Phase shifting: an alternative solution to harmonic problems

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Two basic techniques of phase shifting can get systems in tune.

Harmonic currents on electric power systems of industrial plants is a common problem that can result in higher electric bills, premature failure of machines and power equipment, and improper operation of electronic equipment. Sources of harmonics include ac and dc variable speed drives, PLCs, computers, lighting fixtures using ballasts, and others.

The standard techniques to deal with harmonics include oversizing of neutral conductors, installing K-rated transformers, and adding line filters to the power system. There is another technique being used more often as an alternative to, or in addition to, these and that is phase shifting.

There are two basic techniques used to accomplish phase shifting. One uses an active device to inject harmonic waveforms into the power system 180° out of phase with the problem harmonics. The second is to use transformers to shift one source of harmonics relative to a second source of harmonics. This passive technique will be discussed further.

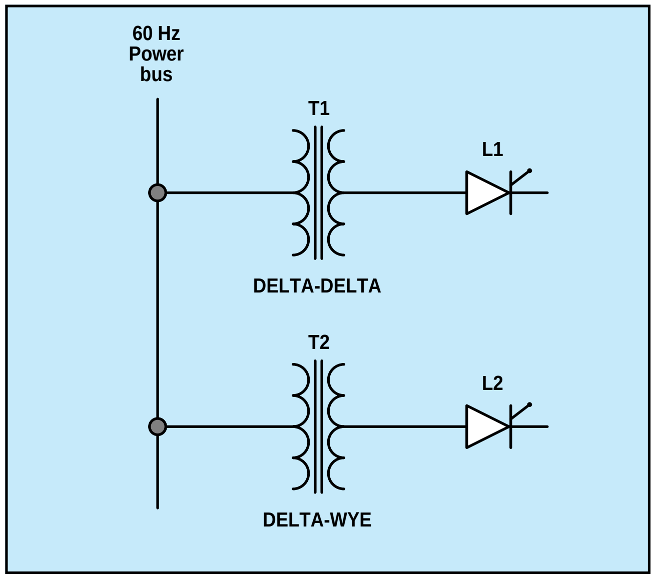
Phase shifting theory

Phase shifting is best understood by examining two sine waves. If two waveforms traveling through a common medium are equal in magnitude, frequency, and phase shift then the resultant wave will have a magnitude of twice the original. However, if one sine wave is shifted 180° then the resultant waveform will have a magnitude of zero. This is because the magnitude of the waves at all points in time will be equal and opposite of one another. This technique can be applied to control harmonics on power systems. In fact, there are a number of companies and consultants offering such solutions.

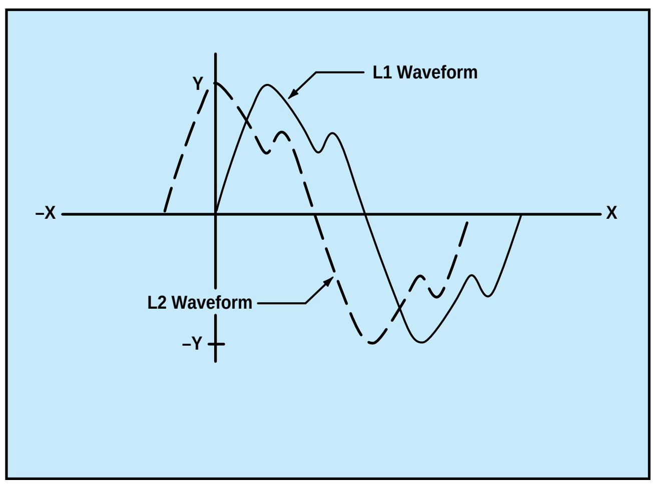
Phase shifting is generally limited to the reduction of the 5th, 7th, 11th, and 13th harmonics. This is due to the increased manufacturing difficulties and costs associated with increasingly complex transformer arrangements.

The reason for the reduction of harmonics when using phase shifting can be seen by examining the Fourier equation of a periodic waveform. Any periodic waveform can be expressed by the general Fourier series of Eq. 1 (shown in the sidebar) where θ_1, θ_2,....θ_n are the relative time-phase posi-

1. Equal nonlinear loads fed from a common power bus through individual transformer banks



2. Equal nonlinear loads with current waveforms displaced 30° due to effects of transformer T2 delta-wye setup. Seen from transformer secondary.



tions of each harmonic and are considered negligible, allowing them to be dropped, and $w = 2\pi f_1$ where f_1 is the fundamental frequency of the distorted waveform. In the United States the fundamental frequency of interest is 60 Hz. Then the associated harmonic frequencies of interest are

