# Assessment of Voltage Unbalance

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***Abstract*—This paper endeavors to present a comprehensive summary of the causes and effects of voltage unbalance and to discuss related standards, definitions and mitigation techniques. Several causes of voltage unbalance on the power system and in industrial facilities are presented as well as the resulting adverse effects on the system and on equipment such as induction motors and power electronic converters and drives. Standards addressing voltage unbalance are discussed and clarified, and several mitigation techniques are suggested to correct voltage unbalance problems. This paper makes apparent the importance of identifying potential unbalance problems for the benefit of both the utility and customer.**

***Index Terms*—Derating, power quality, standards, unbalance, voltage unbalance.**

## I. INTRODUCTION

IN THREE-PHASE power systems the generated voltages are sinusoidal and equal in magnitude, with the individual phases 120° apart. However, the resulting power system voltages at the distribution end and the point of utilization can be unbalanced for several reasons. The nature of the unbalance includes unequal voltage magnitudes at the fundamental system frequency (under-voltages and over-voltages), fundamental phase angle deviation, and unequal levels of harmonic distortion between the phases. A major cause of voltage unbalance is the uneven distribution of single-phase loads, that can be continuously changing across a three-phase power system. Example problem areas can be rural electric power systems with long distribution lines, as well as large urban power systems where heavy single-phase demands, such as lighting loads, are imposed by large commercial facilities [1], [2]. Single-phase traction and electric transit and railroad systems can also cause considerable unbalance on the utility three-phase system unless proper design steps are taken [3]–[5]. Additional causes of power system voltage unbalance can be asymmetrical transformer winding impedances, open wye and open delta transformer banks, asymmetrical transmission impedances possibly caused by incomplete transposition of transmission lines, and blown fuses on three-phase capacitor banks [1], [2], [6]–[11].

Industrial and commercial facilities may have well balanced incoming supply voltages, but unbalance can develop within the building from its own single-phase power requirements if the loads are not uniformly spread among the three phases. Within a user facility, unbalanced voltages can also be caused by unbalanced and overloaded equipment, and high impedance connections (e.g., bad or loose contacts). An example of unbalanced equipment is motor impedance unbalance, which has been seen to increase with time, possibly because of the unbalanced heating of the stator [12]. Motor unbalance can be due to a problem in manufacturing such as unequal number of turns in the windings, a misaligned rotor or an asymmetric stator. The motor winding unbalance can also occur in the repair process where failed windings are quickly and inexpensively repaired by isolating the failed turn, thus reducing the impedance of the repaired phase [13]. Thus, it is prudent to be conservative with repaired motors compared to new machines.

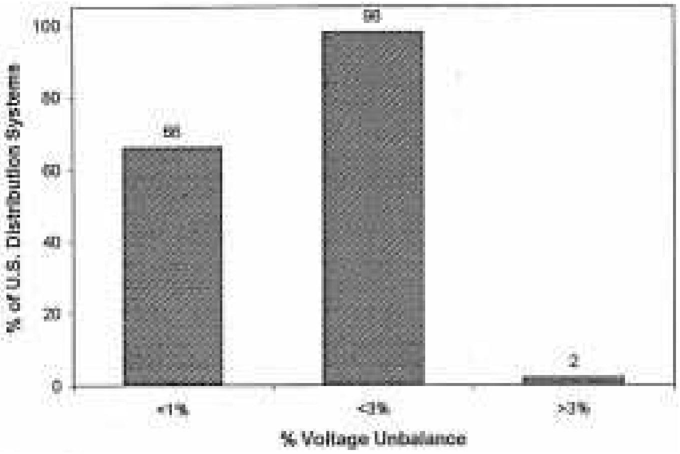

Fig. 1. Approximate percent voltage unbalance on the U.S. Distribution System [16].

The balancing problem becomes particularly difficult to compensate for when the unbalance is continually varying as with large industrial loads such as arc furnaces. In addition, when energy-saving schemes such as adjustable speed drives (ASDs) are employed, the customer load can vary continuously with large hourly variations. When a large number of single-phase ASDs are employed, this can result in continuously varying unbalanced loads [14], [15]. ASDs are also nonlinear loads, with most topologies containing a diode rectifier front-end that draws very nonsinusoidal currents leading to harmonic distortion. The combination of ASDs, with the proliferation of single-phase nonlinear switch-mode power supply based loads such as computers, can lead to unbalanced levels of distortion between phases which can also make the balancing process more challenging.

Fig. 1 presents the approximate percent voltage unbalance on the U.S. distribution system obtained from field surveys [16]. Many utilities do not keep track of their voltage unbalance in the interest of time/task prioritization, because the adverse effects are not as immediately apparent or recognized and thus unbalance is only addressed when there is a complaint.

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Power Quality surveys therefore tend to focus on disturbances involving the following voltage event types: sags, swells, over-voltages, under-voltages, impulses, transients, surges and interruptions (outages), which can also cause severe voltage unbalances but is not the focus of this paper [17], [18]. The problems associated with voltage unbalance will be discussed in the next section.

## II. THE EFFECTS OF VOLTAGE UNBALANCE

Unbalanced voltages can result in adverse effects on equipment and on the power system, which is intensified by the fact that a small unbalance in the phase voltages can cause a disproportionately larger unbalance in the phase currents [9], [10]. Under unbalanced conditions, the power system will incur more losses and heating effects, and be less stable because when the phases are balanced, the system is in a better position to respond to emergency load transfers [15]. The effect of voltage unbalance can also be severe on equipment such as induction motors, power electronic converters and adjustable speed drives (ASDs). Methods for determining the amount of voltage unbalance are presented in the next section, followed by the effects on equipment.

### A. Definitions of Percent Voltage Unbalance

The voltage unbalance in percent is defined by the National Electrical Manufacturers Association (NEMA) in Standards Publication no. MG 1-1993 as [19]:

$$\begin{aligned}&\%\ \text{Unbalance}\\&\quad=\frac{\text{Maximum Deviation from Average}}{\text{Average of Three Phase-to-Phase Voltages}}\times 100.\end{aligned}$$

Note that the line voltages are used in this NEMA standard as opposed to the phase voltages. When phase voltages are used, the phase angle unbalance is not reflected in the % Unbalance and therefore phase voltages are seldom used to calculate voltage unbalance.

