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MARTIN,J.B. Region 5 (Post 820201)

SUBJECT: Forwards analysis of adverse thermal effects caused by harmonic current in electrical equipment & conductors,per NRC 901116 ltr.

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WILLIAM F. CONWAY
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161-03711-WFC/JST

January 18, 1991

Docket Nos. STN 50-528/529/530

Mr. John B. Martin
Regional Administrator, Region V
U. S. Nuclear Regulatory Commission
1450 Maria Lane, Suite 210
Walnut Creek, California 94596-5368

Reference: Letter from R. P. Zimmerman, NRC, to W. F. Conway, APS, dated November 16, 1990
Subject: Referral of a Concern Regarding Palo Verde Nuclear Generating Station

Dear Mr. Martin:

Subject: Palo Verde Nuclear Generating Station (PVNGS)
Units 1, 2 and 3
Analysis of the Effects of Triplen Harmonics on the PVNGS Electrical Distribution System
File: 91-056-026

Arizona Public Service (APS) has completed an analysis (copy attached) of the subject concern. The conclusions of this analysis were: (1) This phenomenon affects only three phase, four wire, wye connected circuits with significant nonlinear loads (e.g., computer facilities, arc furnaces, inverters, devices with switched mode power supplies). (2) The Class 1E electrical systems at PVNGS do not utilize this circuit arrangement. Therefore, the design of safety systems at PVNGS precludes the possibility of equipment damage due to this phenomenon and thus it is not a nuclear safety concern. (3) Although some of the non-Class 1E electrical systems utilize three phase, four wire, wye connected circuits, to date none of the equipment with this connection arrangement has shown any evidence of detrimental effects due to this phenomenon. (4) APS has the equipment and technical expertise in the maintenance and engineering departments to identify and correct any future problems attributable to harmonic currents.

Based on the above conclusions, APS does not consider that sufficient technical justification exists to initiate a monitoring program for this phenomenon, as suggested in the concern. The preponderance of evidence suggests that no potential concern for the effects of triplen harmonics on the PVNGS electrical distribution system currently exists and that PVNGS electrical systems are properly designed for the connected loads. Future installations will be in accordance with current codes and standards which, as evidenced by the 1990 National Electrical Code, are updated as new information is developed.

IE01

If there are any questions concerning this matter, please contact M. E. Powell of my staff at (602) 340-4981.

Sincerely,

WFC/JST/jst

Attachment

cc: J. B. Martin (w/attachment)
C. M. Trammell
D. H. Coe
A. H. Gutterman
A. C. Gehr

ANALYSIS OF ADVERSE THERMAL EFFECTS CAUSED BY HARMONIC CURRENTS IN ELECTRICAL EQUIPMENT AND CONDUCTORS AT PALO VERDE NUCLEAR GENERATING STATION

DESCRIPTION OF PROBLEM

Quality Concerns 90-081-01, 02, and 03 question whether Palo Verde design and maintenance adequately consider potential overheating of electrical equipment and conductors due to harmonic currents.

Nonlinear electrical loads can cause harmonic currents in their source conductors. These additional currents cause an increase in heat rise in the conductors and associated power distribution equipment. If the resulting temperature exceeds the thermal rating of the conductors or equipment, certain adverse effects can occur such as tripping of protective devices or equipment failure.

Nonlinear loads are those in which the current is not proportional to the source voltage, usually involving circuitry which causes pulsing of the input current. Common types of nonlinear loads are:

- Electric discharge lighting (e.g., certain types of fluorescent, mercury vapor, metal halide, and sodium fixtures)
- Equipment utilizing electronic power supplies (e.g., certain battery chargers, inverters, computers and photocopy machines)
- Welding machines
- Variable frequency motor controllers

Protective equipment (relays, circuit breakers, and fuses) would normally sense the total current, including the harmonic component, and, if at a dangerous level, deenergize the circuit, thus preventing thermal damage. However, a condition could exist in which the significant thermal effect of the harmonic current is on the unprotected neutral rather than on the protected phase conductors. In this scenario, the A, B, and C phase conductors of a 3-phase, 4-wire, wye-connected system each carry a harmonic load current whose magnitude is within the conductor and equipment ratings, below the protective device trip setpoint, and thus does not actuate the protective equipment. However, triplen harmonic[1] currents in the phase conductors have their return path through the neutral. These harmonic currents in the 3 phases can be additive in the neutral. Since protective devices are not normally applied to the neutral to detect thermal overloads, it is possible that the neutral current flow could exceed the neutral ampacity without initiating a circuit trip.

DESIGN CONCERNS

Standard design practice accounts for the effect of harmonic currents on neutral heating. It is sometimes permitted that the neutral conductor be smaller than the phase conductors, because it

1. An order of harmonic which is a multiple of three.

carries only the imbalance current from the A, B, and C phases which is subtractive for normal 60 Hz conditions. However, because of the additive characteristic of triplen harmonic currents in the neutral conductor, the 1990 National Electrical Code, paragraph 220-22, states: "There shall be no reduction of the neutral capacity for that portion of the load which consists of electric-discharge lighting, electronic computer/data processing, or similar equipment, and supplied from a 4-wire, wye-connected 3-phase system."

The National Electrical Code further states, in Note 10 of Ampacity Tables B-310-1 thru B-310-10: "On a 4-wire, 3-phase wye circuit where the major portion of the load consists of electric-discharge lighting, data processing, or similar equipment, there are harmonic currents present in the neutral conductor and the neutral shall be considered to be a current-carrying conductor [i.e., in regard to conductor sizing and derating]."

The National Electrical Code does not, in any case, require that the neutral conductor ampacity be greater than that of the phase conductors.

Trade journal articles written during the 1987-90 period have warned against the overloading of neutral conductors due to nonlinear loads. This concern was triggered by the advent of the Switching Mode Power Supply (SMPS) for computer systems supplied during the last few years. It can be shown that for a load that is totally made up of SMPSs, the RMS neutral current can reach 1.73 times the RMS phase current. This is due to the power supply current being rich in triplen harmonics. In spite of this neutral current theoretical maximum of 1.73 times the phase current, in practice this would be very rare as shown by a broad test survey reported in a 1989 IEEE paper.[2] This shows the results from 146 computer sites across the United States and concludes that there were sites where the neutral current exceeded 170% of the average phase currents, but the neutral current exceeded the rated full load current for only 5% of the sites in the survey. This points up the need to be aware of the type of load being served, and where switching mode power supplies are applied an increased neutral may need to be provided.

