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A REVIEW OF POWER QUALITY PROBLEMS AND SOLUTIONS IN ELECTRICAL POWER SYSTEM

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ABSTRACT: Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy. All electrical devices are prone to failure when exposed to one or more power quality problems. The electrical device might be an electric motor, a transformer, a generator, a computer, a printer, communication equipment, or a household appliance. All of these devices and others react adversely to power quality issues depending on the severity of problems. This paper reviewed the power quality problems, effect of power quality problem in different apparatuses and methods for its correction. Some power quality enhancement devices are also listed. It is necessary for engineers, technicians, and system operators to become familiar with power quality issues.

Keywords: Power quality, Voltage spikes, Frequency variation, Power sag, Harmonics, UPQC

I. INTRODUCTION

Power Quality (PQ) related issues are of most concern now days. The widespread use of electronic equipment, such as information technology equipment, power electronics such as adjustable speed drives (ASD), programmable logic controllers (PLC), energy-efficient lighting etc led to a complete change of electric loads nature. These loads are simultaneously the major causers and the major victims of power quality problems [1]. Due to their non-linearity, all these loads cause disturbances in the voltage waveform. Along with technology advance, the organization of the worldwide economy has evolved towards globalization and the profit margins of many activities tend to decrease. The increased sensitivity of the vast majority of processes (industrial, services and even residential) to PQ problems turns the availability of electric power with quality a crucial factor for competitiveness in every activity sector. The most critical areas are the continuous process industry and the information technology services [2].

II.POWER QUALITY

Power is simply the flow of energy and the current demanded by a load is largely uncontrollable. “Power quality” is a convenient term for many; it is the quality of the voltage, rather than power or electric current. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. The performance of electronic devices is directly linked to the power quality level in a facility. The electric power industry comprises electricity generation (AC power), electric power transmission and ultimately electricity distribution to an electricity meter located at the premises of the end user of the electric power. The electricity then moves through the wiring system of the end user until it reaches the load. The complexity of the system to move electric energy from the point of production to the point of consumption combined with variations in weather, generation, demand and other factors provide many opportunities for the quality of supply to be compromised [3].

III.IMPACT OF POWER QUALITY PROBLEMS

Without the proper power, an electrical device may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power. Some of the most common power supply problems and their likely effect on sensitive equipment:

1. Voltage surges/spikes

Voltage surges/spikes are the opposite of dips – a rise that may be nearly instantaneous (spike) or takes place over a longer duration (surge). A voltage surge takes place when the voltage is 110% or more above normal. The most common cause is heavy electrical equipment being turned off. Under these conditions, computer systems and other high tech equipment can experience flickering lights, equipment shutoff, errors or memory loss. Possible Solutions are surge suppressors, voltage regulators, uninterruptable power supplies, power conditioners[4].

2. Voltage Dips

Short duration under-voltages are called “Voltage Sags” or “Voltage Dips [IEC]”. Voltage sag [5, 6] is a reduction in the supply voltage magnitude followed by a voltage recovery after a short period of time. The major cause of voltage dips on a supply system is a fault on the system, i.e. sufficiently remote electrically that a voltage interruption does not occur. Other sources are the starting of large loads and, occasionally, the supply of large inductive loads [6]. The impact on consumers may range from the annoying (non-periodic light flicker) to the serious (tripping of sensitive loads and stalling of motors.

3. Under voltages

Excessive network loading, loss of generation, incorrectly set transformer taps and voltage regulator malfunctions, causes under voltage. Loads with a poor power factor or a general lack of reactive power support on a network also contribute. Under voltage can also indirectly lead to overloading problems as equipment takes an increased current to maintain power output (e.g. motor loads) [5].

4. High-Voltage Spikes

High-voltage spikes occur when there is a sudden voltage peak of up to 6,000 volts. These spikes are usually the result of nearby lightning strikes, but there can be other causes as well. The effects on vulnerable electronic systems can include loss of data and burned circuit boards. Possible Solutions are using Surge Suppressors, Voltage Regulators, Uninterruptable Power Supplies, Power Conditioners [7].

