A Harmonic Distortion Control Technique Applied to Six-Pulse Bridge Converters

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***Abstract*— This paper presents a practical design aspect for controling power system harmonics through the use of transformer connections applied to a distributed set of six-pulse converter type loads in industrial power distribution systems. Since several papers have already been written on nonlinear converter loads, power system harmonics, harmonic modeling and analysis, and capacitor bank filter design, this paper does not attempt to reinvent the "wheel!" Rather, the intent is to define some common system problems associated with harmonic distortion from six-pulse type converters and present a method for reducing harmonic distortion through the use of transformer bank connections to allow for harmonic cancellation.**

I. Introduction

When large three-phase six-pulse type converters[1] are used in industrial systems, only the positive economical and mechanical characteristics tend to be considered in the application. These characteristics are very important and should be utilized. However, most consumers are not aware of or educated about the impact that the converters will have on the power system. Little effort has been made by manufacturers, utilities, or industrial consumers to integrate converter loads into the power system and ensure that power factor correction capacitors banks will not be pushed into a system parallel resonant condition or that the voltage and current waveforms will become excessively distorted and cause other abnormal problems in the system. Moreover, since the utilities seldom have knowledge of the existence of converter loads on the customer's system, they have no way of planning for the layout and operation of power factor correction capacitor banks located on the distribution feeders so that the system performance can be optimized to the loads connected to it. There is an overall lack of communication and planning.

In most cases, however, relatively small converters and even one or two large converters on a strong distribution system do not pose a major problem, and although the harmonic distortion levels of the current waveforms tend to increase, immediate system problems do not become apparent, and the voltage waveforms remain fairly sinusoidal under most operating conditions.

Operating personnel, both industrial and utility, are generally not concerned about the deformation of voltage and current waveforms and have absolutely no idea what they actually look like in the time domain until problems arise and the system is investigated. As a direct result of lack of information, no communication with the utilities, and poor engineering planning when blindly installing converter loads, harmonic filtering usually becomes the "band-aid" solution of choice, which is usually applied after the fact. Filters are not always the only solution; unfortunately, alternatives are seldom considered.

This paper presents a simple method for reducing six-pulse converter harmonics by harmonic cancellation through transformer bank connections. Before the discussion can begin, it is appropriate to define some of the many problems six-pulse converters can cause when they are connected to the distribution system.

II. Understanding the Problem

Is there truth to the saying "A picture is worth a thousand words?" Consider Fig. 1. These are the time domain voltage and current waveforms of a 3000-hp, six-pulse, load commutated inverter drive as viewed from the source. Fig. 2 shows the harmonic components for one of the phase currents in Fig. 1. Note that the total harmonic current distortion (THDi) for this waveform is 31% with appropriately 26% distributed in the fifth harmonic component; the remaining harmonic pairs occur at frequencies that follow the equation $6k \pm 1$ (i.e., 5, 7, 11, 13, 17, 19, etc.) and make up the remainder of the harmonic current distribution. These current harmonics are the source of many problems that can occur on distribution systems.

Most harmonic problems that affect other system equipment and electric loads are associated with the quality of the voltage waveforms on the system. Since the distorted current flows from the generating source to the harmonic producing load, it produces voltage drops across the linear elements of the system, such as transformers and distribution line conductors, which are distorted functions of the current flowing through them. By Kirchhoff's voltage law, the source voltage viewed by other loads and elements connected to the system is composed of two components. One component is the fundamental voltage of the generating source minus the 60-Hz voltage drops across the elements in the system produced by the fundamental 60-Hz frequency components of the currents flowing. The other component is the distortion voltage

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[1] Six-pulse type converters, in this text, are generalized and refer to ac/dc, dc/dc, dc/ac, and ac/ac topologies. These schemes commonly utilize a bridge-type polyphase SCR-type rectifier with either a constant current or voltage source isolation between the input and the output.

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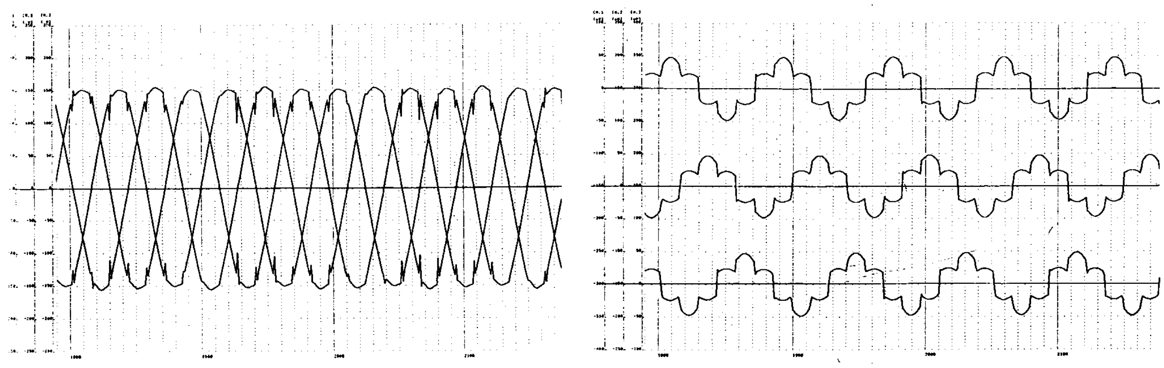

Fig. 1. Time-domain voltage and current waveforms of a 3000-hp, six-pulse, load commutated inverter drive as viewed from the source.

