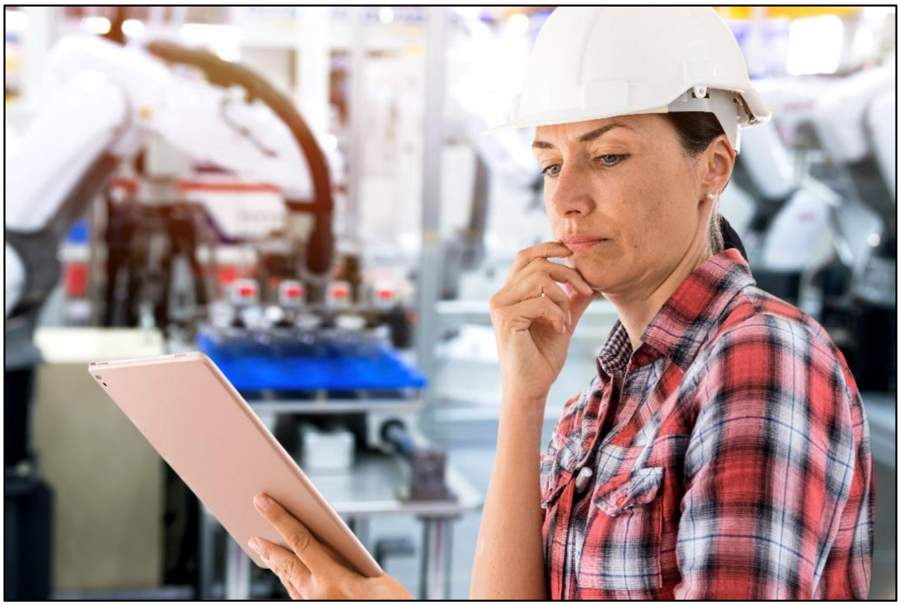
Power Quality Issues in Industrial Facilities



Denison Technologies White Paper

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June 2019

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1-Introduction

Power quality has been a challenge for many years in industrial facilities. Power quality issues are normally hidden from the plant information systems, but their consequences are almost obvious (including plant downtime, reduced capacity, production failure/waste, equipment failure, and utility penalty), which cause significant financial impact on every industrial plant. With automation of plants and application of more nonlinear loads to facilitate the production process, power quality issues are only increasing. Many industrial facilities ignore the necessity of power quality monitoring due to the complexity of detection, analysis, and solving power quality issues (including transients, harmonics, or unbalance). In addition, detection and monitoring of power quality challenges are not a part of a normal plant information system.

Considering the fact that the utility companies take no responsibility for protecting industrial plants from power quality issues, it is often the plant owners that are sole party responsible for protecting their own equipment. By understanding major power quality issues and taking actions before incidents happen, plant owners can mitigate costs and improve the reliability of their production lines. At Denison Technologies, we specialize in advanced monitoring and detection of power quality issues, and protection of industrial facilities from failures caused by power quality problems. We understand that industrial facilities cannot afford keeping full-time control system engineers or their staff to constantly monitor the system, collect data, analyze them, and design algorithms to detect power quality problems or more importantly prevent them from happening in the future. Our monitoring and supervisory system will facilitate the monitoring process and work with the newest technologies with expertise in multidisciplinary industries.

Our team of electrical engineers who are experienced in power usage and quality, as well as with our data scientists who are experts in analyzing and modeling data will make proper recommendations to lower the energy cost in your plant. Therefore, the main purpose of this white paper is to introduce the power quality challenges in industrial facilities, their adverse effects on power apparatus and industrial plant equipment, and possible approaches to mitigate these issues.

Power Quality Definition

Power quality is the quality of the voltage and/or current which is defined as the measure, analysis, and improvement of the bus voltage/current to maintain a sinusoidal waveform at rated frequency during transients and steady-state operation.

