Harmonic Distortion Effects and Mitigation in Distribution Systems

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Abstract: The harmonic distortion in the power system is increasing with wide use of nonlinear loads such as wave rectifiers, and solid-state controlled devices. Thus, it is important to analyze and evaluate the various harmonic problems in the power system and introduce the appropriate solution techniques. This paper, firstly, analyses the propagation of harmonic current and voltage in power system networks and appreciate their consequences on both utility system components and end user equipments. Throughout wave analysis of the harmonic wave forms and the concepts of cancellation and combination, effective techniques have been introduced by application of phase shifting transformers. Besides, other alternatives to mitigate harmonic effects on the system components utilizing harmonic filters are given. The merits of the introduced techniques were highlighted through a study case using Electromagnetic Transient Analysis Program (ETAP) computer package. [Journal of American Science. 2010;6(10):173-183]. (ISSN: 1545-1003).

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1. Introduction

Harmonic currents are present in modern electrical distribution systems caused from non-linear loads such as adjustable speed drives; electronically ballasted lighting; and the power supplies of every computer, copier, and fax machine and much of the telecom equipment used in modern offices. The widespread and growing of these loads has greatly increased the flow of harmonic currents on facility distribution systems and has created a number of problems. These problems include overheated transformers, motors, conductors, and neutral wires; nuisance breaker trips; voltage distortion, which can cause sensitive electronic equipment to malfunction or fail; and elevated neutral-to-ground voltage, which can cause local area networks to malfunction.

Single-phase electronic loads generate harmonics at all odd multiples of the fundamental, but the most dangerous of these are usually the "triplen" harmonics that have frequencies multiples of the third harmonic. Triplens add together in the neutral on the secondary side of a delta-wye transformer and can cause very high neutral currents. In conventional transformers, triplen harmonics are transferred to the primary (delta) winding, of this transformer is thus spared from having causing excessive losses in the transformer [1].

Three-phase loads do not generate triplen harmonics. As a result, harmonic problems in industrial facilities dominated by three-phase loads will most often result from currents flowing at the 5th , 7th, 11th, 17th, 19th , ….., etc. order harmonics. In a three-phase power distribution system, the 5th and 7th harmonics are the most predominant causes of distortion and heating problems. These harmonics will easily cause standard distribution transformers to overheat of neutral conductors and may burn at the worst severe conditions.

The elimination or attenuation of harmonics can be accomplished through a variety of techniques. Active filters are good, but are the most expensive and complex. Active filters digitally create and control reactive power to cancel the harmonics. An effective, basic method to eliminate or attenuate harmonics is through the use of phase shifting transformers.. The principal is to take harmonics generated from separate sources, shift one source of harmonics 180° with respect to the other and then combine them together; this will result in cancellation.

Many choices are available to mitigate harmonic distortion including line reactors, harmonic traps, 12-pulse rectifiers, 18-pulse rectifiers, and low pass filters. Some of these solutions offer guaranteed results and have no adverse effect on the power system, while the performance of others is largely dependent on system conditions. Operation analysis and technical appraisal of these solutions are studied [2].

2. Sources of Harmonic Distortion

The characteristic behavior of non-linear loads is that they draw a distorted current waveform even though the supply voltage is sinusoidal. Most equipment only produces odd harmonics. The current distortion, for each device, changes due to the consumption of active power, background voltage distortion and changes in the source impedance.

An overview will be given of the most common types of single and three phase non-linear loads for residential and industrial use.

2. 1. Single Phase Loads

Electronic equipment, supplied from the low voltage power system, rectifies the ac power to dc power for internal use at different dc voltage levels. Such equipments consist of:

_ TV's _ Video recorders. _ Computers
_ Printers _ Micro wave ovens
_ Adjustable speed drives. _ H.F. fluorescent lighting.
_ Small UPS's. _ etc.

2. 2. Three Phase Loads

Three phase rectifiers are used for higher power applications. The rectifier can either be controlled or non-controlled and can consist of diodes, thyristors or transistors. The DC-link consists, in most cases, of a capacitor for the lower power applications. For larger rectifiers a smoothing inductor and a capacitor are used. For controlled transistor rectifiers the DC link consists of a capacitor and on the line side an inductor is used. The three-phase group is used mainly in industry applications and in the power system. Some examples are:

_ Adjustable speed drives _ Large UPS's _ Arc furnaces _ HVDC-links
_ Traction, vehicles _ SVC's

3. Harmonic Consequences

3. 1. Impact of Harmonics on Power Factor

PF is a measure of the efficiency of utilization of a power distribution system.

The PF for a system powering only linear loads is called the displacement power factor (DPF). Today, many electrical systems have harmonic currents on their lines. Harmonics are caused by non-linear or pulsed loads and their current causes the apparent power to exceed the active and reactive powers by a substantial amount. The apparent power for a nonlinear load can be calculated using the equation:

$$KVA = \sqrt{\left(P^2 + Q^2 + DVA^2\right)} \qquad (1)$$

Where P, Q are the active and reactive powers corresponding to the fundamental component where DVA the distorted volt ampere that corresponds to the other components.

The presence of harmonics increases the apparent power that must be delivered, therefore lowering the PF. In these situations, the form of power factor present is called distortion power factor. In a system consisting of both linear and non linear loads the True Power Factor (TPF) is a sum of Cosine of both Displacement and Distortion Angles. If harmonic currents are introduced into a system, the True PF will always be lower than the displacement PF.

