



Abstract – Harmonics in electrical distribution systems are created from a number of sources and produce a variety of undesirable side effects. It is therefore important to understand all solutions that are available. Phase shifting will be reviewed as one concept for solving certain types of problems related to power quality. Both theoretical concepts and a case study are presented.

Index Terms – Harmonic Mitigation, Power
Factor Correction, Phase Shifting

I. INTRODUCTION

It is well known that harmonic currents are present in modern electrical distribution systems caused from non-linear loads, such as variable frequency drives, lighting and computers. Harmonics can cause a variety of problems ranging from poor power factor and motor failures, to overloaded transformers and conductors. One of the most effective ways to eliminate harmonics is to use a technique known as “phase shifting”. The concept of phase shifting as a harmonic mitigation technique is not as well understood as other methods.

II. PHASE SHIFTING AND HARMONICS

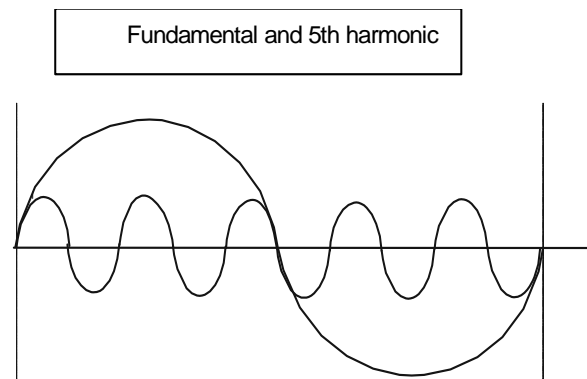
Phase shifting involves separating the electrical supply into two or more outputs; each output being phase shifted with respect to each other with an appropriate angle for the harmonic pairs to be eliminated. The concept is to displace the harmonic current pairs in order to bring each to a 180° phase 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.

Hence, an angular displacement of:

- 60° is required between two three phase outputs to cancel the 3rd harmonic currents
- 30° is required between two three phase outputs to attenuate the 5th and 7th harmonic current pairs
- 15° is required between two three phase outputs to cancel the 11th and 13th harmonic current pairs

For instance, in the case of two 6-pulse variable frequency drives of similar rating, installing a delta-wye transformer (30° with respect to the primary) on one drive, and a delta-delta transformer (0° with respect to the primary) on the other drive, gives an angular displacement of 30° between the two outputs, providing the equivalent of a 12-pulse system. On the common supply of both transformers on the primary, phase shifting between the systems will reduce the 5th and 7th harmonic currents. An angular displacement of 15° between outputs provides the equivalent of a 24-pulse system, but requires four 6-pulse loads.

The approach of phase-shifting non-linear loads can be used to reduce the effects of selected harmonics.



The figure above shows a typical 60 Hz sinusoidal wave, with its 5th harmonic (at 300 Hz) superimposed on it.

III. CURRENT HARMONICS, VOLTAGE DISTORTION AND TRANSFORMERS

The mathematical equation $V = I \times Z$ shows that any current flowing within an impedance generates voltage at the impedance terminals. This equation also applies to harmonic currents flowing through the electrical system.

Therefore, the higher the harmonic current levels, the greater the resulting harmonic voltages, thus creating distortion in the electrical system voltage. As transformers also have impedance, voltage distortion appears at the transformer's secondary terminals when harmonic currents flow through them.

To reduce voltage distortion, two factors can be modified: the level of harmonic currents and transformer impedance.

IV. PHASE-SHIFTING TRANSFORMERS DESIGNED FOR NON-LINEAR LOADS

The level of harmonic currents may be reduced by using phase-shifting techniques and low impedance plays a crucial role in reducing voltage distortion.

New low impedance phase-shifting transformers have been designed to allow the treatment of harmonic currents while providing a path of low impedance. Moreover, these transformers have been designed to withstand the additional overheating caused by harmonic currents and therefore are K-rated. The quality and reliability of the electrical system can be considerably improved through the use of a single piece of equipment.

Below are a few examples of such transformers along with a description of their respective use.