1.2 Origin of Power Quality Issues?

The power quality issues may come from small and predictable sources (e.g., residential customers), large and random sources (e.g., ac furnaces), and large and predictable sources (e.g., static converters). These power quality issues are related to 1) utility, 2) distribution system, and 3) customers [1].

1.2.1 Electric Utility-related Power Quality Issues

It is evident that 60% of power quality problems are generated by natural and unpredictable events including faults, lightning surges, resonance, ferroresonance, and geomagnetically induced current, all of which are related to the utility. Although synchronous generators at the power plants generate nearly perfect sinusoidal voltages with harmonic content less than 3%, power quality problems can be observed at the point of common coupling (PCC), due to maintenance activity, planning, capacity and expansion constraints, scheduling, event leading to forced outages, and load transferring [2].

1.2.2 Distribution System Power Quality Issues

Typical power quality issues originated in the distribution system are transient over voltages, transformer energizing, improper operation of voltage regulators, voltage dips, spikes, and interruptions, slow voltage variations, and power line carries (PLCs) [3].

1.2.3 Customer-related Power Quality Issues

At the customer side, nonlinear loads are the main source of generating harmonics. Customer loads generate a considerable amount of power quality problems including harmonics due to ***a) nonlinear loads*** such as power electronics devices, renewable energy sources, adjustable speed drives, and uninterruptable power supplies (UPSs), ***b) poor power factor*** due to highly inductive loads such as air conditioning systems, ***c) voltage flicker*** generated by furnaces, ***d) transients*** due to device switching, ***d) improper grounding*** (most reported customer problems), and ***e) frequency variations*** when backup power sources are used. Figure 1. illustrates the impact of current harmonics generated by a nonlinear load on a typical power system with linear loads [4].