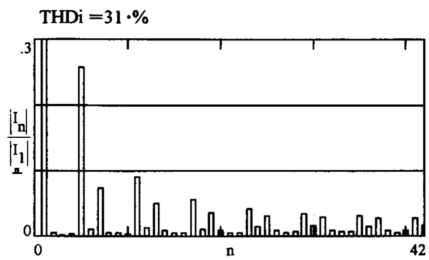

Fig. 2. Current harmonics of one phase shown in Fig. 1.

produced by the higher order harmonic current components flowing from the generating source to the harmonic producing load. These voltage components contain frequencies above the fundamental 60-Hz frequency, which are linear combinations of the harmonic current spectrum. As the harmonic producing load is moved closer to an ideal voltage source (i.e., an infinite bus), the amount of voltage distortion will approach zero since there are no significant impedance elements in series with the load that develop distorted voltage drops. With the exception of increased heating losses in electrical conductors resulting from the harmonic current flow, this configuration is not likely to cause significant voltage harmonic problems on the system. Conversely, as the harmonic producing load is moved farther from an ideal voltage source (i.e., a weaker system), the amount of voltage distortion near the load increases. It is this voltage distortion that can affect the performance of other elements connected to the system in the vicinity of the harmonic-producing load. There are several examples where harmonic voltage and current distortion can cause problems for other equipment on the system.

III. Concerns for Distortion [2]

Since the fifth 11th, 17th, 23rd, etc., harmonic components are of negative sequence when the system is balanced, additional heating losses and negative sequence harmonic torques will be present in all rotating machinery connected to the system where the harmonic voltage distortion is significant. It should be noted that in unbalanced systems, each harmonic can have positive, negative, and zero sequence symmetrical components.

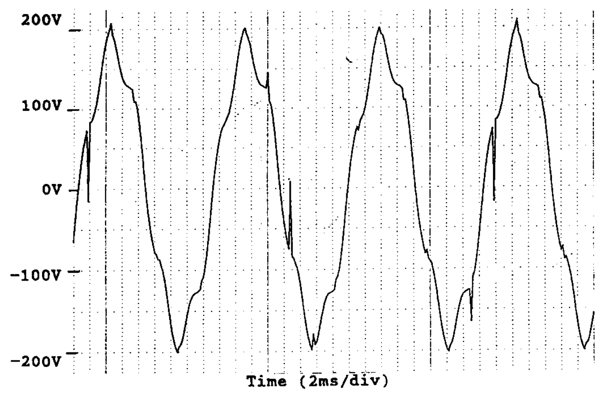

Fig. 3. Voltage waveform showing the extra zero crossings caused by a six-pulse converter.

Induction disc-type watt-hour meters can have positive and negative errors associated with the harmonic frequencies. The errors are produced by the harmonic torques aiding and opposing the fundamental frequency torque on the disc, and they are dependent on which harmonics are present, the direction of power flow, the phase relationships of the harmonic components, and the PT and CT winding connections. Solid-state, microprocessor-type meters have the ability to measure the true energy passing the metering point, but errors associated with sampling techniques, such as windowing, are still possible.

Electronic controls sensitive to zero crossings on the voltage and current waveforms can malfunction if the distortion is great enough to cause additional zero-crossing points between the normal 60-Hz spacings. An electronic power factor or VAR switching control unit on a distribution capacitor bank is a typical example of a device that depends on normal 60-Hz zero crossings. Fig. 3 is a specific example of a voltage waveform containing additional zero crossings caused by a six-pulse SCR bridge converter measured near a large adjustable-speed motor drive in an oil field where VAR capacitor controls are used. Note the two additional zero crossings present in three of the four cycles shown.

Transformer banks in the system that have to conduct the harmonic currents will have higher heating caused by

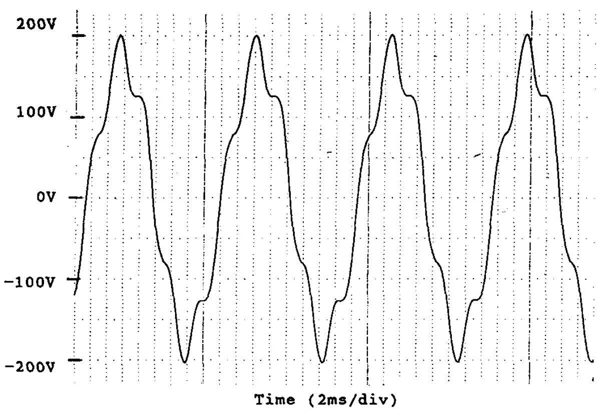

Fig. 4. Twenty-five kilovolt bus PT's showing the voltage amplification from parallel resonance when capacitor banks are connected to the system.

