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Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices

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ABSTRACT This paper discusses the power quality issues for distributed generation systems based on renewable energy sources, such as solar and wind energy. A thorough discussion about the power quality issues is conducted here. This paper starts with the power quality issues, followed by discussions of basic standards. A comprehensive study of power quality in power systems, including the systems with dc and renewable sources is done in this paper. Power quality monitoring techniques and possible solutions of the power quality issues for the power systems are elaborately studied. Then, we analyze the methods of mitigation of these problems using custom power devices, such as D-STATCOM, UPQC, UPS, TVSS, DVR, etc., for micro grid systems. For renewable energy systems, STATCOM can be a potential choice due to its several advantages, whereas spinning reserve can enhance the power quality in traditional systems. At Last, we study the power quality in dc systems. Simpler arrangement and higher reliability are two main advantages of the dc systems though it faces other power quality issues, such as instability and poor detection of faults.

INDEX TERMS DC system, mitigation, monitor, power quality, renewable energy, spinning reserve, standards.

I. INTRODUCTION

The conventional large-scale generation of electricity at centralized facilities include fossil-fuel-fired power plants, nuclear power plants, hydroelectric dams, wind farms etc. These are now being troubled with the shortage of fossil fuel, the exceeding amount of emission and the electrical power loss due to long transmission line [1]. ''Power Quality'' refers to the electrical system's ability to create a perfect power supply that has a pure noise-free sinusoidal wave shape, and is always stable if voltage and frequency is considered. However, practically many loads regularly impose disturbances on the systems that make deviations from this ideal power supply [2]. EPRI carried out a study between 1992 and 1997 in the US and characterized the average duration of disturbances. The result for a typical site, during this period is presented in fig. 1.

The most important power quality issue is voltage stability [2], which requires regulation. Voltage regulation is mainly affected by the balance of reactive power and the time constant of the excitation system [3]. A case study with wind farms (having 12 turbines), done in [4], shows that the harmonic values affect slightly in a negative way. Typical distribution of PQ disturbances by its duration shows that disturbances lasting less than one second far outnumbers the others in occurrence [5]. Standards have been introduced to define Power Quality, such as the ones defined by IEEE and IEC [6]. Being integrated with the renewable energy systems such as solar and wind, distributed generation (DG) can lead to cleaner and more efficient power generation and transmission [1], [7], [8], along with microgrids [9]–[11]. Electric power system operators often try to keep a certain fraction of their generation capacity as Spinning Reserve (SR) for maintaining power quality, and employ custom power devices (CPD) [12].

Power quality issues can be studied from the examples of data centres, residential power systems, and renewable

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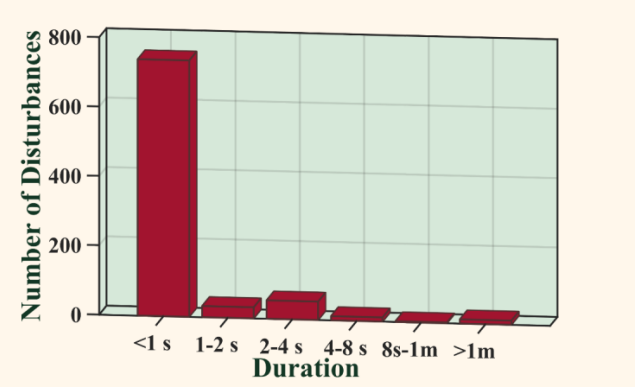

FIGURE 1. Typical distribution of PQ disturbances by its duration, disturbances lasting less than one second far outnumbers the others in occurrence [5].

generation collector systems which can be the motivations of the discussion of DC distribution systems [13]. But they have many problems that are yet to be addressed, harmonics being a prominent one among those. However, a study in data centre efficiency shows that 400V DC system has the highest level of efficiency (∼73%) [13]. In the pursuit of solving power quality problems in Double Fed Induction Generator (DFIG) based grid connected wind power, Fuzzy controlled UPQC method has been developed [14]. Power quality improvement in the integrated wind energy system using FACTS device has been discussed in [15]. Static Synchronous Compensator (STATCOM) can be used for reactive power compensation and power factor improvement with a model using Icosφ algorithm [16], [17]. Another solution which can reduce power quality problems is Uninterruptible Power Supply (UPS). UPS is usually used to protect computers and telecommunication devices, and in off-line stand-by system in utilities [18], [19].

Previous works have been carried out on various topics such as power quality issues, standards, monitoring techniques, mitigation techniques etc. This work aims at a comprehensive study combining all these aspects, especially in the case of renewable energy sources, and perform an analysis based on this study. A promising solution for the problems as sag, swell and flicker [2], [20], [21] can be UPQC [22]–[28]. Also, other issues and their corresponding mitigation techniques are summarized, with a performance evaluation for those techniques according to their effectiveness. Previously, no comprehensive reference paper on power quality and related issues in renewable energy systems was available that also includes mitigation techniques along with a performance evaluation based on their effectiveness. An observation is made in this work based on the severity of the power quality issues and the usefulness of mitigation techniques. This finding will help to understand which power quality issues should be addressed with more attention in future and also which mitigation techniques should be developed in a more advanced way.

The main goal of this paper is a detailed analysis of power quality issues and suggesting their possible solutions. A thorough study of power quality in power systems, including the systems with DC as well as renewable sources are done in this work, along with the standards that define these issues. Power quality monitoring techniques and possible solutions of power quality issues for the power systems are elaborately studied. In short, a comprehensive analysis of overall power quality issues is presented in a single work. The main focus of this paper is on power quality issues. In section II, power quality issues such as transients, long-duration voltage variations, short-duration voltage variations, voltage imbalance, waveform distortion, voltage fluctuation, power frequency variation etc. are explained. Sources and parameters of power quality issues are also addressed in this section. In section III, power quality standards such as IEEE, IEC etc. are discussed. Power quality issues in renewable energy systems are studied in section IV. Tracking and detection of power quality issues are two main objectives of power quality monitoring. Such monitoring techniques - LabVIEW, FFT, ADALINE, HT, TEO etc. are discussed in section V which primarily focuses on harmonics and voltage flicker problems. Devices used in mitigating power quality issues such as SST, SVT, STATCOM, UPQC etc. are discussed in section VI. The applications of custom power devices (CPD) to mitigate those power quality issues are studied in this section. Section VII discusses ways of improving power quality in power systems employing renewable sources such as wind and solar generation. In section VIII, the power quality in DC system is analyzed. Finally, the outcomes of this work are presented in section IX, followed by the conclusion in section X.

II. POWER QUALITY ISSUES AND THEIR IMPORTANCE

As mentioned earlier, power quality refers to maintaining the rated magnitude and frequency of near sinusoidal rated voltage and current of a power system. Any interruption of the power quality would cost the efficiency of the system. In most of the cases, control of the power quality refers to the control of the voltage only. This is because in most cases voltage can be controlled more easily than current [2]. More specifically, the quality of power can be described by some parameters such as continuity of service, variation in voltage magnitude, transient voltages and currents, harmonic content (for AC) etc. [29].

To describe the importance of power quality issues, we can say that poor power quality leads to unnecessary wastage of power and economy [24], [30]. It creates financial burden on the suppliers and consumers. Unstable voltage and frequency often creates disturbance in the power flow through transmission line. Evaluation process of power quality problem is depicted in fig. 2. From the flow diagram, it can be seen that the first stage of this evaluation is to identify the problem category. There are mainly five categories of problems: voltage unbalance, voltage interruptions, flicker, transients, and harmonic distortion. After identifying the category, characterization of the problem is done by measuring or collecting data

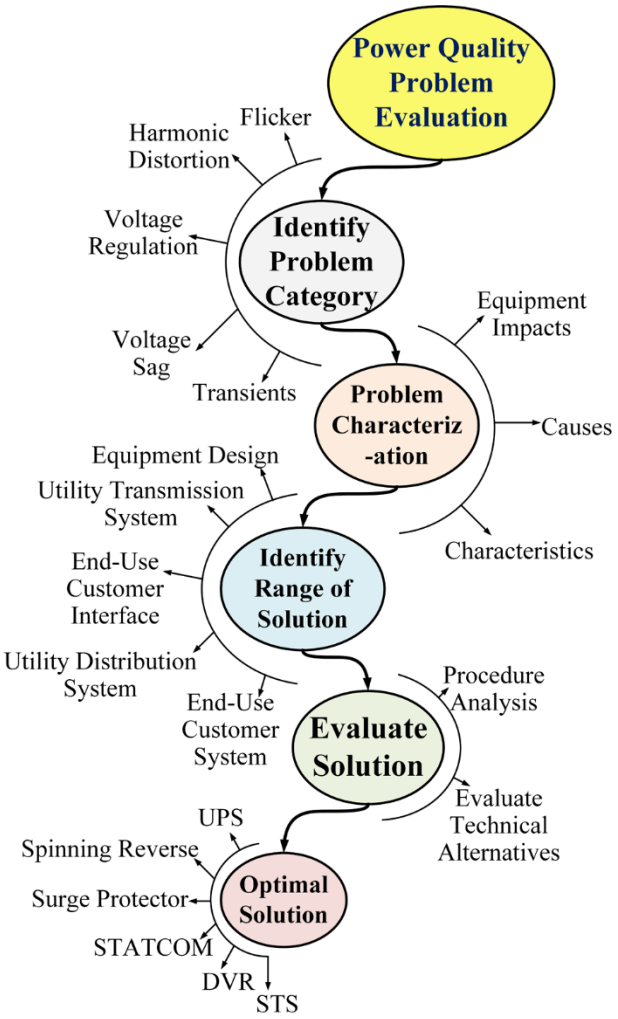

FIGURE 2. Flow diagram for evaluation of power quality problems, solution of a problem comes through a process starting with identification of the problem category [2].

to find out the causes, characteristics, and equipment impacts. The next two steps are identifying the range of solutions, and evaluation of solutions. The final step is to evaluate the optimum solution from all the possibilities to achieve the most economic outcome.

