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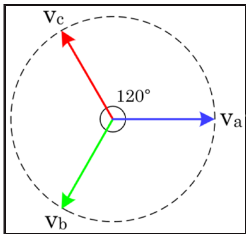

Understanding the Causes and Impacts of Voltage Unbalance

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Contents

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SUMMARY

Many devices attached to multiphase power systems rely on a balanced voltage on all phases to operate most efficiently. While some unbalance may be acceptable, and unavoidable, calculating the amount of unbalance and investigating the causes of voltage unbalances are worthwhile endeavors, especially for the long-term health of motors and adjustable-speed drives. Such investigations may lead to simple steps to mitigation.

This *PQ TechWatch* discusses various contributors to voltage unbalance, how to calculate the balance of a system, and ways to alleviate problems. Importantly, as use of distributed resources increases, monitoring of related distribution systems should also increase, and new and improved communications systems can be considered for providing alerts to any voltage imbalances.

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Voltage unbalance generally should be 3% or less; the National Electrical Manufacturers Association in standard NEMA MG-1 limits voltage unbalance regarding the operation of three-phase motors to no more than 1%.

INTRODUCTION

Equipment designed to operate reliably and efficiently in a multiphase system tends to require the voltage available in that system to be balanced. Ideally, a condition of balanced voltage in any multiphase system occurs when all voltage vectors are of equal magnitude and all phasor angles in some way have equal or symmetrical spacing. For instance, balanced three-phase, phase-to-phase voltage resembles an equilateral triangle as shown at right in the figure below, while balanced three-phase, phase-to-neutral voltage resembles a Y, with all phase-to-neutral voltage vectors being equal in magnitude and all three vectors separated by the same angle (120°) as shown at left in the figure.

Equipment connected only to a single phase may be designed to operate within one voltage tolerance—that is, nominal voltage plus or minus 10%. A device connected to three phases, one phase at nominal voltage, one phase being 10% lower than nominal, and one phase being 10% higher than nominal, would be in a state of voltage unbalance. The Institute of Electrical and Electronics Engineers (in IEEE 1159)prefers the term *imbalance* while American National Standards Institute (ANSI) and National Electrical Manufacturers Association (NEMA) use the term *unbalance* to describe this condition. Voltage unbalance (or imbalance) should be 3% or less. NEMA, in its standard NEMA MG-1, limits voltage unbalance regarding the operation of three-phase motors to no more than 1%.[1]

Induction motors operating in a condition of voltage unbalance will experience less efficient operation, reduction in torque, higher-than-normal current along with heating effects, and early failure due to these heating effects.

For several reasons, the ideal situation shown in the figure below may not be present at all times in the electrical distribution system.

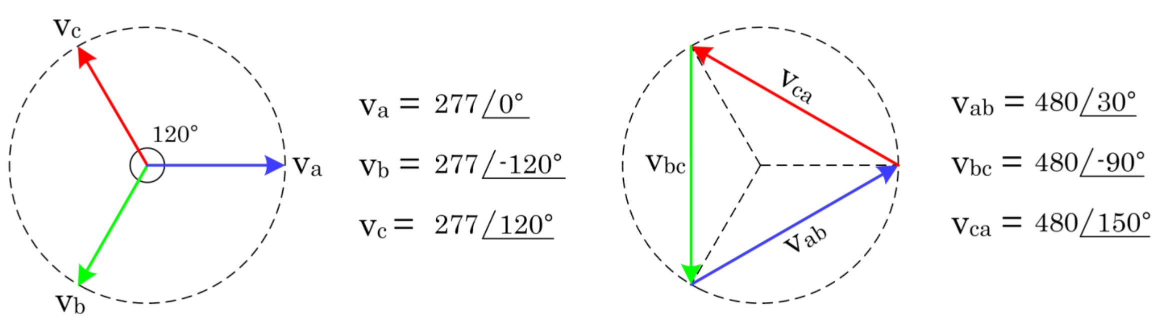
CAUSES OF VOLTAGE UNBALANCE

The presence of unequal voltages on the three phases may result from a condition located anywhere between (and including) the generator windings producing the voltage to the last load on the distribution circuit. The loading on each phase of the circuit may not be equal. A protection fuse may open on one phase, or a fuse on one phase of a capacitor bank may be open, or the line impedance may not be equal on all phases. A substation transformer tap may be frozen on one phase such that the unbalance condition gradually becomes apparent as the other phase taps adjust to changing conditions.

