IEEE Transactions on Power Delivery, Vol. 8, No. 2, April 1993

Effects of Harmonics on Equipment

Report of the IEEE Task Force on the Effects of Harmonics on Equipment

V. E. Wagner, Chairman

J. C. Balda
T. M. Barnes
A. E. Emannuel
R. J. Ferraro
D. C. Griffith
D. P. Hartmann
W. F. Horton
W. T. Jewell
A. McEachern
D. J. Phileggi
W. E. Reid

Abstract

The purpose of this paper is summarize the state-of-knowledge of the effects of power system harmonics on equipment. The general mechanisms presented are thermal overloading, disruption, and dielectric stressing. Quantitative effects are presented or referenced whenever possible. However, many of the effects are can only be qualitatively described. The equipment considered are adjustable speed drives, capacitors, circuit breakers, fuses, conductors, electronic equipment, lighting, metering, protective relays, rotating machines, telephones, and transformers.

Keywords: Harmonics, capacitors, fuses, conductors, electronics, metering, protective relays, rotating machines, telephones, transformers.

INTRODUCTION

The growing use of power electronic applications has increased the fraction of nonsinusoidal currents and voltages in buildings and utility networks. Nonlinear loads have always existed and traditionally included such items as arc furnaces and fluorescent lamps. Aside from the arc furnaces which were electrically segregated from other loads, the nonlinear load was overwhelmed by the linear load of motors and resistance type devices. Today, electronic versions of motors, office and industrial control equipment, and lighting are becoming more common.

As the fraction of nonlinear loads has increased, so has the anxiety over the effect of these loads and whether they should be limited. Several standards organizations have or plan to issue limits for these loads. The limits are based on the effects of these loads and the best judgement of the members of the standards organizations. However, because this problem has only recently emerged, literature on the effects of this waveform distortion is still inconsistent and incomplete.

The purpose of this paper is to document the current state of knowledge of the effects of waveform distortion on equipment updating a paper on the same subject published in 1985 [1]. Wherever possible the paper uses journal articles as the sources of information. Nevertheless, some important mechanisms not previously documented are presented in the paper to increase awareness and promote investigation. The reference section also serves as a bibliography on the topic.

Major equipment categories are discussed alphabetically after a brief introduction to harmonic distortion.

92 WM 035-6 PWRD A paper recommended and approved by the IEEE Transmission and Distribution Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1992 Winter Meeting, New York, New York, January 26 - 30, 1992. Manuscript submitted August 30, 1991; made available for printing January 22, 1992.

HARMONIC DISTORTION CONCEPTS

Periodic voltage or current distorted waveforms can be represented by the sum of a series of multiple frequency terms of varying magnitudes and phase. This expresses the Fourier theorem, whereby a complex waveform is expressed as

$$m(t) = a_0 + \sum_{n = 1, 2, 3....} [\, a_n \cos (nwt + q_n) \,] \qquad (1)$$

where the a_n term is the magnitude of the nth harmonic frequency, q_n is the phase angle of the nth harmonic frequency, and w is the fundamental frequency.

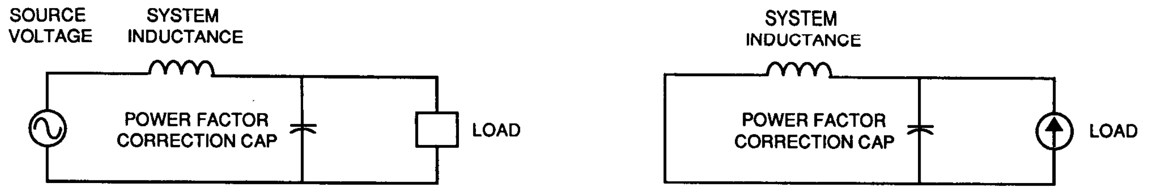
The harmonic distortion can be quantified by several different methods. One of the most common measures of the total distortion as a result of all the harmonic components is the distortion factor (DF) and is defined as

$$DF = \sqrt{[\, (\Sigma\, a_n^2) / (a_1^2) \,]} \quad n = 2, 3, 4... \qquad (2)$$

where a_n are the magnitudes of the harmonic frequencies and a_1 is the magnitude of the fundamental. This quantity is also know as the harmonic factor or total harmonic distortion. Individual harmonic frequency magnitudes can be represented as a percentage of the fundamental component. Many harmonic measuring instruments express results as total harmonic distortion and individual components as a percentage of the fundamental.

The crest factor (CF) is another characteristic of the waveform. It is defined as the ratio of the peak value to the rms value and is 1.41 for a sinusoid. The CF measures one type of distortion that is important for some types of problems but is too limited to indicate general distortion.

One source of distortion is represented by nonlinear loads. When a pure fundamental voltage with a zero source impedance is applied to a nonlinear load, the resulting current differs in shape from the applied voltage. This distorted current affects distribution equipment in the current path such as transformers,



a) Fundamental frequency model of network and load.

b) Harmonic frequency model of network and load.

Fig. 1. Network models for harmonic analysis.

conductors, and circuit breakers. When source impedance is added, the distorted current will produce a voltage drop across the impedance resulting in distorted voltage (see Fig 1). This distorted voltage will be seen by all loads after the impedance and may affect those loads. A nonlinear (or harmonic producing) load is modelled as a harmonic current source with the appropriate source impedances (see Fig 1b). The effect of each harmonic frequency circuit is analyzed separately and then superimposed on the fundamental frequency circuit.

