PQSoft Case Study

Transient Issues
Related to Power Factor Correction

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Abstract:

Power factor correction is an important facet of power quality. Capacitors may be installed on customer systems to minimize charges for poor power factor on their electric bill. These installations may create problems by altering the harmonic frequency response of the network or introducing transient disturbances during their energization. This case study presents an overview of the impact of power factor correction on transient issues, such as voltage magnification and nuisance tripping of customer equipment (e.g., adjustable-speed drives).

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RELATED STANDARDS

IEEE Std. 1036

GLOSSARY AND ACRONYMS

ASD	Adjustable-Speed Drive
DPF	Displacement Power Factor
PWM	Pulse Width Modulation
TPF	True Power Factor

INTRODUCTION

Electric utilities and their customers have long been concerned with power quality. The need for constant voltage and frequency has always been recognized. However, recent trends toward energy conservation, the increasing utilization of power electronic loads, and the proliferation of sensitive electronic equipment are changing the definition of what is meant by "constant voltage." The primary reasons for the growing concern include:

- Load equipment is more sensitive to power quality variations than equipment applied in the past. Many new load devices contain microprocessor-based controls and power electronic devices that are sensitive to many types of disturbances.
- The increasing emphasis on overall power system efficiency has resulted in a continued growth in the application of devices such as high-efficiency adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.
- Increased awareness of power quality issues by the end users. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.
- Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences.

TRANSIENT RELATED ISSUES

Transient voltages and currents are a result of sudden changes within the electric power system. Opening or closing of a switch or circuit breaker causes a change in circuit configuration and the associated voltages and currents. A finite amount of time is required before a new stable operating point is reached. Lightning strokes to exposed distribution circuits inject a large amount of energy into the power system in a very short time, causing deviations in voltages and currents which persist until the excess energy is absorbed by dissipative elements (surge arresters, load resistance, conductor resistance, grounding system, etc.). A principal effect of both these events is a temporary departure of power system voltage and current from the normal steady-state sinusoidal waveforms. All transients are caused by one of two actions:

- connection or disconnection of elements within the electric circuit
- injection of energy due to a direct or indirect lightning stroke or static discharge.

Opening or closing of switches is a very common occurrence, whether it is normal cycling of loads at the utilization level, or utility operations on the transmission and distribution system. Lightning and static discharge are less common, but the potential effects are obvious. The mechanism may also be unintentional, as with initiation of a short circuit.

Transient overvoltages and overcurrents are classified by peak magnitude, frequency, and duration. These parameters are useful indices for evaluating potential impacts of transients on power system equipment. The absolute peak voltage, which is dependent on the transient magnitude and the point on the fundamental frequency voltage waveform at which the event occurs, is important for dielectric breakdown evaluation (e.g., equipment insulation strength). Some equipment and types of insulation, however, may also be sensitive to rates of change in voltage or current. The transient frequency, combined with the peak magnitude, can be used to estimate the rate of change.

Utility Capacitor Switching

The application of utility capacitor banks has long been accepted as a necessary step in the efficient design of utility power systems. In addition, capacitor switching is generally considered a normal operation for a utility system and the transients associated with these operations are generally not a problem for utility equipment. These low frequency transients, however, can be magnified in a customer facility (if the customer has low voltage power factor correction capacitors) or result in nuisance tripping of power electronic-based devices, such as adjustable-speed drives. Capacitor energizing is just one of the many switching events that can cause transients on a utility system. However, due to their regularity and impact on power system equipment, they quite often receive special consideration.

Power quality problems related to utility capacitor switching include customer equipment damage or failure, nuisance tripping of adjustable-speed drives or other process equipment, transient voltage surge suppressors failure, and computer network problems.

Energizing a shunt capacitor bank from a predominantly inductive source creates an oscillatory transient that can approach twice the normal system peak voltage (V_{pk}). The characteristic frequency (f_s) of this transient is given by:

$$f_s = \frac{1}{2\pi\sqrt{(L_s * C)}} \approx f_{system} * \sqrt{\frac{X_c}{X_s}} = f_{system} * \sqrt{\frac{MVA_{sc}}{MVAr_{3\phi}}} = f_{system} * \sqrt{\frac{1}{\Delta V}}$$

where:

f_s = characteristic frequency (Hz)
L_s = positive sequence source inductance (H)
C = capacitance of bank (F)
f_{system} = system frequency (50 or 60 Hz)
X_s = positive sequence source impedance (Ω)
X_c = capacitive reactance of bank (Ω)
MVA_{sc} = three-phase short circuit capacity (MVA)
MVA_r = three-phase capacitor bank rating (MVAr)
ΔV = steady-state voltage rise (per-unit)

