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A Survey of Voltage Sags and Voltage Swells Phenomena in Power Quality Problems

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Abstract: *Power quality is very important issue recently due to the impact on electricity suppliers, equipment manufacture and customers. Power quality is described as the variation of voltage, current and frequency in a power system. It refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location in the power system. Nowadays, there are so many industries using high technology for manufacturing and process unit. This technology requires high quality and high reliability of power supply. The industries like semiconductor, computer, and the equipments of manufacturing unit are very sensitive to the changes of quality in power supply. Power Quality problems encompass a wide range of disturbances such as voltage sags/swells, flicker, harmonics distortion, impulse transient, and interruptions. Voltage sags/swells can occurs more frequently than other Power quality phenomenon. These sags/swells are the most important power quality problems in the power distribution system. The objective and scope of this paper is study of power quality phenomena in distribution systems.*

Keywords: power quality, voltage, current, frequency, distribution system, control.

1. Introduction

The electric power system is considered to be composed of three functional blocks: generation, transmission and distribution. For a reliable power system, the generation unit must produce adequate power to meet customer's demand, transmission systems must transport bulk power over long distances without overloading or jeopardizing system stability and distribution systems must deliver electric power to each customer's premises from bulk power systems. Distribution system locates the end of power system and is connected to the customer directly, so the power quality mainly depends on distribution system[1]. The reason behind this is that the electrical distribution network failures account for about 90% of the average customer interruptions. In the earlier days, the major focus for power system reliability was on generation and transmission only as these more capital cost is involved in these. In addition their insufficiency can cause widespread catastrophic consequences for both society and its environment. But now a day's distribution systems have begun to receive more attention for reliability assessment [2].
Power Quality (PQ) related issues are of most concern nowadays. 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, led to a complete change of electric loads nature. These loads are simultaneously the major causers and the major victims of power quality problems. Due to their non-linearity, all these loads cause disturbances in the voltage waveform [3]. 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. When a disturbance occurs, huge financial losses may happen, with the consequent loss of productivity and competitiveness. There are a lot of power quality problems occurred in reality such as harmonic distortion, voltage swell and etc. In this paper, it focused on power quality problems [4].
Power quality phenomena include all possible situations in which the waveform of the supply voltage (voltage quality) or load current (current quality) deviate from the sinusoidal waveform at rated frequency with amplitude corresponding to the rated rms value for all three phases of a three-phase system. The wide range of power quality disturbances covers sudden, short duration variations, e.g. impulsive and oscillatory transients, voltage sags, short interruptions, as well as steady state deviations, such as harmonics and flicker. One can also distinguish, based on the cause, between disturbances related to the quality of the supply voltage and those related to the quality of the current taken by the load [5].
To the first class belong, among others, voltage dips and interruptions, mostly caused by faults in the power system. These disturbances may cause tripping of "sensitive" electronic equipment with disastrous consequences in industrial plants

where tripping of critical equipment can bear the stoppage of the whole production with high costs associated. One can say that in this case it is the source that disturbs the load. To avoid consistent money losses, industrial customers often decide to install mitigation equipment to protect their plants from such disturbances [6].

The second class covers phenomena due to low quality of the current drawn by the load. In this case, it is the load that disturbs the source. A typical example is current harmonics drawn by disturbing loads like diode rectifiers, or unbalanced currents drawn by unbalanced loads. Customers do not experience any direct production loss related to the occurrence of these power quality phenomena. But poor quality of the current taken by many customers together will ultimately result in low quality of the power delivered to other customers: both harmonics and unbalanced currents ultimately cause distortion and respectively, unbalance in the voltage as well. Therefore, proper standards are issued to limit the quantity of harmonic currents, unbalance and/or flicker that a load may introduce. To comply with limits set by standards, customers often have to install mitigation equipment [1].

