A BETTER UNDERSTANDING OF HARMONIC DISTORTION IN THE PETROCHEMICAL INDUSTRY

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Abstract –This paper provides an in depth discussion on harmonic distortion on power systems in the petrochemical industry. The paper begins with a discussion on harmonics caused by saturable magnetic devices such as generators, transformers and motors. Production and control of harmonic voltages and currents produced in these devices will be covered. Then, a discussion on the production and control of harmonic voltages and currents produced by power electronic devices will be discussed. An example of power system harmonics and harmonic suppression techniques will be presented.

Index Terms – Converter, distortion factor, exciting current, generator, harmonics, non-linear loads, magnetic circuits power factor, power quality, pitch factor, symmetrical components, total harmonic distortion (THD) and transformer.

INTRODUCTION

Electric power systems throughout the petrochemical industry are designed to normally operate at 50 or 60 Hz. Throughout history, efforts have been made to analyze the distortions on the power system created by the non-linear electromagnetic circuits such as generators, transformers and motors. In short, the non-linear devices may, and many times do, create distortions on the sinusoidal voltage of the ac power system.

Non-linear devices are also referred to as harmonic sources that result in the flow of harmonic currents. These sources can be categorized into:

- Saturable magnetic devices
- Power electronic devices

Part 1 of this paper will deal with saturable magnetic devices, and Part 2 will deal with power electronic devices.

The distortion on the power system voltages and currents can be analyzed through the study of higher frequencies commonly referred to as power system harmonics. With the fundamental frequency of 50 or 60 Hz being the first harmonic and integer multiples of the fundamental frequency being referred to as higher order harmonics, some lower order harmonics are shown in Table 1.

In an AC power system, even harmonics do not normally exist. Therefore, the common harmonics in a power system include odd harmonics.

TABLE I
COMMON POWER SYSTEM HARMONICS IN BOLD

FREQUENCY	HARMONIC
60 Hz (50)	**Fundamental**
120 Hz (100)	Second Harmonic
180 Hz (150)	**Third Harmonic**
240 Hz (200)	Fourth Harmonic
300 Hz (250)	**Fifth Harmonic**
360 Hz (300)	Sixth Harmonic
420 Hz (350)	**Seventh Harmonic**
480 Hz (400)	Eighth Harmonic
540 Hz (450)	**Ninth Harmonic**
600 Hz (500)	Tenth Harmonic
660 Hz (550)	**Eleventh Harmonic**
720 Hz (600)	Twelfth Harmonic
780 Hz (650)	**Thirteenth Harmonic**

A term called distortion factor or harmonic factor is often times used to express the amount of harmonic distortion. It can be used to express the amount of voltage distortion or current distortion in a system. The distortion factor is determined as follows:

$$DF = [(\Sigma\ X_{harmonic}^{2})/(X_{Fundamental}^{2})]^{-1/2} \text{ x } 100\% \quad (1)$$

Where,
DF = Distortion Factor
$X_{harmonic}$ = Amplitude of harmonics
$X_{fundamental}$ = Amplitude of the Fundamental

From equation 1, one can calculate the total harmonic voltage distortion factor, THD_V, and total harmonic current distortion factor, THD_I, by substituting the voltage harmonics and current harmonics, respectively, as follows:

$$THD_V = [(\Sigma V_{harmonic}^{2})/(V_{Fundamental}^{2})]^{-1/2} \text{ x } 100\% \quad (2)$$

$$THD_I = [(\Sigma I_{harmonic}^{2})/(I_{Fundamental}^{2})]^{-1/2} \text{ x } 100\% \quad (3)$$

An example of a distorted waveform is a typical office printer. The harmonic distribution for such a waveform is shown in Fig. 1.