Most periodic distortion is not static as assumed above but time varying as a result of changes in load characteristics. Nonlinear loads, such as discharge lighting and power factor correction capacitors, are switched on and off. Other nonlinear loads, such as phase controlled heaters and adjustable speed drives, exhibit varying load patterns. The overall distortion level may be cyclic over seconds, hours or days.

The distortion variation may be analyzed by dividing the observation period into equal subintervals [2]. For each subinterval an average, maximum, and minimum value can be derived. By applying statistics, a representative value for the entire observation period can be found. The thermal effect of time varying harmonics is a function of the thermal time constant of the equipment, mean values of the harmonics and their spectrum, type of density function, and standard deviation of the probability distribution.

EQUIPMENT EFFECTS

Adjustable Speed Drives (ASD)

ASDs are electronic converters that permit ac or dc motor operation at variable speed. Within the literature, ASDs are only discussed as disturbing loads and not as disturbed loads. However, in practice, this equipment is vulnerable to a variety of disturbances and the problems need to be documented. For the purposes of this paper, this group of equipment is vulnerable to harmonic voltage distortion in a manner similar to electronic equipment discussed below.

Capacitors

The use of shunt capacitors to improve power factor and voltage also has a significant influence on harmonic levels. Capacitors do not generate harmonics, but provide network loops for possible resonant conditions. If the addition of capacitors tunes the system to resonate near a harmonic frequency present in the load current or system voltage, large currents or voltages at that frequency will be produced. The resonant frequency of a low voltage system with a capacitor bank can be found from

$$n = \sqrt{(Qs/Qc)} \tag{3}$$

where n is the order of the harmonic at which resonance may occur, Qs is the available short circuit kVA, and Qc is the kvar rating of the bank.

In most low voltage installations, the following guidelines can be followed:

1. If the kVA of the harmonic producing load is less than 10% of the transformer kVA rating, capacitors can be applied without concern for resonance.

2. If the kVA of the harmonic producing load is less than 30% of the transformer kVA rating and the capacitor kvar is less than 20% of the transformer kVA rating, capacitors can be applied without concern for resonance.

3. If the kVA of the harmonic producing load is more than 30% of the transformer kVA rating, capacitors should be applied as filters.

These guidelines are applicable when transformers with a 5-6% impedance are used and the system impedance behind the transformer is less than 1% on the transformer base.

The effect of the harmonic components is to cause additional heating and higher dielectric stress on the capacitors. ANSI/IEEE Standard 18-1980 gives limitations on voltage, current, and reactive power for capacitor banks which can be used to determine the maximum allowable harmonic levels. This standard indicates that the capacitor can be operated continuously within the following limitations, including harmonic components:

110% of rated rms voltage
120% of rated peak voltage
180% of rated rms current
135% of rated reactive power

When one harmonic dominates (as is often the case), Fig. 2 offers a means of determining the maximum allowable harmonic current for a given fundamental voltage per the limitations given in ANSI/IEEE 18.

Despite this attempt to overrate the capacitors for unusual conditions such as harmonics, many harmonic problems first appear at shunt capacitor banks as either blown fuses or capacitor unit failures. The reason for problems at the capacitor is that the capacitor is part of the resonant loop and current or voltage magnification will be highest at that location.

If harmonic currents are above the allowable limits, one or more of the following remedies may be

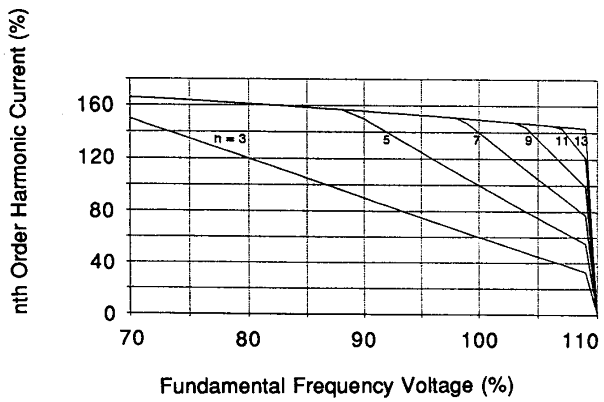


Fig. 2. Maximum allowable harmonic current at fundamental frequency voltage.

undertaken:

1. Relocation of the capacitors to other parts of the circuit may reduce overcurrent due to near resonance. The harmonic generating loads and the capacitor bank should not share the same transformer.

2. For wye connected utility capacitors banks, the neutral connection to ground may be removed to prevent third harmonics from flowing through the capacitors. (Caution: Bank insulation and switch load interrupting rating may be inadequate if the neutral is disconnected.)

3. If the above remedies fail, it may be necessary to add a tuning reactor. The purpose of the reactor is to adjust the resonant frequency away from the current or voltage harmonic frequencies (typically the 5th or 7th harmonic). Careful consideration must be given to allow for increased voltage or current loading on a capacitor as the result of adding a reactor.

Capacitive impedance decreases with increasing frequency. The capacitor current will be

$$I_n = n\,(V_n) \qquad (4)$$

where I_n is the percent harmonic current, n is the harmonic number, and V_n is the percent harmonic voltage applied. For example, if the capacitor voltage has 15% seventh harmonic component, the capacitor current will be 105%. This demonstrates why spurious fuse blowing in capacitor banks is often a symptom of harmonic problems. The current limit, although 180% by standards, may be lower because individual medium voltage capacitors units are often fused at 125% to 165% of their current rating. Low voltage capacitors are often fused at 200% of their rating.