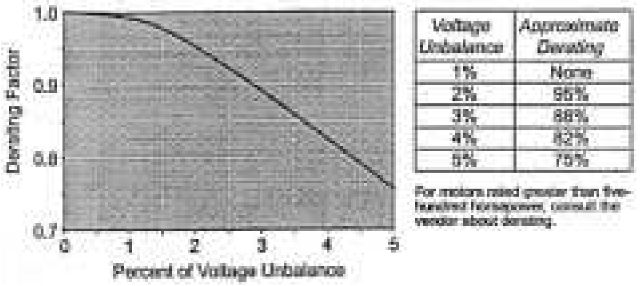
Another index used in European standards to indicate the degree of unbalance is the voltage unbalance factor (VUF) which is the ratio of the negative sequence voltage to the positive sequence voltage represented as [20], [21], [10]:

$$\%\ \text{VUF}=\frac{V_2}{V_1}\times 100.$$

$V_1$ and $V_2$ are the positive and negative sequence voltages, respectively, and can be obtained using symmetrical components as will be described in the next section.

### B. Effects of Voltage Unbalance on Machines

The adverse effects of unbalanced voltages on induction motors has been documented since the 1950s [10]. In 1954, Williams proved that an induction motor operating under unbalanced voltage conditions would experience a reduction in efficiency [7]. In 1959, Gafford *et al.*showed the increased heating effects of unbalanced voltage operation of induction motors, that could lead to premature motor failure [22]. In 1963, Berndt and Schmitz presented a method for the derating of induction motors operating with unbalanced voltages in which the rated stator winding current is taken to be the maximum allowable current [6].



| Voltage Unbalance | Approximate Derating |
|---|---|
| 1% | None |
| 2% | 95% |
| 3% | 88% |
| 4% | 82% |
| 5% | 75% |

For motors rated greater than five-hundred horsepower, consult the vendor about derating.

Fig. 2. Derating graph and table for induction motors based upon percent of voltage unbalance (from NEMA Standard MG 1-1993: Motors and Generators).

The adverse effects of unbalanced voltages on induction motors stem from the fact that the unbalanced voltage breaks down into two opposing components that can be described using the method of symmetrical components. Through the use of symmetrical components, an unbalanced three-phase system of voltage or current phasors can be described using three balanced systems of phasors termed positive, negative and zero sequence. However, in the case of machines, the zero sequence components will be zero since motors are typically connected delta or ungrounded wye and thus there is no path to neutral for zero sequence components to flow. Completely balanced systems would contain only positive sequence components of voltage, current and impedance.

Therefore, the unbalanced motor voltage contains positive and negative sequence components which have opposing phase sequences, i.e., "abc" and "acb", respectively. The positive sequence voltage produces the desired positive torque, whereas the negative sequence voltage produces an air gap flux rotating against the rotation of the rotor, thus generating an unwanted negative (reversing) torque. The result is a reduction in the net torque and speed, and the possibility of speed and torque pulsations and increased motor noise. In addition, the negative sequence component in the unbalanced voltages generates large negative sequence currents due to the low negative sequence impedance, which increases the machine losses and temperatures. At normal operating speeds, unbalanced voltages cause the line currents to be unbalanced in the order of 6 to 10 times the voltage unbalance [19]. Overall, the net effect of the voltage unbalance is reduced efficiency and decreased life of the motor.

Because of the excess heating, the NEMA Standard MG 1-1993 recommends that the rated horsepower of the motor should be multiplied by a derating factor based upon the degree of voltage unbalance as shown in Fig. 2 [19], [23]. The curve assumes that the motor is already operating at its rated load. However, many motors do not operate at the rated load and therefore can handle more voltage unbalance, since the percent load significantly affects the effect of unbalance [24], [23]. From Fig. 2, it can be seen that a 2% voltage unbalance requires about a 5% larger motor. A 3% voltage unbalance requires about a 12% larger motor, or motors with a service factor of 1.15.

The manner in which the voltages are unbalanced has a marked effect on the losses and required derating factor

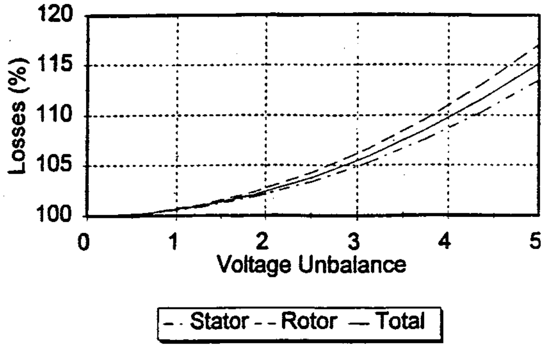


Fig. 3. Losses for unbalanced voltages in Case A, for 240 V 25 hp induction motor.

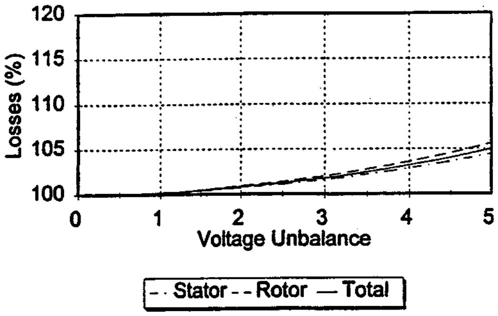


Fig. 4. Losses for unbalanced voltages in Case B, for 240 V 25 hp induction motor.

[25]. There are several possible voltage unbalance conditions including: single-phase under-voltage unbalance, two-phase under-voltage unbalance, single-phase over-voltage unbalance, unequal single-phase angle displacement, etc.

To illustrate the effect of different unbalance conditions, Kersting and Phillips applied two methods of voltage unbalancing to a 240 V, 25 hp induction motor [25]. The first method (Case A) holds the average of the line voltage magnitudes constant at 240 V by holding $|V_{bc}|$ constant and increasing $|V_{ab}|$ at the same rate $|V_{ca}|$ is reduced for unbalances up to 5%. In Case B, the average voltage is again held constant at 240 V by allowing $|V_{ab}|$ and $|V_{ca}|$ to increase, while $|V_{bc}|$ decreases, again for unbalances up to 5%. Figs. 3 and 4 display the total percent increase in losses for the stator, rotor and total motor for Case A and B, respectively, [25]. In Fig. 3 (Case A), the stator, rotor and total losses have increased 114%, 117%, and 115%, respectively. In Fig. 4 (Case B), the increases are 104%, 106%, and 105%, respectively.