One of the major power quality issues is ''Voltage Fluctuation'', which indicates changes in voltage amplitude. ''Voltage Sag'' [31] refers to the reduction in supply voltage magnitude. The phenomenon called ''Voltage Swell'' refers to the momentary increase in the voltage beyond the normal tolerance levels. It has duration of more than one cycle and it lasts typically less than a few seconds. [20]. Transient is a short duration burst of energy. It is usually caused by a sudden change of state, such as surges. This sudden change can occur in the steady-state condition of voltage, current, or both [2].

Another important power quality issue is the ''long time voltage interruption''. This problem refers to the total interruption or decrease of the voltage or load current for a few milliseconds to one or two second durations. This type of problem causes malfunction in data processing equipment [20]. ''Noise'' is the superimposing high frequency signals with the main waveform of power system. It may cause data loss too [5].

''Flicker'' is the fluctuation of voltage, which is between 90% to 110% of nominal, coming from the power supply. This fluctuation damages the equipment at the load side [21]. Waveform distortion is a steady-state deviation from an ideal sine wave of power frequency. It is usually characterized by the spectral content of the deviation. The primary types of waveform distortion are: DC offset harmonics, interharmonics, notching, and noise. Power frequency variation is the deviation of the power system fundamental frequency from its specified nominal value (50 Hz or 60 Hz).

The term harmonics refers to a waveform distortion of the voltages or currents, which are caused by nonlinear loads. We can call a spectral component as harmonic [32] if,

$$f = nf_{fund} \tag{1}$$

It will be a dc component if,

$$f = 0 \tag{2}$$

It will be called interharmonic if,

$$f = nf_{fund} \tag{3}$$

And lastly, it will be subharmonic if,

$$f > 0 \text{ and } f < nf_{fund} \tag{4}$$

Where, $n>0$ and an integer, f = frequency, f_{fund} = fundamental power system frequency. Intermittent lock-up and garbled data can be caused by harmonics.

Voltage spike is the momentary increase of the voltage beyond the normal tolerances. Its duration is more than one cycle and typically less than a few seconds. To summarize the discussions of this section, a list of power quality issues with their effects are depicted in table 1.

According to EPRI, power quality issues vary with severity. One way to consider this severity is by considering the economic damage they do to the equipment. Ranking of this power quality issues according to their economic impact have been demonstrated in table 1. According to the table, transient has the most severe impact on the economic aspect of electrical equipment.

To discuss about the sources of power quality problems, two perspectives can be addressed. The first one is the utility sources and the latter one is the internal sources. The first one includes lightning, power factor correction equipment, faults, switching [33] etc. while the second one includes individual loads, lighting ballasts, arc welders, and medical equipment. Another type of source can be added which can be described as power electronic source. Variable frequency drives, battery chargers, smart grid, microgrid, electronic dimming system, large motors, UPS etc. fall into this category. Fig. 3 depicts this classification.

TABLE 1. Impacts of power quality issues.

Power Quality Issues	Causes	Effects	Severity
Voltage Fluctuations	Load switching	Over/Under voltages, flickering of lighting	***
Voltage Sag	Fault in the system, starting of large loads, excessive network loading, Source Voltage Variation, Inrush current, Inadequate wiring	Overloading problems. Intermittent Lock-up, Grabbled data	**
Voltage Swell	Start/stop of heavy loads, Source Voltage Variation, Inrush current, Inadequate wiring	Data loss, Damage of equipments, Intermittent Lock-up, Grabbled data	*
Long Time Voltage Interruption	Failure of protecting devices, insulation failure or control malfunction	Malfunction in data processing equipments	**
Noise	Electromagnetic interference, improper grounding	Disturbances in the sensitivity of the equipments, data loss	*
Waveform distortion	Noise in the system	Overheating and saturation of the transformers	**
Power frequency variations	Heavy load	Mainly affects the motors and sensitive devices	*
Harmonics	If a sinusoidal voltage is applied across the nonlinear load	Losses in electrical equipments, Overheated transformers or motors, Lock-up, Grabbled data	**
Voltage spike	start/stop of heavy loads, badly dimensioned power sources or badly regulated transformers	Data loss, flickering of lighting and screens, stoppage or damage of sensitive equipment,	***
Transient	PE commutation, RLC snubber circuits, Lightning	Disturbance in electrical equipments	****
Flicker	Fluctuation of supply voltage	Damage the equipments at the load side	**
Spinning Reserve	Load shedding	used by system operators as a response to unforeseen events such as sudden load changes and outages	*

**** = Catastrophic, *** = Severe, ** = Moderate, * = Mild

Impact of power quality issues can affect various equipment and systems. As discussed before, it can create economic burden as well as loss of equipment. Its overall impact can affect every kind of facility: high cost, medium cost, and low cost. Fig. 4 shows various kinds of facilities, classified by cost, which are affected by power quality issues.

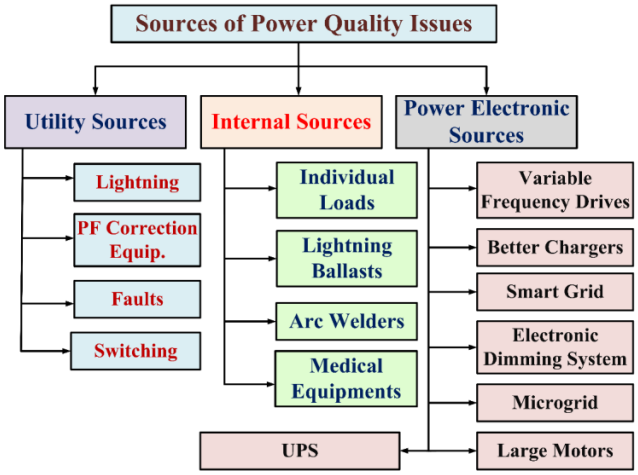

FIGURE 3. Sources of power quality problems. The problems can originate from the utilities, internally, or from power electronic sources.

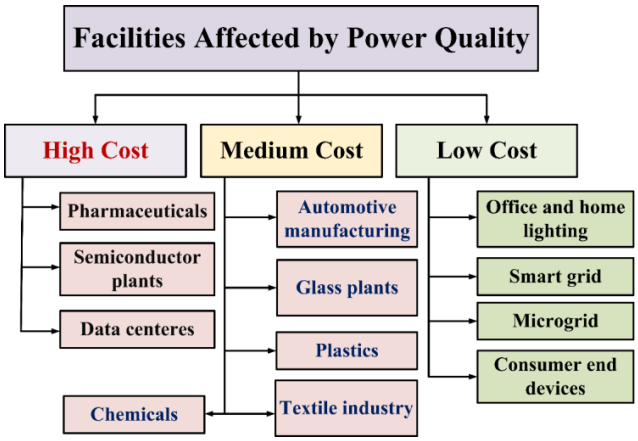

FIGURE 4. Distinct types of facilities affected by power quality issues, classified according to cost.

III. POWER QUALITY STANDARDS

Development of power quality standards is one of the key factors in power quality analysis. Mainly there are two types of standards: IEEE and IEC. Classifications of power quality issues according to IEEE 1159 standards are illustrated in fig. 5. Power quality standards with their basic guidelines are illustrated in table 2.

Apart from these, there are additional regulations for the minimum power quality level. One of them was taken with the Computer and Business Equipment Manufacturer's Association (CBEMA) curve (Fig. 6). This standard specifies the minimum withstanding capability of computer equipment to voltage sags, micro-interruptions and over-voltages. Fig. 6 states that, usually if the voltage is within the limits, the equipment functions normally. When the voltage is on the zone below the permitted area, the equipment may malfunction. When the voltage is comprised in the upper prohibited zone, damage on the equipment may occur [5].

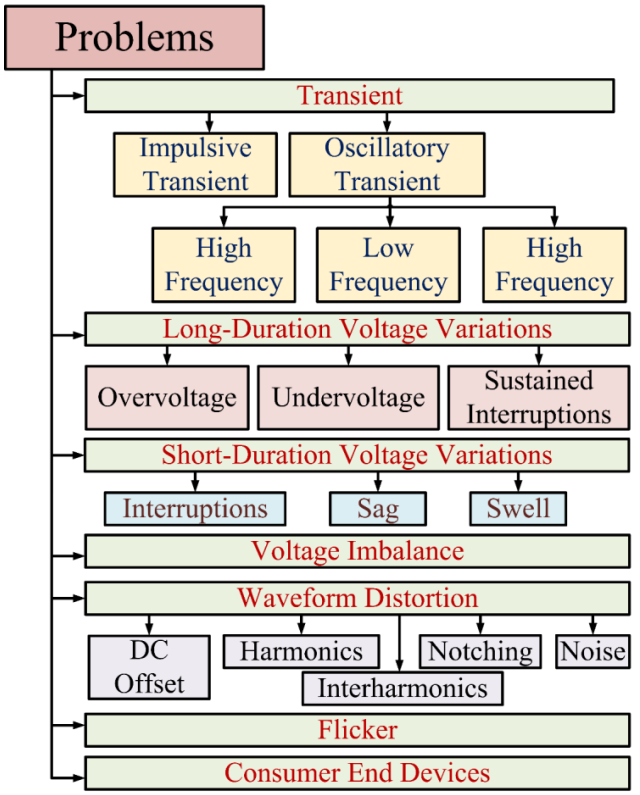

FIGURE 5. Power quality disturbance classification according to IEEE-1159 Standard. The primary categories are Transient, Long-Duration Voltage Variations, Short-Duration Voltage Variations, Voltage Imbalance, Flicker, and Consumer End Devices.

