PDHonline Course E290 (2 PDH)

Power System Quality

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1. INTRODUCTION

1.1. This course provides a technical basis for power system quality as a design consideration and explains different methods of solving power quality problems. Unlike other electrical design requirements, power quality design solutions are very dependent on the types of transients and disturbances that can and will occur in power systems. Also, power quality solutions often involve a certain level of compromise between the electrical system design and the design of the end-use equipment. In many cases, it will be easier to provide protection and power quality design features to specific equipment rather than generically throughout the facility. Nonetheless, power quality is an issue that should be addressed at the facility level in order to be certain that the electrical distribution system is designed properly for the anticipated disturbances and the effects of harmonic distortion.

1.2. Voltage and current surge transients caused by lightning or switching operations are discussed in PDH course E288 “Surge Protection Systems Performance and Evaluation”. Surge protection is not considered a power quality issue, but instead is considered a part of electrical system protection. Power quality design considerations focus on:

1) Longer-term degradation of the ideal sinusoidal voltage and current caused by harmonic distortion or unbalanced system operation and
2) Power system disturbances.

2. UNBALANCED VOLTAGES

2.1. The principal source of a steady-state voltage unbalance is unbalanced single-phase loads on a three-phase system. Voltage unbalance is particularly important for three-phase motor loads. ANSI C84.1 specifies a no-load service entrance voltage unbalance of less than 3 percent to avoid motor overheating or failure. High efficiency motors are particularly susceptible to unbalanced voltages; these motors have a lower negative sequence reactance which causes higher negative sequence currents during unbalanced voltage conditions. Unbalanced voltages can also be caused by blown fuses on one phase of a circuit or single phasing conditions.

2.2. At the design stage, the loading on each phase should be evaluated and balanced as well as possible. As part of acceptance testing, the degree of unbalance should be monitored and necessary corrections made if possible.

2.3. The degree to which a system is unbalanced can be evaluated by symmetrical components. The ratio of the negative or zero sequence component to the positive sequence component is used as an indicator of the percent unbalance:

$$Percent\ \ Unbalance = \frac{V_2 - V_1}{V_1} \times 100\%$$

2.4. A more commonly used method of evaluating voltage unbalance that does not require knowledge of symmetrical components is as follows:

$$Percent\ \ Unbalance = \frac{Maximum\ Phase\ Deviation\ \ from\ Average\,Voltage}{Average\,Voltage} \times 100\%$$

EXAMPLE: Assume that phase voltages are 460, 464, and 450. The average phase voltage is 458. The maximum deviation from the average voltage is 8 volts and the percent unbalance is given by:

$$Percent\ \ Unbalance = \frac{8}{458} \times 100\% = 1.75\%$$

2.5. Either of the above methods are acceptable for evaluating voltage unbalance. If the percent unbalance exceeds 3 percent, the electrical system should be evaluated in more detail to determine if corrective action is necessary.

2.6. The rated load capability of three-phase equipment is normally reduced by voltage unbalance. For example, Figure 1 shows a typical derating factor for three-phase induction motors as a function of voltage unbalance.

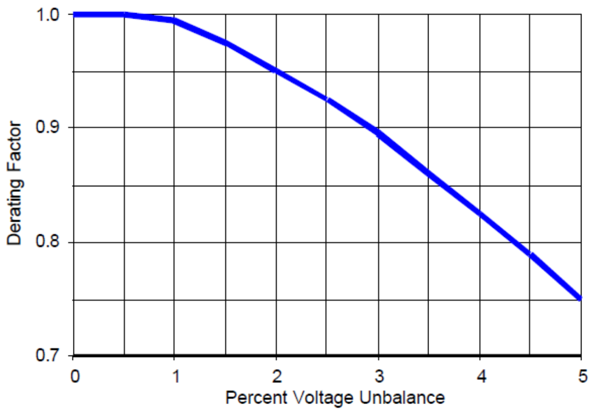


Figure 1. Typical Derating Factor for Three-Phase Induction Motors

3. HARMONIC DISTORTION EVALUATION

3.1. If a significant number of nonlinear loads are to be installed in a facility, a harmonic distortion evaluation should be performed during the facility design phase. If the effect of nonlinear loads is expected to be minor, a detailed harmonic distortion evaluation is not required. Monitoring of the electrical system power quality is recommended to ensure that harmonic distortion limits are not exceeded.