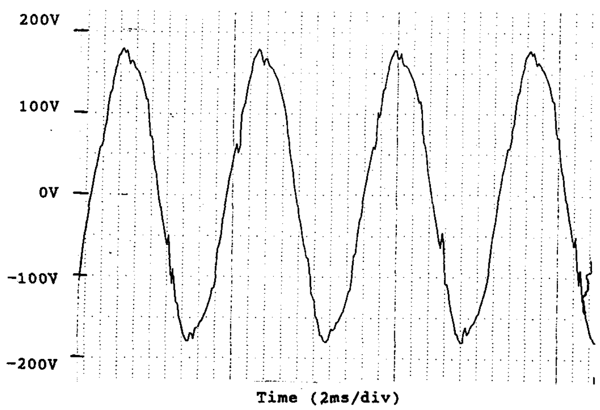

Fig. 5. Same as Fig. 4 except the capacitor banks are off line.

additional copper and stray flux losses in the windings that increase with frequency. Harmonic voltages on transformer windings can produce additional core losses caused by harmonic eddy currents flowing in the iron core laminations. Since this will cause more heat energy buildup in the transformer, the temperature will rise, and the insulation life will be degraded as compared with an equivalent 60-Hz loading.

Harmonic amplification of the voltage waveforms caused by parallel resonance between the system equivalent inductance and capacitive reactance of power factor correction capacitor banks or the distributed capacitance of high-voltage power cables is a very common problem on distribution systems. Figs. 4 and 5 are the voltage waveforms recorded at a 25-kV distribution substation bus (which is connected to the secondary of a 120-V watt-hour meter PT circuit) under the conditions when capacitor banks that are located on three 25-kV distribution feeders were connected on and off line, respectively. At parallel resonance, the system equivalent impedance seen by the drive is a maximum. Since most bridge rectifier converters feed a large link reactor, the drive can be thought of as a constant current source at the harmonic frequencies if the dc time constant of the reactor is $L/R \gg 16.667$ ms [1]. The constant harmonic current at or near the

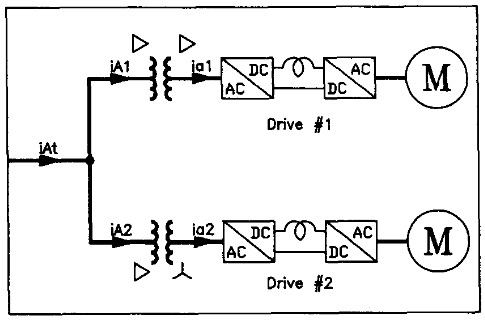

Fig. 6. Two constant current, six-pulse motor drives connected through step-down transformers to achieve harmonic cancellation.

parallel resonant frequency must flow through the parallel resonant impedance of the system, which is at a maximum. This produces large harmonic voltage drops that appear to be amplified, hence, the name harmonic voltage amplification.

The voltage amplification of Fig. 4 is on the order of 18%. Under this condition, increased insulation stress on equipment can occur if the condition is allowed to continue for a prolonged period of time. For example, the peak voltage rating for distribution capacitor banks is 120%. If capacitors are subjected to prolonged voltage peaks above their rated values, reduced insulation life, as well as total failure, is more probable. Electric motors and generators are affected in a similar way.

When capacitors are connected to a distribution system that supplies converter-type loads, the high-frequency components of the harmonic current above the system parallel resonant frequency flow mostly through the capacitor banks. These harmonic currents cause additional heating in the fuse elements protecting the capacitors and can cause them to melt under what seems to be normal 60-Hz capacitive current flow. The reason for the premature melting is the additional heat energy buildup from the harmonic current flow.

Controling the flow of a six-pulse converter current in a power system is very important since many problems associated with the voltage and current waveforms can be eliminated. Harmonic filtering is one possible solution, but another alternative should be considered.

IV. Harmonic Component Cancellation

Before the analysis stages of harmonic filtering are pursued, some attention should be directed towards an alternative solution to controlling harmonics. If the system is still in the planning stages, serious consideration should be made concerning the type of transformer connections serving six-pulse converter loads.

To understand how harmonic cancellation occurs, consider a case where two six-pulse drives are being added to a distribution system and are to run independent of each other as shown in the one-line diagram of Fig. 6. Here, we are assuming that 1) both motor loads are nearly the same in torque and speed and 2) that the dc link reactor in both drives is large enough to serve as a constant current source (i.e., very small dc ripple current) to the invertor sections or dc load, as in the

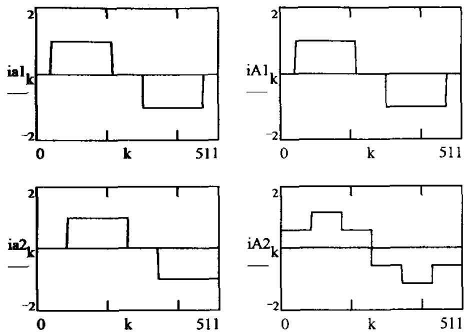

Fig. 7. Time domain current waveforms of the dual converter drive connections shown in Fig. 6.

case of a dc motor drive. It should be noted that if the dc time constant is too large, the control response time of the motor drive goes up beyond practical and economical limits.