Relating the characteristic frequency of the capacitor energizing transient (f_s) to a steady-state voltage rise (ΔV) design range provides a simple way of quickly determining the expected frequency range for utility capacitor switching. For example, a 60 Hz system with a design range of 1.0% to 2.5% would correspond to characteristic frequency range of 380 to 600 Hz. For a shunt capacitor bank on a high voltage bus, transmission line capacitance and other nearby capacitor banks cause the energizing transient to have more than one natural frequency. However, for the first order approximation, this equation can still be used to determine the dominant frequency.

Because capacitor voltage cannot change instantaneously (remembering that i(t)=Cdv/dt), energization of a capacitor bank results in an immediate drop in system voltage toward zero, followed by an oscillating transient voltage superimposed on the 60 Hz fundamental waveform. The peak voltage magnitude depends on the instantaneous system voltage at the instant of energization, and can reach 2.0 times the normal system voltage (V_{pk} – in per-unit) under worst-case conditions.

For a practical capacitor energization without trapped charge, system losses, loads, and other system capacitances cause the transient magnitude to be less than the theoretical 2.0 per-unit. Typical magnitude levels range from 1.3 to 1.5 per-unit and typical transient frequencies generally fall in the range from 300 to 1000 Hz. Figure 1 illustrates an example (measured) distribution system capacitor energizing transient.

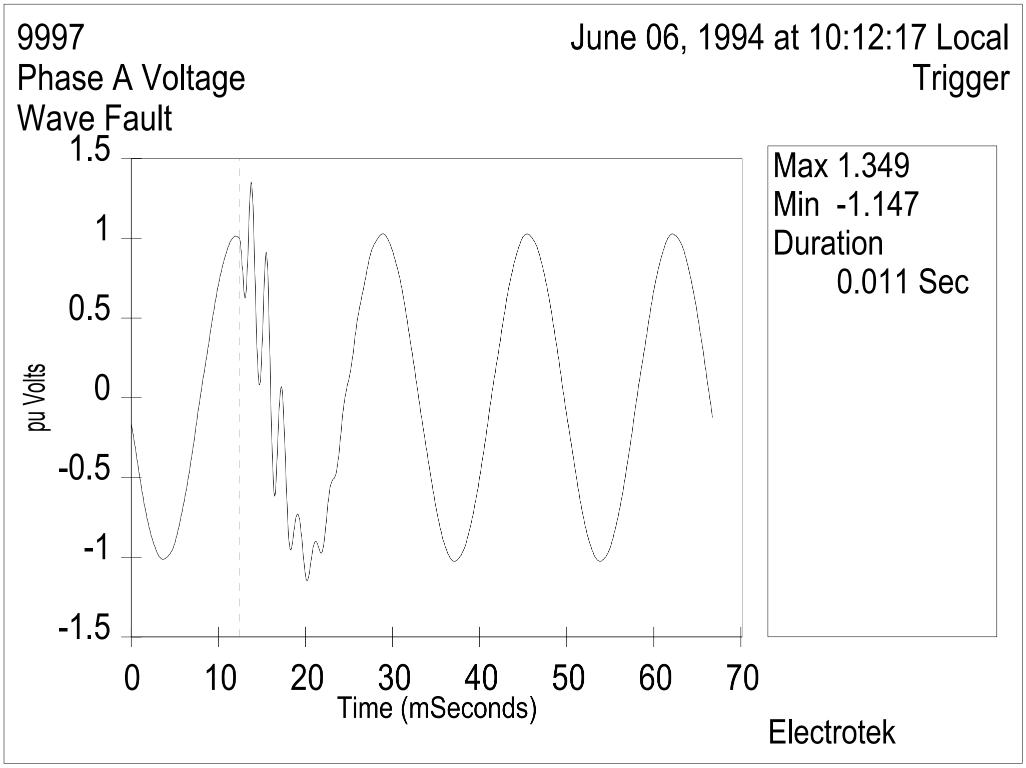


Figure 1 - Example of a Distribution System Capacitor Switching Transient

Voltage Magnification

Voltage magnification occurs when the transient oscillation initiated by the energization of a utility capacitor bank excites a series resonance formed by a step-down transformer and power factor correction bank on a customer's lower voltage system. The result is a higher overvoltage magnitude at the customer's bus (higher than the overvoltage magnitude where the capacitor is switched). Previous analysis has indicated that the worst magnified transient occurs when the following conditions are met (refer to Figure 4):