Several possible causes of steady-state voltage unbalance have already been listed:

- Differing line impedances
- Single-phase loads unevenly distributed

Balanced Three-Phase System Voltage



Phase-to-neutral for each vector should be 277 volts, phase-to-phase 480 volts.

System voltage throughout the United States tends to remain balanced at under 3% voltage unbalance except for a few locations.

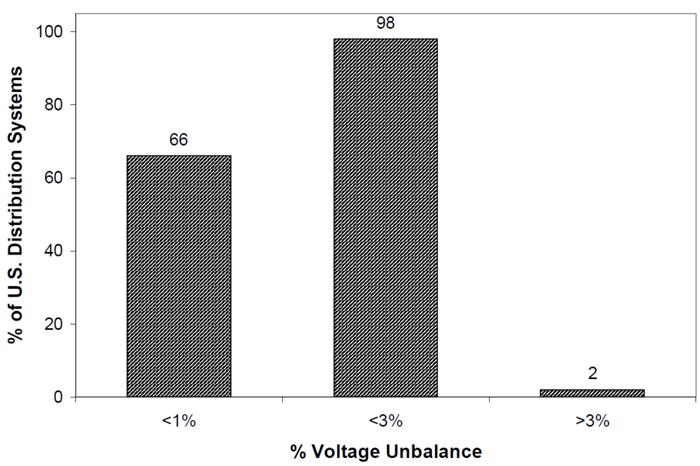
- A "stuck" voltage regulator on one or more phases
- Blown fuses on three-phase capacitor banks

Others may include:

- Open-wye or open-delta transformer banks
- Asymmetrical transformer windings
- Tap changer with a weak connection
- Incomplete transposition of transmission lines
- Time-varying, single-phase loads

Considering all of the many ways that voltage may become unbalanced, balanced systems might seem to be a rarity. However, despite all these possibilities, system voltage nationwide tends to remain balanced at under 3% voltage unbalance except for a few locations, as shown in the figure at left below.[2]

Approximate Percent Voltage Unbalance on the U.S. Distribution System



Despite the many ways a system can become unbalanced, most remain within a healthy state of under 3% unbalance throughout the United States.

Source: EPRI [2]

CALCULATING VOLTAGE UNBALANCE

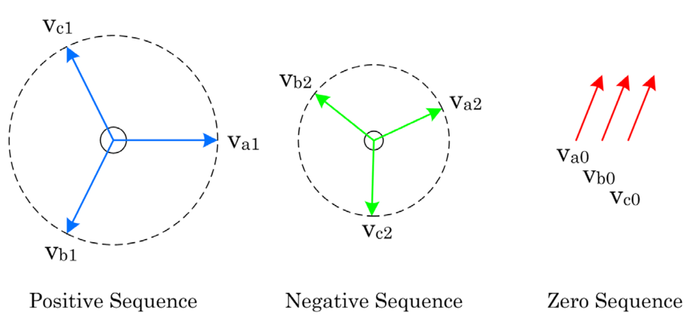
Several methods exist of varying complexity for calculating voltage unbalance for a three-phase system—all achieving nearly the same result with some exceptions. Charles LeGeyt Fortescue published a paper around 1918 describing the separation of an unbalanced system into three symmetrical components—a positive sequence, a negative sequence, and a zero sequence as shown in the figure at right below.

These calculated sequences could be assembled through a process known as vector summation, and the resultant determined. In this way, an event such as a transmission-line short circuit could be characterized as shown in the figure at the top of the next page.