As shown in this example, Drive #1 is connected to the low-voltage terminals of a Delta–Delta step-down transformer that has a 0° phase displacement. Drive #2, on the other hand, is connected to the low-voltage terminals of a Delta–Wye step-down transformer that is connected as an ANSI standard "low-voltage-lags" by 30°. The per-unit, phase "A," ac line currents flowing in the system under these conditions are shown in Fig. 7. When the firing angle α is adjusted to 0° for both motor drives, $ia2$ lags $ia1$ by 30° because the low-voltage line-to-neutral voltages in the Delta–Wye lag those in the Delta–Delta connection. The per-unit line currents on the high-voltage sides of the transformer banks are related to the low-voltage side by (1) and (2).

$$iA1 = ia1 \tag{1}$$

$$iA2 = ia2 - ib2 = \sqrt{3}ia2\angle 30^\circ \tag{2}$$

where

$ia1$	converter #1 line current $a\phi$
$iA1$	transformer 4#1 line current $A\phi$
$ia2$	converter #2 line current $a\phi$
$ib2$	converter #2 line current $b\phi$
$iA2$	transformer #2 line current $A\phi$.

All of the time domain current waveforms shown in Fig. 7 have the same relative harmonic magnitude spectrum shown in Fig. 8. Note that the harmonic components in Fig. 8 occur at frequencies that allow the equation $6k\pm1$ (i.e., 5, 7, 11, 13, 17, 19, etc.), where k is a positive integer. In addition, note that the fundamental harmonic component is not shown; therefore, the others appear more predominant; the first harmonic pairs occur at the fifth and seventh harmonics of 60 Hz. For six-pulse type converters that have ideal constant dc current sources (i.e., the dc ripple current is small), the THDi is 31%, and the higher order harmonic components have magnitudes of $1/n$ relative to the fundamental. Note that this is only the theoretical values of the current harmonic magnitudes.

From a modeling standpoint, assuming a constant current source with no dc ripple or commutation delay makes life

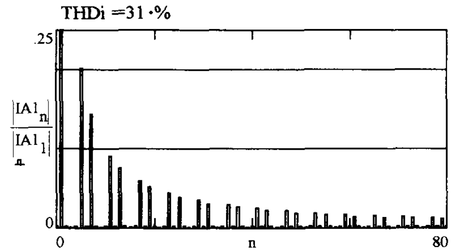

Fig. 8. Harmonic magnitude spectrum for all six-pulse converter waveforms shown in Fig. 7.

much easier since the time-domain functions can be easily assembled and integrated in a Fourier series to derive the harmonic components. For a real six-pulse converter, however, the dc current source is not ideal since discontinuous conduction at light loads can produce a large dc ripple current, and in some cases, where negative half-wave symmetry is lost in uncontroled or half-controlled rectifiers, even-order harmonic currents can be produced [3]. As a result, the harmonic spectrum is not equal to that shown in Fig. 8. Rather, the spectrum shown in Fig. 2 is more realistic, even though the THDi for both is nearly the same. Note that the rounding of the corners of the time-domain six-pulse waveform results in a harmonic spectrum, where much more of the distortion current is distributed into the fifth harmonic component. As shown by [3], as the dc ripple ratio increases towards discontinuous conduction, the fifth harmonic component approaches 50%, whereas the higher order harmonics either remain the same, as in the case of the 11th, or decrease, as in the case of the seventh and 13th harmonics.

Harmonic cancellation between the two converters in Fig. 6 occur when the line currents sum together.

$$iAt = iA1 + iA2. \tag{3}$$

As shown in Fig. 9, the summation produces a 12-pulse equivalent current waveform that has the following properties:

1) The harmonic components occur at frequencies according to $12k \pm 1$.
2) The THDi is approximately one half of that for a six-pulse, and it contains no fifth or seventh harmonics.
3) The harmonic pairs in the 12-pulse have exactly the same relative magnitudes as the six-pulse.

The true 12-pulse harmonic spectrum in Fig. 9 is only valid if the firing angle α is controled to be the same for both converters, and the line currents have equal magnitudes and power factors for both drives. For two drives operating independently, α and i will vary. To see how these variations affect the summation of currents, consider the following sequence of figures.

If the current amplitudes are held constant for both drives and the firing angle $\alpha1$ is delayed with respect to $\alpha2$ by 5°, the resulting time domain waveform and harmonic current spectrum shown in Fig. 10 results. The THDi has increased by 1%, the current $iA1$ lags $iA2$ by 5°, the 11th and 13th harmonics are reduced, and total cancellation of the fifth and seventh harmonic components is not achieved.

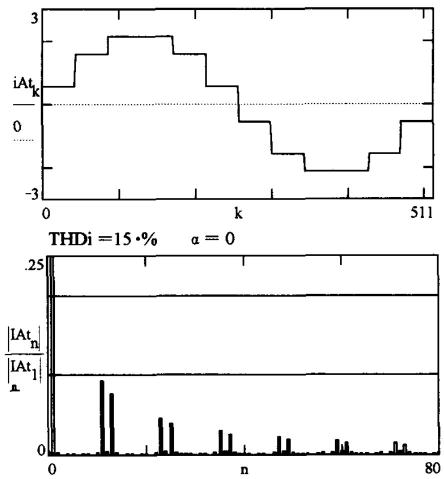

Fig. 9. Twelve-pulse current summation and harmonic magnitude spectrum for $\alpha = 0$ and equal drive current amplitudes.