The Class 1E circuits at Palo Verde Nuclear Generating Station do not utilize a 3-phase, 4-wire, wye-connected arrangement, so they are not subject to the postulated scenario described above. Therefore, the design of the safety systems at Palo Verde precludes the possibility of equipment damage due to this particular phenomenon, and this issue therefore is not a nuclear safety concern.

The 3-phase, 4-wire, wye-connected circuits that are utilized at Palo Verde include lighting, heat tracing, and distribution for facilities such as cooling towers, administration buildings, and water treatment equipment, all of which are Non 1E. In most of these circuits, the neutral conductor is the same size as the phase conductors. Reduced neutrals have been used for a few circuits in outside areas such as cooling towers, administration buildings, and water reclamation facilities, but there is no evidence that this design is inadequate for the particular applications.

No evidence has been found to indicate that any equipment or conductor overheating has occurred on either 1E or Non-1E equipment or conductors at Palo Verde as a result of harmonic currents. Circuit and equipment characteristics conform to conventional design practices which have been used extensively throughout the industry for many years as governed by recognized codes and

2. "A Survey of Neutral Currents In Three-Phase Computer Power Systems," T. M. Gruzs, *Record of the 1989 Industrial and Commercial Power Systems Technical Conference*, pp. 114-122 (Attached).

standards, and the facilities do not contain a significant quantity of equipment which might utilize SMPSs, as would be the case in a dedicated computer facility.

MAINTENANCE CONCERNS

Most equipment and conductor overheating problems are caused by excessive circuit loading or equipment malfunction combined with improper sizing of fuses or circuit breakers. However, for circuits which serve nonlinear loads, the possibility exists that the problem is caused, instead, by excessive harmonic currents. Troubleshooting should take this possibility into account.

At Palo Verde, the expertise and equipment exist to properly assess the contribution of harmonic currents to equipment and conductor overheating. Maintenance organizations are increasingly utilizing RMS ammeters, such as Fluke #87-86 which provide an immediate indication of true RMS current magnitude, with or without harmonics. Problems which are not readily resolved by maintenance personnel are referred to site engineering organizations which have personnel who are cognizant of the technical issues and are capable of performing tests with equipment such as oscilloscopes and spectrum analyzers which can disclose the precise nature of the problem.

There are no known cases where problems of this nature have occurred at Palo Verde.

INDUSTRY EXPERIENCE

A query was issued over the Nuclear Network, requesting information from other plants regarding their experience with this phenomenon. One reply was received, from Southern California Edison, which stated that there have been no known problems of this type at San Onofre.

CONCLUSION

The preponderance of information indicates that Palo Verde electrical systems are properly designed, existing station maintenance and engineering organizations are capable of responding properly to any harmonic problems that might occur, and this issue does not represent a nuclear safety concern at Palo Verde.

H. Leake

H. Leake
1/7/91

J B Barrow, Jr. 1/14/91

A SURVEY OF NEUTRAL CURRENTS IN THREE-PHASE COMPUTER POWER SYSTEMS

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1989 Industrial & Commercial Power Systems Technical Conference Record

ABSTRACT

Neutral current in three-phase power systems is often thought to be only the result of the imbalance of the phase currents. With computer systems, very high neutral currents have been observed even when the phase currents are balanced. Measurements from a sample of computer power systems in the United States are presented to determine the extent of the neutral current problem. This paper explores the cause of high neutral currents in three-phase computer power systems, potential problems, and recommended remedies.

INTRODUCTION

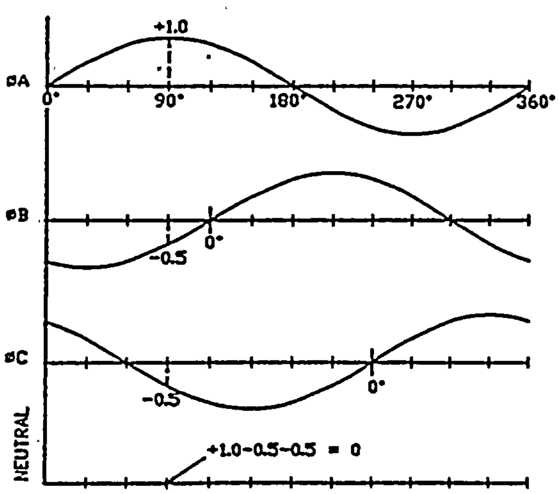
On three-phase wye power systems, neutral current is the vector sum of the three line-to-neutral currents. With balanced, three-phase, linear currents, which consist of sine waves spaced 120 electrical degrees apart, the sum at any instant in time is zero, and so there is no neutral current (see Figure 1). In most three-phase power systems supplying single-phase loads, there will be some phase current imbalance and some neutral current. Small neutral currents resulting from slightly unbalanced loads do not cause problems for typical building power distribution systems.

There are conditions where even perfectly balanced single phase loads can result in significant neutral currents. Nonlinear loads, such as rectifiers and power supplies, have phase currents which are not sinusoidal. The vector sum of balanced, non-sinusoidal, three-phase currents does not necessarily equal zero. For example, balanced square wave currents will result in significant neutral current (see Figure 2).

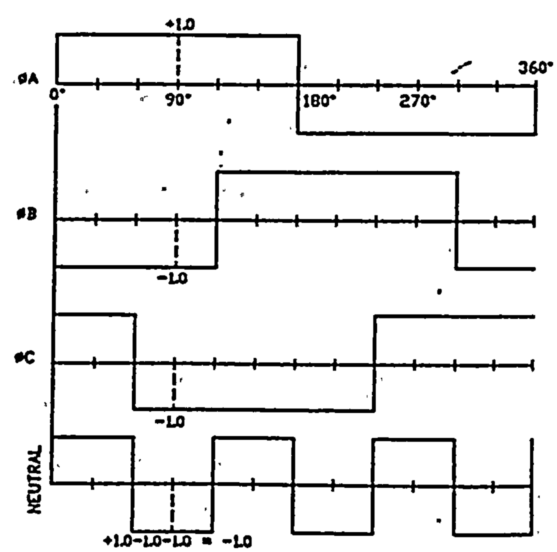
In three-phase circuits, the triplen harmonic neutral currents (third, sixth, ninth, etc.) add instead of cancel. Being three times the fundamental power frequency and spaced in time by 120 electrical degrees based on the fundamental power frequency, the triplen harmonic currents are in phase with each other and so add in the neutral circuit (as shown in Figure 3).

