4.1. Concept of Sinusoidal and non-sinusoidal wave shape

- Generally when dealing with alternating voltages and currents in electrical circuits it is assumed that they are pure and sinusoidal in shape with only one frequency value, called the "fundamental frequency" being present, but this is not always the case.
- In an electrical or electronic device or circuit that has a voltage-current characteristic which is not linear, that is, the current flowing through it is not proportional to the applied voltage. The alternating waveforms associated with the device will be different to a greater or lesser extent to those of an ideal sinusoidal waveform. These types of waveforms are commonly referred to as non-sinusoidal or complex waveforms.
- Complex waveforms are generated by common electrical devices such as iron-cored inductors, switching transformers, electronic ballasts in fluorescent lights and other such heavily inductive loads as well as the output voltage and current waveforms of AC alternators, generators and other such electrical machines. The result is that the current waveform may not be sinusoidal even though the voltage waveform is.
- Also most electronic power supply switching circuits such as rectifiers, silicon controlled rectifier (SCR's), power transistors, power converters and other such solid state switches which cut and chop the power supplies sinusoidal waveform to control motor power, or to convert the sinusoidal AC supply to DC. Theses switching circuits tend to draw current only at the peak values of the AC supply and since the switching current waveform is non-sinusoidal the resulting load current is said to contain Harmonics. Non-sinusoidal complex waveforms are constructed by "adding" together a series of sine wave frequencies known as "Harmonics".

4.2. Fundamental frequency, Harmonics and Harmonic number (*h*)

Fundamental frequency

- A complex waveform, whatever its shape, can be split up mathematically into its individual components called the fundamental frequency and a number of "harmonic frequencies".
- **A Fundamental Waveform** (or first harmonic) is the sinusoidal waveform that has the supply frequency. The fundamental is the lowest or base frequency, ƒ on which the complex waveform is built and as such the periodic time, T of the resulting complex waveform will be equal to the periodic time of the fundamental frequency.

Harmonics

- Non-sinusoidal complex waveforms are constructed by "adding" together a series of sine wave frequencies known as "Harmonics".
- Harmonics is the generalized term used to describe the distortion of a sinusoidal waveform by waveforms of different frequencies.
- **As per IEEE-519 standard**, Harmonics are sinusoidal component of a periodic wave or quantity (voltages or currents) operate at a frequency that is an integer (whole-number) multiple of the fundamental frequency. So given a 50 Hz fundamental

waveform, this means a 2nd harmonic frequency would be 100 Hz (2 x 50 Hz), a 3rd harmonic would be 150 Hz (3 x 50 Hz), a 5th at 250 Hz, a 7th at 350 Hz and so on. Likewise, given a 60 Hz fundamental waveform, the 2nd, 3rd, 4th and 5th harmonic frequencies would be at 120 Hz, 180 Hz, 240 Hz and 300 Hz respectively.

- The fundamental waveform can also be called a 1st harmonics waveform.
- Harmonic sequence refers to the phasor rotation of the harmonic voltages and currents with respect to the fundamental waveform in a balanced, 3-phase 4-wire system.
- A positive sequence harmonic (4th, 7th, 10th …) would rotate in the same direction (forward) as the fundamental frequency. Whereas a negative sequence harmonic (2nd, 5th, 8th …) rotates in the opposite direction (reverse) of the fundamental frequency.
- Generally, positive sequence harmonics are undesirable because they are responsible for overheating of conductors, power lines and transformers due to the addition of the waveforms.
- Negative sequence harmonics on the other hand circulate between the phases creating additional problems with motors as the opposite phasor rotation weakens the rotating magnetic field require by motors, and especially induction motors, causing them to produce less mechanical torque.
- Another set of special harmonics called “triplen” (multiple of three) have a zero rotational sequence. Triplen are multiples of the third harmonic (3rd, 6th, 9th …), etc, hence their name, and are therefore displaced by zero degrees. Zero sequence harmonics circulate between the phase and neutral or ground.
- Unlike the positive and negative sequence harmonic currents that cancel each other out, third order or triplen harmonics do not cancel out. Instead add up arithmetically in the common neutral wire which is subjected to currents from all three phases. The result is that current amplitude in the neutral wire due to these triplen harmonics could be up to 3 times the amplitude of the phase current at the fundamental frequency causing it to become less efficient and overheat.

Harmonic number (*h*)

- Harmonic number (h) refers to the individual frequency elements that comprise a composite waveform.
- For example, h = 5 refers to the fifth harmonic component with a frequency equal to five times the fundamental frequency. If the fundamental frequency is 50 Hz, then the fifth harmonic frequency is 5×50 or 250 Hz.
- Dealing with harmonic numbers and not with harmonic frequencies is done for two reasons. The fundamental frequency varies among individual countries and applications. Also, some applications use frequencies other than 50 Hz.
- The use of harmonic numbers allows us to simplify how we express harmonics. The second reason for using harmonic numbers is the simplification realized in performing mathematical operations involving harmonics.

4.3. Odd and Even order harmonics

- **Harmonic number 1** is assigned to the fundamental frequency component of the periodic wave.
- **Harmonic number 0** represents the constant or DC component of the waveform.
- **The DC component** is the net difference between the positive and negative halves of one complete waveform cycle. The DC component of a waveform has undesirable effects, particularly on transformers, due to the phenomenon of core saturation.
- We usually look at harmonics as integers, but some applications produce harmonic voltages and currents that are **not integers**, e.g. Electric arc furnaces and arc welders. In both cases, once the arc stabilizes, the non-integer harmonics mostly disappear, leaving only the integer harmonics.
- The majority of nonlinear loads produce harmonics that are **odd multiples** of the fundamental frequency. The odd harmonics have odd numbers (e.g., 3, 5, 7, 9, and 11).
- Certain conditions need to exist for production of **even harmonics**. The even harmonics have even numbers (e.g., 2, 4, 6, 8, and 10). Uneven current draw between the positive and negative halves of one cycle of operation can generate even harmonics.
- **Sub-harmonics** have frequencies below the fundamental frequency and are rare in power systems. When subharmonics are present, the underlying cause is resonance between the harmonic currents or voltages with the power system capacitance and inductance. Subharmonics may be generated when a system is highly inductive (such as an arc furnace during startup) or if the power system also contains large capacitor banks for power factor correction or filtering. Such conditions produce slow oscillations that are relatively undamped, resulting in voltage sags and light flicker.