3. 2. Impact of Harmonics on Capacitors

Harmonic component affects the performance of a capacitor unit significantly due to diminishing reactance at higher frequencies, which adds to its loading substantially and can be analyzed as follows:

$$X_c = 1/(2\pi fc) \qquad i.e. X_c \alpha (1/f) \qquad (2)$$

This means that the capacitor will offer a low reactance to the higher harmonics and will tend to magnify the harmonic effect due to higher harmonic currents. In fact, harmonic currents have a greater heating effect compared to fundamental current. The effective current caused by all the harmonics present in the system can be expressed as:

$$I_{ch} = \sqrt{\left(I_c^{\,2} + 9I_{ch3}^{\,2} + 25I_{ch5}^{\,2} + 49I_{ch7}^{\,2} + \ldots\ldots + k^2 I_{ch}^{\,2}\right)} \qquad (3)$$

Where, I_c = rated current of the capacitor
Ich3 , Ich5 , Ich7 etc. = amplitude of the harmonic current components at different orders.

Over current resulting to an over voltage across the capacitor units, which would inflict greater dielectric stress on capacitor elements.Since the harmonic disorders occur at higher frequencies than the fundamental, they cause higher dielectric losses.

$$KVAR = \frac{\sqrt{3} * V * Ic}{1000}$$

$$Ic = \frac{V}{Xc}$$

$$KVAR = \frac{\sqrt{3} * V^2}{1000 * Xc}$$

$$KVAR = \frac{\sqrt{3} * V^2 * 2\pi * f * c}{1000} \qquad (4)$$

general:

$KVAR_h$ is proportional to $V^2{}_h..F_h$,
h=1,3,5,….,k

The rating of the capacitor unit will thus vary in a square proportion of the effective harmonic voltage and in direct proportion to the harmonic frequency. Thus, the output $KVAR$ of the capacitor unit at harmonic existence, is the kvar corresponding to the fundamental in addition to the $KVAR$s corresponding to the other harmonic orders. Since the $KVAR$ due to the fundamental is the only component that contributes in P.F correction of the system, the latter $KVAR$s components don't contribute in P.F correction, but only causes overloading to the capacitor unit.

3. 3. Motor Heating

For frequencies higher than fundamental, three-phase induction motors can be approximated by positive/negative shunt impedances,

$$Z_k = R_{winding} + jKX \qquad (5)$$

Where $R_{winding}$ is the motor winding resistance, K is the harmonic order and X is the fundamental frequency reactance (typically 0.20 pu on motor base). The harmonic voltages can create additional rotor winding currents and increase the $I^2R_{winding}$ losses in three-phase motors by several percent.

3. 4. Overloaded Neutral Conductors

In a three-phase, four-wire system, positive and negative sequence components sum to zero at the neutral point, but zero sequence components are purely additive in the neutral.

Power system engineers are accustomed to the traditional rule that “balanced three-phase systems have no neutral currents.” However, this rule is not true when zero sequence harmonics (i.e., primarily the 3rd harmonic) are present. In commercial buildings with large numbers of PC loads, the rms neutral current can actually exceed rms phase currents.

٤. Harmonic Active Power Flow [3]

This section shows the principles of harmonic active power flow in radial low and medium voltage distribution systems. The main emphasis is on the interaction between loads and the power system. The interaction is due to the change in source impedance caused by harmonic filters or capacitor banks and a mix of single and three phase non-linear and linear loads.

The active harmonic power flow in a certain point in a power system, with non-linear loads, does not represent the actual flow to the loads in the downstream system. The harmonic active power is partly or completely included in the fundamental active power, depending of the mix of loads.

The voltage and the current distortion cause additional losses in power system components and in linear loads. The flow of the harmonic active power components supplying these losses, between different parts of the power system or different loads, depends on the configuration of the system and the mix of loads. This power flow, at a certain point, can be positive (towards the load), negative (from the load) and sometimes it is not seen at all.

4. 1. General Characteristics: Active Power and Losses

The current distortion causes increased losses in power system components. For each harmonic, *n*, the losses can be written as:

$$P_{(n)} = R_{(n)}.I_{(n)}^{2} \qquad (6)$$

With *R* (*n*) the resistance for harmonic, *n*.

The total increase of the losses in a system is the sum of the losses, at each harmonic, for all components and loads.

At a certain point in the power system the instantaneous power flow, including fundamental and harmonic flow, is the time derivative of the exchange of energy between the electrical systems, or between an electrical system and a mechanical system:

$$p(t)_{tot} = \frac{dW(t)}{dt} \qquad (7)$$

The active power is the average over one cycle of the instantaneous power flow. Expressed in voltages and currents Fourier components the total active power, the instantaneous power averaged over the time T, is

$$P_{tot} = \frac{1}{T}\int_{0}^{t} u_{(t)}.i_{(t)}dt = P_{1} + \sum_{n=2}^{\infty} P_{(n)} \qquad (8)$$

The active power flow to a non-linear load consists in most cases of fundamental flow and harmonic flow; i.e. the harmonic parts result in additional losses in the feeding power system. The fundamental active power to a non-linear load, can be obtained from equation (8) as fellow:

$$P_{1} = P_{tot} - \sum_{n=1}^{\infty} P_{(n)} \qquad (9)$$

Linear loads, contrary to non-linear loads, only consume fundamental active power, while non linear loads consume fundamental active power and harmonic powers.

٥. Interaction Load System

Consider a non-linear load taking a (nth harmonic) current *I*(*n*) from an otherwise non-distorted supply. The source impedance at the equipment terminals for harmonic *n* is:

$$Z_{(n)} = R_{(n)} + jX_{(n)} \qquad (10)$$

The losses in the system due to harmonic *n* are equal to:

$$P_{(n)} = R_{(n)}.I_{(n)}^{2} \qquad (11)$$

The total losses due to harmonic distortion are the sum of the losses due to the individual harmonics. The harmonic voltage distortion due to the current distortion is equal to the voltage drop over the source impedance:

$$U_{(n)} = -(R_{(n)} + jX_{(n)})I_{(n)}^{2} \qquad (12)$$

The apparent load power at harmonic *n* is:

$$S_{(n)} = U_{(n)}.I_{(n)} = -(R_{(n)} + jX_{(n)})I_{(n)}^{2} \qquad (13)$$

The active power is the real part of the apparent power, so that

$$P_{(n)} = -R_{(n)}.I_{(n)}^{2} \qquad (14)$$

This is equal to the harmonic losses in the system. When the active power is measured somewhere in the system, i.e. not at the terminals of the non-linear load, the harmonic active power measured is equal to the losses upstream of the measurement location. Let

$$Z_{up(n)} = R_{up(n)} + jX_{up(n)} \qquad (15)$$

be the source impedance at the measurement location, for harmonic *n*, and

$$Z_{Down(n)} = R_{Down(n)} + jX_{Down(n)} \qquad (16)$$

The impedance between the load and the measurement location, for harmonic *n*. Similarly as before it can be shown that the active power flow measured is equal to:

$$P_{Up(n)} = -R_{Up(n)}.I_{(n)}^{2} \qquad (17)$$

The total additional losses due to the nonlinear load are however:

$$P_{(n)} = (R_{Up(n)} + R_{Down}).I_{(n)}^{2} \qquad (18)$$

So, the losses downstream of the measurement location are not included in the harmonic active power measurement. Thus, it is only the exchange of the harmonic power between the two systems that is monitored.

6. Harmonic Effect on Transformers and K-Factor Solution [4]

Losses in transformers are due to stray magnetic losses in the core, and eddy current and resistive losses in the windings. Of these, eddy current losses are of most concern when harmonics are present, because they increase approximately with the square of the frequency. The total eddy current loss P*t* is given by:

$$P_t = P_f \sum_{h=1}^{h=h\max} I_h^{2} h^{2} \qquad (19)$$

Where: P_f is the eddy current loss at the fundamental frequency f.
I_h is the fraction of total rms load current at harmonic number h.

Two solutions are considered in designing such transformers to cope with the increased eddy current loss:

(a) K-Factor Transformers: Calculate the factor increase in eddy current loss "K-Factor" and specify a transformer designed to cope from the standard range from the present industry literature of K-1, K-4, K-9, K-13, K-20, K-30, K-40 K-50. In theory, a transformer could be designed for other K-factor ratings in-between those values, as well as for higher values.

The K-Factor rating assigned to a transformer, is an index of the transformer's ability to supply harmonic content in its load current while remaining within its operating temperature limits. The commonly referenced ratings calculated according to ANSI/IEEE C57.110-1986 are as follows:
K-1: This is the rating of any conventional transformer that has been designed to handle only the heating effects of eddy currents and other losses resulting from 50 Hertz, sine-wave current loading on the transformer.

K-4: A transformer with this rating has been designed to supply rated KVA, without overheating, to a load made-up of 100% of the normal 50 Hertz, sine-wave, fundamental current plus: 16% of the fundamental as 3rd harmonic current; 10% of the fundamental as 5th; 7% of the fundamental as 7th; 5.5% of the fundamental as 9th; and smaller percentages through the 25th harmonic. The "4" indicates its ability to accommodate four times the eddy current losses of a K-1 transformer.

K-9: A K-9 transformer can accommodate 163% of the harmonic loading of a K-4 rated transformer.

K-13: A K-13 transformer can accommodate 200% of the harmonic loading of a K-4 rated transformer.

K-20, K-30, K-40, and K-40: The higher number of each of these K-factor ratings indicates ability to handle successively larger amounts of harmonic load content without overheating.

(b) Factor-K [5]: Estimate how much a standard transformer should be de-rated "Factor-K" so that the total loss on harmonic load does not exceed the fundamental design loss. Derating is a mean of determining the maximum load that may be safely placed on a transformer that supplies harmonic loads.
The factor K is given by:

$$K = \left(1 + \frac{e}{1+e}\left(\frac{I_1}{I}\right)^{2} \sum_{n=2}^{n=N}\left(n^{q}\left(\frac{I_n}{I_1}\right)^{2}\right)\right)^{0.5} \qquad (20)$$

Where *e* is the eddy current loss at the fundamental frequency divided by the loss due to a dc current equal to the RMS value of the sinusoidal current, *n* is the harmonic order and *I* is the rms value of the sinusoidal current including all harmonics given by:

$$I = \left(\sum_{n=1}^{n=N}(I_n)^{2}\right)^{0.5} = I_1\left[\sum_{n=1}^{n=N}\left(\frac{I_n}{I_1}\right)^{2}\right]^{0.5} \qquad (21)$$

I_n is the magnitude of the nth harmonic, I_1 is the magnitude of the fundamental current and q a constant that is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round or rectangular cross section conductors in both windings and 1.5 for those with foil low voltage windings.

7. Harmonic Mitigation and Cancellation

Different strategies are offered for harmonic mitigation to meet the standard regulation limits. No uniform harmonic mitigation standard exists for the busses inside a plant; the appropriate technology is that meets the needs of the client. A cost-benefit analysis shows that inductors are the first best choice. The following are the more popular technologies to eliminate harmonics or mitigate its effects

7.1 Harmonic cancelation

7. 1.1. 6-Pulse rectifier

The 6-pulse rectifier circuit is adopted in most AC drives because of its simple and low cost structure. However, at full load conditions, the input current THD can exceed 100% with no DC link reactor (DCL) and with no harmonic filter with the 5th, 7th and 11th harmonics. The input current THD can be reduced to about 40% at full load conditions when using DCL. The harmonic currents can be further reduced to about 25%. Practically, there are limitations in reducing the THD below 30 % due to increasing AC reactor size and line voltage drop.

7.1. 2. 12-Pulse rectifier solution

The 12-pulse rectifier solution consists of two 6-pulse diode bridges combined with a multi-phase transformer. The output of two diode bridge rectifiers can be connected in parallel through a DC link choke. The multi-phase transformer can be an autotransformer or an isolated transformer with 30° displacement to provide two three-phase voltage sources that cancel the 5th and 7th harmonics. The 11th and 13th harmonics are the dominant components in the input current waveform. And the input current THD of about 10% can be achieved.