Figs. 3 and 4 illustrate three points [25]:

1) The manner in which the voltages are unbalanced has a marked effect on the increase in losses.
2) As the voltages become more unbalanced, the rotor losses increase at a faster rate than the stator losses.
3) With high voltage unbalance, the stator and rotor circuits experience significant increase in losses, which will lead to excessive heating.

To demonstrate the effect of different forms of unbalance on appropriate derating, the same 25 hp motor was studied while holding the stator current fixed at the rated value as suggested in [6], while the voltages were unbalanced for Cases A and B. The derating factor for the two cases is shown in Fig. 5, where the Case A derating factor for 5% voltage unbalance is 0.7018, while for Case B it is 0.7773 [25]. These compare to the NEMA value of 0.75 in Fig. 2. Thus, it is not sufficient to merely know the percent voltage unbalance, but it is equally important to know how they are unbalanced [25].

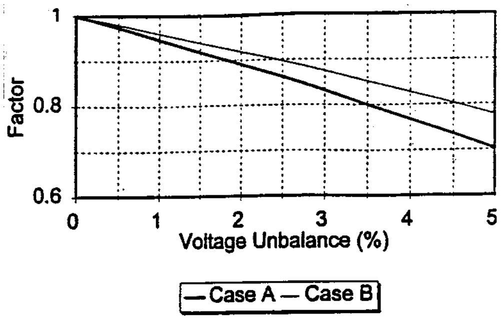


Fig. 5. Derating graph for 240 V 25 hp induction motor based upon percent of voltage unbalance using derating method presented in [6].

### C. Effects of Voltage Unbalance on Power Electronic Converters and Drives

Power electronic converters serve as the interface for many large electronic loads ranging from three-phase uninterruptible power supplies (UPSs) to motors operating at variable speeds through the use of ASDs. Most of these converters contain a diode rectifier front-end, as shown in Fig. 6, and dc-link capacitor to convert the incoming ac voltage to a low-ripple dc voltage. In Fig. 6, the pulse-width modulated (PWM) inverter converts the dc voltage back to variable three-phase ac. The magnitude and frequency of the PWM inverter output control the motor speed.

Three-phase converters with diode rectifier front-ends draw nonsinusoidal currents rich in odd harmonics. For rectifier systems supplied by *balanced* utility voltages, the input current characteristic harmonics are determined by:

$$h = kq \pm 1$$

where

$h$ = order of the harmonics;
$k$ = 1, 2, 3, 4, …;
q = number of pulses of the rectifier system.

Conventional ASDs as shown in Fig. 6 have "six-pulse" rectifiers ($q = 6$), defined by the fact that the dc-bus voltage consists of portions of the line-to-line ac waveform and repeats with a 60° duration, i.e., containing six pulses in 360°. Therefore, the characteristic current harmonics present in the ASD input will be $h = 5$th (300 Hz), 7th (420 Hz), 11th and 13th etc., as shown in Fig. 7 for a 460 V, 80 kVA ASD. Notice in Fig. 7 the characteristic double-pulse current waveform resulting in a total harmonic distortion (THD) for the ASD input current of 79.4% [26].

Under the conditions of utility voltage unbalance, the input current harmonics are not restricted to the converter characteristic harmonics, and uncharacteristic triplen harmonics can appear such as the 3rd and 9th harmonics, as demonstrated in

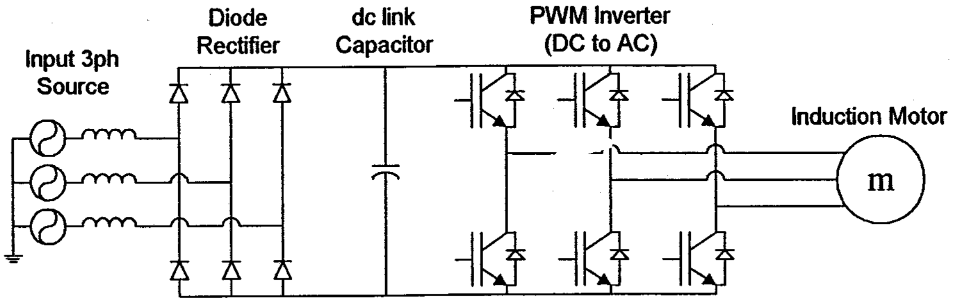
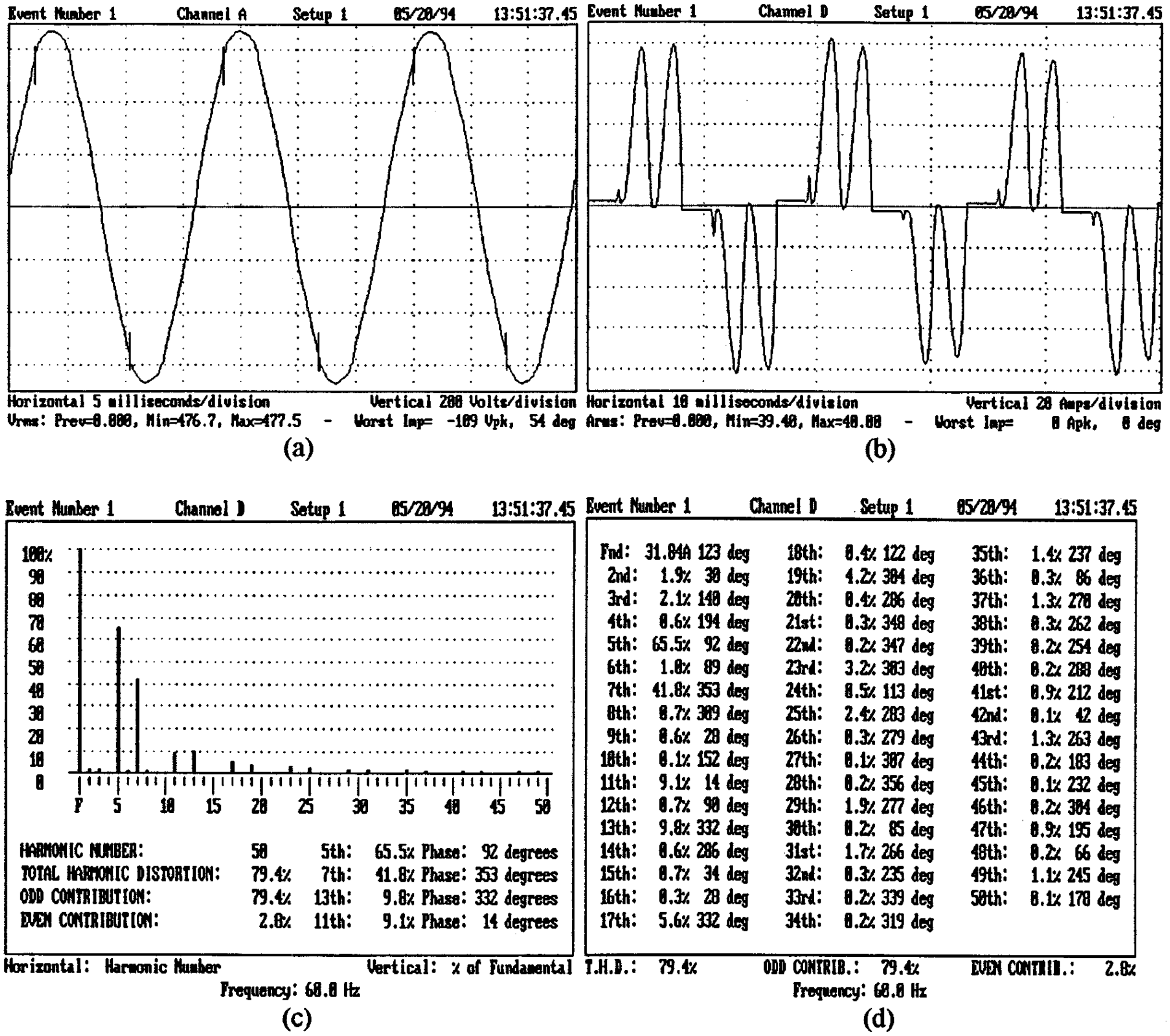


