Power Factor, Harmonic Distortion; Causes, Effects and Considerations

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ABSTRACT: This paper is written for non-technical and technical people with limited understanding of power conversion technology who are tasked with specifying, procuring or using power conversion equipment for non-linear loads such as electronic computers and telecommunications equipment. It is the intent of this paper to clarify terms, definitions and considerations for power factor and power line current harmonic distortion.

Power factor has increasingly become a topic of discussion when specifying loads and AC/DC or AC/AC power sources. The European Community has proposed standards for limiting the mains current distortion caused by non-linear loads. A brief overview of emerging standards is provided.

This paper explains the definition of power factor and the difference between displacement and distortion power factor. The effects of low power factor will be discussed with emphasis on non-linear loads such as switch mode rectifiers.

A basic explanation of total harmonic distortion (THD) will be provided along with a discussion of sources of current distortion, the effects on power distribution equipment, heating effects on transformers and the effects on other loads connected to the network. The relationship between power factor and harmonic distortion is discussed and highlights harmonic distortion as the parameter better representing a figure of merit in defining power line and load quality for non-linear loads.

Methods to reduce THD and increase power factor are illustrated. Economic considerations and trade-offs between power factor correction (PFC) and low PF loads is discussed with suggested applications and conditions not requiring PFC.

1.0 DEFINITIONS: The definitions given in this section are taken from the IEEE 519, "Recommended Practices and Requirements for Harmonic Control in Electric Power Systems".

Definition of Power Factor and Harmonic Distortion:

A "HARMONIC" is a sinusoidal component of a periodic wave or quantity having a frequency that is an integer multiple of the fundamental frequency. An AC periodic voltage or current can be represented by a Fourier series of pure sinusoidal waves which contain the basic or fundamental frequency and its multiples called harmonics.

Harmonic Distortion refers to the distortion factor of a voltage or current waveform with respect to a pure sine wave.

Distortion factor (harmonic factor) is the ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percent of the fundamental.

Total Harmonic Distortion, see distortion factor above. This term is commonly used to define either current or voltage "distortion factor".

Power Factor (PF):

Displacement PF; is the displacement component of power factor, the ratio of the active power of the fundamental wave, in watts, to the fundamental wave, volt-amperes. Power factor in this case is often denoted as a phase angle between the voltage and current wave forms. This is a useful term when the load is linear in nature, however it is not a very meaningful term with non-linear loads. Total/true power factor should then be identified.

Distortion PF; is the distortion component associated with the harmonic voltages and currents present. It is defined as the ratio of the fundamental component of the AC line current to the total line current I_1/I_T (rms).

Total/True PF: the ratio of the total power input in watts to the total volt-ampere (rms) input to the load.

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2.0 HARMONIC DISTORTION

Harmonic distortion is divided into two classes, voltage distortion and current distortion. Since the voltage is common to all loads in a system, any voltage distortion will result in a corresponding current distortion assuming the source impedance is very low. On the other hand, current distortion results in voltage distortion only to the extent that the source impedance provides a common coupling impedance.

The effects of harmonic currents from nonlinear loads are not widely understood. Due to the low impedance of most power systems, the power system can generally absorb significant amounts of harmonic current without converting these to unacceptable voltage distortion levels.

Harmonic distortion can be caused by the utility or by the load. Typical examples of non-linear loads include arcing devices (such as arc furnaces and fluorescent lighting), ferromagnetic regulators, silicon controlled rectifiers and switch mode rectifiers.

Percent impedance (% Z) is an important parameter to specify when defining the ac supply source. This will determine the voltage regulation at the load and the ability to source high peak current demand from loads. A low %Z indicates a "stiff" source and a high %Z indicates a "soft" source. A soft source will present greater voltage distortion albeit at the load connections.

$$\% Z = (I_{rated}/I_{sc}) \times 100$$

where;

$\% Z$ is the percent impedance

I_{rated} is the load or device full rated current in amperes.

I_{sc} is the maximum short circuit current available from the supply in amperes.

A good isolation transformer should be in the 3% to 5% range. Recommended distribution system impedance should not be more than 3% for small branch circuits and not more than 5% for long branch circuits.