A. *Delta-Zigzag Transformer* (0° or -30° primary-secondary angular displacement)

The primary of this transformer has a delta connection and its secondary has a zigzag connection. Although there is only one secondary three phase output, the electromagnetic effect of its secondary winding with a zigzag connection ends up cancelling the 3rd, 9th and 15th (triplen) harmonic currents. Transformer features include:

- A capacity for handling non-linear loads
- Low impedance cancellation of the 3rd, 9th and 15th harmonic currents (zigzag-connected secondary)
- A reduction in voltage distortion (3rd harmonic voltage reduced by low zero-sequence impedance)

When two transformers with a delta-zigzag connection (-30° and 0°) are used for phase-shifting, the 3rd harmonic currents are cancelled due to the secondary windings with a zigzag connection and the 5th and 7th harmonic currents are cancelled in the electrical supply common to both transformers due to the 30° phase shift.

If a single delta-zigzag transformer (0°) is used in a system made up of delta-wye transformers (-30°), the 5th and 7th harmonic currents originating from the delta-zigzag transformer (0°) will attempt to cancel the 5th and 7th harmonic currents originating from the delta-wye transformer (-30°) already present. This reduces the 5th and 7th harmonics in the system with the actual reduction dependent on how similar the secondary loads are in magnitude.

B. *Double-Output Delta-Zigzag Transformer* (0° and -30° primary-secondary angular displacement)

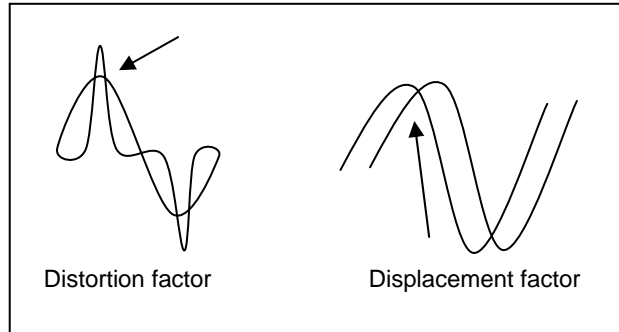
The primary of the transformer has a delta connection and its secondary has a double-output zigzag connection. Although there is only a 30° angular displacement, the electromagnetic effect of its secondary windings with a zigzag connection ends up cancelling the 3rd, 9th and 15th harmonic currents. Transformer features include:

- A capacity for handling non-linear loads
- Low impedance cancellation of the 3rd, 9th and 15th harmonic currents (zigzag-connected secondary)
- Attenuations of the 5th and 7th harmonic currents (30° phase shift between the outputs)
- A reduction in voltage distortion (3rd harmonic voltage reduced by low zero-sequence impedance)

If two of these transformers are used, with the primaries of each phase shifted 15° with respect to one another, then cancellation of harmonics up to the 19th are achievable.

V. POWER FACTOR AND HARMONICS

The power factor is the ratio between the active power (W) and the apparent power (VA). Electricity supplied by Utilities in North America has a sinusoidal voltage wave of 60 Hz. If the current and voltage curves are not aligned, the efficiency of the electrical system is diminished and the apparent power exceeds the active or true power. In an inductive system the voltage curve leads the current curve. In a capacitive system the current curve leads the voltage curve. Historically, when speaking of power factor, we were actually referring to the displacement factor only.



As a result of the increase in non-linear loads in the past few years, we have had to take into account the effect of harmonics in electrical systems and modify certain mathematical equations and include the effect of the distortion factor. Power factor is now defined as follows:

$$PF_{tot} = F_d \times F_{dist}$$

where PF_{tot} = total power factor

F_d (displacement factor) as defined above

$$F_{dist} \text{ (distortion factor)} = \frac{\text{fundamental current}}{\text{rms current}}$$

This new term, “distortion factor”, is defined as being the fundamental current divided by the RMS current (current measured with a true RMS clamp-on ammeter).

There are two elements which combine to reduce total power factor – the inductive or capacitive loads which affect the *displacement factor* – and the harmonic currents of the non-linear loads which affect the *distortion factor*. Reducing the level of harmonic currents in a system therefore improves the system’s total power factor. As Utilities measure the total power factor, we have to check the value of both displacement factor and distortion factor if total power factor is to be corrected. The good news is that companies that manufacture measuring instruments now provide the value of both of these factors or at least make it possible to calculate them. This will help us understand the cause of the reduction in power factor and choose the best way to improve it.