5. Frequency Variation

A frequency variation involves a change in frequency from the normally stable utility frequency of 50 or 60 Hz, depending on your geographic location. This may be caused by erratic operation of emergency generators or unstable frequency power sources. For sensitive equipment, the results can be data loss, program failure, equipment lock-up or complete shutdown. Possible Solutions are using Voltage Regulators and Power Conditioners [7].

6. Power Sag

Power sags are a common power quality problem. Despite being a short duration (10ms to 1s) event during which a reduction in the RMS voltage magnitude takes place, a small reduction in the system voltage can cause serious consequences. Sages are usually caused by system faults, and often the result of switching on loads with high demand startup currents. For more details about power sags visit our newsletter archives. Possible Solutions are using Voltage Regulators, Uninterruptable Power Supplies, and Power Conditioners [8].

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7. Electrical Line Noise

Electrical line noise is defined as Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI) and causes unwanted effects in the circuits of computer systems. Sources of the problems include motors, relays, motor control devices, broadcast transmissions, microwave radiation, and distant electrical storms. RFI, EMI and other frequency problems can cause equipment to lock-up, and data error or loss. Possible Solutions are using Voltage Regulators, Uninterruptable Power Supplies, and Power Conditioners [7].

8. Brownouts

A brownout is a steady lower voltage state. An example of a brownout is what happens during peak electrical demand in the summer, when utilities can't always meet the requirements and must lower the voltage to limit maximum power. When this happens, systems can experience glitches, data loss and equipment failure. Possible Solutions are using Voltage Regulators, Uninterruptable Power Supplies, and Power Conditioners [9].

9. Blackouts

A power failure or blackout is a zero-voltage condition that lasts for more than two cycles. It may be caused by tripping a circuit breaker, power distribution failure or utility power failure. A blackout can cause data loss or corruption and equipment damage. Possible Solutions is using Generators [10].

10. Very short interruptions

Total interruption of electrical supply for duration from few milliseconds to one or two seconds. Mainly due to the opening and automatic reclosure of protection devices to decommission a faulty section of the network. The main fault causes are insulation failure, lightning and insulator flashover. Consequences of these interruptions are tripping of protection devices, loss of information and malfunction of data processing equipment [11].

11. Long interruptions

Long interruption of electrical supply for duration greater than 1 to 2 seconds. The main fault causes are Equipment failure in the power system network, storms and objects (trees, cars, etc) striking lines or poles, fire, human error, bad coordination or failure of protection devices. A consequence of these interruptions is stoppage of all equipment [1].

12. Voltage swell

Momentary increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds. The main causes are Start/stop of heavy loads, badly dimensioned power sources, badly regulated transformers (mainly during off-peak hours).Consequences is data loss, flickering of lighting and screens, stoppage or damage of sensitive equipment, if the voltage values are too high [11].

13. Harmonic distortion

Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency. Main Causes are Classic sources: electric machines working above the knee of the magnetization curve (magnetic saturation), arc furnaces, welding machines, rectifiers, and DC brush motors. Modern sources: all non-linear loads, such as power electronics equipment including ASDs, switched mode power supplies, data processing equipment, high efficiency lighting [11]. Consequences are increased probability in occurrence of resonance, neutral overload in 3-phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems, and errors in measures when using average reading meters, nuisance tripping of thermal protections.

14. Voltage fluctuation
Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz. Causes are arc furnaces, frequent start/stop of electric motors (for instance elevators), oscillating loads. Consequences are most consequences are common to under voltages. The most perceptible consequence is the flickering of lighting and screens, giving the impression of unsteadiness of visual perception [1].

15. Noise
Superimposing of high frequency signals on the waveform of the power-system frequency. Main Causes are Electromagnetic interferences provoked by Hertzian waves such as microwaves, television diffusion, and radiation due to welding machines, arc furnaces, and electronic equipment. Improper grounding may also be a cause. Consequences are disturbances on sensitive electronic equipment, usually not destructive. It may cause data loss and data processing errors [12].

