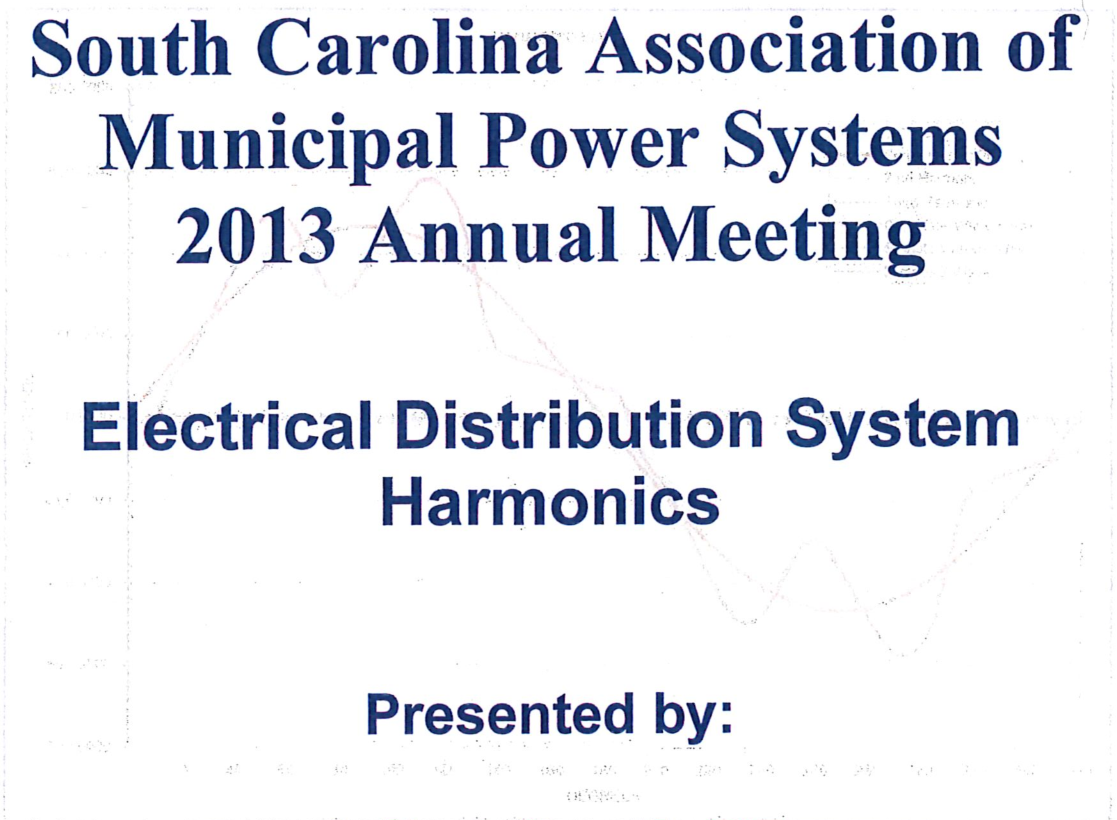

South Carolina Association of Municipal Power Systems 2013 Annual Meeting

Electrical Distribution System Harmonics

Presented by:

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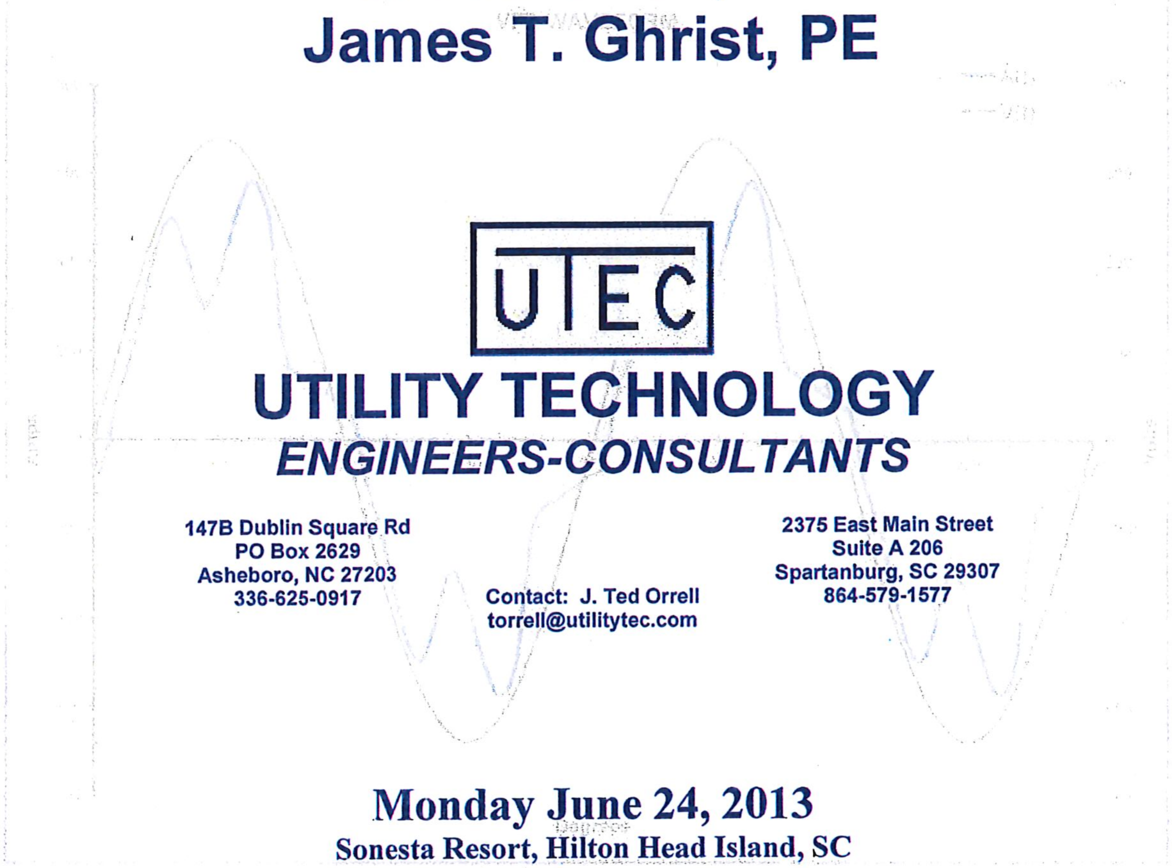
James T. Ghrist, PE



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Monday June 24, 2013
Sonesta Resort, Hilton Head Island, SC

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1. THE THEORETICAL "LINEAR" AC ELECTRIC SYSTEM

The ideal "perfect" electric system is linear. What does this mean?

1.1. Electric System Basic Elements

The basic elements of any electric circuit or system are:

- Resistance (or resistors)
- Inductance (or inductors)
- Capacitance (or capacitors)

For an electric power system, examples of "resistance" are:

- Resistance of the conductors that deliver electricity to customers
- Customer loads such as light bulbs, heaters, ovens, etc.

Examples of "inductance" are:

- Inductance of the conductors that deliver electricity to customers
- Inductance of transformers that serve customers
- Customer motor loads, etc.

Examples of "capacitance" are:

- Capacitance of the conductors that deliver electricity to customers
- Shunt capacitors used within the electric system
- Customer capacitors or capacitive loads, etc.

Elementary electric circuit theory assumes that these three electric circuit elements are "linear". This means that when an AC voltage is impressed across one of these circuit elements, regardless of the magnitude, the impedance to current flow is a constant and the resulting current is directly proportional to the magnitude of the voltage.