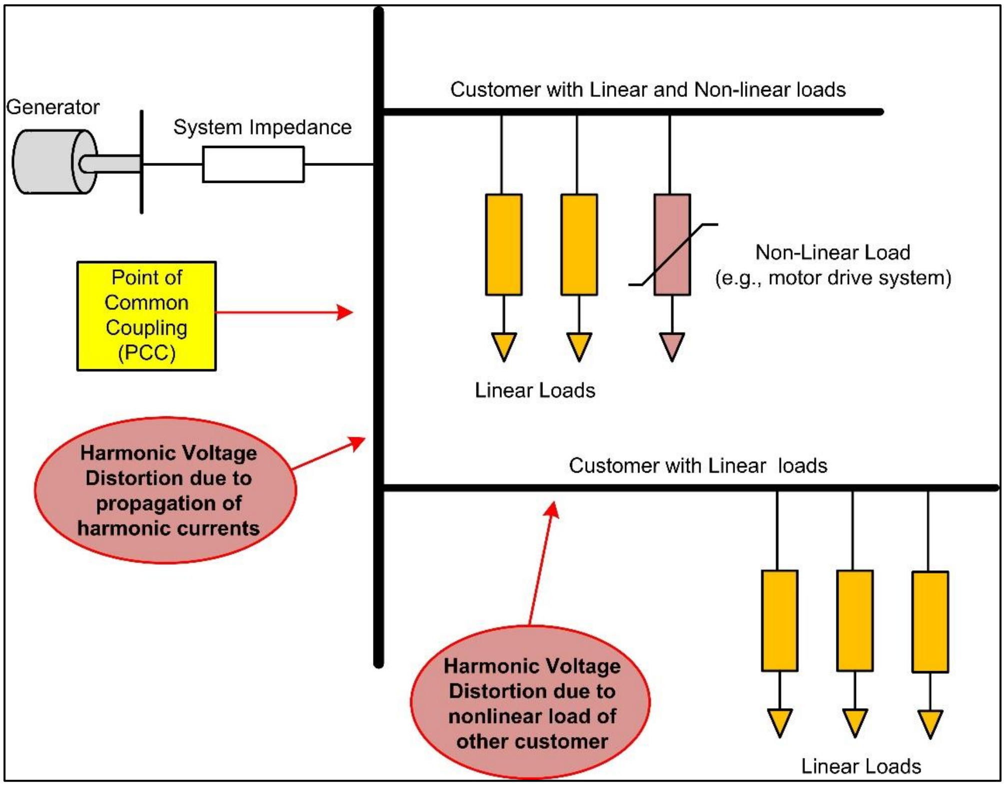

Figure 1. Propagation of harmonics in the system due to non-linear loads

1.3 Power Quality Standards and Regulations

There are two sources of poor power quality related to manufacturing regulations: standards, and equipment sensitivity. In some cases, lack of standards for testing, certification, purchase, or installation of electronic equipment is a major cause of power quality problems. In other cases, the proliferation of sensitive electronic equipment is the main issue for power quality challenges. Therefore, some of the best practices for the power quality regulations are [1-5]:

- Designing and maintaining the system with minimum power quality issues from the electric utility side.
- Proper wiring and grounding of the system with electronic devices from the customer side.
- Design and development of electronic devices that are immune to anomalies of the power supply line from manufacturer side.
- Continuous monitoring of the system to detect potential power quality issues from the utility and customer sides.

There are a few standards for the power quality problems in power systems. Some standards strictly pay attention to the duration of the event, such as ANSI C84.1 [5]. In other standards such as IEEE-519, the waveform (duration and magnitude) of each event is used to classify the power quality issue [6,7]. Finally, IEC standards such as IEC 61000-2-5 use the frequency range of the event for the classification [8]. Some IEEE standards such as IEEE-1159 use a few additional terms as compared with the IEC standards to classify power quality issues [9]. Based on these standards, the power quality issues can come from one of the following:

1. Transients
2. Short-duration Voltage Variations
3. Interruption
4. Voltage/current Sag
5. Voltage Swells
6. Long-duration Voltage Variations
7. Sustained Interruption
8. Undervoltage
9. Waveform Distortion (including DC offset, or harmonics, intra-harmonics, notching, and flicker)
10. Frequency Variation
11. Voltage Fluctuation

In this report, the focus is mainly on power quality issues due to waveform distortion caused by harmonics. A full description of the harmonics is given in **Section 2, sub-harmonics and intra-harmonics definitions**, followed by details of **The Total Harmonic Distortion (THD), and Harmonic Factors** in **Section 3.** Harmonic interactions and resonances are covered in **Section 4** to illustrate the effects of voltage/current unbalance on industrial facilities, and **Section 5** concludes the report.

2 - Harmonics

Equipment with nonlinear features such as electrical machines, flexible ac transmission systems (FACTS), transformers, diodes, and power electronics devices (e.g., motor drives, inverters, and converters) cause nonsinusoidal current and voltage waveforms in power systems. Such nonlinear equipment is widely used in switch-mode power supplies, fluorescent lamps, induction furnaces, AC and DC adjustable drives, and renewable energy sources. These nonsinusoidal waveforms, are also known as harmonics cause malfunctional of control devices, additional losses, and decreased lifetime of power apparatus. Furthermore, these harmonics cause increased losses in utility equipment such as transformers, rotating machines, and capacitor banks.

Any periodic nonsinusoidal waveform can be decomposed to its harmonic components using Fourier series. Consider a nonsinusoidal voltage waveform $v(t)$ defined as [1-3]:

$$v(t) = V_{dc} + \sum_{h=1}^{n} V_{rms}^{h} \cos(h\omega_1 t + \theta_h) = V_{dc} + v^{(1)}(t) + v^{(2)}(t) + v^{(3)}(t) + \ldots \quad (1)$$

where ω_1 is the fundamental frequency of the system (377 rad/s for 60 Hz), h is the harmonic order (1st, 2nd, …), V_{rms}^{h} is the voltage magnitude of the harmonic order, θ_h is the voltage angle of harmonic order, and $v^{(h)}(t)$ are the harmonic components of the voltage waveform (e.g., $v^{(1)}(t)$ is the first harmonic (or fundamental) component of the nonsinusoidal voltage).

