DOE/RA/50150--23

DE87 008018

INVESTIGATIONS ON THE IMPACT OF VOLTAGE AND CURRENT HARMONICS ON END-USE DEVICES AND THEIR PROTECTION

Summary Report
for Period January 1, 1980 - June 30, 1986

E. F. Fuchs

University of Colorado
Boulder, Colorado 80309

January 1987

Prepared for

THE U.S. DEPARTMENT OF ENERGY
CONTRACT No. DE-AC02-80RA 50150

ABSTRACT

After defining the relation between harmonic voltages and currents through harmonic impedances, the impact of harmonics on electromagnetic end-use devices such as transformers and machines is formulated based on analytical and experimental investigations. A harmonic factor representing the square of a weighted total harmonic distortion factor provides a mechanism for estimating the reduction of lifetime of electromagnetic end-use devices due to additional losses generated by sets of harmonics of frequencies below 2000 Hz. The forces and torques of saturable three-phase induction machines during starting and steady-state operation are computed from magnetic field solutions. Within the above frequency range the accuracy of induction watthour meters is reduced and the impact of harmonics or fractional harmonics (which exhibit a frequency other than those of harmonics and subharmonics) on distribution system relays can be severe. Also, the performance of television sets deteriorates for fractional harmonics below 2000Hz. The impact of harmonics on shunt capacitors limits the harmonic amplitudes with frequencies above 2000Hz. Depending upon the size of the system impedance either the harmonic voltages or the harmonic currents will be predominant. For small impedances the values of the harmonic currents will be limited by the permissible harmonic current loading of pole and substation transformers, whereas for large impedances the harmonic voltage amplitudes will be limited by the permissible additional losses in parallel connected electromagnetic end-use devices. The propagation of harmonics within a distribution feeder is such that for dispersed harmonic sources of the same kind no significant cancelling of harmonic amplitudes occurs. Under certain circumstances the propagation of harmonics within a distribution feeder can cause resonances.

INTRODUCTION

The major goal of this study, sponsored by the Electric Energy Systems Program of the U.S. Department of Energy (DOE), was to determine the impacts of both current and voltage harmonics as well as fractional* harmonics on single- and three-phase transformers and induction motors, universal machines, television sets, induction watthour meters and distribution system protection relays. In addition, the propagation and possible cancelling of harmonics within a distribution system have been evaluated. Analytical and experimental investigations were performed to establish a correlation between temperature rise and lifetime reduction due to thermal aging of electromagnetic devices and to determine the decrease in performance of television sets, induction watthour meters, electromechanical and solid-state relays as employed for power distribution system protection. A harmonic factor was developed and used to evaluate the effects of temperature rise and corresponding reduction of life on electromagnetic equipment due to voltage harmonics. This evaluation technique can also be used to determine guidelines for acceptable levels of harmonic and fractional harmonic contents in distribution systems.

BACKGROUND

Ideal voltage and current waveforms in a power system are sinusoidal. In reality, however, a number of devices produce nonsinusoidal currents and voltage distortions in the electric power system. Distorted waveforms can be thought of as the sum of several sinusoidal components of different magnitudes and frequencies. Components having frequencies which are integer multiples of the fundamental are referred to as harmonics. Components with frequencies which are submultipes of the fundamental are called subharmonics. Those components with frequencies which are neither an integer multiple nor a submultipe of the fundamental will be referred to as fractional harmonics. The level of distortion is commonly given by the total harmonic distortion factor (THD) which is calculated as the square root of the sum of the squares of each harmonic current or voltage expressed in percentage of the fundamental. At present the THD of the voltage in residential power systems is in the range of one to four percent.

There are three major harmonic issues to be considered in a power system: sources of harmonics, propagation of harmonics, and the impact of harmonics on end-use devices such as single- and three-phase transformers and induction motors, universal machines, television sets, induction watthour meters and distribution system relays. Major harmonic sources are nonlinear circuit elements, such as switched-mode power converters, power electronic devices for motor control, generators for furnaces, and saturated transformers [1]. Harmonic propagation depends on the impedance that the power system presents to the harmonic source. Current and voltage harmonics are related by the system impedance. Voltage harmonics can be neglected in high voltage networks because of their high short-circuit capacity and stiffness [2]. In other words, a high voltage network can be considered as an infinite bus with negligible voltage distortion. Since most harmonic sources are located in the distribution system, the harmonic content of the voltage can be expected to be higher than that of high voltage networks. Therefore, the effect of voltage harmonics on parallel low voltage loads is more significant. This report only considers the effects of voltage harmonics for application loads which are connected in parallel at distribution voltage levels. The effects of currents harmonics are studied for capacitors and overcurrent relays within a distribution feeder. The impacts of harmonics that have been evaluated include additional losses, audible noise and vibration, decreasing useful motor torques, decreasing power factors, decreasing performance of television sets and distribution protection relays, and increasing reading errors of induction watthour meters.

RESEARCH DISCUSSION AND RESULTS

The investigations were performed analytically and experimentally. First, equivalent models for the different devices were developed from which analytical expressions were derived to calculate the additional losses due to harmonics. The analytical results were then validated through actual testing.

Figure 1 shows the typical test set-up to determine the impact of harmonics and fractional harmonics on the operation of induction watthour meters, single-phase and three-phase induction motors, universal motors, relays, and transformers. All devices were tested with rated voltages or currents applied to their terminals. A locked-phase frequency generator permitted a continuous phase shifting of any harmonic or fractional harmonic with respect to the fundamental. The frequency ranges used during testing were as follows: 1) between 90 and 960 Hz for induction watthour

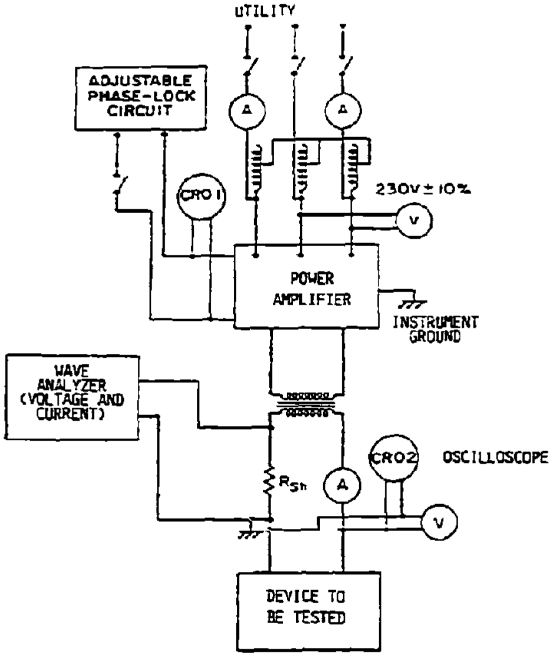

Figure 1 Typical test set-up to measure impact of voltage and current harmonics

---

* All other sinusoidal voltage and current components not being harmonic or subharmonic are called fractional harmonics.

meters, relays, universal machines, single- and three-phase transformers and induction motors; 2) between 30 and 1000 Hz for color television sets; and 3) between 30 and 2000 Hz for black-and-white television sets.