3.2. IEEE 519, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, provides the industry-accepted method of evaluating harmonic voltages and currents. IEEE 519 provides system level guidance, not equipment specific guidance. What this means is that harmonic distortion limits are established for the facility and the installation of any equipment should not degrade the system to beyond acceptable levels. Meeting IEEE 519 limits can be easy for a facility with primarily linear loads and it can be more difficult for a facility with predominantly nonlinear loads. As an example, some facilities have installed many Variable Frequency Drives (VFD) for HVAC system motors in an attempt to reduce energy usage. Unfortunately, each VFD can generate a large current harmonic distortion and nuisance tripping of other equipment has occurred at some facilities as a consequence.

3.3. IEEE 519 provides the distortion limits for a low voltage system; Table 1 summarizes the various limits. IEEE 519 distortion limits should be treated as design limits for interior applications. Hospitals and airports are classified as special applications and have the most stringent criteria. The criterion of most interest in this table is the voltage total harmonic distortion (THD) limit of 3 percent for special applications or 5 percent for general applications. All critical systems should be treated as special applications.

	Special Applications	General System	Dedicated System
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area (A_N – volt microseconds)	16,400	22,800	36,500

Table 1. Low Voltage System Classification and Distortion Limits

4. HARMONIC CURRENT EFFECTS ON TRANSFORMERS

4.1. Excessive harmonic distortion causes higher eddy current losses inside a transformer, resulting in overheating. ANSI C57.110, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents, states that a transformer should be capable of carrying its rated current provided that the total harmonic distortion is less than 5 percent. Beyond this amount, derating of the transformer might be necessary. Newer transformers are often, but not always, already designed for a higher harmonic distortion environment. Older transformers likely were not designed for harmonic distortion. The effects of harmonic currents on transformers should be evaluated in accordance with the following subsections.

4.2. Whenever significant nonlinear loads are expected in a facility, the system should be evaluated to determine if transformer derating will be required. Transformer derating is not the same as calculating the transformer k-factor. The k-factor is used to match a harmonic current condition with a k-factor rating. For transformers without a k-factor rating, derating must be used to determine the maximum fundamental load current that the transformer can maintain with the additional harmonic currents.

Note: Derating applies to the full-load capability of the transformer when applied in an environment containing significant harmonic distortion. If the transformer is not fully loaded, the derating process might have little or no practical significance unless it is expected that the transformer will eventually be fully loaded. Nationwide surveys indicate average loading levels for dry-type transformers of between 35 percent for commercial facilities and 50 percent for industrial facilities.

4.3. ANSI/IEEE C57.110 provides additional information regarding the evaluation and derating process.

4.4. If it is determined that a transformer will require derating because of harmonic distortion, the following additional reviews should be performed:

4.4.1. Studies have to be performed to see if the harmonic distortion environment can be improved by design changes for the most offending loads.

4.4.2. If the transformer requires more than 10 percent derating, the feasibility of installing a new transformer designed for a harmonic distortion environment (often referred to as a k-factor transformer) should be evaluated. Delivery and replacement time scheduling as well as cost should be part of the evaluation.

4.4.3. If transformer derating is the selected option, the percent derating should be annotated on the applicable design drawings, and a label should be installed near the transformer nameplate indicating that the transformer has been derated. The purpose of these actions is to prevent inadvertent overloading of the transformer in the future.

4.5. If it is determined that an installed transformer requires derating, a transformer inspection should be performed to confirm whether the transformer has been operating in an overloaded condition. Because of the method by which flux is produced in a transformer, current heating paths can develop along any magnetic material. Signs of overheating include the following:

- General excessive heating of the enclosure.
- Bubbled, peeling, discolored, or burnt paint on the enclosure.

- Evidence of overheating at the ends of internal components.
- Premature gasket failure.
- Methane gas generation.
- Heat-damaged bayonet fuse holders.