- The size of the switched capacitor bank is significantly larger (>10) than the low voltage power factor correction bank (e.g., C_2 vs. C_4).
- The energizing frequency (e.g., f_2) is close to the series resonant frequency formed by the step-down transformer and the power factor correction capacitor bank (f_4) (refer to the equations provided with Figure 4).
- There is relatively little damping (resistive) provided by the low voltage load (typical industrial plant configuration - primarily motor load).

Figure 2 shows an example secondary bus voltage during utility capacitor energizing. Previous computer simulations and onsite measurements have indicated that magnified transients between 2.0 and 4.0 per-unit are possible over a wide range of low voltage capacitor sizes. Typically, the transient overvoltages will simply damage low-energy protective devices (e.g., MOVs) or cause a nuisance trip of a power electronic device. Important system variables to consider when analyzing this phenomenon include:

- Switched capacitor bank size / lower voltage capacitor bank size and location
- System loading / transformer characteristics
- Circuit breaker characteristics (closing resistors/inductors, closing control, etc.).
- Arrester size(s), rating(s), and location(s)

Figure 3 illustrates an example simulated capacitor energizing transient and the resulting transient voltage at the lower voltage customer power factor correction capacitor bank. Solutions to the voltage magnification usually involve:

- Using an overvoltage control method, such as pre-insertion resistors or synchronous closing control.
- Detuning the circuit by changing capacitor bank sizes, moving banks, and/or removing banks from service.
- Switching large banks in more than one section.
- Applying surge arresters (MOVs) at the remote location.
- Converting the customer's power factor correction banks into harmonic filters.

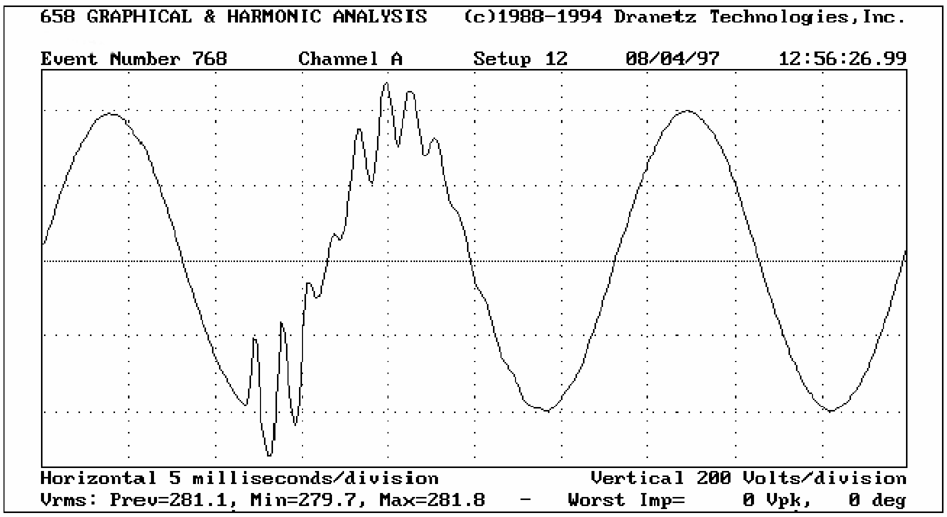


Figure 2 - Example of a Secondary Bus Voltage during Utility Capacitor Energizing