1. Harmonic Impedances

At the outset of any investigation of the influence of harmonics on end-use devices one has to define the magnitudes and frequencies of voltage and current harmonics which may have a detrimental influence on the performance of such devices. It is well known that solid-state circuits and other nonlinear devices of the power system generate harmonic currents [3] which result in a harmonic voltage drop across the power system impedance and produce amplitude modulations of the power system voltage. In addition, certain components of the power system, e.g. cycloconverters and induction motors, may generate either subharmonics, harmonics or fractional harmonics. Most single- and three-phase induction motors generate fractional harmonics within the rotating flux wave and the terminal currents due to the choice of the stator and the rotor slots or because of air gap eccentricity [4]. Figure 2 shows the voltages induced within two full-pitch search coils placed in quadrature within the stator of a 2 hp single-phase induction motor. Note that some of the harmonic orders are not an integer multiple of 60 Hz and therefore produce a nonstationary image on the oscilloscope screen.

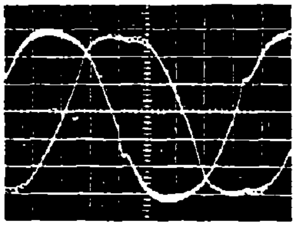

Figure 2 The generation of fractional harmonics within an induction motor.

For a given injected current harmonic amplitude the generated voltage modulations are dependent upon the power system impedance measured at the location where the injection occurs. To estimate the magnitudes of occurring harmonics within an urban residential distribution system an equivalent power system impedance has been determined for a single-phase (Figure 3a) as well as for a three-phase (Figure 3b) network at 60 Hz [5].

From Figure 3a one obtains for the harmonic voltage drop across the line-to-line impedance

$$V_{(l-l)\nu}^{single,urban} = \frac{\sqrt{(0.102)^2 + \nu^2(0.0252)^2}}{2V_{l-N}} \cdot I_\nu \cdot 100\%, \quad (1)$$

where ν is the harmonic order. For the harmonic voltage drop across the line-to-neutral (centertap) impedance

$$V_{(l-n)\nu}^{single,urban} = \frac{\sqrt{(0.0984)^2 + \nu^2(0.0188)^2}}{V_{l-N}} \cdot I_\nu \cdot 100\%. \quad (2)$$

From Figure 3b the following harmonic voltage drops result

$$V_{(l-n)\nu}^{three,urban} = \frac{\sqrt{(0.752)^2 + \nu^2(0.0157)^2}}{V_{l-N}} \cdot I_\nu \cdot 100\%, \quad (3)$$

and

$$V_{(l-l)\nu}^{three,urban} = \frac{2\sqrt{(0.051)^2 + \nu^2(0.0126)^2}}{\sqrt{3}V_{l-N}} \cdot I_\nu \cdot 100\%. \quad (4)$$

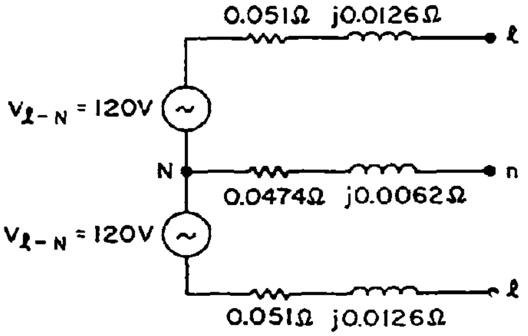

Figure 3a Equivalent circuit of a single-phase system.

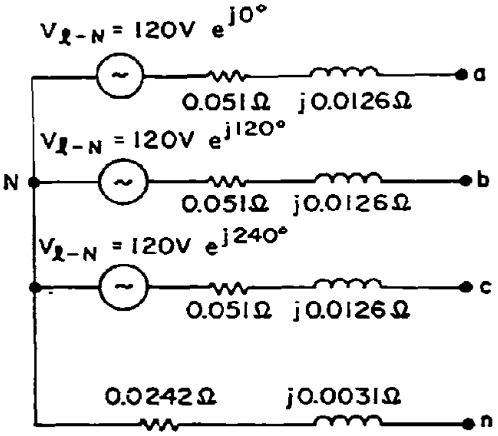

Figure 3b Equivalent circuit of a three-phase system.

For rural distribution feeders the system impedances tend to be larger than those of urban systems, therefore for a given current harmonic amplitude I_ν the voltage harmonics will be correspondingly larger.

Example: For an assumed third harmonic ($\nu = 3$) current amplitude, $I_3 = 20\%$ one obtains from Eq. 2 for the third harmonic line-to-neutral (centertap) voltage $V_{(l-n)3}^{single,urban} =$ 2.27% of the fundamental voltage. If one supposes that the corresponding impedance of a rural single-phase system is three times larger than that of the urban system (Eq. 2) one would get $V_{(l-n)3}^{single,rural} =$ 6.81% of the fundamental voltage.

2. Investigations of Transformers and Machines

Voltage harmonics generate additional ohmic and iron losses in the windings and the iron cores of transformers [6] and electric machines [7 to 12]. A theoretical linear analysis was used to predict these additional ohmic and iron-core losses taking into account the effects of eddy currents in the core laminations. The analysis shows that these losses depend upon the applied harmonics, the thickness of the core lamination and other characteristics of the core material. In saturable circuits, e.g., transformers and electric machines, the iron losses depend upon the maximum excursions of the flux density within the iron portions. Since the phase shifts of the flux density harmonics with respect to the fundamental determine the peak-to-peak value of the resultant flux density, these harmonic phase shifts influence the iron-core losses of nonlinear magnetic devices. It is important to point out that this discussion involves transformers and machines found in end-use devices only. The analytical and experimental investigations were performed on single- and three-phase transformers and induction machines, as well as on universal machines. In order to illustrate the experimental results, the single-phase induction motor is used here as an example. Results for the other devices can be found in References [6 to 12].

Calculated total harmonic losses in the stator and rotor of a typical single-phase, 2 hp, squirrel cage, induction motor operating at rated load are plotted in Figures 4 and 5, respectively, for harmonic voltage amplitudes of 5%, 7.5% *and* 10%. These calculations were based on technical and design data supplied by the manufacturer. Note that the additional harmonic losses are higher for the rotor than those for the stator from a percentage point of view. For a harmonic frequency of 180 Hz and a THD of 7.5% the rotor losses are about 3.5% while the stator losses are about 2.5%. For comparison purposes it is assumed that the cooling properties of the electromagnetic device are not changed due to the additional temperature rise, and the additional losses are proportional to the additional temperature rises. This is true for additional losses or temperature rises which are small as compared to the rated losses and temperature rises, respectively. Therefore, temperature rises can be compared with the above losses on a percentage basis. In all cases, the additional losses were calculated for full-load condition assuming linear or linearized iron-core characteristics.

Experimental studies verified that the additional temperature rise due to voltage harmonics in single-phase transformers and induction machines depends upon the amplitudes and the phase shifts of the voltage harmonics. Figure 6 and Figure 7 depict the additional temperature rise in the windings of the same 2 hp, squirrel cage motor at full

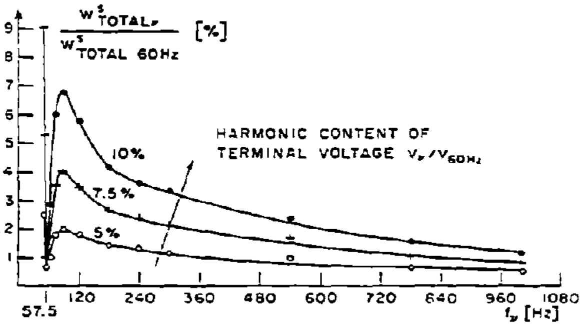

Figure 4 Calculated total harmonic losses of the stator referred to the rated losses of the stator at a full load as a function of the harmonic frequency for a 2 hp, single-phase motor.