3) Sources of Non-unity Power Factor and Harmonic distortion:

Linear reactive loads (inductive or capacitive) draw current from the power source which is at the same frequency of the power system (50 or 60 Hz for example). For the general passive linear network having voltage $v = V_M \mathrm{Sin}(wt)$ and resulting current $i = I_M \mathrm{Sin}(wt + \theta)$ then instantaneous power is defined by

$$p = vi = V_M I_M \mathrm{Sin}(wt)\mathrm{Sin}(wt + \theta) \qquad (1)$$

and the average value of p is

$$P = 1/2 V_M I_M \cos(\theta) = VI\cos(\theta) \qquad (2)$$

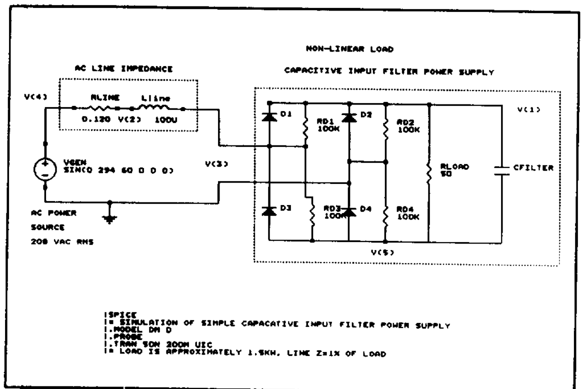
where V and I are the RMS value, V_M and I_M are the peak value of the sinusoidal voltage and current. The phase angle $<\theta$ also defines the power factor ($\cos(\theta)$) in linear systems.

Large inductive devices such as motors exhibit lagging currents and power factor can be determined by the phase angle between the voltage and current. Motor loads are mostly linear but also have non-linear characteristics. Capacitors and synchronous motors are used in industry to compensate for the large inductive loading in factories caused by motors. They exhibit a leading current and can adjust power factor within a building or system to keep reactive power flow provided by the network to a minimum. The reactive power generates power losses in the transmission system cables and reduces the overall efficiency of the power system.

Non-linear loads generally do not cause reactive power to flow at the fundamental line frequency. They can, however, draw higher RMS currents and hence add to distribution system losses for a given load. The non-linear nature of these loads then draws non-pure sine wave currents thus causing harmonics of the fundamental current to be present. Since harmonic distortion is caused by non-linear elements connected to the power system, any device that has non-linear characteristics will cause harmonic distortion. Examples of common sources of power system harmonics, some of which never cause serious problems, are :

1) Transformer saturation and inrush
2) Transformer neutral connections
3) MMF distribution in AC rotating machines
4) Electric arc furnaces
5) Fluorescent lighting
6) Computer switch mode power supplies
7) Battery charges
8) Imperfect AC sources
9) Variable frequency motor drives (VFD)
10) Inverters
11) Television power supplies

Switch mode power supplies, Uninterruptable Power Supplies (UPS) and electronic lighting ballasts may have low power factor and can generate harmonic distortion. This is not because they are high frequency switching converters but rather because the input stage is usually a low cost rectifier/capacitor filter. Figure 1 is a simplified but representative schematic diagram of the AC power source and load with a typical capacitive input filter.



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|SPICE
|* SIMULATION OF SIMPLE CAPACATIVE INPUT FILTER POWER SUPPLY
|.MODEL DM D
|.PROBE
|.TRAN 50N 200M UIC
|* LOAD IS APPROXIMATELY 1.5KW, LINE Z=1% OF LOAD
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Figure 1: AC power source with line impedance and equivalent circuit for a low cost, low power single phase AC/DC power supply.

This type of load causes current to be drawn from the AC line only when the AC voltage is higher then the rectified voltage of the input filter capacitor. The input filter capacitor is then charged to the peak of the line minus some voltage drop from semiconductors and internal and external source impedances. This type of input stage is found on most low power (P < 1500 watt for single phase) power supplies (switching or linear). Figures 2 and 3 illustrate the effect of line impedance on voltage and current distortion. Although the current THD can be high (100% - 150%) the voltage distortion is a function of line impedance and can be within specified limits (< 5%).