Capacitors in filter banks permit control of harmonic distortion as well as the benefits associated with power factor correction. In these applications, the capacitors must still meet the ratings given above. The addition of the reactor actually increases capacitor voltage because the capacitor must cancel the small voltage drop introduced across the reactor. As a result, capacitors in filter banks are often rated at least 10% higher in voltage than the nominal system voltage. If the filter resonates near the system harmonic frequency, the filter may sink harmonic currents from distant loads (as a low impedance shunt circuit) and the current carrying capacity of the conductors may need to be substantially increased.

Circuit Breakers and Fuses

There is some evidence that harmonic distortion of the current can affect the interruption capability of circuit breakers. Load current can be distorted and low level faults may contain high percentages of distorted load current. High level fault currents will not be influenced by distorted load currents. When load distortion is present, it can result in higher di/dt at zero crossing than for a sinusoidal waveform making interruption more difficult.

Lembo and D'Onofrio [3] describe 15 kV breaker failures due to harmonic currents. Currents with 50 % distortion factor limited the breaker blowout coil's ability to force the arc into the arc chute. Furthermore, the prolonged interruption also delayed fault current dissipation and caused re-ignition after fast reclosure. Vacuum interrupters are less sensitive to harmonic current distortion than air magnetic breakers.

Brozek describes [4] how harmonic distortion affects the current sensing ability of thermal magnetic breakers. The instantaneous mechanism of some breakers is a solenoid that dissipates additional heat due to losses for frequencies above the fundamental. That heat then raises the temperature of the thermal device and reduces the trip point. At 300 Hz, the trip point of a 225 A frame molded case circuit breaker can be reduced 10% - 20%.

Because fuses are thermally actuated, they are inherent rms overcurrent devices [4]. The link in some utility distribution fuses consists of several ribbons that are susceptible to skin effect heating by harmonic currents. However, most reported harmonic fuse problems may actually be measurement problems. Depending on the waveform and the measurement process, an ammeter can indicate current above or below the rms value. If distorted current is measured with something other than an rms ammeter, it may appear that fuses behave improperly. Internal tests by one fuse manufacturer of fuses up to 415 Hz have shown no change in operating characteristics.

Conductors

There are two mechanisms in which harmonic currents can cause heating in conductors that is greater than expected for the rms value of the current. The first mechanism is due to current redistribution within the conductor and include the skin effect and the proximity effect. The skin effect is due to the shielding of the inner portion of the conductor by the outer layer. Since the current is concentrated in the outer layer, the effective resistance of the conductor is increased. Skin effect increases with frequency and conductor diameter.

The proximity effect is due to the magnetic field of conductors distorting the current distribution in adjacent conductors. In round wires, proximity effect is much less pronounced than skin effect [5]. Metal sheaths and conduit also contribute to the proximity effect.

Arrillaga [6] and Rice [7] present formulas and tables for the effective or ac conductor resistances due to skin and proximity effects. For example, the ratio of the ac to dc resistance for a fifth harmonic (300 Hz) current in immediately adjacent 4/0 AWG conductors is 1.33 [7].

The second mechanism causes abnormally high currents on the neutral conductor of 3-phase 4-wire distribution systems feeding single phase loads. Some loads, such as switched-mode power supplies, produce significant third harmonic currents. Balanced fundamental frequency three-phase currents will result in no neutral current. However, in three-phase circuits, third harmonic currents add rather than cancel in the neutral and can be as much as 1.7 times the phase current for converter loads. Since the neutral conductor is usually sized the same as the phase conductors, the neutral conductor can be overloaded. The problem is most likely to occur in commercial buildings where a three-phase distribution system feeds large single-phase electronic office equipment loads. A survey of actual neutral currents at data processing centers and recommended remedies are presented by Gruz in [8]. The most common fix is to size the neutral conductor to be at least twice the phase conductor ampacity.

Electronic Equipment

There are several mechanisms by which harmonic distortion affects electronic equipment. Multiple voltage zero crossings as a result of harmonic distortion is the first to be considered. It is common for electronic circuits to use the voltage zero crossing of the fundamental power frequency for timing purposes. However, harmonic distortion that causes more frequent zero crossings than the fundamental frequency can disrupt operation of the equipment. A vivid example is a household digital clock that will rapidly advance the time in the presence of additional zero crossing from harmonic distortion. Any device that synchronizes to the zero crossing should be considered vulnerable to disruption by harmonic distortion.

Semiconductors are often switched at zero voltage crossing to reduce electromagnetic interference and inrush current. Multiple crossings can change the switching times of the device and disrupt operation of the equipment. Girgis et al. describe the effect of harmonics on solid state relays in electrophotographic page printers in [9]. They recommend broader window zero crossing switching or random (unsynchronized) switching to minimize the effects of harmonics.

Electronic power supplies use the peak voltage of the waveform to maintain the filter capacitors at full charge. Depending on the harmonic frequency and phase relationship to the fundamental, harmonic voltage distortion can increase or flatten the waveform peak. Consequently, the power supply will be effectively operating with over or under input voltage even though the rms input voltage can be nominal. With severe distortion, equipment operation may be disrupted. A moderately flattened waveform may reduce effective operating voltage to the point that the equipment is vulnerable to minor voltage sags. The waveform crest factor should indicate voltage distortion is a problem. The crest factor is the ratio of the peak of the waveform to the rms value and is $\sqrt{2}$ for a perfect sine wave. Undervoltage due to a flattened waveform is most likely to cause disruption. One computer manufacturer limits crest factor deviations to $\sqrt{2} \pm 0.1$.