3 x 60 Hz = 180 Hz   5 x 60 Hz = 300 Hz

7 x 60 Hz = 420 Hz   9 x 60 Hz = 540 Hz

11 x 60 Hz = 660 Hz 13 x 60 Hz = 780 Hz

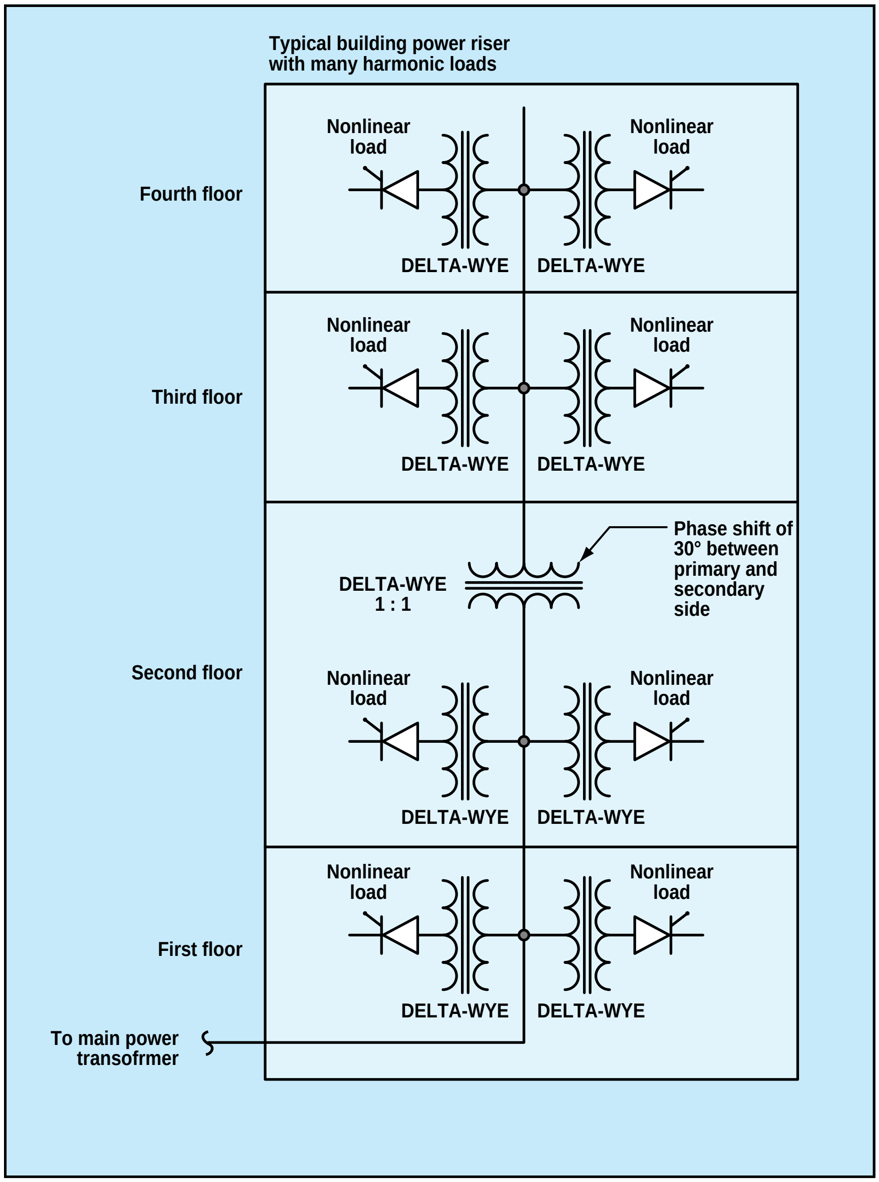
Each harmonic has a rotational sequence associated with it of positive, negative, or zero starting with the fundamental and repeating to the highest harmonic.

Further, consider two equivalent nonlinear loads being fed by separate three-phase transformers from a common power bus as in Fig. 1. Each load causes a distorted current waveform due to harmonics associated with these loads. Figure 2 shows the potential waveforms as seen from the secondary side of each transformer bank, referenced to a common coordinate system, where it is assumed that the waveform of load L2 leads that of load L1 by 30° (π/6 radians) due to the transformer arrangement of T2. T1 is a delta-delta connected transformer and cannot support zero sequence currents since it has no neutral conductor. Under most circumstances even harmonics can be ignored. The general Fourier series for each waveform on the load side of each transformer are represented by Eqs. 2 and 3a of the sidebar. At this point, Eqs. 2 and 3a do not share a common timeframe of reference. Referring to Fig. 2, it can be seen that $wt_{L2} = wt_{L1} + \pi/6$. Making this substitution into Eq. 3a results in Eq. 3b.

If Eqs. 2 and 3b are reflected over to the primary side of each transformer ignoring the turns ratio, Eq. 2 does not change. However, transformer T2 causes a -30° phase shift (-π/6 radians) of the positive sequence harmonics of Eq. 3b and a +30° (+ π/6 radians) for the negative sequence harmonics due to the delta-wye hookup, assuming an initial +30° phase shift from primary to secondary of the delta-wye transformer for positive sequence waveforms.