The voltage and current harmonics were calculated using the computer model shown in Figure 1 for 1% and 5% line impedance. The results are as follows:

1% Line impedance: (0.120 ohms, 100 uH inductance)
Voltage THD = 1.4% Current THD = 149%

5% Line impedance: (1.20 ohms, 100 uH inductance)
Voltage THD = 4.6% Current THD = 104%

		1% Z_{LINE} component		5% Z_{LINE} component	
n	f	V	I	V	I
1	60	292.6	11.4	281.7	10.2
2	120	0.0	0.0	0.02	0.0
3	180	1.8	10.6	10.25	8.5
4	240	0.0	0.0	0.02	0.0
5	300	2.1	9.3	6.96	5.7
6	360	0.0	0.0	0.00	0.0
7	420	2.2	7.5	3.43	2.8
8	480	0.0	0.0	0.02	0.0
9	540	2.0	5.5	0.66	0.5

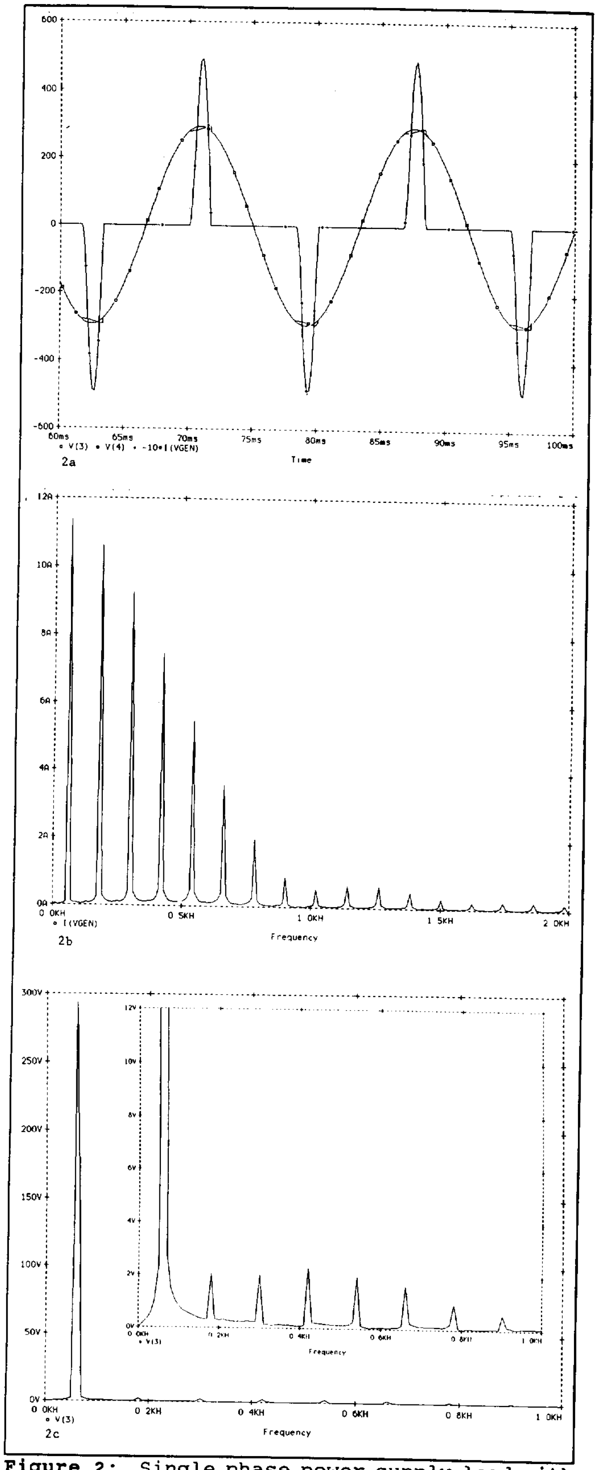


Figure 2: Single phase power supply load with 1% line impedance. Figure 2a illustrates the line current (x 10 for clarity) I(VGEN), the load voltage V(3) and the generator voltage V(4). Figure 2b and 2C are the load current and load voltage frequency spectrum.