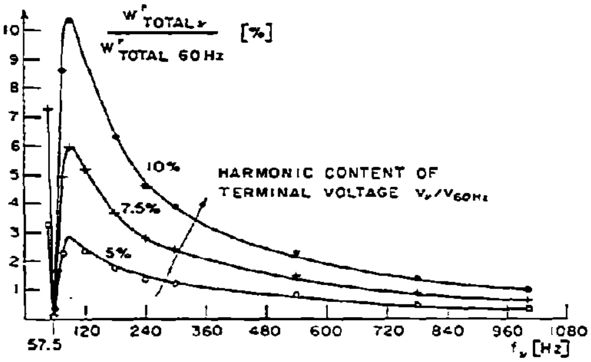

Figure 5 Calculated total harmonic losses of the rotor referred to the rated losses of the rotor at a full load as a function of the harmonic frequency for a 2 hp, single-phase motor.

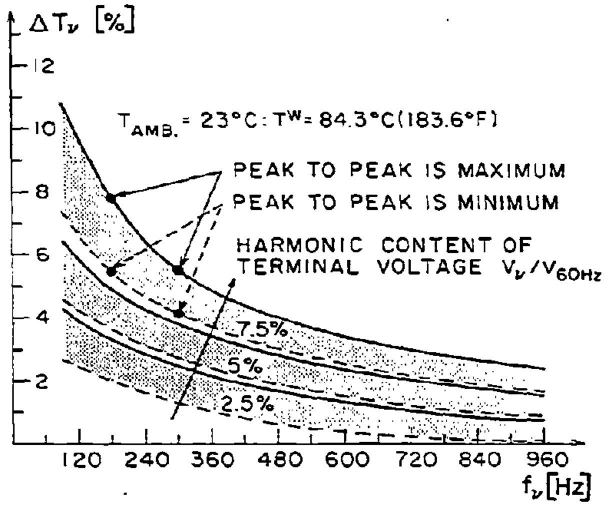

Figure 6 Measured additional temperature rise of the stator-end winding at full load as a function of the harmonic voltage amplitude, phase shift and frequency for a 2 hp single-phase induction machine.

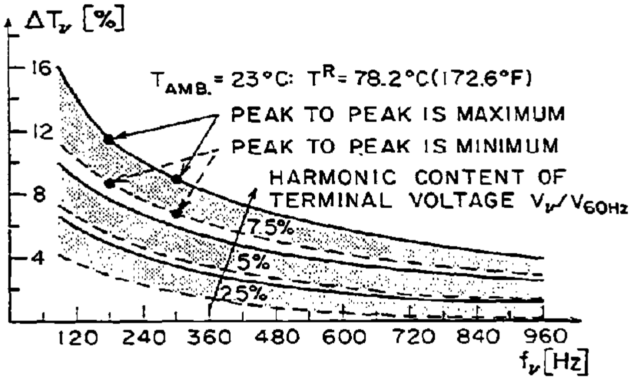

Figure 7 Measured additional temperature rise of the squirrel-cage rotor winding at full load as a function of the harmonic voltage amplitude, phase shift and frequency for a 2 hp single-phase induction machine.

load. Note that at 180 and 300 Hz the maximum additional temperature rises occur when the peak-to-peak value of the terminal voltage is a maximum. In addition, for a given harmonic content the percentage additional temperature rise is higher in the rotor windings than in the stator windings. For instance, for a frequency of 180 Hz and a THD of 7.5% the temperature rise for the stator is between 5 and 8% while for the rotor it is between 9 and 12%. Similarly,additional temperature rises occur in universal machines, three-phase transformers and induction machines.

Temperatures at no load are relatively low. Therefore, large harmonic voltage amplitudes could be superimposed on the rated voltage without resulting in excessive temperature increases. In the no load case, the maximum additional temperature rise is also obtained at 180 and 300 Hz when the peak-to-peak value of the terminal voltage is a maximum.

The reasons for the discrepancies between the calculated (Figures 4 and 5) and measured characteristics (Figures 6 and 7) lie in the insufficient modelling of the single-phase machine with respect to harmonics: the iron-nonlinearity (and therefore the harmonic phase shift dependency) was neglected, the eddy current losses in the iron sheets were assumed to be uniform throughout the machine and the calculated losses were assumed to produce an average temperature. The measured temperature values (hot spot) are considered to be more accurate than the calculated harmonic losses since each temperature run has been repeated at least once. It can be seen, however, that the calculated shapes of the loss characteristics agree with those of the measured temperature characteristics. Differences between the calculated and measured characteristics for transformers and other electromagnetic devices are also the result of insufficient modeling. Therefore, improvement in the models is desirable.

3. Harmonic Factor

The voltage harmonic content (order, amplitude and phase shift) of power systems varies with the type and size of harmonic generators and loads as well as with the topology of the system. Since voltage harmonics result in additional losses and temperature rises in electromagnetic devices, it would be desirable to derive one single criterion that can predict these losses and temperature rises as a function of the harmonic content of their terminal voltage. This single criterion, called the "Harmonic Factor," is defined as the ratio of the ohmic and iron losses due to the harmonic voltages to the ohmic and iron losses due to the fundamental. The harmonic factor is a weighted total harmonic distortion factor representing additional temperature rises in electromagnetic equipment due to the harmonics in the terminal voltage and is expressed for temperature rises in terms of harmonic voltage frequency and amplitudes as

$$\Delta T_\nu = C_1 \sum_{\nu=2}^{\infty} \frac{1}{\nu^k} \left(\frac{V_\nu}{V_1}\right)^l, \qquad (5)$$

where

ν is the order of the harmonic frequency,
V_ν is the harmonic voltage of order ν,
ΔT_ν is the additional temperature rise due to voltage harmonic V_ν,
C_i is a constant of proportionality relating temperature rise and harmonic voltage frequency and amplitude,
k, l are functions of both the harmonic frequencies and the amplitudes of the harmonic voltages as well as the type of electromagnetic end-use device.

Based on the theoretical and experimental studies, values for the exponents k and l of the harmonic factor can be derived (see Table I).

Table I
Values for exponents k and l

Apparatus	k	k_{av}	l	l_{av}
single-phase transformer	0.6-1.2	0.90	1.5-2.0	1.75
three-phase transformer	0.6-1.2	0.90	1.5-2.0	1.75
single-phase ind. machine	0.5-1.2	0.85	1.0-1.8	1.40
three-phase ind. machine	0.7-1.2	0.95	1.2-2.0	1.60
universal machine	0.8-1.2	1.00	1.5-2.5	2.00

Knowing the harmonic factor, the corresponding additional temperature rises can be calculated for the different types of electromagnetic devices. It is evident from Figure 8 that single- and three-phase induction machines are more sensitive to voltage harmonics than transformers and universal machines. For a harmonic factor of 5.8% the temperature of a single-phase induction motor and a three-phase induction machine will rise about 6.2% and 3.2% of the rated temperature, respectively. However, for the same value of harmonic factor the temperature rise of single- and three-phase transformers and universal machines will be only 0.85%. This difference occurs because the harmonic currents are limited by the load of transformers as used in end-use devices while in an induction machine the total rotor circuit resistance becomes very small for large harmonic slips.