Voltage notching can also disrupt operation of electronic equipment. Notches are produced by the commutation of power semiconductors in converters and are quantified by voltage rate of change (dV/dt) and the volt-time product. A voltage notch may cross zero and affect zero crossing sensitive equipment as explained above. For high values of dV/dt, the notch is seen as a voltage step change by the power supply network and can cause the power supply to ring at its natural frequency. As Ludbrook explains [10], the notch, amplified by the power supply resonance, can then disrupt equipment. It is also possible that the high rate of change of voltage associated with the notch can couple through the power supply into digital circuitry and cause a state change that disrupts operation. A large dV/dt may also falsely trigger thyristors into conduction in power circuits. An impedance, either a transformer or reactor, ahead of the notching equipment will reduce the dV/dt to other loads and decrease the resonant excitation of the system. IEEE Standard 519 -1981 [11] provides limits for notching.

Fractional and sub-harmonics can affect video displays or televisions. Fractional harmonics are frequencies that are not integer multiples of the fundamental frequency and sub-harmonics are frequencies below the fundamental. The fractional harmonic produces an amplitude modulation of the fundamental frequency. Fuchs et al. [12] have found that even 0.5% of a fractional harmonic (referred to the rated terminal voltage) produces periodic enlargement and reduction of the image of the cathode ray tube.

Lighting

The incandescent lamp will have a definite loss of life when operated with distorted voltage because lamps are sensitive to operating voltage level. If the operating rms voltage is above the rated voltage due to harmonic distortion, the elevated filament temperature will reduce lamp life. Kaufman presents an expression in [13] that relates for continuous operation at 105% rated rms voltage, lamp life will decrease by 47%.

Aside from audible noise, there is no known effect of harmonic voltage distortion on discharge lighting. Discharge lamps such as low pressure sodium, high pressure metal halide, or fluorescent need inductive ballasts as a series current limiting element. Capacitors are often added to correct the power factor to near unity. Dual fluorescent lamp ballasts use lamp current phase shifting to improve power factor without capacitors. In fixtures with capacitors, the capacitors together with the ballast inductor and the lamp may present a resonance problem. However, the resonant frequency of most lamps is in the range of 75 - 80 Hz and should not interact with the power supply.

Meters

Modern rms responding voltmeters and ammeters are relatively immune to the influences of waveform distortion. In such meters, the input voltage or current is processed using an electronic multiplier. Commonly used multiplier techniques are variable transconductance, log/antilog, time division, thermal, and digital sampling. All of these techniques can be configured to respond to the rms value of the voltage or current, independent of the harmonic amplitude or phase, as long as the harmonics are within the operating bandwidth of the instrument and the crest factor of the waveform is not excessively large.

Test results for modern rms responding voltmeters and ammeters, using a 60 Hz chopped sine wave as the signal yield errors of less than 0.2% due to the non-sinusoidal signal [14]. Firing angles of the chopped sine wave were from 0 to 135° to simulate common applications. The corresponding values of the distortion factor and crest factor (CF) are shown in Table 1.

Firing Angle	DF	CF
0°	0	1.41
45°	0.26	1.48
90°	0.65	2.00
135°	1.31	4.69

Table 1. Distortion Factor and Crest Factor for various firing angles of a chopped sine wave.

Absolute average responding meters which are calibrated in rms and peak responding meters which are calibrated in rms are not suitable in the presence of harmonic distortion. For example, with a chopped sine wave signal at a firing angle of 45°, an absolute averaging meter will indicate an rms value about 13% less than the true rms value. Such an ammeter could indicate that an overloaded conductor is loaded within its rating.

An ideal wattmeter or watthour meter should indicate proportionally to the active power. Errors result from the frequency characteristics of the voltage and current channels of the meter and from nonlinearities. Linearity can be degraded when the power factor is low or waveforms have large crest factors.

In modern wattmeters electronic multiplication of the voltage and current takes place using time division multiplication, digital sampling and multiplying, thermal quarter-square multiplication, or translinear multiplication. All of these are capable of excellent performance. In chopped 60 Hz sine wave tests, with firing angle varied from 0 to 90°, errors due to non-sinusoidal signals were less than 0.1% [15].

The induction disk watthour meter is the most commonly used energy meter. Its registration is subject to errors due to its frequency characteristics and nonlinearities. In 60 Hz chopped sine wave tests, with both load voltage and current wave forms distorted, the registration errors may be as large as -20% (under registration) at a firing angle of 90°. With an undistorted voltage waveform and chopped sine wave load current, registration errors are +5% (over registration) at a firing angle of 90° [16]. Application of an induction watthour meter should be avoided in highly nonsinusoidal situations because of registration errors and the possibility of mechanical resonance failure in the range of 400 - 1000 Hz [15].

The sampling watthour meter calculates energy from digital samples of voltage and current. As in all sampling meters, the bandwidth of the meter is limited by the sampling frequency. Commercial sampling watthour meters provide essentially flat frequency response to input frequencies of over 1200 Hz (20 th harmonic). A 12 bit sampler provides a least significant bit equivalent to 0.024% of full scale. In tests simulating field conditions, with the current having a DF of as much as 88.4% and voltage having a DF of 4.9%, the registration errors of the sampling watthour meter were less than 1%.