4.4. Harmonic phase rotation and phase angle relationship

- **Harmonics** are treated as stand-alone entities to produce waveform distortion in ac voltages and currents by considering 1-phase system. However, in a 3-phase power system, the harmonics of one phase have a rotational and phase angle relationship with the harmonics of the other phases.
- In a balanced three-phase electrical system, the voltages and currents have a positional relationship as shown in Figure 4.1.
- The three voltages and currents are 120° apart. The normal phase rotation or sequence is a–b–c, which is counterclockwise and designated as the positive-phase sequence. For harmonic analyses, these relationships are still applicable, but the fundamental components of voltages and currents are used as reference.
- All other harmonics use the fundamental frequency as the reference. The fundamental frequencies have a positive-phase sequence.

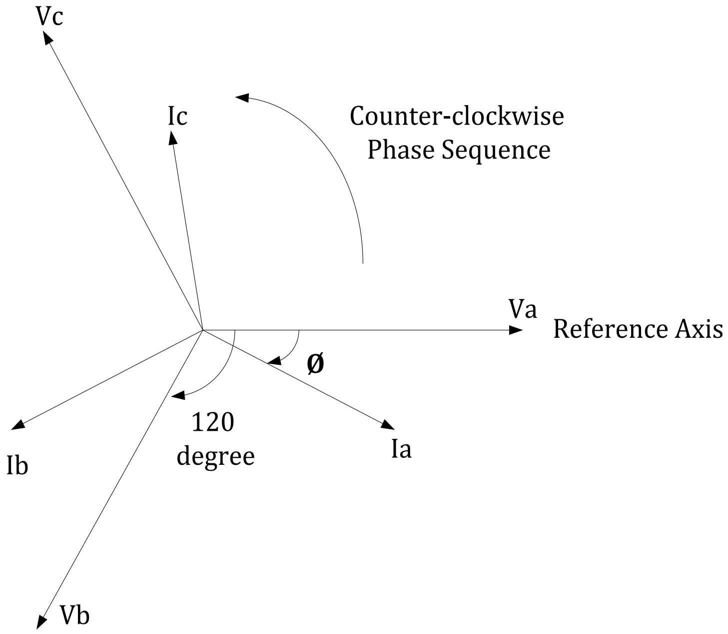

Figure 4. 1 Balanced three-phase power system. Phase sequence refers to the order in which phasors move past a reference axis. The positive phase sequence is assigned a counterclockwise rotation.

- The following relationships are true for the fundamental frequency current components in three-phase power system:

$$i_{a1} = I_{a1}\sin\omega t \text{..............................}(1)$$

$$i_{b1} = I_{b1}\sin(\omega t - 120°) \text{.................}(2)$$

$$i_{c1} = I_{c1}\sin(\omega t - 240°) \text{.................}(3)$$

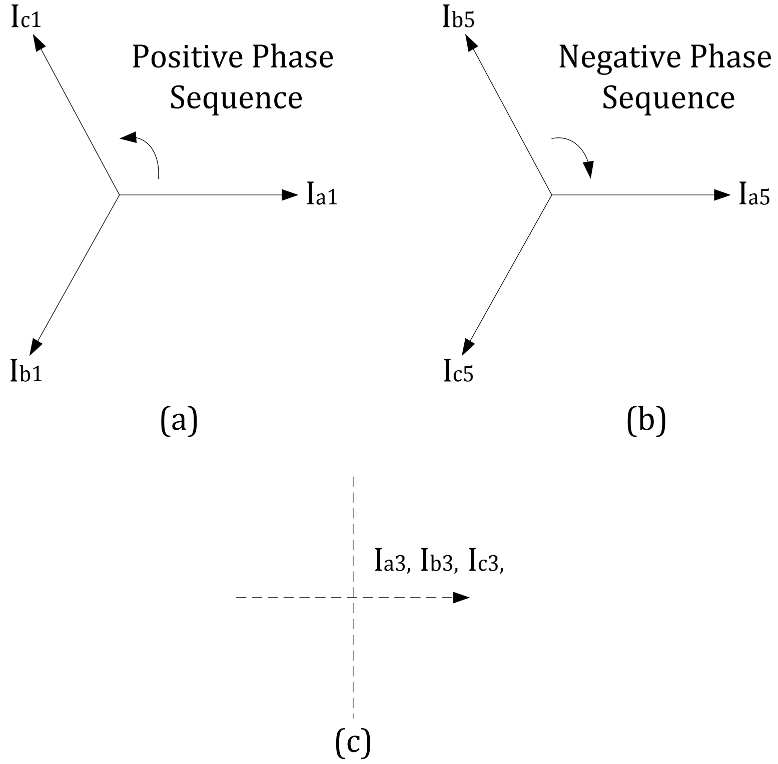

Figure 4. 2 (a) Fundamental phasors (b) Fifth harmonic phasors (c) Third harmonic phasors

The negative displacement angles indicate that the fundamental phasors i_{b1} and i_{c1} trail the i_{a1} phasor by the indicated angle. Figure 4.2a shows the fundamental current phasors.

The expression for the third harmonic currents are:

$$i_{a3} = I_{a3}\sin 3\omega t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$
$$i_{b3} = I_{b3}\sin 3(\omega t - 120^\circ) = I_{b3}\sin 3\omega t \ldots\ldots\ldots\ldots(5)$$
$$i_{c3} = I_{c3}\sin 3(\omega t - 240^\circ) = I_{c3}\sin 3\omega t \ldots\ldots\ldots\ldots(6)$$

The expressions for the third harmonics shows that they are in phase and have zero displacement angle between them. Figure 4.2c shows the third harmonic phasors. The third harmonic currents are known as zero sequence harmonics due to the zero displacement angle between the three phases.

The expressions for the fifth harmonic currents are:

$$i_{a5} = I_{a5}\sin 5\omega t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$
$$i_{b5} = I_{b5}\sin 5(\omega t - 120^\circ) = I_{b5}\sin(5\omega t - 240^\circ) \ldots\ldots\ldots\ldots(5)$$
$$i_{c5} = I_{c5}\sin 5(\omega t - 240^\circ) = I_{c5}\sin(5\omega t - 120^\circ) \ldots\ldots\ldots\ldots(6)$$

Figure 4.2b shows the fifth harmonic phasors. Note that the phase sequence of the fifth harmonic currents is clockwise and opposite to that of the fundamental. The fifth harmonics are negative sequence harmonics.