Computer loads are generally nonlinear loads. The typical current waveform and harmonic content of the two popular computer power supply connections are shown in Figure 4 and given in Table 1. The current of typical line-to-line connected power supplies contains no triplen harmonics. However, the typical current of line-to-neutral connected power supplies is very rich in triplens. For balanced line-to-neutral power supplies as described in Table 1, the neutral current would be 1.61 times the phase current. Under worst-case conditions with rectifier conduction angles of 30°, the neutral current could be 1.73 times the phase current. Therefore, when line-to-neutral connected power supplies are used on three-phase power systems, significant neutral current can be expected.

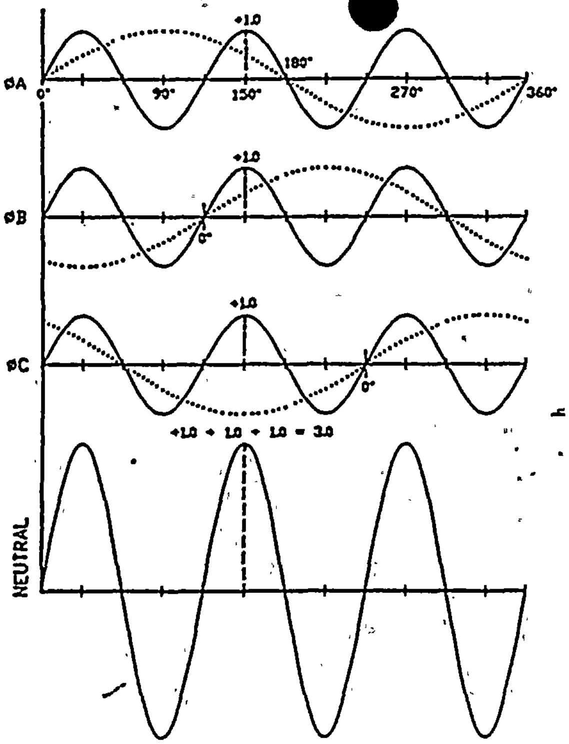
Recent trends in computer systems have increased the likelihood of significant neutral currents. There has been a shift from three-phase power supplies to single-phase power supplies. The development of switched-mode power supplies, with their advantages of improved efficiency and lower cost, have also increased the triplen harmonic content of the current waveform over the previous linear power supplies. Switched-mode power supplies are connected directly to the line-to-neutral voltage without a stepdown transformer. The stepdown transformer used with linear



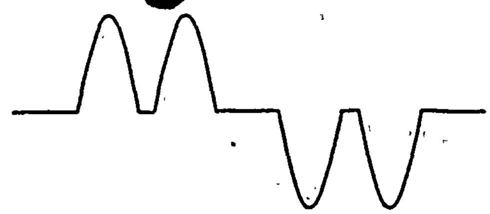
BALANCED LINEAR 3-PHASE LOADS RESULT IN ZERO NEUTRAL CURRENT
Figure 1



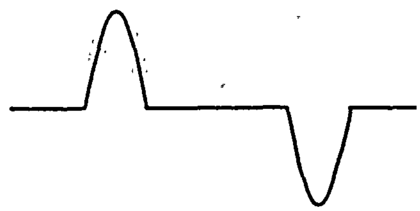
EXAMPLE OF BALANCED NON-SINUSOIDAL 3-PHASE LOADS HAVING NEUTRAL CURRENT
Figure 2



THIRD HARMONIC CURRENTS IN THREE-PHASE POWER SYSTEMS
Figure 3



TYPICAL LINE-TO-LINE CONNECTED POWER SUPPLY LINE CURRENT WAVEFORM



TYPICAL LINE-TO-NEUTRAL CONNECTED POWER SUPPLY LINE CURRENT WAVEFORM
Figure 4

power supplies reduces the triplen harmonic currents because of its series inductance and because it allows connection to the line-to-line voltage.

Another trend in computer systems is the shift from AC motors with linear input currents to DC motors having nonlinear input currents for such uses as fans, tape drives and disc drives. DC motors require power supplies with similar characteristics as other computer power supplies. The increased use of DC motors therefore has increased the harmonic current distortion of the total computer system.

PROBLEMS OF HIGH NEUTRAL CURRENT

High neutral currents in computer power systems can cause overloaded power feeders, overloaded transformers, voltage distortion, and common mode noise.

Three-phase, four-wire building power feeders are often sized based on three current-carrying conductors in a conduit in accordance with the National Electrical Code (NEC) [1] Table 310-16. When the neutral conductor carries harmonic currents, additional heat is generated and the ampacity of the power feeder is reduced. With four current-carrying conductors, the ampacity of the power feeder is derated to 80% of the three-current-carrying-conductor rating in accordance with NEC Table 310-16 Notes 8 and 10. Neutral conductors, which are usually sized the same as the phase conductors, can be overloaded since the neutral current can exceed the rated phase current.

Table 1
TYPICAL COMPUTER POWER SUPPLY HARMONIC CURRENT COMPONENTS

HARMONIC	LINE-TO-LINE POWER SUPPLY	LINE-TO-NEUTRAL POWER SUPPLY
h		
1	0.82	0.65
3	—	0.52
5	0.49	0.42
7	0.287	0.29
9	—	0.13
11	0.074	0.12
13	0.033	0.098
Total Phase Current = $\sqrt{\Sigma i_h^2}$ =	1.00	1.00
Neutral Current $\sqrt{i_3^2 + i_9^2}$ =	0.0	1.61
Ratio of Neutral Current to Total Phase Current =	0.0	1.61

The triplen harmonic currents which add in the neutral conductor are canceled in a delta–wye transformer. The triplen currents flow as circulating currents in the transformer's delta primary. As a result, more current flows in the primary windings (causing additional heating) than is detected by the transformer's primary circuit overcurrent protection device. Overloading of the transformer can result.

Because the power supplies which produce the harmonic neutral currents have high peak–to–RMS current waveforms, the voltage waveform can become distorted. "Flat–topping" of the waveform can result due to the impedance of the power system at the harmonic current frequencies. Since the power supplies use the peak voltage of the sine wave to keep the capacitors at full charge, reductions in the peak voltage appear as low voltage to the power supply even though the RMS of the voltage may be normal. The waveform distortion can also cause additional heating in motors and other magnetic devices which are operated from the same (distorted) voltage source.