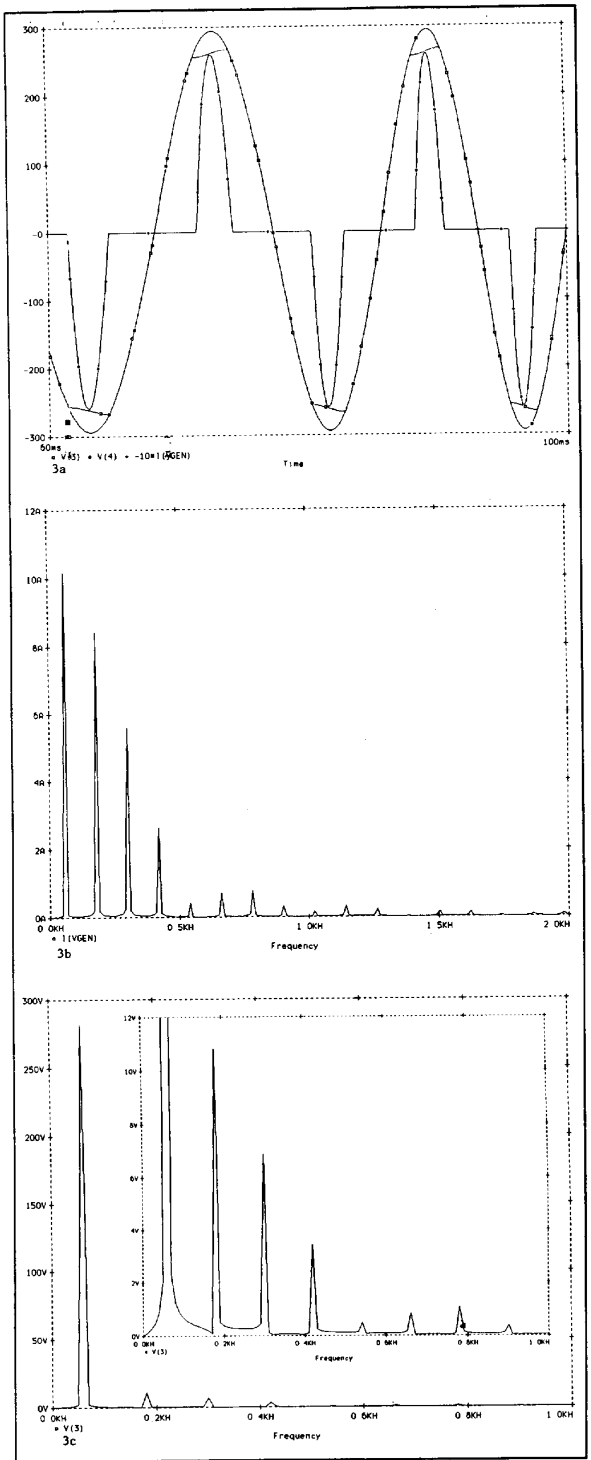


Figure 3 : Single phase power supply load with 5% line impedance. Figure 3a illustrates the line current (x 10 for clarity) I(VGEN), the load voltage V(3) and the generator voltage V(4). Figure 3b and 3c are the load current and load voltage frequency spectrum.

Figure 2a shows the line voltage with the load voltage and load current superimposed. The load voltage is distorted near its peak.

These non-linear loads reduce power factor not because of phase shift of the fundamental current with respect to the voltage but because of higher RMS currents caused by the pulsed nature of the input current. That is, the power is taken from the source only during a short period of time near the peak of the voltage wave. Since total power factor is defined as the real power (Watts) divided by the product of the RMS line voltage and current, the higher line current reduces power factor.

It is important to understand that the actual power consumed by the load is not determined by the power factor. It is determined by the real power measured by a watt meter or calculated by using expression (1). The consumer of low power (approximately < 100KW) is charged only for real power (watts) used. The power factor is an indication of the apparent power vs the real power. Low power factor means more current is flowing in the network than would be ideally with unity power factor. The extra current flow means the conduction losses in the wiring and transformers are higher than would be with higher power factor for a given load. There can be second order effects also generated by voltage distortion caused by the distorted load current. This will be discussed in more detail further on in the paper.

Harmonic power factor is related to harmonic distortion and can be calculated using expression (4). Users of power equipment having non-linear characteristics would be better to discuss harmonic distortion rather than power factor since it is the distortion of the load current that causes the lower power factor.

$$\mathrm{THD} = (I_3^2+I_5^2+I_7^2+I_{11}^2+....)^{1/2}/(\,I_1\,) \qquad (3)$$

I_3 is the third harmonic, I_5 is the 5th harmonic ....

$$\mathrm{P.F.} = 1\,/\,(1 + \mathrm{THD})^{1/2} \qquad (4)$$

or if the power factor is known, then the current THD can be estimated by:

$$\mathrm{THD} = [\,(1/\mathrm{PF}^2) - 1\,] \qquad (5)$$

Note that (4) & (5) only apply to non-linear loads where displacement PF is minimal.