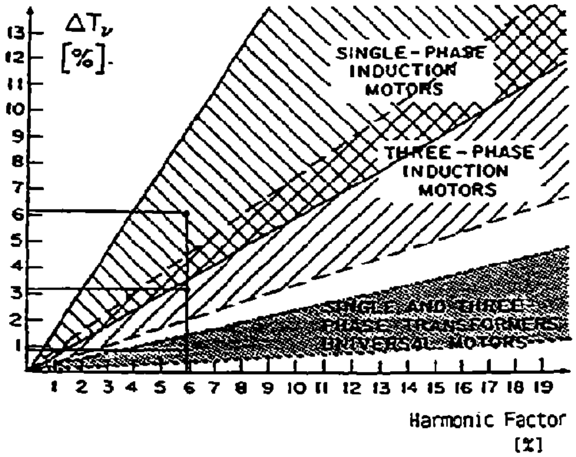

Figure 8 Additional temperature rise (or loss) versus weighted harmonic-factor function.

The harmonic factor can be used to calculate a possible set of harmonic voltages. For a harmonic factor of about 5.8%, one can obtain the harmonic voltage distributions for single-phase and three-phase feeders as shown in Table II using the average values for k and l from Table I for single- and three-phase induction machines. Any other set of voltage harmonics is feasible if the above condition (5.8%) is satisfied.

Table II
Possible sets of voltage harmonics

ν	$\left[\frac{V_\nu}{V_{60Hz}}\right]_{1\phi}$	$\left[\frac{V_\nu}{V_{60Hz}}\right]_{3\phi}$
	[%]	[%]
1	100	100
2	0.5	0.5
3	4.0	2.0
4	0.3	0.5
5	3.0	5.0
6	0.2	0.2
7	2.0	3.5
8	0.2	0.2
9	1.0	0.3
10	0.1	0.1
11	1.5	1.5
12	0.1	0.1
13	1.5	1.0
14	0.1	0.05
15	0.5	0.1
16	0.05	0.05
17	1.0	0.5
18	0.05	0.01
19	1.0	0.5
> 19	< 0.5	< 0.5

The impact of the present-day voltage harmonics on electromagnetic equipment is small. It results in a temperature increase of less than 1.5°C for single-phase induction machines, and 0.6°C for three-phase induction motors. The corresponding temperature rise in transformers and machines is negligible.

4. Thermal Aging

The insulating materials used in electric home appliances are of organic or inorganic origin. Due to the heating of these materials, caused by the losses, a deterioration of the insulating material occurs. This deterioration is manifested either by lowering of the mechanical strength and/or by a change in the dielectric behavior of the insulating material. Small motions due to expansion and contraction of the conductors and iron sheets also cause deteriorating through mechanical friction. Mechanical failure of the insulation is the result of the decrease in the tensile strength or flexibility of the insulating material. The thermal lifetime of electric machines and transformers is highly dependent upon the mode of utilization; there is no doubt that machines with variable loads are more prone to mechanical insulation failure. All investigations in this work assume machines operating at constant rated load and temperature; thus, the chemical changes of the insulating materials are responsible for the thermal aging. Any additional temperature rise beyond the rated temperature will reduce the rated lifetime of the insulating material.

For many years it has been recognized that thermal degradation of organic or inorganic materials can be best represented by the reaction rate equation [13 to 15]

$$\frac{dR}{dt} = Ae^{-E/KT}. \tag{6}$$

In this equation $\frac{dR}{dt}$ is the reduction in property with respect to time. A is a constant, K is the gas constant or, depending upon the units, the Boltzmann constant; T is the absolute temperature, and E is the activation energy in electron volt (eV). The range of the activation energy based upon 225 different insulating materials goes from 0.29 eV to 2 eV. Figure 9 shows the frequency distribution graph of these materials. Note that the peak of the distribution curve lies at about 1.1 eV.

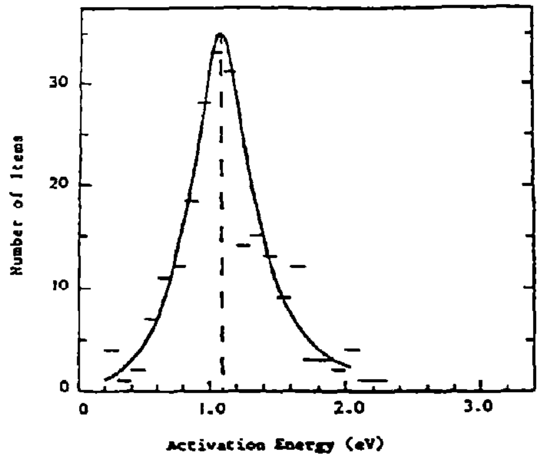

Figure 9 Frequency distribution of activation energies of 225 materials.

Suppose one knows the rated lifetime t_2 of an apparatus, the rated temperature T_2 and the additional temperature rise ΔT; then, after some algebraic manipulation of the reaction rate equation, the reduced lifetime t_1 is obtained as:

$$t_1 = t_2 e^{-\left(\frac{E}{K}\right)\frac{\Delta T}{T_2(T_2+\Delta T)}}. \tag{7}$$

A graphic representation of the temperature effect on lifetime is given in Figure 10; one can conclude that the insulation material with lower activation energy is less affected by an additional temperature rise.

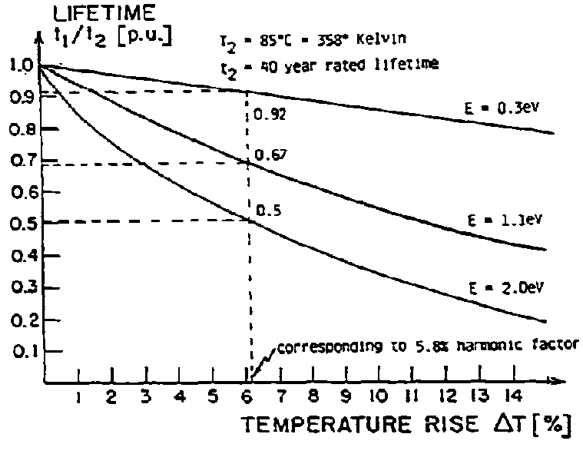

Figure 10 Lifetime decrease versus temperature rise

The introduction of the harmonic factor which relates harmonic voltages to additional temperature rises and the Arrhenius plots [13 to 15] which relate additional temperature rise to reduction of lifetime give us the tools to correlate ΔT to a reduction of lifetime of electromagnetic equipment. For example, according to Figure 8, a harmonic voltage factor of 5.8% corresponds to an additional temperature rise of about 6.2% (or about 3.8°C) for single-phase induction machines. This value of temperature rise for $T_2 = 85°C$ at an ambient temperature of 23°C results in a reduction of life of about 8% for insulating materials with activation energy of 0.3 eV, 33% for materials with activation energy of 1.1 eV and almost 50% life reduction for those materials with activation energy of 2.0 eV. This method provides a good rationale to select a permissible harmonic distortion based upon an acceptable decrease in lifetime expectancy of electromagnetic devices.