Fig. 6. Typical adjustable speed drive (ASD) system.



HARMONIC NUMBER: 50 5th: 65.5% Phase: 92 degrees
TOTAL HARMONIC DISTORTION: 79.4% 7th: 41.0% Phase: 353 degrees
ODD CONTRIBUTION: 79.4% 13th: 9.0% Phase: 332 degrees
EVEN CONTRIBUTION: 2.0% 11th: 9.1% Phase: 14 degrees

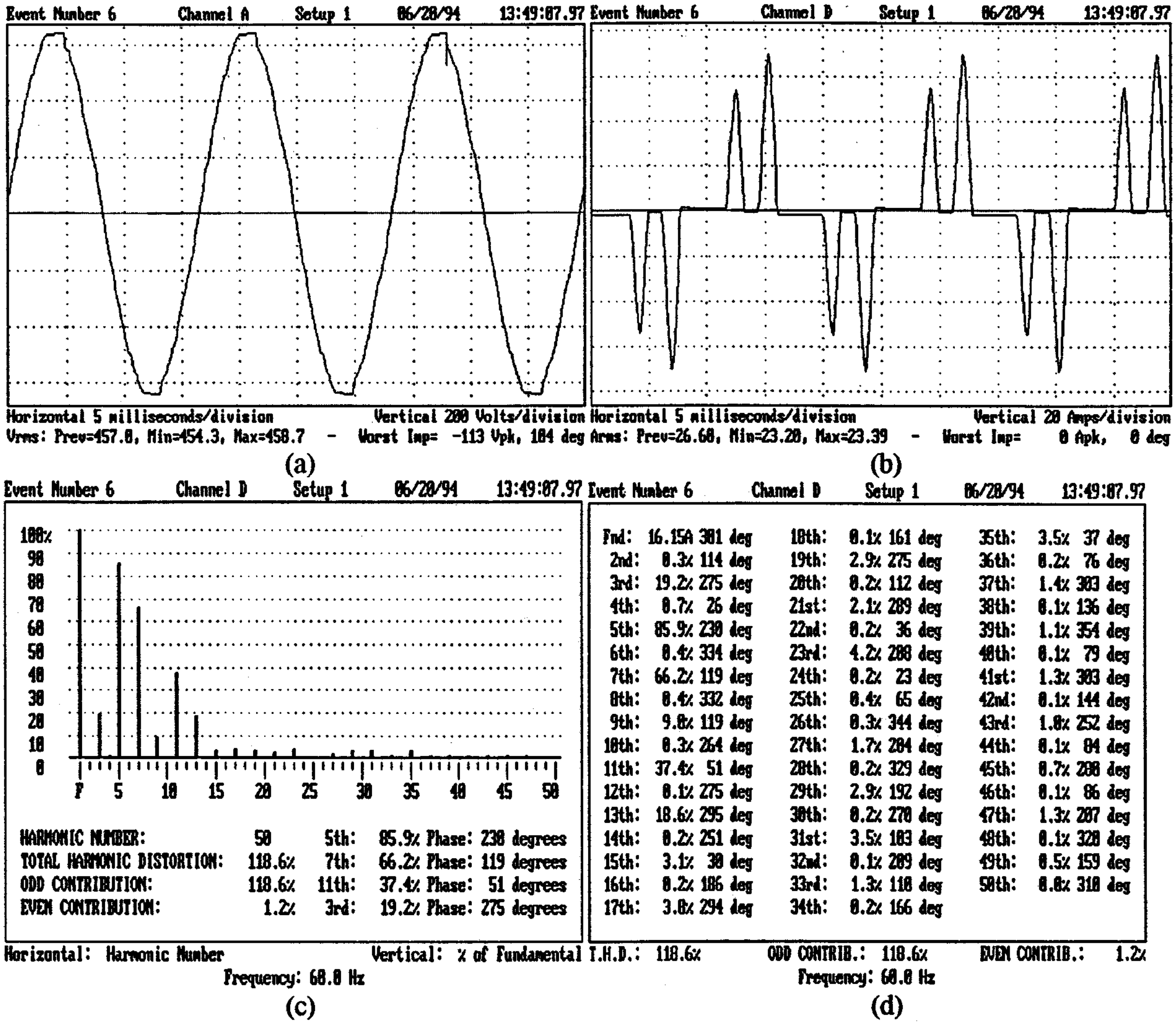
| | | | | | |
|---|---|---|---|---|---|
| Fnd: | 31.04A 123 deg | 18th: | 0.4% 122 deg | 35th: | 1.4% 237 deg |
| 2nd: | 1.9% 30 deg | 19th: | 4.2% 304 deg | 36th: | 0.3% 86 deg |
| 3rd: | 2.1% 140 deg | 20th: | 0.4% 286 deg | 37th: | 1.3% 270 deg |
| 4th: | 0.6% 194 deg | 21st: | 0.3% 348 deg | 38th: | 0.3% 262 deg |
| 5th: | 65.5% 92 deg | 22nd: | 0.2% 347 deg | 39th: | 0.2% 254 deg |
| 6th: | 1.0% 89 deg | 23rd: | 3.2% 303 deg | 40th: | 0.2% 208 deg |
| 7th: | 41.0% 353 deg | 24th: | 0.5% 113 deg | 41st: | 0.9% 212 deg |
| 8th: | 0.7% 309 deg | 25th: | 2.4% 283 deg | 42nd: | 0.1% 42 deg |
| 9th: | 0.6% 20 deg | 26th: | 0.3% 279 deg | 43rd: | 1.3% 263 deg |
| 10th: | 0.1% 152 deg | 27th: | 0.1% 307 deg | 44th: | 0.2% 183 deg |
| 11th: | 9.1% 14 deg | 28th: | 0.2% 356 deg | 45th: | 0.1% 232 deg |
| 12th: | 0.7% 90 deg | 29th: | 1.9% 277 deg | 46th: | 0.2% 304 deg |
| 13th: | 9.0% 332 deg | 30th: | 0.2% 85 deg | 47th: | 0.9% 195 deg |
| 14th: | 0.6% 286 deg | 31st: | 1.7% 266 deg | 48th: | 0.2% 66 deg |
| 15th: | 0.7% 34 deg | 32nd: | 0.3% 235 deg | 49th: | 1.1% 245 deg |
| 16th: | 0.3% 28 deg | 33rd: | 0.2% 339 deg | 50th: | 0.1% 170 deg |
| 17th: | 5.6% 332 deg | 34th: | 0.2% 319 deg | | |

