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SWITCHMODE POWER CONVERSION IN DATA PROCESSING EQUIPMENT

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Abstract

Equipment technology has irreversibly altered the data processing environment. Advances in circuit miniaturization, peripherals, power supplies have yielded higher power supply efficiency coupled with greater data throughput.

Data processing, once relegated to computer and control rooms, is increasingly the domain of personal computers, word processors, work stations, servers and the like, all of which are found in the general office area.

The loads these typically single phase devices present to the electrical distribution system are far more non-linear than that of their predecessors'. Comparisons of power supply technology and effects on power distribution systems are presented.

Power Supply Technology

Developments in data processing and other micro-processor based equipment as well as the proliferation of such equipment over the last twenty years have resulted in a different type of load presented to typical premises wiring.

Integrated circuits began replacing discreet components in the early 1970's. As manufacturing technologies improved, higher and higher circuit densities resulted. The size and power requirements of equipment using this technology decreased dramatically. As progress continued, computers originally operating on 208V or 240/120V single phase or, in some cases, 208V three phase power were replaced with newer models capable of operating on 120V single phase circuits. Disk drives and tape drives as well as cooling fans using induction or synchronous motors powered directly from the ac line were replaced in large part by smaller, higher capacity versions of the same driven by brushless dc motors powered by the computer's dc supply. Along with decreased size, increased capacity, reductions in power and environmental (air conditioning) requirements, also came decreased cost making data processing equipment economical to more and more of the business community.

Twenty years ago in an office of, say 300 people, data was batch processed using punch cards or entered at a handful of data entry terminals. Today in that same office nearly every desk has a word processor, work station or personal computer probably connected to a local area network (LAN), which, in turn, may be connected to a mainframe computer or wide area network (WAN).

The technology which led to higher and higher circuit densities in logic circuits also led to increased power densities in power supplies. The size of power supplies, once measured in cubic inches per watt is now measured in watts per cubic inch. Power semiconductors capable of operating at line voltage made it possible to do away with large, heavy 50Hz or 60Hz input transformers.

Previously, data processing equipment used series regulated power supplies with transformers, perhaps ferroresonant, at the input, followed by rectifiers, filters and voltage regulators. Series regulator topology is shown in Figure 1. Input voltage is stepped down by a line frequency transformer, rectified, filtered, passed to a series pass transistor which is controlled to provide regulated output voltage, then filtered again at the output.

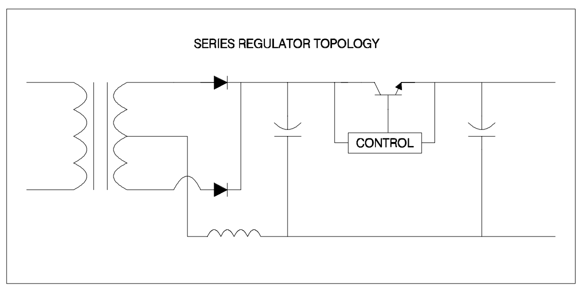

Figure 1

Originally, an LC filter was used to reduce ripple to a sufficiently low value so that the remaining ripple could be regulated out by the series control elements. Required ripple attenuation is related to the LC product and is selected to minimize size and weight. In this design, inductive reactance predominated. The input current waveform was flat topped as shown in figure 2.

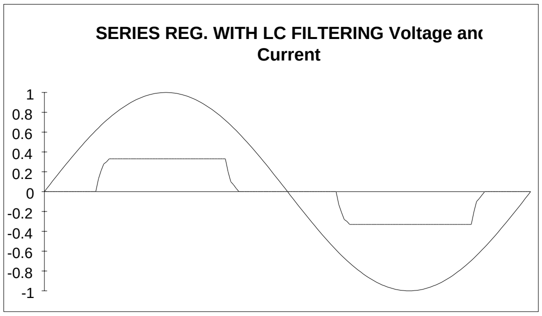

Figure 2

Since a momentary voltage dip or outage is disastrous for a computer, it was necessary to increase the bulk capacitance significantly to provide some immunity from power line aberrations. The increased capacitance made the inductance unnecessary and it was eliminated. With this change, the current waveform resembles that shown in Figure 3.