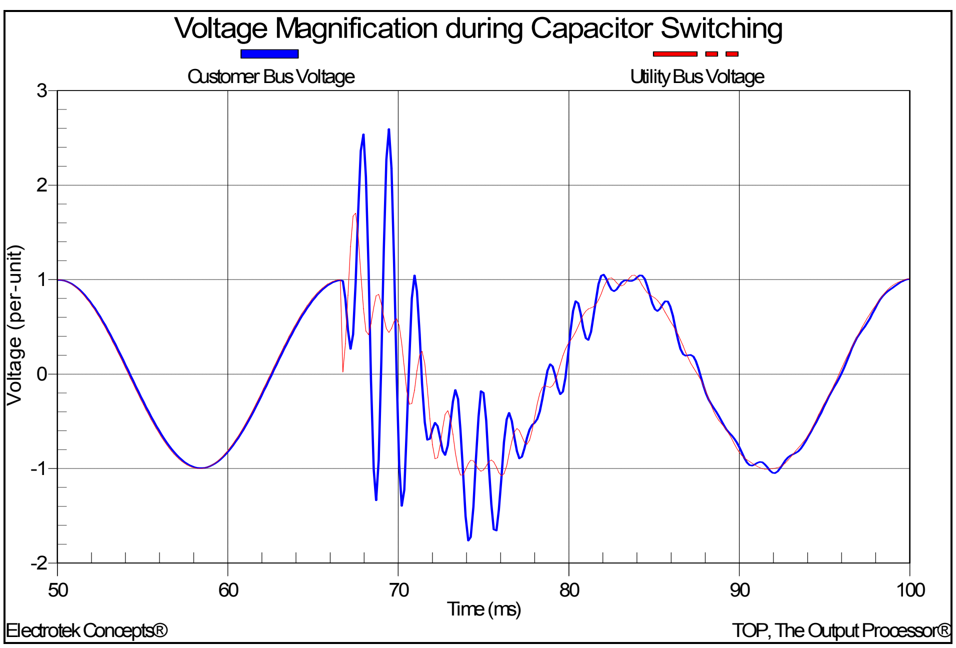
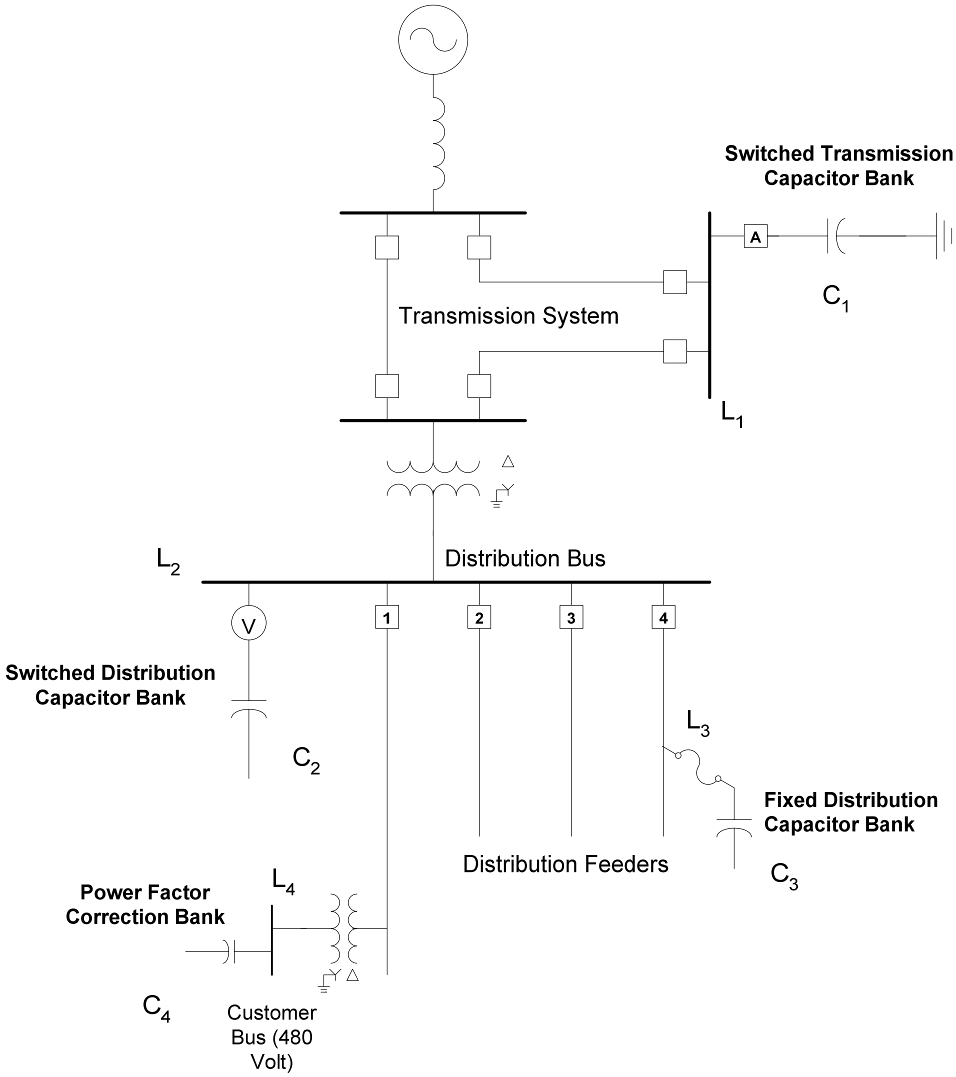