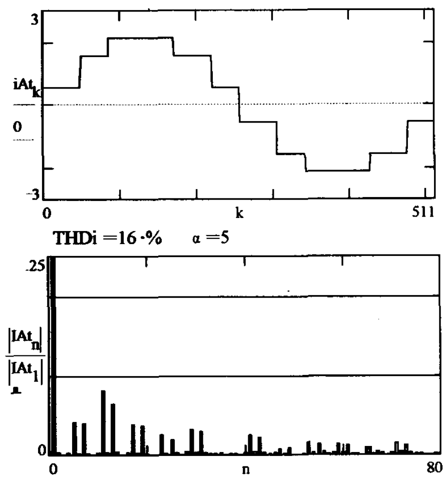

Fig. 10. Same as Fig. 9 except $\alpha = 5$.

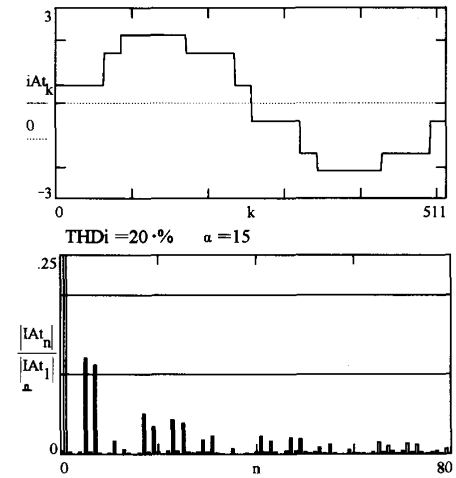

Fig. 11. $\alpha = 15$.

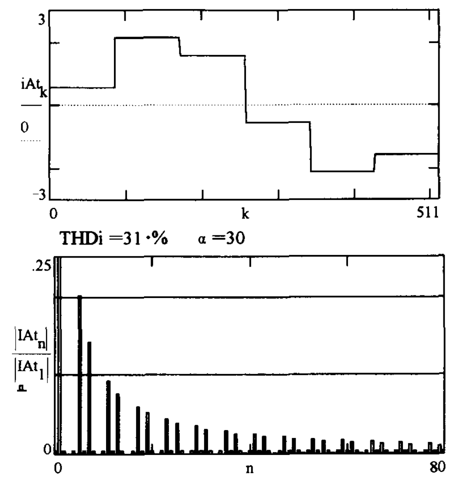

Fig. 12. $\alpha = 30$.

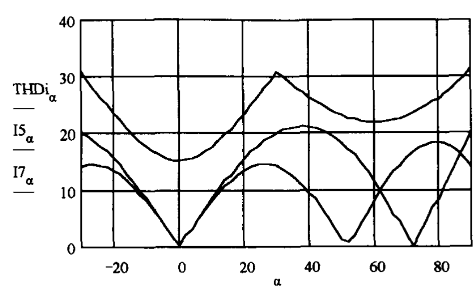

Fig. 13. THDi versus α for equal drive currents.

As $\alpha 1$ is delayed to 15° shown in Fig. 11, the THDi increases by 5%, and the 11th and 13th harmonics are almost canceled out completely. At this point, the fifth and seventh harmonics become predominant in the spectrum.

Fig. 12 shows the classic six-pulse spectrum for $\alpha 1$ adjusted to 30°. Beyond 30°, the THDi increases dramatically because the fundamental harmonic component starts to cancel out at the current summation point. When $\alpha 1$ equals 180°, the fundamental component of the current is canceled completely, and the THDi goes to infinity. This happens because in the definition of the THDi, the function is not analytic at $I_1 = 0$:

$$\text{THDi} \equiv \frac{1}{|I_1|}\sqrt{\sum_{n=2}^{\infty} |I_n|^2} \tag{4}$$

where I_n is the Fourier coefficient of the nth harmonic, and n is the harmonic index.

If the firing angles of the two drives are adjusted so that $\alpha 2$ lags $\alpha 1$, the variation of the THDi is similar to the cases above in Figs. 10–13.

Holding α constant and varying the amplitudes of the converter current causes the THDi at the summation point to increase. As shown in Fig. 14, if $iA1$ is held constant, and α is adjusted to be zero for both drives, then by letting $iA2$

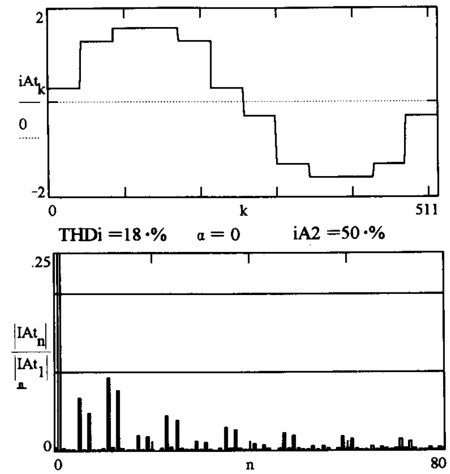

Fig. 14. With $\alpha = 0$, $iA2$ is adjusted to 50% of $iA1$.