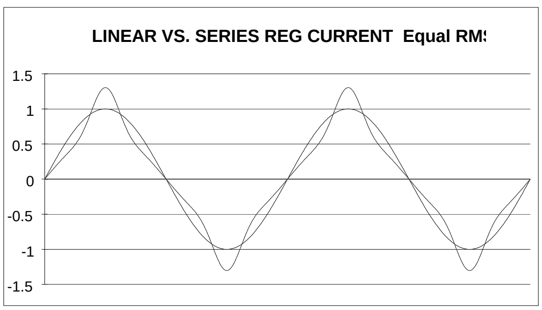

Figure 3

Series regulator supplies operate at only 35%-50% efficiency, are large, heavy and even with improvements have very little hold up time (ability to "ride through" momentary voltage sags or dropouts). The operating voltage range is fairly tight (typically +5% to -10%) limited by the fixed turns ratio of the input transformer.

Today's switchmode power supplies do not use an input transformer, but rectify line voltage directly. Figure 4 shows typical topology of a switchmode supply. Input voltage is rectified then filtered by large bulk capacitors. The power semiconductors are alternatively switched into conduction at high frequency with each semiconductor conducting less than 50% of the cycle. The resulting voltage across the small high frequency transformer is stepped down and rectified. The rectified pulse train is filtered by an LC network to provide an average output voltage.

Switchmode supplies are small, light, operate at 70% to 80% efficiency, have hold up times of 20 milliseconds or longer and are less susceptible to power line disturbances than series regulated supplies. Many can operate in dual voltage ranges (100-127V) and (200-240V) at either 50Hz or 60Hz. Typical current draw of switchmode supplies is shown in Figure 5.

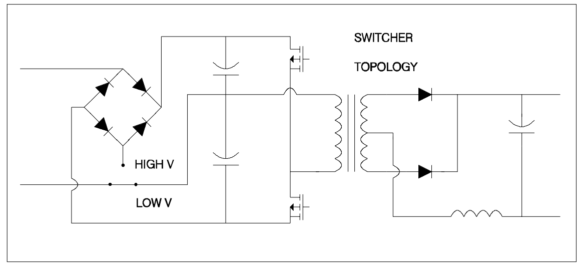

Figure 4

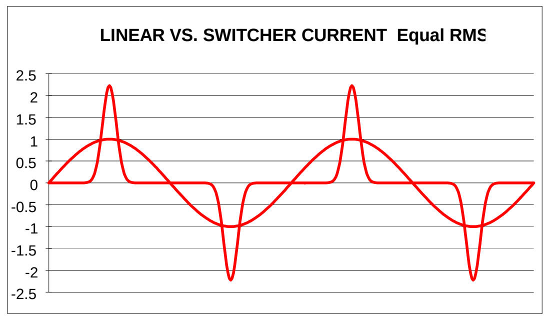

Figure 5

AC Power Utilization

Apparent power is the product of rms voltage and rms current. Its dimension, Volt-Amperes (VA), is a figure of merit indicating the maximum energy transfer capability of an ac system. VA values do not follow the law of conservation of energy; that is, VA measured at the input of a device such as a distribution transformer may be less than VA measured at the output.

Real power, the time average of the instantaneous power (instantaneous volts x instantaneous amps) over one period, has the dimension of Watts (W). Watts is the measure of the energy consumption of load equipment on an ac system. Watts measurements obey the law of conservation of energy; that is, output Watts cannot exceed input Watts.

Power factor, W/VA, is a figure of merit indicating the effectiveness of load equipment in utilizing Volt-Amperes. Two criteria determine power factor:

(1) waveshapes of the voltage and current,
(2) phase displacement between voltage and current waveforms.

When voltage and current waveshapes are identical and in time phase, the power factor is unity. For load equipment with sinusoidal current draw from a sinusoidal voltage source, power factor is equal to the cosine of the angle (cosθ) between the current and voltage waveforms.

Load equipment with differing current and voltage waveshapes is non-linear. Cosθ is meaningless as an expression of power factor in this case as are the terms "leading" or "lagging." With this type of load equipment, harmonics are present in the current and/or voltage waveforms, and to be accurate, power factor must be expressed as the ratio W/VA.

Effect of Non-Linear Loads on Power Distribution

The series regulator current waveform in Figure 3 has a load power factor of about 0.80; the switchmode current waveform in Figure 5 has a load power factor of about 0.65. Current waveforms of a series regulator supply at 45% efficiency and a switchmode supply at 75% efficiency powering identical 250 watt loads are seen in Figure 6. Note the higher efficiency switchmode supply will allow three of these loads to be powered from a 15 amp branch circuit whereas the series regulator supply will allow only two.