Table 4.1 Harmonic order vs. Phase sequence

Harmonic Order	**Phase Sequence**
1, 4, 7, 10, 13, 16, 19	Positive
2, 5, 8, 11, 14, 17, 20	Negative
3, 6, 9, 12, 15, 18, 21	Zero

4.5. Causes of Current and Voltage Harmonics

- The voltage waveform, even at the point of generation, contains a small amount of distortion due to non-uniformity in the excitation magnetic field and discrete spatial distribution of coils around the generator stator slots.
- The distortion at the point of generation is usually very low, typically less than 1.0%. The generated voltage is transmitted many hundreds of miles, transformed to several levels, and ultimately distributed to the power user.
- The user equipment generates currents that are rich in harmonic frequency components, especially in large commercial or industrial installations. As harmonic currents travel to the power source, the current distortion results in additional voltage distortion due to impedance voltages associated with the various power distribution equipment, such as transmission and distribution lines, transformers, cables, buses, and so on.
- All voltage distortion is due to the flow of distorted current through the power system impedance. As nonlinear loads are propagated into the power system, voltage

distortions are introduced which become greater moving from the source to the load because of the circuit impedances.

- Current distortions for the most part are caused by loads. Even loads that are linear will generate nonlinear currents if the supply voltage waveform is significantly distorted.
- When several power users share a common power line, the voltage distortion produced by harmonic current injection of one user can affect the other users.
- The major causes of current distortion are nonlinear loads due to adjustable speed drives, fluorescent lighting, rectifier banks, computer and data-processing loads, arc furnaces, and so on.

4.6. Individual and Total Harmonic Distortion

- **Individual Harmonic Distortion (IHD)** is the ratio between the RMS value of the individual harmonic and the RMS value of the fundamental.

$$IHD_n = \frac{I_n}{I_1} \text{............}(7)$$

- Under this definition, the value of IHD_1 is always 100%. This method of quantifying the harmonics is known as harmonic distortion based on the fundamental. This is the convention used by the IEEE. The IEC quantifies harmonics based on the total RMS value of the waveform.

Example: Assume that the RMS value of the 3rd harmonic current in a nonlinear load is 20 A, the RMS value of the fundamental is 60 A.

As per IEEE convention,

$$IHD_3 = \frac{20}{60} = 0.333 \, or \, 33.3\%$$

As per IEC convention,

The RMS value of the waveform is

$$I_{rms} = \sqrt{60^2 + 20^2} = 65A$$

$$IHD_1 = \frac{60}{65} = 0.923 \, or \, 92.3\%$$

$$IHD_3 = \frac{20}{65} = 0.308 \, or \, 30.8\%$$

The examples illustrate that even though the magnitudes of the harmonic currents are the same, the distortion percentages are different because of a change in the definition.

- **Total harmonic distortion (THD)** is the ratio between the RMS value of the harmonics and the RMS value of the fundamental. THD is a term used to describe the net deviation of a non-linear waveform from ideal sine waveform characteristics.
- If a non-linear current has a fundamental component of I_1 and harmonic components I_2, I_3, I_4, I_5, ……, then the RMS value of the harmonics is:

$$I_H = \sqrt{I_2{}^2 + I_3{}^2 + I_4{}^2 + I_5{}^2}$$

$$THD = (\frac{IH}{I_1}) \times 100\%$$

The individual harmonic distortion indicates the contribution of each harmonic frequency to the distorted waveform, and the total harmonic distortion describes the net deviation due to all the harmonics.

Example: Find the total harmonic distortion of a voltage waveform with the following harmonic frequency make up:
Fundamental = V1 = 114 V
3rd harmonic = V3 = 4 V
5th harmonic = V5 = 2 V
7th harmonic = V7 = 1.5 V
9th Harmonic = V9 = 1 V

This problem can be solved in two ways.

Method-1,

RMS value of the harmonics = $V_H = \sqrt{4^2 + 2^2 + 1.5^2 + 1^2} = 4.82V$

$$THD = (\frac{4.82}{114}) \times 100 \cong 4.23\%$$

Method-2,

The individual harmonic distortions,

$$IHD_3 = (\frac{4}{114}) \times 100 = 3.51\%$$

$$IHD_5 = (\frac{2}{114}) \times 100 = 1.75\%$$

$$IHD_7 = (\frac{1.5}{114}) \times 100 = 1.32\%$$

$$IHD_9 = (\frac{1}{114}) \times 100 = 0.88\%$$

By definition, IHD_1 = 100% so,

$$THD = \sqrt{IHD_3{}^2 + IHD_5{}^2 + IHD_7{}^2 + IHD_9{}^2} \cong 4.33\%$$

The results are not altered by using either the magnitude of the RMS quantities or the individual harmonic distortion values.

4.7. Harmonic Signatures

- Combined with the impedance of the electrical system, the loads also produce harmonic voltages. The nonlinear loads may therefore be viewed as both harmonic current generators and harmonic voltage generators.
- ASDs are generators of large harmonic currents. Fluorescent lights use less electrical energy for the same light output as incandescent lighting but produce substantial harmonic currents in the process. The explosion of personal computer use has resulted in harmonic current proliferation in commercial buildings.

4.7.1 Fluorescent Lighting

Table 4.2 Harmonic number vs. IHD for a fluorescent lighting load

h (n)	IHD (%)	h (n)	IHD (%)	h (n)	IHD (%)
1	100	10	0.1	19	1.4
2	0.3	11	2.2	20	0.4
3	13.9	12	0.3	21	1.2
4	0.3	13	1.7	22	0.6
5	9	14	0.3	23	0.6
6	0.2	15	1.9	24	0.7
7	3.3	16	0.3	25	1.4
8	0	17	0.8	26	1.1
9	3.2	18	0.5	27	0.3

- The fluorescent lighting is primarily comprised of the third and the fifth harmonic frequencies. The individual current harmonic distortion makeup is provided in Table 4.2. The table value also contains slight traces of even harmonics, especially of the higher frequency order.