16. Voltage Unbalance
A voltage variation in a three-phase system in which the three voltage magnitudes or the phase angle differences between them are not equal. Causes are large single-phase loads (induction furnaces, traction loads), incorrect distribution of all single-phase loads by the three phases of the system (this may be also due to a fault). Consequences are Unbalanced systems imply the existence of a negative sequence that is harmful to all three phase loads. The most affected loads are three-phase induction machines [13].

IV.IMPROVE POWER QUALITY

1. Grounding & Bonding Integrity
Computer based industrial system performance is directly related to the quality of the equipment grounding and bonding. If the grounding and bonding is incorrectly configured, poor system performance is the result. Grounding is one of the most important and misunderstood aspects of the electrical system. It is essential to differentiate the functions of the grounded conductor (neutral) from the equipment grounding system (safety ground). The safety ground protects the electrical system and equipment from super-imposed voltages caused by lightning or accidental contact with higher voltage systems. It also prevents static charges build-up. The safety ground establishes a “zero-voltage” reference point for the system. The safety ground must be a low impedance path from the equipment to the bonding point to the grounding electrode at the service entrance. This allows fault currents high enough to clear the circuit interrupters in the system preventing unsafe conditions. The grounded conductor (neutral) is a current carrying conductor which is bonded to the grounding system at one point. Grounding this conductor limits the voltage potential inside the equipment in reference to grounded parts. Neutral and ground should only be bonded together at the service entrance or after a separately derived source. One of the most common errors in a system is bonding the neutral to ground in multiple locations. Whether intentional or unintentional, these ‘extra’ bonding points should be identified and eliminated. Proper grounding and bonding minimizes costly disturbances [13].

2. Proper Wiring
An overall equipment inspection is crucial to ensure proper wiring within a facility. The entire electrical system should be checked for loose, missing or improper connections at panels, receptacles and equipment. Article 300 of the National Electrical Code cover wiring methods and should be followed to ensure safe and reliable operation. There are many types of commonly available circuit testers that can be used to check for improper conditions such as reversed polarity, open neutral or floating grounds. Make certain to isolate panels feeding sensitive electronic loads from heavy inductive loads, or

other electrically noisy equipment such as air compressors or refrigeration equipment. Also check neutral and ground conductors to make sure they are not shared between branch circuits [13].

3. Power Disturbances
Voltage fluctuations and noise are common power disturbances present in any electrical environment that directly affect electronic equipment. These disturbances exist in numerous forms including transients, sags, swells, over voltages, under voltages, harmonics, outages, frequency variations and high frequency noise. Harmonic distortion has emerged as significant problem due to the increased use of electronic equipment. This electronic equipment draws current that is not linear to the voltage waveform. This non-linear current can cause high neutral current, overheated neutral conductors, overheated transformers, voltage distortion and breaker tripping. Loads such as solid-state controls for adjustable speed motors, computers and switched mode power supplies are sources of non-linear currents. The Information Technology Industry Council (ITIC) has revised the CBEMA curve in 2000. This curve is used to define the voltage operating envelope within which electronic equipment should operate reliably. Equipment should be able to tolerate voltage disturbances in the "no interruption" region of the chart. When the voltage disturbance is in the "no-damage" region, the equipment may not operate properly, but should recover when voltage returns to normal. If voltages reach the "prohibited region," connected equipment may be permanently damaged. Expensive equipment should be protected from voltages in the prohibited region. Processes which require high reliability should be protected from both the prohibited and no-damage regions [13].

V. POWER QUALITY SOLUTIONS

Besides energy storage systems and DG, some other devices may be used to solve PQ problems. Using proper interface devices, one can isolate the loads from disturbances deriving from the grid.

A. POWER CONDITIONING EQUIPMENT

Several types of power enhancement devices have been developed over the years to protect equipment from power disturbances. The following devices play a crucial role in developing an effective power quality strategy.