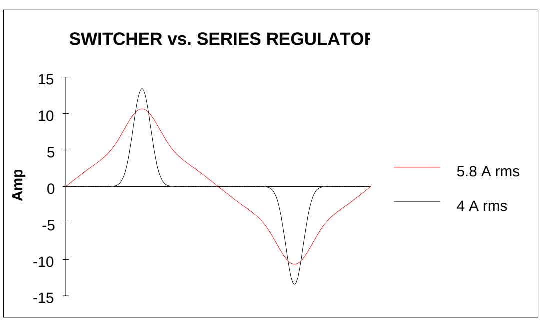

Figure 6

Assuming the single phase branch circuits powering the switchmode loads are robust ("stiff") enough to deliver the higher peak current required without "flat-topping" the voltage waveform, completely satisfactory operation can be expected.

The situation may be different, however, at the three phase distribution powering a multitude of single phase switchmode loads.

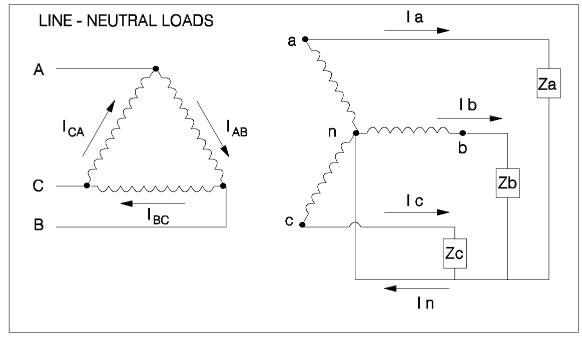

Figure 7

If all the loads on a three phase supply are linear (sinusoidal) single phase line to neutral, the return current in the neutral conductor is only the imbalance of the current among the individual phases. If the single phase currents are balanced and of the same relative phase displacement as in Figure 8, no current flows in the common neutral conductor.

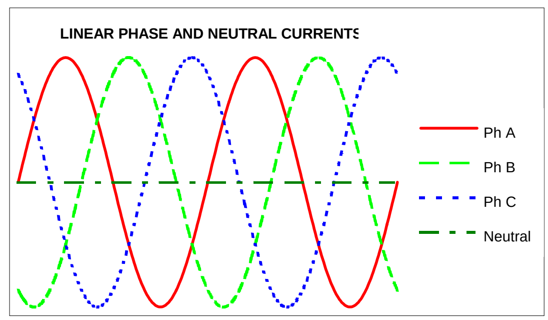

Figure 8

When all single phase loads are sinusoidal at the fundamental frequency (50Hz or 60Hz), the neutral current is also a sinusoid at the fundamental frequency, the magnitude of which is less than or equal to the magnitude of the most heavily loaded phase. It is true, exotic, unworldly conditions can be conjured up showing neutral current exceeding phase current by a substantial margin, but in the real world such situations rarely occur. Figure 9 shows such a condition. In this example, load magnitude on each phase is identical. The load on phase A is purely resistive, the load on phase B purely capacitive, and the load on phase C purely inductive. In this example, the current in the common neutral conductor is 2.73 times the current in any phase.

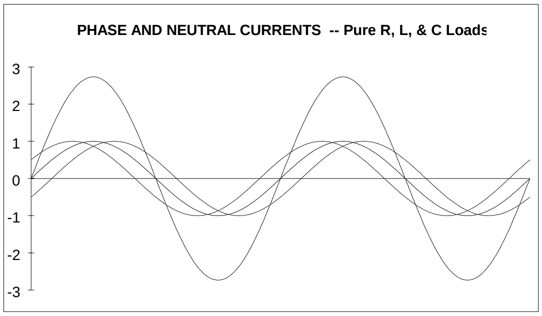

Figure 9

Power supplies using rectified power and front end smoothing filters are non-linear devices with harmonics present in the current waveform. If the single phase loads on a three phase distribution system are series regulated supplies, not all the current cancels in the common neutral even if the loads are perfectly balanced and of the same relative phase displacement.

Defining the positive sequence of the phase voltages to be A-B-C, the voltage in phase B lags the voltage in phase A by 120° or 1/3 of a cycle. The voltage in phase C lags the voltage in phase A by 240° or 2/3 of a cycle. Likewise, the fundamental (50Hz or 60Hz) component of the phase B-to-Neutral current lags the fundamental component of the phase A-to-Neutral current by 120° or 1/3 of a cycle, etc.

The second harmonic, if present, of the phase B-to-Neutral current lags the second harmonic of phase A-to-Neutral current by 240° or 2/3 of a cycle, etc. This is equivalent to saying the second harmonic of phase B-to-Neutral current *leads* the second harmonic of phase A-to-Neutral current by 120° or 1/3 of a cycle. Therefore, second harmonic components occur in reverse order or negative sequence, C-B-A.