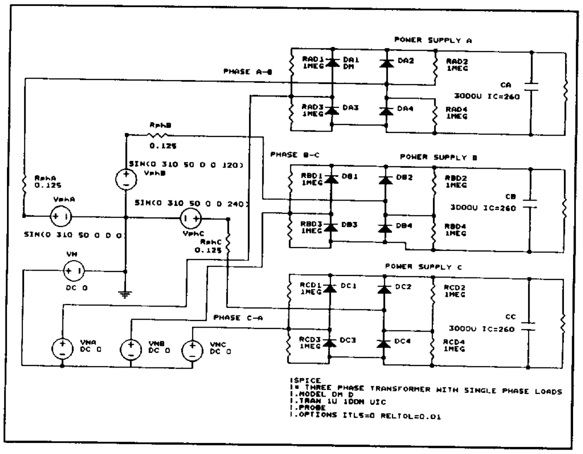
4) Effects on the Power Network and connected Equipment:

The effects of harmonic distortion vary with the application. The degree to which harmonics can be tolerated is determined by the susceptibility of the load to them.

The presence of harmonic currents or voltages produce magnetic and electric fields that may impair the satisfactory performance of communications systems susceptible to the disturbance by virtue of their proximity. The disturbance is a function of both amplitude and frequency of the harmonic components. In practice, telephone interference is often expressed as a product of the RMS line current (I) and the Telephone Influence Factor (TIF). The TIF weighting is determined from the relative interfering effects of different frequencies of noise in a telephone circuit and the coupling between power and telephone circuits. Loads having high harmonic current will have a high I-TIF product because the RMS current is higher and the TIF weighting increases with frequency from 0.5 at 60Hz to a peak of 10600 at 2580 Hz. The interference can be reduced by reducing the proximity of power and communication cabling, filtering and by using power equipment with low harmonic distortion.

Metering and instrumentation are affected by harmonic components. Induction disk devices such as watthour meters normally see only fundamental current, but erroneous operation resulting in positive or negative errors are possible with harmonic distortion present, depending on the type of meter and harmonics involved.

Power system are affected in various ways and the extent of the influence is application and configuration dependent. Three common configurations to power loads are: a) single phase (120VAC or 220VAC phase to neutral in a 208 or 380 VAC system), b) single phase loads connect phase to phase, and c) three phase connected loads. Figure 4 illustrates the computer model used to simulate single phase loading of a 3 phase WYE distribution transformer.



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ISPICE
I* THREE PHASE TRANSFORMER WITH SINGLE PHASE LOADS
I.MODEL DM D
I.TRAN 1U 100M UIC
I.PROBE
I.OPTIONS ITL5=0 RELTOL=0.01
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Figure 4: Computer model for three phase wye distribution transformers with phase to neutral connected power supply loads.

A) Single Phase loads connected phase to neutral. This configuration is very common in industrial and commercial application for low power loads. It is likely the single most frequent cause for concern and is the source of a great deal of discussion of harmonic effects and their problems.[2] [3] [4] [5] Unfortunately the problems in this configuration have been generalized to cover all configurations having non-linear loads.

Electronic office equipment such as personal computers, printers, copiers and FAX machines have low cost power supplies with capacitive input filters discussed earlier. Consequently, the input current harmonic distortion is high. The building wiring is often three phase (208 VAC in North America and 380 VAC in Europe and in most of the rest of the world). The low power loads are connected phase to neutral thus providing 120 VAC from a 208 source and 220VAC from a 380 VAC source. This distribution method is applied because it makes use of the fact (I should say assumption) that current will cancel in the neutral of a three phase system having phase to neutral loads. Non-linear loads have a very different effect. Non-linear load current adds in the neutral and can be as high as 1.73 times the phase current. The RMS neutral current for this case is:

$$[I^2_{\text{phase-A}} + I^2_{\text{phase-B}} + I^2_{\text{phase-C}}]^{1/2} = 3^{1/2} I_{\text{phase}}$$

In this case the neutral current will overheat if it is not sized for the higher current. Figure 5 illustrates the effect of single phase load current accumulation in the neutral conductor and Figure 6 illustrates the cancellation of neutral currents with loads having low distortion. This is true only for pure sine wave loads, ie linear loads.This problem appears to be more prevalent in Europe because the higher voltage (220 VAC) allows high power loads to be connected in single phase systems and hence the problem becomes that much more wide spread.