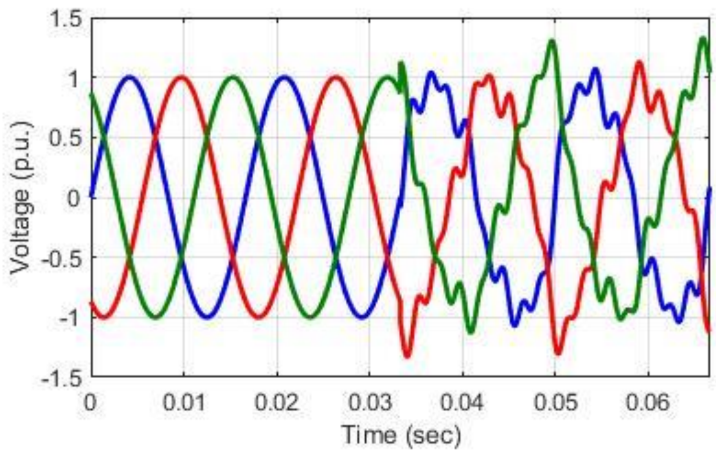

Figure 2. A highly distorted three-phase voltage waveform

Figure 2 illustrates a three-phase balanced signal which is distorted with harmonics after 0.2 seconds. It is noted that even and odd harmonics are often used in power quality studies, where they are referred to even (e.g., 2,4, 6,…) and odd (e.g., 3,5,7,…) components of the Fourier series represented in (1). In addition, harmonic order of 0 is assigned to the DC component of the waveform. The odd multiples of the third harmonic such as $h = 3,9,15,\ldots$ are considered as triplen harmonics. Triplen harmonics become an important issue for grounded wye-connected three-phase systems with current flowing in the neutral line of the wye circuit. Some important features of harmonics in power systems are listed in the following [1-5]:

- For a perfectly balanced three-phase system, fundamental current components in the neutral wires are zero.
- Transformer windings play a major role on the flow of triplen harmonic currents by three-phase nonlinear loads.
- In a wye-delta transformer with grounded wye side, the triplen harmonic currents appear in the wye side and add in the neutral wire.

- For the delta side of a wye-delta transformer, the triplen harmonics can flow in the delta windings, but they remain trapped in the delta and are absent in the line currents of the delta side.
- For grounded wye-wye transformers, triplen harmonics appear on both sides of the transformer neutral windings.
- ***Sub-harmonics*** have frequencies below the fundamental frequency, and they mainly appear in the system because of fast switching power electronics components in power systems. These subharmonics are normally created by resonances between power system capacitance and inductances.
- ***Intra-harmonics*** are harmonic components that are not integer multiples of the fundamental frequency. The main sources of intra-harmonics are static frequency converters, cycloconverters, induction motors and computers. Intra harmonics cause flicker, temperature rise in induction machines, and malfunction of protection devices.

3- Power Quality Index Terms

3.1 Root Mean Square (RMS)

The rms value of a sinusoidal waveform $v(t) = V_{\max}\cos(\omega t + \theta)$ is defined as [1]:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} = \frac{V_{\max}}{\sqrt{2}} \quad (2)$$

For a nonsinusoidal waveform expressed in (1), the rms value of the voltage waveform is represented as [1]:

$$V_{rms} = \sqrt{V_{dc} + (V_{rms}^{(1)})^2 + (V_{rms}^{(2)})^2 + (V_{rms}^{(3)})^2 + \ldots + (V_{rms}^{(H)})^2} \quad (3)$$

where H is the total number of harmonic orders in the voltage signal. Similarly, for a nonsinusoidal current waveform $i(t) = I_{\max}\cos(\omega t + \theta)$, the rms current value is defined as [1]:

$$I_{rms} = \sqrt{I_{dc} + (I_{rms}^{(1)})^2 + (I_{rms}^{(2)})^2 + (I_{rms}^{(3)})^2 + \ldots + (I_{rms}^{(H)})^2} \quad (4)$$

3.2 Form Factor

The form factor (FF) is a measure of the shape of the signal which is defined as [3]:

$$FF = \frac{I_{rms}}{I_{avg}} \quad (5)$$

where I_{avg} is the average value of the signal. Since the average value of a sinusoidal signal is normally zero, the average over a half-cycle is normally considered. Therefore, as the harmonic content of the signal increases, the FF value will increase.