In recent years, both industrial and commercial customers of utilities have reported a rising tide of misadventures related to power quality. The trouble stems from the increased refinement of today's automated equipment, whether variable speed drives or robots, automated production lines or machine tools, programmable logic controllers or power supplies in computers. They and their like are far vulnerable to disturbances on the utility system than were the previous generation of electromechanical equipment and the previous less automated production and information systems [2]. A growing number of loads are sensitive to customers' critical processes which have costly consequences if disturbed by either poor power quality or power interruption [3].

For the reasons described above, there is a growing interest in equipment for mitigation of power quality disturbances, especially in newer devices based on power electronics called "custom power devices"[4] able to deliver customized solutions to power quality problems [3].

The concept of Custom Power was introduced by N.G. Hingorani [2]. The term Custom Power describes the value-added power that electric utilities and other service providers will offer their customers in the future. The improved level of reliability of this power, in terms of reduced interruptions and less variation, will stem from an integrated solution to present problems, of which a prominent feature will be the application of power electronic controllers to the utility distribution systems and/or at the supply and of many industrial and commercial customers and industrial parks [4].

Many techniques are used to mitigate voltage sag and swells, but the use of a custom power device is considered to be the most efficient method. Like Flexible AC Transmission Systems (FACTS) for transmission systems, the term custom power pertains to the use of power electronics controllers in a distribution system, especially, to deal with various power quality problems. Just as FACTS improves the power transfer capabilities and stability margins, custom power makes sure customers get pre-specified quality and reliability of supply [4]. DVR has been used to compensate the voltage sag in [5, 6, 7&8]. The DVR with Uninterruptible Power Supply (UPS) was proposed for sag reduction [9]. Adaptive Neural Network with Dynamic Voltage Restorer was applied to solve sag's problem [10]. A new device which is named Inter-line Dynamic Voltage Restorer is discussed in [11].

The custom power devices which are increasingly being used to reduce voltage sag and swell are mainly Dynamic Voltage Restorer (DVR), Distributed Static Compensator (D-STATCOM) and Solid State Transfer Switch (SSTS) [12]. However, there are many other problems that make the power quality worse, such as voltage harmonics, notch and the distortion by nonlinear load currents [13].

2. Definition of Power Quality

Power quality is a term that means different things to different people. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE1100 defines power quality as [14] "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment." As appropriate as this description might seem, the limitation of power quality to "sensitive electronic equipment" might be subject to disagreement. Electrical equipment susceptible to power quality or more appropriately to lack of power quality would fall within a seemingly boundless domain. All electrical devices are prone to failure or malfunction 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. A simpler and perhaps more concise definition might state: "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." This definition embraces two things that we demand from an electrical device: performance and life expectancy. Any power-related problem that compromises either attribute is a power quality concern. Along with definitions of the terms, explanations are included in parentheses where necessary.

A well-established definition of power quality does not exist because it depends on one's reference frame. For instance, whilst one customer considers a certain voltage waveform as having a "sufficient quality" in order to maintain the production working properly, another customer can realize that the same voltage has a "poor quality".

One aspect of common agreement is to consider the power quality as a customer driven issue, i.e. the customers point of view is determinant for indicating the quality of the power (in fact, the quality of the voltage). Based on this assumption, a power quality problem can be defined as [15]:

"Any power problem manifested in voltage/current or leading to frequency deviations that results in failure or misoperation of customer equipment".

This definition means that the decisive measurement of power quality is taken from the performance and productivity of end-user equipment (customer). If the electric power is inadequate for those needs, the quality is said to be "lacking".

3. Problem Associated with Power Quality

Power quality problems are associated to an extensive number of electromagnetic phenomena in power systems with a broad range of time. For instance, it includes impulsive transients (in the range of nanoseconds) as well as frequency deviations (in the range of some seconds7). A comprehensive description of the categories and characteristics of power systems electromagnetic phenomena related to variations in the voltage magnitude is available in [16]. The classification takes the voltage into account, as the quality of the voltage is the addressed issue in most of the cases. However, it is well known that there is always a close relationship between voltages and currents in a power system. Specifications regarding current are applied to dimensioning an equipment or in the case of harmonics. There are a number of different types of power quality disturbances and also a number of different ways to define and categorize them. Here follows one possible list of power quality disturbances types, categorized in one of many possible ways.