Protective Relaying

Waveform distortion does affect the performance of protective relays and may cause relays to operate improperly or to not operate when required. In most cases, the waveform distortion of the load current has little effect on the fault current. However, for low magnitude faults, the load may consist of a large part of the load current and distortion can become a significant factor. Furthermore, the relay must function properly even with distorted load currents.

Every relay performs differently in the presence of waveform distortion. Different manufacturer's models of the same type of relay respond very differently to the same distortion. Relays of the same type and model from one manufacturer may even respond differently to the same distortion. Distortion may cause a relay to fail to trip under fault conditions, or it may cause nuisance tripping when no fault exists. Varying the phase angle between the fundamental and harmonic components of a voltage or current waveform may significantly alter a relay's response. For dual input relays, performance can be affected by the phase relationship between the respective input harmonics. Most studies conclude it is very difficult to predict performance of the relay without testing. The studies published have evaluated electromechanical and electronic relays but there is no information on the new digital relays [17-23].

Rotating Machines

Nonsinusoidal voltages applied to electric machines may cause overheating, pulsating torques, or noise. In addition to across the line applications, adjustable speed drive motors are fed from inverters that can produce significant voltage distortion.

Rotor overheating has been the main problem associated with voltage distortion [24-34]. Losses in electric machines are dependant upon the frequency spectrum of the applied voltage. Core and stray losses may become significant in an induction motor with a skewed rotor supplied from an inverter producing high harmonic frequencies [6,32,34]. An increase in motor operating temperature will cause reduction of the motor operating life. Single phase motors are the most affected [12,25,26]. The temperature rise is not uniform throughout the motor; hot spots appear near the conductors within the iron core portions. If the harmonics are time varying, the motor can tolerate higher peak distortion levels without increasing the hot spot temperature [2]. This is possible because the motor thermal time constant is much longer than the period of the harmonic variation.

Several loss factors may be defined to evaluate the weight of the various motor losses throughout the entire harmonic spectrum. Murphy and Egan [28] evaluate several strategies for pulse-width-modulated (PWM) inverters by using a comparative copper-loss factor, L, that neglects the skin effect

$$L = \sum (V_n / f_n)^2 \qquad n = 2, 3, 4... \qquad (5)$$

where V_n is the applied nth harmonic voltage and f_n is the nth harmonic frequency. Although this approach may be an over-simplification of the harmonic losses, it could be quite useful when evaluating different PWM schemes.

Boys and Walton [29] propose to add a third harmonic to the PWM reference signal to alter the harmonic spectrum of sinusoidal PWM inverters and thus reduce motor losses.

Connors et al. [31] emphasize that harmonic losses are also dependant upon the motor characteristics. The motor leakage impedance will increase linearly with harmonic frequency. To reduce harmonic currents with a voltage source inverter, a large leakage inductance is necessary. On the other hand, current source inverters inject harmonic currents into the motor and, thus, a small leakage inductance is preferred to reduce the harmonic voltages.

Pulsating torques are produced by interaction between the air gap flux (mainly the fundamental component) and the fluxes produced by the harmonic currents in the rotor [28,38,39]. Fixed speed induction motors have been traditionally designed to place the operating speed approximately 30 - 40% above the first critical mechanical speed [39]. For adjustable speed drive motors, an analysis of the mechanical resonance speeds is necessary to avoid any damage due to amplification of pulsating torques [28,30,38-40].

References [41-43] conclude that audible noise is produced by the difference between time harmonic frequencies. Therefore, inaudible high frequency harmonics can also contribute to audible noise.

Telephone Interference

The juxtaposition of telephone and power lines on utility poles creates opportunities for power frequency interference with telephone communication. Since human hearing sensitivity and telephone response peak near 1 kHz, power system harmonic frequencies can present greater problems than fundamental frequency. The interference can be expressed by several different measures that are discussed in [6] and [11]. One of the measures is the telephone influence factor (TIF) that incorporates frequency, magnitude, and a weighting factor for the frequency. A common measure is the IT product which is the product of the rms current and the TIF. An IT product of less than 10,000 should not cause problems while a product of over 25,000 probably will cause interference problems.

There are four mechanisms of coupling the power line to the telephone line. One is loop induction in which the power line magnetic field induces a voltage in the loop formed by the two telephone conductors. The standard practice of power conductor transposition or twisted telephone pairs limits this mechanism. The second mechanism is similar to the first except that the loop formed is between a telephone conductor and the earth. The path through the ground is created by the ground connections at opposite ends of the circuit. Since the area of the loop can be very large, this mechanism is the most common type of interference.

The third mechanism is capacitive coupling between the power conductor and the phone conductor. The inter-conductor and conductor-to-ground capacitances form a voltage divider for the power conductor potential. Single line power conductors and the reduced capacitive reactance at harmonic frequencies increase interference. Shielding the telephone conductors is effective at eliminating capacitive coupling.

The last mechanism is conductive coupling in which a local ground potential rise due to the power neutral is applied to the grounded telephone conductor. This creates a potential between the elevated ground point and the distant ground point on the telephone circuit. A poor power neutral connection may cause abnormal local ground potential rise resulting in this form of interference.

Where the above discussed mitigation techniques techniques are not applicable or successful, the harmonics may be reduced or a filter added. Both Arrillaga et al. [6] and an IEEE committee report [44] discuss the mechanisms and mitigation techniques in greater detail.