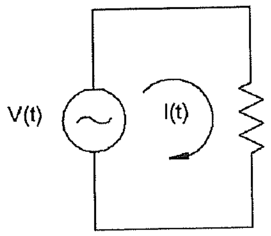
The simple mathematical expressions of current, I, that will pass through each of these three basic circuit elements when an AC voltage "V" is impressed across the element are:

- Resistor with impedance "R", $I = V/R$
- Inductor with impedance "X_L", $I = V/X_L$
- Capacitor with impedance "X_C", $I = V/X_C$

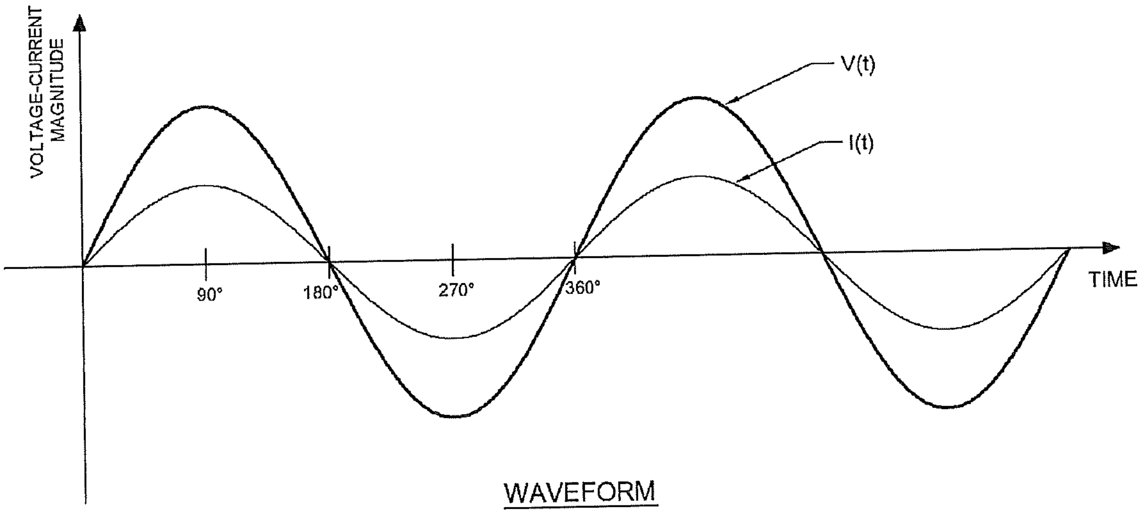
Figure 1 shows a couple of cycles of a perfect sine wave voltage impressed across a linear resistance and the resulting current through the linear resistance. Figure 1 includes a simple circuit, the alternating voltage and current waveforms, and the vector representation of the voltage and current. Note that the resulting current is not only a perfect sine wave, but is also exactly "in phase" with the voltage wave.

Figure 2 shows a couple of cycles of a perfect sine wave voltage impressed across a linear inductance and the resulting current through the linear inductance. Figure 2 includes a simple circuit, the alternating voltage and current waveforms, and the vector representation of the voltage and current. Note that the resulting current is a perfect sine wave, but the current wave is 90 electrical degrees behind, or following, the voltage waveform.

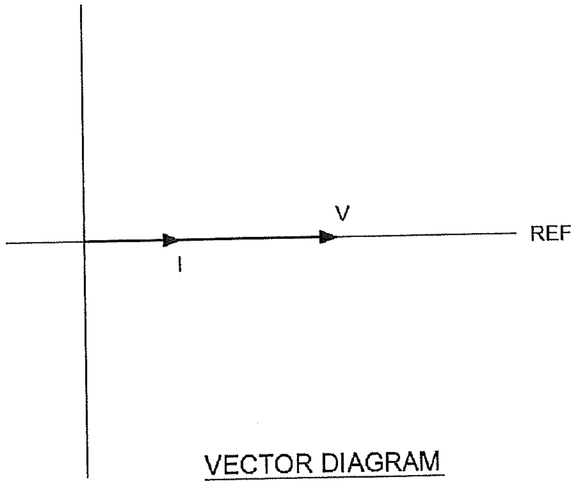
Figure 3 shows a couple of cycles of a perfect sine wave voltage impressed across a linear capacitance and the resulting current through the linear capacitance. Figure 3 includes a simple circuit, the alternating voltage and current waveforms, and the vector representation of the voltage and current. Note that the resulting current is a perfect sine wave, but the current wave is 90 electrical degrees ahead, or leading, the voltage waveform.