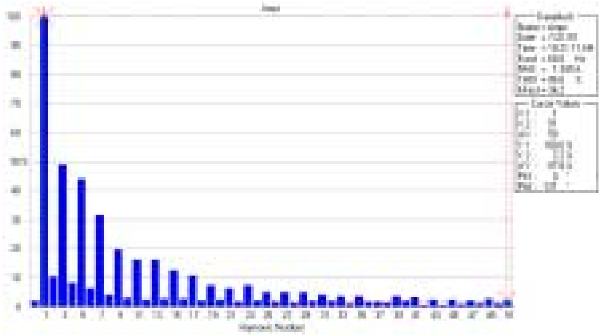


Fig. 1 – Harmonic Current Distribution of Office Printer

Harmonics frequencies also can be identified by symmetrical components where the sequence components are determined by the following equations:

$$P_{har} = 1 + n(3) \quad (4)$$
$$N_{har} = 2 + n(3) \quad (5)$$
$$Z_{har} = 3 + n(3) \quad (6)$$

Where,

n = 0 or any positive integer.
P_{har} = positive sequence harmonic,
N_{har} = negative sequence harmonic, and
Z_{har} = zero sequence harmonic

See Appendix 1 for a list of the first fifteen harmonics with each respective type of symmetrical component.

One of the important aspects of symmetrical components in analyzing the effects of harmonics on a power system is that:

- positive sequence harmonics produce positive torque
- negative sequence harmonics produce negative torque
- zero sequence harmonics produce no torque

PART 1 – SATURABLE MAGNETIC CIRCUITS

Saturable magnetic devices include power generators, transformers, motors and other iron core devices. Harmonics are due primarily from iron saturation. In the design of these devices, most equipment is designed at or above the knee of the saturation curve. As a result, the magnetizing current can be highly distorted and rich in third harmonic harmonics. The third harmonics caused by iron saturation have been around since the advent of magnetic circuits. And, power engineers have dealt with and mitigated the problems of third harmonics through transformer connections and generator designs as will be discussed later.

Harmonics Created In Generators

The magnetic circuit of an ac generator produces harmonics which can be minimized through the arrangement of the stator windings. A particular harmonic can be eliminated from the generated voltage by choosing a pitch factor that eliminates a particular harmonic. The magnitude of the pitch factor for any particular harmonic n, K_P, is equal to:

$$K_P = \text{Sin } np/2 \quad (7)$$

By setting K_P = 0 for a particular harmonic, the generator winding arrangement essentially can eliminate that harmonic:

$$K_P = \text{Sin } np/2 = 0 \quad (8)$$

And for odd harmonics,

$$K_P = \cos n(180 – p)/2 \quad (9)$$

Or,

$$p = 2m(180^o)/n \quad (10)$$

Where,

p = Pitch expressed in electrical degrees
n = harmonic
m = any integer

With proper planning during the design phase of the power system for a petrochemical plant, certain harmonics can be minimized. For example the pitch factor of a generator can be modified to minimize and eliminate certain harmonics. (The pitch of two conductors in a generator is normally thought of as being at 180 electrical degrees apart. By adjusting the pitch at an angle other than 180 electrical degrees, the magnitude of the fundamental and all harmonic waves will be impacted.) See table II. [3]

TABLE II
PITCH FACTOR IMPACT ON HARMONIC VOLTAGE MAGNITUDES

Pitch	Fund	3rd	5th	7th	9th
2/3	0.866	0.000	0.866	0.866	0.866
4/6	0.951	0.588	0.000	0.588	0.951
5/6	0.966	0.707	0.259	0.259	0.966
6/7	0.975	0.782	0.434	0.000	0.782

If there is a delta-wye transformer between the generator and power system, then the 3rd and multiples of the third harmonic are eliminated since the delta-wye transformer connection filters the zero sequence components. This is accomplished by the fact that the third and multiples of the third harmonic voltage are the same in all three legs of the delta and there is no resulting change in zero sequence flux, dΦ/dt. Therefore, a generator could be designed with a large third harmonic voltage component thus minimizing other generated harmonics. For example, from table 3, use of the 5/6th pitch would reduce the 5th and 7th harmonics and the transformer would filter the 3rd and 9th harmonics resulting in a relatively good reduction in harmonics passed through to the power system.