1. Transient Voltage Surge Suppressors (TVSS)

It provides the simplest and least expensive way to condition power. These units clamp transient impulses (spikes) to a level that is safe for the electronic load. Employing an entire facility protection strategy will safeguard the electrical system against most transients. Multi-stage protection entails using TVSS at the service entrance, sub-panel a at the point of use. This co-ordination of devices provides the lowest possible let through voltage to the equipment.
Transient voltage surge suppressors are used as interface between the power source and sensitive loads, so that the transient voltage is clamped by the TVSS before it reaches the load. TVSSs usually contain a component with a nonlinear resistance (a metal oxide varistor or a zener diode) that limits excessive line voltage and conduct any excess impulse energy to ground [14].

2. Filters
- Noise Filters

Noise filters are used to avoid unwanted frequency current or voltage signals (noise) from reaching sensitive equipment. This can be accomplished by using a combination of capacitors and inductances that creates a low impedance path to the fundamental frequency and high impedance to higher frequencies, that is, a low-pass filter. They should be used when noise with frequency in the kHz range is considerable.

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- Harmonic Filters

Harmonic filters are used to reduce undesirable harmonics. They can be divided in two groups: passive filters and active filters. Passive filters consist in a low impedance path to the frequencies of the harmonics to be attenuated using passive components (inductors, capacitors and resistors). Several passive filters connected in parallel may be necessary to eliminate several harmonic components. If the system varies (change of harmonic components), passive filters may become ineffective and cause resonance. Active filters analyze the current consumed by the load and create a current that cancel the harmonic current generated by the loads. Active filters were expensive in the past, but they are now becoming cost effective compensating for unknown or changing harmonics [15].

3. Isolation Transformers

Isolation transformers are used to isolate sensitive loads from transients and noise deriving from the mains. In some cases (Delta-Wye connection) isolation transformers keep harmonic currents generated by loads from getting upstream the transformer. The particularity of isolation transformers is a grounded shield made of nonmagnetic foil located between the primary and the secondary. Any noise or transient that come from the source in transmitted through the capacitance between the primary and the shield and on to the ground and does not reach the load. It provides a degree of isolation and filtering. These devices effectively reduce conducted electrical noise by physical separation of the primary and secondary through magnetic isolation. Isolation transformers reduce normal and common mode noises, however, they do not compensate for voltage fluctuations and power outages [16].

4. Voltage Regulators

Voltage regulators maintain output voltage at nominal voltage under all but the most severe input voltage variations. Voltage regulators are normally installed where the input voltage fluctuates, but total loss of power is uncommon. There are three basic types of regulators:

- Tap Changers: Designed to adjust for varying input voltages by automatically transferring taps on a power transformer. The main advantage of tap changes over other voltage regulation technology is high efficiency. Other advantages are wide input range, high overload current capability and good noise isolation. Disadvantages are noise created when changing taps and no waveform correction.
- Buck Boost: Utilize similar technology to the tap changers except the transformer is not isolated. Advantages are the units withstand high in-rush currents and have high efficiency. Disadvantages are noise created when changing taps, poor noise isolation and no waveform correction.
- Constant Voltage Transformer (CVT): Also known as ferroresonant transformers. The CVT is a completely static regulator that maintains a nearly constant output voltage during large variations in input voltage. Advantages are superior noise isolation, very precise output voltage and current limiting for overload protection. The lack of moving parts mean the transformer requires little or no maintenance. Disadvantages are large size, audible noise and low efficiency.

Constant voltage transformers (CVT) were one of the first PQ solutions used to mitigate the effects of voltage sags and transients. To maintain the voltage constant, they use two principles that are normally avoided: resonance and core saturation. When the resonance occurs, the current will increase to a point that causes the saturation of the magnetic core of the transformer. If the magnetic core is saturated, then the magnetic flux will remain roughly constant and the transformer will produce an approximately constant voltage output. If not properly used, a CVT will originate more PQ problems than the ones mitigated. It can produce transients, harmonics (voltage wave clipped on the top and sides) and it is inefficient (about 80% at full load). Its application is becoming uncommon due to technological advances in other areas [14].