One form of common mode noise in three–phase power systems is the voltage difference between neutral and ground. With high harmonic neutral currents, the impedance of the neutral conductors at the harmonic frequencies can cause significant neutral conductor voltage drops. The neutral conductor voltage drop appears as common mode noise to the computer system (see Figure 5). The effect of these relatively low frequency common mode noise voltages on the computer system is somewhat debatable, yet computer vendor specifications typically call for less than 0.5 to 3 volts RMS, neutral to ground, regardless of frequency.

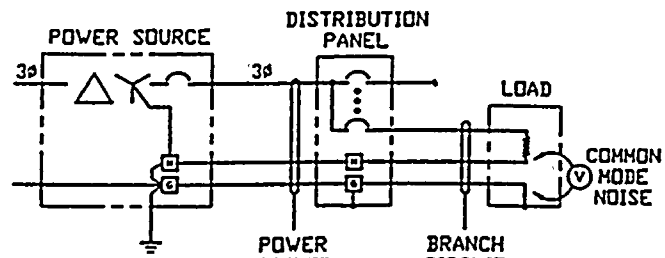
COMPUTER LOAD CURRENT SURVEY

While it has been recognized that high neutral current in computer power systems is a potential problem, the extent of the problem in today's computer power systems has not been determined. To determine the extent of the neutral current problem, a survey of computer power system load currents was taken across the United States with a variety of computer vendors' equipment.

The survey was conducted in two parts. First, ten sites were visited and detailed harmonic current measurements were taken to verify that simplified current measurements used in the second part of survey would yield the desired information. The second part of the survey included measuring only the RMS voltages and currents, and recording site data such as location, computer vendor, and rated system capacity.

The survey data collection was kept simple as a matter of practicality to allow a larger number of sites to be surveyed. Liebert Customer Service Engineers collected the data during their normal visits to computer sites across the country. This method of sampling introduces some bias since only computer sites having Liebert power centers, power conditioners, or UPS systems are included. However, the bias would not be expected to be too substantial since computer systems from over 30 different vendors were included in the survey.

Survey data was collected from over 195 sites across the United States during the period of April to December, 1988. After excluding incomplete measurements, 480 volt systems, and 400 Hz systems, 146 sites were included in the survey results.



COMMON MODE NOISE IN A THREE PHASE POWER SYSTEM
Figure 5

The survey does not include conventional building wiring systems, modular office wiring systems, and other non–data processing areas (for definition of data processing areas, see NFPA75–1987 [2]) where computer equipment and other non-linear loads may cause significant neutral currents.

To evaluate the extent of the computer system neutral current problem, the following information was deemed to be of interest:

1. The ratio of average load to rated system capacity (percent capacity).
2. The ratio of neutral current to average phase current.
3. The ratio of neutral current to rated full load current.
4. The ratio of neutral triplen harmonic current to average phase current.
5. The ratio of neutral triplen harmonic current to rated full load current.

Items 1, 2, and 3 are straightforward calculations directly from the survey data (RMS voltages, RMS phase and neutral currents, and rated system capacity). Items 4 and 5 are of interest because they indicate the extent of the harmonic neutral current problem by excluding neutral current which is the result of simple phase current imbalance, a problem which can usually be readily corrected by better balancing of the loads.

A rigorous mathematical analysis indicates that if only the RMS phase and neutral currents are known, the exact harmonic content of the neutral current cannot be determined. However, a practical approximation of the harmonic content of the neutral current can be made by assuming that the fundamental and all non–triplen harmonics exist in the neutral according to the RMS phase current imbalance and that all neutral current in excess of the phase current imbalance is due to triplen harmonics. Implicit in this approximation is the assumption that the phase angles of harmonic currents of the same frequency are approximately the same.

$$\text{Neutral Current Due to Phase Current Imbalance} = \sqrt{A^2+B^2+C^2-(AB)-(BC)-(CA)}$$

$$\text{Neutral Current Due to Triplen Harmonics} = \sqrt{N^2-(A^2+B^2+C^2-(AB)-(BC)-(CA))}$$

Where: A = Phase A RMS Current
B = Phase B RMS Current
C = Phase C RMS Current
N = Neutral RMS Current

Table 2
COMPARISON OF MEASURED VS.
CALCULATED NEUTRAL TRIPLEN CURRENT

RMS CURRENTS				NEUTRAL TRIPLEN CURRENT		
A	B	C	N	MEAS.	CALC.	% ERROR
189A	193A	209A	110A	108.6A	108.5A	− 0.1%
166A	149A	164A	115A	110.6A	113.9A	+ 3.0%
292A	286A	277A	81A	77.3A	79.9A	+ 3.4%
188A	231A	145A	137A	111.6A	115.0A	+ 3.0%
174A	191A	146A	66A	47.8A	53.0A	+ 10.9%
127A	70A	115A	176A	165.7A	168.2A	+ 1.5%
143A	164A	187A	120A	100.8A	113.8A	+ 12.9%
226A	225A	224A	223A	220.6A	223.0A	+ 1.1%
19A	24A	17A	9A	6.8A	6.5A	− 4.4%
120A	127A	120A	23A	21.8A	21.9A	+ 0.5%

The data from the ten sites where detailed harmonic currents were measured is summarized in Table 2. Since there is a good correlation of the measured neutral triplen currents with the calculated neutral triplen currents, it was decided that the practical approximation was valid.