CIRCUIT

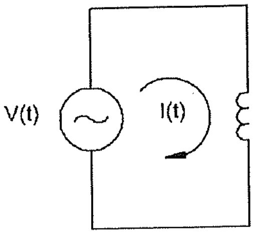


WAVEFORM

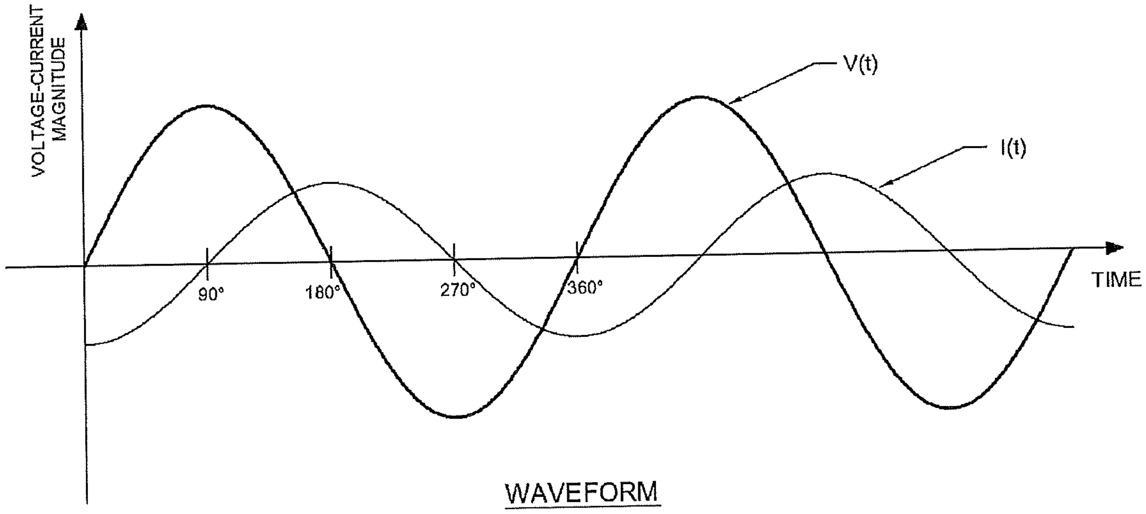


VECTOR DIAGRAM

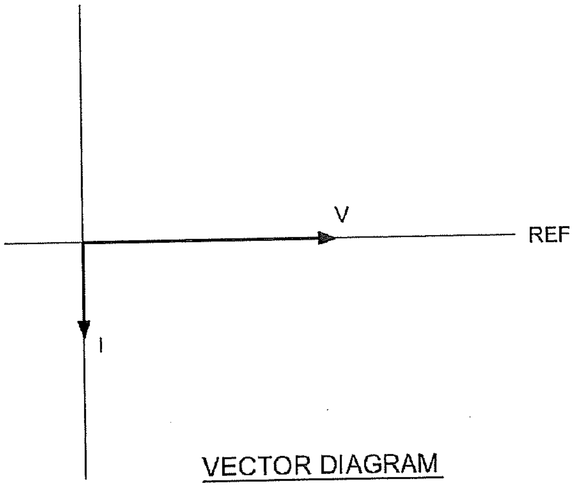
LINEAR RESISTANCE
CURRENT FLOW
FIGURE 1



CIRCUIT

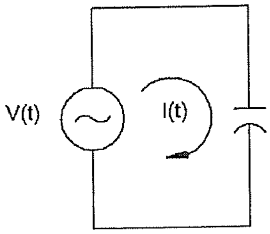


WAVEFORM

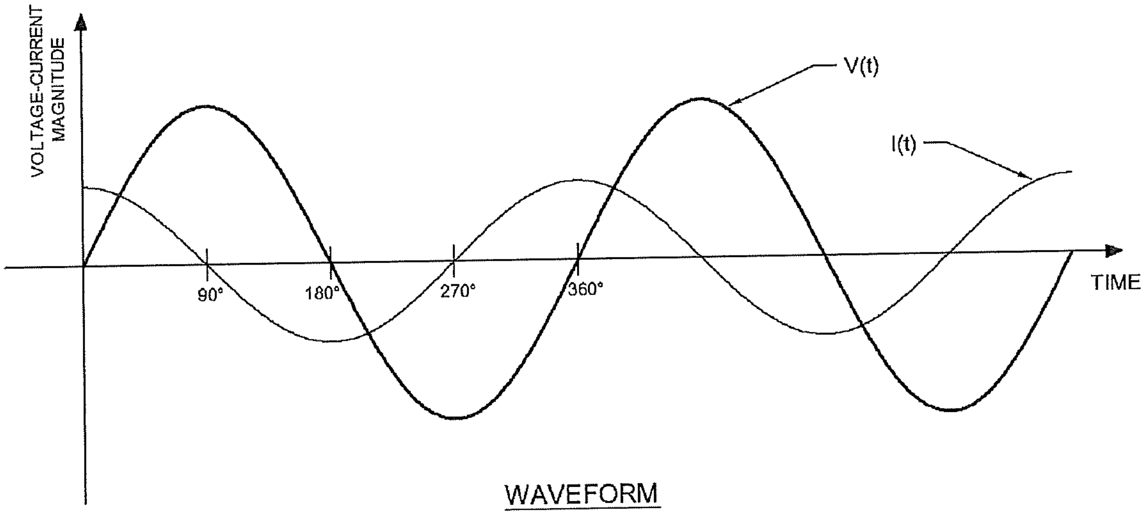


VECTOR DIAGRAM

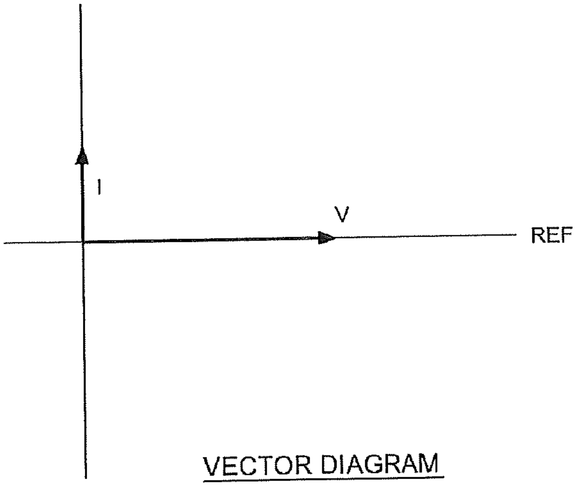
LINEAR INDUCTANCE
CURRENT FLOW
FIGURE 2



CIRCUIT



WAVEFORM



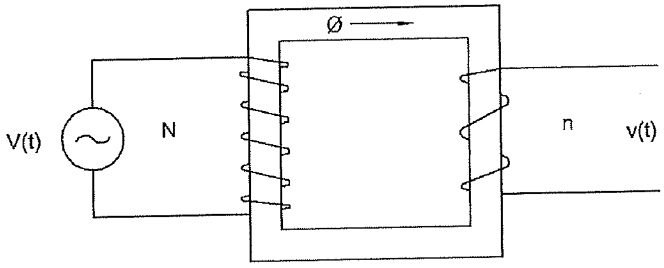
VECTOR DIAGRAM

LINEAR CAPACITANCE
CURRENT FLOW
FIGURE 3

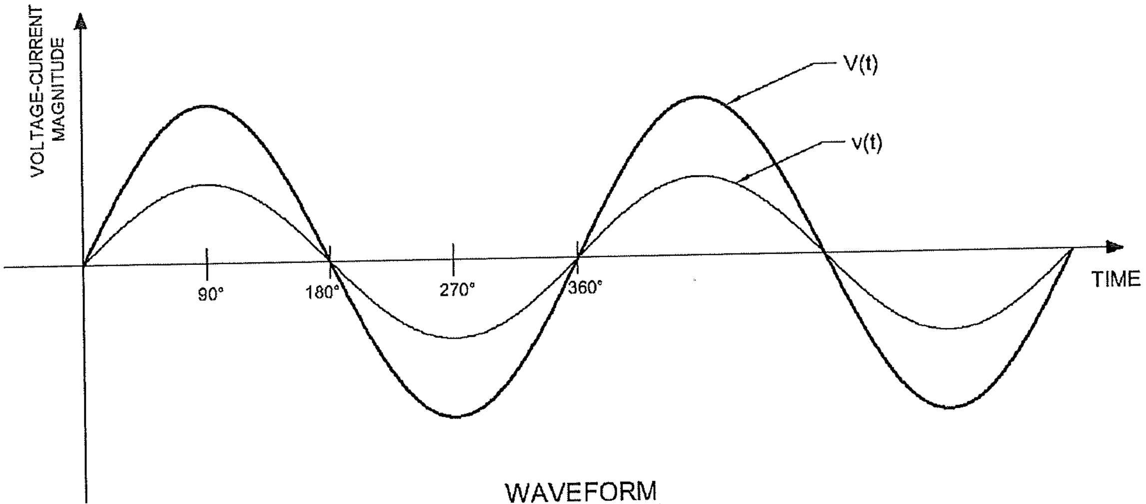
A good example of a common inductive device used in an AC electric system is transformers. A simple transformer is two separate coils of insulated conductor wrapped around a steel core. The primary winding is "N" turns wrapped around the core and the secondary winding is "n" turns wrapped around the core. For a perfect or "ideal" linear steel core, if the primary coil is energized by a perfect sine waveform voltage V, the secondary coil will produce a perfect sine waveform voltage v. The secondary voltage v is equal to the primary volt V times the ratio n/N.

Mathematically, $v = V * (n/N)$ volts

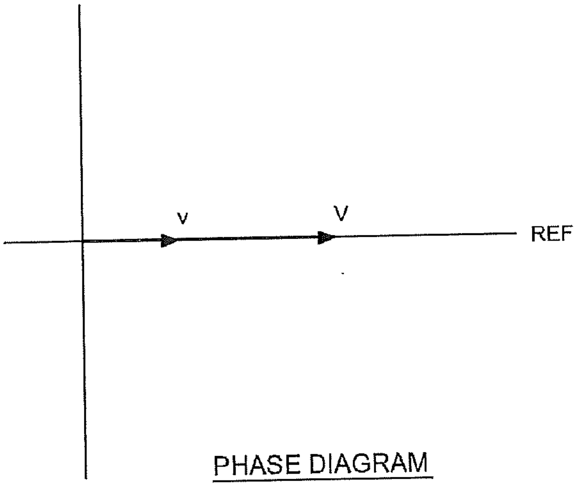
Figure 4 depicts the windings N and n of a simple transformer and the profile of voltages for an ideal transformer. If the number of primary windings, N, is 750 and the number of secondary windings, n, is 25, the ratio of n/N is 25/750 = 0.0333. If the primary voltage V is 7,200 volts, the secondary voltage is 7,200 X 0.0333 = 240 volts. Figure 4 includes a simple circuit, the alternating voltage and current waveforms, and the vector representation of the voltages.



SIMPLE TRANSFORMER



WAVEFORM



PHASE DIAGRAM

IDEAL TRANSFORMER
FIGURE 4

Customer loads are devices made from the three basic elements. A motor, for example, is made using insulated wire wound around a stator (non-moving component) and a rotor (moving component). AC current from the utility system flowing through the stator windings produces a rotating magnetic field. A magnetic field associated with the rotor moves the rotor to try and line up with the rotating magnetic field produced by current in the stator. Motors are used in common equipment such as heat pumps, fans, etc.

Other devices like televisions, radios, computers, and various electronic devices are composed of these basic elements and numerous electronic components that control the flow of current in these devices.

1.2. Electric System AC Voltage and Current

Normal electric utility supply voltage is alternating current, AC. Utility supply voltage is typically produced from synchronous generators installed throughout the electric system. A synchronous generator is constructed using insulated conductor wrapped around the stator and insulated conductor wrapped around the rotor. DC voltage is connected to the rotor coils and the rotor is mechanically spun by an external source such as steam, hydro, ignited gas, etc. The rotating DC magnetic field of the rotor produces the voltage across the stator windings which are connected to the electric system. The supply voltage is theoretically a perfect sine waveform that oscillates 60 times per second, 60 hertz. The current flowing into the system is as required to serve the ever changing loads. For the theoretical linear loads, the current is considered to be a sine wave.

2. THE REAL WORLD "NON-LINEAR" AC ELECTRIC SYSTEM

The real world electric system is not exactly linear. Current and voltage waveforms repeat each cycle, but the waveforms are not perfect sine waves. In many cases, the waveforms are extremely different than sine waves.

2.1. Electric System Non-linear Elements

Resistive and capacitive elements are essentially linear. However, Inductive elements and loads are a different story. The main reason inductive elements are not perfectly linear is because inductive devices are conductors wound around iron or steel, and the magnetic characteristics of iron and steel are not perfectly linear.

A good example of a common non-linear inductive device used in an AC electric system is a transformer. The magnetic characteristic of steel used to manufacturer a transformer can be demonstrated by a graph or chart called the hysteresis curve. A hysteresis curve is a plot of the magnetic field in ampere-turns per meter, usually referred to as *H*, caused by current in the windings around the metallic core, and the resulting magnetic flux density within the metallic core, usually referred to as *B* webers per square meter. In an ideal inductor, the relationship between *H* and *B* is linear, or proportional, throughout the full range of *H*.

In real inductors and transformers, two things occur differently than this ideal proportional relationship between *H* and *B*.