7.1. 3. 18-Pulse rectifier solution

The 18-pulse rectifier topology consists of a multi-phase transformer and three 6-pulse diode bridges, the output of which is connected in parallel through a DC link choke. In the theoretical 18-pulse system, the three phase-shifted voltage sources connected to the three 6-diode bridges will cancel the 5th , 7th ,11th ,and 13th harmonics and the remaining dominant harmonic components are the 17th and 19th. The multi-phase transformer can be an autotransformer or a phase-shifting isolation transformer with 20° displacement used to provide three three-phase voltage sources that cancel the 5th , 7th , 11th , and 13th harmonics. In many cases, a phase-shifting autotransformer is a practical approach when considering the size and cost. If additional input AC reactors are combined with the 18-pulse rectifier, the input current THD is about 5%; This 18-pulse rectifier solution complies with IEEE-519-1992 standard at the equipment level.

٧,٢ . Harmonic mitigation

Phase shifting involves separating the electrical supply into two or more outputs; each output being phase shifted with respect to each other with an appropriate angle for the harmonic pairs to be eliminated. The concept is to displace the harmonic current pairs in order to bring each to a 180° phase shift so that they cancel each other out. Positive-sequence currents will act against negative-sequence currents, whereas zero-sequence currents act against each other in a three-phase system. Triplen harmonics are zero-sequence vectors; 5th, 11th and 17th harmonics are negative-sequence vectors, and 7th, 13th and 19th harmonics are positive-sequence vectors [6].

7.2.1. Mitigating the +ve Sequence Harmonics

Consider the 7th Order, for the current wave pairs shown in Figure 1 – from two similar loads a and b - each half wave occupy 180°/7 = 26°. Superimposing phase shift 30° between the two currents will lead to mitigating the 7th Order harmonic. The same result can be obtained for phase shift n*30°, where n is an odd number.

Consider the 13th Order, for the current wave pairs, each half wave occupy 180°/13 = 14°. Superimposing phase shift 15° between the two currents will lead to mitigating the 13th Order harmonic. The same result can be obtained for phase shift n*15°, where n is an odd number.

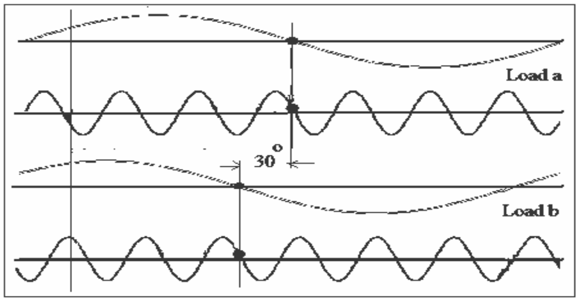

Figure 1: Mitigation of the 7th harmonics (+ve Sequence).

7.2.2. Mitigating the -ve Sequence Harmonics

Consider the 5th order, for the current wave pairs shown in Figure 2 – for two similar loads a and b - each half wave occupy 180°/5 = 36°. Superimposing phase shift 30° between the two currents will lead to mitigating the 5th Order harmonic. The same result can be obtained for phase shift n*30° , where n is an odd number.

Consider the 11th Order, for the current wave pairs, each half wave occupy 180°/11 = 16°. Superimposing phase shift 15° between the two currents will lead to mitigating the 11th Order harmonic. The same result can be obtained for phase shift n*15° , where n is an odd number.

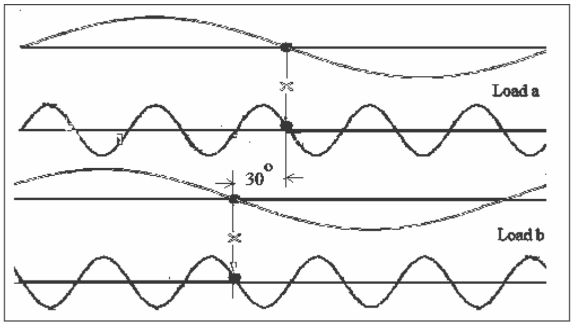

Figure 2: Mitigation of the 5th harmonics (-ve Sequence).

7.2.3. Mitigating The Zero Sequence (Triplen) Harmonics

Consider the 3rd Order, for the current wave pairs shown in Figure 3 – from two similar loads a and b - each half wave occupy 180°/3 = 60°. Superimposing phase shift

60° between the two currents will lead to cancellation of the 3rd Order harmonic. The same result can be obtained for phase shift n*60°, where n is an odd number.

Consider the 9th order, for the current wave pairs, each half wave occupy 180°/9 = 20°. Superimposing phase shift 60° between the two currents will lead to cancellation of the 9th Order harmonic. Thus, in resulting 60° phase shift will completely cancel the 3rd and 9th harmonic order.

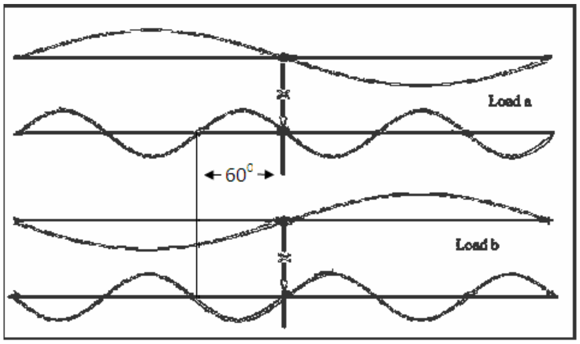

Figure 3 Cancellation of the 3rd order harmonics (Zero-Sequence).

7.2.4. Summary of Mitigation / Cancellation for Harmonic Orders

From the above illustration, it may be concluded that an angular displacement of:

- 60° is required for two three-phase outputs to cancel the triplen harmonic currents
- 30°is required for two three-phase outputs to cancel the 5th and 7th harmonic currents.
- 15°is required for two three-phase outputs to cancel the 11th and 13th harmonic currents.