Transformers

The primary effect of power system harmonics on transformers is the additional heat generated by the losses caused by the harmonic content of the load current. Other problems include possible resonance between the transformer inductance and system capacitance, mechanical insulation stresses (winding and lamination) due to temperature cycling and possible small core vibrations [26].

The additional heating caused by system harmonics requires load capability derating to remain within the temperature rating of the transformer or use of speciality transformers designed for nonsinusoidal load currents. Transformer life will be reduced as the result of operating above rated temperatures.

The primary loss components are winding I^2R losses, winding eddy-current losses and stray losses from electromagnetic flux in areas such as windings, core, clamp assemblies and tanks. The losses due to the I^2R component will be due to conductor heating and the skin effect. Losses from the winding eddy-current will increase with the square of the load current and the square of the frequency. Other stray losses will also increase with frequency although at a power slightly less than two [45].

Several IEEE standards provide guidelines on transformer loading and capability [46-48]. The loading guides are based on load current distortion factor limits of 0.05 per unit as stated in IEEE/ANSI C57.12.00-1987 [49] and C57.12.01-1989 [50].

IEEE/ANSI Standard C57.110-1986, "IEEE Recommended Practice for Establishing Transformer Capability when Supplying Nonsinusoidal Load Currents" [45], recognizes that load currents, in many cases, exceed the distortion factor limit of 0.05 per unit. This standard outlines two methods to determine transformer capability with nonsinusoidal load currents without loss of normal life expectancy. Both methods require knowledge of the load current characteristics. The first method requires detailed transformer design data and the second method relies on data available in certified test reports.

Both methods are based on the premise that all stray losses results from winding eddy currents and these losses increase with the square of the current and frequency. The per unit winding eddy current losses are expressed as

$$P_{ec} = P_{ec\text{-}r} \sum I_n^2 n^2 \quad n = 1, 2, 3, 4... \qquad (6)$$

where

P_{ec} = winding eddy current loss (per unit of rated I^2R loss)
$P_{ec\text{-}r}$ = winding eddy current loss at rated load and frequency (per unit of rated I^2R loss)
I_n = rms current of the n harmonic (per unit of rated load rms current)
n = harmonic order.

Hwang et al. have shown that for low order harmonics through the 9th, the above equation is valid [51]. However, for the 11th through the 25th order harmonic, the losses vary with n to the power of 1.94 to 1.98 in (6). This would increase the conservatism of the results obtained with the methods in the standard.

Current standards outline transformer overvoltage ratings on an rms steady state basis. The maximum overvoltage is 5% at rated load and 10% at no load [49]. These limits include any contribution resulting of harmonic waveform distortion.

The loading of a delta connected transformer may be misleading because of circulating triplen harmonic currents. Balanced triplen harmonic load currents (3rd, 6th, 9th, etc.) will circulate in a transformer delta connection and not appear in the primary conductors. Consequently, current measurements on the primary will not reflect true transformer loading. Single phase electronic loads are rich in third harmonic current and 3-phase transformers feeding these loads are susceptible to this condition.

As of this writing, transformer ratings are being developed that can incorporate large harmonic loads. Underwriters Laboratories, Inc is investigating a rating factor for dry-type power transformers based on UL 1561, "Standard for Dry-Type General Purpose and Power Transformers" and IEEE/ANSI C57.110. This factor is $I_n^2 n^2$ from (6) and is defined as the *K factor* by Dini in [52]. For example, transformers that meet the testing requirements for a K factor of four will be capable of carrying rated load within rated temperature limits at harmonic loading that produces four times the rated eddy current losses. Greater K factor indicates increased harmonic current capability.

CONCLUSION

There are two major categories of harmonic effects of on equipment. The first is heating effects in power handling equipment such as motors, capacitors, and transformers that, most often, reduce equipment operating life. The second category is disruption of operation that includes, for the most part, electronically controlled equipment. Perhaps because power handling equipment represents a more mature technology, there is better documentation and quantification of problems for this group of equipment. On the other hand, possibly because of the rapid growth of electronics, the documentation of harmonic problems associated with electronic equipment of almost every type is deficient. Where it does exist, it is almost always qualitative or anecdotal. For example, the enormous growth in the application of adjustable speed motor drives has generated numerous papers on the current harmonics these drives create. Yet there are no published accounts, to the authors' knowledge, of the effects of voltage harmonics on the drives.

The aura of mystery surrounding the subject of harmonics distortion is partially due to the lack of information on the disruption mechanisms and robustness of equipment. Harmonic standards are being developed with only a partial understanding of the impact on equipment operation. It is imperative that work to understand the effects of harmonics on equipment be accelerated.

REFERENCES

[1] IEEE Task Force, "The Effects of Power System Harmonics on Power System Equipment and Loads," *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-104, No. 9, Sept. 1985, pp 2555 - 2563.

[2] A. E. Emanuel, "Estimating the Effects of Harmonic Voltage Fluctuations on the Temperature Rise of Squirrel-Cage Motors," *IEEE Trans. Energy Conversion*, Vol. 6, No. 1, Mar 1991, pp. 162-169.

[3] F. Lembo and V. H. D'Onofrio., "Distribution Harmonics Cause Breaker Problems," *Electrical World*, Sept 1981, pp 121- 122.

[4] J. P. Brozek, "The Effects of Harmonics on Overcurrent Protection Devices," *Proc. 1990 IAS*, 1990, pp 1965 - 1967.