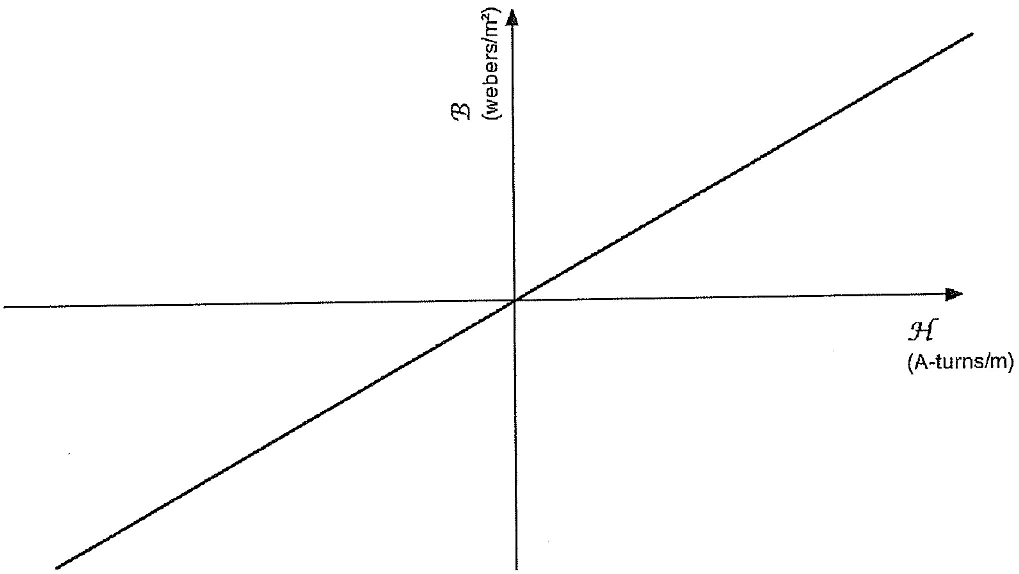
1. As the current in the windings increases, the metallic core becomes saturated and higher current does not increase the magnetic flux proportionally
2. As the current decreases to a value of zero, some of the molecules in the core remain magnetized and a small magnetic flux remains. As the current reverses direction, the metallic plot follows a similar profile as the forward current flow and the core becomes saturated in the opposite direction. Again, as the current reduces to zero, some of the molecules in the core remain magnetized and a small magnetic flux remains in the opposite direction.

Figure 5 shows the relationship of *H* and *B* for an ideal metallic core and the relationship of *H* and *B* in the real world. As AC current flows through the windings, first in one direction then in the opposite direction, the magnetic flux follows the hysteresis curve as shown. These non-linear characteristics of the metallic core produce a transformer magnetizing current waveform that repeats itself, but is not a sine wave. Figure 6 depicts the real transformer magnetizing current waveform. The non-linear magnetizing current will, through interaction with the system impedance, create a non-linear voltage.

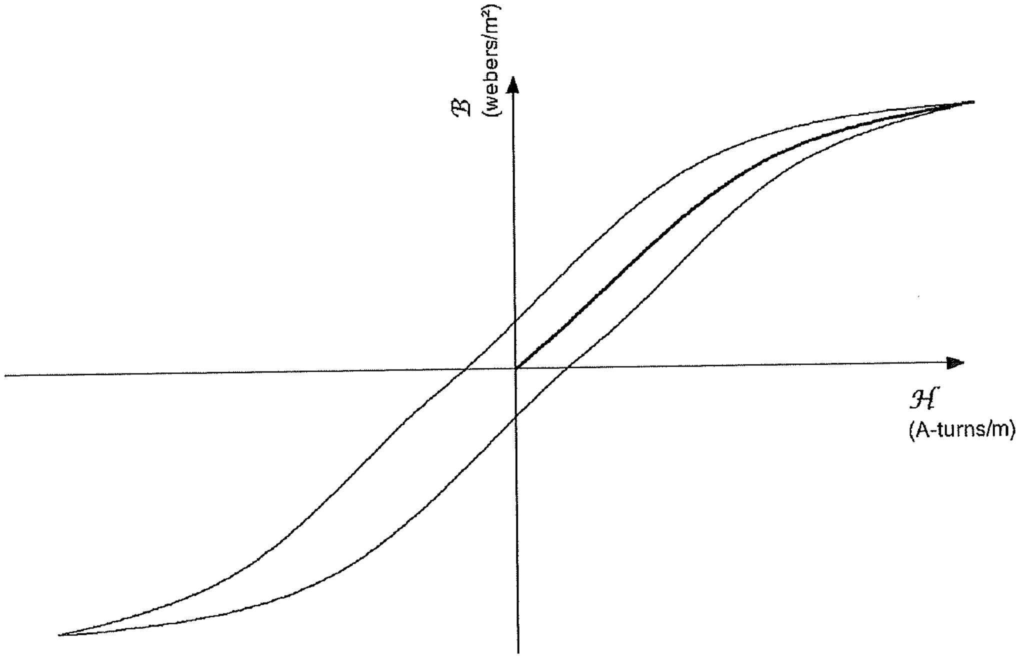
So, transformers are one of the causes of non-linear voltage within an electric power system. If this non-linear voltage is supplied to customer loads, even if the customer loads are perfect linear elements, the result will be a non-linear current flow to the customer. Non-linear current flow through the electric system produces non-linear voltage drops throughout the electric system and the non-linear voltage is exasperated.

A <u>now</u> common customer load that causes significant non-linear current is computer load. Computer's typically convert the AC voltage supply to DC and using diodes and computer chips, clip voltage waves at various points in the waveform. The result of computer loads is significant non-linear current flow within electric systems and therefore resulting non-linear voltage drops. Figure 7 shows a typical current flow to computer equipment.

An example of an industrial load that causes significant non-linear current is a Variable Frequency Drive (VFD) for a motor. A VFD clips and rectifies the voltage of each phase to essentially produce a DC source that is then converted into an AC source with a different frequency for the motor. The result is a current flow to the VFD that is nowhere close to a sine wave. Pump motors for water treatment and waste water treatment plants frequently use VFDs. Figure 8 shows actual current flow to the VFDs for several motors (total 630 hp) for a UTEC hospital client in North Carolina. The current flow is periodic, but clearly not a sine wave.