A. Long Duration Voltage Variations

Deviations in the operating rms values during longer time than one minute are usually considered *long-duration variations*. According to the amplitude variation, they can be related to permanent faults, load variations, and switching operations in the system. As an example, switching a capacitor bank or a large load can cause noticeable changes in the voltage. If the countermeasures, in this case the voltage regulation, acts very slowly, the voltage change can be characterized as a long-duration variation. Depending on the magnitude of the voltage change, long-duration voltage variations can be classified as [17]:

Undervoltage – decrease in the rms voltage to less than 90% of the nominal voltage.

Overvoltage – increase in the rms voltage to more than 110% of the nominal voltage.

Sustained Interruption – supply voltage equal to zero for more than one minute. These interruptions are usually permanent and require human intervention to repair the system. Although utilities use the term *"outage"* as a sustained interruption for reliability reporting purposes, the term *"outage"* should be avoided in the power quality context. The reason is that end-users associate the term *"outage"* to any interruption of power that shuts down a process, even when the power supplied by the utility is restored in a few cycles. Meanwhile, in the reliability context, the term *"outage"* refers to the state of a component in a system that has failed to function as expected. The sustained interruptions are studied in the area of reliability, where the duration and number of these interrupts are computed by different indexes.

B. Short Duration Voltage Variations

This type of voltage variation is mainly caused by either fault conditions – and associated fault currents - or energization of large loads that require high starting currents. Depending on the electrical distance - related to impedance, type of grounding, and connection of transformers - between the fault/load location and the analyzed node, the disturbance can cause a temporary loss of voltage (denoted interruption) or temporary voltage reduction (denoted sag or dip) or voltage rises (denoted swells) at different nodes of the system. In any case, the impact on the voltage during the disturbance is of short-duration, until protective devices start operating.

- **Voltage sags(dips)**

A voltage sag, sometimes known as a voltage dip, is a short term reduction in the rms voltage. The IEC electrotechnical vocabulary, IEC 60050 [18], defines a voltage sag as any *"sudden reduction of the voltage at a point in the electrical system, followed by voltage recovery after a short period of time, from half a cycle to a few seconds".* Voltage sags are characterised by their duration and depth. Duration is the length of time for which the voltage remains below a threshold. The concept of depth is somewhat a misnomer as a sag is characterised by the retained voltage, that is the voltage which persists during the sag, as opposed to the voltage decrease or 'lost' voltage. While the IEC definition does not give a set of definitive durations or level of retained voltage that must be observed for a disturbance to be classified as a voltage sag, IEEE Std 1159 [16] defines a voltage sag as a variation in the rms voltage of duration greater than ½ a cycle and less than 1 minute with a retained voltage of between 10% and 90% of nominal. This is the generally accepted definition of a voltage sag. Any disturbance that persists for less than ½ cycle is considered transient phenomena while voltage variations or disturbances of duration greater than 1 minute with retained voltages of less than 90 % of nominal may be considered as either sustained undervoltages or interruptions. Voltage sags are caused by large currents interacting with network impedances. The two main causes of voltage sags are network faults and the starting of equipment which draw large currents, particularly direct-on-line motors. A voltage sag (Figure 1) is a short-duration reduction in rms voltage caused by faults on the power system and the starting of large loads, such as motors [19].

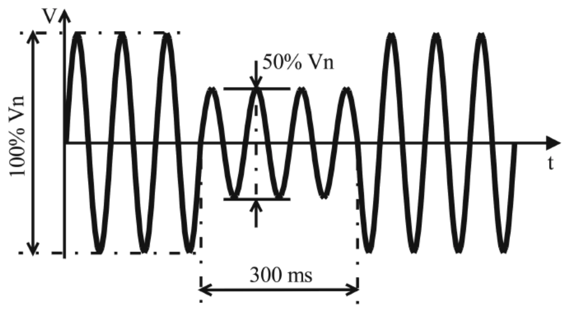

Figure 1: An example of voltage sag.

