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Research/Technical Note

Issues of Power Quality in Electrical Systems

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Abstract: It is not enough to have power supply. The characteristics of supply voltage at all-time are very essential for smooth operation and service-life of equipment. The voltage characteristics determine the quality of the power supply. The degree to which the supply voltage characteristics conform to the acceptable standard is referred to as Power Quality. With ever increasing use of power electronic devices in domestic and commercial settings as well as sensitive equipment in the industries for automated production, the need for maintaining good power quality has become necessary. This paper elucidates on Power Quality as well as issues associated with it. The causes and consequences of power quality problems are discussed. Techniques for mitigating power quality problems are presented.

Keywords: Harmonics, Overvoltage, Power Quality, Power Quality Monitoring, Voltage Quality, Voltage Sag, Voltage Swell, Undervoltage

1. Introduction

The quality of power supply is very important in any power network particularly to electricity consumers. Power quality encompasses availability of supply, frequency and voltage magnitude as well as waveform characteristics of the power supply. Power is described to be of good quality if the electricity supply is constant at acceptable, steady values of voltage and frequency; and has smooth sinusoidal waveform. However, in practice, varying electricity demands, certain equipment (at home, office and industry) and faults cause disturbances on the power system, thereby causing it to deviate from normal characteristics.

Power quality is poor when at least one of these occurs

- the supply is not constant (outage or interruption),
- when the supplied voltage is lower to or above acceptable range of magnitude,
- when the power system frequency is fluctuating.
- and when the current and voltage sinusoidal waveform of the supply is distorted.

So power quality can be defined as the extent of deviation from nominal values of frequency, current and voltage magnitude. The deviation can also be in term of shape of waveform. Power Quality may also be explained to be the degree to which the supplied power is compatible with the smooth operation of electrical equipment. In other words, it is a measure of how well a power system supports smooth operation of its loads. From a customer perspective, Power Quality problem is any power problem manifested in voltage, current, or frequency deviations which result in power failure or misoperation of customers' equipment [1].

Poor power quality is a serious problem for domestic, commercial and industrial consumers. For instance, some appliances and gadget at domestic level may not work properly if the voltage is below or above acceptable value which may even damage the appliance. Poor power quality may cause bulb and electrical equipment to malfunction or not operate at all and which eventually leads to early failure. In industries, low power quality is problematic for increasingly automated sensitive production machineries.

There has been steady increase of power quality research and publications in the last two decades as result of significant concern and increase of power quality problems mostly caused by proliferation of electronics equipment such as power electronic, energy-efficient lighting, information technology equipment etc. Most of the publications detail some causes and mitigation techniques of poor power quality. In this paper, in addition to presentations of more causes and its effect, emphasis is placed on power quality monitoring and in design stage of electrical systems and equipment. Power quality challenges can be drastically reduced if equipment and power systems are designed to cope well with it.

Power Quality issues surface in electric equipment, electric arc furnace, aircraft electrical system, railway systems, renewable energy, electric motors, industrial processes, in power transmission and distribution systems; and in many other electric power systems applications. Power Quality involves areas of voltage variations, frequency fluctuations, transient, harmonics, current and voltage imbalance etc. [2]

2. Causes of Poor Power Quality

The complexity of a power system to convey electric energy from the point of generation far away from load centres to the point of utilization combined with variations in demand, weather conditions, unbalanced loading on distribution transformer phases as well as the use of complex and electronic equipment by consumers and many other factors allow many chances for reduction in the delivered power quality.

Quite a number of issues causes power quality to be poor. Whatever happen in power systems that causes changes from nominal values of supplied voltage, that distort the waveform sinusoid, that affect frequency stability, will degrade power quality. Some of these are listed below.

2.1. Voltage Variation

The common problems of voltages have to do with their magnitudes. Voltage variation occurs in many forms and each form has appropriate terminology. Voltage variation is deviation from nominal voltage value which can be for a very short duration (millisecond to seconds) or long duration (longer than one minute). Short-duration voltage variation mostly occurs as dips or sags, spike or surge, swells, while long duration voltage variation occurs as flicker (voltage fluctuation), under-voltage, overvoltage, and interruption. These cause the line voltage to go higher or lower than the nominal voltage magnitude for certain period. Voltage variations occur as result of faults on the transmission or distribution network, switching of capacitive loads, loading problems.