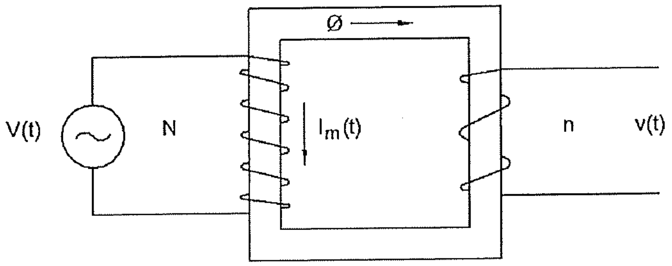


IDEAL INDUCTOR OR TRANSFORMER
$\mathcal{B}$ & $\mathcal{H}$ RELATIONSHIP

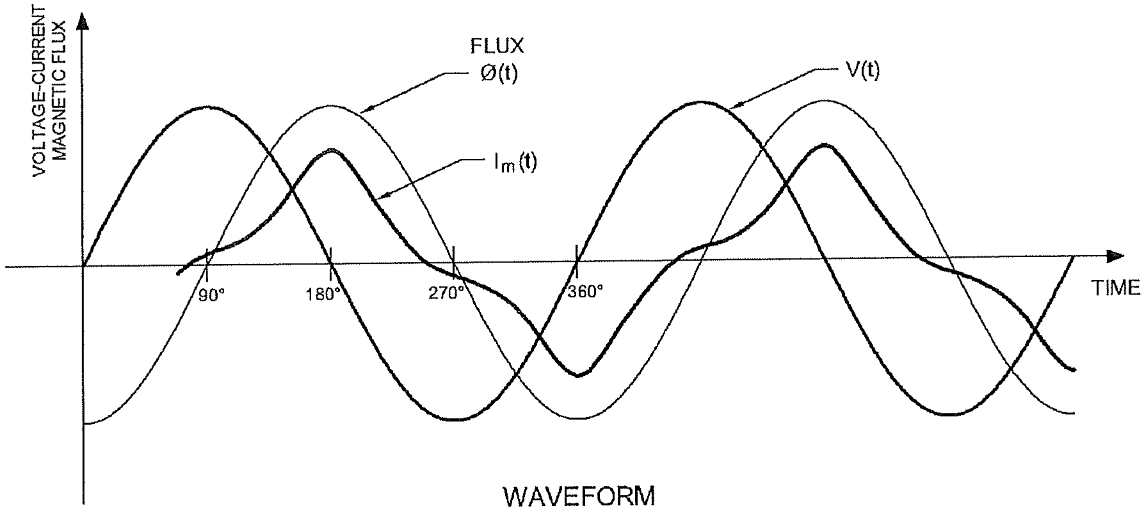


REAL WORLD HYSTERESIS CURVE
$\mathcal{B}$ & $\mathcal{H}$ RELATIONSHIP

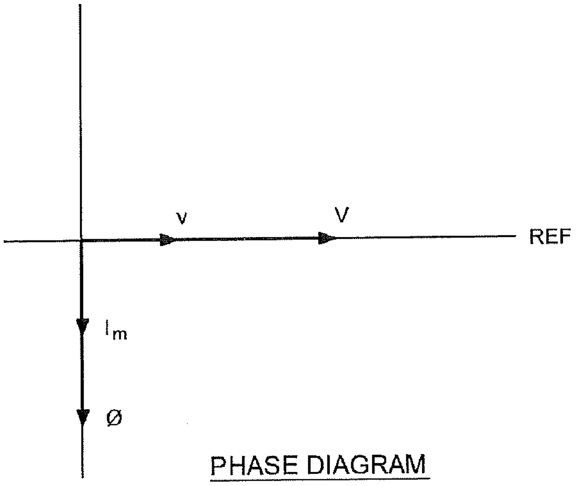
HYSTERESIS CURVE
STEEL CORE
FIGURE 5



SIMPLE TRANSFORMER

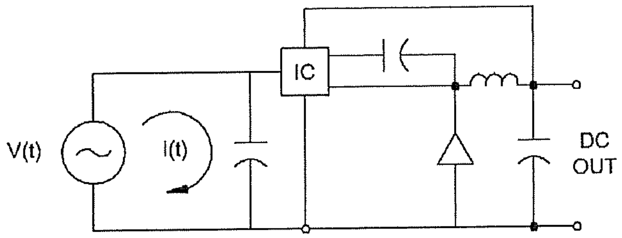


WAVEFORM

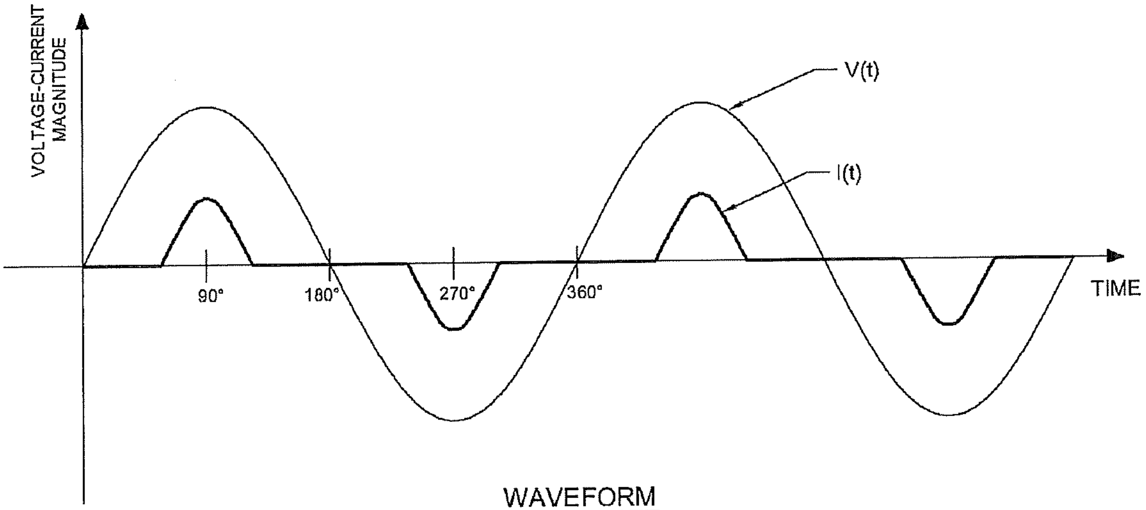


PHASE DIAGRAM

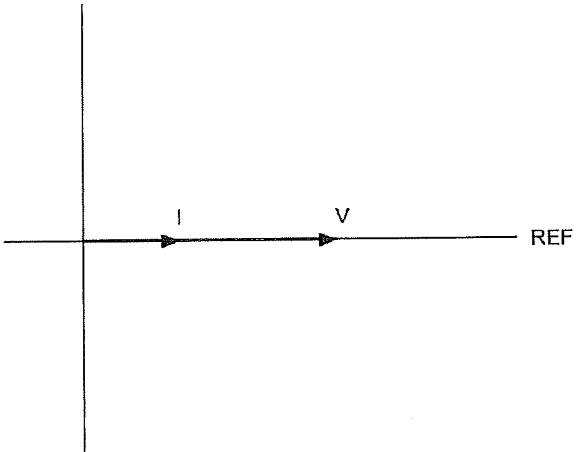
TRANSFORMER
MAGNETIZING CURRENT
FIGURE 6



CIRCUIT

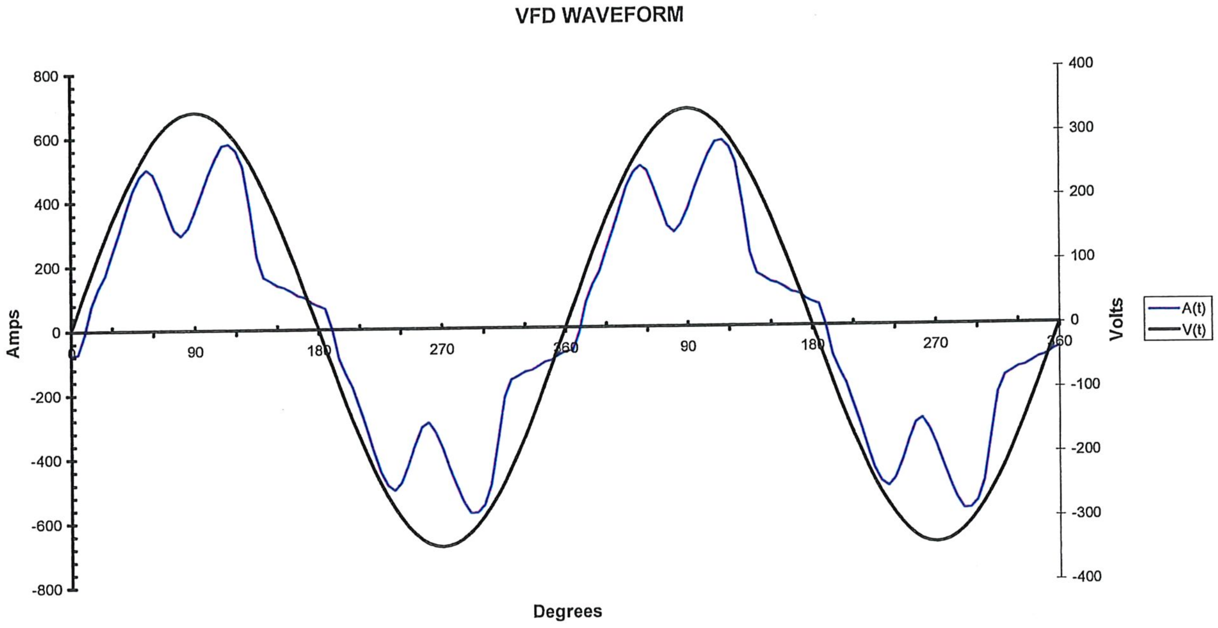


WAVEFORM



PHASE DIAGRAM

COMPUTER POWER SUPPLY
FIGURE 7



VFD WAVEFORM

FIGURE 8

2.2. Electric System Non-linear AC Voltage and Current

It's a real world fact that perfect AC voltage waves can not be generated from synchronous electro-mechanical generators. Many windings are required to be wound around the stator of generators to produce the required voltage magnitude and power capacity. Each of these windings can not physically occupy the same space around the stator and must be stacked and wound adjacent to each other. Therefore the voltage produced by each stator winding is slightly different. The result of the design of electro-mechanical generators is a voltage waveform that repeats itself, but is not a sine wave. By manufacturing variations in the stator winding physical locations, generated voltages close to sine waveforms can be produced, but not exact sine waveforms. Adjusting the physical location of windings to improve the voltage waveform is referred to as adjustments in the winding "pitch".

3. MATHEMATICAL EQUIVALENT "NON-LINEAR" ELECTRIC SYSTEM

We have reviewed both the ideal linear electric system and the real world "non-linear" electric system. The non-linear waveforms repeat themselves every cycle. Any repeating non-sinusoidal waveform can be mathematically represented and modeled by a series of waveforms that are multiples of the fundamental frequency of the non-sinusoidal waveform.