Harmonics Created By Nonlinear Transformer Circuits

Harmonics can be and are typically created due to the non-linearity of the iron core circuit. In a transformer circuit, a voltage is applied to a set of windings. As a result of the voltage, a current flows creating a magnetizing flux. This current is also called the magnetizing or exciting current.

When a sinusoidal voltage is applied to the transformer winding, a distorted magnetizing current is produced. While the current is still somewhat sinusoidal, third harmonic current is present, the amount being dependent on the amount saturation being present. Likewise, if severe saturation exists, then there may be a considerable amount of fifth harmonic current as well. See fig. 2

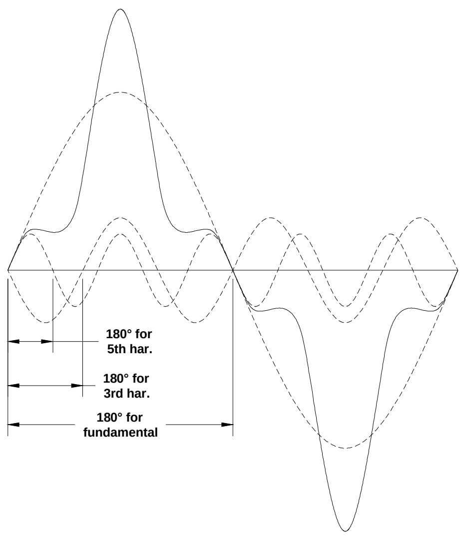


Fig. 2 – Magnetizing Current

Transformer manufacturers typically design the transformer to operate slightly above the knee of the saturation curve. The higher the operation is on the saturation curve, the greater the amount of distortion will be present in the magnetizing current. As the over excitation increases, the amount of fifth harmonic content increases. Fifth harmonic current sensed in a transformer can be used for over excitation protection.

Next, energizing a transformer causes a transient magnetizing current to flow that is rich in second harmonics. (See fig. 3) A current 12-25 times normal with a total dc offset is common. The current in the transformer during inrush are typically seen in one set of windings and the respective current transformers (CT's). As such, the inrush current may appear as a fault to the protective relay.

The fact that the inrush current on transformer energization is rich in harmonics while a transformer fault current is composed primarily of the fundamental frequency, the second harmonic current can be filtered and used to restrain the relay from tripping.

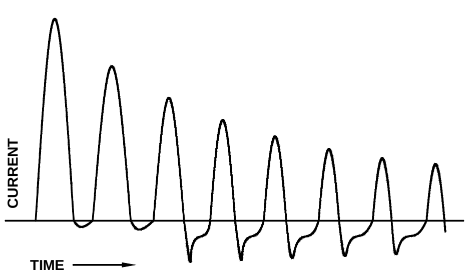


Fig 3 – Transformer Inrush Current

Inrush current can typically be 12 times for a tenth of a second (six cycles) and as high as 25 times for one hundredth (0.01) of a second. This information is important for the proper setting of protective relays.

Another way to minimize harmonics in the petrochemical power system is to minimize the saturation of transformers by maintaining the operation of the transformer in a reasonable voltage range. For example, consider a 4.16 kV generator operating on a 13.8 kV plant bus. A typical step-up transformer would be rated 4.16 kV – 13.8 kV. However, in order to transfer power and VARS through the generator, the generator may need to operate overexcited, possibly as high as 4400 volts to account for the voltage drop through the transformer. As such, the transformer may be operating substantially overexcited. Now consider operating the transformer with high side taps placed on a higher than nominal tap. Then the generator may now be operated at 4.16 kV with a + 2.5% or + 5.0% tap on the 13.8 kV side of the transformer.

The question that must arise from this example is, so what if the generator is operating at 4400 Volts? First of all, the generator in the example would be operating above its nominal rating, and so would be operating farther up on the saturation curve than necessary. As such, there are most likely additional harmonics being generated. Next, the transformer would be operating farther up on its saturation curve resulting in still more harmonics. Therefore, the system suffers from additional harmonics due to an improper, but seemingly correct transformer selection.