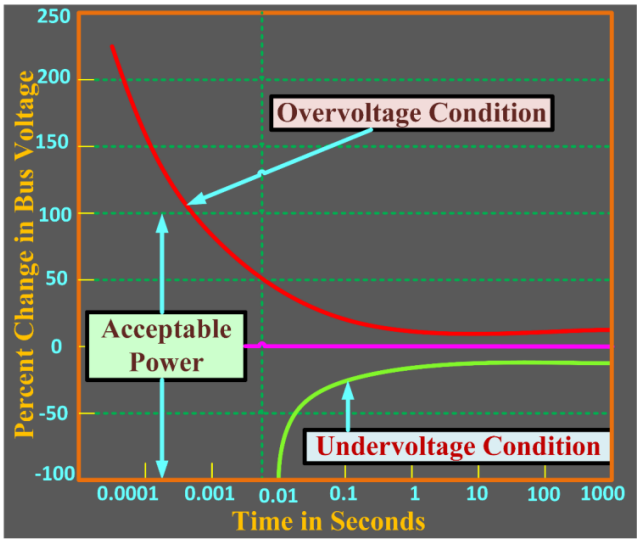

FIGURE 6. Computer and Business Equipment Manufacturer's Association (CBEMA) curve showing overvoltage, undervoltage, and acceptable power conditions for computer equipment [5].

IV. POWER QUALITY FOR RENEWABLE ENERGY SOURCES

One of our primary focuses are the renewable energy sources such as wind turbines and solar photovoltaic (PV) systems which are reliable sources of clean energy. Globally, pursuit of green energy sources is increasing. In 2015, it has been reported that, renewable energy sources provided 52.4% electricity generation in Latin America, about 34.2% in Europe, and 27.7% in North America. Fig. 7 shows contribution of renewable energy sources in different areas' electricity generation. Despite being a promising source of clean energy, renewable sources create significant technical challenges to power system [48]–[53]. In the following part, the basics of renewable sources such as wind energy systems and solar PV panels, and power quality issues in these two systems are discussed.

In 2014, Energy Modeling Forum's EMF27 model showed that, renewable sources provided more than 35% power supply in the last half of the century. In this period, the plants with predominantly wind and solar PV sources will provide 40% in the second half of the century [55]. A study from Masirah Island, Oman, shows that around 75% cost of energy could be reduced by using PV-wind-diesel hybrid power system. The study has also deduced that, 25% of greenhouse emission could be reduced if diesel plants are replaced by hybrid systems [56].

TABLE 2. Power standards and their guidelines.

Power Quality Standards	Corresponding Guidelines
IEEE- 519	Limit harmonic currents and voltages at the point common control [34, 35].
IEC 61000-3-2 (1995-03)	To limit the harmonic currents for the equipments with input current < 16A [32, 34-36].
IEC/TS 61000-3-4 (1998-10)	To limit the harmonic currents for the equipments with input current > 16A [37].
IEEE Standard 141-1993	Safety of life, preservation of property, reliability, simplicity, voltage regulation within the tolerance limit, care and maintenance, flexibility [38].
IEEE Standard 1159-1995	Monitoring of power quality (AC systems), definitions of power quality terminology, Impact of poor power quality on utility and customer equipment, and the measurement of electromagnetic phenomena [39-41]. Classifications of power quality issues according to IEEE 1159 standards are illustrated in fig. 5.
IEEE Standard 1250-1995	Momentary voltage disturbances in ac systems, their effects on new, sensitive, user equipments and mitigation of these effects, to limit harmonic distortion etc. [42].
IEEE Standard P1564	Characterizing voltage sag performance [43].
IEC Standard 61000-4-15	Characterizing flicker [44].
IEEE Standard P1409	Developing guidelines for custom power technologies to improve power quality issues [42, 45, 46].
IEEE Standard P1547	Interconnecting distributed generation with the power system [45, 46].
IEEE Standard 1547a	Allow the equipment to tolerate voltage sag with more stability [47].

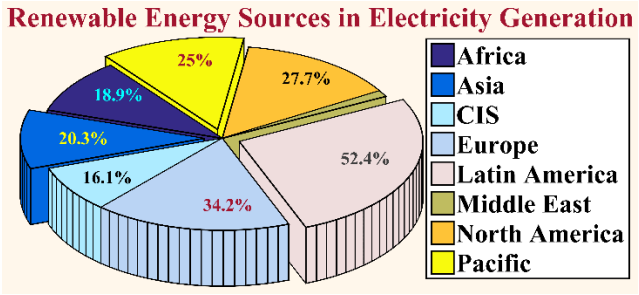

FIGURE 7. Contribution of renewable energy sources in different areas' electricity generation in 2015, Latin America generated more than half of its power from renewables – 52.4%. CIS: Commonwealth of Independent States [54].

The offshore turbines which are mostly located in Europe had an approximate cumulative wind capacity of 4 GW at the end of 2011 [57]. The general configuration of a wind power plant is shown in fig. 8(a) [57]; a more detailed topology of the system connecting wind turbines to the grid is shown in fig. 8(b) [58].

Solar PV power plants, residential or commercial PV can create grid-connected solar PV power systems which can be capable of generation exceeding 100 MW. Large power plants are connected to transmission systems but residential (up to several kilowatts) and commercial PV cells (up to several megawatts) are connected to distribution networks [59]. Solar PV systems had 22 GW of global capacity and produced 20 TWh of electricity in 2009 [57]. By 2013, total capacity had become 138.9 GW globally [60].

Generally, sufficient amount of spinning reserve is provided in the power systems for frequency balancing with load shedding. Thus, a high-quality energy sustainability is achieved. In case of renewable energy systems, two major types of power quality issues exist. Those are voltage and frequency fluctuations and harmonics. Voltage and frequency fluctuations are mainly caused by two reasons: i) non-controllable variability of renewable energy resources, and ii) power grid-side disturbances. Harmonics are produced by power electronic converters which are used in renewable energy generation. As defined by the IEEE Standard 929-2000 there are four major parameters to evaluate the power quality in PV systems such as voltage, voltage flicker, frequency, and distortion. Deviation from these parameters creates power quality problems. The inverter may be required to cease power quality deviation in the utility lines in this case [22]. Those problems can be discussed from two angles: renewable energy side [61], and power grid side.

At first, we discuss about the renewable energy side. Wind and solar PV power generation both experience intermittency due to a combination of partial unpredictability features of wind and solar resources and non-controllable variability - which cause fluctuations in the performance of both wind and PV power generation [62], [63]. Outputs of these two types of renewable energy sources vary greatly due to the variations in wind speed and incident solar energy. Major problems are voltage and frequency fluctuations. To mitigate

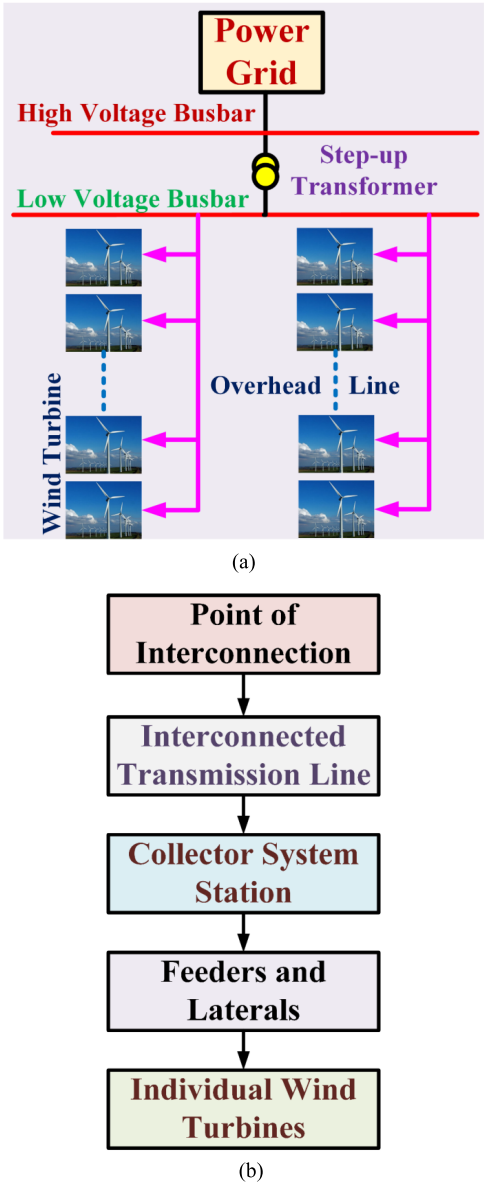

FIGURE 8. Wind power plant: (a) general configuration [57]; and (b) detailed topology of the system connecting wind turbines to the grid [58].

these fluctuations additional energy is required to balance supply and demand of the power grid on an instantaneous basis; spinning reserve is also an option. Improved weather and generation forecasting technologies, which aim to predict weather and generation output from wind and solar resources more accurately at various timescales, can be another solution to mitigate the partial unpredictability features of wind and solar resources [57]. The power quality issue remains at device level for low penetration and in that case usually the solution is device specific. However, grid-level technologies are required at high penetration – which can have serious impacts [64], [65].