2.1.1. Voltage Dip or a Sag

Voltage sag is reduction in rms nominal voltage for short period of time. Voltage dip occurs when the supply voltage falls within 0.1 to 0.9 pu of the nominal voltage for period of up to one minute. It is caused by fault on the line, starting of electric motor or switching of heavy load, excessive loading, starting up of wind turbine etc. Fig. 1 shows voltage dip of reduction of line voltage to half.

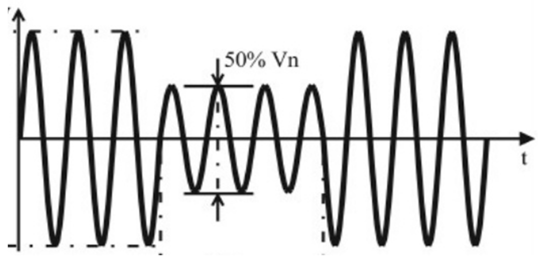

Figure 1. *Voltage sag [3].*

2.1.2. Voltage Swell

Voltage swell is the opposite of voltage sag which is momentary increase in nominal supply voltage. Voltage swell is rise to within 1.1 to 1.8 pu of the normal voltage for duration from half a cycle to several seconds. It occurs when heavy load is turned off, loss of generation, badly regulated transformer, faulty conditions at various points in the AC distribution system, under-loading of a phase while other two phases in a 3-phase system are overloaded. Figure 2 shows the waveform of voltage swell.

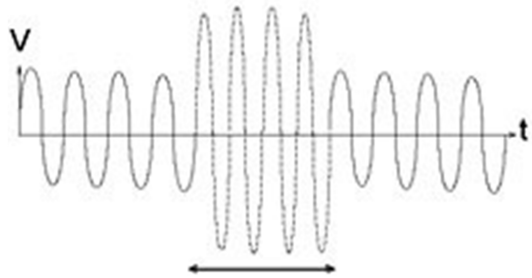

Figure 2. *Voltage swell.*

2.1.3. Flicker

Flicker is the effect of random and repetitive variations in voltage between 0.9-1.1 pu. It result in rapid visible changes in brightening and dimming of screen and variation in the luminosity produced by light bulb. It causes irritation to human sight. It is caused by switching on and off of electric motor, pulsating load, arc furnaces and welding equipment.

2.1.4. Voltage Spikes or Surge

Voltage surge is similar to voltage swell but it is very high increase on the nominal voltage usually for very short duration. It is usually caused by lightning strikes, arcing during switching operation on circuit breakers and contactors, switching surge or transient.

2.1.5. Overvoltage

Overvoltage is an increase in nominal rms voltage greater than 1.1 pu for duration longer than one minute. It result from switching off of large load, incorrect tap setting of transformers, inadequate voltage control, fault on the line.

2.1.6. Undervoltage

Undervoltage is decrease in nominal voltage to less than 0.9 pu for longer than one minute duration. Causes include switching on of large load, circuit overloading, fault on the line.

2.1.7. Interruption

Power interruption occurs when the supply line voltage reduces to less than 0.1 pu for a period not longer than 60 seconds. It becomes sustained interruption if it is longer than one minutes. Causes include insulation failure, improper/faulty grounding, and lightning and insulator flashover. It results in opening and automatic re-closure of protection devices to isolate faulty section of the system. Figure 3 gives illustrates interruption.