3.3 Harmonic Factor

The harmonic factor (HF) of *h*th harmonic component is defined as the measure of individual harmonic component over the fundamental component:

$$HF = \frac{I_{rms}^{h}}{I_{rms}^{1}} \tag{6}$$

3.4 Total Harmonic Distortion (THD)

THD is the most common harmonic index used to indicate the overall harmonic content of a distorted signal as a single number. The THD of a current waveform is defined as [1-5]:

$$THD = \frac{\sqrt{\sum_{h=2}^{H} (I^{h})^{2}}}{I^{1}} \tag{7}$$

The ANSI standard recommends a value of 5% as the dividing line between a high and low distortion level and truncation of THD series at 5 kHz. The main advantage of the THD is that it can easily be calculated. However, it does not provide the amplitude information, and the detailed information of the spectrum is normally lost.

3.5 Total Demand Distortion (TDD)

Due to the above-mentioned disadvantages of THD, the IEEE-519 standard has defined the total demand distortion factor, which is similar to THD except that the distortion is expressed as a percentage of rated or maximum value instead of the fundamental value [6,7].

$$THD = \frac{\sqrt{\sum_{h=2}^{50} (I^{h})^{2}}}{I_{rated}} \tag{8}$$

The IEEE-519 standard normally represent the harmonic current limits based on the ratio of short circuit current to maximum demand load current at the point of common coupling. This means that the small customers will have higher distortion limits than large customers. Based on the IEEE-519 standard, the voltage distortion at the point of common coupling needs to be below 5% THD. For the current distortion limits, the IEEE-519 provides a table for general distribution systems ranging from 120V to 69kV. A summary of the table is provided in the following Table 1.

Table 1. Current distortion limits in general distribution systems [6,7].

I_{sc}/I_{rated}	$h \le 11$	$11 \le h \le 17$	$17 \le h \le 23$	$23 \le h \le 35$	$35 \le h$	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20 to 50	7.0	3.5	2.5	1.0	0.5	8.0
50 to 100	10.0	4.5	4.0	1.5	0.7	12.0
100 to 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

It is noted that TDD for even harmonics are limited to 25% of the TDD mentioned in Table 1 for odd harmonics.

3.6 K-Factor

Power system transformers must be derated when supplying nonlinear loads. The impact of nonlinear loads (such as motor drives) on transformers usually depends on the nature of harmonic components caused by the load, which differs based on the application and cannot be considered by transformer manufacturers. In this case, the K-factor is used as an alternative to transformer derating.

The recommendations for calculation of K-factor is summarized in ANSI/IEEE C57.110, named as IEEE recommended practice for establishing transformer capability when supplying nonsinusoidal loads. Based on this standard, the K-factor is defined as [10,11]:

$$K = \frac{\sum_{h=1}^{H} I_h^2 h^2}{I_{rated}^2} = \sum_{h=1}^{H} I_h^2 (p.u.) h^2 \quad (9)$$

The K-factor is used to identify the transformer rating for various load conditions. A transformer's K-factor represents its ability to handle varying percentage of nonlinear loads without exceeding the rated temperature rise limits. If the load current harmonics are known, the K-factor can be calculated and compared to the transformer's nameplate K-factor. As long as the calculated K-factor is less than the nameplate, the transformer does not need to be derated. In general, the following table provides a relationship between the K-factor and the electronic loads, where non-linear load represents the power electronics-based loads and linear load is considered as general inductive and resistive loads.

Table 2. Recommended K-Factors for linear and non-linear loads [10,11].

