usual overvoltages range from 1.3 to 1.4 pu and the frequencies range from 250 to 1000 Hz. Utility capacitor banks that are powered by transients have the potential to spread to client facilities. Switching transients frequently cause sensitive equipment, such as adjustable-speed drives and other electronically controlled loads, to trip off.The position of the capacitor bank will likely be determined by a bigger end-user facilities module.Regarding the monitoring location, there are only two possible locations: upstream and downstream. With grounded, ungrounded, delta-, and wye- (or star-) designed capacitor banks, the expert system module performs admirably. Back-to-back capacitor banks also function nicely with it. Algorithms are built into the capacitor-switching transient direction module to assess the accuracy of the data it gathers. As a result, the module might offer an ambiguous response. Certainly, this response is preferable to the wrong one.

6.5.6 Inspection module for the operation of capacitor-switching.

As previously mentioned, capacitor bank energization process leads to capacitance-switching transients, which are the most frequent cause of transient events on the power system. Fuse blowing is a frequent issue that can arise with a capacitor bank. Before utility workers identify a problem with one or more capacitor banks, the capacitor bank may have been malfunctioning for months. Typically, driving along the line and visually examining the capacitor bank is how routine maintenance is carried out.

For substation applications, an autonomous expert system was created to evaluate downstream transient data, assess if a capacitor-switching operation was completed successfully, and, in the event that it wasn't, to display a warning message.[14]Power systems engineers can greatly benefit from this expert system module in identifying issues and connecting them to capacitor-switching events because most power systems include a high number of capacitor banks. The hallmark of a successful capacitor bank energization is a consistent kvar increase on each phase, the sum of which matches the capacitance kvar size. For instance, reactive power of about 400 kvar should be shown on each phase when a 1200-kvar capacitor bank is powered. By computing the kvar changes in various phases from the current and voltage waveforms before and after the switching operation, the overall kvar increase can be ascertained.Next, the total computed kvar change is contrasted with the user-supplied actual or physical capacitor bank kvar. If the anticipated kvar was not realised, there may be an issue with the capacitor bank's switching mechanism.

6.5.7 Applications for industrial power quality monitoring

Identifying options for energy savings and demand reduction while profiling energy and demand

assessments of harmonics to find resonance issues related to power factor correction, sources of harmonics, issues indicating equipment malfunction (such as converters), and concerns about transformer loading

Evaluation of voltage sag's effects on sensitive equipment and potential avenues for process ride-through improvement

An assessment of power factor correction is necessary to determine whether capacitor banks are operating properly, as well as whether switching, resonance, and performance optimisation can reduce electricity costs.

Evaluation of the motor's starting to spot switching issues, inrush current issues, and protection device functionality

Evaluation of short-circuit protection to assess if protective devices are operating properly based on time-current curves, short-circuit current characteristics, etc.

6.6 Benchmarking and performance evaluation of power systems

Constant-state power quality metrics (voltage regulation, imbalance, flicker, harmonics) are trended and analysed for performance trends, correlation with system conditions (generation, loading, capacitor banks, etc.), and conditions that require attention are identified.

Characterising and assessing voltage sags in order to determine their source (transmission or distribution), as well as characterising the events for categorization and analysis (which may involve grouping several events together and identifying subevents for examination of protective device operations).

Characterizing capacitor-switching to locate the capacitor bank, determine the transient's source (upline or downline), and characterise the events for database administration and analysi.

Computing and reporting performance indices for the purpose of system benchmarking and setting investment priorities for system maintenance and enhancement.

6.7 Applications for reliability, operations, and system maintenance

finding fault is one of the most significant advantages of the monitoring systems is this. It can significantly speed up the reaction time for circuit repairs and pinpoint the root causes of several failures occurring at one site over time.

Evaluation of capacitor bank performance. Fuse blowing, can failures, switch issues (resets, reinstallations), and resonance issues can all be detected by intelligent software.