Another side is the power grid side. Apart from partial unpredictability features of wind and solar resources and

TABLE 3. IEEE standard 1547a-2014 [47].

Voltage range (% of base voltage)	Clearing Time (Default) (s)	Maximum Settings Clearing Time: Adjustable up to and including (s)
V < 45	0.16	0.16
45 <V < 60	1	11
60 < V < 88	2	21
110 < V < 120	1	13
V >120	0.16	0.16

non-controllable variability, power grid-side disturbances affect renewable energy integration. According to several European grid codes, PV power plants must withstand specific disturbance levels without disconnections [22]. In 2014, the IEEE Standard 1547a published a new guideline which is related to voltage sag. This includes new settings that would allow the equipment to tolerate voltage sag with more stability. Besides, an agreement is reached among the distributed resource owner and the local utility to maintain these settings. Table 3 depicts these settings which are to be maintained to mitigate power quality issues due to disturbances regarding voltage sag trip [47].

The oceans are vast sources of renewable energy which can be of six distinct types: ocean wave, tidal range, tidal current, ocean current, ocean thermal energy, and salinity gradient [66]–[68]. Ocean wave and tidal current energy can contribute significantly to the supply of energy in future [66], [69], [70]. The ocean energy industry has made noteworthy progress recently but is still at very early stage. Some advanced prototypes that are currently being tested are shown in [71]. Most important impact of ocean energy is on the environment. Other major impacts of ocean wave and tidal current technology include impact on the benthic community, habitat change, and the entanglement of marine mammals, turtles, larger fish and seabirds.

V. POWER QUALITY MONITORING

To guarantee a uniform power quality, proper monitoring is necessary. Monitor and analysis systems are widely used for power quality. Previously, fluctuated condition of power quality index was monitored in [72]. This was done by means of frequency spectrum analysis method based on acquisition of time domain signals. Influence factor of fluctuation of power quality was also analysed. LabVIEW - which is a monitoring and analysing tool - was also developed.

As mentioned earlier, harmonics threaten power quality of electric network and harm safety of equipment. Compensating harmonic signals is necessary to improve power quality. There are several methods of harmonic analysis to improve power quality such as: Fast Fourier Transform (FFT) [73], singular value decomposition (SVD) [74], artificial neural network (ANN) [75] etc.

Distributed system of power quality monitoring is necessary for the detection of power quality issues [76], [77]. In most of the cases, focus of monitoring scheme has been

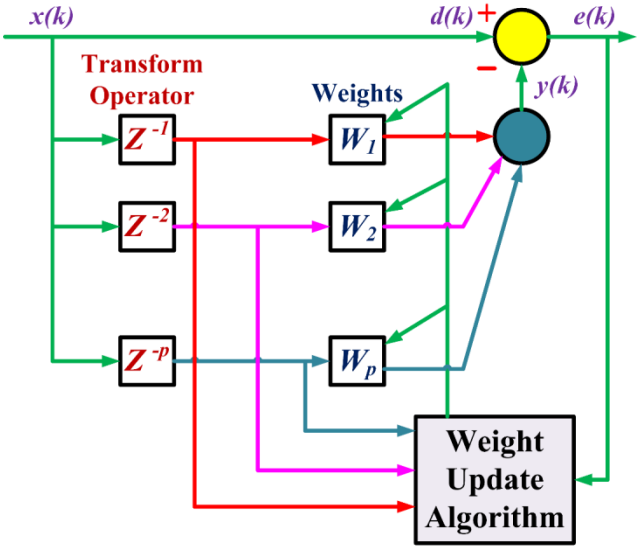

FIGURE 9. ADALINE based detection scheme, where time delayed samples are the inputs and predicted values of the signal are the outputs.

limited to the harmonics in supply voltage in the mode close to a real-time mode. For this purpose, there exists Phasor Measurement Unit (PMU) structure, where instantaneous values of electric current and voltage in different cutsets are measured. After that, their values are transferred to the control centre [72].

Another technique for detection and adjustment of harmonics problem is adaptive linear combiner (ADALINE) [78]. ADALINE is also effective for the detection of voltage sag, swell, transients, interruptions etc. This method removes the need of setting up a threshold value for power quality detection. Rather it provides an honest and high tracking capability. The input of ADALINE are the time delayed samples. The output is the predicted value of the signal (Fig. 9).

High-Resolution Technique has been developed for monitoring "flicker" problem [21]. According to this technique, the frequency spectrum of the signal is analyzed for the flicker detection purpose. Effective use of this method can be achieved more easily than other techniques as it has used Pony's Method which is more accurate and robust [21].

Kalman Filtering (KF) approach is very useful for the detection of sag, swell, brief time interruptions etc. Previously, disturbance waveforms were automatically identified in the time domain with an individual artificial neural network. Using KF approach, this can be done in the wavelet domain which has been proved to be more efficient [79]. Application of KF approach for the tracking of harmonics problems has also been investigated thoroughly in [80].

The Total Energy Operator (TEO) algorithm, which is a non-linear operator, is used to track the instantaneous energy content of the signal. Measurement of the mechanical process that generates the signal can be usefully done by TEO. The value of this operator is the square of the multiplication of the signal amplitude and frequency. The distorted signal

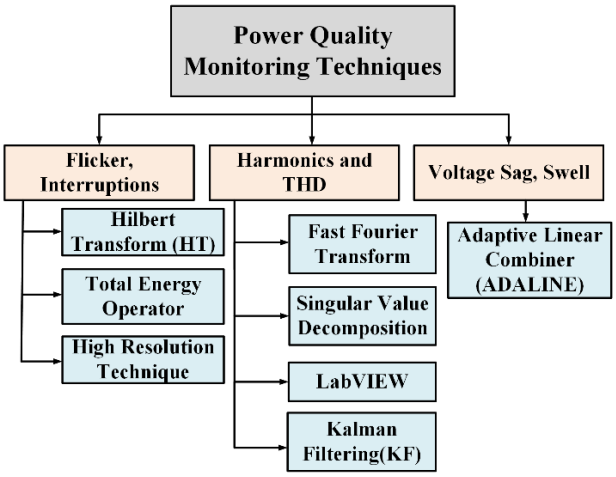

FIGURE 10. Power quality monitoring techniques to measure different parameters.

is divided into two separate signals: the smoothed version, and a detailed version. High frequency can be detected in the detailed version where low frequency disturbances can be detected from the smoothed version using TEO [81]. Another mathematical approach to track the envelope of the signal is Hilbert Transform (HT) algorithm. HT method shifts each frequency component of the instantaneous spectrum by 90 degrees. This method can be used in a specific frequency band, using an analog all-pass filter [82]. Both TEO and HT are useful for monitoring voltage flicker problem. In fig. 10 power quality monitoring techniques are summarized.

VI. POWER QUALITY MITIGATION METHODS

In this section, some basic mitigation methods of power quality issues such as STATCOM, UPQC, UPS etc. are discussed. Generally, in a traditional power system, SR allows systems to compensate unpredictability, imbalances, and errors in load and generation estimation [83], [84]. Spinning reserve is defined by the ability of a generator to provide supply in excess of its rated capacity if additional torque is applied. In case of renewables, there is now way to measure that. Approaches to measure this parameter of renewables have produced different approaches, but they are hardly efficient to provide a satisfactory result.

A D-Statcom, which is a shunt connected custom power device, corrects power factor and current harmonics, thus improves the power quality [85], [86]. Also, it provides filtering, voltage regulation at distribution bus, and load balancing. It is sometimes referred to as an active power filter consisting of a shunt-connected voltage source converter (VSC) mounting IGBTS, and operated with PWM [87]. It is called D-Statcom because of its being installed at the distribution side. IGBTs with high switching frequencies are mainly used to improve the speed. Capacitor is used for energy storage purpose and the L-C branch acts as a passive filter [87]. D-STATCOM compensates the harmonics by injecting the

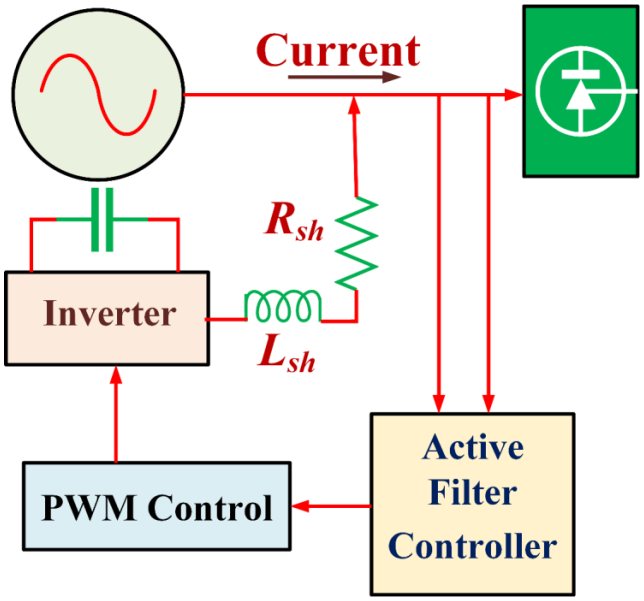

FIGURE 11. System configuration of D-STATCOM with active filter and PWM controller [1].

harmonic component generated by the load which is phase shifted by 180 degrees. D-STATCOM can also be used to compensate poor power factor. Fig. 11 depicts the system configuration of a D-STATCOM with PWM controller and active filters.