% of Linear Load	% of Non-linear Load	K-Factor
0	100	20
25	75	13
50	50	9
75	25	4
100	0	1

4- Harmonic Interactions and Resonances

Motor drive application includes a power electronics-based motor drive, passive filters, and the motor. The motor drive itself has a capacitor named dc-link capacitor that could cause parallel and/or series resonances. In traditional power systems, capacitor banks were normally implemented for power factor correction purposes without consideration for resonances or other harmonics [1-5]. Capacitor banks in general can cause:

- High overvoltages could result if the system the system is tuned to a harmonic that is being supplied by a load or transformers. For example, second, third, fourth, and fifth harmonics result from transformer inrush currents.
- Capacitive reactance is inversely proportional to the frequency of the system, as a result, harmonic currents may overload capacitors which would cause failure of these capacitive banks.

4.1 Resonance

If the capacitive component of the system offsets the inductive component, only small resistive element remains in the network and resonances may occur. Two types of resonances exist; 1) parallel resonance, and 2) series resonance. Figure 3 illustrates two schematics for the parallel and series resonances.

If the inductive and capacitive reactance impedances are in parallel to a source of harmonic current, parallel resonance might occur which eventually can cause system failure. The resonance frequency of the parallel or series circuit can be derived as

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{10}$$

If the resonance frequency coincides with the resonant frequency of the harmonic source, excessive voltages and currents will appear that could damage other electrical equipment.

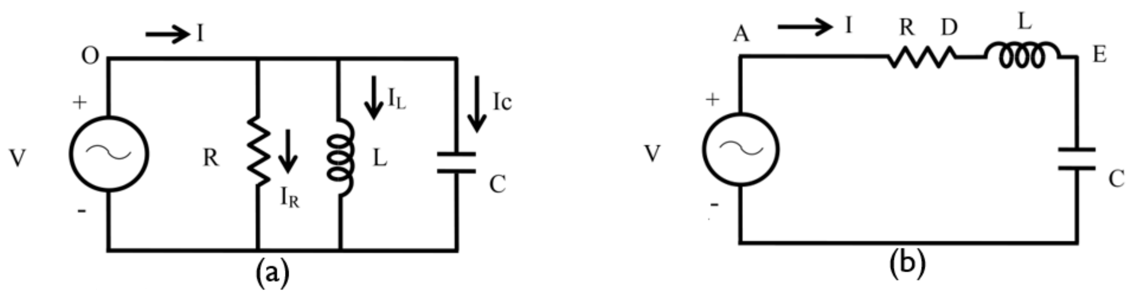

Figure 3. Harmonic resonance diagrams; a) parallel resonance, b) series resonance [13].

If the inductive impedance of the system and the capacitive reactance of the capacitor bank are in series to a source of harmonic current, series resonances occur. At the resonant frequency of this combination, the series impedance is very low, if the harmonic source generates currents near this resonant frequency, the harmonic current will flow through the low-impedance path, which will cause high amplitude currents.

Consider the series connected circuit in Figure 3, the total impedance of the system can be viewed as $Z = R + j\left(\omega L - \frac{1}{\omega C}\right)$, the current flowing into the circuit can be derived as [1-5]:

$$I\angle\theta = \frac{V\angle 0}{Z} \tag{11}$$

where,

$$I = \frac{V}{\left[R^2 + (\omega L - (1/\omega C)^2\right]^{\frac{1}{2}}} \tag{12}$$

Therefore, the current in the circuit is maximum if $\omega L = \frac{1}{\omega C}$ and the frequency under this condition will be the resonant frequency (f_0) in equation (10). Therefore, at resonant frequency the magnitude of the current flowing into the circuit is maximum, see Figure 4.