5. Forces and Torques of Saturable Three – Phase Induction Machines

Harmonic voltages and currents of the power system generate harmonic forces acting on the iron cores and windings as well as harmonic torques acting on the shaft during starting and steady-state operation. It was found that harmonic vibrations and audible noise, and harmonic torques for all tested induction motors at steady state and during starting were sufficiently small, if the harmonic amplitude of either voltage or current was less than 10% of the respective fundamental. Low order fractional and subharmonics should be avoided since they cause audible noise and radial vibrations. Winding and iron-core forces were numerically calculated in References 7, 8 and 19. Harmonic torques at steady-state operation were investigated in References 9, 10 and 18, while starting torques were computed in Ref. 20 as a function of the terminal voltage.

6. Impact of Harmonics on Capacitors

Subsections 2 to 4 dealt with the harmonic loading of electromagnetic end-use devices. From these results it is apparent that electromagnetic devices are sensitive to harmonics within the frequency range $0 \leq f \leq 1000\ Hz$. Capacitors as they occur in power systems are not very sensitive to the above frequency range, however, they are very sensitive within the frequency range $2000\ Hz \leq f \leq \infty$. Criteria formulating the amplitude limitations for capacitors are given in standards [16, 17]. These are

- a voltage harmonic distortion:

$$VHD = \frac{V}{V_{rated}} = [1 + \sum_{\nu=2}^{\infty}(\frac{V_\nu}{V_{rated}})^2]^{1/2} \leq 1.10; \qquad (8)$$

- a current harmonic distortion:

$$IHD = \frac{I}{I_{rated}} = [1 + \sum_{\nu=2}^{\infty}(\nu^2-1)(\frac{V_\nu}{V_{rated}})^2]^{1/2} \leq 1.30; \quad (9)$$

- a reactive power harmonic distortion:

$$QHD = \frac{Q}{Q_{rated}} = 1 + \sum_{\nu=2}^{\infty}(\nu - 1)(\frac{V_\nu}{V_{rated}})^2 \leq 1.35. \quad (10)$$

These criteria are plotted in Figure 11. Note that low order harmonics can have relatively large amplitudes while high order harmonics must be relatively small for capacitors.

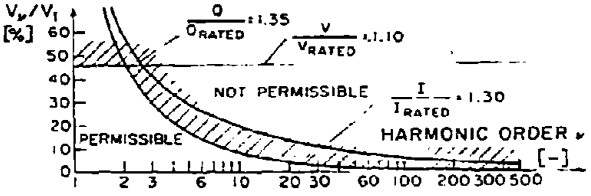

Figure 11 Distortion Criteria for capacitor banks

7. Impacts on Television Sets

Certain power system devices generate harmonic as well as fractional harmonic currents (e.g., induction motors) and corresponding voltage drops across the power system impedance, producing amplitude modulations of the power system voltage. Analytical as well as experimental investigations described here show the effects of harmonics and fractional harmonics on black-and-white and color television sets [10, 12, 18]. Voltage harmonics distort the wave shape of the terminal voltage of 60 Hz, but do not cause any modulation of the voltage amplitude as long as the harmonic voltage amplitude is less than 50% of the fundamental. However, sub- and fractional harmonics distort the wave shape and modulate the voltage amplitude of the terminal voltage at much lower levels. As a consequence of this modulation, the television picture becomes periodically larger and smaller, even at very low sub- or fractional harmonic voltage levels (e.g., less than 1%). Figures 12 and 13 show the measured fractional harmonic voltages causing a periodic enlargement and reduction of the pictures of black-and-white and color television sets, respectively. The dots (•) in both figures indicate at which fractional harmonic voltage the periodic distortion of the television picture begins.

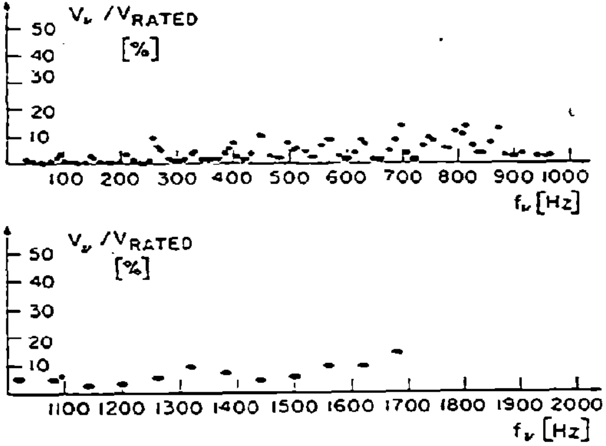

Figure 12 Fractional harmonic voltage levels causing disturbances of black & white TV pictures.

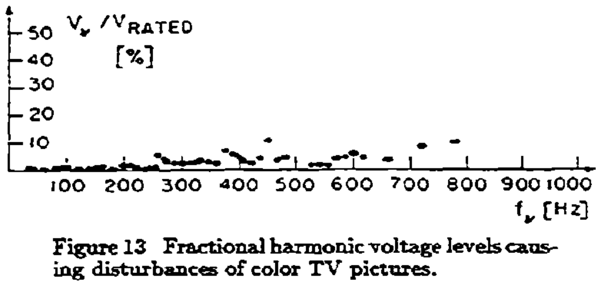

Figure 13 Fractional harmonic voltage levels causing disturbances of color TV pictures.

8. Impacts on Induction Watthour Meters

Measurements and theoretical studies performed with a single-phase watthour meter indicate that the presence of harmonic voltages in the power system voltage generate eddy currents in the disk of the drive which result in positive harmonic torques that accelerate the aluminum disk producing an increase in reading [10, 12, 18]. Figure 14 shows the measured increase of the reading of a single-phase induction watthour meter under the influence of one individual voltage harmonic with amplitudes of 5%, 7.5%, and 10% with respect to the fundamental component of 60 Hz. Figure 15 shows the measured increase of the reading of the watthour meter under the influence of two simultaneously occurring voltage harmonics with amplitudes of 7.5% of rated voltage. Curves A of the latter figure correspond to a 120 Hz voltage superimposed with all other individually applied higher harmonics within the frequency range of 180 Hz$\leq f \leq$ 2040 Hz; Curves B correspond to 180 Hz component superimposed with all other higher harmonics and curves C are valid for a 240 Hz component superimposed with all other higher harmonics.

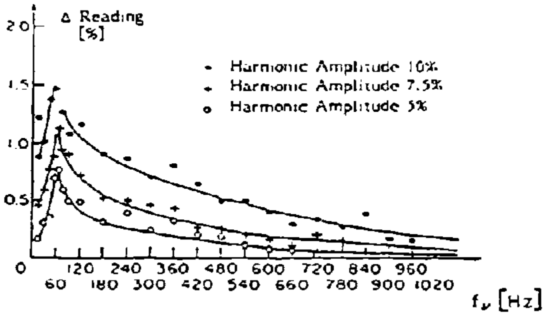

Figure 14 Indicated increase of electricity consumption as measured by an induction watthour meter if the voltage across a resistive load contains an individual harmonic of 5%, 7.5%, or 10% of rated voltage.