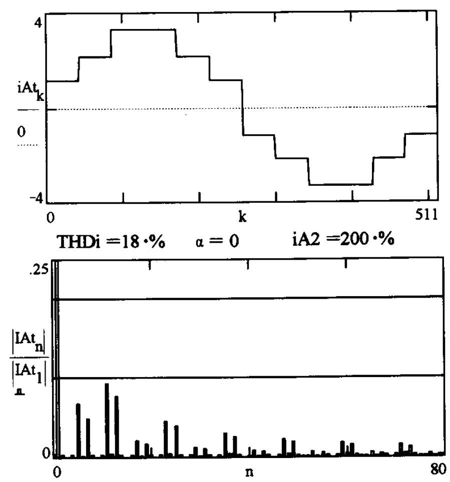

Fig. 15. Same as Fig. 14 except $iA2$ = 200%.

equal 50% of $iA1$, the THDi increases by 3%. The fifth and seventh harmonic components increase from zero as do all odd harmonic pairs that occur at frequencies corresponding to $6(2k+1) \pm 1$ for $k = 0, 1, 2\ldots$. In the same way, as shown in Fig. 15, if $iA2$ is fixed at 200%, the THDi increases by 3%, and the odd harmonic pairs appear. For values of $iA2$ between 0 and 200%, the THDi varies as shown in Fig. 16. The true 12-pulse operation is achieved when the THDi is a minimum at $iA2$ equal to 100%.

The figures shown have been computed under the conditions when the loading of the drives are held constant, and the firing angles $\alpha 1$ and $\alpha 2$ are varied. In a similar manner, the α's have been held constant, and the loadings have been varied. This was done to show how the THDi of the current flowing into the converter terminals varied with α and loading. In practical converters, however, the load current varies in magnitude and phase as the firing angle is changed. They are not independent variables. For inductive power transfer, the current may increase from zero, hit a maximum at $\alpha = 90^\circ$,

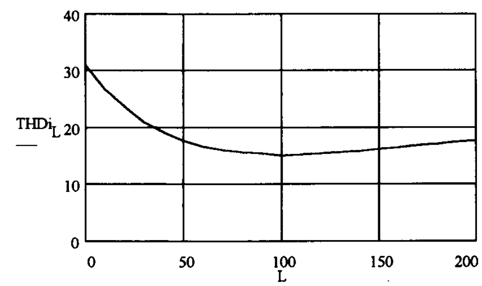

Fig. 16. THDi versus relative loading between drives from 0 to 200% at $\alpha = 0$.

and fall off to 0 as α goes to 180°. If the power transfer contains a real and reactive component, the maximum may occur between 0 and 90°. In either case, the current magnitude, power factor, and harmonic content will vary with α. However, if two drives are connected to the system through transformers as shown in Fig. 6 and the their relative firing angles and loadings are fairly close to each other as shown in Figs. 13 and 16, the harmonic distortion at the summation point will be less than an equivalent six-pulse current flow that would result from transformers having the same type of connections with no phase shift.

V. An Application for Distributed Converters

Consider applying harmonic cancellation transformer connections to a distributed set of variable frequency drives (VFD's) used in an oil field as shown in the one-line diagram of Fig. 17. Three of the four 25-kV distribution feeders serve several down-hole pumping motors through VFD's connected to the secondary of 480-V step-down transformer banks. A small co-generator is connected to the fourth feeder.

All of the transformers have been installed with the same connection. What will the 69-kV source see as it looks into the oil field distribution system? If all of the VFD α's are fairly coincident, the system will look like a giant six-pulse load with approximately 20%, if not more, of the total VFD current being composed of the fifth harmonic. Under these conditions, the harmonic voltage distortion on the 25-kV system will be significant if the parallel resonant frequency of the system and the capacitor banks is near the fifth harmonic. For this example, Fig. 4 shows the measured voltage waveform at the 254-kV bus. The voltage has approximately 15.4% THDv with the fifth harmonic component at 15.3% [2].

At the design and planning stages of the development of this distribution system, half of the VFD loads could have been connected with Delta–Delta step-down transformers and the other half with Delta–Wye's at the same cost as installing all of the same type connection. Although the odd harmonic pairs would not be canceled out completely, as in a true 12-pulse configuration where the α's are controled, they could have been reduced significantly. This would greatly reduce the amount of fifth harmonic voltage distortion on both the 25- and 69-kV systems.