Table 1 addresses the ideal and the practical phase shift required for harmonic solutions utilizing phase shifting transformers. The practical values are limited by the manufacturing facilities of the phase shifting transformers.

Table 1. Phase shifts required for harmonic mitigation or cancellation for 1-ph. loads.

Harmonic Order	Sequence	Phase Shift Required		Solution Mode
		Ideal	Practical	
3	Zero	60° Or 180°	180°	Cancellation
5	-ve	36°	30°	Mitigation
7	+ve	26°	30°	Mitigation
9	Zero	60° Or 180°	180°	Cancellation
11	-ve	16°	15°	Mitigation
13	+ve	14°	15°	Mitigation
15	Zero	60° Or 180°	180°	Cancellation

8. Phase Shifting Transformers And Harmonic Mitigation For 3-Ph. Loads

Consider two similar non-linear 3-phase loads L_1 and L_2 Fed from two transformers having 180° phase shift, the triplen harmonics (3, 9, 15,) will act against each other and complete cancellation of zero sequence harmonics will occur. Figure 4 shows the cancellation process of the 3rd harmonic. Also, positive-sequence currents will act against each other and negative-sequence currents will act against each other. Table 2 shows Phase shifts required for harmonic mitigation or cancellation for 3-ph. nonlinear loads.

9. Methods Of Addressing Harmonics With Transformers

Harmonic Mitigating Transformers (HMTS) accomplish harmonic mitigation by providing good source impedance through sine wave recombination. Transformers may be used to address harmonics generated by non-sinusoidal (non-linear) loads by combining sine waves within the transformer and at the common bus feeding different transformers. Two or more transformers of different phase angle shift(s) can be used to achieve further combination sine waves providing for more harmonic mitigation

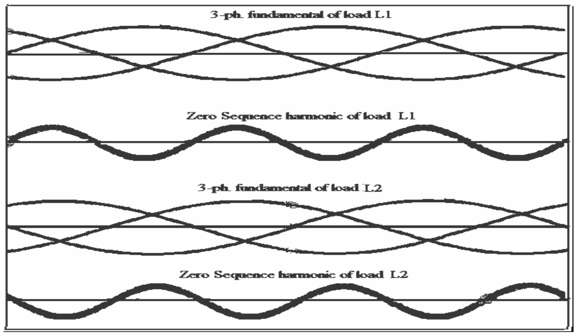

Figure 4. The cancellation process of the 3rd harmonic.

9. 1. Combining Sine Wave Theory

The theory of combining sine waves is accomplished through two ways:

- By using the inherent phase angle displacement of the electrical wave shapes within the transformer which are then combined at the nodes or connection points, of the windings within the transformer.
- By combining the sine waves at the common bus feeding two transformers of different phase shift.

Table 2 Phase shifts for harmonic mitigation or cancellation for 3-ph. nonlinear loads

Harmonic Order	Sequence	Phase Shift	Solution
3	Zero	60° 180°	Cancellation Cancellation
5	-ve	30° 180°	Mitigation Cancellation
7	+ve	30° 180°	Mitigation Cancellation
9	Zero	60° 180°	Cancellation Cancellation
11	-ve	15° 180°	Mitigation Mitigation
13	+ve	15° 180°	Mitigation Cancellation
15	Zero	60° 180°	Cancellation Cancellation
17	-ve	30°	Mitigation
19	+ve	30°	Mitigation

Scenario 1 : Cancellation of the Triplen Harmonics
Cancellation of the triplen harmonics (3rd, 9th, 15th…) can be achieved if a 60° phase shift is created between the two waves shapes, and then combined (Figure 5).
The resultant wave shape of Figure 5 will be referred to as wave shape “A” throughout this paper. The triplen harmonics are no longer part of the wave shape. More importantly, none of the energy was removed from the wave shape. Rather, the waves were simply combined. This is one step where some mistakenly assume the triplen harmonics to be circulating in the delta winding of a delta-wye transformer.

Scenario 2 : Cancellation of the triplen and mitigation of the 5th, 7th, 17th, and 19th Harmonics
The Figure 6 combination is created with two “A” wave shapes and a 60° phase shift so the new “B” wave shape can be more easily understood. No harmonic cancellation takes place in the (“A”) + (“A”+60°) combination. This applies to harmonic mitigation/attenuation via transformers in two ways.

- The “B” wave shape combination (remember, no triplen harmonics present) can be obtained through tiering delta-wye transformers as is commonly done in many commercial and industrial facilities. The “B” wave shape is found on the source side of a delta-wye transformer that is feeding another delta-wye transformer downstream
    - that is serving computers, fax machines, and other office equipment.
- The delta-zigzag transformer takes the single-phase, line-to-neutral nonlinear single hump sine waves and combines them to get the “B” wave shape (Figure 6). Once again, no energy was removed from the wave shape. The sine waves are combined to yield a new sine wave in which the triplen harmonics are not present.

Scenario 3 : Cancellation of the triplen and the 5th, 7th, 17th, and 19th Harmonics
When a 30° phase shift is achieved between an “A” and “B” wave shape and the two are combined (see Figure 7), “cancellation” of the 5th, 7th, 17th, and 19th occurs. The 30° phase shift of the “A” wave shape occurs with either the standard Delta-Wye transformer or a Wye-Zigzag transformer. The “B” wave shape occurs with a Delta-Zigzag transformer (see Figure 7), which has (0°) shift between the primary and secondary. When the two wave shapes “A+30°” and “B” are combined, cancellation” of the 5th, 7th, 17th, and 19th occurs. The resultant wave at the supply side will include only the 11th and 13th harmonic orders.