T.H.D.: 79.4% ODD CONTRIB.: 79.4% EVEN CONTRIB.: 2.0%

Fig. 7. Case 1: 460 V, 80 kVA ASD. (a) $v_{ab}$. (b) $i_a$. (c) Line frequency spectrum for $i_a$. (d) Harmonic quantities in percent of the fundamental rms current, $I_a$.

Figs. 8 and 9 with a 0.3% and 3.75% voltage unbalance, respectively, on a 460 V, 30 kVA ASD [26]. Notice that as the ASD input voltage unbalance increases, the input current becomes significantly more unbalanced and changes from a double-pulse waveform to a single-pulse waveform (Fig. 9) due to the asymmetric conduction of the diodes. The voltage unbalance may cause excessive current in one or two phases, which can trip overload-protection circuits [27]. The increased current can also cause excess heating of the diodes and decrease the life of the capacitor or require the use of a larger capacitor. Table I gives a comparison of the three cases. Note the increase in the percent of the 3rd harmonic from 2.1% to 19.2% to 83.7% as the voltage unbalance increases. The significant 3rd harmonic can increase harmonic and resonance problems on the system as well as require larger filter ratings.

Fig. 10 shows an ASD with an active PWM rectifier, which is becoming more commonly offered among ASD manufacturers. Replacing the diode rectifier with an active PWM rectifier has



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Event Number 6        Channel D      Setup 1      06/20/94      13:49:07.97

  Fnd:  16.15A 301 deg     18th:   0.1% 161 deg     35th:   3.5%  37 deg
  2nd:   0.3% 114 deg      19th:   2.9% 275 deg     36th:   0.2%  76 deg
  3rd:  19.2% 275 deg      20th:   0.2% 112 deg     37th:   1.4% 303 deg
  4th:   0.7%  26 deg      21st:   2.1% 289 deg     38th:   0.1% 136 deg
  5th:  85.9% 230 deg      22nd:   0.2%  36 deg     39th:   1.1% 354 deg
  6th:   0.4% 334 deg      23rd:   4.2% 280 deg     40th:   0.1%  79 deg
  7th:  66.2% 119 deg      24th:   0.2%  23 deg     41st:   1.3% 303 deg
  8th:   0.4% 332 deg      25th:   0.4%  65 deg     42nd:   0.1% 144 deg
  9th:   9.0% 119 deg      26th:   0.3% 344 deg     43rd:   1.0% 252 deg
 10th:   0.3% 264 deg      27th:   1.7% 284 deg     44th:   0.1%  84 deg
 11th:  37.4%  51 deg      28th:   0.2% 329 deg     45th:   0.7% 208 deg
 12th:   0.1% 275 deg      29th:   2.9% 192 deg     46th:   0.1%  86 deg
 13th:  18.6% 295 deg      30th:   0.2% 270 deg     47th:   1.3% 207 deg
 14th:   0.2% 251 deg      31st:   3.5% 103 deg     48th:   0.1% 320 deg
 15th:   3.1%  30 deg      32nd:   0.1% 209 deg     49th:   0.5% 159 deg
 16th:   0.2% 186 deg      33rd:   1.3% 110 deg     50th:   0.0% 310 deg
 17th:   3.0% 294 deg      34th:   0.2% 166 deg