It is said that a voltage sag has taken place in an electrical network point when the voltage in one or more phases falls suddenly beneath an established limit (generally a 90% of the normal voltage), and recovers after a short period of time (usually between 10 ms and some seconds). The maximum limit of this period is probably the most controversial issue about the voltage sag definition: some authors consider that a voltage sag exists when its duration reaches 1 min, or even 3 min. The expected number of events during one year can oscillate between ten and a thousand. Based on the time duration and voltage magnitude, sag is further classified as:

a) **Instantaneous Sag**: Instantaneous sag is said to occur when the r.m.s voltage decreases to between 0.1 and 0.9 per unit for time duration of 0.008333 second to 0.5 second.

b) **Momentary Sag**: Momentary sag is said to occur when the r.m.s voltage decreases to between 0.1 and 0.9 per unit for time duration of 0.5 second to 3 seconds.

c) **Temporary Sag**: Temporary sag is said to occur when the r.m.s voltage decreases to between 0.1 and 0.9 per unit for time duration of 3 to 60 seconds.

- **General causes of voltage sags**

❖ **Voltage sags due to faults**

Voltage sags can caused by faults (more than 70% are weather related such as lightning) on the transmission or distribution system or by switching of loads with large amounts of initial starting or inrush current such as motors, transformers, and large dc power supply [20]. Voltage sag due to fault can be critical to the operation of a power plant. The magnitude of voltage sag can be equal in each phase or unequal respectively and it depends on the nature of the fault whether it is symmetrical or unsymmetrical. For a fault in the transmission line system, customers do not experience interruption, since transmission systems are looped or networked.

❖ **Voltage sags due to motor starting**

Voltage sag due to motor starting are symmetrical since the induction motors are balanced three phase loads, which will be resulting in each of the phase drawing approximately the same inrush current. The magnitude of voltage sag depends upon:

a) Characteristic of induction motor.

b) Strength of the system node where motor is connected.

❖ **Voltage sags due to transformer energizing**

There are mainly two causes of voltage sag due to transformer energizing. One is normal system operations which include manual energizing of a transformer and another is the reclosing actions. These voltage sags are unsymmetrical in nature and often depicted as a sudden drop in system voltage followed by a slow recovery. The main reason behind voltage sag due to transformer energizing is the over fluxing of the transformer core which leads to saturation. The voltage sags are unsymmetrical in nature and oftenly depicted as a sudden drop in system voltage followed by a slow recovery. The main reason for transformer energizing is the over-fluxing of the transformer core which leads to saturation. Sometimes, for long duration voltage sags, more transformers are driven into saturation. This is called Sympathetic Interaction [21].

Generally, voltage sags experienced by distribution system customers originate from the (HV) transmission and sub-transmission systems, or the (MV) distribution system itself. In the case of weak transmission systems it is also possible to get sags from neighbouring MV distribution systems through the transmission network. Fig. 2 gives an example.

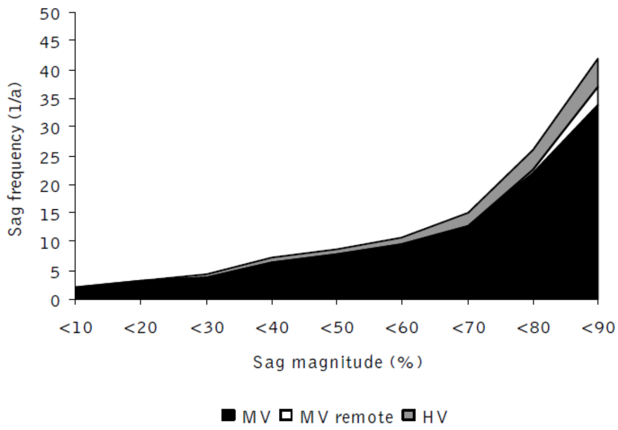

Figure 2: Example of distribution of sags propagating from different power system levels.