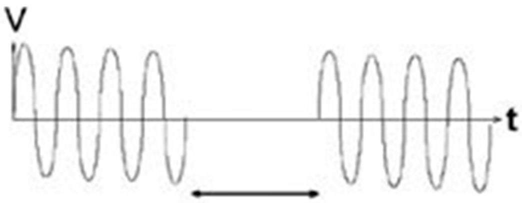

Figure 3. *Interruption.*

2.1.8. Outage

Power outage is a condition of zero voltage for long period. Outage is also use of power equipment failure. Failure of equipment in the power system network, storms, objects (trees, cars, etc.) falling on or hitting power lines or poles, human error, badly coordinated or failure of protection systems are causes of power outage [4].

2.2. Harmonics

Harmonics are AC voltage and current integral multiples of the supply fundamental frequency. For instance in a 50Hz system, a second harmonic is 2× 50 = 100Hz, third harmonics is 3 × 50Hz = 150Hz while the seventh harmonic is 350Hz. Interharmonics are frequencies that are not integer multiples of the fundamental power frequency.

When harmonics and fundamental frequency are added together, it results in single distorted waveform. Normally in a three-phase system, only odd harmonic occurs (3^{rd}, 5^{th}, 7^{th} etc.) [5].

Harmonic frequencies in the power systems are common cause of power quality problems. Harmonics distorts current and voltage waveform of the supply. Causes of harmonic are usually nonlinear electric loads which include UPS, rectifier, inverter, variable drives, arc furnace, welders, voltage controller, and frequency converters [6].

Electric arc furnace is major culprit of power quality degradation in a connected distribution system, it introduces harmonics, propagate flicker and causes imbalance in currents and voltages [7].

Nonlinear load are harmonic-producing in a power distribution system. When connected to supply, their impedance changes with supplied voltage and draw non-sinusoidal current even if the supply is sinusoidal. The non-sinusoidal current has harmonic content that interact with the power distribution system to create voltage distortion in the network [8]. So any other load connected to the distribution network is affected by this voltage distortion. [2, 9].

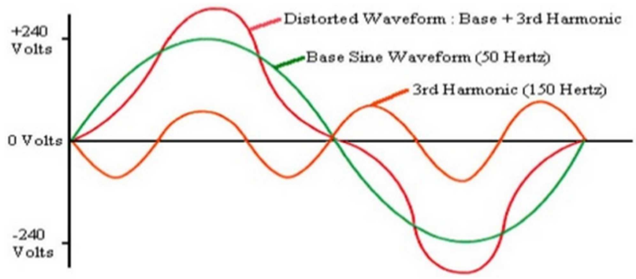

Figure 4. *Harmonic [10].*

In figure 4 above, the green waveform shows the normal ac voltage at 50Hz which is sine wave or sinusoid. The smaller waveform at 150Hz is the third harmonic. Its presence, combined with normal sine waveform to make the operating voltage waveform to be distorted as shown in the figure.

2.3. Frequency Fluctuation

Frequency variation or fluctuation is deviation of power system frequency from acceptable standard nominal value (usually 50 or 60Hz). At any time, power generation on power system should be equal to power demand, if there is more demand than generation the frequency tend to drop but if demand is less than generation, frequency tend to go higher. Fault on transmission line, disconnection of large load, shutting down or going off of large generator may also result in frequency fluctuations. Frequency fluctuations outside tolerance value of ± 5% is not healthy for power system which may lead to system collapse.

2.4. Supply Interruptions

Instability of or epileptic power supply is still major socioeconomic concern particularly in the developing countries. In fact, it is the major power quality problem in these countries. This is due to acute shortage in the grid to meet electricity demand, occasioned by lack of adequate investment in the power sector. Aging power facilities and poor maintenance of the existing ones contribute in no small measure to power quality problems.

3. Effect of Poor Power Quality

The effect of power quality problem is distortion in voltage waveform of the supply from sinusoid, or deviation from its nominal value or complete outage. Power quality problem can last for milliseconds to up to hours. [11]

The nonlinear load characteristics of several power electronic; domestic, industrial and office equipment connected to electric power supply could cause electrical disturbances leading to poor power quality. Equipment such as photocopier, computer, printer etc. can produces electrical disturbance that can destroy certain sensitive equipment connected to the same supply source or in some cases could cause them to malfunction. Industrial drives powered by electronic converter create electrical disturbance. When disturbance occur or power quality is poor, loss of production happen with consequent financial losses.