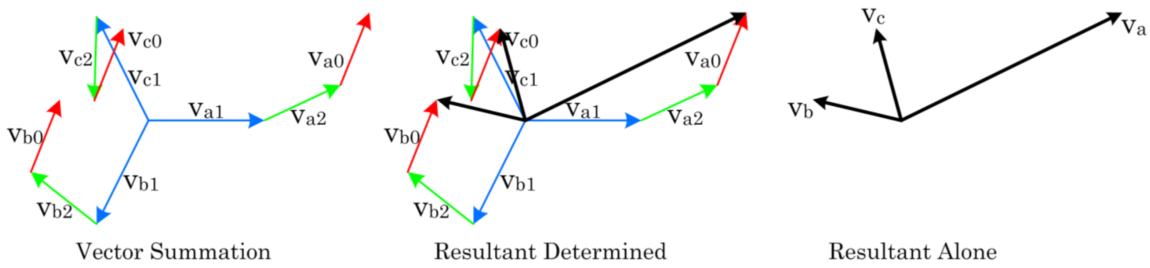
The "preferred method," provided by IEEE 1159, applies the relationship between positive and negative sequences. This method may apply the ratio of the positive- and negative-sequence component magnitudes and either phase-to-phase or phase-to-neutral voltages—therefore, this method may be applied to either delta or wye systems. However, due to the difficulty in determining ground paths, zero currents and voltages pose problems.

Indeed, factoring in zero-sequence voltages may prove to be very problematic with voltage unbalance (VU) calculations. In 2002, M. H. J. Bollen provided an analysis of two IEEE definitions of

Symmetrical Vector Components of an Unbalanced System



Vector Summation of Symmetrical Components



Voltage unbalance results in a disproportionately large phase current unbalance, which can cause overheating in induction motors, adjustable speed drives, and power-electronic converters.

voltage unbalance along with the NEMA method. The analysis showed that by varying the angle of the negative-sequence component from 0 to 360 degrees, the calculated voltage unbalance of the two IEEE definitions differed from each other between 1% and almost 2%. The simultaneous addition of 1.5% zero-sequence voltage caused the two IEEE definitions to vary from that using the NEMA definition (a constant VU of 2%) by about ±1.5% (VU between 0.5% and 3.5%) in the case of one IEEE definition, and by +3.5% and –1% (VU between 1% and over 5.5%) in the case of the other.[3]

The "preferred" method of calculation is as follows:

$$\%\ Unbalance = \frac{|V_{neg}|}{|V_{pos}|} \times 100$$

V_{neg} and V_{pos} may be calculated in the following manner:

$$V_{pos} = \frac{1}{3}\left(V_{AB} + V_{BC} \bullet 1\angle 120° + V_{CA} \bullet 1\angle -120°\right)$$

$$V_{neg} = \frac{1}{3}\left(V_{AB} + V_{BC} \bullet 1\angle -120° + V_{CA} \bullet 1\angle 120°\right)$$

Thus, this method may be easily adapted to delta connections, which have no zero-sequence components.

Perhaps the most straightforward method is from NEMA. This method, applicable only to delta-wound motors (conveniently, most industrial motors are delta-wound), involves calculating the average of the three measured phase-to-phase voltages, calculating which voltage deviates the most from the average, and dividing that voltage by the average:

$$\%\ Unbalance = \frac{\text{Maxium Deviation from Average}}{\text{Average of Three Phase-to-Phase Voltages}} \times 100.$$

CONSEQUENCES OF VOLTAGE UNBALANCE

Three-phase equipment may tolerate short-term deviations from normal voltage and phase angle; however, long-term exposure to such deviations may cause premature failure of motors and adjustable-speed drives (ASDs) due to the heating effects within the equipment. Voltage unbalance results in a disproportionately large phase current unbalance (6 to 10 times), which can cause overheating in induction motors, adjustable speed drives, and power-electronic converters.

The effect of voltage unbalance on polyphase motors—especially for open-phase conditions—reveals itself in these aspects of motor performance:

- Current increases proportionately.
- Torque varies as the square of the applied voltage.
- Operating temperature rise and motor heating will vary as the square of the motor current.

Facilities should install loss of phase monitors at the facility level and on large motors, as this loss of phase condition may not be obvious and motors could suffer damage if allowed to operate in this condition.

- Any increase in motor current will result in a decrease in efficiency due to motor losses related to power factor and efficiency.