4.7.2 Adjustable Speed Drive

- The PWM (pulse-width-modulation) drive technology is currently the most widely used for creating a variable voltage and variable frequency power source for the speed control of AC motors.

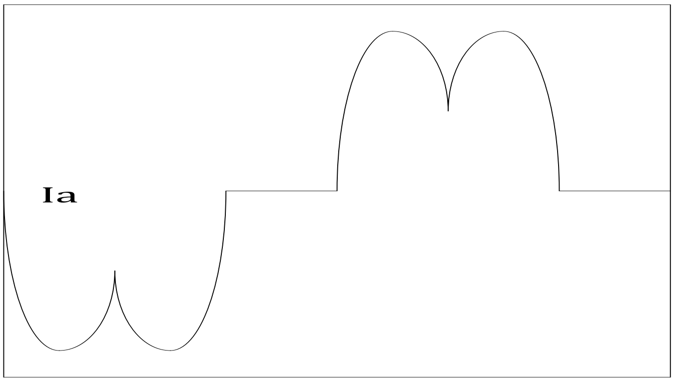

Figure 4. 3 Adjustable speed drive input current with motor operating at 60 Hz

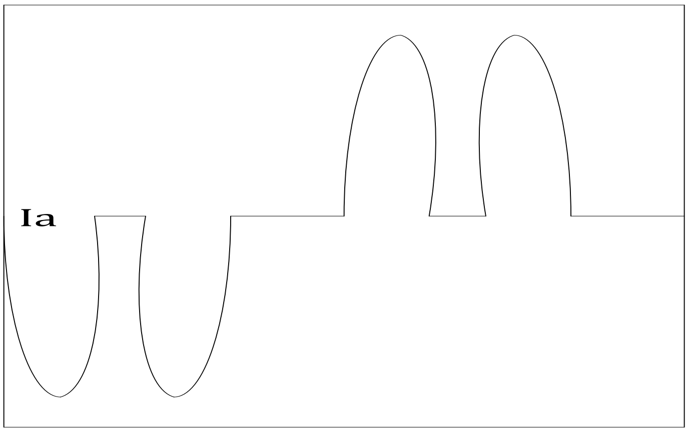

Figure 4. 4 Adjustable speed drive input current with motor operating at 45 Hz

- Figure 4.3 and 4.4 show current waveforms at the ASD input lines with a motor operating at 60 Hz and 45 Hz respectively.
- Table 4.3 and 4.4 show the harmonic current distortion spectrum for the two respective frequencies. The characteristic double hump for each half cycle of the AC waveform is due to conduction of the input rectifier modules for a duration of two 60° periods for each half cycle. As the operating frequency is reduced, the humps become pronounced with a large increase in the total harmonic distortion. The THD of 74.2% for 45 Hz operation is excessive and can produce many deleterious effects.

Table 4. 3 Harmonic number vs. IHD for an ASD input current with motor operation at 60 Hz

h (n)	IHD (%)	h (n)	IHD (%)	h (n)	IHD (%)
1	100	10	0.73	19	0.67
2	4.12	11	9.99	20	0.31
3	0.78	12	0.03	21	0.04
4	1.79	13	0.19	22	0.39
5	35.01	14	0.48	23	2.95
6	0.21	15	0.07	24	0.02
7	2.62	16	0.52	25	0.66
8	1	17	4.85	26	0.15
9	0.06	18	0.03	27	0.05

Total harmonic distortion = 37.3%

Table 4. 4 Harmonic number vs. IHD for an ASD input current with motor operation at 45 Hz

h (n)	IHD (%)	h (n)	IHD (%)	h (n)	IHD (%)
1	100	10	0.58	19	1.96
2	4.56	11	6.36	20	0.64
3	2.44	12	0.03	21	0.22
4	3.29	13	9.99	22	0.16
5	62.9	14	0.11	23	3.75
6	1.4	15	0.62	24	0.12
7	36.1	16	0.35	25	1.73
8	0.43	17	5.22	26	0.42
9	0.73	18	0.35	27	0.33

Total harmonic distortion = 74.2%

4.8. Effect of Harmonics on power system equipments

- The effects of harmonics are not known until failure occurs. Insight into how harmonics can interact within a power system and how they can affect power system components is important for preventing failures. In this section, the effect of harmonics on some common power system devices are described.

4.8.1 Transformers

- Harmonics can affect transformers primarily in two ways.
- Voltage harmonics produce additional losses in the transformer core as the higher frequency harmonic voltages set up hysteresis loops, which superimpose on the fundamental loop. Each loop represents higher magnetization power requirements and higher core losses.
- A second and a more serious effect of harmonics is due to harmonic frequency currents in the transformer windings.
- The harmonic currents increase the net RMS current flowing in the transformer windings which results in additional I^2R losses.
- Winding eddy current losses are also increased. Winding eddy currents are circulating currents induced in the conductors by the leakage magnetic flux. Eddy current concentrations are higher at the ends of the windings due to the crowding effect of the leakage magnetic field at the coil extremities. The winding eddy current losses increase as the square of the harmonic current and the square of the frequency of the current.
- Eddy currents due to harmonics can significantly increase the transformer winding temperature. Transformers that are required to supply large nonlinear loads must be derated to handle the harmonics. This derating factor is based on the percentage of the harmonic currents in the load and the rated winding eddy current losses.

- One method by which transformers may be rated for suitability to handle harmonic loads is by *k* factor ratings. The *k* factor is equal to the sum of the square of the harmonic frequency currents (expressed as a ratio of the total RMS current) multiplied by the square of the harmonic frequency numbers:

$$k = I_1^2(1)^2 + I_2^2(2)^2 + I_3^2(3)^2 + \ldots + I_n^2(n)^2$$

Where,

I_1 is the ratio between the fundamental current and the total RMS current.
I_2 is the ratio between the second harmonic current and the total RMS current.
I_3 is the ratio between the third harmonic current and the total RMS current.