Another common mistake in the application of generator step up transformers is to use a lower rated voltage on the step-up transformer to compensate for the voltage drop in the transformer. As such, a 3.95-13.8 kV transformer may be chosen to produce 13.8 kV output from the transformer. While that transformer connection would work and the generator would not be overexcited, the transformer would be.

The best solution that would minimize harmonics in the power system would be to choose a transformer with the rating of 4.16 kV – 14.4 kV. Under normal conditions and prior to operation of the generator, the system operating at 13.8 kV would produce a voltage at the generator breaker of approximately 95%. As the generator voltage is increased to compensate for the voltage drop across the transformer and to ship vars to the system, the voltage will increase closer to the 4.16 kV rating without overexciting either the generator or transformer.

If the 1.05 per unit rating on the high side of the generator step-up transformer is too high for a particular application, a 1.025 per unit rating or lower tap could be used.

Third Harmonic And Zero Sequence Problems

Generators – Electric utility generators typically are isolated from the power system through a delta-wye step-up transformer which filters out the inherent zero sequence voltages. The delta-wye transformer provides a zero sequence and, thus, a third harmonic filter that eliminates the third harmonic voltages from being transferred into the power system. However, in the petrochemical industry, generators are many times connected directly to the plant electrical bus and do not have the benefit of having the third harmonic voltages being filtered. Therefore, the third harmonic voltage generation can be a problem and needs to be considered during the system design. A detailed discussion of this problem and various solutions are described in one of the references [6].

Special consideration needs to be given to the selection of the generators when more than one will be operated in parallel so that the generator pitch factor is matched. In addition, precautions need to be taken on the proper grounding of multiple generators. [8] Otherwise, circulating currents between the generators may occur. Likewise, if there is a wye-connected transformer on the same bus as a grounded generator, avoidance of circulating currents must also be considered. [8]

Solutions to the circulating current problem include the following:

- Selection of a 2/3 pitch generator
- Impedance grounding of each generator
- Impedance grounding of each parallel, wye-connected transformer
- Matching generator characteristics and operating conditions
- Single point grounding and isolation of the equipment neutrals

PART 2 – POWER ELECTRONICS

Power Electronics And The Generation Of Harmonics

Power engineers have spent years perfecting the generation of a sinusoidal voltage waveform for delivering power from the generating stations to the end users. With the proliferation of power electronic devices, more and more non-sinusoidal load devices are being placed on the power system. The petrochemical industry is no exception.

Power electronic devices create harmonics by drawing power only during part of the voltage cycle. Some of the earlier electronic devices were simple power rectifiers converting power from AC to DC. These loads were created using half-wave or full-wave rectifiers similar to the one shown in Fig. 4. The power electronic devices have become more complex with the use of sophisticated power electronic switching devices including the SCR (silicon controlled rectifier) and the IGBT (insulated gate, bi-polar transistor). The latter allows many switching cycles within the normal 50 or 60 Hz power cycle.

Some of the present day power electronic systems in the petrochemical industry include:

- Electronic power supplies
- Variable speed drives
- Large rectifiers
- Static VAR generators

The response of the power system to these power electronic devices depends on a number of factors including the characteristic of distortion produced by the load. With power electronic devices, it is common to consider the device

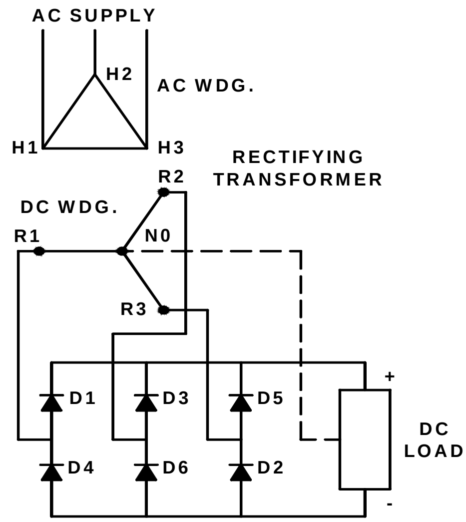


Fig 4 - Three Phase Rectifier

as a current source of harmonics. Using this method of modeling the load presents a clear picture on the impact of the load on the power system. System factors which should be considered include:

- System short-circuit capacity
- System Capacitance
    - Capacitor banks
    - Cable capacitance
- System load characteristics
    - Resistive loads provide dampening
    - Motors increase short-circuit capacity
    - Transformers can create phase shifts

The system short-circuit capacity is an important factor in determining the impact of power electronic loads in a petrochemical industry. Where the power system is weak with a relatively low short-circuit capacity, the voltage distortion caused by the harmonic currents can be significant. Conversely, where the power system is strong with a relatively high short-circuit capacity; the voltage distortion caused by the same harmonic current sources might be negligible. So one solution to minimize the voltage distortion caused by power electronic equipment is to install the equipment on a strong power source. However, that factor is usually not a controllable variable in the petrochemical industry.

System capacitance can be a source of problems when using power electronic devices in the petrochemical industry.

1) Switching of power factor correction or voltage support capacitors can result in control problems with equipment due to the switching transients.
2) The connection of capacitors can cause a change in the frequency response of the system to the harmonic currents produced by the power electronic equipment. As such resonance conditions may occur and that can magnify harmonic levels.

Therefore, care must be taken in the application of capacitors on power systems with power electronic equipment.

System load characteristics can be beneficial towards mitigating harmonic problems. For example, resistive loads will have a tendency to dampen the circuit, especially if the system has a harmonic level of current near a parallel resonance frequency. Dynamic motor loads have a tendency to increase the short-circuit capacity of the system. As such, they will change the effects of the harmonic currents on the voltage distortion by changing the system impedance. Also, by changing the system impedance, the motor loads will have a tendency to shift the resonance frequency of the system.

Transformers can have several impacts on the application of power electronics. First, a transformer can help isolate the power electronic loads from the power system with its impedance. Next, if the transformer has a winding connection other than a wye-wye or delta-delta, there will be an inherent phase shift that can be beneficial [4]. In fact, the phase shift is key in minimizing the generated harmonic currents in the 12, 18, 24 and higher pulse power electronic equipment. The key to this is through what is called phase multiplication where the number of phases is increased through the use of multiple winding transformers. Since the number of pulses is twice the number of phases, the number of phases and pulses are as follows:

$$\text{Phases} = 3m \qquad (11)$$

Where,

m = any positive integer

and,

$$\text{Pulses} = 6m \qquad (12)$$

To create multiple phases in excess of the standard three phase source to power electronics, it is necessary to use:

- Transformers with identical transformer ratios
- Transformers with identical impedances
- Transformer connections with phase shift equal to 60/m degrees
- Share dc currents equally

The harmonics present in the system will then be of the order of

$$\text{Harmonic} = (k\ 6m) \pm 1 \qquad (13)$$

Where,

k = 1, 2, 3 …

The simplest and least expensive rectifier is the six pulse drive. The six pulse drive creates harmonics of the following values,

$$K_6 = 6n \pm 1 \qquad (14)$$

Where n = 1, 2, 3 and so forth

So that K_6 = 5, 7, 11, 13, 17, 19 and so forth.

Likewise, a 12 pulse drive will create harmonics as follows:

$$K_{12} = 12n \pm 1 \qquad (15)$$

So that K12 = 11, 13, 23, 25, 35, 27 and so forth. So a major reduction in the number of harmonics have been reduced.

Similarly, an 18 pulse drive will limit harmonics to:

$$K_{18} = 18n \pm 1 \qquad (16)$$

So that K_{18} = 17, 19, 35, 37, 53, 55 and so forth

And, a 24 pulse drive will limit harmonics to:

$$K_{24} = 24n \pm 1 \qquad (17)$$

So that K_{24} = 23, 25, 47, 49, 71, 73 and so forth

On a six pulse drive, the current seen by the system is essentially a wave form that closely approximates a square-wave. See the wave forms in Figs. 5 and 6 which were taken from two-halves of a 12 pulse drive, but each shows the 6-pulse type of current.