Evaluation of voltage regulator performance to find anomalous operations, arcing issues, regulation issues, etc.

Distributed evaluation of generator performance. Interconnection difficulties, like islanding, harmonic injection, and protective device coordination, should be detected by smart systems.

Identification of impending faults. According to research, current discharges frequently take place weeks before cable and arrester failures actually occur. For the monitoring system, this expert system application is perfect.

Transformer loss of life issues related to loading can be assessed by transformer loading assessments, which can also take into account the effects of harmonic loading in the computations.

An evaluation of the performance of feeder breakers might reveal issues with coordination, correct operation under short-circuit situations, nuisance tripping, etc.

6.8 Monitoring power quality and the Internet

Power quality monitoring systems have been implemented by numerous utilities in order to continuously evaluate system performance and respond more quickly to issues with the system. It is evident that the success of these systems has been greatly attributed to intranet and Internet access to the information. A fully Web-based power quality monitoring system is an example that came about as a result of research that TVA and EPRI started.With the assistance of every member of the EPRI Power Quality Target group, specifications for the system were created to support the variety of applications that such a system must serve. The end product was a modular system that can connect with a wide range of platforms thanks to its fully open architecture.

TVA is installing Web-based monitoring systems at significant clients and sub-stations across their system after contributing to its development. Distributors for TVA are also benefiting from the system.It already has a robust power quality monitoring system in place, and at the central data management (enterprise) level, the new system is connected with the infrastructure of the monitoring system already in place.Integration with additional data-collection devices in the substation and facility is a future requirement for these systems. Information is shared using standard interfaces such as the Power Quality Data Interchange Format (PQDIF) and COMTRADE, and communications are conducted using standard protocols such as UCA. When suitable, the intelligent applications that have been outlined will be implemented at both the enterprise and substation levels.

6.9 Future Scope

Power quality monitoring is quickly becoming into a crucial customer service and an essential part of general distribution system monitoring. Power producers are combining monitoring for energy management, distribution automation, and the assessment of protective device operation with monitoring for power quality. Customers should have access to the power quality data via the intranet, which should be provided to the entire organisation for the purpose of determining the power conditioning needs of their facilities.In order to help consumers understand the performance of the system and to prioritise system expenditures, the power quality information should be examined and condensed. As a result, client equipment sensitivity should serve as the foundation for power quality indices. This idea is well illustrated by the SARFI index for voltage sags.

Power quality includes a broad spectrum of circumstances and disturbances.The data obtained from power quality monitoring systems has the potential to enhance system operating efficiency and customer operations reliability. These are advantages that are indisputable. Power quality monitors have capabilities and uses that are always changing. Many websites provide descriptions of new apps and ongoing development.

6.10 Standards for Monitoring Power Quality

When it comes to the monitoring of electricity quality, standards are crucial. If power quality levels are to be compared between sites and between systems, they must be defined uniformly and described using the same techniques. The IEEE Working Group responsible for coordinating the creation of standards for power quality monitoring is IEEE 1159. Three distinct task teams are working on more detailed recommendations and standards, while the current IEEE 1159 offers general definitions and guidelines for power quality monitoring. In order to improve international consistency in the monitoring requirements, a large portion of this effort is being coordinated with IEC activities. The most significant IEEE and IEC standards are discussed in this section.These guidelines are subject to change because numerous organisations are working on new innovations.

IEEE 1159: Power quality monitoring guide

In order to give standard definitions for the many types of power quality issues as well as broad guidelines for power quality measurements, IEEE Standard 115915 was created. This language can be used by power quality monitoring devices to accurately distinguish between various power quality disturbances and changes.

Working groups were formed to create more complex standards for power quality monitoring following the release of the basic monitoring guidelines. There were three working groups formed. The IEEE 1159 website, located at http://grouper.ieee.org/groups/1159/, allows users to follow progress.