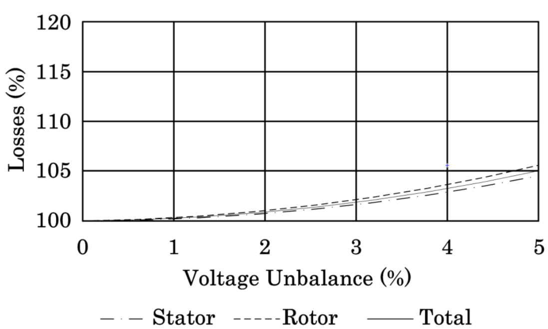
Positive, negative, and zero sequence voltages occur during voltage unbalance conditions. The positive sequence voltage produces torque in the normal direction of rotation, while negative sequence voltage produces torque in the opposite direction. Thus, the motor must overcome the effects of the negative sequence voltage or the motor may stall. In this condition, slip may increase, causing higher current—and higher temperature—in the stator windings. Higher currents result in greater voltage drops in conductors and transformer windings ahead of the motor—resulting in lower voltage available at the motor terminals. Losses in the rotor also increase. The worst condition for voltage unbalance—during a single-phasing condition—may result in the motor stalling if trying to start, or coming to a stop if already rotating.[4]

Facilities should install loss of phase monitors at the facility level and on large motors, as this loss of phase condition may not be obvious and motors could suffer damage if allowed to operate in this condition. Voltage unbalance affects motors during startup, and it affects running conditions due to the decrease in effective torque and increase in current flow.

The figures below illustrate the increasing effects on equipment with increasing levels of voltage unbalance for a delta-wound motor. In the first case, V_{bc} is held constant, while V_{ab} increases and V_{ca} decreases by the same amount as V_{ab}. The motor losses (which typically result in increasing motor temperature) may be seen to increase slightly with increasing voltage unbalance. In the second figure, V_{bc} decreases while V_{ab} and V_{ca} increase by the same amount—making the condition of voltage unbalance more severe. Here, losses increase over the first case—meaning the motor temperature also increases further.

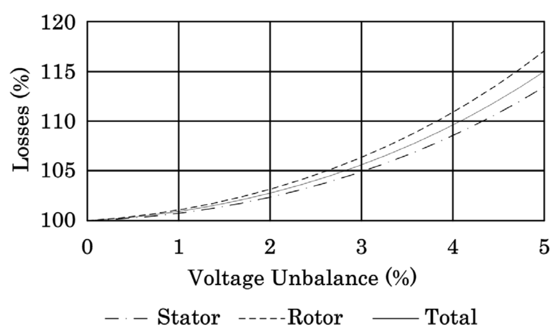
Fortunately, induction motors are often under 100% loaded. With lighter loading, an induction motor may tolerate greater amounts of voltage unbalance. Motor loading may be reduced (or larger motors specified) to accommodate known levels of voltage unbalance as shown in the figure at the top of the next page. NEMA does not recommend that any motor be operated during voltage unbalance conditions greater than 5%.

Example Voltage Unbalance (Delta-Wound Motor), V_{bc} Held Constant



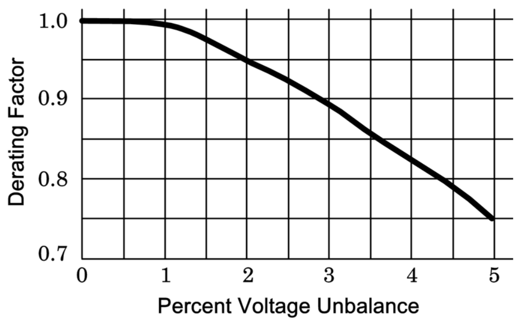
In this example, V_{bc} is held constant, while V_{ab} increases and V_{ca} decreases by the same amount.

Example Voltage Unbalance (Delta-Wound Motor), V_{bc} Decreases



In this example, V_{bc} decreases while V_{ab} and V_{ca} increase by the same amount.