10. Detuned Filters and Harmonics [6]

Adding a reactor to detune the system can modify adverse system response to harmonics

Harmful resonance is generally between the system inductance and shunt power factor correction capacitors. The reactor must be added between the capacitor and the system. One method is to simply put a reactor in series with the capacitor to move the system resonance without actually tuning the capacitor to create a filter.
Depending upon the actual system short circuit level, a reactor in each phase may be required. The inductor is sized to take into consideration the actual capacitor bank, size, S . The capacitor reactance, X_C, is [7]:

$$Xc = \frac{V^2}{S} \tag{22}$$

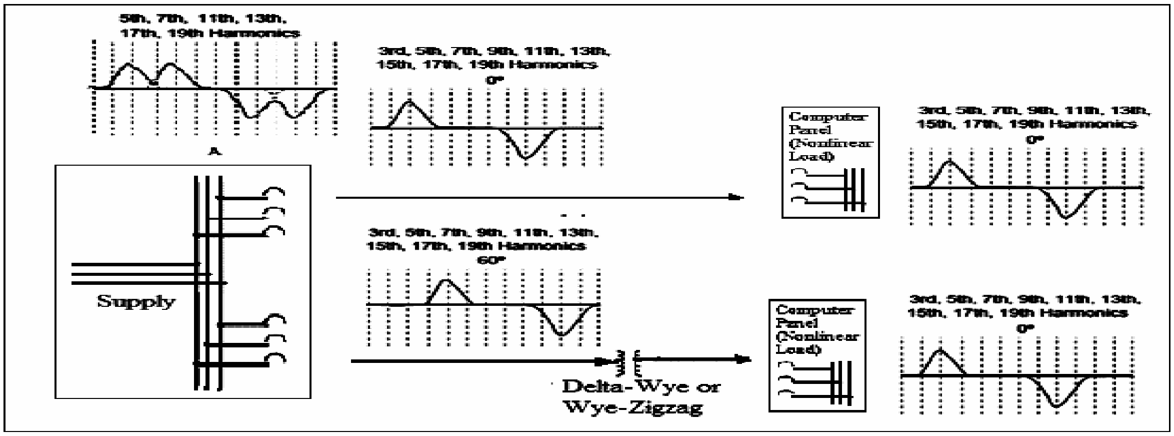

Figure 5, Scenario 1 Cancellation” of the triplen harmonics by achieving a 60° phase shift between the two wave shapes, and then combining them.

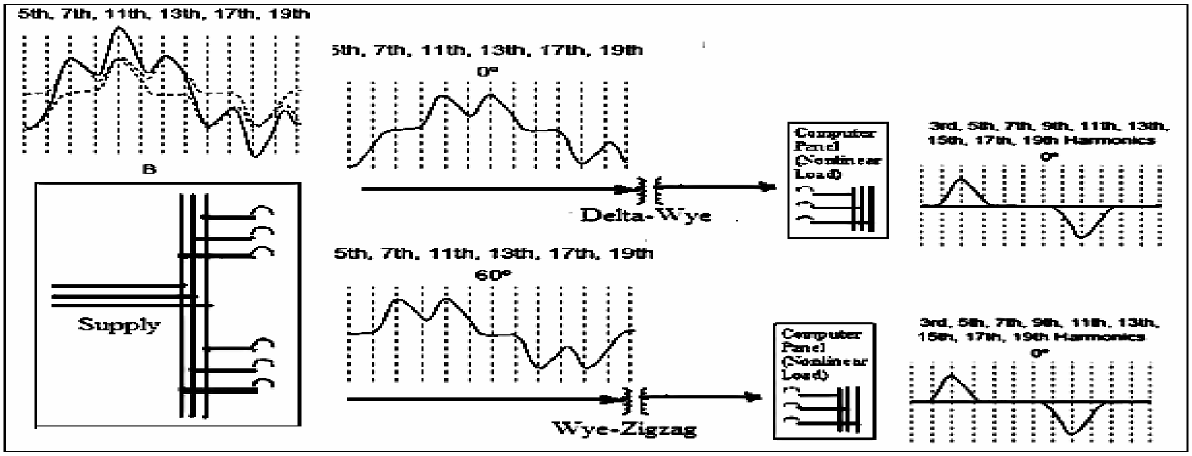

Figure 6, Scenario 2 : Cancellation of the 5th, 7th, 17th, and 19th harmonics by (“A”) + (“A”+60°) combination to obtain the“B” wave shape.

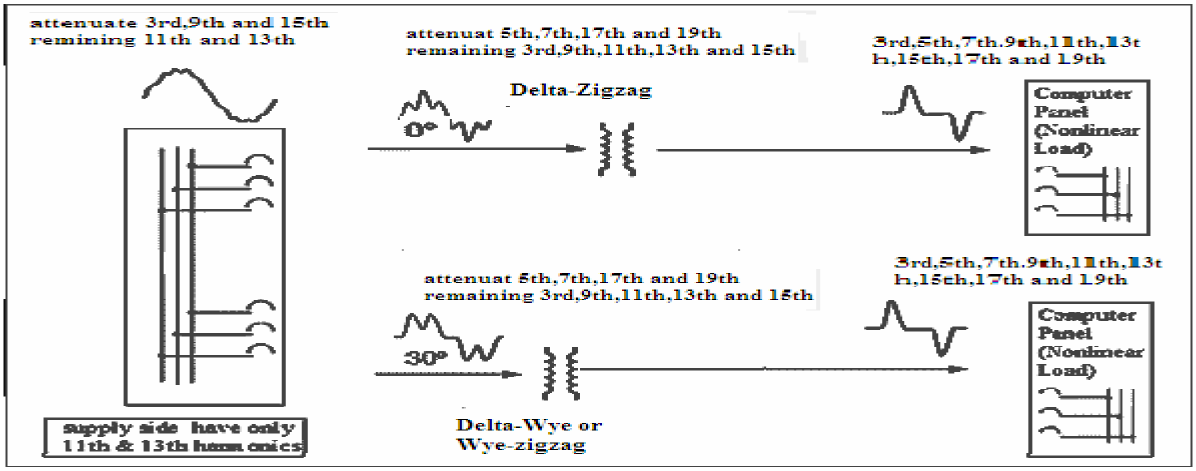

Figure 7, Scenario 3 : Cancellation of the 5th, 7th, 17th, and 19th harmonics by (“A + 30°”) + (“B”) combination.

