Voltage Unbalance and Motors

Background

Voltage unbalance occurs when the RMS line voltages on a poly-phase system are unequal. Voltages are seldom perfectly balanced between phases, but when this unbalance becomes excessive, it can create problems for poly-phase motors. Many of the newer induction motors are now more sensitive to unbalance than the older designs, and furthermore, adjustable speed drives can be even more vulnerable than standard motors. This Power Note is intended to provide a brief overview of voltage unbalance, the related standards, and possible mitigation techniques to improve unbalance. For more information on the use of controls for motor protection, please refer to the PG&E Power Notes, "Motor Controls" and "Open-phase Protection Issues for Motors."

What are the Effects of Voltage Unbalance?

The main effect of voltage unbalance is motor damage from excessive heat. Voltage unbalance can create a current unbalance 6 to 10 times the magnitude of voltage unbalance. Consequently, this current unbalance creates heat in the motor windings that breaks down motor insulation causing cumulative and permanent damage to the motor. Figure 1 below, shows the percentage of temperature rise as related to the voltage unbalance. The relationship is exponential, and approximately increases by twice the square of the percent of voltage unbalance.[4]

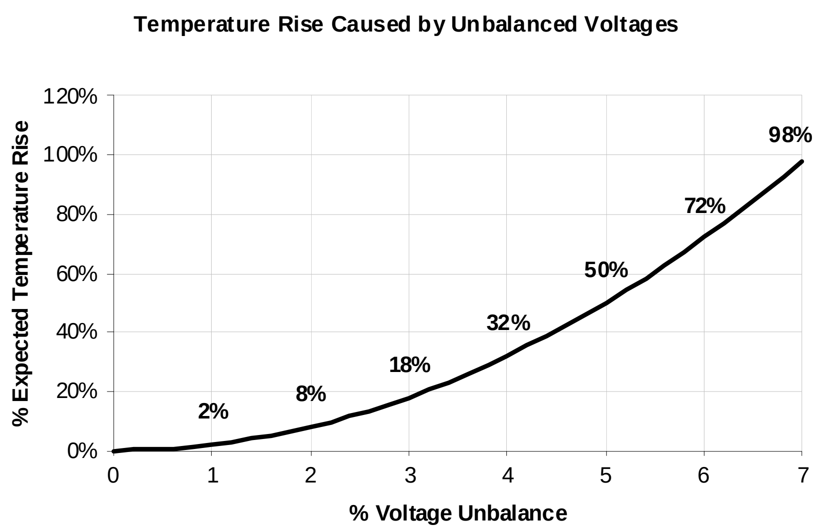

Figure 1: Percent Temperature Rise Due to Voltage Unbalance

Voltage Unbalance Standards

Unfortunately, there are different standards regarding the appropriate limits for voltage unbalance.

The American National Standard for Electric Power Systems and Equipment ANSI C84.1 recommends that “electric supply systems should be designed and operated to limit the maximum voltage unbalance to 3 percent when measured at the electric-utility revenue meter under no-load conditions.”

Pacific Gas and Electric lays out its own requirements in Rule 2, which states that “the voltage balance between phases will be maintained by PG&E as close as practicable to 2 ½ percent maximum deviation from the average voltage between the three phases.”

The National Equipment Manufacturers Association (NEMA), which represents motor and drive manufacturers, only requires motors to give rated output for 1% of voltage unbalance per NEMA MG-1-1998. By limiting voltage unbalance to 1%, this is more stringent than either ANSI C84.1 or utility guidelines. Furthermore, some motor manufacturers have tried to require less than 5% current unbalance for a valid warranty. NEMA MG-1 states that 1% of voltage unbalance can create 6-10% current unbalance; thus, these motor manufacturers have requirements that are potentially more restrictive than even NEMA MG-1.

This inconsistency can create disputes between customers, motor manufacturers, and the utility. Careful consideration should be made in each location to the utility’s service guidelines versus the motor manufacturer’s guidelines, to ensure a proper understanding of the two.

What Causes Voltage Unbalance?

Voltage unbalance issues for motors can come from three possible sources: the utility, the facility housing the motor, and the motor itself.

Sometimes the power supplied by the utility can be the source of unbalanced voltages. This can be due to malfunctioning equipment including blown capacitor fuses, open-delta regulators, and open-delta transformers. Open-delta equipment can be more susceptible to unbalance issues than closed-delta equipment because they only use two phases to perform their transformations. In addition to faulty equipment, voltage unbalance can also be caused by uneven single-phase load distribution among the three phases.

The facility housing the motor can create unbalanced voltages even if the utility supplied power is well balanced. Again, this could be caused by malfunctioning equipment or even mismatched transformer taps. Similar to the utility, poor load distribution within the facility can create voltage unbalance issues. To help ensure proper load distribution for customer three-wire single-phase and three-phase services, PG&E Rule 2 requires that the "difference in amperes between any two phases at the customer's peak load should not be greater than 10 percent or 50 amperes, whichever is greater."

The motor itself can also be the source of unbalance issues. Resistive and inductive unbalances within the motor can create unbalanced currents and unbalanced voltages. Defects in the power circuit connections, the motor contacts, or the rotor and stator windings, can all cause irregular impedances between phases in the motor that lead to unbalanced conditions.

Testing for Voltage Unbalance

When testing for voltage unbalance, the phase-to-phase voltages should be measured rather than the phase-to-neutral voltages since poly-phase motors are connected across phases. After measuring the phase-phase voltages with a properly calibrated voltmeter, the following calculation can determine the percent of voltage unbalance.