RESULTS

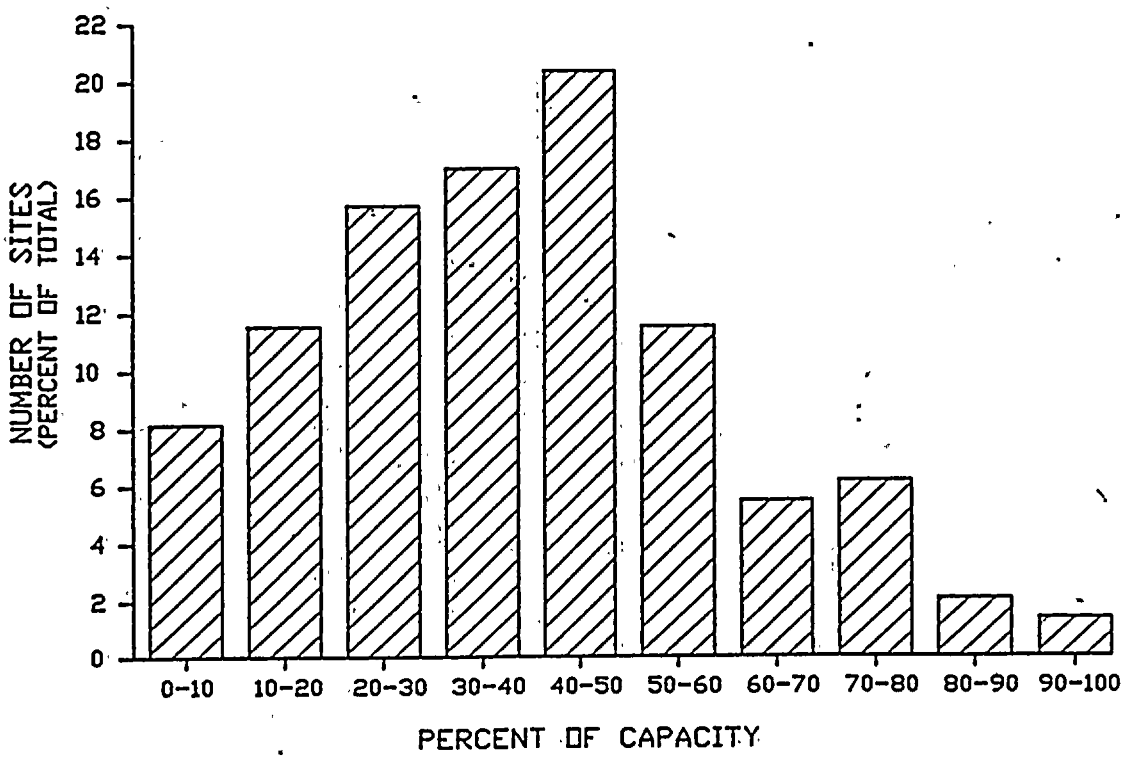
Figures 6 to 10 summarize the results of the survey.

Figures 6 shows the distribution of the present computer system load (KVA) compared to the rated power system capacity (nameplate KVA) in percent capacity. The distribution appears to be fairly normally distributed about a mean (average) of 39% capacity with a standard deviation of 22.6%. The median is 38.5% capacity with a range of 3.5% to 101% capacity.

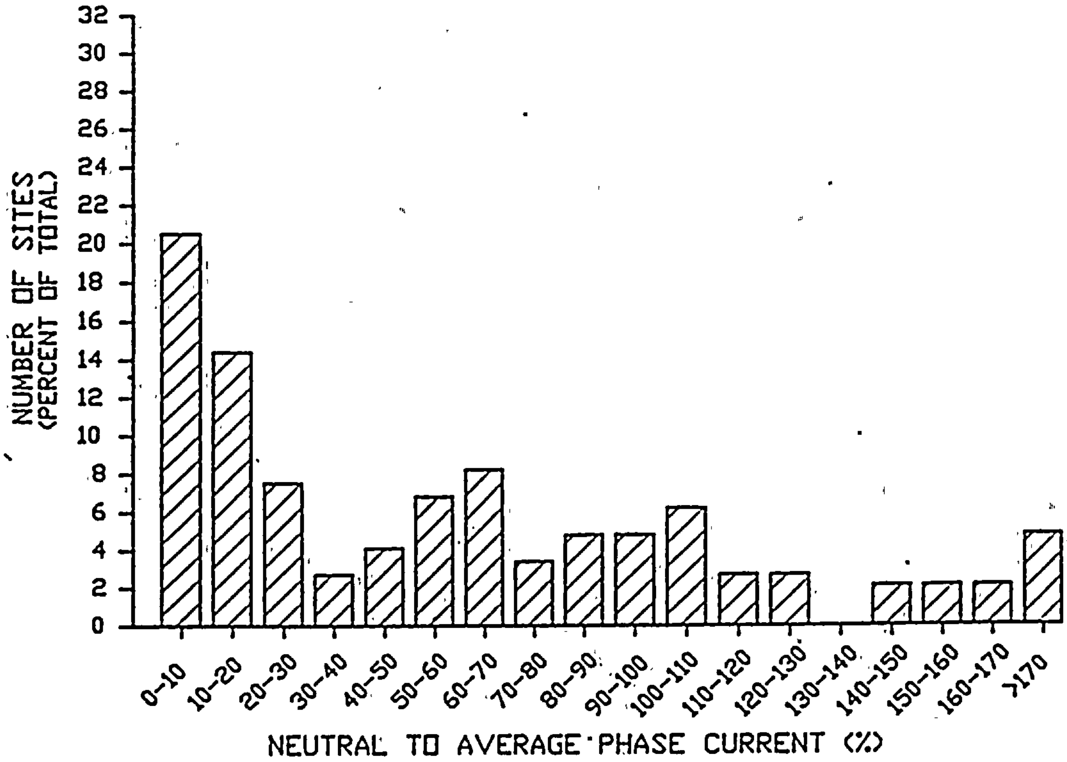
Figure 7 shows the distribution of the ratio of neutral current to the average of the phase currents in percent. The distribution is not normally distributed and has a mean of 60%, median of 50%, and a range of 0% to 244%. There are a large cluster of sites having less than 25% neutral current. 22.6% of the sites had neutral current in excess of 100% of the phase current. High ratios of neutral current to average phase current were the result of both severe phase imbalance and triplen harmonic currents.

Figure 8 shows the distribution of the ratio of neutral current to rated system full load current. This distribution reflects the combination of the distributions of Figures 6 and 7. Since the average computer power system is relatively lightly loaded, even high neutral–current–to–phase current ratios result in low neutral–current–to–rated–full–load–current ratios. The mean is only 22.4% with a median of 10.8% and a range of 0% to 147%. Only 3.4% of the sites had neutral current in excess of the rated phase current (greater than 100%).