Derating Graph and Table for Induction Motors Based upon Percent of Voltage Unbalance

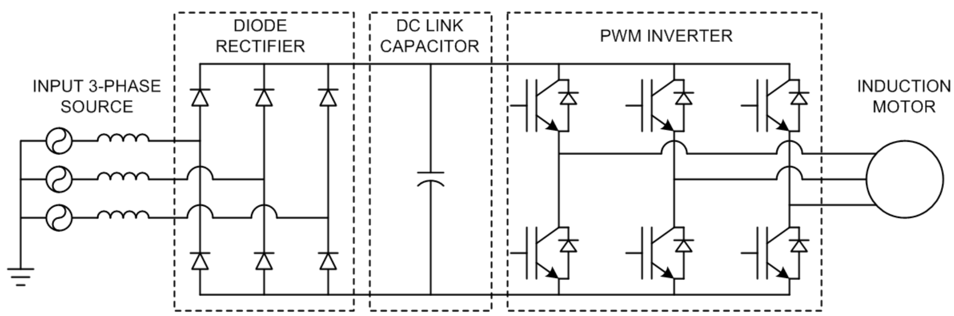


Voltage Unbalance (%)	Derating (%)
1	na
2	95
3	88
4	82
5	75

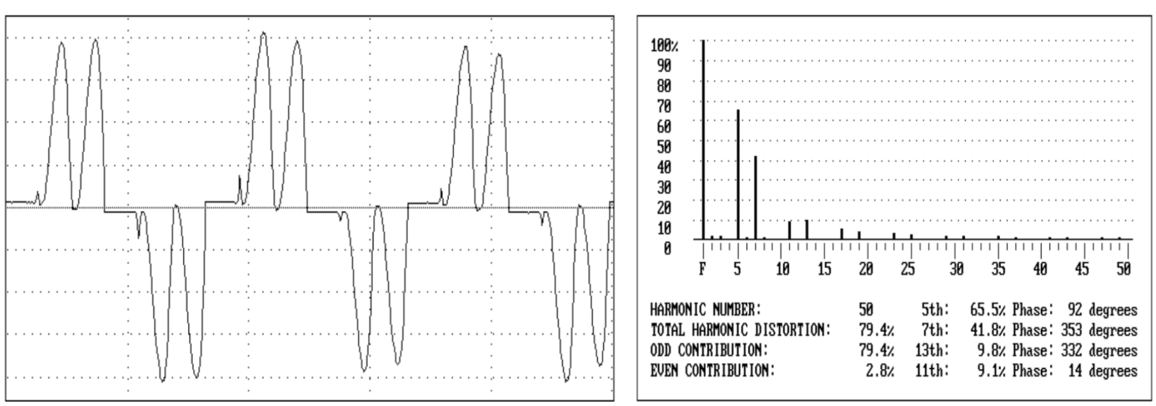
Source: Adapted from NEMA Standard MG 1-1993: Motors and Generators

The effect on ASDs most directly concerns the rectifier at the front end. The schematic of a six-pulse ASD is shown in the figure below. The characteristic double pulse in the current waveform is shown in the figure at the bottom of the page. In figures on the next page, increasing voltage unbalance may be seen to make the current double pulse approach a single pulse, while harmonic distortion may be seen to increase—particularly for the 3rd and 9th harmonics known as *triplen* harmonics. The current