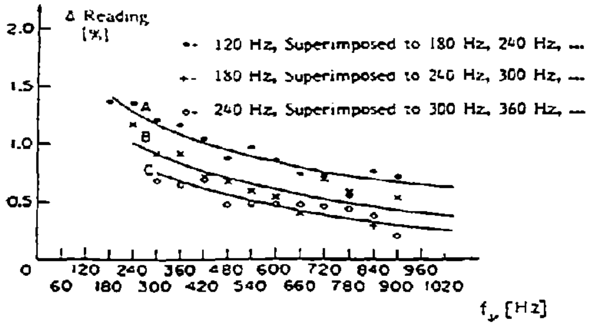

Figure 15 Indicated increase of electricity consumption as measured by an induction watthour meter if the voltage across a resistive load contains two simultaneously occurring harmonics of 7.5% of rated voltage.

9. Influence on Power Distribution System Protection

The fast growing use of solid-state switching devices has caused an increasing content of harmonics in both the voltage and current on electrical utility systems. The switching devices are applied to a wide range of equipments including variable frequency drives for induction motors, single- and three-phase battery chargers, dc motor controllers fed from ac lines and high frequency lighting power supplies.

During this same period static relays have been introduced which in many cases have supplanted the induction cup or disk relays. If the relay has appreciably different characteristics in the presence of harmonics, the effect on a feeder or system can be devastating if operation of relays is either too soon or too late. Installations that were initially trouble free may cause problems as the total harmonic distortion grows.

Most textbooks and handbooks concerning relays as they occur in power system protection deal with the design and performance of relays under sinusoidal conditions. The IEEE Transactions on Power Apparatus and Systems have published every three or four years since 1941 the most pertinent relay literature published in English. To date only a few publications are concerned with the effect of harmonics on electromechanical overcurrent relays.

The intent of Ref.21 is to discuss the influence of voltage harmonics on the performance of a static underfrequency relay, the impact of current harmonics on the operation of two different types of solid-state overcurrent relays and effect of current harmonics on the pick-up of an electromechanical overcurrent relay.

At the outset of any investigation of the influence of harmonics on relays one has to define the magnitudes and frequencies of voltage and current harmonics which may have a detrimental influence on the performance of such relays. For a given injected current harmonic amplitude the generated voltage modulations are dependent upon the power system impedance measured at the location where the injection occurs. To estimate the magnitudes of occuring harmonics within an urban residential distribution system an equivalent power system impedance has been calculated for a single-phase as well as for a three-phase network at 60 Hz. These equivalent power system impedances are shown in Figures 3a and b. For rural distribution feeders the system impedances tend to be larger than those of urban systems, therefore for a given current harmonic amplitude I_ν the voltage harmonics will be correspondingly larger.

The maximum voltage and current harmonic contents were estimated to be 15% and 40%, respectively. The experiments were performed in a controlled manner such that only one harmonic with a prescribed amplitude, phase shift and frequency was superimposed on the fundamental and no dc offset was used. A locked-phase frequency generator permitted a continuous phase shifting of any harmonic with respect to the fundamental. Two distinct phase shift were tested: the first one where the peak-to-peak value of the quantity (either voltage or current) was a maximum and the other one where the peak-to-peak value was a minimum.

In order to investigate the effect on either the operating time or the pickup value of current or voltage, the above mentioned harmonic generator was inserted in series with a 60 Hz fundamental that initially contained no more than 3% harmonics. The harmonic generator was capable of having the phase shifted. This allowed the percent harmonics to be kept constant while the observed wave shape changed from a maximum peak-to-peak to a minimum peak-to-peak.

For the relays investigated it was found that static and electromechanical overcurrent relays behave in a similar manner as far as the instantaneous and time-delay operations are concerned. Underfrequency relays are very sensitive to fractional harmonics and therefore such harmonics should be limited to less than 0.5%.

10. Relation between Harmonic Voltages and Currents

Harmonic voltages and currents are related by the impedance that they encounter in the power system as outlined in Subsection 1. Depending upon the size of the system impedance the harmonic voltages or the harmonic currents will be predominant. For relatively low impedances (urban residential area) the harmonic currents will be predominant and the size of the harmonic currents should be limited by the permissible harmonic current loading of pole- and substation transformers (which have relatively smaller impedances than transformers found in end-use devices). For relatively large impedances (overhead lines in rural residential areas) the harmonic voltages will be predominant and the values of the harmonic voltages should be limited by the permissible additional losses in parallel connected electromagnetic end-use devices. For example, the harmonic voltages given in Table II for a single-phase system corresponding to a harmonic factor of 5.8% will be used to demonstrate the calculation of the harmonic currents for two cases: 1) a typical residential area with an impedance of (0.0188+j0.0984) Ω (line to center tap at 60Hz); and 2) a high impedance network with three times the impedance given above. The first case will result in a total harmonic distortion of the current THD = 39.03% with most harmonics passing through the pole transformer. Since the pole transformer should not be subjected to more than a current THD = 20%, the limiting factor is the harmonic current and not the harmonic voltage. Therefore, the harmonic voltages have be reduced from those specified in Table II in order to bring the harmonic current down to a THD of about 20%. For the second case, the total harmonic distortion of the current becomes 13%. In this case the harmonic currents are limited by the harmonic voltage factor.

11. Propagation of Harmonics within a Distribution Feeder Due to Dispersed Harmonic Sources

The generation and propagation of voltage and current harmonics in a residential distribution power system due to dispersed single dc generation installations using line-commutated inverters is discussed in References 5, 22 and 23. These inverters offer the advantages of being simple and inexpensive, generating low order harmonics only and having an inherent shut-down capability. That is, in case the power system voltage vanishes, the line-commutated inverter ceases to provide either voltage or current. However, electric utilities are concerned about the injection of harmonic current into their power grids and have questions about the propagation of harmonics and the requirements of reactive power needed by such systems.

A digital computer model is developed where the interactions of harmonics of different orders due to the nonlinear elements like transformers, inverters and solar arrays are included. The distribution feeder is modeled as a succession of quadrupoles by using a nodal method. Each quadrupole represents a network element and the representation of the single- or three-phase network elements employed are detailed enough to model the propagation of voltage harmonics and their interactions.

The line-commutated inverter is modeled as a thyristor bridge that can be operated either in discontinuous or continuous conduction modes. Equations are derived where voltage harmonics at the inverter terminals are not neglected and the nonlinear array characteristic is included in the analysis. In transformers, changes in the current harmonic spectra occur because of the core saturation. Therefore, the nonlinear relationship between the iron core flux density and the field intensity is used to compute the magnetizing current.

The models for the various network components are used to represent a residential distribution feeder. Results of computations show that is is not advisable to operate the solar arrays and inverters at their maximum output power. Such operating conditions lead to low power factors. Instead, it is proposed to design the system for an operation at minimum output current distortion. Since the optimal operating point cannot be maintained for the varying insolation levels during a day, the solar array must be rearranged in a number of series/parallel configurations and the inverter must be operated in the transition between continuous and discontinuous conduction modes (see Figure 16). A practical implementation of these modifications is proposed for the above-mentioned system.