Unified Power Quality Controller (UPQC) is an integration of series and shunt active filters connected back to back. Usually these two filters are connected at the DC side and they share a common DC capacitor. The series components compensate the supply side disturbances such as voltage sags/swells, flicker, voltage unbalance, and harmonics. A UPQC supplies voltage to maintain the load voltages at the target level. The shunt component mitigates the issues such as poor power factor, load harmonic currents, and load unbalance. It injects currents in the system to make the source currents balanced sinusoids in-phase with the source voltages [18].

Fig. 12 illustrates the principal scheme of UPQC with series and shunt active filters. UPQC compensates for distortions such as unbalanced system voltages and load currents of a three-phase system. The equivalent circuit of UPQC is shown in fig. 13.

An unbalanced 3-phase system consists of positive, negative, and zero sequence fundamental and harmonic components. The system voltage can be expressed as in equation (5):

$$V_s(t) = V_{s+}(t) + V_{s-}(t) + V_{s0}(t) + \sum V_{sh}(t) \quad (5)$$

Here subscripts $+$, $-$, and 0 represent positive, negative and zero sequence components respectively. The series converter compensates for the following components of voltage:

$$V_0(t) = V_L(t) - V_S(t) \quad (6)$$

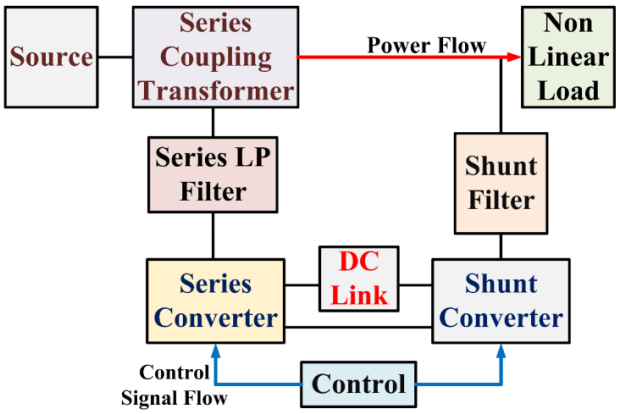

FIGURE 12. Principal scheme of Unified Power Quality Controller (UPQC), it has both series and shunt converters, with a DC link and control system coordinating them [23].

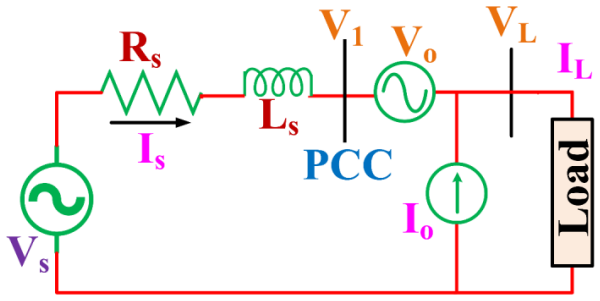

FIGURE 13. Equivalent circuit of Unified Power Quality Controller (UPQC) [11].

Control system automatically controls the series converter so that the output converter voltage is $V_0(t)$. The nonlinear load current (equation (7)) with distortion can be expressed as:

$$I_L(t) = I_{L+}(t) + I_{L-}(t) + I_{L0}(t) + \sum I_{lh}(t) \quad (7)$$

The shunt converter provides compensation of the load harmonic currents to reduce voltage distortion. Output current with harmonic, negative and zero sequence currents controls the shunt converter so that load current distortions can be nullified. The current component which is compensated by the shunt converter is given by equation (8),

$$I_0(t) = I_L(t) - I_S(t) \quad (8)$$

Equation (6) and equation (8) establish the basic principles of an ideal UPQC.

An Uninterruptible Power Supply (UPS) is mainly used to provide emergency back-up power to the load when the main power fails. Its primary use is in telecommunication devices and computers, where data loss is a major concern. Though static UPS is only suitable for small systems, rotating UPS is more useful in large systems [18]. Usually, high-quality UPS units have double conversion topology which breaks down an incoming AC power into DC to charge the batteries. After that it reproduces the AC sine wave which has higher

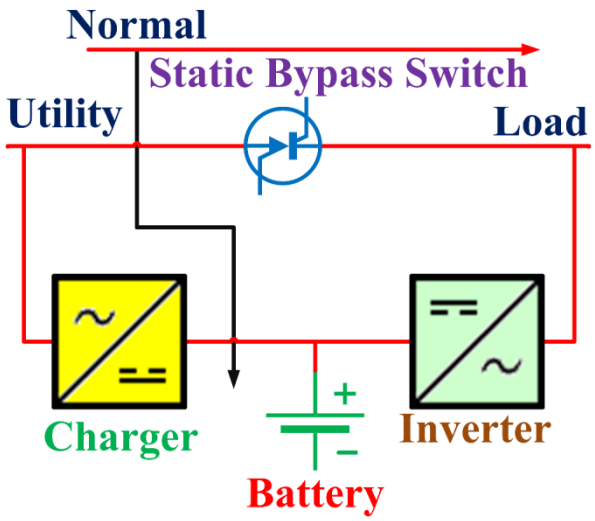

FIGURE 14. Simplified diagram of off-line Uninterruptible Power Supply (UPS) topology. The battery gets charged from the utility during normal condition, and discharges through the inverter to supply the load when power flow from utility gets disrupted [88].

quality than the original AC wave [87]. DC UPS has been used to correct the power factor previously in [88]. Off-line UPS is referred to as passive-standby UPS. It is usually used in low power applications with power ratings less than 2 kVA. Its basic schematic is illustrated in fig. 14 [88].

A novel topology of a modular per-phase UPS system based on reduced-switch-count configuration has been proposed previously in [19]. According to this proposed topology, active front-end filtering and seamless transition from normal to backup mode can be achieved. Grid isolation is also possible so that there is no backward power feed into the utility during power failure. As a result, it eliminates the need of circuit breaker [19].

Transient voltage surge suppressor, which is also known as TVSS, provides the simplest structure to mitigate power quality issues. It is used as an interface between power load and sensitive load. It clamps transient voltage to a safe level. TVSS contains a component with a nonlinear resistance (such as Zener diode) to limit the excessive line voltage. It conducts the excessive impulse to the ground. A complete TVSS system has been developed in [89] which consists of shunt protectors at both input and output.

Isolation transformers are mainly used to isolate sensitive loads from transients. They also isolate sensitive loads from noise. The main component of isolation transformers is a grounded shield made of nonmagnetic foil located between the primary and the secondary. Any disturbance that comes from the source is transmitted through the capacitance between the primary and the shield. Then it conducts the unnecessary disturbance to the ground. One additional advantage of isolation transformer is that it can improve the harmonics and neutral to ground voltage [90]. On the other hand, one of the main limitations of isolation transformer

is that it does not protect the system from voltage fluctuation [91]. A dynamic voltage restorer (DVR) consists of a voltage source connected in series with the load. The output voltage is constant at the load terminals. It is done with a step-up transformer. Additionally, both active and reactive powers are injected in the output supply through a voltage converter. This type of dynamic voltage restorer (DVR) is very effective to mitigate some important power quality issues such as voltage sag and swells [92]. For renewable energy sources, STATCOM can be a suitable candidate for mitigating power quality issues. STATCOM is a power electronics device whose basic principle is injection or absorption of reactive current at PCC. Additional converters and power conditioning instruments are required to integrate renewable energy source with power electronic interface. The STATCOM unit is mainly designed for reactive power compensation to the load. This STATCOM unit is an inverter with DC link capacitor. It receives control pulses which are generated using modified Icosφ algorithm, which in turn causes the STATCOM to provide real power and reactive power compensation [17]. The Icosφ algorithm is developed to compensate harmonic, reactive and unbalance effects in a balanced or unbalanced 3-phase source/load [93].

The actual load current subtracted from the expected main current per phase equals the compensation currents (ref) for the STATCOM.

Let U_a, U_b, U_c be the unit amplitudes in all the phases of the phase-to-ground source voltages respectively, which are:

$$U_a = 1.\sin(\omega t), \quad U_b = 1.\sin(\omega t - 120^\circ),$$
$$U_b = 1.\sin(\omega t + 120^\circ);$$

The reference source currents in all the phases are:

$$\mathrm{Isa(ref)} = \mathrm{K}\,|\mathrm{Is(ref)}| \times U_a = \mathrm{K}\,|\mathrm{Is(ref)}|\sin\omega t \tag{9}$$

$$\mathrm{Isb(ref)} = \mathrm{K}\,|\mathrm{Is(ref)}| \times U_b = \mathrm{K}\,|\mathrm{Is(ref)}|\sin(\omega t - 120^\circ) \tag{10}$$

$$\mathrm{Isc(ref)} = \mathrm{K}\,|\mathrm{Is(ref)}| \times U_c = \mathrm{K}\,|\mathrm{Is(ref)}|\sin(\omega t + 120^\circ) \tag{11}$$

where K = load factor. It determines the amount of real power that has to be supplied by the source/grid.