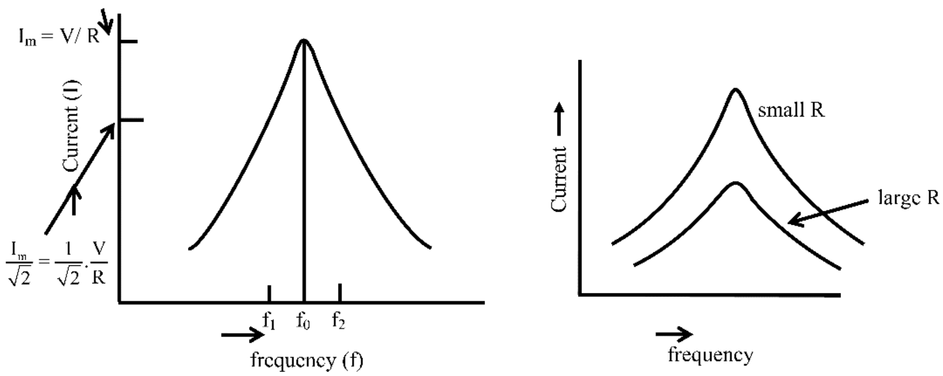

Figure 4. Resonant frequency and effect of system resistance on current [13].

4.2 Solution to Resonance Problems

Harmonic currents and voltages that resonate with power system impedance are usually amplified and result in grave power quality problems such as destruction of capacitors, saturation of electromagnetic devices, high losses, and reduced lifetime of loads, especially motor drives. Depending on the application, various methods can be used to mitigate the resonances [1-10]:

- Moving the resonance frequency away from system harmonics
- Performing system analysis and harmonic simulations for optimal capacitor placement
- Installation of damping circuits (passive or active resistors in series)
- Installation of a power converter to act as a virtual resistor

5 - Impact of Poor Power Quality on Power Apparatus

As discussed in the past sections, power quality issues can cause serious damage to electrical system components and power apparatus including synchronous machines, induction motors, power transformers, transmission lines, or load. These damages normally appear in terms of losses, overheat, increased stress, or equipment loss in power systems. The effect of harmonics on major power equipment is illustrated in Figure 5.