The IEEE 1159.1 Working Group is creating standards for the instruments needed to measure various power quality phenomena. These requirements cover topics like the required sampling rate, synchronisation, A/D sampling precision, and the required number of sampling cycles.A working group on IEEE 1159.2 is creating standards for characterising various power quality occurrences. This includes defining key parameters (such minimum magnitude, duration, phase shift, and number of phases for voltage sags) that may be related to the effects of fluctuations in power quality. Sample waveforms that highlight the significance of the various aspects of power quality fluctuations have been gathered.Following their recent merger into a single task force, the IEEE 1159.1 and 1159.2 Working Groups' efforts are now being coordinated with the creation of IEC 61000-4-3016, an international standard for characterising power quality variations with monitoring equipment.An interchange format that can be used to transfer power quality monitoring data between various applications is being defined by the IEEE 1159.3 Working Group. The COMTRADE format was created by IEEE to facilitate the exchange of waveform data between fault recorders and other devices, such relay testing apparatus. Power quality data, which might contain steady-state and disturbed waveforms, harmonic spectra, rms envelopes, characterised power quality data, and statistical power quality data, requires a more comprehensive data exchange format. The new Power Quality Data Interchange Format (PQDIF) has been developed, and at the time of writing, the standard is being put to a vote.17. Software developers will be able to create apps for analysing power quality events and issues independently of the companies who make the actual power quality monitoring equipment thanks to the universal data interchange protocol.

2IEC 61000-4-30: Power Quality Measurement Methods: Testing and Measurement Techniques

A group of documents with the numbers 61000-4-xx provide IEC standards for tracking power quality phenomena. For each kind of power quality variation or issue, there are specific requirements covered by the separate standards in this series. IEC 61000-4-7, for instance, offers the specifications for checking harmonic distortion levels. The specifications for monitoring flicker are provided by IEC 61000-4-15, as previously mentioned. A new standard, in development within IEC, will provide a summary of the general requirements for characterising power quality phenomena (61000-4-30). Where applicable, this new standard refers to the relevant individual standards (such as 61000-4-7 and 61000-4-15) for full specifications.This standard lays out in great detail the requirements for measurement accuracy and measurement techniques. Not every monitoring device will be able to satisfy all of this standard's requirements. Two classes of measurement equipment have been defined as a result, and each of them can be regarded as complying with the guidelines of IEC 61000-4-30:

Class A performance is meant for measurements that need to be done with extreme precision. Any form of power quality fluctuation that is taken into consideration should yield identical findings (within the prescribed levels of accuracy) for two instruments that meet the requirements of class A. These tools could be useful in scientific settings or for specialised uses requiring extremely accurate findings.

Class B performance nevertheless shows that, although the precise accuracy standards might not be fulfilled, the suggested procedures for characterising power quality variances are followed. For the majority of system power quality monitoring tasks (such as surveys, troubleshooting, performance characterization, etc.), these equipment are suitable.

This standard also introduces the idea of aggregation. In order to prevent counting measures that are virtually related to the same event more than once, aggregation is employed. For example, when assessing the effect on customers and the quantity of problem events on the system, repeated voltage sags brought on by reclosing operations should only be counted as a single event. IEC 61000-4-30 specifies three different aggregation intervals: 3 s, 10 min, and 2 h.As previously indicated, changes and improvements to the IEEE power quality monitoring standards (IEEE 1159 series) are also based on the work in IEC 61000-4-30. This is a component of the broader movement towards globalising standards for power quality.

Furthermore, these aggregation times are critical for characterising steady-state power quality fluctuations such as flicker, harmonics, imbalance, and voltage amplitude. The most significant quantity, 10-min values, are used to statistically characterise all of these qualities.

It should be noted that 200 ms is the fundamental measurement period for the steady-state power quality metrics. This makes it possible to characterise inter-harmonics in 5-Hz bins and offers some smoothing of abrupt fluctuations that aren't really part of the performance of steady-state power quality. Naturally, real waveforms and rms versus time charts are used to characterise voltage sags and transients.

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