The reference compensation currents for the STATCOM are:

$$\mathrm{Ia(comp)} = I_{La} - \mathrm{Isa(ref)} \tag{12}$$

$$\mathrm{Ia(comp)} = I_{La} - \mathrm{Isa(ref)} \tag{13}$$

$$\mathrm{Ia(comp)} = I_{La} - \mathrm{Isa(ref)} \tag{14}$$

Additionally, a hysteresis current controller is also used. If compensation current drops below the value of switch-off point, the relay is turned off. This pulse is then passed through a circuit block. The proportion of the gain factor decides the amount of real power supply from the mains while renewable energy sources supply the rest using STATCOM.

The configuration of STATCOM interface for renewable energy source is shown in fig. 15.

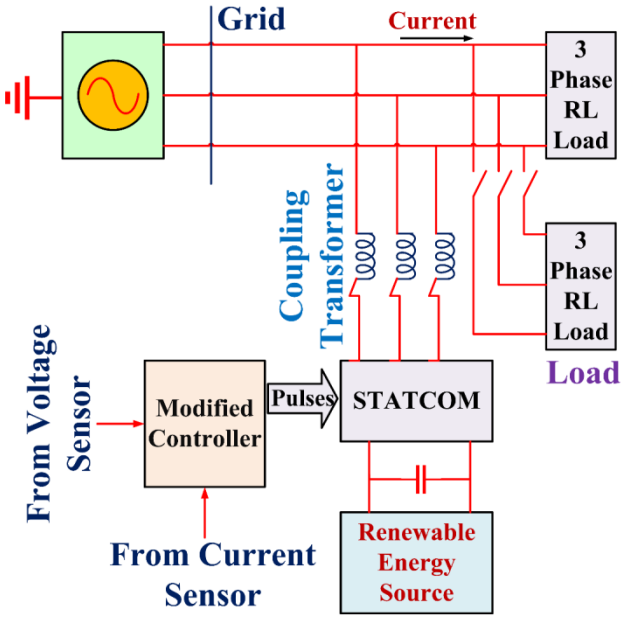

FIGURE 15. Schematic of the three-phase grid system with the STATCOM interface for renewable energy source [94].

To mitigate the power quality issues in a wind power system, STATCOM can be very useful [16]. It acts as a Flexible AC Transmission System (FACTS) device used in transmission system in shunt manner. In this configuration, VSC is connected to system bus through a coupling transformer. Reactive power depends on the amplitude of VSC. In overloading condition, STATCOM injects reactive power in system. And if terminal voltage (V_{DC}) is less than the system voltage, which means it is facing under voltage, STATCOM absorbs reactive power [94].

The drawbacks of using the additional circuits in STATCOM include high switching loss, increased costs, and a bulkier system. But the model described above replaces the additional converters with a STATCOM unit. There are several advantages of STATCOM. One of them is that the compensating current does not get lowered as the voltage drops. The other reasons for preferring a STATCOM are overall superior functional characteristics, faster performance, smaller size, cost reduction, and the ability to provide both active and reactive power. STATCOM can be used to improve transient conditions as well as voltage fluctuations. It is also very useful to control voltage flickers and power oscillatory damping of system [17].

Surge protector, varistor and capacitor can protect against over-voltages for providing clean and reliable AC power. Voltage surges are voltage increases that typically last from about 15 milliseconds to one-half of a second. Surges are commonly caused by the switching of heavy loads and power network switching. A surge that lasts more than two seconds is typically referred to as an overvoltage. Varistors such as the metal oxide varistors (MOVs) are devices composed of ceramic-like material usually formed into a disk shape.

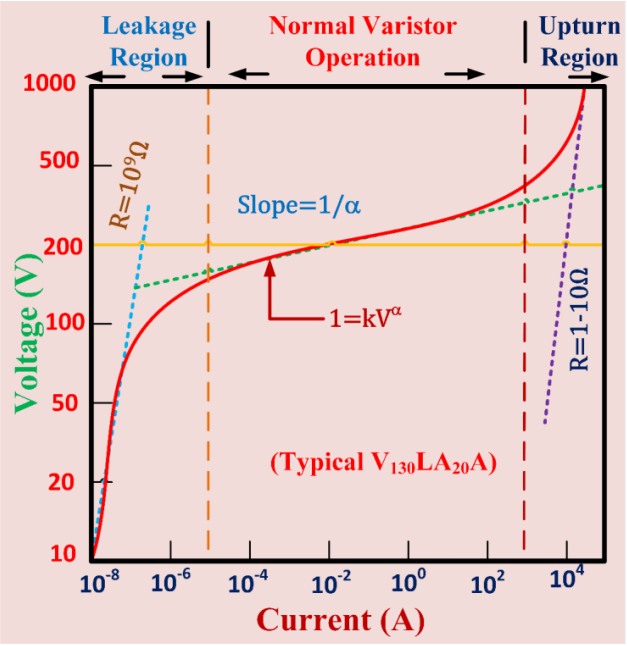

FIGURE 16. V-I characteristics of metal oxide varistor [95].

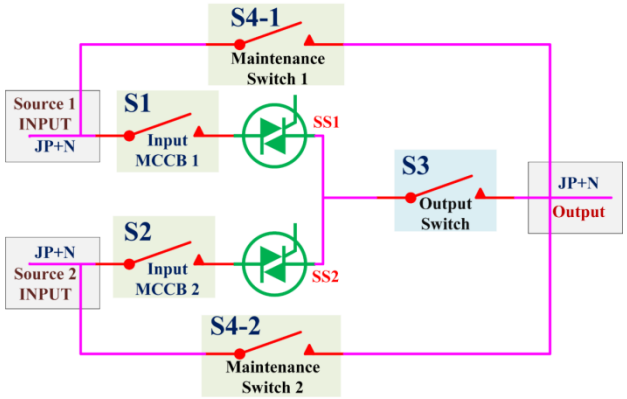

FIGURE 17. Static Transfer Switch (STS) configuration. It can transfer the load from the preferred source to an alternative healthy source in the event of voltage disturbance [95].

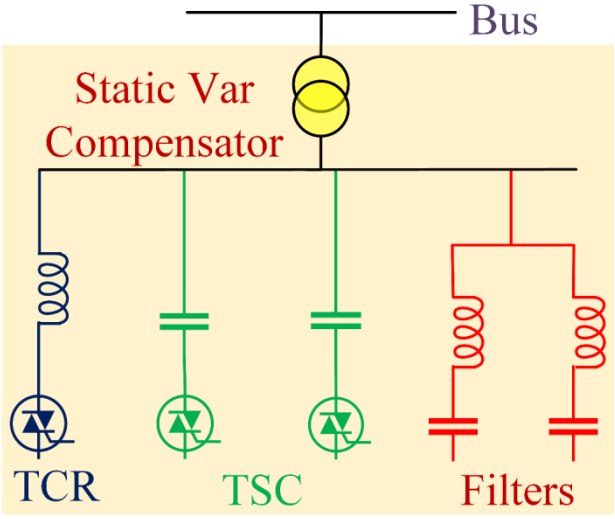

FIGURE 18. Principle scheme of a Static VAR Compensator (SVC) [87].

They are typically constructed from zinc oxide mixed with a suitable additive. Each intergranular boundary displays a rectifying action and presents a specific voltage barrier. When these conduct, they form a low ohmic path to absorb surge energy. A varistor's voltage-current behavior is defined by fig. 16. High transient energy absorbent capability is achieved by increasing the size of the disc. MOVs turn on in a few nanoseconds and have high clamping voltages (fig.16). There are some modern MOVs that prevent the device from over-heating, smoke, and even potential fire. Thermally protected MOVs (TPMOVs) are useful in occasions where continuous AC line over-voltages could occur [95].

A Static transfer switch (STS) transfers the load from the preferred source to an alternative healthy source in the event of voltage disturbance. It helps mitigating interruptions and voltage dips [87]. The STS consists of two three-phase static switches, each constituted in turn by two anti-parallel thyristors per phase (fig. 17). Normally, the static switch on the primary source is fired regularly, while the other one is off. This results in a very effective way of mitigating the effects of both interruptions and voltage dips by limiting their duration as seen by the load. The success of the STS is mainly due to its rather low cost compared with other solutions. A secondary in-feed, independent from the main source is required [87].

A Static VAR compensator (SVC) can be used for AC voltage control by generation and absorption of reactive power by means of passive elements. The ability to absorb changes in reactive power makes the SVC suitable for flicker reduction to some extent. It can also be used for balancing unsymmetrical loads [87]. It is normally constituted by one thyristor controllable reactor (TCR) and a few of thyristor switched capacitor (TSC) branches [96]. The value of the reactance of the inductor is changed continuously by controlling the firing angle of the thyristors, while each capacitor can only be switched on and off at the instants corresponding to the current zero crossings, to avoid inrush currents in the capacitors. With this arrangement, the SVC can generate continuously variable reactive power in a specified range, and the size of the TCR is limited to the rating of one TSC branch. However, the ability of SVC to mitigate flicker is limited by its low speed of response [87]. Principle scheme of an SVC is shown in fig. 18.