The loading conditions of the distribution feeder have not been found to be important. No cancellation of harmonics due to different loads or different locations of the loads has been observed. The harmonic currents do not depend on the values of the loads and their locations. Only the fundamentals are affected by them. Such a conclusion is not valid for capacitor banks. It is proposed to generate the reactive power needed at the inverters directly in parallel to the house loads through capacitors, instead of connecting capacitor banks near substation transformers as it is usually done in the design of todays distribution feeders. This decreases the magnitudes of the fundamental currents at the pole transformers because of the higher power factor at these locations. Therefore, power factors similar to those present in todays distribution networks are maintained and costs for oversizing the transformers can be avoided. If these conditions are met, the voltage and current distortions within the entire distribution system will be within the guidelines as proposed by the International Electrotechnical Commission [3] and the American National Standard Institute [17]. It should be noted that resonances in the distribution network at harmonic frequencies could occur destroying capacitors. More information on this topic can be found in Ref.25.

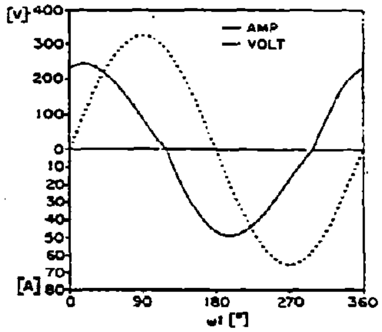

Figure 16 Inverter ac current at the transition between continuous and discontinuous conduction modes.

A new harmonic load flow model was developed because the available models did not include the interdependence of individual harmonics due to nonlinear elements. This new harmonic load flow model confirms measured inverter current waveforms and measured transformer responses.

CONCLUSIONS

- Relation between Current and Voltage Harmonics

(1) The representative equivalent impedances of urban dis-

tribution feeders within the U.S. are such that for harmonic currents of 20 to 40% of low harmonic frequency, harmonic voltages in the range of 5 to 10% result.

(2) Representative equivalent impedances of rural distribution feeders within the U.S. are somewhat larger than those of urban systems that means for the same harmonic currents as for an urban distribution system one obtains larger harmonic voltages for rural power distribution systems.

- Investigations of Transformers and Machines

(1) A harmonic factor has been introduced that represents a weighted total harmonic distortion factor and can be used to determine the losses and the corresponding temperature rises of electric machines and transformers due to harmonics in the terminal voltage.

(2) A correlation has been established between temperature rise and lifetime reduction due to thermal aging.

(3) Flexible permissibe levels of voltage harmonics can be determined through the harmonic factor by selecting an acceptable lifetime reduction of electromagnetic end-use devices.

(4) Voltage harmonics produce less additional losses in transformers as used in end-use devices than in induction machines. This occurs because the harmonic currents are limited by the load of a transformer while in an induction machine the total rotor circuit resistance becomes very small for large harmonic slips.

(5) Universal machines are not very sensitive to harmonics of the power system voltage and their additional temperature rises are comparable to those of transformers.

(6) The losses generated by low order harmonic voltages are highly dependent upon the lamination thickness of the iron-core sheets in electromagnetic devices.

- Forces and Torques of Induction Machines

(1) Harmonic vibrations, audible noise and rotor torques are sufficiently small if voltage and current harmonics are less than 10% of the fundamental terminal quantities.

(2) Low order fractional and sub-harmonics should be avoided (amplitudes of larger than 0.5%) since they may cause audible noise and vibrations.

- Impact of Harmonics on Capacitors

All harmonic current and voltage amplitudes of frequencies larger than 2000Hz should be limited to less than 0.5%.

- Relation between Harmonic Voltages and Currents

(1) For distribution feeders with high representative equivalent impedances (e.g. rural distribution systems) the harmonic voltage levels as specified by the harmonic factor will be the limiting quantities.

(2) For distribution feeders with low representative equivalent impedances (e.g. urban distribution systems) the harmonic current loading of pole and substation transformers will be the limiting quantity. The corresponding harmonic voltage levels can be computed from the equivalent impedances of the distribution system (Eqs.1 to 4).

- Impacts on Television Sets

Television sets are very sensitive to sub-and fractional voltage harmonics and therefore the amplitudes of such harmonics should be limited to less than 0.5%.

- Impacts on Induction Watthour Meters

(1) If harmonics of the power system voltage are present induction watthour meters always indicate a larger consumption of electricity than for the fundamental power but less than the total of fundamental and harmonic powers. This behavior of induction watthour meters is due to the generation of eddy current losses (harmonics only) within the iron laminations representing a damping. This increase in the reading of induction watthour meters is for harmonics of present-day power systems in the neighborhood of a fraction of one percent.

(2) Note, the case where the harmonic power originates in the nonlinear consumers has not been investigated.

- Influence on Power Distribution System Protection

For the relays investigated one can draw the following conclusions:

(1) Static and electromechanical overcurrent relays behave in a similar manner as far as the instantaneous and the time-delay operation are concerned. The (nonsinusoidal) rms value of the pick-up current depends upon the waveshape, that is the phase shifts of the harmonics with respect to the fundamental current. For a harmonics content of 40% the overcurrent devices operating under the instantaneous characteristic pick-up in the worst case at about (100 ± 15%) of the nominal pick-up value. Under the time-delay characteristic both types of relays pick-up in the worst case at about (100±45)% of the nominal time delay.

(2) Static overcurrent relays have worst case long-time delay pick-up current values of about 80% of the nominal value which occur at a harmonic content of 40%. Such a large harmonic content can be caused by battery chargers, variable-speed motor controllers and high frequency lighting devices.

(3) The static underfrequency relay has under the influence of voltage harmonics increased operating times and at 10% of voltage harmonics, in the worst case time almost doubled. Tests indicated that the underfrequency relay is very sensitive to fractional voltage harmonics and therefore such harmonics should be limited to less than 0.5%.

(4) Relay engineers must be alert to when loads are added to a system that uses solid-state switching devices.

(5) Relay standards may need to address the problems of harmonic content and their impact on relay characteristics.

(6) It is impossible to generalize the behavior of any relay response to harmonics without testing or reviewing and understanding the actual device design. This applies to static, solid-state, induction cup or disk or plunger or clapper type relays.

(7) Any one relay may have two different responses of higher and lower pick-up values to different harmonics or even to the same harmonic with the phase shifted.

(8) Installations that initially cause no trouble may experience nuisance operation of relays in the future as the percentage of harmonics on the system grows.

- Propagation of Harmonics within a Distribution Feeder Due to Dispersed Harmonic Sources

(1) Nonlinear elements (e.g. solar arrays, inverters, transformers) need to be accurately modeled. The nonlinear characteristic of the solar array, the saturation of the transformers with transitions from the phasor domain to the time domain and vice-versa, and the possibility of having voltage harmonics must be considered.

(2) A single-phase representation of the three-phase feeder is not sufficient and all three phases must be modeled due to the unbalanced operation and the presence of harmonics in the three-phase voltages.

(3) The operation of dispersed residential power plants connected to the utility through line-commutated inverters results in high harmonic currents and a low power factor. To limit the harmonic currents, a novel operating strategy (minimum THD and improved power factor) has been developed.