The third harmonic component of phase B-to-Neutral current lags the third harmonic component of phase A-to-Neutral current by 360° or 3/3 of a cycle. Therefore, the third harmonic components are in time phase. These are zero sequence components.

The sequences of harmonic components repeat as follows:

Positive Sequence: 1, 4, 7, 10,…
Negative Sequence: 2, 5, 8, 11,…
Zero Sequence: 3, 6, 9, 12,…

Waveforms symmetrical about the time (X) axis such as those shown previously do not contain even order harmonics. Actual physical power supplies do exhibit some even harmonics of low order (2,4,6) due to component imbalances, diode drops, transformer tolerances, etc., but these are of such low magnitude to be of no consequence.

Odd positive and negative sequence harmonic currents cancel in the common neutral to the extent the harmonic phase currents are balanced. Zero sequence currents (triplens) add arithmetically in the common neutral.

With series regulated supplies installed line-to-neutral on a three phase system, the magnitude of the harmonic currents is low enough that the rms value of the resultant common neutral current is less than the rms value of the highest phase current. Figure 10 shows the line and neutral currents from balanced, single phase, line-to-neutral connected series regulator loads on all three phases.

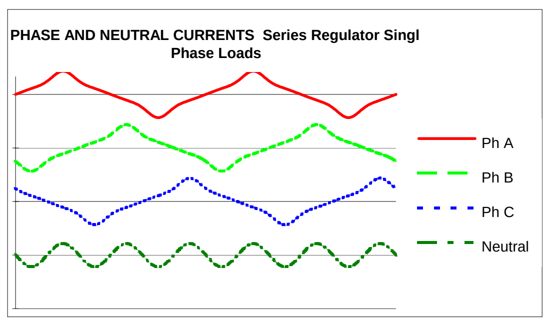

Figure 10

When the single phase line-to-neutral loads are switchmode supplies, the rms value of the harmonic current in the common neutral can be substantially greater than the rms value of the phase currents. Figure 11 shows this phenomenon. Note that none of the loads are drawing current at the same time, and hence there is essentially no cancellation of current in the common neutral conductor. With balanced loads of magnitude I_m on each phase, the current flowing in the common neutral is:

$$I_n = \sqrt{I_m{}^2 + I_m{}^2 + I_m{}^2} = \sqrt{3} \cdot I_m = 1.73 \cdot I_m$$

Hence, with balanced line-neutral switchmode-type loads, current flowing in the common neutral may be as great as 1.73 times the phase current.

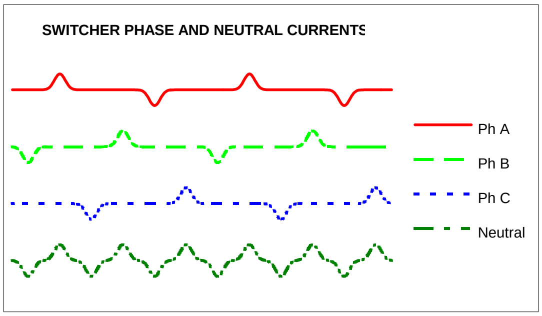

Figure 11

Distribution systems of single phase line-to-neutral loads typically have some imbalance. In such cases, the neutral current will contain harmonic currents of other than triplen orders. Depending which other harmonic predominates, the neutral current may be amplitude modulated by that harmonic. Figure 12 shows a common phenomenon -- triplen harmonic currents modulated by the fundamental.

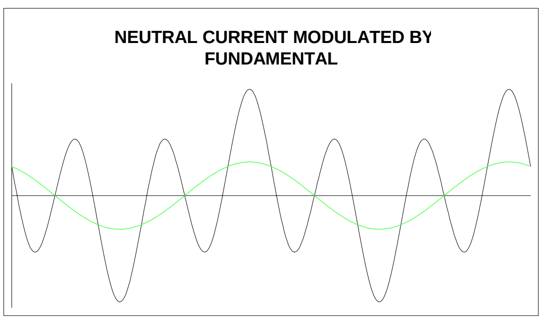

Figure 12

Harmonic Content of Switchmode Current

Relative magnitude of the first four odd harmonic components is given below for a typical single phase switchmode power supply.

n	$\boldsymbol{I_1}$**%**
1	100.
3	82.
5	65.
7	44.
9	23.

n is the harmonic order; $\boldsymbol{I_1}$**%** is the percent of the fundamental component magnitude.