Example: Determine the *k* rating of a transformer required to carry a load consisting of 500 A of fundamental, 200 A of third harmonics, 120 A of fifth harmonics, and 90 A of seventh harmonics:

$$(I) = \sqrt{(500)^2 + 200^2 + 120^2 + 90^2} = 559A$$

$$I_1 = \frac{500}{559} = 0.894A$$

$$I_3 = \frac{200}{559} = 0.358A$$

$$I_5 = \frac{120}{559} = 0.215A$$

$$I_7 = \frac{90}{559} = 0.161A$$

$$k = 0.894^2(1)^2 + 0.358^2(3)^2 + 0.215^2(5)^2 + 0.161^2(7)^2 = 4.378$$

The transformer specified should be capable of handling 559 A of total RMS current with a *k* factor of not less than 4.378. Typically, transformers are marked with *k* ratings of 4, 9, 13, 20, 30, 40, and 50, so a transformer with a *k* rating of 9 should be chosen. Such a transformer would have the capability to carry the full RMS load current and handle winding eddy current losses equal to *k* times the normal rated eddy current losses.

4.8.2 AC Motors

- Harmonics Application of distorted voltage to a motor results in additional losses in the magnetic core of the motor. Hysteresis and eddy current losses in the core increase as higher frequency harmonic voltages are impressed on the motor windings. Hysteresis losses increase with frequency and eddy current losses increase as the square of the frequency. Also, harmonic currents produce additional I^2R losses in the motor windings which must be accounted for.
- Another effect, and perhaps a more serious one, is **torsional oscillations** due to harmonics.
- Two of the more prominent harmonics found in a typical power system are the fifth and seventh harmonics. The fifth harmonic is a negative sequence harmonic, and the resulting magnetic field resolves in a direction opposite to that of the fundamental field at a speed five times the fundamental.

- The seventh harmonic is a positive sequence harmonic with a resulting magnetic field revolving in the same direction as the fundamental field at a speed seven times the fundamental.
- The net effect is a magnetic field that revolves at a relative speed of six times the speed of the rotor. This induces currents in the rotor bars at a frequency of six times the fundamental frequency.
- The resulting interaction between the magnetic fields and the rotor-induced currents produces torsional oscillations of the motor shaft. If the frequency of the oscillation coincides with the natural frequency of the motor rotating members, severe damage to the motor can result. Excessive vibration and noise in a motor operating in a harmonic environment should be investigated to prevent failures.

4.8.3 Capacitor Banks

- Capacitor banks are commonly found in commercial and industrial power systems to correct for low power factor conditions. Capacitor banks are designed to operate at a maximum voltage of 110 % of their rated voltages and at 135 % of their rated kVAr.
- When large levels of voltage and current harmonics are present, the ratings are quite often exceeded, resulting in failures. Because the reactance of a capacitor bank is inversely proportional to frequency, harmonic currents can find their way into a capacitor bank. The capacitor bank acts as a sink, absorbing stray harmonic currents and causing overloads and subsequent failure of the bank.
- A more serious condition with potential for substantial damage occurs due to a phenomenon called harmonic resonance. Resonance conditions are created when the inductive and capacitive reactance become equal at one of the harmonic frequencies. The two types of resonances are series and parallel. In general, series resonance produces voltage amplification and parallel resonance results in current multiplication.
- In a harmonic-rich environment, both series and parallel resonance may be present. If a high level of harmonic voltage or current corresponding to the resonance frequency exists in a power system, considerable damage to the capacitor bank as well as other power system devices can result.

4.8.4 Cables

- Current flowing in a cable produces I^2R losses. When the load current contains harmonic content, additional losses are introduced. To compound the problem, the effective resistance of the cable increases with frequency because of the phenomenon known as skin effect.
- Skin effect is due to unequal flux linkage across the cross section of the conductor which causes AC currents to flow only on the outer periphery of the conductor. This has the effect of increasing the resistance of the conductor for AC currents.
- The higher the frequency of the current, the greater the tendency of the current to crowd at the outer periphery of the conductor and the greater the effective resistance for that frequency.

- The capacity of a cable to carry nonlinear loads may be determined as follows. The skin effect factor is calculated first. The skin effect factor depends on the skin depth, which is an indicator of the penetration of the current in a conductor. Skin depth (d) is inversely proportional to the square root of the frequency:

$$\delta = S \div \sqrt{f}$$

Where *S* is a proportionality constant based on the physical characteristics of the cable and its magnetic permeability and *f* is the frequency of the current.

Table 4.5 Cable Skin Effect Factor

X	K	X	K	X	K
0	1	1.4	1.01969	2.7	1.22753
0.1	1	1.5	1.02558	2.8	1.2662
0.2	1	1.6	1.03323	2.9	1.28644
0.3	1.00004	1.7	1.04205	3.0	1.31809
0.5	1.00032	1.8	1.0524	3.1	1.35102
0.6	1.00067	1.9	1.0644	3.2	1.38504
0.7	1.00124	2.0	1.07816	3.3	1.41999
0.8	1.00212	2.1	1.09375	3.4	1.4577
0.9	1.0034	2.2	1.11126	3.5	1.49202
1.0	1.00519	2.3	1.13069	3.6	1.52879
1.1	1.00758	2.4	1.15207	3.7	1.56587
1.2	1.01071	2.5	1.17538	3.8	1.60312
1.3	1.0147	2.6	1.20056	3.9	1.64051

If R_{dc} is the DC resistance of the cable, then the AC resistance at frequency *f*, (R_f) = K×R_{dc}. The value of K is determined from Table 4.5 according to the value of X, which is calculated as:

$$X = 0.0636\sqrt{f\mu \div R_{dc}}$$

Where 0.0636 is a constant for copper conductors, *f* is the frequency, μ is the magnetic permeability of the conductor material, and R_{dc} is the DC resistance per mile of the conductor. The magnetic permeability of a nonmagnetic material such as copper is approximately equal to 1.0. Tables or graphs containing values of *X* and *K* are available from cable manufacturers.

4.8.5 Busways

- Busways that incorporate sandwiched busbars are susceptible to nonlinear loading, especially if the neutral bus carries large levels of triplen harmonic currents (third, ninth, etc.).
- Under the worst possible conditions, the neutral bus may be forced to carry a current equal to 173 % of the phase currents. In cases where substantial neutral currents are expected, the busways must be suitably derated.

- Table 4.6 indicates the amount of nonlinear loads that may be allowed to flow in the phase busbars for different neutral currents. The data are shown for busways with neutral busbars that are 100 % and 200 % in size.