B) Single phase loads connected phase to phase: This is a common configuration to power loads greater than 1KW. However most electronic loads are limited to input voltages of 270VAC. Hence in North America the 208 VAC is quite acceptable. In Europe and other countries having 380 VAC the loads tend to be connected phase to neutral as discussed in (A). Connecting the load phase to phase eliminated the HOT neutral problem. However transformer heating may be a concern because the harmonic currents now circulate in the delta winding of some delta-wye transformers.

C) Three phase connected loads: This is the preferred connection for large loads (> 10KVA). It is also much easier and more cost effective to reduce harmonic distortion and provide power factor greater than 0.9. However, if the three phase load is a simple rectifier-capacitor filter it is no different from three single phase

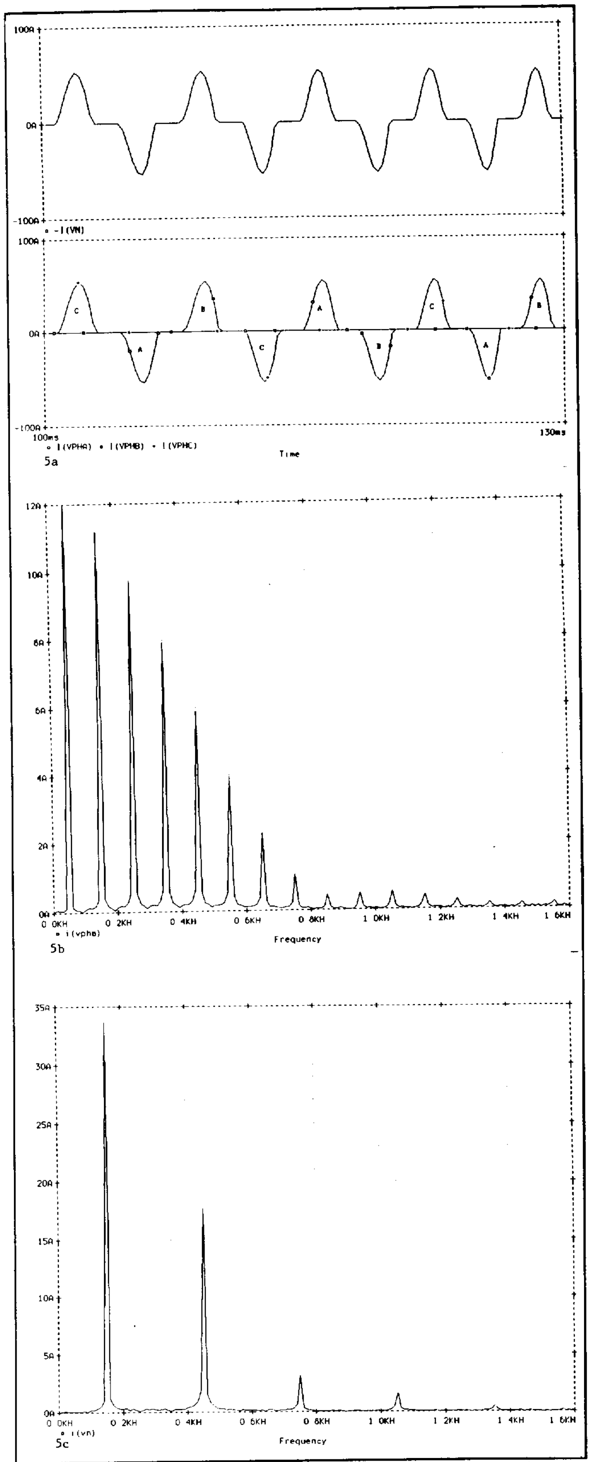

Figure 5: 3 Phase transformer with single phase loads. Phase and neutral current simulation; a) top, neutral current, bottom, phase A,B&C current. b) Phase A current frequency spectrum, c) neutral current frequency spectrum.

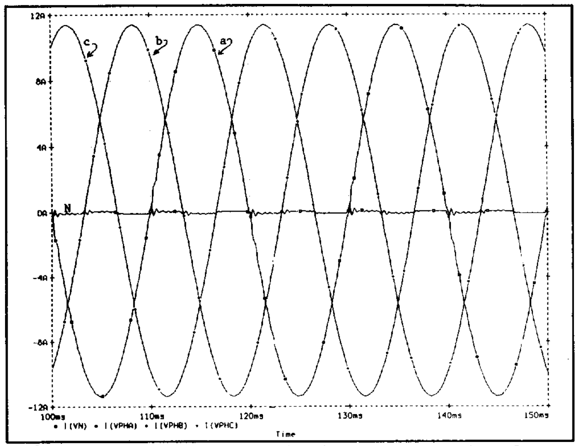

Figure 6: Neutral and phase currents for 3 linear phase to neutral connected loads. Phase A [I(VPHA)],B [I(VPHB)],C[I(PHC)] and neutral I(VN) current. Note the neutral current is zero.