3.1. Harmonic Components

A sinusoidal mathematical analysis of a repeating periodic waveform is referenced as a Fourier Series Analysis. Let's say we have a non-sinusoidal waveform A(t) that repeats itself at a frequency of ω radians per second. For a fundamental frequency, f, of 60 hertz, ω is $2 \cdot \pi \cdot f$, or 377 radians per second. Two times the fundamental frequency is 120 hertz or 754 radians per second, three times the fundamental frequency is 180 hertz or 1,131 radians per second, and so on. It is mathematically possible to determine the magnitude of each frequency component, including the zero frequency component (DC component), and exactly match the non-sinusoidal waveform A(t) . The mathematical expression of this equation is:

$$A(t) = A_0 + A_1 \sin(\omega t + \Theta_1) + A_2 \sin(2 \omega t + \Theta_2) + A_3 \sin(3 \omega t + \Theta_3) + A_4 \sin(4 \omega t + \Theta_4) + \dots$$

Where:

A_0 – Is the magnitude of the DC component of the wave

A_1 – Is the magnitude of the fundamental frequency (60 Hz) component of the wave

Θ_1 – Is the phase angle of the fundamental frequency wave relative to zero degrees

A_2 – Is the magnitude of 2 X the fundamental frequency (120 Hz) component of the wave.

Θ_2 – Is the phase angle of 2 X the fundamental frequency wave relative to zero degrees

A_3 – Is the magnitude of 3 X the fundamental frequency (180 Hz) component of the wave

Θ_3 – Is the phase angle of 3 X the fundamental frequency wave relative to zero degrees

A_4 – Is the magnitude of 4 X the fundamental frequency (240 Hz) component of the wave

Θ_4 – Is the phase angle of 4 X the fundamental frequency wave relative to zero degrees

3.2. Fourier Series Analysis of Non-Sinusoidal Waveform

In order to exactly match the non-sinusoidal waveform A(t), the magnitude and angle of every multiple of the fundamental frequency must be determined. This, of course, would be an impossible task. The good news is, for practical waveforms, one is able to closely match the actual waveform with relatively few multiples of the fundamental frequency. Typically, a Fourier analysis of a non-linear power system waveforms will result in smaller and smaller magnitudes of the higher and higher frequency components. In the analysis, one reaches a point where they realize they can ignore higher order frequency components and adequately represent the non-sinusoidal wave with a reasonable number of orders of the fundamental frequency.

Each of the calculated components for each frequency is called a "Harmonic Component". So, for our 60 hertz electric systems, the zero harmonic is the DC component, the first harmonic is the fundamental frequency 60 hertz component, the second harmonic is the 120 hertz component, the third harmonic is the 180 hertz component, the fourth harmonic is the 240 hertz component, the fifth harmonic is the 300 hertz component, and so on. The multiple of the fundamental frequency is referred to as the harmonic order "h".

Software is available to perform the Fourier analysis of any repeating waveform to determine the magnitudes of any significant harmonic components. However, if one is tenacious, they can perform the analysis manually. The procedure is to solve simultaneous equations for the number of harmonic components necessary to adequately represent the actual waveform. Say one wishes to determine up to twenty harmonic components of a repeating waveform. The general equation for A(t) indicates there would be 21 unknown harmonic magnitudes (DC magnitude plus 20 harmonic magnitudes) and 20 wave displacement angles Θ. There would be 41 unknowns. Therefore one requires 41 equations each containing the 41 unknowns. The steps to perform the analysis manually are as follows:

- Divide the time-line of one complete cycle into 40 even time periods
- From the waveform, determine the magnitude of the wave at the beginning of each time period and the end of the last time period (41 wave sample points)
- Prepare the matrix equations for the 41 unknowns
- Solve the matrix equations and determine the 41 unknowns
- Plot the resulting Harmonic equations and compare with the actual waveform
- If the match is acceptable, you have your solution. If the match is not acceptable, additional data points are needed and additional harmonic magnitudes and displacement angles are required
- Repeat the process until you have an acceptable waveform match

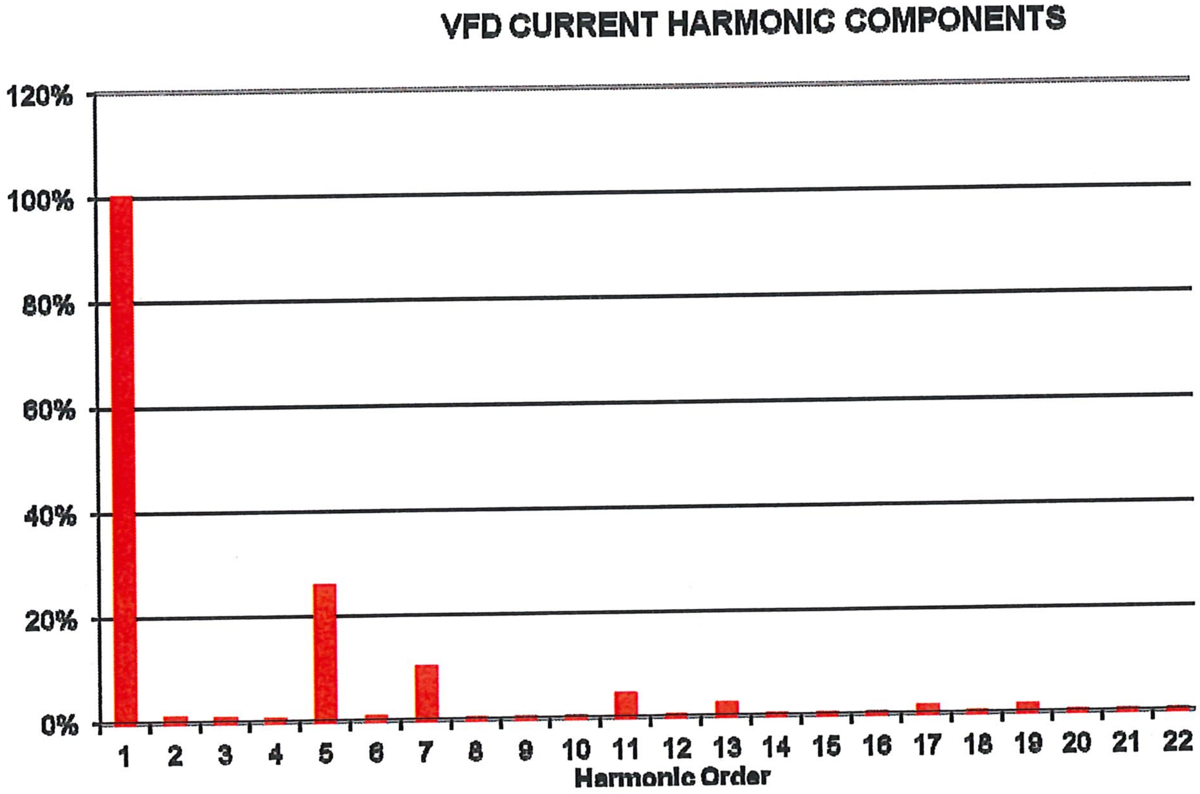
As an example harmonic analysis, consider the current wave for the VFD shown in Figure 6. The harmonic components are shown in the table below.

Harmonic Order	Magnitude as % of Fundamental	Angle of Sine Terms (deg)
dc	0.0%	0.0
1	100.0%	0.4
2	0.8%	-142.1
3	0.8%	-38.6
4	0.5%	-136.7
5	25.8%	-127.1
6	0.7%	54.7
7	10.2%	30.8
8	0.4%	-166.6
9	0.2%	153.7
10	0.2%	-161.4
11	4.4%	-163.5
12	0.2%	5.9
13	2.2%	-86.4
14	0.2%	92.7
15	0.2%	72.8
16	0.1%	143.5
17	1.5%	133.0
18	0.1%	-85.0
19	1.3%	-176.4
20	0.1%	17.0
21	0.1%	32.7
22	0.1%	78.4
23	0.8%	81.6
24	0.0%	-113.8
25	0.7%	122.6
26	0.1%	-41.8
27	0.1%	-2.5

The harmonic orders shaded green are the significant harmonic orders for this waveform. These harmonic components were calculated from measured values using a discrete Fast Fourier Transform (FFT) with Mathcad, a general mathematics program. A discrete FFT is used when the waveform is derived from instantaneous measurements sampled many times per cycle instead of from continuous formulas.

The 5th, 7th, 11th, 13th, 17th, and 19th harmonic components are significant. This is typical of three phase power electronic devices with converters such as three phase bridge rectifiers that create six pulses per phase in the dc output. Harmonic components are often shown as bar charts, or histograms. Figure 9 shows the histogram of the VFD current harmonic components.

An overall indication of harmonic distortion of a wave is called the Total Harmonic Distortion (THD). THD is defined as the square root of the sum of the squared harmonic magnitudes divided by the fundamental magnitude. The THD of the VFD current shown in Figure 8 is 28.4%.