A simplified schematic is shown in Fig. 19, which is normally used for frequency control. This embodiment generally includes three parts of control, which are named Tertiary, Secondary and Primary control [97]. In big interconnected systems, three forms of control are usually available. In small isolated system, secondary controller may not be present. In a simple manner, demand-side actions using the frequency adjustment is not included in this scheme. Other schemes

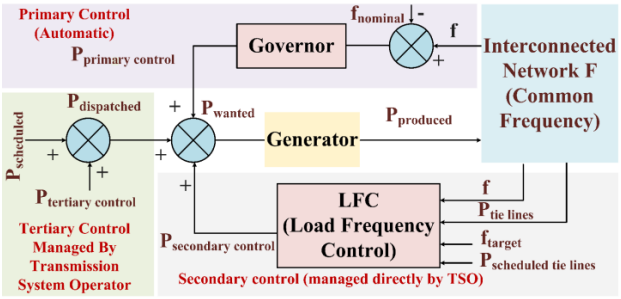

FIGURE 19. Frequency stabilization system., a closed loop system tracks the variables and adjusts the frequency.

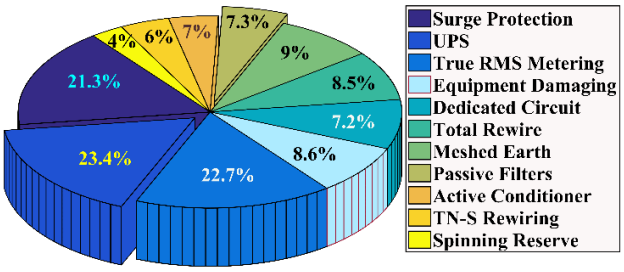

FIGURE 20. Usage percentage of different mitigation techniques for power quality issues, UPS being the most used one, followed closely by True RMS Metering and Surge Protection.

without conceptual changes could be considered. Control of the three types can be defined as follows: Primary Reserve provides a power reserve against any frequency change, which is local automated control. Secondary Reserve provides back-up power for frequency and brings it back to the target value of exchange programs, which is automatic control. Tertiary Reserve is for the unit commitment (UC) and dispatches the secondary reserve to repair, to control the final congestions, and to bring back the frequency of their target points if the secondary reserve is not enough.

There are many more mitigation techniques such as: true RMS metering, equipment damaging, dedicated circuits, total rewire, meshed earth, passive filters, active conditioner, TN-S rewiring, upsized neutral etc. Not all of them are used by the same amount. Some are used more frequently than the others. Fig. 20 illustrates the usage percentage of these mitigation techniques.

VII. MITIGATION OF VOLTAGE AND FREQUENCY FLUCTUATIONS OF WIND AND SOLAR POWER SYSTEMS

In the case of power systems with solar resources and wind farms, there may be frequency and voltage fluctuations due to the instability of output. Variations of wind speed and solar radiation intensity - the intermittent characteristics [98], are the main causes of this instability. For the case of the systems with large amount of PV and wind farm installed, a possible solution may be the frequency control with dead band by High Voltage Direct Current (HVDC) interconnection line [98]. Frequency fluctuations are suppressed by the turbine output

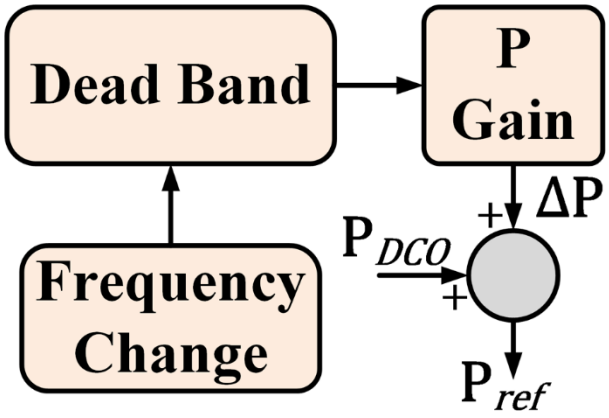

FIGURE 21. Frequency control system with dead band by HVDC [98].

of conventional governors. Control of short period components are usually done by the Governor Free (GF) operation method while control of longer period components is usually done by the Load Frequency Control (LFC) method. Fig. 21 depicts this method of frequency control with dead band by HVDC line.

Storage system with solar resource is also an important issue that needs to be addressed. Massive storage systems with solar energy resources require a high degree of supply/demand matching. Recently, a framework called Opti-Match has been developed to address this issue [93]. If the aggregate power supply is made to be proportional to the Input/Output (I/O) demand, then the maximum utilization of renewable sources is possible. In this method, ∼94% utilization has been made possible.

In the case of Wind Energy System (WES), another approach can be introduced which is the LCL filter interfaced grid connected Permanent Magnet Synchronous Generator (PMSG) based WES model. The proposed system can be predicted to have good performance for reactive power compensation, DC link voltage control and LCL Filter [99]. The control algorithm has been developed on the basis of Synchronous Rotating Frame (SRF) with Takagi-Sugeno (TS) fuzzy controller which is found to provide superior performance over conventional controller. The complete system is depicted in Fig. 22. In this model, there are four components: PMSG, MPPT control, LCL Filter, and DC link voltage. This model has been discussed thoroughly by Gupta *et al.* [99].

The stability analysis of a multimachine power system connected with a 375-MW hybrid wind-PV farm has been analyzed previously [100]. Specific operating condition keeps the system stable. When the wind speed and solar irradiance increases, the damping condition of the electromechanical modes are improved [100]. Fluctuations in the power, wind speed and solar irradiance can be suppressed with Super Capacitor (SC). The diagram of the model used to study the stability of multimachine power system is depicted in Fig. 23.

In the proposed model of stability analysis in multimachine system, the Wind Turbine Generator (WTG) and the PV array

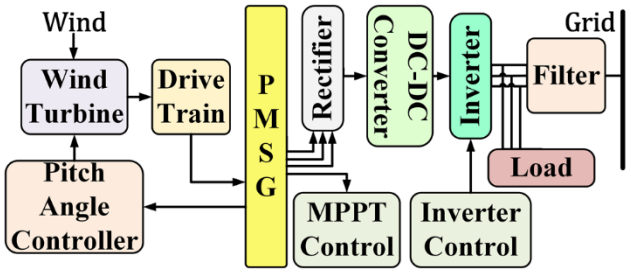

FIGURE 22. Grid Integrated PMSG based Wind Energy System Configuration [75].

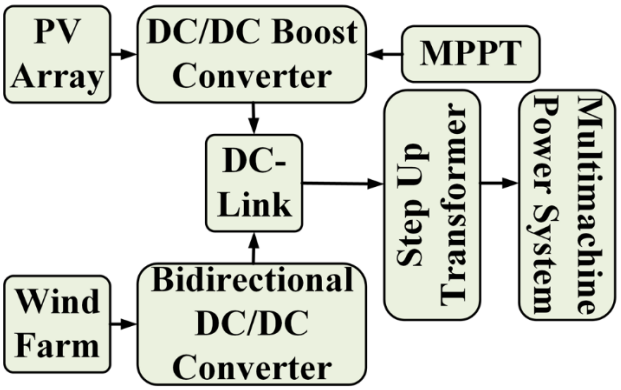

FIGURE 23. Multimachine power system which is connected with a large-scale hybrid wind-PV farm [100].

both are connected to a common dc link. The WTG is connected through a voltage-source converter and the PV array is connected through a dc/dc boost converter. In this model, the power associated with the common dc link is conveyed to the multimachine power system through a complex system. The system comprises of voltage-source inverter, step-up transformers, and a connection line. The super capacitor based energy storage unit is integrated into the common dc link through a bidirectional dc/dc converter (Fig. 24). This unit is used to reduce power fluctuations caused by wind speed and/or solar irradiance variation [100].

VIII. POWER QUALITY IN DC SYSTEMS

To discuss power quality in DC distribution system, first the basic application of DC distribution system needs to be studied. These types of systems support more efficient integration of energy storage and generation by eliminating some rectifying and inverting power electronics converter stages. Previously it has been demonstrated that DC systems have enabled simpler integration of energy storage devices. It can meet both energy and power buffer needs. From the telecommunications industry where both AC and DC systems have been used, it has been concluded that well designed DC systems have superior reliability than AC system [101]. Additionally, integrating multiple sources into a DC system does not require frequency control and phase synchronization which makes it simpler to design than AC. On the contrary, detection and clearing faults on the DC bus is a

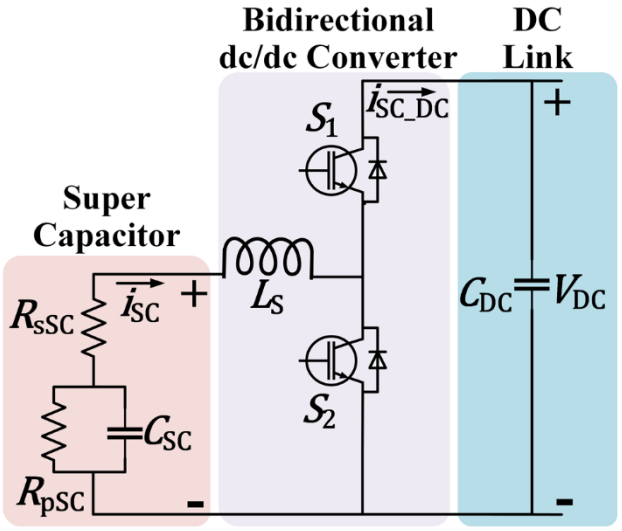

FIGURE 24. Integration of super capacitor into the common dc link through bidirectional dc/dc converter [100].