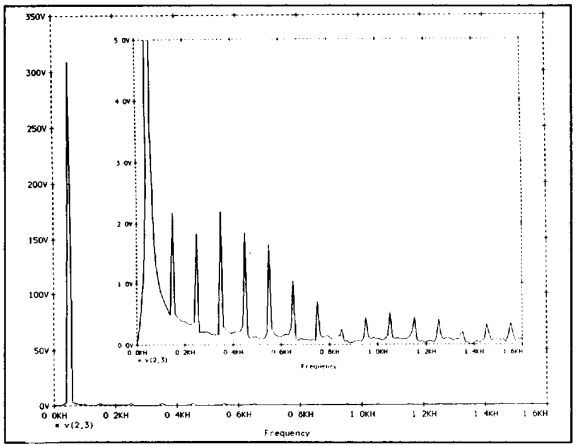

Figure 7: Phase A load voltage frequency spectrum from figure 5, voltage distortion is less then 5%. Line impedance is approximately 4%.

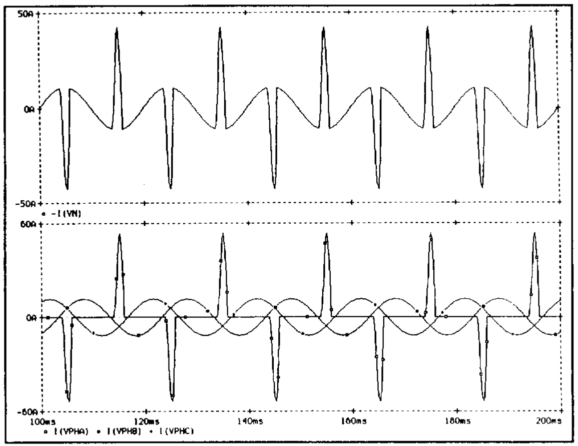

Figure 8: Neutral (top) and phase (bottom) current for 2 linear and 1 non-linear loads connected across three phase power system. Each load consumes the same amount of power but the non-linear load has high RMS current and high current distortion.

However, if the three phase load is again a simple rectifier loads connected phase to phase. In this case the third harmonic will be reduced or eliminated depending on how balanced the line voltage and load current is, but the 5th, 7th, 11th and higher harmonics are still present.

The source impedance, that is the impedance between the AC generator and the load, is what will determine the amount of voltage distortion caused by the non-linear load current. Figure 7 shows the load voltage harmonic content for aload powered with a source having approximately 5% line impedance. The amount of voltage distortion will vary from the generator to the load. The load will see the highest voltage distortion. Low source impedance will reduce the amount of voltage distortion. Also, adding impedance between the source and load will reduce the voltage distortion seen by other loads before the impedance but increase the voltage distortion at the load.

Motors and generators can be adversely affected by high harmonic currents resulting in higher audible noise, cogging, oscillating torques and increased copper and iron losses resulting in added thermal stress. The effects of harmonics on transformers arises from both current and voltage harmonics. Current harmonics cause an increase in copper losses and stray flux losses while voltage harmonics cause an increase in iron losses. Derating generators and transformers has been suggested but a more effective approach is to use generators and transformers designed specifically for harmonic generating loads. Power cables conducting harmonic current are prone to parasitic heating which could be over and above what would be expected for the RMS value of the waveform. This is due to two phenomena known as "skin effect" and "proximity effect" both of which vary as a function of frequency, conductor size and conductor spacing.[6]

Capacitors are often used to correct power factor and limit the amount of reactive power flowing in the system. This is effective for linear reactive systems but can be cause for concern with harmonic loads because of the possibility of system resonance. Resonance occurs when the system inductive reactance and capacitive reactance are equal at some frequency. If the combination of capacitor banks and system inductance results in a parallel resonance near one of the characteristic harmonics generated by the loads, that harmonic current then feeds the resonant circuit. This will cause an amplified current to oscillate between the inductance and the capacitance. This oscillating current will cause voltage distortion and increased thermal stress on the power cables and especially on the capacitors.