Voltage Unbalance Formula:

Percent Voltage Unbalance = $100 \times \frac{Maximum\ Voltage\ Deviation}{Average\ Voltage}$

Example:
Assume the following phase-phase voltages were measured:
A-B = 479V
B-C = 472 V
C-A = 450 V

Average Voltage = $\frac{479\,V + 472\,V + 450\,V}{3} = 467\,V$

Maximum Voltage Deviation from Average = $467\,V - 450\,V = 17\,V$

Voltage Unbalance = $100 \times \frac{17\,V}{467\,V} = 3.6\%$

If an unbalance issue is found, then the following test can help determine whether the problem source is the motor itself or the power supplying the motor.

Checking for the Source of Unbalance:

1. Measure and record the current through each motor lead.
2. Rotate all three input power lines by one position, making sure not to change the order of the leads. (Changing the order will change the motor's rotation)
3. Measure and record the current in each lead in the new configuration.
4. Rotate all three input power lines by one more position.

5. Measure and record the current in each lead in the new configuration.
6. For each of the three rotation configurations, determine the average current, and note the particular power-line/motor-lead combination that has the maximum deviation from the average current.
7. Compare the three power-line/motor-lead combinations with maximum current deviation. If the combination always contains the same motor lead, then it indicates a problem with the motor. If the combination always contains the same power line, then the power supply may be at fault.

An example is provided below for clarification.

Example:
Motor Leads: M1, M2, M3
Input Power Lines: P1, P2, P3

Original Hookup	***Rotate Leads Once***	***Rotate Leads Twice***
M1-P1: 56A M2-P2: 54A M3-P3: **46A** Average: 52A <u>Max Deviation:</u> **M3-P3**: 6A	M1-P3: **47A** M2-P1: 58A M3-P2: 54A Average: 53A <u>Max Deviation:</u> **M1-P3**: 6A	M1-P2: 56A M2-P3: **48A** M3-P1: 55A Average: 53A <u>Max Deviation:</u> **M2-P3**: 5A

The above example indicates the incoming power is the source of the unbalance, because the current farthest from average follows the input power line "P3."

Mitigating Voltage Unbalance

Because voltage unbalance can be very harmful to motors, the source of the problem should be thoroughly investigated and corrected. By balancing the voltage it can help save energy and money by increasing a motor's efficiency and possibly preventing expensive facility downtime due to motor failures. Proper testing and communication with the utility can help locate and resolve the problem. Often, it is just a matter of repairing malfunctioning equipment or redistributing loads to improve the unbalance.

Adjustable speed drives (ASDs) can be more sensitive to voltage unbalance than standard motors; however, they can be equipped with AC-line reactors and DC-link reactors to mitigate the effects of unbalance. Depending on how the ASD is configured with AC and/or DC reactors, both the magnitude of RMS currents and the percent of current unbalance can be potentially reduced. Before applying reactors to an ASD, the drive manufacturer should be consulted. It is often most cost effective to request reactors at the time of purchase. There are additional benefits to adding reactors to an ASD, including improved power factor, harmonic mitigation, and protection against transients. For more information on the benefits of reactors in ASDs, please refer to the Power Note, "Application of Line Reactors or DC Link Reactors for Variable-Frequency Drives."

Per NEMA MG-1, motors should not operate with a voltage unbalance of more than 5%. However, motors can be derated to a certain extent to reduce the possibility of damage. Figure 2 shows the typical derating factor for motors per NEMA MG-1. The motor manufacturer should always be consulted to find the specific derating factor of the motor in question. Derating a motor is one of the least desirable methods for dealing with voltage unbalance, because the unbalance situation still exists and the motor cannot operate at its full potential.

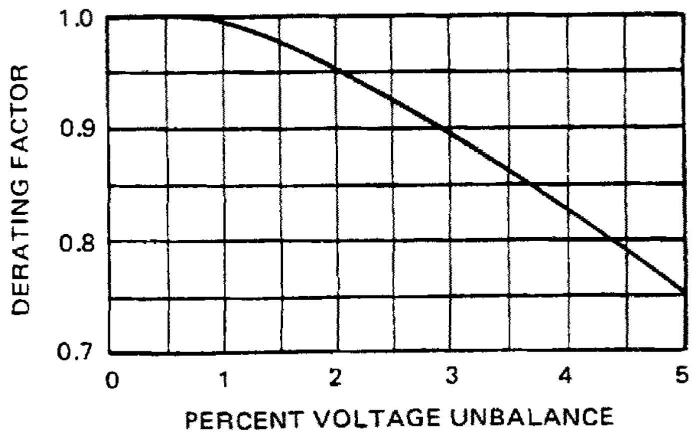

Figure 2: Derating Factor

Summary

Voltage unbalance and the resulting current unbalance can create excessive heat that damages motors. Presently, there are different standards regarding the level of acceptable voltage unbalance. While the standards differ, motors are generally able to handle a certain amount of voltage unbalance up to 5% through derating. However, relying on derating should be one of the last resorts when dealing with unbalance. A thorough investigation by the facility and the utility can often find and resolve the origin of the voltage unbalance.

References:

1. American National Standard for Electrical Power Systems and Equipment – Voltage Ratings (60 Hertz), ANSI C84.1-1995.
2. PG&E Rule 2 – Description of Service as Approved by the California Public Utility Commission.
3. National Electrical Manufacturers Association (NEMA) Publication No. MG 1-1998 Motors and Generators.
4. P. Hofmann and P. Pillay, "Derating of Induction Motors Operating with a Combination of Unbalanced Voltages and Over- or Undervoltages", IEEE Transactions on Energy Conversion, vol 17, No. 4, Dec 2002 , pp 485-491.