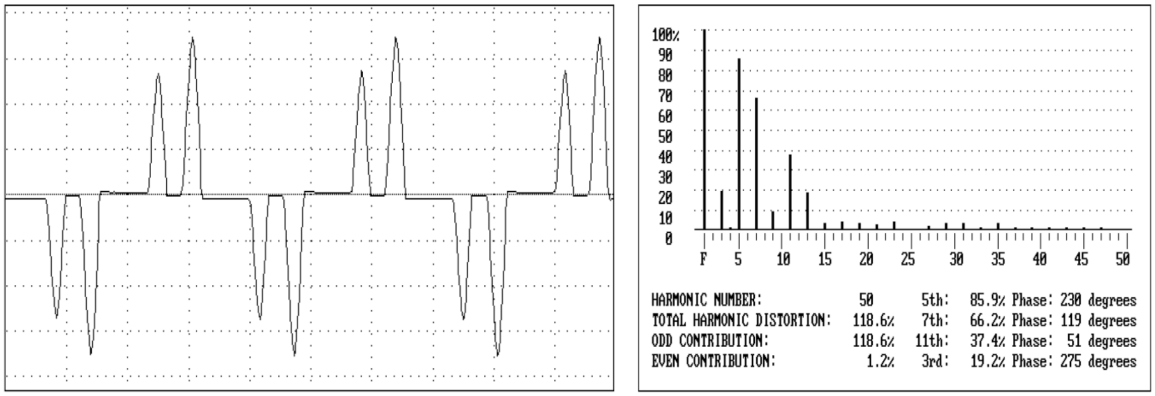
Schematic of Six-Pulse ASD



Current Pulse and Harmonics, 460 Volt 30 kVA ASD, Minimal Voltage Unbalance

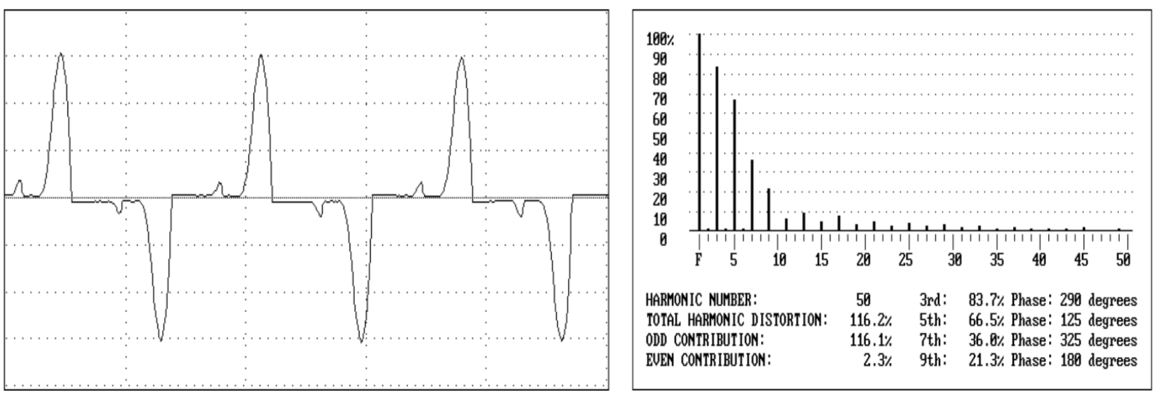


Current Pulse and Harmonics, 460 Volt 30 kVA ASD, 0.3% Voltage Unbalance



Current harmonic distortion may be seen to increase.

Figure 11. Current Pulse and Harmonics, 460 Volt 30 kVA ASD, 3.75% Voltage Unbalance



Further increase is seen in harmonic distortion.

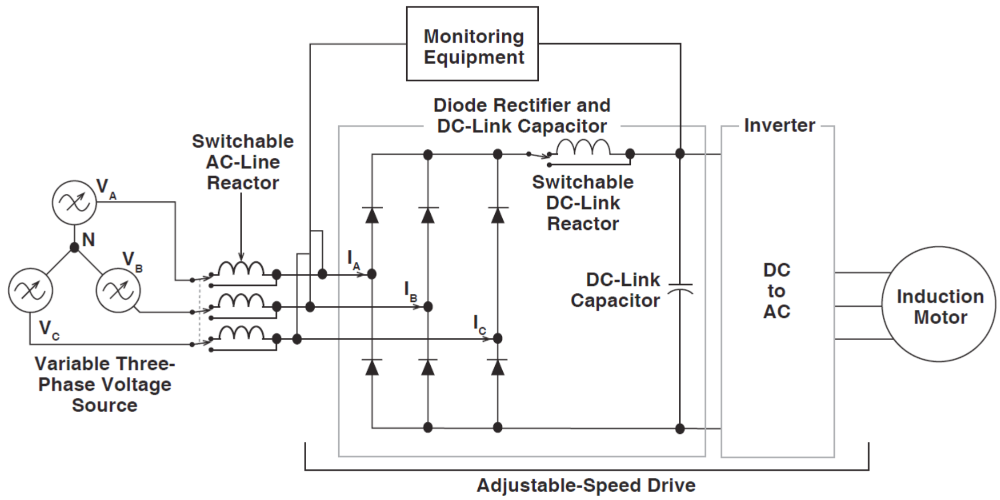
AC line reactors and DC-link reactors can together reduce current unbalance when used with adjustable speed drives.

in one or two phases may increase to the point that overcurrent protection devices trip the ASD off-line. Even worse, the rectifying diodes may overheat and fail prematurely.[5]