[5] A. E. Kennelly, F. A. Laws, and P. H. Pierce, "Experimental Researches on Skin Effects in Conductors," *Trans. AIEE*, 34, 1915, pp. 1953 - 2018.

[6] J. Arrillaga, D. A. Bradley, and P. S. Bodger, *Power System Harmonics*, John Wiley & Sons, 1985.

[7] D. E. Rice, "Adjustable Speed Drive and Power Rectifier Harmonics - Their Effect on Power System Components," *IEEE Trans. Industrial Applications*, Vol IA-22, No. 1, Jan/Feb 1986, pp 161 - 177.

[8] T. M. Gruzs, "A Survey of Neutral Currents in Three-Phase Computer Power Systems," *IEEE Trans. Industrial Applications*, Vol 26, No. 4, Jul/Aug 1990, pp 719 - 725.

[9] A. A. Girgis., J. W. Nims, J. Jacamino, J. G. Dalton, and A. Bishop, "Effect of Voltage Harmonics on the Operation of Solid State Relays in Industrial Applications," *Proc. 1990 IAS*, Part II, pp 1821 - 1828.

[10] A. Ludbrook, "Harmonic Filters for Notch Reduction," *IEEE Trans. Industrial Applications*, Vol. 24, No. 5, Sept/Oct 1988, pp 947 - 954.

[11] IEEE Standard 519-1981, Guide for Harmonic Control and Reactive Compensation of Static Power Converters.

[12] E. F. Fuchs, D. J. Roesler, and K. P. Kovacs, "Sensitivity of Electrical Appliances to Harmonics and Fractional Harmonics of the Power System's Voltage. Part II: Television Sets, Induction Watthour Meters and Universal Machines," *IEEE Trans. Power Delivery*, Vol. PWRD-2, No. 2, April 1987.

[13] J. E. Kaufman, ed., *IES Lighting Handbook*, Illuminating Engineering Society of North America, New York, 1981.

[14] N. M. Oldham. and T. L. Nelson, "Influence of Non-sinusoidal Waveforms on Voltmeters, Ammeters, and Phase Meters," IEEE Publication 90 EH 0327-7-PWR (IEEE tutorial course).

[15] P. S. Filipski and R. Arseneau, "Behavior of Wattmeters and Watthour Meters Under Distorted Waveform Conditions," IEEE Publication 90 EH 0327-7-PWR (IEEE tutorial course).

[16] S. Goldberg and W. F. Horton, "An Experimental Study of the Effects of Non-Sinsoidal Currents on the Registration of Induction Watthour Meters," *Proceedings of the 21st Annual North American Power Symposium*, University of Missouri-Rolla, Oct. 9-10, 1989.

[17] IEEE PES Power System Relaying Committee, "Fault Induced Wave Distortion of Interest to Relay Engineers," *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-104, No. 12, December 1985, pp. 3574-3584.

[18] IEEE PES Power System Relaying Committee, "Sine-Wave Distortions in Power Systems and the Impact on Protective Relaying," 84 TH 0115-6 PWR, 1984.

[19] F. A. Jost, D. F. Menzies, and S. W. Sachdev, "Effects of System Harmonics on Power System Relays," *Transactions of the Operation and Planning Division of the Canadian Electric Association Conference*, Vol. 3, March 1974.

[20] D. E. Saramaga, R. W. Menzies, and G. W. Swift, "Effect of Harmonic Currents on Induction Disc Operating Torque," IEEE Conference Paper PESC 73351-4.

[21] Wave Distortion on Consumer's Interconnection Working Group, "The Impact of Sine-Wave Distortions on Protective Relays," *IEEE Trans. Industrial Applications*, Vol. IA-20, No. 2, March/April 1984, pp. 335-343.

[22] W. F. Horton and S. Goldberg, "The Effect of Harmonics on the Operating Points of Electromechanical Relays," *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-104, No. 5, May 1985, pp. 1178-1186.

[23] W. T. Jewell, "The Effects of Voltage and Current Distortion on Power System Protective Relay Operation," Final Report for KEURP Project 245, Kansas Electric Utilities Research Program, P.O. Box 1007, Topeka, Kansas, 66601-1007. September 1989.

[24] C. J. Erickson, "Motor Design Features for Adjustable-Frequency Drives," *IEEE Trans. Industrial Applications*, Vol. 24, No. 2, Mar/Apr 1988, pp. 192-198.

[25] E. F. Fuchs, D. J. Roesler, and F. S. Alashhab, "Sensitivity of Electrical Appliances to Harmonics and Fractional Harmonics of the Power System's Voltage. Part I: Transformers and Induction Machines," *IEEE Trans. on Power Delivery*, Vol. PWRD-2, No. 2, Apr 1987, pp. 437-444.

[26] E. F. Fuchs, D. J. Roesler, and K. P. Kovacs, "Aging of Electrical Appliances due to Harmonics of the Power System's Voltage," *IEEE Trans. Power Delivery*, Vol. PWRD-1, No. 3, Jul 1986, pp. 301-307.

[27] R. A. Hanna, "Harmonics and Technical Barriers in Adjustable Speed Drives," *IEEE Trans. Industry Applications*, Vol. 25, No. 5, Sep/Oct 1989, pp. 894-900.

[28] J. M. D. Murphy and M. G. Egan, "A Comparison of PWM Strategies for Inverter-Fed Induction Motors," *IEEE Trans. Industry Applications*, Vol. IA-19, No. 3, May/Jun 1983, pp. 363-369.