Equation 3b is transformed to Eq. 4a, which can be reduced to Eq. 4b. Zero sequence currents were eliminated since the delta secondary of T2 will trap them.

3. Strategically placed and sized transformer provides necessary phase shift resulting in partial elimination of 5th and 7th harmonics on primary of transformer.



From a comparison of Eqs. 2 and 4b, it can be seen that the 5th and 7th harmonics cancel at the common power bus. The same can be shown to be true of the 11th and 13th harmonics if a 15° phase shift existed between the two transformer banks.

Results

If one source of harmonics is fed through a delta-delta connected transformer bank and a second source is fed with a delta-wye transformer bank, then the result is a partial cancellation of the 5th and 7th harmonics. The reason for this is that the delta-wye transformer connection results in a 30° phase shift between the delta primary and wye secondary connections of the fundamental frequency as seen on the wye side of the delta-wye transformer with accompanying harmonic phase shifts. Delta-delta connected transformers cause no phase shift. In practice, only partial elimination is achieved due to uneven loading and varying degrees of harmonic content of loads.

Implementation

This technique has its limitations just as all the others have, but its use may be appropriate for any number of reasons. One in particular is during any major renovations or expansions to a facility known to have harmonic problems.

An article discussing harmonic problems in a large wire mill was reviewed while working on this article[1]. The electric utility supplying the mill spent millions of dollars to stiffen its system. This greatly reduced problems to their equipment and customers near the wire mill.

Among various recommendations given to the plant was to add filters to their system. However, during the course of resolving the harmonic problems at the wire mill its power system was in the process of being doubled in size with the addition of two new substation transformers. This would have provided an excellent opportunity to review whether phase shifting would have been appropriate. Since the plant was expanding anyway there would have been little increased cost and harmonic problems there could possibly have been reduced.

In the case of an existing power system with harmonic problems, a delta-wye transformer with a 1:1 turns ratio could be installed at a predetermined location in the power system (Fig. 3), resulting in the 30° phase shift required to reduce 5th and 7th harmonics on the common primary power bus.

Conclusion

Phase shifting is nothing new. It may prove to be a viable option in place of or in conjunction with other techniques to reduce the effects of harmonics on a power system. There are a few companies and consultants that currently offer services and equipment to perform phase shifting. They can provide solutions for systems with primarily three-phase harmonic loads or single-phase harmonic loads. It is recommended that one be contacted to ensure adequate results are achieved. TJ

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[1] Borose, B.P., Forester, K.R., and Miller, R., "Harmonics and the impact on utility and industrial customer," presented at Florida Power & Light Seminar, Understanding and solving harmonic problems within electrical facilities, Feb. 19, 1993.

Fourier equations to resolve harmonic currents

Equation 1

$$y = Y_1\sin(wt+\theta_1)+Y_2\sin(2wt+\theta_2)+Y_3\sin(3wt+\theta_3)+...+Y_n\sin(nwt+\theta_n)$$

Equation 2

$$y_{L1} = Y_1\sin(wt)_{L1} + Y_5\sin5(wt)_{L1} + Y_7\sin(7wt)_{L1} +...+Y_n\sin(nwt)_{L1}$$

Equation 3a

$$y_{L2} = Y_1\sin(wt)_{L2} + Y_5\sin5(wt)_{L2} + Y_7\sin(7wt)_{L2} +...+Y_n\sin(nwt)_{L2}$$

substituting $wt_{L2} = wt_{L1} + \pi/6$ will give both equations a common timeframe reference. The subscripts L1 and L2 can then be dropped with the following result:

Equation 3b

$$y_{L2} = Y_1\sin(wt+\pi/6) + Y_3\sin3(wt+\pi/6)+ Y_5\sin5(wt+\pi/6)Y_7\sin7(wt+\pi/6) +...+ Y_n\sin[n(wt+\pi/6)]$$

Reflecting over to the transformer primary of T2 gives

Equation 4a

$$y_{L2} = Y_1\sin[(wt+\pi/6-\pi/6)] + Y_5\sin[5(wt+\pi/6)+\pi/6)] +Y_7\sin[7(wt+\pi/6)-\pi/6] +...+ Y_n\sin[n(wt+\pi/6) \pm\pi/6]$$

or

$$y_{L2} = Y_1\sin wt + Y_5\sin(5wt+5\pi/6 +\pi/6) + Y_7\sin(7wt+7\pi/6 -\pi/6) +...+Y_n\sin[n(wt+\pi/6)\pm \pi/6]$$

$$y_{L2} = Y_1\sin wt + Y_5\sin(5wt+\pi) + Y_7\sin(7wt+\pi) +...+ Y_n\sin[n(wt+\pi/6)\pm \pi/6]$$

then

Equation 4b

$$y_{L2} = Y_1\sin wt - Y_5\sin 5 wt - Y_7\sin 7 wt +...+ Y_n\sin[n(wt +\pi /6)\pm \pi/6]$$