Major effect of voltage sag includes early failure of equipment, loss of efficiency in rotating machine, malfunction of information technology equipment, loss of data or stability, process interrupt, malfunction of measuring and control instrument etc.

Voltage spike and swell causes destruction of electronic component, melting of insulation materials, too much bright screen, excessive light glow, damage or stoppage of sensitive equipment, data processing errors or data loss, electromagnetic interference.

Harmonics causes power wastage and makes power to be used inefficiently and untimely failure of equipment. It affect smooth operation of industrial machine, thereby causes production stoppage. In hospitals it can result in loss of life. It affect data processing activities of information technology equipment, for instance, in real time such as banking transaction processing may be lost, etc. [12] Overheating of wiring and equipment are among effect of harmonic.

When communication cable lie in parallel with power cables, harmonic frequencies interfere with communication signal resulting in erroneous signal. This can cause disaster in train. Harmonic can cause incorrect operation of protective relays.

Economic cost of Power Quality problems is huge particularly in industry. The cost include production loss, damage to expensive equipment, salary cost, restart cost. Non-financial cost include inconvenience, for instance being unable to watch news or football match or programme on TV. This may be quantify in extra amount of money a customer want to pay to avoid this inconvenience [4, 13, 14].

4. Regulating Standards on Power Quality

There are quite a number of professional standard organisations for power quality while many are national body, few are transnational. The most widely accepted standards are International Electrotechnical Commission IEC and Institute of Electrical and Electronics Engineer IEEE. These standard organisations provides the minimum benchmark required, acceptable technical practice and gives recommendation on electrical and electronic technical issues. Table 1 provides recognise international standard on specific power quality issues.

Table 1. *IEC and IEEE standard on power quality issues.*

Power Quality Issues		Appropriate Standards
1	Voltage sag/swell	IEC 61000-4-11, IEC 61000-4-31 IEEE P1564
2	Flickers	IEC 61000-2-2, IEEE P 1453
4	Harmonic	IEC SC 77 A, IEEE 1346, IEEE SA - 519-2014
5	PQ test, measurement and monitoring	IEEE 1159, IEC SC 77 A/WG 9, IEC 61000-4-1, IEC 61000-4-30

5. Power Quality Standard for IT Equipment

ITI curve is published by Informaton Technology Industry Council (ITI, formerly known as the Computer & Business Equipment Manufacturers Association CBEMA). The curve describes the supply input voltage range (voltage sag, swell, interruption) that can be tolerated by most Information Technology Equipment ITE [1, 15]. The curve is specifically prepare based on 120V 60Hz line supply system typical of USA but it is applicable to any other voltage supply system (e.g. 240V, 50Hz) because it is scaled in percentage of voltage not in the voltage magnitude.

The ITI curve shows the length of time in millisecond or cycle (horizontal axis) IT equipment can safely operate and survive under-voltage, overvoltage, sags and swell at the given percentage of the nominal voltage (vertical axis) [16]. The figure 5 below provide more details about the ITI curve, for instance at 90-110% of the nominal voltage the equipment will operate satisfactorily for infinite length of time. At 120% nominal voltage (swell) it will operate safely for 25 cycle which is 0.5 second, this may be the time when heavy load is switched off.