T.H.D.:  118.6%            ODD CONTRIB.:  118.6%          EVEN CONTRIB.:    1.2%
                          Frequency: 60.0 Hz
```

(d)

Fig. 8. Case 2: 460 V, 30 kVA, ASD with 0.30% line voltage unbalance. (a) $v_{ab}$. (b) $i_a$. (c) Line frequency spectrum for $i_a$. (d) Harmonic quantities in percent of the fundamental rms current, $I_a$.

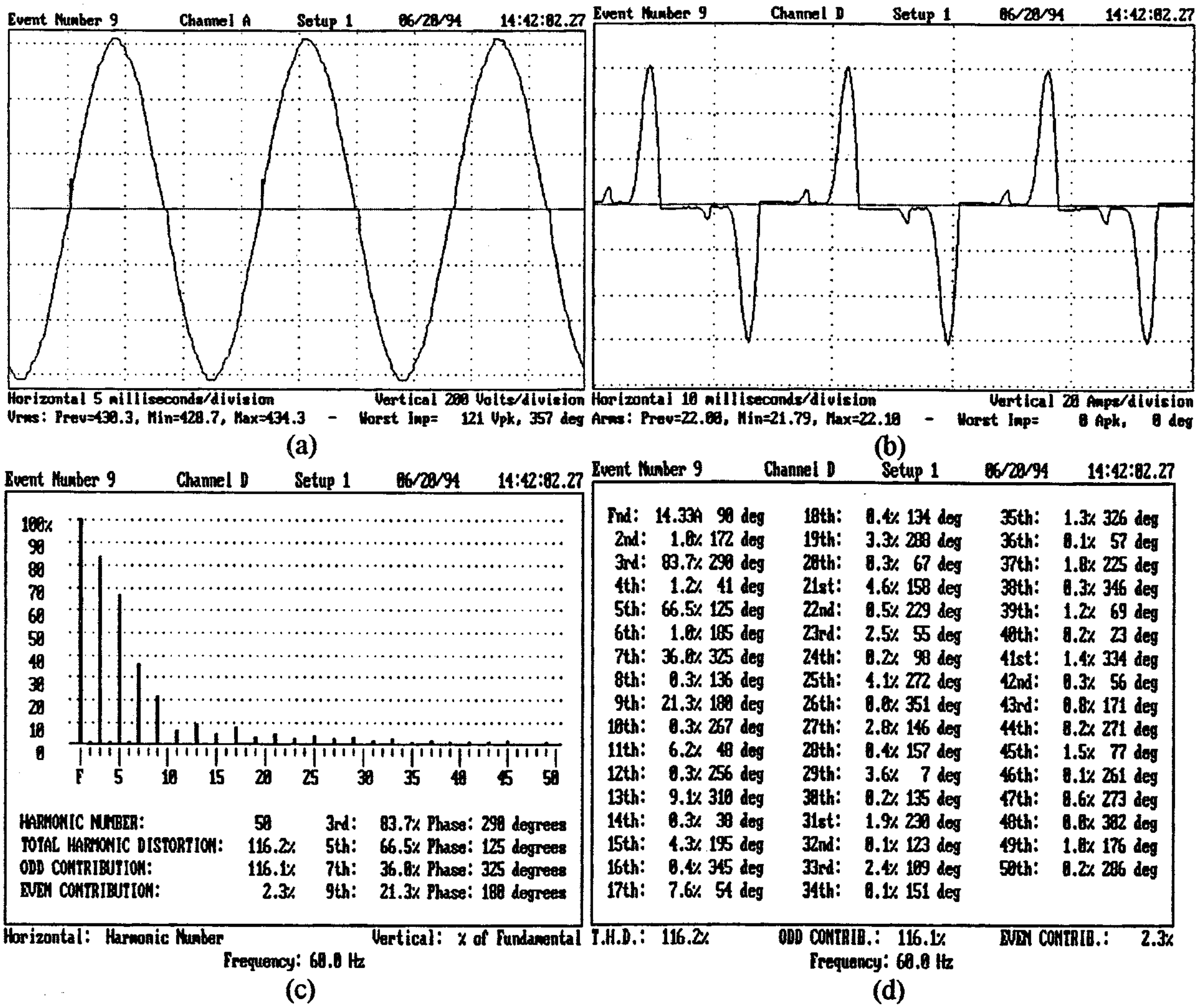
the following advantages: regulated dc-bus which offers immunity to voltage sags and transients; unity power factor with low input current harmonics (near sinusoidal) and compliance with IEEE 519 harmonic limits; power flow in both directions which enables regenerative braking. The effects of input voltage unbalance on PWM rectifiers include increased input current distortion, the generation of 120 Hz voltage ripple in the dc-link and an increase in reactive power [28]–[31].

## III. CURRENT STANDARDS ON VOLTAGE UNBALANCE

The American National Standards Institute (ANSI) standard C84.1-1995 "for Electric Power Systems and Equipment-Voltage Ratings (60 Hertz)," was developed by the National Electrical Manufacturers Association (NEMA). ANSI C84.1-1995 recommends that electrical supply systems should be designed and operated to limit the maximum voltage unbalance to 3% when measured at the electric-utility revenue meter under no-load conditions [16]. The International Electrotechnical Commission (IEC) recommends that the maximum voltage unbalance of electrical supply systems be limited to 2% [27].

Concurrently, NEMA, the developer of ANSI C84.1-1995, in the standard NEMA MG1-1993 "Motors and Generators" recommends that for voltage unbalance greater than 1%, induction motors should be derated by the appropriate factor given in Fig. 2. IEC standards also restrict the permissible voltage unbalance on induction motors to 1% and require a derating of the machines if unbalance is greater [14], [4]. The derating factor graph in Fig. 2 also appears in the ANSI/IEEE Std. 141-1993, "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants" (Red Book), and ANSI/IEEE Std. 241-1990, "IEEE Recommended Practice for Electric Power Systems in Commercial Buildings" (Gray Book). Both the Red Book and the Gray Book indicate that some electronic equipment, such as computers, may experience problems if the voltage unbalance is more than 2 or 2.5%. They both also state that in general, single-phase loads should not be connected to three-phase low voltage circuits supplying equipment sensitive to phase-voltage unbalance. Instead, a separate circuit should be used [32], [33].

The apparent contradiction in ANSI C84.1-1995 (allowing a 3% voltage unbalance on power systems) and the NEMA MG1-1993 (recommending motor derating in the presence of



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HARMONIC NUMBER:               50      3rd:  83.7% Phase: 290 degrees
TOTAL HARMONIC DISTORTION:  116.2%     5th:  66.5% Phase: 125 degrees
ODD CONTRIBUTION:           116.1%     7th:  36.0% Phase: 325 degrees
EVEN CONTRIBUTION:            2.3%     9th:  21.3% Phase: 100 degrees
```

```
Event Number 9        Channel D        Setup 1        06/20/94        14:42:02.27

 Fnd:  14.33A  90 deg      18th:  0.4% 134 deg      35th:  1.3% 326 deg
  2nd:   1.0% 172 deg      19th:  3.3% 280 deg      36th:  0.1%  57 deg
  3rd:  83.7% 290 deg      20th:  0.3%  67 deg      37th:  1.0% 225 deg
  4th:   1.2%  41 deg      21st:  4.6% 150 deg      38th:  0.3% 346 deg
  5th:  66.5% 125 deg      22nd:  0.5% 229 deg      39th:  1.2%  69 deg
  6th:   1.0% 185 deg      23rd:  2.5%  55 deg      40th:  0.2%  23 deg
  7th:  36.0% 325 deg      24th:  0.2%  90 deg      41st:  1.4% 334 deg
  8th:   0.3% 136 deg      25th:  4.1% 272 deg      42nd:  0.3%  56 deg
  9th:  21.3% 100 deg      26th:  0.0% 351 deg      43rd:  0.8% 171 deg
 10th:   0.3% 267 deg      27th:  2.0% 146 deg      44th:  0.2% 271 deg
 11th:   6.2%  40 deg      28th:  0.4% 157 deg      45th:  1.5%  77 deg
 12th:   0.3% 256 deg      29th:  3.6%   7 deg      46th:  0.1% 261 deg
 13th:   9.1% 310 deg      30th:  0.2% 135 deg      47th:  0.6% 273 deg
 14th:   0.3%  30 deg      31st:  1.9% 230 deg      48th:  0.0% 302 deg
 15th:   4.3% 195 deg      32nd:  0.1% 123 deg      49th:  1.0% 176 deg
 16th:   0.4% 345 deg      33rd:  2.4% 109 deg      50th:  0.2% 206 deg
 17th:   7.6%  54 deg      34th:  0.1% 151 deg

T.H.D.:  116.2%         ODD CONTRIB.:  116.1%         EVEN CONTRIB.:    2.3%
                         Frequency: 60.0 Hz
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Fig. 9. Case 3: 460 V, 30 kVA ASD with 3.75% line voltage unbalance. (a) $v_{ab}$. (b) $i_a$. (c) Line frequency spectrum for $i_a$. (d) Harmonic quantities in percent of the fundamental rms current, $I_a$.

TABLE I
COMPARISON OF VOLTAGE UNBALANCE CASES