5. POWER QUALITY DESIGN

5.1. A facility should be designed to withstand the most likely power quality problems, commensurate with the importance of the facility's mission. For critical equipment, power quality features should be included at the design stage to ensure that system reliability goals are maintained. Acceptable power quality is not achieved by a single system design feature. The following elements should be evaluated as part of the facility design:

- Appropriate grounding, including considerations of unbalanced and nonlinear loads. Voltage sags and power interruption impacts.
- Effect of switching transients, particularly if the local utility operates capacitors electrically near the facility.
- Harmonic distortion limits.
- Power factor correction requirements.
- Voltage variations associated with motor starting and other transients.
- Degree of unbalanced voltage for three phase systems supplying single phase loads.

5.2. The requirement for continued reliable facility operation, the impact of electrical system-related power disruptions, the types of power disturbances that can occur, and the various cost-effective methods of ensuring power quality should be considered as part of the overall electrical system design.

5.3. The addition of power quality design equipment often has an iterative effect on the electrical system design. For example, the addition of power conditioners affects the system voltage drop to downstream devices. Not all power quality issues can be addressed during the system design. Power system quality at the service entrance should be monitored to determine if additional design measures will be needed.

5.4. Each power quality issue can require a different type of design solution; a single standardized design approach will not satisfy all power quality issues. Table 2 provides a summary of typical design approaches to power quality problems.

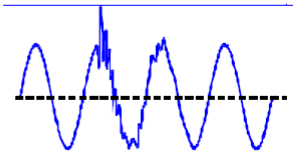
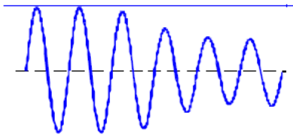
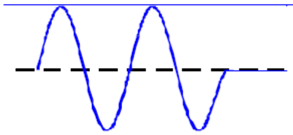
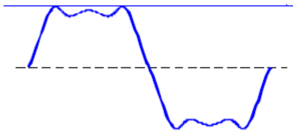
Example Waveform	Power Quality Category	Typical Cause	Typical Solutions
	Impulsive transients	Lightning Capacitor switching Load switching	Surge protectors Filters/reactors Isolation transformers
	Oscillatory transients	Capacitor switching Line switching Load switching	Surge protectors Filters/reactors Isolation transformers
	Sags and Swells	Remote system faults Overloads Switching operations	UPS systems Ferroresonant transformers Energy storage devices
	Interruptions	System fault clearing Loss of generation	UPS systems Backup generators
	Harmonic distortion	Nonlinear loads System resonance	Filters/reactors Isolation transformers K-factor transformers Rotary UPS

Table 2. Power Quality Summary

5.5. The following subsections provide additional information regarding different possible equipment types and design solutions.

5.5.1. Surge Protectors:

- Surge protectors are not normally considered a solution for power quality problems; their principal purpose is to protect against surge transients. Refer to PDH Course Ex01 for further information on surge protections.

5.5.2. Filter Reactors:

- Reactors can be a cost-effective solution in an existing facility where rewiring is difficult or costly. Reactors provide a filtering function by blocking offending harmonic currents, thereby lessening the harmonic effects elsewhere in the facility.
- Reactors are rated in terms of percent impedance. Higher impedance reactors provide greater filtering, but also increase the voltage drop. For example, a 3% impedance reactor will introduce a 3% voltage drop across it under rated conditions. The effect of the additional voltage drop should be evaluated as part of any filter application. Reactors use energy or consume power in proportion to their impedance, and will decrease overall efficiency because of these added losses.

- The filter design depends on the equipment and where it is installed. If the equipment is changed, the filter might no longer be effective for its intended purpose. Also, the filtering characteristics are strongly influenced by the source impedance, which is not always known accurately and varies with the system configuration. For this reason, filters should be carefully selected for the application and location. Filters can be relatively expensive on a per-kVA basis and they can cause more problems than they solve if they are applied improperly.
- The filters described in this course are called passive filters. Active filters have been developed that act as current sources to nonlinear inductive loads to cancel current harmonics. These products are still new to the market and require professional design assistance in their selection and application.

5.5.3. **Shielded Isolation Transformers:**

- Shielded isolation transformers provide a filtering function by separating the harmonic frequencies between the source and the load. These transformers can be used for retrofit applications to address existing facility problems, but should not be arbitrarily used in new facilities because of the high per-kVA cost.