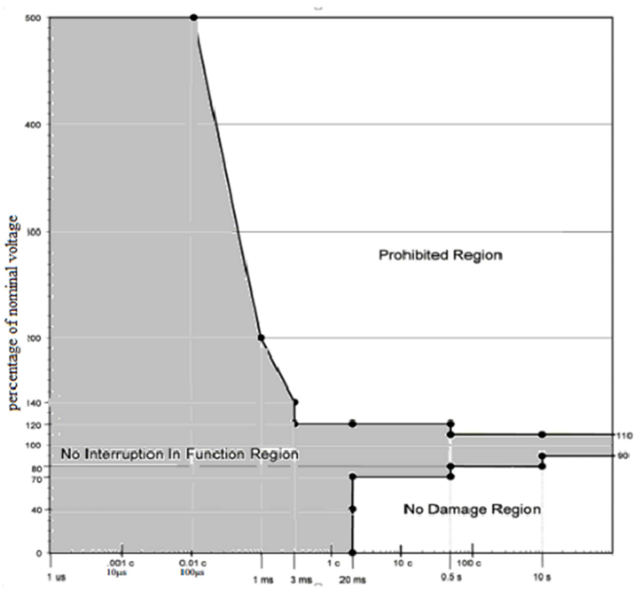

Figure 5. *ITI Curve.*

At 200% of the nominal voltage, the equipment can tolerate it for it for 0.05 cycle, when longer than this period, it enters prohibition zone. At 500% of the nominal voltage, it can only operate for 0.2ms or 0.01 cycle,

In short, when the voltage is within the constraint define by the shaded area, the equipment will operate or function normally. When the voltage fall below the shaded region i.e. no damage region, the equipment may stop operating or malfunction though no damage should result. When the voltage fall in the region above and outside the shaded region (prohibited zone), the equipment might damage except it is protected with fuse or any other protective device.

6. Power Quality Monitoring

Power Quality Monitoring (PQM) is the process of gathering, analysing and interpreting raw power measurement data into useful information [1]. It involve, over a period of time, process of measuring voltage and current of the supply and examining their waveform, although the analysis is not limited to these two quantities. It includes inspection of wiring, grounding, equipment connections. The monitoring of power supply helps to detect present and potential power quality problems that may gradually shortens the life span of equipment. PQ monitoring help to improve facilities' power quality performance.

Power utilities are to ensure that the quality of power supplied is within specified and acceptable standards and be ever ready to normalise any technical issues that affect the quality of power delivered. The latest advances in electronic and communication technologies offers opportunities for monitoring large and complex power systems in an efficient manner. Utilities can take this advantage to collect data on different part of power networks, assess the performance of the system and respond accordingly as well as address complains from the power consumers [17].

Good power monitoring instrument provides useful information and reliable analysis about power quality. Examples includes:

In-plant power monitor which gives the voltage profile and wave shape of the supply for voltage sag, swell, voltage variation and harmonic level evaluation.

Digital Fault Recorder DFR, triggers on fault event and records current, voltage and their waveform at the time of the fault for analysis.

Disturbance Analyser can measure wide variety of power disturbance from a very short duration transient voltage to long duration undervoltages and outages

Flicker Meter is a measuring device to evaluate the level of voltage flicker annoyance. The flicker meter is a special analyzer modelling response of a chain consisting of reference 60W incandescent lamp-eye-brain of an average observer. It has two main part, the first part attempt to simulate the behaviour of the set lamp-eye-brain and the second part focus on statistical analysis of the instantaneous flicker perception [18, 19]

Circuit Monitor provides accurate, reliable and fast alarm detection and multiple levels of information on each power quality issue to help identify the source and cause of a problem including harmonic power flows, flickering, sag, swell.

Oscilloscope measure voltage and current and can display harmonics present in all power quality events.

Power Quality Meter and Analyser is an instrument similar to oscilloscope but more suitable and more versatile for power quality monitoring. It can measures frequency, voltage, current, phase rotation, apparent and real power, harmonics and can also record and store the measured data and analyse them with PC-software.

7. Mitigation Technique

There are numbers of measures to ensure good power quality delivery. Mitigation of power quality problem may take place at different level of power system: at power plant, at transmission lines and stations, at primary and secondary distribution networks as well as at the service equipment and customers' building wiring. It should be noted that the problem of power quality cannot be eliminated completely except some equipment can be done away or if lightning strike can be prevented or if fault can be eliminated. However effect of power quality problem can be drastically reduced to almost zero.

7.1. Availability

Ensuring there is adequate power in the grid. Adequacy of the grid is the capacity of the power plant and transmission lines to meet up with the load demand and energy need of the customers. It relates to the sufficient generation, transmission and distribution infrastructure within the system to satisfy customer electric demand [20, 21]. This is necessary to minimise power quality problems.