And the inductor reactance, X_L, is

$$X_L = \frac{Xc}{n^2} \tag{23}$$

With quality factor, Q,

$$Q = \frac{X_L}{R} \tag{24}$$

Where V: Line voltage
S: capacitor bank rating
n: notch frequency
R: resistance of the inductor

In practice a filter is always tuned below the harmonic frequency that it is intended to suppress because the power system frequency may change, thus causing the harmonic frequency to change proportionally, the inductance of the inductor and the capacitance of the capacitor may change [8]. Of these two, the capacitance changes more because of aging and change of temperature due to ambient temperature and self heating, the initial tuning may be off because of finite size of tuning step.

11. Case Study

Consider the distribution system [9], under study, shown in Figure 8. The distribution system is fed from 34.5 KV, 1500 $MVA_{s.c.}$ utility supply. A cluster of different linear and nonlinear loads are connected to the system. The portion of interest for harmonic appraisal is that including the two 'DC System' similar loads which are fed from transformer T_4. Each 'DC System' load composes the following:

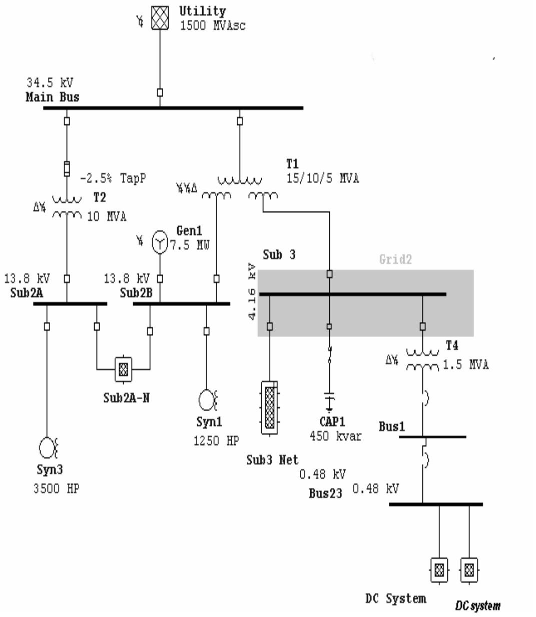

Figure (8) The base case system

loads which are fed from transformer T_4. Each 'DC System' load composes the following:

- Dc lumped load 100 KW,
- Dc individual static loads of sum 445 KW,
- Dc motors 25KW.

Etap-Ssoftware Package was utilizes to appreciate the harmonic problem of the system. The problem was handled through the following three stages :

١١,١ Base Case :

Table 3 and Table 4 give the harmonic orders and THD for the voltage at bus 23 and the current at branch bus1-bus23, respectively.

The results show that the harmonic distortion exceeds the permissible limits for both voltage and current. The more salient orders are the 5th and the 7th harmonic orders. The standard values for the current distortion correspond to $I_{SC}/I_{FL} = 28$ for the considered DC systems at bus-23. To satisfy standard limits, the 5th and the 7th orders have to be mitigated. Phase shifting transformers or passive harmonic filters are proposed as shown below.

Table 3: Voltage distortion at bus B23

Harm. Order h	5	7	11	13	17	19	THD
%age Dist.	7.2	2.2	2.5	2.6	1.3	1.1	9.24
%age Std.	3	3	3	3	3	3	5

Table 4: Current distortion at branch bus1-bus23

Harm. Order h	5	7	11	13	17	19	THD
%age Dist.	21	4	3	2.5	2	1	22.63
%age Std.	7	7	3.5	3.5	2.5	2.5	8

11.2- Using Phase-Shifting Transformer:

Two phase-shifting transformers with phase shifts 0° and 30° are chosen to mitigate the 5th and the 7th orders. Therefore, a Delta-Delta and Delta-Wye connected transformers are used. Table 5 and Table 6 give the harmonic orders and THD for the voltage at bus 23 and the current at branch bus1-bus23, respectively. The results show that the standard limits are satisfied and the harmonic problem has been solved. Figure 9 shows the insertion of the two phase shifting transformers in the system.

Table 5: Voltage distortion at bus B23

Harm. Order h	5	7	11	13	17	19	THD
%age Dist.	0	0	.75	.65	0	0	1.07
%age Std.	3	3	3	3	3	3	5

Table 6: Current distortion at branch bus1bus23

Harm. Order h	5	7	11	13	17	19	THD
%age Dist.	0	0	.88	.62	0	0	.96
%age Std.	7	7	3.5	3.5	2.5	2.5	8

11.3. Using Filter Technique

Two passive filters are considered to cancel the 5th and the 7th harmonic orders.

From equations in Sec. 12, the values of the two filter pareameters are :

$n = 5$, $V_n = .48kv, I = 924A, k_{var} = 48.98, Q_{factor} = 40$

$n = 7$, $V_n = .48kv, I = 924A, k_{var} = 48.98, Q_{factor} = 40$

For the 5th order: $X_L = 0.18\ \Omega$, $X_C = 4.515\ \Omega$

For the 7th order: $X_L = 0.09\ \Omega$, $X_C = 4.608\ \Omega$

Table 7 and Table 8 give the harmonic orders and THD for the voltage at bus 23 and the current at branch bus1-bus23, respectively. The results show that the standard limits are satisfied and the harmonic problem has been solved. Figure 10 shows the insertion of the two harmonic filters in the system.