5.5.4. **k-Factor Transformers:**

- Some transformers are available for high harmonic-content power distribution systems without derating, often referred to as k-factor transformers. Refer to section 8 for additional information regarding k-factor transformer selection.

5.5.5. **Phase Shifting Transformers:**

- Phase shifting transformers are intended to cancel harmonic currents produced by nonlinear loads. These transformers can be used for retrofit applications to address existing facility problems, but should not be arbitrarily used in new facilities because of the high per-kVA cost.

5.5.6. **UPS Systems:**

- UPS systems provide protection from many power quality problems. Refer to PDH Corse E127 for additional information regarding UPS system selection, installation, and maintenance.

5.5.7. **Power Conditioners:**

- Power conditioners are available in a variety of designs. As the name implies, these devices provide a power conditioning function to achieve a pre-defined result. The design of each type of power conditioner varies and a detailed evaluation of equipment specifications is necessary to ensure that the desired result will be achieved.

5.5.8. Grounding:

- Grounding is not necessarily a power quality design feature. However, many power quality problems can be traced back to poor wiring and grounding practices. For this reason, any power quality evaluation must consider the grounding system design.

6. NONLINEAR LOAD DESIGN CONSIDERATIONS

6.1. Planned electrical loads on new projects should be analyzed to determine whether or not they are considered potential nonlinear loads with high harmonic content. The following guidelines are provided if nonlinear loads are a significant portion of the total load.

6.1.1. Transformer, motor, and generator outputs need to be derated if necessary to prevent overheating or burnout. Care has to be taken to make sure that design documents and equipment nameplates reflect the derated capability.

6.1.2. If standby generators represent the only power source upon loss of normal power, the generator design must account for nonlinear loads. Generators are designed to deliver a pure sinusoidal frequency, usually at a frequency of 60 Hertz in North America and 50 Hertz elsewhere. When harmonic currents are drawn through a generator, losses increase causing greater heat generation. Voltage distortions can cause generator and voltage regulator stability problems. Harmonics can also affect the parallel operation of multiple generators. If the generator cannot be protected from the effect of harmonic load currents, the generator supplier should be advised of the nonlinear load environment to ensure that the generator is designed and sized properly. If a significant portion of the load is nonlinear, it might be necessary to apply a multiplying factor of 1.3 to 1.5 to the generator size to compensate for the expected heat losses. Also, the generator manufacturer can design the generator to withstand better a harmonic environment by adjusting the generator pitch and decreasing the subtransient reactance. A voltage regulator capable of achieving proper voltage regulation in high harmonic content and distorted sine wave load conditions should be specified for nonlinear loads. If the generator manufacturer lowers the generator subtransient reactance, care has to be taken to make sure that the facility design remains acceptable for short circuit conditions.

6.1.3. A single three-phase transformer with common core, delta connected primary and wye connected secondary should be used instead of three single-phase transformers connected for three-phase service. The use of a k-factor transformer should be considered if a standard transformer has to be derated by more than 10 percent. The cost of a k-factor transformer should be compared to an equivalent standard transformer. Even if derating of a standard transformer is not required, the k-factor transformer should be selected if the cost of the two types is within 5 percent, provided that the lead time of a k-factor transformer satisfies facility schedule requirements.

6.1.4. If common-mode noise is a concern, electrostatically shielded isolation transformers should be specified for critical loads and each transformer should be located as near to the served loads as practical to reduce the load requirement and cost of each transformer. The shield should be bonded and grounded in accordance with the manufacturer's requirements. The transformer should be grounded in accordance with the NEC.

6.1.5. UPS systems must be capable of performing properly with nonlinear loads. The UPS should be capable of withstanding high crest factors (the ratio of peak current to RMS current). The UPS should provide a sine wave output with a total harmonic distortion of less than 5 percent. If the presence of nonlinear loads causes a leading power factor, the UPS must still operate properly. The total demand distortion (TDD) that the UPS can create on its input terminals should be determined. This will be seen as harmonic distortion to other electrically connected loads. The TDD should be evaluated at UPS full-load and light-load conditions.