Table 4.6 Bus Duct Derating Factor for Harmonic Loading

$\frac{I_N}{I_{\emptyset H}}$	$\frac{I_{\emptyset H}}{I_{\emptyset}}$	
	100% N	**200% N**
0	1	1
0.25	0.99	0.995
0.5	0.961	0.98
0.75	0.918	0.956
1	0.866	0.926
1.25	0.811	0.891
1.5	0.756	0.853
1.75	0.703	0.814
2	0.655	0.775

4.8.6 Protective Devices

- Harmonic currents influence the operation of protective devices. Fuses and motor thermal overload devices are prone to nuisance operation when subjected to nonlinear currents. This factor should be given due consideration when sizing protective devices for use in a harmonic environment.
- Electromechanical relays are also affected by harmonics. Depending on the design, an electromechanical relay may operate faster or slower than the expected times for operation at the fundamental frequency alone. Such factors should be carefully considered prior to placing the relays in service.

4.9. Guidelines for Harmonic Voltage and Current Limitation

- The IEEE 519 standard provides guidelines for harmonic current limits at the point of common coupling (PCC) between the facility and the utility. The rationale behind the use of the PCC as the reference location is simple. It is a given fact that within a particular power use environment, harmonic currents will be generated and propagated. Harmonic current injection at the PCC determines how one facility might affect other power users and the utility that supplies the power.
- Table 4.7 (as per IEEE 519) lists harmonic current limits based on the size of the power user. As the ratio between the maximum available short circuit current at the PCC and the maximum demand load current increases, the percentage of the harmonic currents that are allowed also increases. This means that larger power users are allowed to inject into the system only a minimal amount of harmonic current (as a percentage of the fundamental current). Such a scheme tends to equalize the amounts of harmonic currents that large and small users of power are allowed to inject into the power system at the PCC.
- IEEE 519 also provides guidelines for maximum voltage distortion at the PCC (refer Table 4.8). Limiting the voltage distortion at the PCC is the concern of the utility. It can

be expected that as long as a facility's harmonic current contribution is within the IEEE 519 limits the voltage distortion at the PCC will also be within the specified limits.

Table 4. 7 Harmonic Current Limits for General Distribution Systems (120-69000 V)

I_{SC}/I_L	h<11	11<=h<17	17<=h<23	23<=h<35	35<=h	THD
<20	4	2	1.5	0.6	0.3	5
20-50	7	3.5	2.5	1	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

Note: I_{SC} = maximum short-circuit current at PCC; I_L = maximum fundamental frequency demand load current at PCC (average current of the maximum demand for the preceding 12 months); h = individual harmonic order; THD = total harmonic distortion based on the maximum demand load current. The table applies to odd harmonics; even harmonics are limited to 25% of the odd harmonic limits shown above.

Table 4. 8 Voltage Harmonic Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3	5
69 kV through 161 kV	1.5	2.5
161 kV and above	1	1.5

Note: PCC = point of common coupling; THD = total harmonic distortion

When the IEEE 519 harmonic limits are used as guidelines within a facility, the PCC is the common junction between the harmonic generating loads and other electrical equipment in the power system.

4.10. Harmonic Current Mitigation

4.10.1 Equipment Design

- The importance of equipment design in minimizing harmonic current production has taken on greater importance, as reflected by technological improvements in fluorescent lamp ballasts, adjustable speed drives, battery chargers, and uninterruptible power source (UPS) units.
- Adjustable speed drive (ASD) technology is evolving steadily, with greater emphasis being placed on a reduction in harmonic currents. Older generation ASDs using current source inverter (CSI) and voltage source inverter (VSI) technologies produced considerable harmonic frequency currents. The significant harmonic frequency currents generated in power conversion equipment can be stated as:

$$n = kq \pm 1$$

Where n is the significant harmonic frequency, k is any positive integer (1, 2, 3, etc.), and q is the pulse number of the power conversion equipment which is the number of power pulses that are in one complete sequence of power conversion.

- For example, a three-phase full wave bridge rectifier has six power pulses and therefore has a pulse number of 6. With six-pulse-power conversion equipment, the following significant harmonics may be generated:

$$For\ k = 1, n = (1X6) \pm 1 = 5^{th}\ and\ 7^{th}\ harmonics$$

$$For\ k = 2, n = (2X6) \pm 1 = 11^{th}\ and\ 13^{th}\ harmonics$$

- With six-pulse-power conversion equipment, harmonics below the 5th harmonic are insignificant. Also, as the harmonic number increases, the individual harmonic distortions become lower due to increasing impedance presented to higher frequency components by the power system inductive reactance. So, typically, for six-pulse-power conversion equipment, the 5th harmonic current would be the highest, the 7th would be lower than the 5th, the 11th would be lower than the 7th, and so on, as shown below:

$$I_{13} < I_{11} < I_7 < I_5$$

- We can deduce that, when using 12-pulse-power conversion equipment, harmonics below the 11th harmonic can be made insignificant. The total harmonic distortion is also considerably reduced. Twelve-pulse-power conversion equipment costs more than six-pulse-power equipment. Where harmonic currents are the primary concern, 24-pulse-power conversion equipment may be considered.

4.10.2 Harmonic Current Cancellation

- Transformer connections employing phase shift are sometimes used to effect cancellation of harmonic currents in a power system. Triplen harmonic (3rd, 9th, 15th, etc.) currents are a set of currents that can be effectively trapped using a special transformer configuration called the zigzag connection. In power systems, triplen harmonics add in the neutral circuit, as these currents are in phase. Using a zigzag connection, the triplens can be effectively kept away from the source. Figure 4.5 illustrates how this is accomplished.