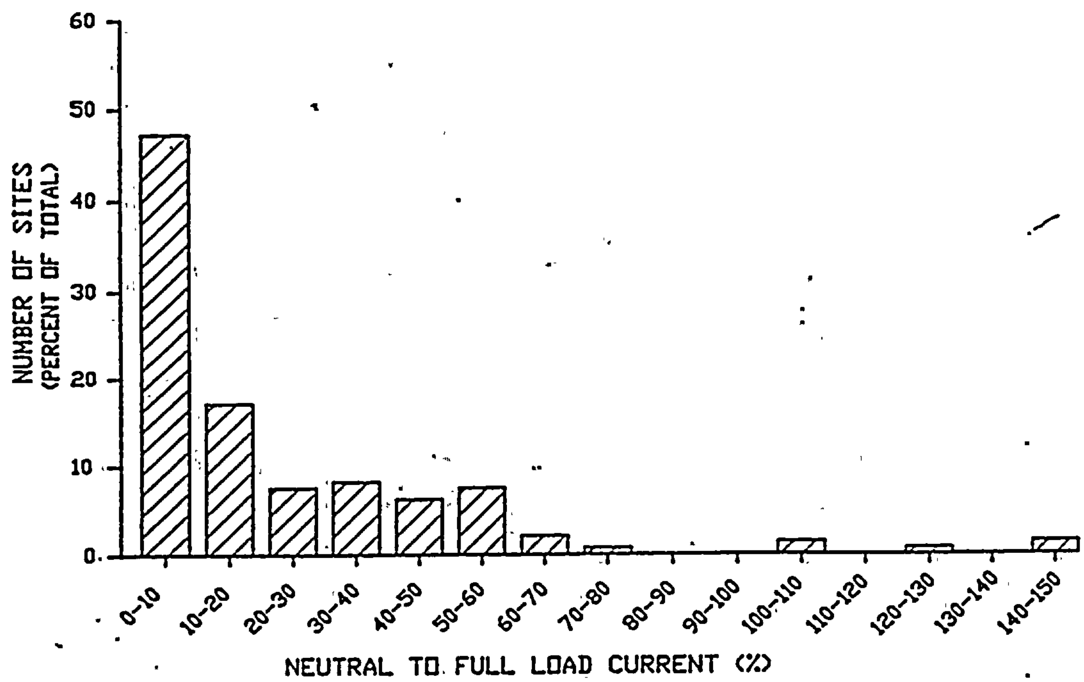
Figure 9 shows the distribution of the ratio of neutral triplen harmonic current to the average of the phase currents. This ratio is the same as the distribution in Figure 7 except that the effect of any phase current imbalance has been removed, and allows the evaluation of the harmonic neutral current problem by itself. The mean is 45.8% with a median of 31% and a range of 0% to 173%.



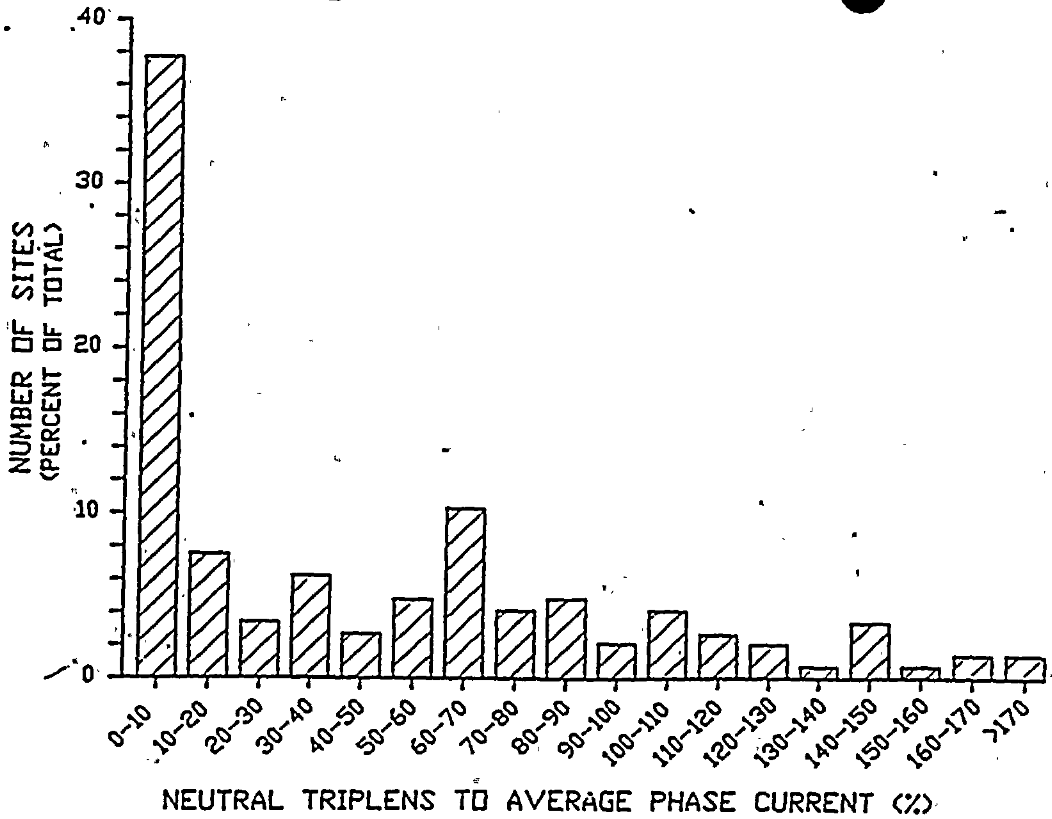
PRESENT COMPUTER SYSTEM LOAD
Figure 6



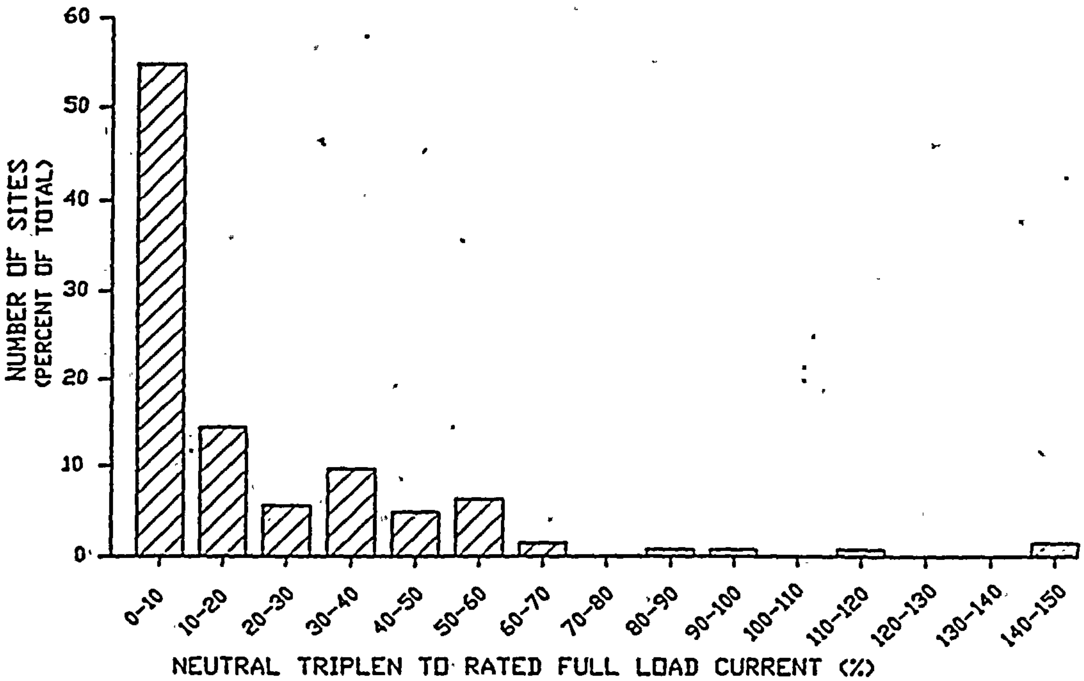
NEUTRAL CURRENT COMPARED TO AVERAGE PHASE CURRENT
Figure 7