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5. Dynamic Voltage Restorer

A dynamic voltage restorer (DVR) acts like a voltage source connected in series with the load. The output voltage of the DVR is kept approximately constant voltage at the load terminals by using a step-up transformer and/or stored energy to inject active and reactive power in the output supply trough a voltage converter [19].

6. Uninterruptible Power Supply (UPS)

UPS systems provide protection in the case of a complete power interruption (blackout). They should be applied where "down time" resulting from any loss of power is unacceptable. UPS are designed to provide continuous power to the load in the event of momentary interruptions. They also provide varying degrees of protection from surges, sags, noise or brownouts depending on the technology used [14]. There are three major UPS topologies each providing different levels of protection:

- Off-Line UPS (also called Standby)

Low cost solution for small, less critical, stand-alone applications such as programmable logic controllers, personal computers and peripherals. Off-line UPS systems supply the load directly from the electrical utility with a limited conditioning. The unit provides power to the load from the battery during sags, swells and power interruptions. They offer some noise suppression through a filter/surge suppressor module. Advantages of off-line UPS are high efficiency, low cost and high reliability. The main disadvantage is that protection from high and low voltages is limited by the battery capacity. Other disadvantages are poor output voltage regulation and noticeable transfer time. To keep unit cost low, most off-line units utilize step-sine wave outputs when on battery power.

- Line-Interactive UPS

Line-Interactive UPS provides highly effective power conditioning plus battery back-up. These units are ideal in areas where voltage fluctuations are frequent. The defining characteristic of line-interactive models is they can regulate output voltage without depleting the battery. Advantages are good voltage regulation and high efficiency. Disadvantages are noticeable transfer time and difficulty in comparing competing units. The output waveform can be either a sine wave or step-sine wave depending on the manufacturer and model.

- True On-Line UPS

True On-Line UPS provides the highest level of power protection, conditioning and power availability. True on-line technology, also called double conversion is unique in that the power is converted from AC utility to DC for battery charging and to power the inverter. The DC is then converted back to AC to power the critical load. Advantages of the on-line UPS include the elimination of any transfer time and superior protection from voltage fluctuations. Voltage regulation is achieved by continuously regenerating a clean sine wave. Disadvantages are lower efficiency and higher audible noise.

7. Motor-Generators Set

Generators are machines that convert mechanical energy into electrical energy. They are usually used as a backup power source for a facility's critical systems such as elevators and emergency lighting in case of blackout. However, they do not offer protection against utility power problems such as over voltages and frequency fluctuations, and although most can be equipped with automatic switching mechanisms, the electrical supply is interrupted before switching is completed, so it cannot protect against the damage that blackouts can cause to expensive equipment and machinery. Motor generators are consists of an electric motor driving a generator with coupling through a mechanical shaft. This solution provides complete decoupling from incoming disturbances such as voltage transients, surges and sags. Motor-Generators ride through short

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periods of power loss, but will not protect against sustained outages without the addition of an additional motor powered by an alternate fuel source (such as diesel or propane) [14].

8. Static Var Compensators (SVCS)

Static VAR compensators (SVR) use a combination of capacitors and reactors to regulate the voltage quickly. Solid-state switches control the insertion of the capacitors and reactors at the right magnitude to prevent the voltage from fluctuating. The main application of SVR is the voltage regulation in high voltage and the elimination of flicker caused by large loads (such as induction furnaces). It is normally applied to transmission networks to counter voltage dips/surges during faults and enhance power transmission capacity on long [14].

9. Thyristor-Based Static Switch

The static switch is a versatile device for switching a new element into the circuit when voltage support is needed. To correct quickly for voltage spikes, sags, or interruptions, the static switch can be used to switch in one of the following: Capacitor, Filter, Alternate power line, Energy storage system. The static switch can be used in the alternate power line application. This scheme requires two independent power lines from the utility. It protects against 85% of the interruptions and voltage sags [17].