VI. CAPACITORS

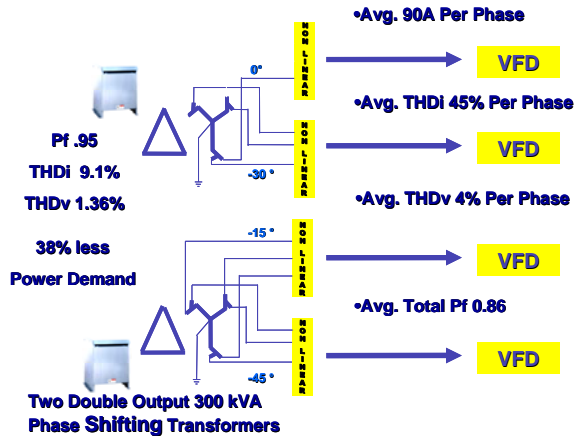
Capacitors have been commonly used as harmonic current filters or to correct the power factor in industrial electrical installations. This correction generally assumes we are correcting the displacement factor and that there is little, if any, distortion factor. If a system has not been properly designed or if certain modifications were made without taking existing parameters into account, capacitor impedance nears the inductive impedance of the load at a certain harmonic frequency and creates resonance in the system. Major voltage spikes and distortions will then occur in the system, damaging sensitive electrical equipment and shortening the capacitors’ lifespan. It is therefore very important to consult electrical system experts when applying this technology.

VII. CASE STUDY

The subject case study featured the replacement of 84 existing motors with more energy efficient units and the installation of 33 variable frequency drives (6-pulse PWM type). Approximately 1,000 horsepower of motor load was retrofitted, connected to four different motor control centers.

Because of the number of VFDs concentrated in the penthouse mechanical room, it was decided to use phase shifting to control the harmonics generated by the new VFDs. Filtering (either active or passive type) would be more expensive and using line reactors would not have met IEEE 519 limits in this application.

Similar loads on four busses were achieved by reconfiguring the main motor control center bussing, allowing these loads to be selectively connected to the secondary's of two individual double-output zigzag transformers. The secondary's of the transformers are phase shifted 30° with respect to each other, while the primaries are phase shifted 15°, causing all harmonics up to the 19th to be reduced. In practice, because the loads on each output are not identical, complete harmonic elimination cannot be achieved. Regardless, the test results were impressive, with a 38% reduction in power demand being achieved from the retrofit measures with little degradation in total harmonic distortion.



Although a significant amount of non-linear current was introduced into the building distribution system, harmonic voltage and current distortion limits are maintained within IEEE 519 guidelines, based on an I_{SC}/I_L of 58.6 at the point of common coupling.

The current waveform shots shown below were taken on a single phase of one of the two transformer secondary legs and on a primary leg, respectively. Note the improvement in the wave shape on the primary side relative to the secondary side, which is the input side of the VFDs.

The two secondary loads averaged 86.55 A and 92.80 A, with corresponding current THD of 39.62 and 49.31, and voltage THD of 3.44 and 5.42. The resultant primary averaged 164.0 A, with current THD of 9.11 and voltage THD of 1.36.

Figure 1 Secondary

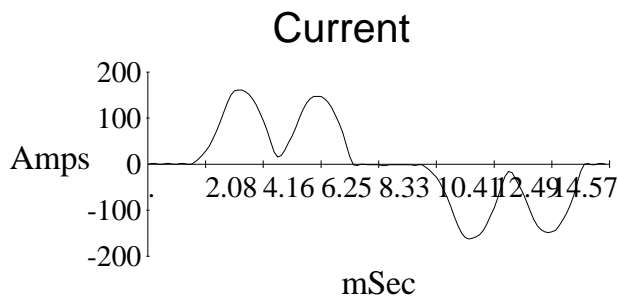
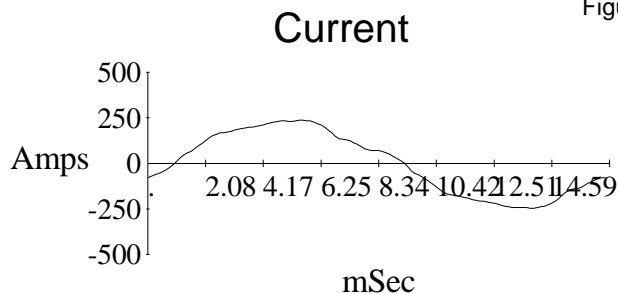


Figure 2 Secondary



The Fourier transforms shown below are another method used to indicate the amount of harmonic current in a particular waveform and shows the relative amount of current that exists at each frequency from the fundamental on the left (60 Hz) up to the 31st harmonic (1860 Hz).