[29] J. T. Boys. and S. J. Walton, "A Loss Minimisied Sinusoidal PWM Inverter," *IEE Proceedings*, Vol. 132, Pt. B, No. 5, Sept 1985, pp 260-268.

[30] E. C. Anderesen and K. Bieniek, "On the Torques and Losses of Voltage- and Current-Source Inverter Drives," *IEEE Trans. Industry Applications*, Vol. IA-20, No. 2, Mar/Apr 1984, pp. 321-327.

[31] D. P. Connors, D. A. Jarc, and R. H. Daugherty, "Considerations in Applying Induction Motors with Solid-State Adjustable Frequency Controllers," *IEEE Trans. Industry Applications*, Vol. IA-20, No. 1, Jan/Feb 1984, pp. 113-121.

[32] R. M. Green and J. T. Boys, "Inverter AC-Drive Efficiency," *IEE Proceedings*, Vol. 129, Pt. B, No. 2, Mar 1982, pp. 75-81.

[33] F. G. G. de Buch, P. Gistelinck, and D. de Backer, " A Simple but Reliable Loss Model for Inverter-Supplied Induction Motors," *IEEE Trans. Industry Applications*, Vol. IA-20, No. 1, Jan/Feb 1984, pp. 190-202.

[34] D. S. Kirschen, D. W. Novotny, and W. Suwanwisoot, "Minimizing Induction Motor Losses by Excitation Control in Variable Frequency Drives," *IEEE Trans. Industry Applications*, Vol. IA-20, No. 5, Sep/Oct 1984, pp. 1244-1250.

[35] M. K. Jamil. and N. A. Demerdash, "Effects of Chopper Control Circuits on Core Losses of Permanent Magnet DC Motors," *IEEE Trans. Magnetics*, Vol. 25, No. 5, Sep 1989, pp. 3572-

3574.

[36] M. K. Jamil and N. A. Demerdash, "Harmonic Analysis of Permanent Magnet DC Motors Operated by Chopper Control Circuits," *Proc. 1989 IEEE-PESC*, pp. 799-806.

[37] M. K. Jamil and N. A. Demerdash, "Harmonics and Core Losses of Permanent Magnet DC Motors Controlled by Chopper Circuits," *IEEE Trans. Energy Conversion*, Vol. 5, No. 2, Jun 1990, pp. 408-414.

[38] S. R. Bowes and R. I. Bullough, "Harmonic Minimisation in Microprocessor Controlled Current Fed PWM Drives," *IEE Proceedings*, Vol. 134, Pt. B, No. 1, Jan 1982, pp. 25-41.

[39] R. J. M. Belmans, A. J. Vandenput, and W. Geysen, "Influence of Unbalanced Magnetic Pull on the Radial Stability of Flexible-Shaft Induction Machines," *IEE Proceedings*, Vol. 134, Pt. B, No. 2, Mar 1987, pp. 101-109.

[40] D. J. Sheppard, "Torsional Vibration Resulting from Adjustable-Frequency AC Drives", *IEEE Trans. Industry Applications*, Vol. 24, No. 5, Sep/Octr 1988, pp. 812-817.

[41] R. J. M. Belmans, L. D'Hondt, A. J. Vandenput, and W. Geysen, "Analysis of the Audible Noise of Three-Phase Squirrel-Cage Induction Motors Supplied by Inverters," *IEEE Trans. Industry Applications*, Vol. IA-23, No. 5, Sep/Oct 1987, pp. 842-847.

[42] R. J. M. Belmans, D. Verdyck, W. Geysen, and T. Findlsy, "Electro-Mechanical Analysis of the Audible Noise of an Inverter-Fed Squirrel-Cage Induction Motor," *Proc. 1989 IEEE-IAS*, San Diego CA, Oct 1-5, 1989 pp. 232-237.

[43] A.K. Wallace, R. Spree, and L. G. Martin, "Current Harmonics and Acoustic Noise in AC Adjustable-Speed Drives," *IEEE Trans. Industry Applications*, Vol. 26, No. 2, Mar/Apr 1990, pp. 267-273.

[44] IEEE Working Group, "Power Line Harmonic Effects on Communication Line Interference", *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-104, No. 9, Sept 1985, pp. 2578-2587.

[45] ANSI/IEEE Standard C57.110-1986, Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.

[46] ANSI/IEEE Standard C57.91-1981, Guide for Loading Mineral-Oil-Immersed Overhead and Pad-Mounted Distribution Transformers Rated 500 kVA and Less with 65°C or 55°C Average Winding Rise.

[47] ANSI/IEEE Standard C57.92-1981, Guide for Loading Mineral-Oil-Immersed Power Transformers Up to and Including 100 MVA with 65°C or 55°C Average Winding Rise.

[48] ANSI/IEEE Standard C57.96-1989, Guide for Loading Dry-Type Distribution and Power Transformers.

[49] ANSI/IEEE Standard C57.12.00-1987, General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

[50] ANSI/IEEE Standard C57.12.01-1989, General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin-Encapsulated Windings.

[51] M. S. Hwang, W. M. Grady, and H. W. Sanders, Jr., "Distribution Transformer Winding Losses Due to Nonsinusoidal Currents," *IEEE Trans. Power Delivery*, Vol. PWRD-2, Jan. 1987, pp. 140-146.

[52] D. A. Dini, "The Nature of Harmonic Distortion and Its Impact on Electrical Safety," *IAEI News*, Jul/Aug 1991, pp. 33-37.