RMS line current:

$$I_L = \sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_9^2} \qquad [1]$$

$$= \sqrt{I_1^2 + (0.82 \cdot I_1)^2 + (0.65 \cdot I_1)^2 + (0.44 \cdot I_1)^2 + (0.23 \cdot I_1)^2}$$

$$I_L = 1.53 \cdot I_1$$

As mentioned previously, the common neutral conductor in a balanced three phase system carries only zero sequence components; in this case, the 3rd and 9th harmonics. The magnitude of the current flowing in the common neutral in a system with balanced single phase loads as above is as follows:

$$I_3 = 0.82 \cdot I_1 = \left(\frac{0.82}{1.53}\right) I_L = 0.54 \cdot I_L$$

$$I_9 = 0.23 \cdot I_1 = \left(\frac{0.23}{1.53}\right) I_L = 0.15 \cdot I_L$$

$$I_N = \sqrt{(3 \times 0.54 \cdot I_L)^2 + (3 \times 0.15 \cdot I_L)^2}$$

$$I_N = 1.68 \cdot I_L$$

Here, the neutral current is over 2/3 greater that the phase currents. With overcurrent protection on the phase conductors only, circuits can operate well within breaker capacity yet seriously overload the common neutral conductor, busbar, etc.

If the single phase switchmode loads are equipped with dual voltage range power supplies, it is possible to operate them line-to-line at 208V as in Figure 13. Doing so eliminates the neutral conductor as part of the circuit thereby avoiding the potential of neutral overloading. This should only be done with prior approval of the equipment manufacturer to ensure safe operation and that safety agency listings are not violated. This is neither a recommendation for nor a warning against such operation. It is probably impractical in most existing facilities since extensive facility rewiring is likely to be necessary.

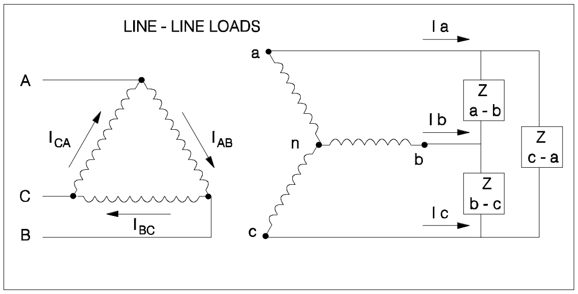

Figure 13

Harmonic content of the load currents ($I_{a\text{-}b}$, $I_{b\text{-}c}$, $I_{c\text{-}a}$) remain unchanged; however, triplen harmonics are canceled in the line currents (I_a, I_b, I_c) as shown in Figure 14.

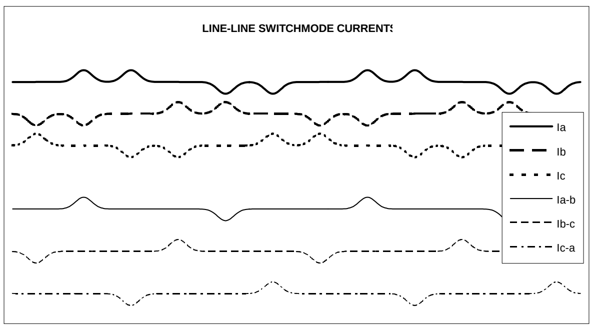

Figure 14

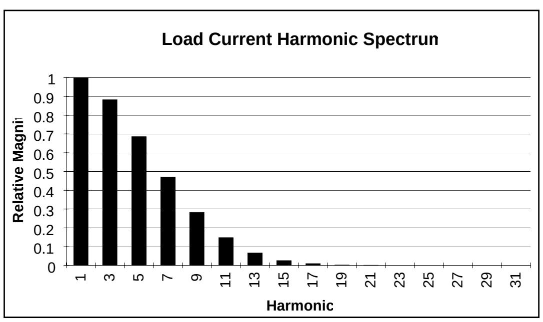

Figure 15

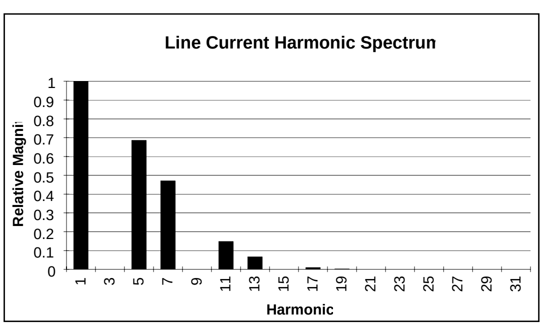

Figure 16

Note that triplen harmonics are absent in the line currents. Harmonic distortion is 85% compared with the same loads operated line-to-neutral at a harmonic distortion of 125% -- assuming the switchmode supplies respond exactly the same regardless of the method of connection to the distribution system. They do not.