NEUTRAL CURRENT COMPARED TO RATED SYSTEM FULL LOAD CURRENT
Figure 8



NEUTRAL TRIPLEN HARMONIC CURRENT
COMPARED TO AVERAGE PHASE CURRENT
Figure 9



NEUTRAL TRIPLEN HARMONIC CURRENT
COMPARED TO RATED SYSTEM FULL LOAD
CURRENT
Figure 10

Figure 10 shows the distribution of the ratio of neutral triplen harmonic current to the rated system full load currents. This distribution is the same as Figure 8 except that the effect of any phase current imbalance has been removed. The mean is 18.6% with a median of 7% and a range of 0% to 146%. Only 2.7% of the sites surveyed had neutral triplen currents in excess of the rated system full load current.

Significant phase current imbalance was observed in about half of the sites. The significance of the unbalance can be seen in the difference between Figures 7 and 9, where the average was reduced by 14.2 points (-23.7%), and Figures 8 and 10, where the average was reduced by 3.8 points (-17%).

CONCLUSIONS

While very high neutral currents are possible in three-phase computer power systems, a very low percentage of data processing sites in the US are actually experiencing neutral currents in excess of the rated full load current (see Figure 8). However, most systems operate at less than half of the rated load (see Figure 6). As the systems are more fully loaded, more sites would be expected to experience neutral current in excess of the rated full load current. Even if all sites were operated at rated full load, 22.6% of the sites would be expected to have neutral current greater than the full load phase currents (see Figure 7). If the loads are able to be better balanced, then the number of sites expected to experience high neutral currents because of triplen harmonic currents would be significantly lower (see Figures 9 and 10). Recent trends in computer systems, including the increased use of line-to-neutral switched mode power supplies, are expected to increase the percentage of sites having high neutral current as older computer systems are replaced.

It should be noted that this survey does not include building wiring systems, modular office wiring systems, etc. which also supply power to computers and other electronic loads. High neutral currents and the resulting problems have also been observed in these systems. It is arguable that the harmonic neutral current problem is potentially a greater hazard in these systems because the system design did not anticipate high neutral currents and the system loading is less controlled due to a lack of monitoring. The first indication of high neutral current is often a failed component.

RECOMMENDED REMEDIES

Observations of computer power systems have indicated harmonic neutral currents from nearly zero (with predominately line-to-line power supplies) to 1.73 times the phase current (with predominately line-to-neutral power supplies). Even though the majority of computer power systems today do not have significant neutral currents, changes made to the computer system may produce high neutral currents. Therefore, for safety, high neutral currents should be considered in the design of all three-phase computer power systems.

All four-wire, three-phase power feeders or branch circuits for computer systems should be designed to accommodate neutral currents up to 1.73 times the phase current. The wiring ampacities should be calculated considering the neutral to be a current-carrying conductor. For four-wire, three-phase circuits in a conduit or raceway, the ampacity should be derated to 80% of the three-conductor-in-a-conduit ampacity (reference NEC Table 310-16 Notes 8 and 10).

One proposed method of dealing with the potentially high neutral currents involves using full-sized neutral wiring and monitoring the neutral current. The neutral conductor would be treated like other circuit conductors with the load on the system intentionally limited to keep from overloading the neutral conductor(s). This method is generally recommended since it can be applied to new as well as existing installations.

Another proposed method, which ensures adequate neutral wiring ampacity for any possible load condition, is to size the neutral conductor for 1.73 times the phase conductor ampacity. When the conductors are #1/0 AWG or larger, parallel neutral conductors each sized the same as the phase conductors can be used (reference NEC Article 310-4 which limits parallel circuit conductors to #1/0 or larger). In this way, double the neutral ampacity is provided. For example, 3-#2/0 phase wires, 2-#2/0 neutral wires, and a ground conductor in a conduit would be suitable for a 140 amp computer power system feeder with up to 280 amps of neutral current.

All neutral components, including neutral terminals and neutral busbars, should be sized for the additional neutral current. Often, with standard electrical systems, oversizing of the neutral components is not practical, such as with panelboard assemblies with neutral accessories. The panelboard manufacturer may not allow a larger (non-standard) neutral accessory to be used. In these cases, the maximum loading on the phases must be limited to prevent overloading the neutral components. In the case of a 225 amp panelboard with a 225 amp neutral accessory, assuming the worst case of neutral current's being 1.73 times the phase current, the loading on the panelboard phases must be limited to 130 amps (225/1.73) to ensure that the neutral current will be less than 225 amps.

For branch circuits, a separate neutral conductor should be used for each circuit. The widespread practice of using a common neutral for multiple branch circuits should be avoided. Good practice for computer systems is to use a dedicated branch circuit (in its own conduit or raceway) for each load to minimize interaction between loads.

The loading on the three phases should be kept as balanced as possible. In this way, neutral current in excess of the triplen harmonic current is minimized. Whenever changes are made to the computer system, the phase current balance should be checked.

A delta-wye transformer or other delta-wye power source should be located as close to the computer loads as practical to cancel the triplen harmonic neutral currents and to minimize the length of the output power feeders and branch circuits. In this way, common mode noise at the loads and the effect of neutral current are minimized. For best results, the transformer and branch circuit distribution should be combined, such as in a computer power center. The transformer should be of a three-legged common core construction to provide the best path for the circulating triplen harmonic currents. Individual (single-phase) transformers connected for three-phase operation (as is common practice for building transformers) should not be used with computer systems because they do not provide a low impedance path for the circulating triplen harmonic currents.