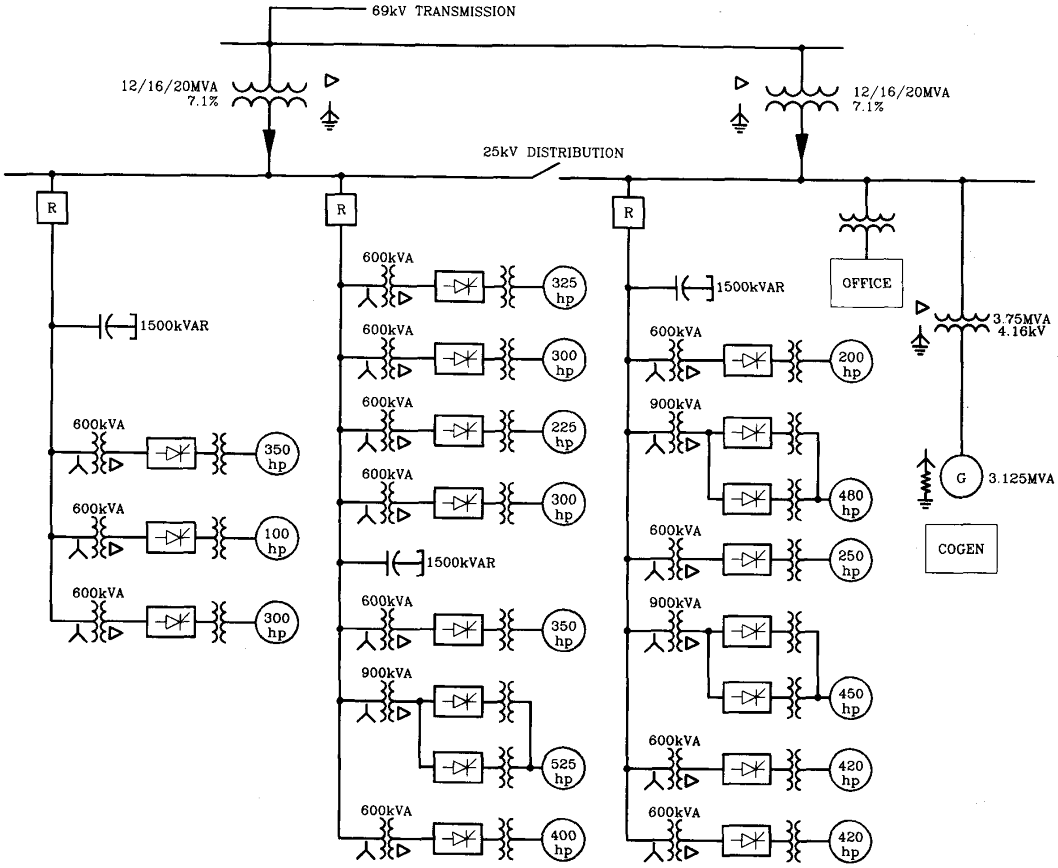

Fig. 17. One-line diagram of a distributed set of VFD loads used in an oil field.

VI. An Application for Ski Lift Converters

As shown in Fig. 18, a Wye–Delta phase-shifting transformer was applied to a new motor drive ac/dc converter on a detachable-quad ski lift for harmonic cancellation with an existing ski lift ac/dc converter. Fig. 19 shows the measured phase "A" time-domain current and harmonic spectrum for Lift #1 running at approximately 50% of rated full load. As shown, the current waveform has a dc ripple ratio very close to 1.5 and contains a fifth harmonic component of nearly 46%. The seventh and 11th harmonics are small by comparison.

Fig. 20 shows the phase "A" current for Lift #2 running at approximately 90% of rated full load. The fifth harmonic component is approximately 32%, and the dc ripple ratio is between 0.7 and 0.8. Note that the predominant harmonics occur at frequencies corresponding to $6k-1$ for $k = 1, 2, 3\ldots$ and that the upper harmonics occuring at frequencies corresponding to $6k + 1$ are very small by comparison. As shown in [3], the upper components of each harmonic pair cross zero for ripple ratios between 0.7 and 1.4, whereas the lower components of each harmonic pair remain nearly constant for ripple ratios between 0 and 1.5.

With both converters running and adjusting the firing angles to be nearly equal, the phase "A" current waveform and harmonic spectrum shown in Fig. 21 was measured at the secondary of the main power transformer as shown in Fig. 18. Note the significant reduction in the THDi and fifth harmonic component. The fifth harmonic component was reduced below 4%.

Under typical operating conditions, the current waveform and spectrum shown in Fig. 22 was measured when both ski lifts were running close to full speed, and the firing angles of the converters were not controled. The fifth harmonic component was approximately 13%, and the THDi was only 18%. Although these harmonic current levels may seem large compared with IEEE-519 limits, they are much less than what they would have been if a phase shifting transformer was not used. In this case, the THDi could have been as high as 40%.

If filters were designed to further reduce the harmonic current injected into the utility, the fifth harmonic filter size could be significantly reduced from what would normally be required if a phase shifting transformer was not used. Since transformer costs are typically around \$15/kVA and low-voltage filter costs are around \$70/kVAr, it is both economical and practical to use phase-shifting transformers to reduce the filtering costs.