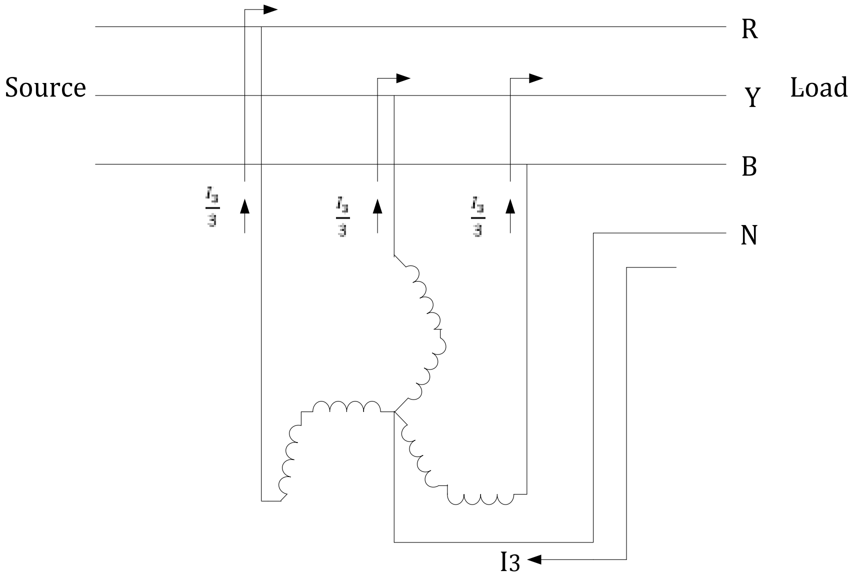

Figure 4. 5 Zig-zag transformer application as third harmonic filter

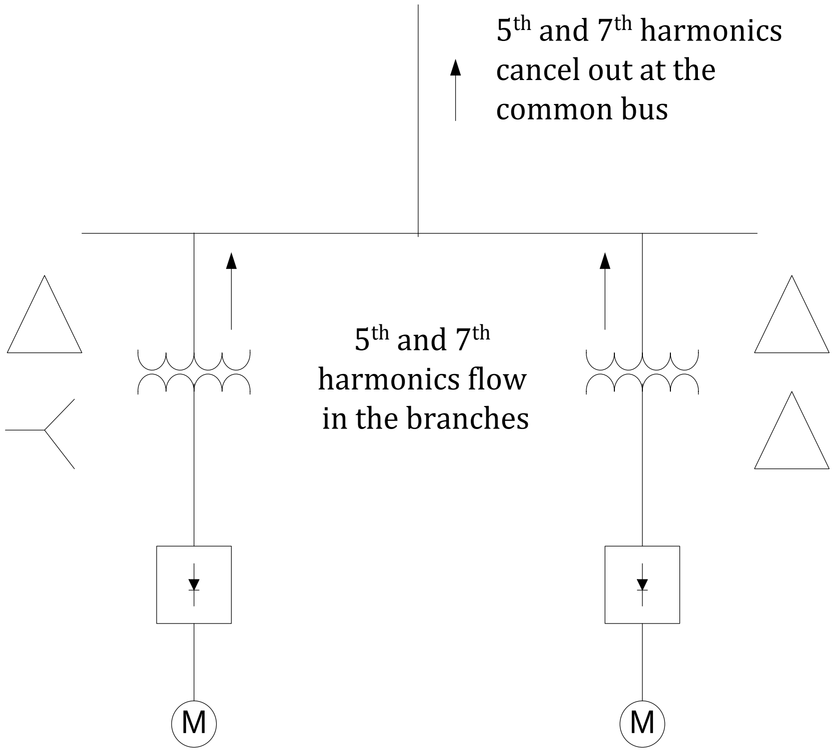

Figure 4. 6 Cancellation of fifth and seventh harmonic currents by using 30° phase-shifted transformer connections

- The transformer phase-shifting principle is also used to achieve cancellation of the 5th and the 7th harmonic currents. Using a Δ–Δ and a Δ–Y transformer to supply harmonic producing loads in parallel as shown in Figure 4.6, the 5th and the 7th harmonics are cancelled at the point of common connection. This is due to the 30° phase shift between the two transformer connections.
- As the result of this, the source does not see any significant amount of the 5th and 7th harmonics. If the nonlinear loads supplied by the two transformers are identical, then maximum harmonic current cancellation takes place; otherwise, some 5th and 7th harmonic currents would still be present. Other phase-shifting methods may be used to cancel higher harmonics if they are found to be a problem. Some transformer manufacturers offer multiple phase-shifting connections in a single package which saves cost and space compared to using individual transformers.

4.10.3 Harmonic Filters

- Nonlinear loads produce harmonic currents that can travel to other locations in the power system and eventually back to the source. One means of ensuring that harmonic currents produced by a nonlinear current source will not unduly interfere with the rest of the power system is to filter out the harmonics. Application of harmonic filters helps to accomplish this.
- Harmonic filters are broadly classified into passive and active filters. Passive filters, as the name implies, use passive components such as resistors, inductors, and capacitors.
- A combination of passive components is tuned to the harmonic frequency that is to be filtered. In a typical series-tuned filter, the values of the inductor and the capacitor are

chosen to present a low impedance to the harmonic frequency that is to be filtered out.

- Due to the lower impedance of the filter in comparison to the impedance of the source, the harmonic frequency current will circulate between the load and the filter. This keeps the harmonic current of the desired frequency away from the source and other loads in the power system. If other harmonic frequencies are to be filtered out, additional tuned filters are applied in parallel. Applications such as arc furnaces require multiple harmonic filters, as they generate large quantities of harmonic currents at several frequencies.
- Applying harmonic filters requires careful consideration. Series-tuned filters appear to be of low impedance to harmonic currents but they also form a parallel resonance circuit with the source impedance. In some instances, a situation can be created that is worse than the condition being corrected.
- It is imperative that computer simulations of the entire power system be performed prior to applying harmonic filters. As a first step in the computer simulation, the power system is modelled to indicate the locations of the harmonic sources, then hypothetical harmonic filters are placed in the model and the response of the power system to the filter is examined.
- If unacceptable results are obtained, the location and values of the filter parameters are changed until the results are satisfactory. When applying harmonic filters, the units are almost never tuned to the exact harmonic frequency. For example, the 5th harmonic frequency may be designed for resonance at the 7th harmonic frequency.
- By not creating a resonance circuit at precisely the 5th harmonic frequency, we can minimize the possibility of the filter resonating with other loads or the source, thus forming a parallel resonance circuit at the 5th harmonic. The 7th harmonic filter would still be effective in filtering out the 5th harmonic currents.