▪ **Voltage swells**

Voltage Swell is defined by IEEE 1159 as the increase in the RMS voltage level to 110% - 180% of nominal, at the power frequency for durations of ½ cycle to one (1) minute. It is classified as a short duration voltage variation phenomena, which is one of the general categories of power quality problems [15]. A swell is defined as an increase to between 1.1 and 1.8 p.u. in rms voltage at the network fundamental frequency with duration from 0.5 cycles to one minute. The term momentary overvoltage is also used as a synonym for swell. Switching off a large inductive load or energizing a large capacitor bank are typical system maneuvers that cause swells.

Although not as common as voltage sags, swells are also usually associated to system faults. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding. During a single phase-to-ground fault on an impedance grounded system, i.e. with some zero sequence impedance, the non-faulted phase-to-ground voltages can increase up to $\sqrt{3}$ times the per-unit value (in the case of a non-grounded or high impedance grounded system). The difference in the zero- and positive-sequence impedance causes a change in the non-faulted phases, not only in magnitude but also in phase [22].

For voltage swells the start threshold is equal to 110% of the reference voltage. The end threshold is usually set 1 - 2% of the reference voltage below the start threshold. In other words, the duration of a voltage swell is measured from when one phase rises above 110% of the reference voltage until all three phases have again fallen below 108% - 109% of the reference voltage. If the event persists longer than 1 min it will be re-classified as an overvoltage [23]. Main causes of voltage swells include energizing of capacitor banks, shutdown of large loads, unbalanced faults (one or more phase-to-phase voltages will increase, see Figure 3), transients, and power frequency surges .The effects of voltage swells are largely the same as for voltage dips [23].

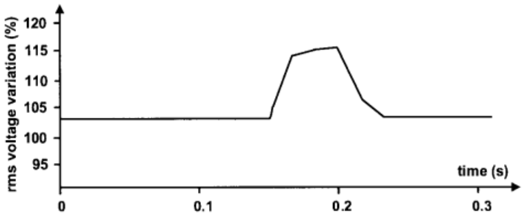

Figure 3. Voltage swell in the phase-to-phase voltage between a faultless phase and the faulted phase during an SLG fault.

- **General causes of voltage swells**

Voltage swells are usually associated with system fault conditions - just like voltage sags but are much less common. This is particularly true for ungrounded or floating delta systems, where the sudden change in ground reference result in a voltage rise on the ungrounded phases. In the case of a voltage swell due to a single line-to-ground (SLG) fault on the system, the result is a temporary voltage rise on the unfaulted phases, which last for the duration of the fault [24].

4. Conclusion

Nowadays, reliability and quality of electric power is one of the most discuss topics in power industry. There are numerous types of power quality issues and power problems and each of them might have varying and diverse causes. The types of power quality problems that a customer may encounter classified depending on how the voltage waveform is being distorted.

There are transients, short duration variations (sags, swells, and interruption), long duration variations (sustained interruptions, under voltages, over voltages), voltage imbalance, waveform distortion (dc offset, harmonics, interharmonics, notching, and noise), voltage fluctuations and power frequency variations. Among them, two power quality problems have been identified to be of major concern to the customers are voltage sags and harmonics, but this project is focusing on voltage sags.

Voltage sags are huge problems for many industries, and it is probably the most pressing power quality problem today. Voltage sags may cause tripping and large torque peaks in electrical machines. Generally, voltage sags are short duration reductions in rms voltage caused by faults in the electric supply system and the starting of large loads, such as motors.

Voltage sags are also generally created on the electric system when faults occur due to lightning, which are accidental shorting of the phases by trees, animals, birds, human error such as digging underground lines or automobiles hitting electric poles, and failure of electrical equipment. Sags also may be produced when large motor loads are started, or due to operation of certain types of electrical equipment such as welders, arc furnaces, smelters, etc.

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