Next, a 12 pulse drive is considered. On the twelve pulse drive, the equivalent of a 6 phase system is developed using the equivalent of two, three phase transformers: one with no phase shift such as a wye-wye or delta-delta transformer, and the second with a 30 degree phase shift such as a delta-wye or wye-delta.

On the twelve pulse drive, the secondary on each transformer has a six pulse rectifier, but the pulses are now approximately 30 degrees in width compare. On the primary sides of the transformer, one of the currents is reflected directly through the transformer while the current on the other transformer will be phase-shifted by 30 degrees. When the primary currents are added, the result is a current which appears more sinusoidal. See fig. 7 which appears more sinusoidal than figs. 5 and 6.

An 18 pulse drive uses the equivalent of three, three-phase transformers making a nine-phase system and the equivalent of 15 degree phase shifts. A 24 pulse drive uses the equivalent of four, three phase transformers making a twelve-phase system and the equivalent of 7.5 degree phase shifts.

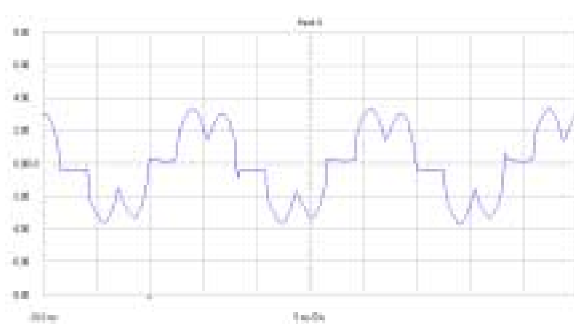


Fig. 5 – Current from Y drive

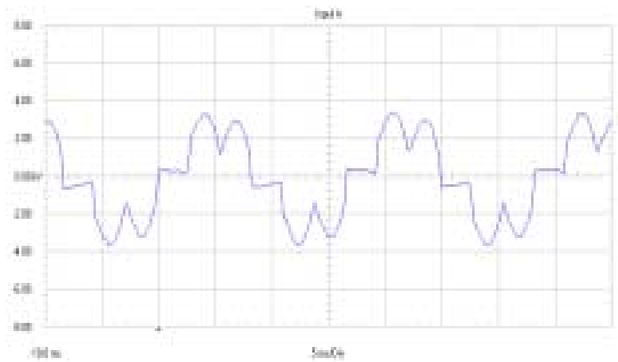


Fig. 6 – Current from X drive

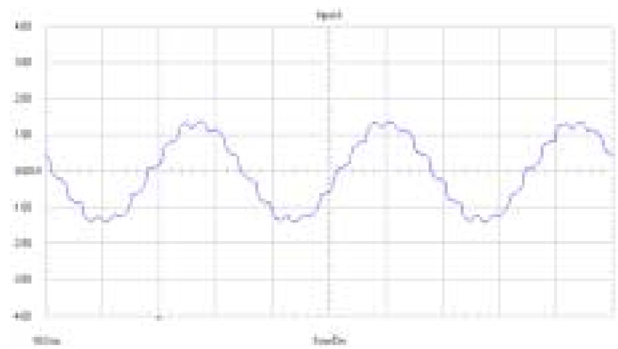


Fig. 7 – Result current of Y+X Drive

Harmonic Problems

Petrochemical plants have reported operational problems when harmonic voltage distortion is high. The following typical problems have been experienced in on plant prior to rectifying the harmonic problem:

- Heating in motors and generators
- Derating of power transformers
- Power cable problems
- Power Capacitor Problems
- Unreliable operation of Relays

Motors and Generators - One of the problems of harmonics, which may or may not be obvious in the petrochemical industry, is the increase in heating as a result of iron and copper losses due to harmonic frequencies. The adverse affects of harmonics on motors and generators includes possible decrease in efficiency and a reduction of torque. For example, the fifth and eleventh harmonics are negative sequence components which provide retarding, or backward torque.

Transformers – Transformers are affected by both harmonic currents and voltages. The harmonic currents increase copper losses and stray flux losses. The harmonic voltages result in higher frequencies being induced in the iron core which in turn results in increased heating in the form of iron losses. As a result of the increase in losses and the resultant heating, the transformer may be subject to derating.