VFD CURRENT HARMONIC COMPONENT HISTOGRAM

FIGURE 9

4. PROBLEMS CAUSED BY NON-LINEAR LOADS

The level of harmonic distortion that is acceptable depends on the susceptibility of the load to the distortion. The least susceptible type of equipment is that for which the main function is heating, such as a furnace. The most susceptible type of equipment is that whose design assumes a nearly perfect sinusoidal waveform, such as communications equipment or data processing equipment. Power supplies of communications and data processing equipment are designed to block harmonics to some degree. However, excessive distortion can still cause problems. Motors, transformers, and cables are susceptible to harmonics because higher frequency current causes higher losses.

4.1. High Neutral Current

If current harmonics of an order divisible by three (3rd, 9th, 27th, etc. called triplen harmonics) are present, these currents can cause high neutral currents because the three phase currents do not add to zero like balanced fundamental currents. Triplen harmonic currents of the three phases add together, so the triplen harmonic current in the neutral will be three times the current magnitude in each phase. Single phase computer power supplies and electronic ballasts create large third harmonic currents. Measurements made on a personal computer indicated a third harmonic current component of 89% of the fundamental.

4.2. Equipment Overheating

Transformers and other inductive devices are particularly susceptible to overheating and loss of efficiency when subjected to higher frequency current. Excessive harmonics have a particularly pronounced effect on Eddy current losses which increase with the square of the frequency.

4.3. Control Equipment Malfunction

Control equipment is often dependent upon accurate measurements of voltage zero crossings. Harmonic distortion can shift zero crossing points or create additional zero crossing points. Other types of electronic equipment can be affected by transmission of AC supply harmonics through the equipment power supply or by magnetic coupling of harmonic current into other equipment components.

Higher levels of harmonics can result in erratic, sometimes subtle, malfunctions of the equipment that can, in some cases have serious consequences. Instruments can be affected similarly, giving erroneous data or otherwise performing unpredictably.

4.4. Telephone Circuit Noise

The presence of harmonic currents or voltages in power lines can produce magnetic and electric fields that will impair the performance of communication systems that are close to the power lines. Telephone circuits are particularly susceptible to ground return currents.

5. CIRCUIT ANALYSIS METHODOLOGY

So why is it necessary to be able to model a non-linear voltage or current wave as a series of linear harmonic current components? The answer to this question is that normal electric steady state engineering analyses are based on sine wave equations. After one determines the magnitude of each harmonic, one can use standard analysis techniques to evaluate the impact of the harmonic loads on the rest of the electric system. Because of "skin effect", the resistance of an element is different at DC than at other oscillating frequencies. The impedance of an inductor is directly proportional to the harmonic frequency, ω, being analyzed:

XL = j ω L Ohms

Where:

- j is phase shift vector +90°
- ω is the radian frequency for the specific harmonic being analyzed
- L is the element inductance

The impedance of a capacitor is inversely proportional to the harmonic frequency, ω, being analyzed:

XC = -j / (ω C) Ohms

Where:

- -j is phase shift vector -90°
- ω is the radian frequency for the specific harmonic being analyzed
- C is the element capacitance

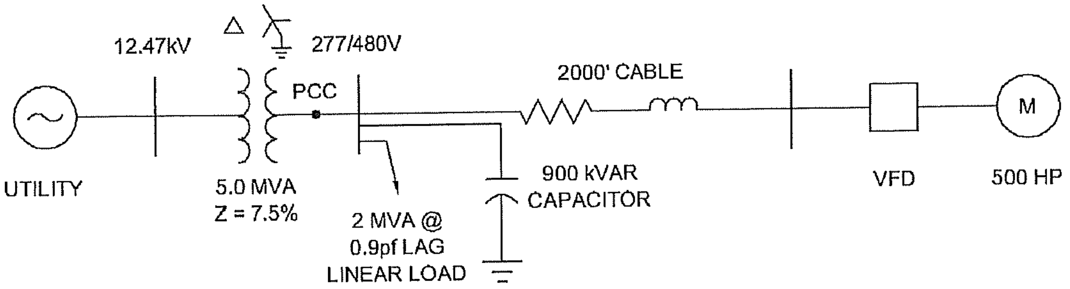
Therefore, for each significant frequency component identified, a standard AC circuit analysis can be performed to determine the effect of each frequency component on the electric system.

Let's consider a simple system as shown in Figure 10. System parameters are:

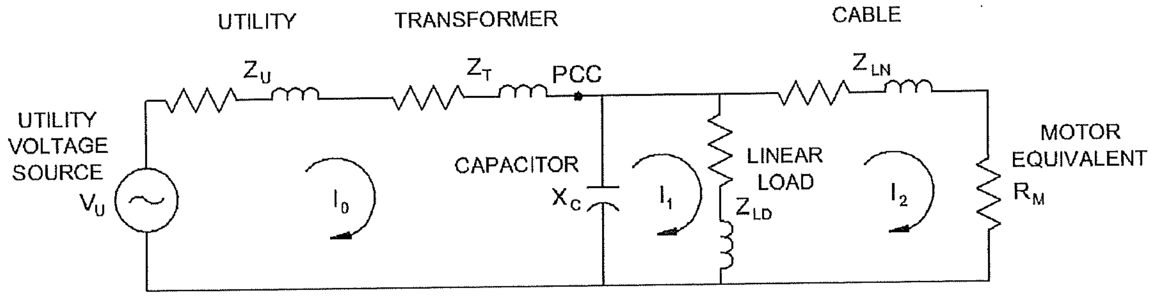
- Utility Primary voltage 12.47/7.2 kV
- Thevenin Equivalent Impedance of utility at the high voltage side of the customer transformer:
  - R = 0.00907 ohms at 60 hertz
  - X_L = 0.06999 ohms at 60 hertz
  - L = 2.406 millihenries
- Customer Transformer:
  - Capacity = 5.0 MVA
  - Winding Voltage and Connections – 12.47 kV Delta Primary, 480/277 volt Grounded-Wye Secondary
  - Z = 7.5% at 60 hertz
  - R = 0.1166 ohms at 60 hertz
  - X_L = 2.32964 ohms at 60 hertz
  - L = 6.1795 millihenries
- Customer Linear Load at transformer 480 Volt Bus:
  - 2 MVA at 0.9 pf lag
- Capacitor bank at transformer 480 Volt Bus:

  - 3-300 kVAR per phase (900 kVAR total)
  - X_C = 0.256 ohms at 60 hertz
  - C = 10371 microfarads
- Line Impedance from Customer Transformer to VFD motor
  - 750 kcmil copper cable
  - R = 0.018 ohms/1000'
  - XL = 0.025 ohms/1000' at 60 hertz
  - L = 0.0663 millilhenries/1000'
  - Circuit length = 2000'
- VFD Pump Motor
  - 500 hp
  - VFD input = 500 kVA at unity pf
  - Harmonic Content – same as example in Section 3.1

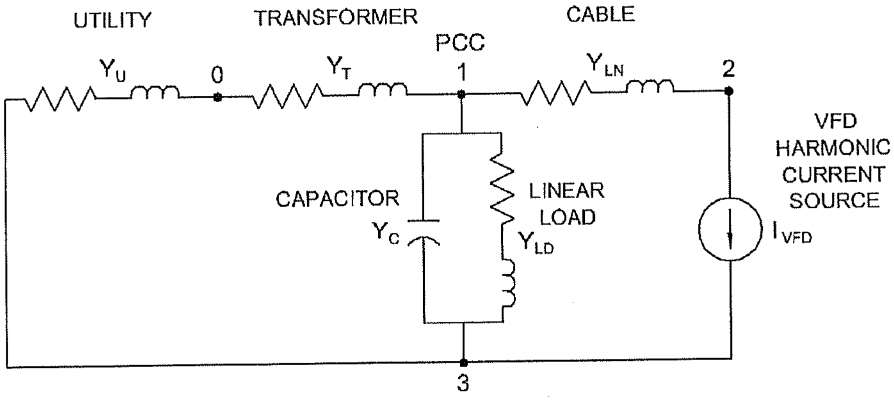
Harmonic analysis of a circuit involves calculating current and voltage at critical points in the circuit using standard AC circuit analysis methods. Analyses are made at the fundamental frequency and at each harmonic frequency of interest. The impedances of the circuit elements are different at each different frequency as described Section 3.2. The utility source is represented as a short circuit at harmonic frequencies. Non-linear loads are represented as current sources. Figure 10 shows the equivalent circuit for an analysis of one of the harmonic frequencies of interest.