Harmonic content of switchmode load currents is a function of: 1) load on the power supply, 2) impedance of the supply source, 3) operating voltage and 4) line frequency. Other factors such as the design implementation of the power supply may also have an impact. Harmonic current distortion of a 750 watt single phase switchmode supply operated at varying loads, voltages and line frequencies is shown in Figure 17.

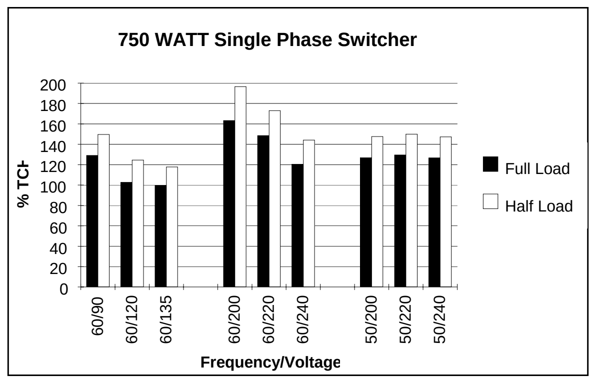

Figure 17

Power factor (PF) of the above, shown in Figure 18, may be very closely approximated from total harmonic distortion (THD) using the following relationship:

$$PF \cong \sqrt{\frac{1}{THD^2 + 1}} \qquad [2]$$

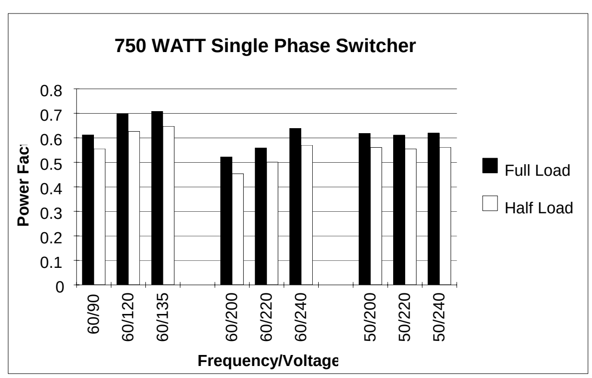

Figure 18

Although neutral current overloads are averted, increased harmonic distortion is introduced. In solving one problem, another is exacerbated.

Harmonic currents are not only a problem in common neutral conductors, but also in other distribution equipment such as transformers. Harmonic currents flowing in the windings and core of a transformer may greatly restrict its load carrying capacity and shorten its life. If standard dry-type distribution transformers are to be used to power non-linear loads, they must be derated according to ANSI/IEEE C57.110; or, if the non-linear loads are single phase, line-to-neutral connected switchmode-type loads, the simpler CBEMA recommended derating factor may be used:

$$DeratingFactor = \frac{\sqrt{2} \times I_{Load(rms)}}{I_{Load(peak)}} \qquad [3]$$

The ubiquitous switchmode power supply is here to stay as are many other non-linear load devices. If misunderstood or ignored, negative effects on three phase distribution systems can be serious. Proper planning and maintenance if distribution systems can forestall potentially serious problems and even improve systems' performance.

References:

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Mr. Wagner received his BS in '67 and MS in Electrical Engineering in '85 from Purdue University, W. Lafayette, IN. He is currently Lead Engineer for Regulatory Compliance with Lucent Technologies Bell Laboratories, Denver where his principal focus is electromagnetic compatibility. Former responsibilities have included qualifying power conditioning devices; site planning, training company and customer personnel in areas of installation planning; troubleshooting and consulting on installation related matters. He has actively contributed in the development of the international powerline harmonics standards, IEC 1000-3-2 and IEC 1000-3-4. He is a member of CBEMA subcommittees ESC-3 (Power Interface), ESC-5 (EMC) and ESC-9 (Installation) and a member of the US Technical Advisory Group for CISPR-G. He co-authored the CBEMA Information Letter "Three Phase Power Source Overloading caused by Small Computers and Electronic Office Equipment," authored the CBEMA Information Letter "Guidelines for Grounding ITE," and numerous company standards, practices and guidelines on electromagnetic compatibility.