11. 4. Analysis of Results

Tables (5) – (8) show that the THD of the voltage and current are reduced below the IEEE-519 limit after using either phase shifting transformers or detuned passive filters. THD is a measure of the effective value of the harmonic components of a distorted waveform, that is, the potential heating of the harmonics relative to the fundamental. The K-Factor rating, equation 25, is an index of the transformer's ability to withstand harmonic content while operating within the temperature limits of its insulating system.

Table 7: Voltage distortion at bus B23

Harm. Order h	5	7	11	13	17	19	THD
%age Dist.	.05	.01	.65	.55	.13	.23	1.01
%age Std.	3	3	3	3	3	3	5

Table 8: Current distortion at branch bus1-bus23

Harm. Order h	5	7	11	13	17	19	THD
%age Dist.	.15	.02	.81	.58	.07	.12	.95
%age Std.	7	7	3.5	3.5	2.5	2.5	8

$$K = \frac{\sum_{h=1}^{\infty} h^2 \left(I_h / I_1 \right)^2}{\sum_{h=1}^{\infty} \left(I_h / I_1 \right)^2} \tag{25}$$

From results of Table (4), the K-factor is 1.84 for the base case, while K-factors are 1.016 and 1.014 when using phase shifting transformers or harmonic filters, respectively

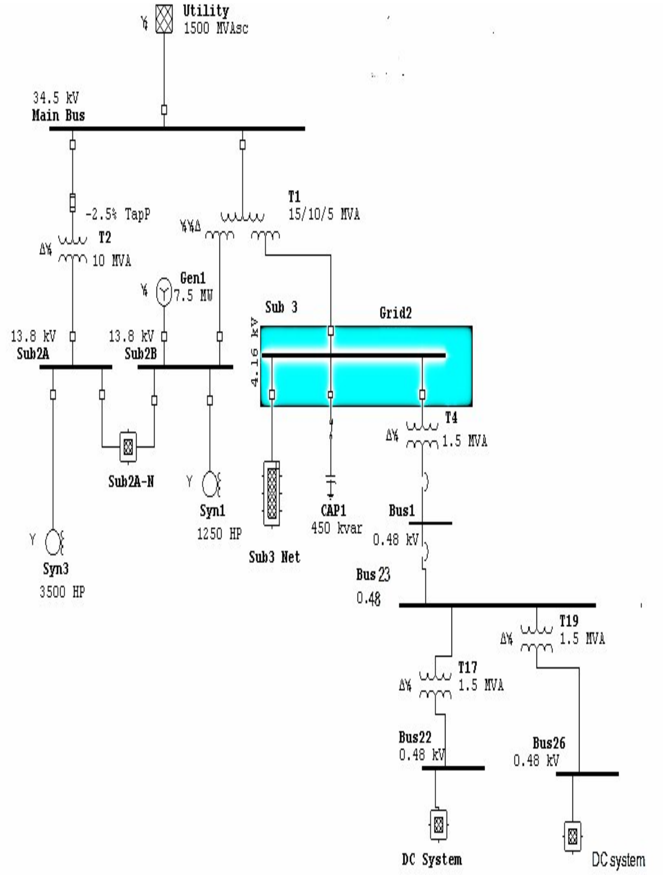

Figure (9) Insertion of the two phase shifting transformers

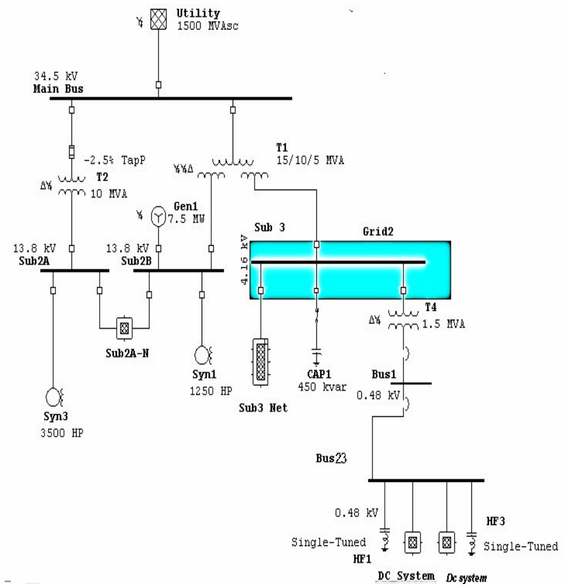

Figure (10) Insertion of the two harmonic filters

12. Conclusions

The harmonic level has a great effect on the performance of the system components and equipments. Harmonic map for the distribution system is necessary for appreciating system operation and upgrade. During the next decade, an increase of the nonlinear loads up to 70% is expected. Understanding electrical system problems will help in implementing appropriate solutions.

Phase shifting transformers can efficiently mitigate harmonic distortion. They are rigid and more economically than harmonic filters. Besides, they are secure for resonance problem that may arise in passive filter applications.

Utilizing passive harmonic filters requires recurrent analysis, measurements and precautions for system reconfiguration or upgrading and load changes for save system operation.

Solving harmonic problem is not just for satisfying standard regulations, it is an economical business. It decrease the overall power losses on the system, improves voltage profile and improves power factor. It, also, saves a deferred capacity for both transformers and lines and improves the lifetime of the system components and equipments.

It was found due to using phase shift and filter transformer the voltage distortion at bus 23 is reduced from 9.24 to 1.07 and 1.01 and current distortion is reduced at branch bus1-bus23 from 22.63 to .96 and .95.Besides the k-factor of the transformer has improved from 1.84 to 1.01.

Finally, careful considerations are necessary when studying harmonic problems in any power system and on instrumentation requirements for measurements. Important issues must be included as types of loads, power factor characteristics harmonic generating characteristics, frequency response.

Characteristics of the supply system, power factor correction in the customer facility, and harmonic filters in the customer facility. It is recommended to proceed a non-sinusoidal tariff schemes towards a regulatory tariff system for the non-linear loads.

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