| | Line Voltage Un-balance | RMS Input Current $I_a$ | 60 Hz rms Line Current $I_1$ | $I_3$ (% of $I_1$ ) | | $I_5$ (% of $I_1$ ) | | $I_7$ (% of $I_1$ ) | | THD | Input PF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | Amps | Amps | Amps | % | Amps | % | Amps | % | % | |
| Case 1 | - | 40.66 | 31.84 | 0.67 | 2.1 | 20.86 | 65.5 | 13.31 | 41.8 | 79.4 | .78 |
| Case 2 | 0.30 | 25.04 | 16.15 | 3.10 | 19.2 | 13.87 | 85.9 | 10.69 | 66.2 | 118.6 | .64 |
| Case 3 | 3.75 | 21.96 | 14.33 | 12.0 | 83.7 | 9.53 | 66.5 | 5.16 | 36.0 | 116.2 | .65 |

greater than 1% voltage unbalance) can be explained by the following rationalization. In developing the ANSI C84.1 recommendation for voltage unbalance, economic studies were conducted indicating the following [16]:

1) Ultimately, the customer ends up paying for the utility related costs required to reduce voltage unbalance, and the manufacturing related costs required to expand a motor's unbalanced voltage operating range,
2) Utilities' incremental improvement costs are maximum as the voltage unbalance approaches zero and decline as the unbalance is permitted to increase,
3) Manufacturers' incremental motor related costs are lowest at zero voltage unbalance and increase rapidly as the unbalance increases.

When these costs, excluding motor related energy costs, are combined, curves can be developed as shown in Fig. 11, that

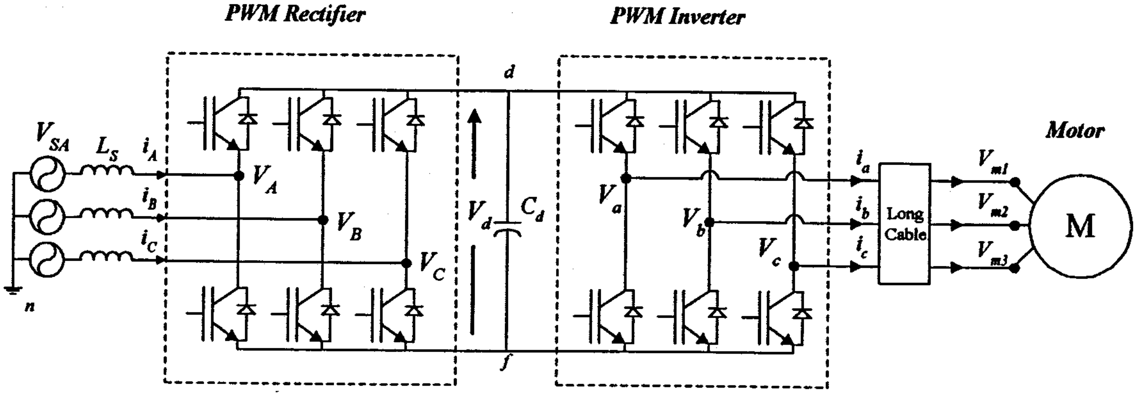

Fig. 10. ASD with PWM rectifier.

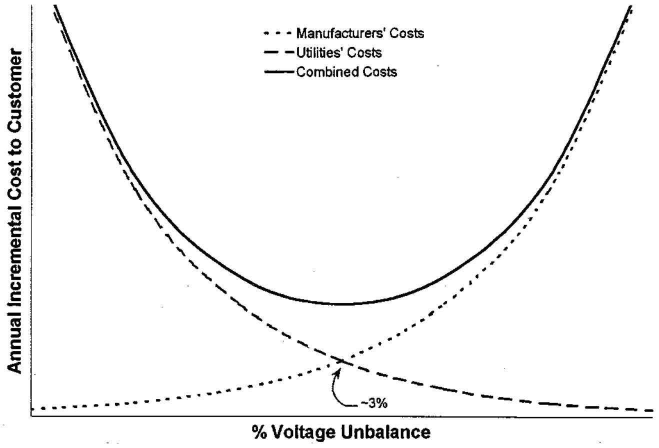

Fig. 11. Annual incremental cost to the customer for various percent voltage unbalance limits, showing minimum costs at approximately 3% voltage unbalance.

indicate the annual incremental cost to the customer for various percent voltage unbalance limits. The optimal range of voltage unbalance occurs when the cost to the customer is minimized, which is implied in ANSI C84.1 to be at approximately 3% voltage unbalance as shown in Fig. 11.

In a report to the Canadian Electrical Association (CAE) on voltage unbalance in distribution systems, Bergeron presents another commentary on the apparent contradiction in appropriate unbalance levels on power systems and in commercial and industrial facilities [3]. Until the 1970s, energy savings were not considered a significant design factor, as it is today, and computer-based assistance for designing power apparatus was unavailable. Consequently, older motor and equipment designs allowed much higher disturbance levels than can now be tolerated. Motor manufacturers and users are therefore calling for a power supply with a lower voltage unbalance level, which would allow them to operate with minimal derating, i.e., that lets them use the smallest motors possible. However, Bergeron indicates that due to the increased magnitude of single-phase loads including electric train and traction loads, voltage unbalance on the power distribution system is actually increasing, with the result that power distributors would like equipment to be able to tolerate a higher voltage unbalance [3].

## IV. MITIGATION TECHNIQUES

While several mitigation techniques have been suggested to correct voltage unbalance, maintaining an exact voltage balance on all three phases at the point of use is virtually impossible for the following reasons [27]:

- Single-phase loads are continually connected to, and disconnected from, the power system,
- Single-phase loads are not evenly distributed between the three phases,
- Power systems may be inherently asymmetrical.

Therefore, some voltage unbalance will be present in any type of low-voltage three-phase three-wire or three-phase four-wire system [11].

### *A. Mitigation Techniques on the Power System*

Unbalanced loads are the main cause of unbalanced voltages on distribution circuits and thus a great deal can be gained by attempting to distribute single-phase loads equally across all three voltage phases [1]. Electrical distribution systems can be balanced by changing the system configuration through manual and automatic feeder switching operations to transfer loads among circuits. This reconfiguration can be performed to reduce losses, and has the natural tendency to balance loading among circuits [15]. Several reconfiguration algorithms have been developed to optimize feeder switch positions using load estimation algorithms providing load information for each time point under analysis [15]. Since this is performed in a discrete manner, it cannot dynamically balance the system load.