ASD VOLTAGE UNBALANCE MITIGATION

One effective means of mitigating voltage unbalance regarding ASDs involves the use of reactors (or inductors) as illustrated in the figure at the top of the next page. These reactors could be switched in or out as indicated in the first table on the next page. Specifically, AC line reactors were installed at the three-phase input connections, and a DC-link reactor was installed between the input diode rectifiers and the DC-link capacitor (some drives may already have the DC-link reactor). Testing by EPRI determined that the AC line reactors and the DC-link reactor together reduced the current unbalance by about half and balanced the line currents. Total harmonic distortion (THD) was also significantly reduced, as may be seen in the second and third tables on the next page.[6]

ASD Line and DC-Link Reactors



The addition of AC line reactors and a DC-link reactor reduced current unbalance and total harmonic distortion in this setup.

ASD Reactor Configurations

Configuration	AC-Line Reactor	DC-Link Reactor
Number 1	Switched off	Switched off
Number 2	Switched on	Switched off
Number 3	Switched off	Switched on
Number 4	Switched on	Switched on

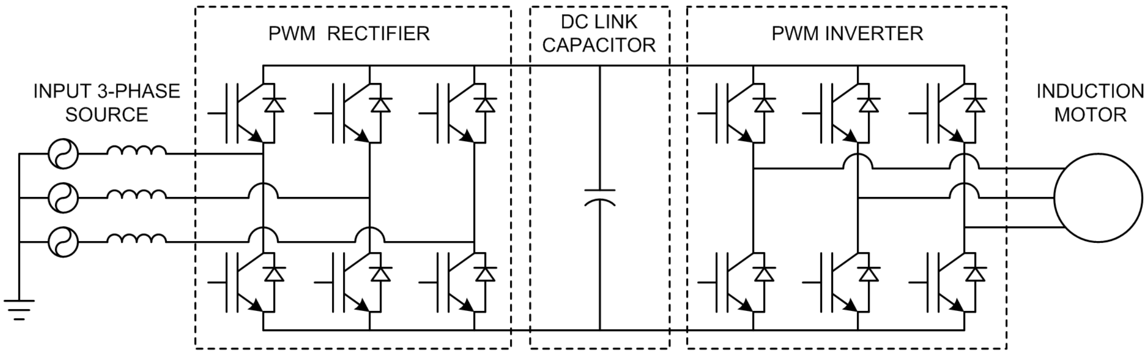
Measured ASD Voltage and Current Values

Configuration	V_{AB} (volts)	V_{BC} (volts)	V_{CA} (volts)	V_{dc} (volts)	I_{ARMS} (amps)	I_{BRMS} (amps)	I_{CRMS} (amps)	I_{UB} (amps)
1	449	465	450	664	5.8	8.7	10.4	30.5
2	448	465	451	620	3.1	5.6	5.4	33.4
3	448	465	452	620	3.3	5.7	5.2	30.8
4	447	465	450	604	3.6	4.8	4.2	14.5

Measured ASD THD Current Values

Configuration	I_{ATHD} (%)	I_{A3} (%)	I_{A5} (%)	I_{BTHD} (%)	I_{A3} (%)	I_{A5} (%)	I_{CTHD} (%)	I_{A3} (%)	I_{A5} (%)
1	136	86	84	145	87	80	111	24	74
2	72	22	63	48	33	29	61	36	46
3	75	40	55	42	31	23	69	42	46
4	77	39	57	45	33	25	70	42	48

Pulse-Width Modulated Rectifier Design



This newer ASD design produces fewer harmonics, but may still be susceptible to complications from voltage unbalance.

Distributed energy resources or distributed generation may increase the likelihood of voltage unbalance as many of these new types of generation may be single-phase installations.

The six-pulse drive design may still be common in the industrial environment; however, the ASD has developed further with the active pulse-width modulated (PWM) design illustrated in the figure above, as well as 16-pulse and 18-pulse designs. While these newer designs may produce fewer 3rd, 5th, and other lower harmonics, they may not be immune to voltage unbalance and may experience increased reactive power, increased current distortion at the input to the ASD, and 120-Hz ripple appearing on the DC-link capacitor voltage.