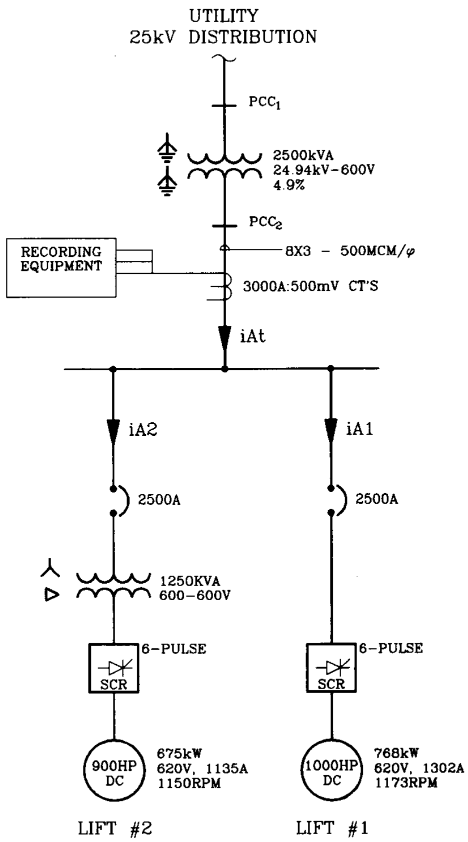

Fig. 18. One-line diagram of independent six-pulse ac/dc converter motor drives used for two detachable-quad ski lifts.

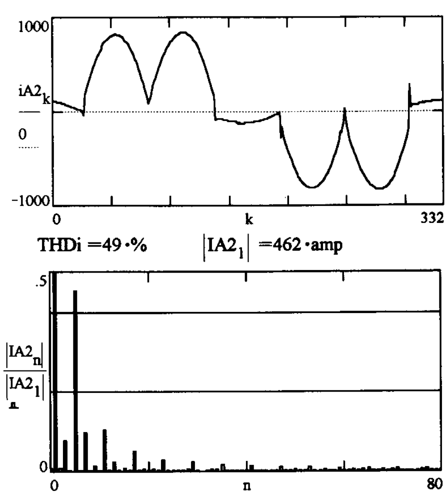

Fig. 19. Lift #1 phase "A" time domain current waveform and harmonic spectrum.

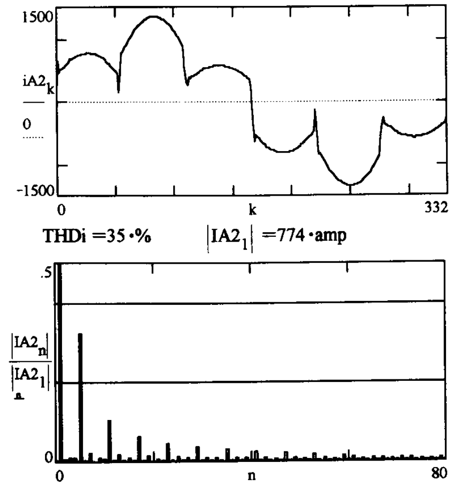

Fig. 20. Lift #2 phase "A" time domain current waveform and harmonic spectrum.

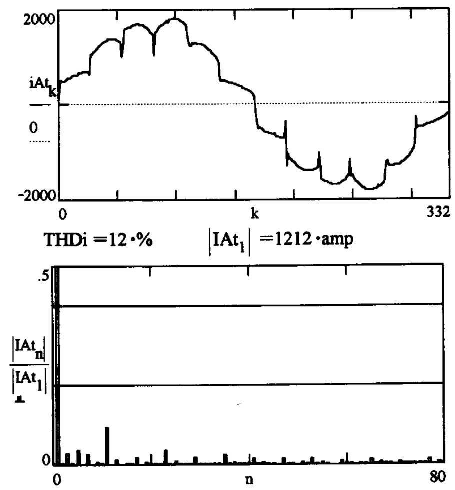

Fig. 21. Phase "A" current summation and harmonic spectrum of Lifts #1 and #2 with nearly equal firing angles.

VII. Conclusion

Harmonic producing loads are being added to distribution systems at an increasing rate. Power system harmonic problems are more frequent because the voltage and current distortion on the systems is increasing. Utilities do not have the time or resources to track individual harmonic loads and design the frequency response of their distribution and transmission systems to fit the harmonic loads so that parallel resonant points are avoided. IEEE is adopting more strict and detailed harmonic distortion limits for systems. What does this mean?

Better planning for harmonic producing loads is going to have to take place if system harmonic problems are going to be avoided in the future. One technique for reducing the amount of harmonic distortion associated with six-pulse type converters has been presented in this paper. By providing a 30° phase shift between sets of six-pulse type converters, significant THDi, and fifth and seventh harmonic reduction, and cancelation can take place if the relative current amplitudes and firing angles are fairly coincident.

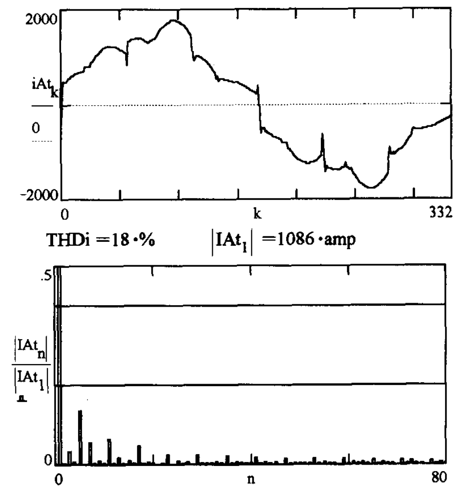

Fig. 22. Typical operating conditions: Phase "A" current summation and harmonic spectrum of Lifts #1 and #2 with uncontroled firing angles.

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