Unbalanced impedances, including transformers and their connections, are often the next largest contributor to unbalanced voltages. Therefore, proper selection of distribution transformers is a very important step in preventing voltage unbalance, paying particular attention to the balancing of open wye and open delta transformer banks. It should also be noted that open wye-open delta banks can significantly magnify the voltage unbalance of the primary system as it converts primary system zero sequence voltage into secondary system negative sequence voltage [11]. If the amount of unbalance tends to vary with the customer load, it is a good possibility that the transformer is the cause of the unbalanced condition. One way to determine the transformer bank's contribution to voltage unbalance is to measure the voltages on the primary and the voltages on the secondary and calculate the percent unbalance at each point. A bank of three single-phase regulators can also provide some correction for unbalanced voltages, but the settings must be controlled carefully to prevent causing additional voltage unbalance.

In addition, overload conditions on the power system should always be corrected as soon as possible for a number of protection and safety reasons as well as unbalance compensation. Unbalance compensation can also be achieved by means of passive power filters that balance the load impedance [34], [35], where the load current is balanced by adding reactive elements in parallel to the load. For variable loads, voltage unbalance in ac supply systems can be corrected by means of a shunt connected thrysitor-controlled static VAR compensator [34]–[36], where again the load current is balanced by adding reactive elements in parallel to the load. Disadvantages include harmonic injection into the ac system.

A number of additional power electronic solutions have been reported in the literature [9][14][37]. For example, an active line conditioner was presented in [14] that dynamically corrects voltage unbalances through the injection of a correction voltage in one phase.

In years past, much attention was paid to transposing the conductors to keep the series inductive and the shunt capacitive reactances balanced on transmission lines. As the number of substations connected to transmission lines increased, it became impractical to have multiple transpositions between each station. In addition, transposed conductors increased confusion when addressing emergency fault situations. Thus, since the unbalance introduced by the incomplete transposition is not comparatively significant, modern power lines are seldom transposed, though an interchange in the positions of the conductors may be made at switching stations in order to balance the inductance of the phases more closely [38].

### B. Mitigation Techniques in a User Facility

First, within a user facility, all overloaded equipment should be corrected. In addition, passive power filters and shunt connected static VAR compensators, similar to those described in Section IV-A for mitigation on power systems, can be used for unbalance compensation in user facilities [34]–[36].

Mitigation of the adverse effects of unbalanced voltage on ASDs can be achieved through the use of properly sized ac-line and dc-link reactors as demonstrated in [39]. The test results showed that connecting both the ac-line and dc-link reactors to the ASD has the greatest effect on phase-current unbalance, reducing it by more than half. Either reactor alone was shown to be enough to significantly mitigate current distortion and reduce the rms line current, thus reducing the risk of overloading the ASD. Reactors will also improve the performance of PWM rectifier ASDs in unbalanced voltage conditions. In addition, modified PWM rectifier control strategies have been proposed to reduce the dc link ripple and input current distortion caused by unbalanced voltages [28]–[31].

Finally, along the lines of protection, the study by Cummings' provided methods employing various relays to protect induction motors from unbalanced voltages, where the relay settings and applications depend on the motor horsepower, loading, insulation class and service factor [40]. Lerley showed in [41] that negative sequence current relays are more reliable and effective because relays measuring negative sequence voltage can lack the necessary sensitivity in some system and load configurations.

## V. CONCLUSION

This paper has identified several causes of voltage unbalance and has described the resulting adverse effects on both the power system and on equipment such as induction motors and power electronic converters and drives. Standards addressing voltage unbalance were discussed and clarified, and several mitigation techniques were suggested to correct voltage unbalance problems. Finally, this paper has made apparent the importance of identifying potential unbalance problems, which can be accomplished through load flow studies or field measurements, and taking corrective action for the benefit of both the utility and customer.

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