(4) For the correction of the power factor, the capacitor banks should not be connected near the substation as proposed in [24]. It is proposed to generate the reactive power needed at the inverters directly at the house loads though capacitors, instead of connecting capacitor banks near substation transformers as it is usually done in the design of todays distribution feeders. This decreases the magnitudes of the fundamental currents at the pole transformers because of the higher power factor at these locations. Power factors similar to those present in today's distribution network are maintained and therefore costs for oversizing the transformers can be avoided.

(5) A significant cancellation of harmonics has not been observed. The harmonic contents of the currents at the pole transformer tend to be similar regardless of the loads. At any branch point of the network, the harmonics usually add and do not cancel, since the harmonic phase shifts are not significantly different. In the same way, no cancellation effect has been observed in the three-phase portion of the network under consideration, when the imbalance of the system is modified.

ACKNOWLEDGEMENT

Concepts developed by D. J. Roesler, Department of Energy, and his frequent discussions as well as the contributions of Mr. Jose I. Herrera and Ms. Jean M. Lacy of ELECTROTEK Concepts Inc., are gratefully acknowledged.

REFERENCES

[1] M. D. Higgins and D. E. Joslyn, "Interaction Between Harmonic Loads and the Power System," Proceedings of the International Conference on Harmonics in Power Systems, Worcester Polytechnic Institute, October, 1984.

[2] R. C. Dugan and C. D. Ko, "Analyzing and Controlling Harmonic Distortion on Distribution Feeders," Proceedings of the International Conference on Harmonics in Power Systems, Worcester Polytechnic Institute, October 1984.

[3] "The Limitation of Disturbances in Electricity Supply Networks Caused by Domestic and Similar Appliances Equipped with Electronic Devices," European Standard EN 50 006, European Committee for Electrotechnical Standardization, 5, Boulevard de l' Empereur - Bte n° 14 - 1000 Bruxelles, Belgium.

[4] J. R. Cameron, W. T. Thomson and A. B. Dow, "Vibration and Current Monitoring for Detecting Air Gap Eccentricity in Large Induction Motors," IEE Proceedings, Vol. 133, Pt. B, no. 3, May 1986.

[5] J. -P. Montu, "Impact of Dispersed Photovoltaic Systems on the Design of Residential Distribution Networks," Doctoral Dissertation, University of Colorado, June 1986.

[6] E. F. Fuchs, A. J. Sek, and D. J. Roesler, "No-Load Currents, Iron and Ohmic Losses of Saturated Transformers at Sinusoidal and Nonsinusoidal Terminal Voltages," Proceedings of the International Conference on Electrical Machines, September 6-8, 1982, Budapest, pp. 96-99.

[7] E. F. Fuchs, L. H. Chang, J. Appelbaum, "Magnetizing Current, Iron Losses and Forces of Three-Phase Induction Machines at Sinusoidal and Nonsinusoidal Terminal Voltages, Part I: Analysis," IEEE Trans. on Power Apparatus and Systems, November 1984, Vol. PAS-103, No. 11, pp. 3303-3312.

[8] E. F. Fuchs, D. J. Roesler, and L. H. Chang, "Magnetizing Current, Iron Losses and Forces of Three-Phase Induction Machines at Sinusoidal and Nonsinusoidal Terminal Voltages, Part II: Results," IEEE Trans. on Power Apparatus and Systems, November 1984, Vol. PAS-103, No. 11, pp. 3313-3326.

[9] E. F. Fuchs, D. J. Roesler, and F. S. Alashhab, "Sensitivity of Home Applicances to Harmonics and Fractional Harmonics of the Power System's Voltage, Part I: Transformers and Induction Machines," Proceedings of the International Conference onHarmonics in Power Systems, Worcester, MA, October 22-23, 1984.

[10] E. F. Fuchs, D. J. Roesler, and K. P. Kovacs, "Sensitivity of Home Appliances to Harmonics and Fractional Harmonics of the Power System's Voltage, Part II: Television Sets, Induction Watthour Meters, and Universal Machines," Proceedings of the International Conference on Harmonics in Power Systems, Worcester, MA, October 22-23, 1984.

[11] 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," IEEE Winter Power Meeting 1986, Feb. 2-8, 1986, New York, NY, Paper #86WM170-5, to be published in IEEE Trans. on Power Delivery.

[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," IEEE Winter Power Meeting 1986, Feb. 2-8, 1986, New York, NY, Paper #86WM171-3, to be published in IEEE Trans. on Power Delivery

[13] E. F. Fuchs, D. J. Roesler, and K. P. Kovacs, "Aging of Home Appliances Due to Harmonics of the Power System's Voltage," Proceeding of the International Conference on Harmonics in Power Systems, Worcester, MA, October 22-23, 1984.

[14] E. F. Fuchs, D. J. Roesler, and K. P. Kovacs, "Aging of Electrical Appliances Due to Harmonics of the Power System's Voltage," IEEE Transactions on Power Delivery, July 1986, Vol. PWRD-1, No. 3, pp. 301-307.

[15] E. F. Fuchs, K. P. Kovacs, and D. J. Roesler, "Reduction of Lifetime of Induction Motors Due to Harmonics of the Terminal Voltage," Proceedings of the International Conference on Electrical Machines, Munich, West Germany, September 1986.

[16] International Electrotechnical Commission, Publication 70/1967.

[17] American National Standard Institute, ANSI/IEEE Std 18-1980.

[18] E. F. Fuchs and D. J. Roesler, "Impact of Harmonics and Fractional Harmonics on the Operation of Home Appliances," Proceedings of the Fifth European Conference on Electrotechnics, June 14-18, 1982, Copenhagen, pp. 591-599.

[19] E. F. Fuchs and D. J. Roesler, "Determination of the No-load Currents and Associated Winding and Iron-Core Forces of Saturable Induction Machines for Sinusoidal and Nonsinusoidal Terminal Voltages," Proceedings of the NATO Symposium on Vibrations and Noise in Alternating Current Machines, August 4-8, 1986, University of Leuven, Belgium.

[20] E. F. Fuchs, M. Poloujadoff and G. W. Neal, "Starting Performance of Saturable Three-Phase Induction Motors," IEEE Summer Power Meeting 1987, San Francisco, CA, July 12-17, 1987.

[21] J. F. Fuller, E. F. Fuchs, and D. J. Roesler, "Influence of Harmonics on Power Distribution System Protection," IEEE Winter Power Meeting 1987, New Orleans, Louisiana, Paper #87WM108-4, Feb. 1-6, 1987.

[22] A. J. Vandenput and J. -P. Montu, "Impact of Nonlinear Transformers on the Propagation of Current Harmonics in a Residential Distribution System," Proceedings of the International Conference on Harmonics in Power Systems, Worcester, MA, October 22-23,1984.

[23] J. -P. Montu, E. F. Fuchs and D. J. Roesler, "Harmonic Generation and Propagation in a Distribution Feeder Due to Residential Photovoltaic Systems," Submitted to IEEE Winter Power Meeting, 1988.

[24] R. C.Dugan, W. J. Jewell, D. J. Roesler, "Harmonics and Reactive Power from Line-Commutated Inverters in Proposed Photovoltaic Subdivision," IEEE Trans. on Power *Apparatus and Systems*, PAS-102, No. 9, pp. 3205-3211.

[25] ______, Power System Harmonics Seminar Notebook, Report prepared by the McGraw-Edison Power Systems Division for the U.S. Department of Energy, ORNL /Sub /81-95011/2.