5) Methods to reduce Total Harmonic Distortion:

The triplen harmonics, that is odd harmonics that are three times a multiple of the fundamental frequency (3rd, 9th, 15th ...), are additive in the neutral conductor of a 3 phase 4 wire system. Under the conditions of a three phase balanced load the fundamental and all non-triplen harmonic currents cancel while the triplen harmonic currents and can approach 1.73 times the RMS phase current. The problem may be solved in a simple and cost effective manner by using a zigzag or Scott-T transformer. The neutral current is reduced to zero even if the load currents are unbalanced. Triplen harmonic currents are eliminated from the three phase lines only if the triplen harmonic currents were balanced.[7]

Another simple method to reduce effects of harmonics is to power loads from phase to phase (ie from 208 vs 120 VAC) wherever possible to eliminate the accumulation of harmonic currents in the neutral.

It is possible to eliminate harmonics in the design of a product using active or passive means and products are available with power factor correction/low harmonic distortion. Using these types of products will reduce energy loss in the distribution system and eliminate the adverse effects of harmonic distortion. Some power rectifiers for the telecommunications industry have total harmonic distortion less then 5% and power factor of 0.999.[8] [9]

Passive harmonic distortion correction filters are available also which remove the offending harmonics. This can be done with inductor-capacitor filters available in "after market" application tailored to the system. The drawback with this technique is they require large reactive components and that the filters are tuned to filter a specific frequency and hence become less effective as component values change over time.

6) Recommended Practices:

Economic factors and effectiveness of the harmonic control must be balanced. The sources of harmonic current are varied and wide spread. Although loads with low current distortion are becoming more available some harmonic loading can be acceptable. Harmonic current limits can be based on the size of the load with respect to the size of the power system to which the load is connected. IEEE-519 recommends limits of 5% to 20% maximum harmonic current distortion in % of load current. The application in question should be investigated to determine the size of the harmonic load to the total load. The present facilities may be adequate to handle the harmonic loading.

The International Electrotechnical Commission standard IEC 555-2 sets limits on current harmonic distortion generated by equipment connected to the public supply system. The standard has four classifications: Class A for motor drives, light dimmers and other equipment not in class B,C or D. Class B is for portable tools, class C is for lighting equipment except light dimmers and self ballasted lamps with special wave shape, class D is for equipment having a special wave shape. The low cost capacitor input filter used on many power supplies is class D equipment. Although this standard has not gained wide acceptance yet, the Europeans are working to adopt this standard throughout the European Economic Community.

The American National Standard ANSI C57.110 "Recommended Practice for Establishing Transformer Capability when supplying nonsinusoidal load currents" describes procedures to determine transformer capability to supply nonsinusoidal currents. Two methods are detailed for use both by transformer design engineers and for by users of power distribution transformers.

As an alternative to changing building transformers and wiring, one or more delta/wye transformers designed for rectifier loads should be placed near the harmonic generating loads. Select three-phase transformers with low internal impedances with a Delta primary and Wye secondary configuration. Power factor correction capacitors are not recommended with harmonic loads since power system resonances generating higher currents may occur unless the system has been specifically designed to avoid them.[10]

True RMS ammeters should be used to measure load currents in all phase and neutral conductors. Non-true RMS responding meters will not measure distorted voltage or current waveforms accurately.

7) Summary:

Non-linear loads have low power factor because of the high harmonic content of the current. Displacement power factor does not represent a meaningful parameter when discussing most non-linear loads. However, harmonic distortion in an indicator of power factor and can cause power system malfunctions if not understood and properly contained. Power system voltage distortion increases with line impedance. Acceptable levels of voltage distortion are achievable even with loads generating high current distortion.

High harmonic loads cause neutral current to add when connected phase to neutral resulting in neutral conductor overheating if not properly sized. Power transformer, generator and distribution equipment may also overheat if not designed to accommodate harmonic currents. Power factor correction capacitors are not generally effective in reducing harmonic distortion. Harmonic filters specifically designed for the application are recommended.

Selection of power factor corrected loads vs high harmonic loads is based on economic factors. A thorough analysis of the power losses in the distribution systems and effects of harmonic currents is required to determine the compatibility of the power system and the loads. Low power equipment generally may have high harmonic distortion which must be accommodated by the power system while high power equipment is available with very lower harmonic distortion.

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