6.1.6. Harmonic filters should be specified as necessary to minimize the localized effects of harmonics. If separate harmonic filters are installed specifically to protect against offending loads, each filter should be located as close to each load as practical.

6.1.7. True RMS sensing meters, relays, and circuit breaker trip elements should be specified.

6.1.8. The end-use equipment has the most impact on the system power quality and is the easiest to address on an individual level. Wherever possible, equipment with reduced harmonic generation should be specified. For example, a simple input filter on an ASD can reduce the generated harmonic currents by half. Adjustable speed drives are an example of a type of equipment that can quickly degrade the power quality as they are added throughout a facility.

6.2. Analysis alone will not always adequately predict power quality problems. Power quality monitoring after the facility is in full operation is needed because many of the nonlinear loads might not be running during initial system operation. If standby or emergency power is provided upon loss of normal power, power quality monitoring should be performed with the system powered from these sources also. Power quality problems should be corrected as necessary, based on the results of the monitoring. Refer to IEEE 1159, IEEE Recommended Practice for Monitoring Electric Power Quality, for additional information regarding power quality monitoring.

7. NEUTRAL CIRCUIT SIZING FOR NONLINEAR LOAD CONDITIONS

7.1. Potential Neutral Current Magnitudes

7.1.1. Nonlinear electrical loads distort the shape of the electrical system voltage and current waveform, thereby generating harmonics, eddy currents, increased hysteresis losses, and skin effects. In extreme cases, wiring systems, transformers, motors, and generators can overheat, leading to deteriorating equipment performance. One common result of nonlinear loads is overloading of the neutral conductor because of the increased neutral current created by the distorted waveform.

7.1.2. Single phase nonlinear loads such as computers and electronics equipment can have significant triple frequency harmonic currents (3, 9, 15, and so on). When these single phase loads are combined in a three phase circuit, these harmonic currents appear as zero sequence components, adding in magnitude in the neutral. For example, if there are 5 amperes of third harmonic current on each phase of a three phase circuit, the neutral current will include 15 amperes of third harmonic current. Because of this effect, neutral currents in low voltage systems can be higher than the phase currents. Figure 2 shows one estimate of the change in neutral current as the single phase load becomes dominated by nonlinear loads. Notice that the neutral current can be as high as 1.73 times the phase current.

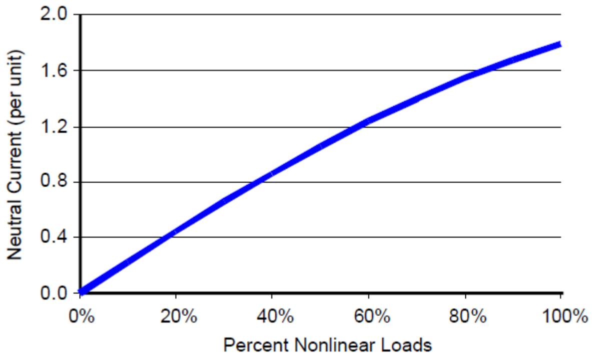


Figure 2. Effect of Single Phase Nonlinear Loads on Neutral Currents

7.2. Installation Design Criteria

7.2.1. Neutral circuit overheating should be minimized by specifying separate neutral conductors for line-to-neutral connected nonlinear loads with high harmonic content. When a shared neutral conductor must be used for three-phase, four-wire systems, the neutral conductor should be sized to have an ampacity equal to at least 1.73 times the ampacity of the phase conductors. Some cable manufacturers provide cable with oversized or extra neutral conductors included to meet this design requirement.

7.2.2. Two paralleled, full size neutral conductors can be used to obtain the required neutral ampacity for conductors sized #1/0 AWG and larger. The neutral conductor between the transformer and the panelboard should be sized to a minimum of 1.73 times the ampacity of the phase conductors. Panelboards that have been rated for nonlinear loads should be selected. Circuits for nonlinear loads approaching 100 percent should be provided a neutral ampacity of a minimum of 1.73 times the phase ampacity.

7.2.3. If necessary, third harmonic filters should be installed at specific analyzed locations in the electrical distribution system. Care has to be taken to make sure that the selected locations provide the best benefit in terms of neutral current reduction.