Figure 3 - Example of a Computer Simulation Showing Voltage Magnification



$$C_n = \frac{MVAr_n}{\omega * kV_n^2} \qquad L_n = \frac{kV_n^2}{\omega * MVA_{sc_n}}$$

$$f_n = \frac{1}{2\pi\sqrt{(L_n * C_n)}} \approx f_{system} * \sqrt{\frac{MVA_{sc_n}}{MVAr_n}} = f_{system} * \sqrt{\left(\frac{\sqrt{3} * kV_n^2 * kA_{sc_n}}{MVAr_n}\right)}$$

where:

f_n = characteristic frequency (f_1 & f_2)
$\omega = 2*\pi*f_{system}$
$MVAr_n$ = three-phase rating of the capacitor bank
MVA_{scn} = three-phase short circuit capacity (kA_{scn} in amps)
kV_n = system voltage (line-to-line)

Figure 4 - Illustration of Circuit for Evaluating Voltage Magnification

Nuisance Tripping of Customer Equipment

Nuisance tripping refers to the undesired shutdown of a customer's adjustable-speed drive or other power-electronic-based process device due to the transient overvoltage on the device's dc bus. Very often, this overvoltage is caused by utility transmission or distribution capacitor bank energization. Considering the fact that many distribution banks are time clock controlled, it is easy to see how this event can occur on a regular basis, thereby causing numerous process interruptions for the customer.

An adjustable-speed drive system consists of three basic components and a control system as illustrated in Figure 5. The rectifier converts the three-phase ac input to a dc voltage, and an inverter circuit utilizes the dc signal to produce a variable magnitude, variable frequency ac voltage, that is used to control the speed of an ac motor. A dc motor drive differs from this configuration in that the rectifier is used to control the motor directly.

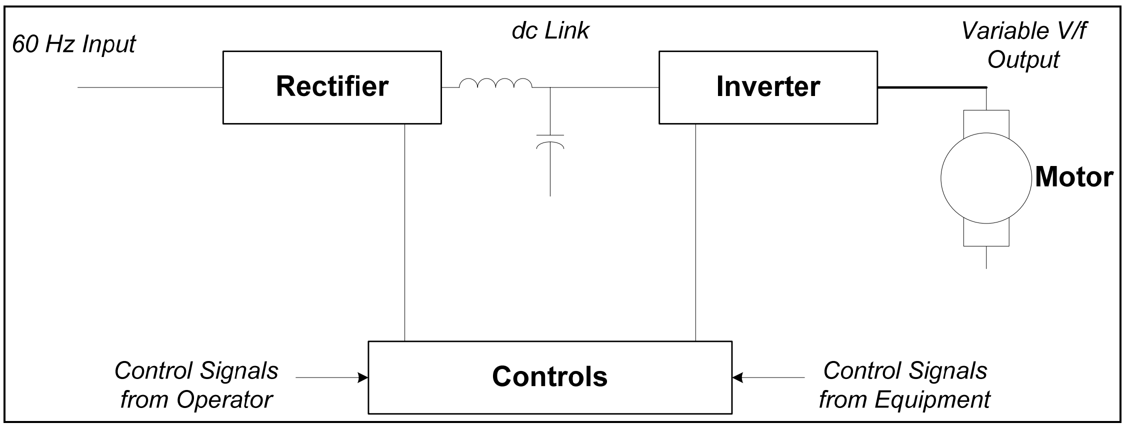


Figure 5 - Illustration of Adjustable-Speed Drive Circuit Components

The nuisance tripping event consists of an overvoltage trip due to a dc bus overvoltage on voltage-source inverter drives (e.g., pulse-width modulated). Typically, for the protection of the dc capacitor and inverter components, the dc bus voltage is monitored and the drive tripped when it exceeds a preset level. This level is typically around 780 volts (for 480 volt applications), which is only 120% of the nominal dc voltage. The potential for nuisance tripping is primarily dependent on the switched capacitor bank size, overvoltage controls for the switched bank, the dc bus capacitor size, and the inductance between the two capacitors. It is important to note that nuisance tripping can occur even if the customer does not have power factor correction capacitors.