7.2. Design of Equipment

Equipment manufacturer should be well aware of power quality issues and design equipment in such a way that the equipment itself does not contributes to power quality problems. Also the equipment should be design to withstand and be less sensitive to disturbances in the power systems. This will help in reducing effect of power quality problems.

7.3. Interfacing Devices

There are numbers of power electronic devices that can be employed to interface between the supply socket and sensitive equipment. This is to prevent power quality problem in the supply from reaching the equipment. An example is the use of automatic voltage regulator AVR to maintain constant voltage into sensitive equipment in spite of any voltage sag, swell and any form of under or overvoltage. Another example is UPS which maintains supply to equipment when there is momentary power interruption. Another one is Dynamic Voltage Restorer DVR which restore smooth sinusoidal line voltage even if the source voltage waveform is degraded or distorted. DVR is voltage source converter. DVR is usually use to interface between the power source and sensitive load to be protected.

7.4. Filter

Filter are used to permit the flow of wanted frequency and block unwanted signal from getting to the protected equipment. Filter is constructed with capacitors inductor and resistor that create low impedance path for the wanted fundamental frequency and high impedance path for the frequency intended for elimination. Harmonic filter cancel harmonics produced by nonlinear load by injecting an exact complimentary harmonic current to it. Different filters types include active harmonic filters, passive harmonic filters, line-reactors, electronic feedback filters and special transformers that use out of phase windings to accomplish harmonic reduction [22]

7.5. Proper Grounding of Electrical System

Proper grounding of electrical system does not only protect installation, equipment and users but also play a key role in enhancing better performance of the system. Poor earthing is one of the causes of poor power quality, particularly at the consumers end.

7.6. Mitigating Devices and Equipment

These are devices and equipment use to correct power quality problems.

7.6.1. Tap Changing Transformer

It is power transformer that incorporate tap changing device. Once, an incoming voltage is outside the expected range, it switch to change winding ratio of the transformer primary to secondary in such a way as to produce the desired voltage values at the secondary. The electronic-switching transformer type is highly efficient, much faster in operation (in millisecond), has low impedance. It consist of electronic sensing circuit and solid state switches (thyristors) to change turns ratio [23]

7.6.2. Static Var Compensator SVC

This is usually use on transmitting system to boost the supply of reactive power and regulate voltage. SVC is a shunt-connection of reactors and capacitors to control voltage and prevent sag and surge during fault as well as improve transmission capability of long transmission line [22]

7.6.3. Transient Voltage Surge Suppression TVSS

Transient voltage surge suppressor is device that clamp transient voltage and limit excessive voltage by a means of nonlinear resistance thereby preventing dangerous voltage from reaching appliances and equipment. It can be installed as interface between power socket and sensitive equipment or at the main consumer electrical service panel.

7.6.4. Lightning Arrester

Lightning arrestor is usually use in power transmission and distribution systems to prevent very high voltage from lightening from being induced into main electrical system by capturing the voltage and diverting it to the general mass of the earth through the earth electrode. This protect electrical installation and equipment from damage from voltage surge which is usually in millions of volts.

Other mitigating devices are Isolation Transformers, Constant Voltage Transformers CVT, Harmonic-cancelling Transformers (at high tech facility) etc.

8. Conclusion

This paper has, in details, properly expatiated what power quality is. It pointed out the causes of power quality problems as inadequate grid, voltage variations/deviation, frequency fluctuations and waveform distortions. The effect of power quality problems include inefficiency, overheating and shortening service-life of equipment, loss of data, process interrupt, insulation breakdown. While, it is not feasible to completely eliminate the causes, the quality of power supply can be improved and the remaining effect in the supply can be mitigated. The proven mitigating techniques are adequate energy availability in the grid, use of interfacing devices (UPS, AVR, DVR etc.), use of power quality improving devices (tap changing transformer, lightning arrestor, SVS), use of filter to block harmonics, as well as proper grounding of electrical installations.

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