NEW COMPLICATIONS

With the development of distributed energy resources (DER) or distributed generation (DG), the likelihood of voltage unbalance may increase as many of these new types of generation may be single-phase installations (such as residential solar photovoltaic [PV]) that can interact with the distribution circuit in unpredictable ways. For instance, the following could happen:

- The DER site may not be visible or dispatchable by the local area electric power system (EPS).
- The DER site may unpredictably connect to or disconnect from the EPS.
- The peak power contribution of PV or wind generation sites may not coincide with the peak loading of the distribution lines to which they connect.
- The variable nature of wind and solar power production may cause voltage to vary along the single-phase distribution lines to which they connect.
- Maintaining the line voltage via smart grid communications may result in greater-than-normal tap changes, thus causing premature failure of a voltage regulator or a tap-changing transformer—possibly resulting in voltage unbalance.

A recent study using stochastic methods estimated the future voltage unbalance due to high numbers of single-phase PV inverters on three low-voltage, distribution networks located in Sweden and Germany. For the networks in Sweden (two), unbalance conditions might be expected in the 1% to 2% range, while the German network might experience unbalance between 1.35% and 2.62%. The paper suggested that the risk of voltage unbalance might be reduced through controlling the distribution of PV on each phase and reducing the maximum size (power rating) for single-phase PV inverters.[7]

Despite the possibility of DER-induced voltage unbalance, the improved line communications required to allow the effective operation of the so-

Improved line communications required to allow the effective operation of the smart grid may make for faster detection of voltage unbalance and its speedier mitigation.

called *smart grid* may make for faster detection of voltage unbalance and its speedier mitigation.

For instance, a demonstration project recently undertaken by one utility (Southern Company), with assistance from the U.S. Department of Energy, successfully implemented and integrated multiple aspects of a smart grid. Among many other accomplishments, this complicated project made use of an integrated distribution management system (IDMS) along with advanced metering infrastructure (AMI) meters to monitor the distribution circuit, including the "health" of capacitor banks. Through the existing supervisory control and data acquisition (SCADA) system, these meters could quickly alert the operators of the distribution system to problems with a capacitor bank (open fuses, failed switches, or bad capacitor cans) within 24 hours, such that any problems could be resolved within days. Prior to using these meters, capacitor bank problems might typically be identified only during a once-a-year inspection.

Better communication of data from the distribution system also allowed the operators to monitor power factor at specific points in the distribution system. Differences in power factor led to a capacitor bank being turned off to alleviate the voltage unbalance at one location.[8]

CONCLUSION

Voltage unbalance (or imbalance) may often occur on the distribution system for a variety of reasons. If left unresolved, voltage unbalance may cause early failure of three-phase motors and ASDs—largely through the effects of elevated current resulting from voltage unbalance. In addition to the usual causes of voltage unbalance, the addition of DER on single-phase distribution lines may further complicate efforts to achieve balanced system voltage. However, improved communications infrastructure along with advanced metering at various points in the distribution system may allow for the timely detection and correction of voltage unbalance.

NOTES

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2. *Voltage Unbalance: Power Quality Issues, Related Standards and Mitigation Techniques: Effect of Unbalanced Voltage on End Use Equipment Performance.* Palo Alto, CA: EPRI, 2000. 1000092.
3. M. H. J. Bollen, "Definitions of Voltage Unbalance (2)," Published in *IEEE Power Engineering Letters,* v. 22, no. 11 (November 2002), pp. 49–50.
4. *Guidance for Operating Motors Under Unbalanced Voltage Conditions.* Palo Alto, CA: EPRI, 2015. 3002005358.
5. *Voltage Unbalance* [2].
6. "Input Performance of an ASD with AC and DC Reactors During Supply Voltage Unbalance," *PQTN Brief* (Palo Alto, CA: EPRI). 01017044.
7. Daphne Schwanz, Friedemann Möller, Sarah K. Rönnberg, Jan Meyer, and Math H. J. Bollen, "Stochastic Assessment of Voltage Unbalance due to Single-Phase-Connected Solar Power," 17th International Conference on Harmonics and Quality of Power (ICHQP), 2016.
8. *Southern Company Smart Grid Host Site Progress Report: Final Update.* Palo Alto, CA: EPRI, 2015. 3002004670.

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