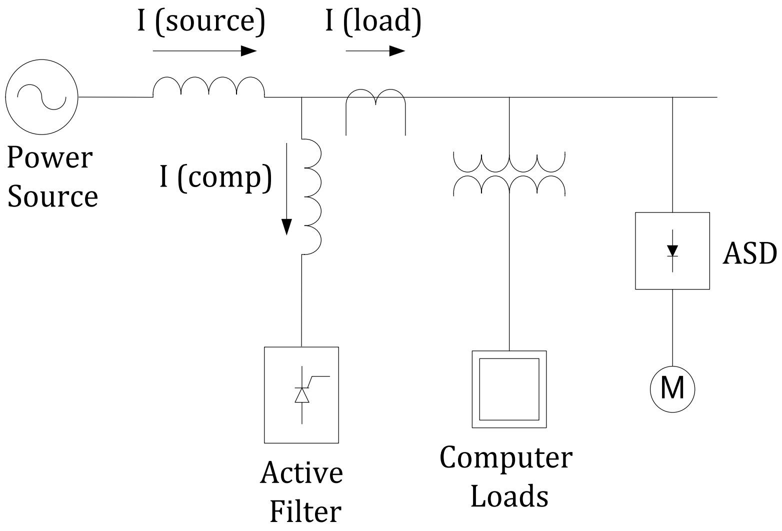

Figure 4. 7 Active filter to cancel harmonic currents

- Active filters use active conditioning to compensate for harmonic currents in a power system. Figure 4.7 shows an active filter applied in a harmonic environment. The filter samples the distorted current and, using power electronic switching devices, draws a current from the source of such magnitude, frequency composition, and phase shift to cancel the harmonics in the load.

- The result is that the current drawn from the source is free of harmonics. An advantage of active filters over passive filters is that the active filters can respond to changing load and harmonic conditions, whereas passive filters are fixed in their harmonic response. Active filters are expensive and not suited for application in small facilities.

4.11. Total Demand Distortion (TDD)

Concept

- The **TDD(I)** = Total Current Demand Distortion is Calculated harmonic current distortion against the full load (demand) level of the electrical system.
- At the full load TDD(I) = THD(I). So TDD gives us better insight about how big impact of harmonic distortion in our system. For example we could have very high THD but the load of the system is low. In this case the impact on the system is also low.
- We can characterize current distortion levels with a THD value, but this can be misleading. A small current can have a high THD but not be a significant threat. For example, many adjustable-speed drives will exhibit high THD values for the input current while operating at very light loads. This shouldn't be a concern, because the magnitude of harmonic current would be low in this instance, even though its relative current distortion is quite high.
- Responding to such scenarios, some analysts have referred to THD as the **fundamental of the peak demand load current** rather than the fundamental of the present sample. This is called total demand distortion, or **TDD**. Contrary to popular belief, TDD and not THD serves as the basis for the guidelines in IEEE 519, “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.” In fact, IEEE 519 defines TDD as **“the total root-sum-square harmonic current distortion, in percent of the maximum demand load current.”**
- TDD is equal to the **square root of the sum of squares of each of the maximum demand currents from the second harmonic to the maximum harmonic present, divided by the maximum demand load current at the fundamental**. TDD is meaningful when monitored at the PCC over a period of time that reflects maximum customer demand. Per IEEE 519, this is typically 15 minutes to 30 minutes.

$$TDD = \sqrt{\frac{sum\ of\ squares\ of\ amplitudes\ of\ all\ harmonics}{square\ of\ maximum\ demand\ load\ current}} \times 100\ \%$$

Calculations

- The Total Demand Distortion (TDD) can be calculated by the following two methods:

  Method-1: If the per phase THD and Fundamental currents are known,

  Method-2: If the per phase THD and true RMS currents are known

Method-1: If the per phase THD and Fundamental currents are known

If you know the THD and Fundamental current, you can derive ha, hb, and hc necessary to calculate TDD.

- **Thus, for phase A**

$$THD_A = \frac{\sqrt{H_2A_2 + H_2A_3 + H_2A_4 + \dots}}{H_{A1}} \times 100\%$$

$$h_a = \frac{(THD_A \times H_{A1})}{100}\%$$

- **For phase B**

$$THD_B = \frac{\sqrt{H_2B_2 + H_2B_3 + H_2B_4} + \dots}{H_{B1}} \times 100\%$$

$$h_b = \frac{(THD_B \times H_{B1})}{100}\%$$

- **For phase C**

$$THD_C = \frac{\sqrt{H_2C_2 + H_2C_3 + H_2C_4}}{H_{C1}} \times 100\%$$

$$h_c = \frac{(THD_C \times H_{C1})}{100}\%$$

Where,
H_{A1} is the fundamental current for phase A,
H_{B1} is the fundamental current for phase B,
H_{C1} is the fundamental current for phase C

From above point,

$$TDD = \frac{\sqrt{h_a^2 + h_b^2 + h_c^2}}{Peak\ demand\ current} \times 100\%$$

Method-2: If the per phase THD and true RMS currents are known

If you know the THD and "true" RMS currents, you can derive h_a, h_b, and h_c necessary to calculate TDD.

$$THD = \frac{\sqrt{H_2^2 + H_3^2 + H_4^2 + \dots}}{Total\ RMS\ current} \times 100\%$$

- Thus, **for phase A**

$$THD_A = \frac{\sqrt{H_{A2}^2 + H_{A3}^2 + H_{A4}^2 + \dots}}{I_{RMS,A1}} \times 100\%$$

$$\mathrm{h}_a = \frac{(THD_A \times I_{RMS,A1})}{100}\%$$

- **For phase B**

$$THD_B = \frac{\sqrt{H_{B2}{}^2 + H_{B3}{}^2 + H_{B4}{}^2 + \ldots}}{I_{RMS,B1}} \times 100\%$$

$$\mathrm{h}_b = \frac{(THD_B \times I_{RMS,B1})}{100}\%$$

- **For phase C**

$$THD_C = \frac{\sqrt{H_{C2}{}^2 + H_{C3}{}^2 + H_{C4}{}^2 + \ldots}}{I_{RMS,C1}} \times 100\%$$

$$\mathrm{h}_c = \frac{(THD_C \times I_{RMS,C1})}{100}\%$$

Where,

$I_{RMS,\,A1}$ is the “true” current for phase A,
$I_{RMS,\,B1}$ is the “true” current for phase B,
$I_{RMS,\,C1}$ is the “true” current for phase C

From above point,

$$TDD = \frac{\sqrt{h_a{}^2 + h_b{}^2 + h_c{}^2}}{Peak\ demand\ current} \times 100\%$$