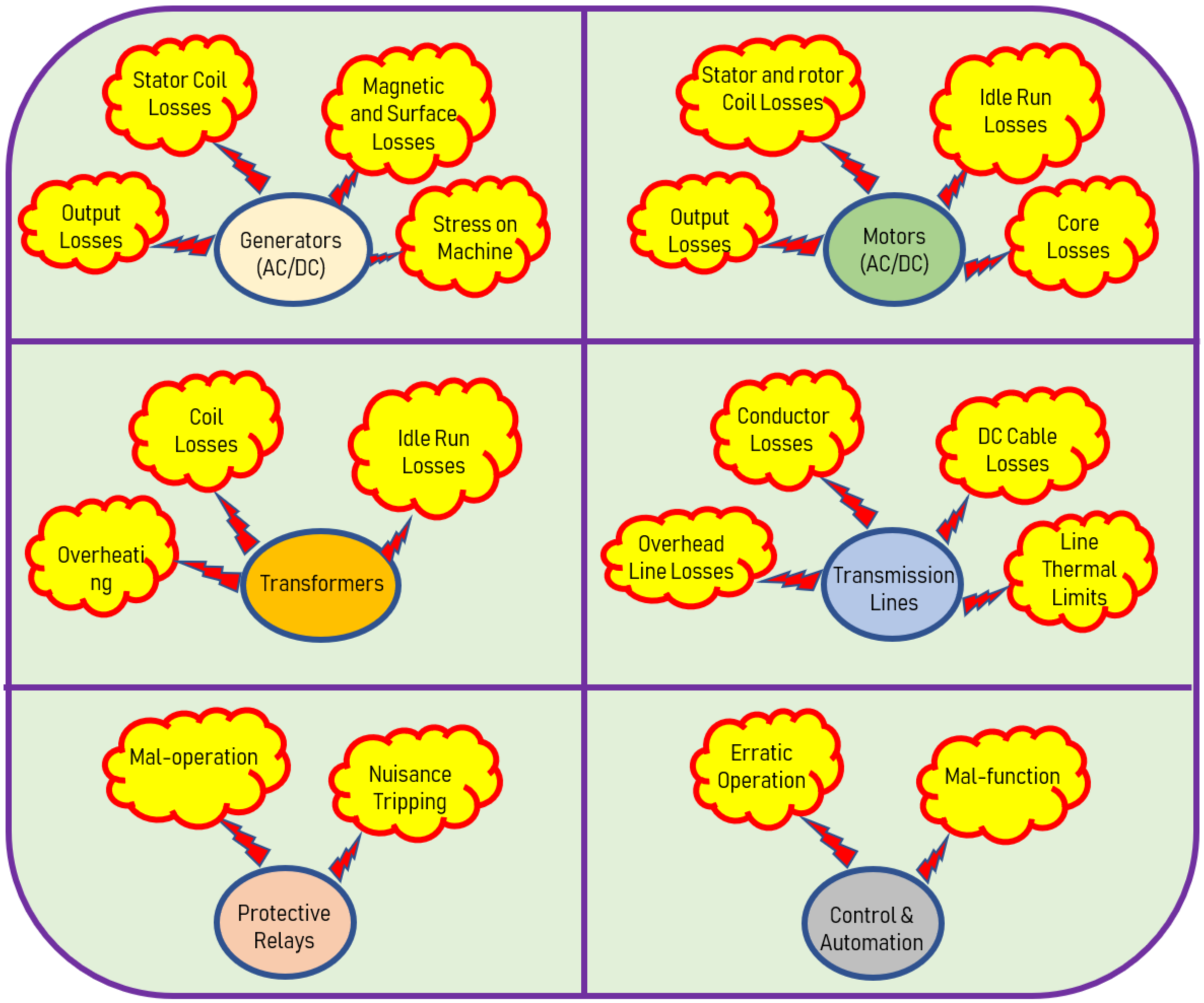

Figure 5. Poor power quality effects on power apparatus

6 – Conclusion

This paper focused on definition, measures, and classification of power quality in industrial plants and related power quality issues. In summary, main causes of power quality issues are unpredictable events, the electric utility supply, and the manufacturer. To summarize, main causes of disturbances leading to power quality issues can be listed in Table 3.

Table 3. Main causes of poor power quality and disturbances

Disturbance	**Possible Cause**
Transients	Nonlinear Loads
Voltage variations	Adjustable Speed Drives
Interruptions	Traction Drives
Waveform Distortion	Load Transients
Harmonics	Lightning and Faults

IEEE standards can be used to classify power quality issues, where the main formulations and measures can be found in IEEE 100, IEC 61000-1-1, and CENELEC EN 50160 [12].

The IEEE 519 and IEC 61000 standards list the appropriate guidelines to monitor and control power quality issues in the United States and Europe. For harmonic analysis, time-domain simulations, frequency-domain modeling, and iterative procedures can be used. Mitigation processes for power quality issues include:

1. Continuous monitoring
2. Harmonic cancellation
3. Derating devices
4. Installing harmonic filters
5. Optimal placement of capacitor banks

Existence of capacitors in the system may cause resonance problems including high voltage magnitudes, too high-amplitude currents, and reactive power harmonics.

Finally, poor power quality can cause serious problems in plants including temperature rise in power apparatus, increased losses in the system, failure of equipment, decrease in lifetime of devices, malfunction of devices, saturation, and high voltage/current magnitudes.

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About Denison Technologies

Denison Technologies is your engineering partner identifying and correcting often unseen power quality events that are frequently the cause of costly production failure, destruction of critical plant assets, and the confusion of plant floor operations. Denison Technologies provides an easy path to remedy the unseen power events from initial snapshot diagnostic reporting with a click and upload of your data to continuous monitoring of your global plant operations. Our turnkey, open architecture and vendor agnostic approach has garnered Denison as "one of the top 10 in the country" in manufacturing intelligence for 2 consecutive years.

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