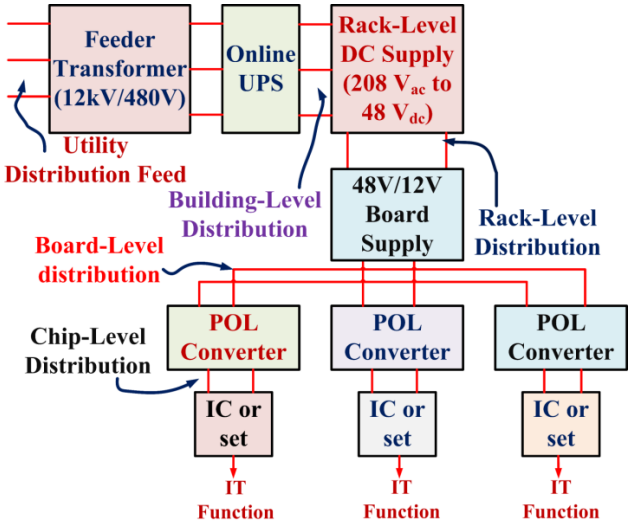

FIGURE 25. Typical AC data center layout emphasizing power distribution voltage levels. IT Function indicates IT equipment those act as constant power loads (CPL) and causes destabilization in the system [103].

significant obstacle for DC systems [13]. Furthermore, DC systems have stability problems. Nonlinear dynamics of the power electronic converters are used to create the DC voltage. In fig. 25, load converters point the interfaces where IT equipment act as constant power loads. These loads destabilize the system [102].

IX. OUTCOMES

This paper focuses on the key power quality problems, standards regarding those issues, possible ways to mitigate those, and power quality issues in DC systems. The overall outcomes of this work can be classified among five parts.

The first one is that loss of efficiency of electrical equipment as well as over and under voltage are the two most common impacts of power quality problems. Load switching

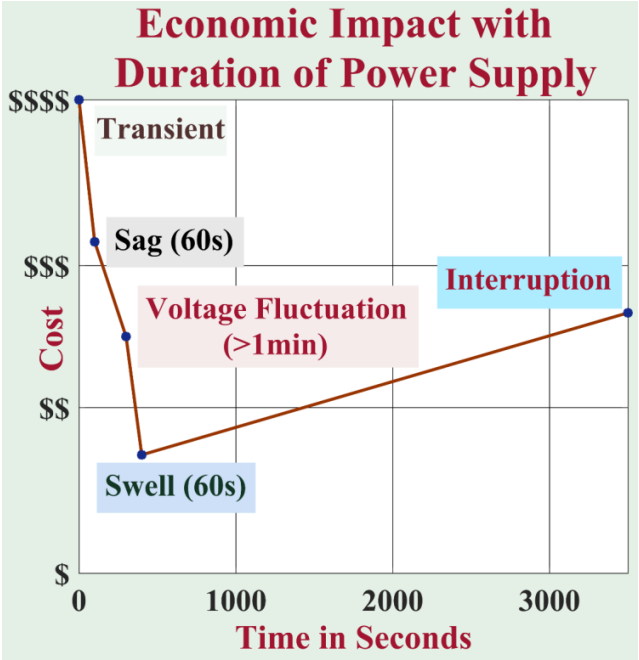

FIGURE 26. Economic impact vs duration of power quality issues, costs are high for voltage fluctuations lasting less than one minute.

TABLE 4. Power quality mitigation techniques with their performance levels.

Mitigation technique	Problems that are mitigated	Performance level
UPQC	voltage sags/swells, flicker, voltage unbalance, harmonics, power factor, load harmonic currents, and load unbalance	***
D-STATCOM	power factor, current harmonics, filtering, voltage regulation, and load balancing	**
UPS	emergency power shortage	*
TVSS	voltage transients	*
Isolation transformer	isolation of sensitive loads	*
STATCOM	transient conditions, voltage fluctuations, voltage flickers, and power oscillatory damping	***
DVR	voltage sag and swells	*
Surge Protector, Varistor and Capacitor	overvoltages	*
STS	interruptions and voltage dips	*
SVC	flicker, unsymmetrical loads	**
Spinning Reserve	harmonics, THD, Power oscillatory damping	***

*** = Excellent, ** = Satisfactory, * = Acceptable

causes voltage fluctuations, start of heavy loads causes voltage sag/swell, insulation failure causes long time voltage interruption, switching load causes long duration voltage interruption and non-linear loads create harmonics problems.

Guidelines to limit harmonic problems are provided in the IEEE- 519, IEC 61000-3-2 (1995-03), and IEC/TS 61000-3-4 (1998-10) standards. Voltage sag problem is addressed in IEEE Standard P1564 and IEEE Standard P1547a. The first one discusses about the impacts of voltage sag and the second one discusses about the ways to make a system more stable by mitigating voltage sag problems. IEC Standard 61000-4-15 characterizes flicker problem. General power quality issues are characterized in IEEE Standard 1159-1995. Impacts of power quality issues and the corresponding solutions are described in IEEE Standard 1250-1995 and IEEE Standard P1409. Characteristics of microgrid and its interconnections with the power system are discussed in IEEE Standard P1547.

Voltage and frequency fluctuations and harmonics are two major power quality issues in renewable energy systems consisting of wind farms and/or PV panels. Partial unpredictability features of renewable resources and non-controllable variability are the causes of power quality issues in the renewable energy side. Power grid side disturbance is another reason of power quality problems in renewable energy based systems. All these issues last for different timespans or durations, and different issues have different frequencies of occurrence. Fig. 26 depicts the duration of power quality issues and the corresponding economic impact on the overall system.

Monitoring of power quality is necessary. Several techniques have been developed for this purpose. Among them, LabVIEW tool, PMU technique, ADALINE, KF etc. are very effective for harmonic detection and monitoring. ADALINE technique is also effective for detection of other power quality issues such as sag, swell, interruptions etc. High resolution method, HT, and TEO methods are useful to monitor voltage flicker problem.

Among the solutions of power quality problems, UPQC provides solution to voltage sags/swells, flicker, voltage unbalance, and harmonics with its series circuit. With its shunt circuit, it provides solution to power factor, load harmonic currents, and load unbalance. D-STATCOM mitigates poor power factor and current harmonics. It also works as filter, voltage regulator at distribution bus, and load balancer. Emergency power shortage can be handled by using UPS which is mainly used for electronic and telecommunication devices.

Voltage transients are corrected by TVSS. Isolation of sensitive loads from transients can be done with isolation transformer. To solve voltage sag/swell problems, DVR can be a potential choice. STATCOM with modified Icosφ algorithm can be used to reduce power quality issues in renewable energy systems. Because of its various advantages such as superior functional characteristics, faster performance, smaller size, cost reduction and the ability to provide both active and reactive power, STATCOM can be the best choice to solve power quality problems in the systems with renewable energy sources. Table 4 depicts the mitigation techniques and their performance levels.

DC systems have higher reliability than AC systems. They also provide simpler integration of energy storage and generation by reducing the need of rectifications and power

electronic converters. However, the DC systems face other obstacles such as stability problem. Detection and clearing of faults are other concerns in DC systems.

Most of the literature cited in this work are from various countries or research works. There may be little variations in those studies which may affect the analysis. Moreover, among renewable energy sources, solar and wind sources are considered only. Other energy sources such as tidal energy and ocean energy are only briefly mentioned here. Also there may be many more research works going on aiming at mitigation of power quality issues that are not addressed here. Only the most significant problems and solutions are discussed in this work.

The scopes for future research in power quality issues are many. These include, but not limited to:

- Comprehensive study of power quality issues with hydropower system need to be investigated. An extensive investigation on the power quality issues as well as their mitigation techniques need to be studied more thoroughly. Usually, non-controllable variability of renewable energy resources affects the systems which use renewable energy sources. This variability along with power grid-side disturbances can be potential future academic research topic.
- Mitigation and monitoring technique for the voltage spike is another topic which can be further discussed. Proper monitoring, tracking and detection schemes need to be developed for this type of very fast varying voltage.
- Monitoring devices for voltage sag, swell, noise, interruptions, transients etc. need to be developed to track and detect those issues more accurately. Both time domain and wavelet domain analysis can be done and efficiencies of both methods for monitoring power quality issues can be compared.
- Detection and mitigation of higher order harmonics and inter-harmonics requires in-depth research. Monitoring of these two problems is also another important aspect that can be addressed in future research.
- Moreover, interactions between microgrids and utility grids can introduce additional power quality problems such as loss, instability etc. Mitigation and monitoring of these problems also need to be analyzed.
- Proper design of the SR level need to be investigated, as for inappropriate levels of SR in the power systems, unexpected events such as sudden load change, and intermittency of renewable sources, can have severe effects on power quality.

X. CONCLUSION

This paper discusses the power quality issues for distributed generation systems based on renewable energy sources such as solar and wind energy. A thorough discussion about power quality issues, their sources, and parameters have been presented here. Discussion on power quality standards have been carried out afterwards. After that, power quality issues in renewable energy systems, techniques to monitor power quality, the devices used for that purpose, and application of CPDs for mitigating power quality problems have been described. Ways of improving power quality in renewable systems, and analysis of power quality in DC systems have followed all these; and the outcomes have been presented finally to summarize the findings of this work.

From the outcomes of this research, transient has been found out to be the most severe power quality issue, followed by voltage spike and fluctuation. The power quality monitoring techniques have been found to be employed for monitoring harmonics mainly, while UPQC, STATCOM, and spinning reserve have been found out to be the most effective CPDs. It has been resolved that STATCOM can be a potential choice due to the advantages it offers.

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