7.2.4. Although other power quality designs could be implemented to reduce the electrical system neutral currents, the above approach has been selected to ensure that neutral currents do not exceed wiring system limits. This method also ensures greater system flexibility in the future.

8. k-FACTOR TRANSFROMERS

8.1. Transformers are available for high harmonic-content power distribution systems without derating, often referred to as k-factor transformers, and usually have the following characteristics:

- Low induction core to reduce the flux density. Voltage harmonic distortion increases the core flux density, thereby creating higher core losses, higher magnetizing currents, higher audible noise, and overheating.
- Larger primary winding conductors to compensate for additional heating effects.
- Individual insulated secondary conductors to reduce stray losses.
- Larger neutral connections to compensate for harmonic currents causing larger neutral currents.

8.2. The effect of nonlinear loads should be evaluated as part of the facility design. In some cases, nonlinear loads can require transformer derating or, in extreme cases, a transformer designed specifically for nonlinear loads might be required. Also, the transformer neutral conductors might require sizing for up to 200 percent of rated current. Excessive harmonic distortion causes higher eddy current losses inside a transformer, resulting in overheating. IEEE C57.110, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents, states that a transformer should be capable of carrying its rated current provided that the total harmonic distortion is less than 5 percent. Beyond this amount, derating of the transformer might be necessary. Newer transformers are often, but not always, already designed for some level of a higher harmonic distortion environment. Older transformers likely were not designed for harmonic distortion.

8.3. The k-factor relates transformer capability to serve varying degrees of nonlinear load without exceeding the rated temperature rise limits. The most common k-factor ratings are k-4 and k-13. Manufacturers recommend k-4 transformers if the connected load is 50 percent nonlinear electronic loads and k-13 transformers are recommended for 100 percent nonlinear electronic loads. This simplified approach allows the user to avoid calculating actual k-factor values for the facility. Transformer k-factor ratings greater than k-13 should never be necessary and the use of such transformers actually can contribute to harmonic distortion problems because of their low impedance.

8.4. In practice, the system k-factor tends to decrease as the overall load increases. Thus, k-factor measurements taken in lightly loaded conditions can be quite high, but can be significantly lower on a fully loaded system. Transformer coil losses decrease with the square of the load and this reduction far exceeds the increased heating effect of higher harmonics at lighter loads. So, regardless of the load current harmonic distortion variation, the maximum loss point in transformer coils is always at full load. This is why transformer k-factor ratings must be based on full-load conditions. Nationwide surveys indicate average loading levels for dry-type transformers of between 35 percent for commercial facilities and 50 percent for industrial facilities. With such a light loading, a general purpose transformer will provide acceptable performance. A k-4 rating will provide acceptable performance in all but the most extreme harmonic distortion environments.

8.5. In almost all applications, the service entrance transformer will be acceptable if it is a general purpose dry-type transformer rather than a k-rated transformer. An individual lower-voltage transformer within the facility might need a k-factor rating (or derating if it is a general purpose transformer) under the following conditions:

- It supplies a large concentration of nonlinear electronic equipment, and
- It is operating near full load or there is a reasonable expectation that it will eventually be fully loaded.

8.6. Equipment suppliers can provide bundled power distribution systems that contain k-rated transformers or otherwise address power quality issues. The applicability of this equipment should be evaluated before selecting a k-rated transformer.

9. INFORMATION SOURCES

9.1. Power quality is a broad topic and the industry standards are still developing in many areas. The following references provide additional information regarding power quality:

9.1.1. IEEE 519—provides the industry-accepted position of harmonic distortion limits and methods of analysis.

9.1.2. IEEE 1100—addresses power quality issues and provides an overview of power quality design approaches.

9.1.3. IEEE 1159—provides information regarding power quality monitoring.

9.1.4. IEEE 1346, Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment—provides guidance for ensuring acceptable operation of electronic equipment.

9.1.5. FIPS PUB 94—a widely referenced publication devoted to assuring acceptable power quality for computer installations. This document is listed here as a useful background document, but it was officially withdrawn in July 1997.

9.2. In addition to the above references, manufacturers of power quality-related equipment provide extensive technical literature to help users better understand the subject.