The loading of the transformer with nonlinear loads requires additional considerations. Most transformers are designed for linear loads with a peak current of 1.414 times the RMS current. With nonlinear loads, the maximum loading of the transformer should be reduced to less than nameplate capacity to avoid overheating the transformer and to avoid causing excessive output voltage distortion.

One proposed derating method for standard transformers is to base the transformer's capacity with nonlinear loads on the nominal peak current with linear loading. For example, with nonlinear loads having a crest factor of 2.5 and linear loads having a crest factor of 1.414, the nonlinear capacity of the transformer would be 56.6% of nameplate capacity (1.414/2.5).

Another proposed derating method for computer power system transformers is to limit the neutral current to the rated full load phase current. For computer systems with a ratio of neutral current to phase current of 1.5, the nonlinear capacity would be 66.7% of nameplate capacity (1/1.5). For the worst-case harmonic neutral current of 1.73 times the phase current, the nonlinear capacity would be 57.7% of nameplate capacity (1/1.73).

ANSI/IEEE C57.110-1986 Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents [3] provides two methods to establish the maximum capacity of a power transformer when the harmonic content of the load current is known. One method uses the design eddy current loss data while the other method estimates the eddy current loss using the DC winding resistances and total power loss data. For typical computer power system transformers in the range of 15 to 225 KVA, using the DC winding resistances and total power loss data, the calculated maximum per unit winding eddy current loss at rated load (max. Pec-r) is in the range of 1.0 to 3.0. Table 3 shows the calculated transformer nonlinear load capacities (in percent of rated capacity with linear load) for the two nonlinear loads described in Table 1 and for two typical computer systems with currents having 42% and 23% total harmonic distortion (THD). The calculated deratings according to ANSI/IEEE C57.110-1986 appear to be quite conservative since the survey includes systems operating in excess of these calculated nonlinear load capacities without observed problems.

The design of a computer power system transformer could be altered to improve its ability to supply nonlinear currents. However, oversizing (or derating) the transformer is often a more practical and less costly approach. Generally, power systems dedicated for computer loads are recommended to be operated at less than 80% capacity to lower the stress on all components and improve performance and reliability. Where a high concentration of line-to-neutral power supplies exist, it is recommended that the transformer loading be limited to less than 50 to 60% of nameplate capacity. The reduced loading on the transformer is required to prevent overloading of the transformer as well as to control the amount of voltage distortion caused by the nonlinear loads.

The overcurrent protection of transformers feeding computer systems require additional considerations. The NEC allows primary-only overcurrent protection as long as the primary overcurrent protection does not exceed 125% of the transformer full load amps. Because the triplen harmonic load currents circulate in the delta primary windings of the transformer, the transformer input KVA can be less than the output KVA. The transformer can be damaged by overload without tripping the primary overcurrent protection device. For better protection of transformers feeding computer systems, secondary overcurrent protection should be used to detect the actual KVA loading on the transformer. The recommended supplemental overcurrent protection of computer power transformers uses temperature sensors in the transformer windings which detect the actual transformer loading, as well as the additional heating effects of the harmonic currents. The temperature sensors can be used to sound an alarm and/or shut down the system before damage to the transformer occurs.

Computer power centers (power distribution units) are the recommended method to supply power to computer/data processing areas [4]. The power center uses an isolation transformer or other power conditioning technology to provide a controlled power and computer grounding system, thereby minimizing common mode power disturbances. Power centers from reputable manufacturers are proven designs which accommodate nonlinear loads and high harmonic neutral currents of modern data processing systems. The power center design should follow the previously mentioned recommended remedies. Power centers are better able to

Table 3
ANSI / IEEE C57.110-1986
TRANSFORMER NONLINEAR LOAD CAPACITIES

TYPE OF LOAD	CURRENT THD	$\sqrt{\Sigma I_h^2}$	$\sqrt{\Sigma I_h^2 h^2}$	MAX. Pec-r (PER UNIT)	CALC. CAPACITY (% OF RATING)
Line-to-Line Power Supplies	70%	1.49	17.65	1.0 - 3.0	39% to 33%
Line-to-Neutral Power Supplies	116%	2.34	31.28	1.0 - 3.0	37% to 31%
Typical Observed Computer Systems	42%	1.18	4.79	1.0 - 3.0	63% to 55%
	23%	1.05	2.25	1.0 - 3.0	80% to 73%

supply computer loads than comparable building power systems. Power centers are typically designed for use in up to 40°C ambients while the data processing room temperature is usually less than 25°C. Most power centers are designed for convection cooling while most data processing areas use pressurized raised floor cooling systems which effectively provide forced-air cooling for the power center, thereby reducing component operating temperatures and providing greater design safety margins. Temperature sensors for alarm and shutdown are included in the power center to provide supplemental protection of the transformer from inadequate cooling, overload, or the effects of nonlinear loads. Monitoring systems are often included in the power center to provide annunciation and display of parameters and alarm conditions. The power center capacity and neutral current are readily available to operating and maintenance personnel which helps prevent accidental system overloading.

SUMMARY

The magnitude of the neutral current in three-phase computer power systems depends on the harmonic content and phase balance of the load currents. While very high neutral currents are possible due to the additive nature of triplen harmonic currents, a low percentage of data processing sites in the US are actually experiencing neutral currents in excess of the rated phase current. However, recent trends in computer systems make high harmonic neutral currents more likely. Power system problems associated with high harmonic neutral currents include overloaded four-wire power feeders and branch circuits, overloaded transformers, voltage distortion, and common mode noise. Whenever three-phase, wye power systems are used to supply power to computer systems or other similar electronic loads, the power system design should allow for the possibility of high harmonic neutral current to avoid potential problems.

REFERENCES

[1] National Electrical Code, NFPA 70-1987, National Fire Protection Association, Quincy, MA.

[2] Protection of Electronic Computer/Data Processing Equipment, NFPA 75-1987, National Fire Protection Association, Quincy, MA.

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[4] Guideline on Electrical Power For ADP Installations, Federal Information Processing Standard Publication 94, National Bureau of Standards, 1983.

[5] T. M. Gruzs, "Power System Problems Associated From High Harmonic Neutral Currents", Computer Technology Review, Winter, 1988.