The most effective methods for eliminating nuisance tripping are to significantly reduce the energizing transient overvoltage, or to isolate the drives from the power system with series inductors, often referred to as chokes. The additional series inductance of the choke will reduce the transient magnitude at the input to the drive and the associated current surge into the dc link filter capacitor, thereby limiting the dc overvoltage.

While determining the precise inductor size for a particular application may require a detailed computer simulation study, a more common approach involves the widespread application of a standard 3% value. The 3% size is based upon the drive kVA rating and is usually sufficient for most applications where voltage magnification isn't also a concern. Figure 6 illustrates an example of a computer simulation showing the dc overvoltage transient before-and-after the application of a 3% ac choke.

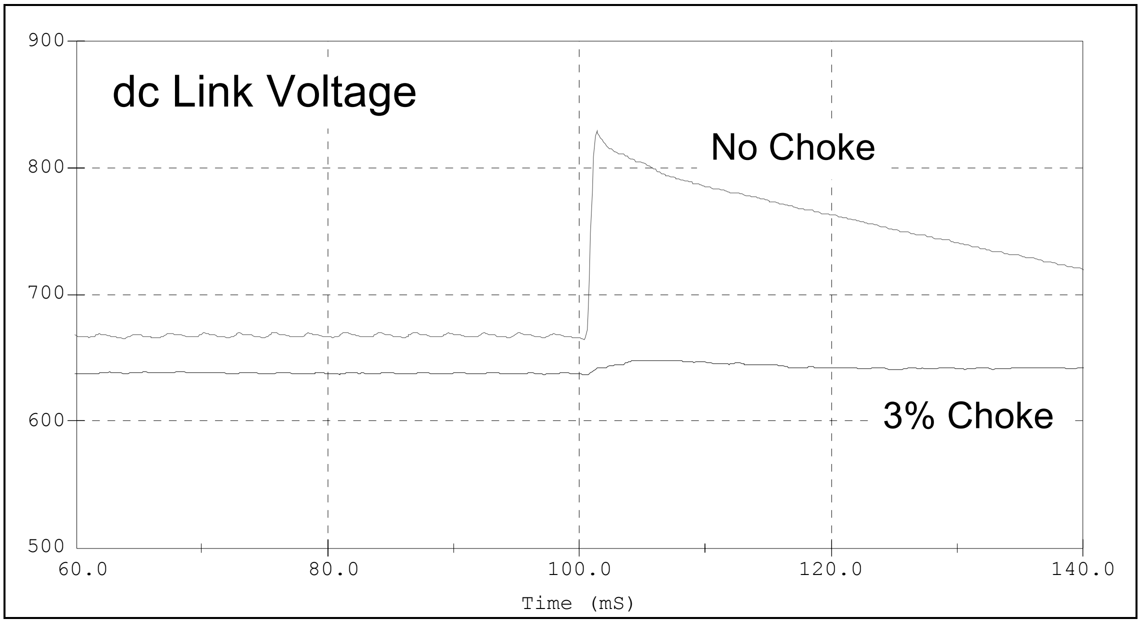


Figure 6 - Example of a Simulation Showing Effect of Choke on dc Voltage Level

Generally, the choke is specified in %X and hp. However, for simulation purposes, the inductance of the choke may be approximated using the following relationship. An example of a 3% choke being added to a 10 hp drive is provided for reference.

$$L_{choke} \approx \left(\frac{\left(\frac{kV_{\phi\phi}^2}{\left(hp/1000 \right)} \right) * X\%}{2 * \pi * f_{system}} \right) = \left(\frac{\left(\frac{0.480^2}{\left(10/1000 \right)} \right) * 0.03}{2 * \pi * 60} \right) = 1.83\text{mH}$$

where:

f_{system} = system frequency (50 or 60 Hz)
X = inductive reactance of ac choke (%)
$kV_{\phi\phi}$ = system rms phase-to-phase voltage (kV)
hp = Horsepower rating of the drive (hp)

SUMMARY

Power factor correction is an important facet of power quality. Capacitors may be installed on customer systems to minimize charges for poor power factor on their electric bill. These installations may create problems by altering the harmonic frequency response of the network or introducing transient disturbances during their energization. This case study presented an overview of the impact of power factor correction on transient issues, such as voltage magnification and nuisance tripping of customer adjustable-speed drives.

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