10. Unified Power Quality Conditioner (UPQC)

The unified power quality conditioner (UPQC) is a custom power device, which mitigates voltage and current-related PQ issues in the power distribution systems. The UPQC employs two voltage source inverters (VSIs) that is connected to a dc. energy storage capacitor .A UPQC, combines the operations of a Distribution Static Compensator (DSTATCOM) and Dynamic Voltage Regulator (DVR) together. This combination allows a simultaneous compensation of the load currents and the supply voltages, so that compensated current drawn from the network and the compensated supply voltage delivered to the load are sinusoidal and balanced [17].

B. ENERGY STORAGE SYSTEMS

Energy storage systems, also known as restoring technologies, are used to provide the electric loads with ride-through capability in poor PQ environment. Storage systems can be used to protect sensitive production equipment from shutdowns caused by voltage sags or momentary interruptions. These are usually dc storage systems, such as UPS, batteries, superconducting magnet energy storage (SMES) [18], storage capacitors etc. The output of these devices is supplied to the system through an inverter on a momentary basis by a fast acting electronic switch. Enough energy is fed to the system to replace the energy that would be lost by the voltage sag or interruption. Energy storage systems, also known as restoring technologies, are used to provide the electric loads with ride-through capability in poor PQ environment.

1. Flywheels

A flywheel is an electromechanical device that couples a rotating electric machine (motor/generator) with a rotating mass to store energy for short durations. The motor/generator draws power provided by the grid to keep the rotor of the flywheel spinning. During a power disturbance, the kinetic energy stored in the rotor is transformed to DC electric energy by the generator, and the energy is delivered at a constant frequency and voltage through an inverter and a control system. Fig. 8 depicts the scheme of a flywheel, where the major advantages of this system are explained. Steel and are limited to a spin rate of a few thousand revolutions per minute (RPM). Advanced flywheels constructed from carbon fibre materials and magnetic bearings can spin in vacuum at speeds up to 40,000 to 60,000 RPM. The stored energy is proportional to the moment of inertia and to the square of the rotational speed. High speed flywheels can store much more energy than the conventional flywheels. The flywheel provides power during a period between the loss of utility supplied power and either the return of utility power or the start of a back-up power system (i.e., diesel generator). Flywheels typically provide 1-100 seconds of ride-through time, and back-up generators are able to get online within 5-20 seconds [18].

2. Supercapacitors

Supercapacitors (also known as ultracapacitors) are DC energy sources and must be interfaced to the electric grid with a static power conditioner, providing energy output at the grid frequency. A supercapacitor provides power during short duration interruptions or voltage sags. Medium size supercapacitors (1 MJoule) are commercially available to implement ride-through capability in small electronic equipment, but large supercapacitors are still in development, but may soon become a viable component of the energy storage field. Capacitance is very large because the distance between the plates is very small (several angstroms), and because the area of conductor surface (for instance of the activated carbon) reaches 1500-2000 m2/g (16000-21500 ft2/g). Thus, the energy stored by such capacitors may reach 50-60 J/g [19].

3. Superconducting Magnetic Energy Storage (SMES)

A magnetic field is created by circulating a DC current in a closed coil of superconducting wire. The path of the coil circulating current can be opened with a solid-state switch, which is modulated on and off. Due to the high inductance of the coil, when the switch is off (open), the magnetic coil behaves as a current source and will force current into the power converter which will charge to some voltage level. Proper modulation of the solid-state switch can hold the voltage within the proper operating range of the inverter, which converts the DC voltage into AC power. Low temperature SMES cooled by liquid helium is commercially available. High temperature SMES cooled by liquid nitrogen is still in the development stage and may become a viable commercial energy storage source in the future due to its potentially lower costs. SMES systems are large and generally used for short durations, such as utility switching events [18].

VI.CONCLUSIONS

The availability of electric power with high quality is crucial for the running of the modern society. If some sectors are satisfied with the quality of the power provided by utilities, some others are more demanding. To avoid the huge losses related to PQ problems, the most demanding consumers must take action to prevent the problems. Among the various measures, selection of less sensitive equipment can play an important role. When even the most robust equipment is affected, then other measures must be taken, such as installation of restoring technologies, distributed generation or an interface device to prevent PQ problems.

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