ONE LINE



60 HZ ANALYSIS IMPEDANCE DIAGRAM

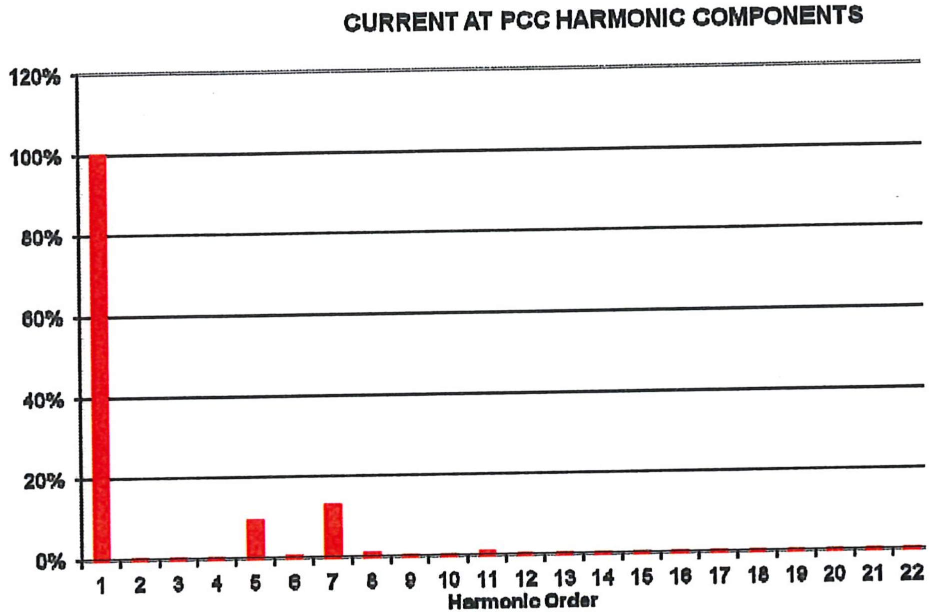


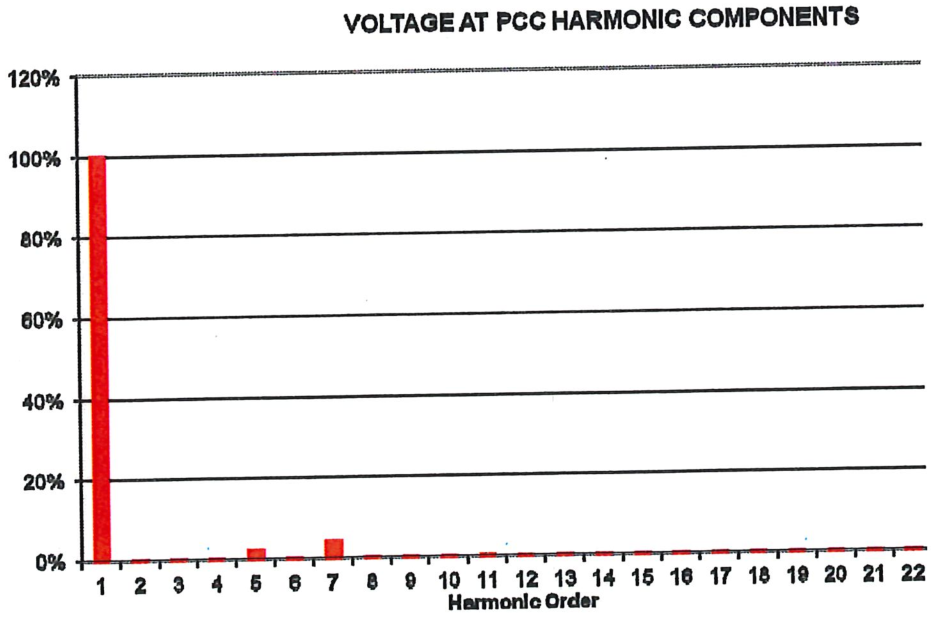
HARMONIC ANALYSIS ADMITTANCE DIAGRAM

EXAMPLE SYSTEM
FIGURE 10

A particular point of interest in the circuit is the transformer secondary. This is a point that is accessible to both the utility and the customer, known as the Point of Common Coupling or PCC. Industry standards provide limits at the PCC of the voltage harmonic distortion that the utility can supply and of the current harmonic distortion that the customer can inject into the system.

Analysis of the system in Figure 10 shows that the current THD at the PCC is 15.8% and the highest current harmonic component (5th) is 9.1% of the fundamental current. The percent harmonic distortion is different at the PCC than at the VFD because of the effect of the other load and the capacitor. Harmonic currents flowing through the system cause voltage drops and voltage harmonic distortion. The voltage THD at the PCC is 4.8% and the 5th harmonic voltage distortion is 2.2%. Figure 11 shows histograms of the PCC current and voltage harmonic components.





PCC HARMONIC COMPONENT HISTOGRAMS

FIGURE 11

The capacitor in the system, while not a source of harmonic current, increases the harmonic current distortion because of resonance with the source inductance. Resonance between the source inductance and the capacitor occurs at the harmonic frequency where the source (utility and transformer) inductive reactance X_L equals the capacitor reactance X_C. Resonance in the example circuit occurs at h = 7.3. This is close to harmonic frequencies that are present in the VFD current. The impedance of the parallel combination of the capacitor and the source becomes very high at the resonant harmonic. With a very high impedance in the parallel combination, the harmonic current can flow only through the other loads, creating high voltage distortion. If the capacitor bank was 1921.6 kvar, there would be resonance at the 5th harmonic. 5th harmonic voltage would be 14.7% of the fundamental voltage. Voltage THD would also be 14.7%.

6. INDUSTRY STANDARDS

The Institute of Electrical and Electronics Engineers (IEEE) provides recommended maximum limits for harmonic distortion. These limits can be found in IEEE Std 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.*

For voltages below 69 kV, IEEE Std 519 limits utility voltage distortion at the PCC to a THD of 5% and a maximum individual harmonic voltage distortion to 3%. Current distortion limits apply to customer load and depend on the strength of the utility system (as measured by maximum short-circuit current) and the maximum demand load current. If the ratio of short circuit current to demand load current is less than 20, the current THD limit is 5% and the maximum individual harmonic current limit is 4% for h<11.

7. SOLUTIONS TO HARMONIC PROBLEMS

There are several ways that harmonic problems can be mitigated. It is incumbent unon the designer to analyze options to determine the best or most economic solution. Following is a discussion of several of the most common mitigation methods.

7.1. Passive Filters

Harmonic currents can be reduced by the installation of filters that are manufactured with basic passive circuit elements such as resistors, capacitors, and inductors. Two types of passive filters are:

- Series filters which block the introduction of harmonic currents from flowing into the electrical system with passive elements that are a high impedance to the harmonic frequencies of concern.
- Shunt filters which draw the harmonic currents out of the electrical system with passive elements that are a low impedance to the harmonic frequencies of concern.

The capacitor in the Section 5 example can be converted into a shunt filter "tuned" to a single harmonic frequency by the addition of an inductor in series with the capacitor. At the tuned frequency, the capacitive reactance will equal the inductive reactance. The total series reactance at the tuned frequency would be zero. The addition of a 26.1 microhenry inductor in series with each phase of the 900 kvar capacitor bank would tune the bank to just above the 5th harmonic component. With this shunt filter in place, the current THD at the PCC would be reduced from 15.8% to 1.4%. The 5th harmonic current at the PCC would be only 0.5%. Voltage THD would be reduced from 4.8% to 0.6%.

7.2. Active Harmonic Filters

Active filters use power electronics to provide the harmonic currents required by non-linear loads and avoid distortion on the power system. Active filters are installed parallel to the loads, measure the load current, and inject, in opposite phase, the harmonics drawn by the load such that the line current from the power source remains sinusoidal. Active filters are effective on a broad spectrum of harmonic distortion. If an active filter fails, it takes itself off line and doesn't interrupt power to the loads.

7.3. Harmonic Mitigation Transformers (HMT's)

Harmonic mitigation transformers operate by shifting the phase angle of half of the load current. Shifting the load current by 30° will completely eliminate balanced 6th harmonic currents if added to an equal unshifted load. The more predominate 5th and 7th harmonics are reduced to low levels by a 30° phase shift.

7.4. Circuit Modification

If harmonic voltage distortion is causing resonance points in the electrical system, distortion may be able to be reduced to tolerable levels by modifying the circuit. Capacitor banks can be relocated or the bank size changed to eliminate resonances at frequencies that are produced by non-linear loads on the system.

7.5. Equipment and Cable Sizing

If high harmonic currents are causing excessive heating in a transformer, the transformer can be replaced with a larger transformer or one with a "k" rating. K rated transformers are designed to withstand higher harmonic distortion currents.

Often, neutral conductors of three-phase circuits are sized much smaller than the phase conductors because balanced phase currents cancel out in the neutral return. If high harmonic neutral currents occur because of third harmonic distortion, it may be necessary to use full-size neutrals. In very high distortion situations, the neutral may have to be sized larger than the phase conductors.