Figure 3 Secondary

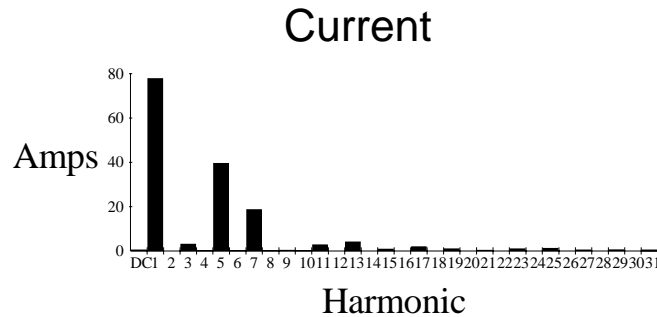
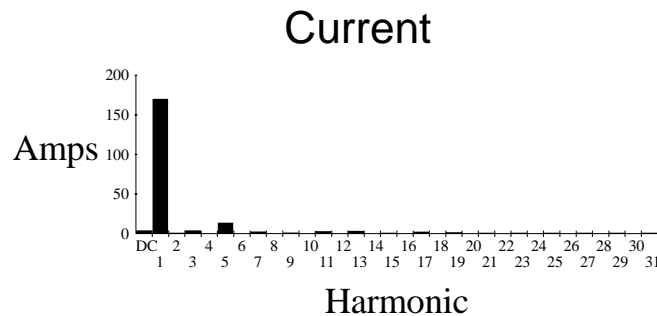


Figure 4 Primary



The first chart (secondary side) clearly shows that there is a significant amount of 5th, 7th, 11th and 13th order harmonics, typical of a VFD harmonic “signature”. The second chart (primary side) shows how the phase shifting transformer has essentially removed all higher order harmonics, with only a minimal amount of 5th order harmonic current remaining.

The K-factor of the load ranged from 6.10 to 8.65 depending upon the phase that was measured, indicating the choice of a K-13 rating on the phase shifting transformers as appropriate for this application. With regard to power factor improvement, the total power factor on the transformer secondary’s averaged 0.86 (corresponding displacement factor was 0.96). On the primary side, the total power factor was measured to be 0.95 (displacement factor was unchanged at 0.96) which indicates a significant total power factor improvement due to the effect of the phase shifting transformer, reducing harmonics and consequently the distortion factor. Note that displacement factor is relatively good at 0.96 because VFDs inherently provide power factor correction on motor loads.

VIII. CONCLUSION

A thorough understanding of electrical system-related problems will help us implement better solutions. It is estimated that 70% of electrical loads are non-linear. The deterioration of total power factor will therefore mainly be caused by harmonic currents which affect the distortion factor.

To find proper techniques for correcting the total power factor and reduce harmonic currents in an electrical distribution system, the following must be considered:

- Determine the components making up the total power factor
- Correct the displacement factor at the source (by adding capacitors or VFDs)
- Correct the distortion factor at the source (by reducing harmonic currents)

Case studies show that phase shifting does work as promoted, can mitigate harmonics very significantly, and improve total power factor. Their ability to control harmonics is predicated on how closely matched the individual secondary loads are on the transformer(s).

IX. REFERENCES

Additional information may be found at the following sources:

- [1] IEEE Std 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, New York, NY: IEEE.
- [2] IEEE Std 1100-1999, *IEEE Recommended Practice for Powering and Grounding Electronic Equipment*, New York, NY: IEEE.
- [3] Paice, Derek A., *Power Electronic Converter Harmonics: Multipulse Methods for Clean Power*, New York, NY: IEEE.

Copyright Material IEEE
Paper No. PCIC-2002-12