An important aspect of the third harmonic is that it is zero sequence, equal in magnitude and equal in phase. Therefore, transformer connections are important in the flow of magnetizing current in a three-phase transformer. For a wye connection, the wye must be grounded to allow the flow of the third harmonic current. For a delta connection, the third harmonic current can flow around the delta winding.

Power Cables – The effects of harmonics on power cable have the similar heating problems as found on transformers, motors and generators. The higher frequencies increase the copper losses some of which can be explained by the skin effect on the cables by the higher frequency currents. A less obvious problem is the potential of resonance caused by the harmonic currents and the shunt capacitance of the cable.

Power Capacitors – Power Capacitors have a frequency dependent impedance that decreases as the frequency increases. Therefore, resonance is possible with the application of power capacitors on the system. Also, a capacitor is a "sink" for higher frequency currents and may result in false operation of power fuses if not properly sized.

Protective Relays – Protective relays may be dependent on voltage, current or a combination of the two. The higher frequencies present to harmonics may have an adverse impact on the operation of relays. For, example, a voltage waveform rich in fifth harmonic voltage (negative sequence) may result in an improper operation of a voltage balance relay. With the new microprocessor based relays, harmonics may adversely affect the electronics within the relay.

Applying Capacitors On A Power System With Harmonics – What Happens?

Inductive reactance, X_L, is proportional to frequency and capacitive, X_C, reactance is inversely proportional to frequency:

$$X_L = 2*\pi*f*L \tag{18}$$

$$X_C = (2*\pi*f*C)^{-1} \tag{19}$$

Resonance occurs when $X_C = X_L$

Resonance occurs when the frequency for a given L and C at

$$f = (2\pi\sqrt{LC})^{-1} \tag{20}$$

Resonance, both parallel and series, can cause numerous problems including dangerous over voltage and dangerous over current conditions. As a result, capacitors may be subjected to premature failures, capacitor fuses may blow and lightning arresters may fail under a resonant or near resonant condition.

PLATFORM HARMONIC CONCERNS AND DESIGN CONSIDERATIONS

An example will be used as a means of introducing a potential solution for harmonics generated by power electronics. In 1999, an off shore platform located in the Cook Inlet in Alaska was contemplating the installation of electric submersible pumps (ESP's) to replace gas-lift production.

Prior to the project, the platform had a no significant power electronic loads and relatively pure sinusoidal voltage with less than 1.5% THDv. ESP No. 1 was installed first, followed by ESP No. 2. Both units were added to an existing water flood room and both units were of a twelve pulse design. Then ESP Nos. 3, 4 and 5 were installed in a new ESP room where the three were bused together. The approximate system one-line diagram for the platform is shown in fig. 8.

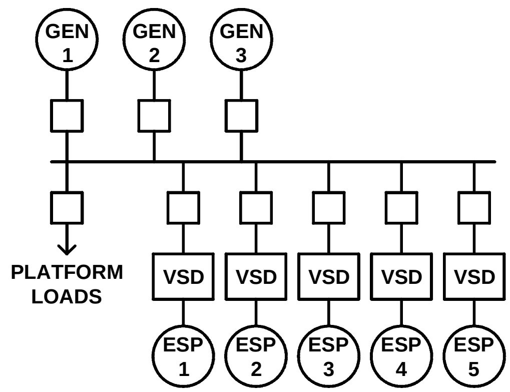


Fig. 8 – One Line Diagram

The platform electrical system was composed of three, generators rated 5.0 MVA and 0.8 PF. However, the turbines were limited to approximately 3300 kW, each. Two generators normally operated with one generator as a non-running spare. The primary loads on the platform were electrical pumps for water flood, oil transportation gas compression and other rotating equipment. Normal platform load was in the range of 2500 kW with an additional 2500 kW during drilling at which time a third generator was run. While the present mode of oil production was through gas lift, the production engineers decided that the installation of electric submersible pumps would be economically attractive. Liquid production had an approximate split of 93% water and 7% petroleum.

The electric submersible pumps were to be placed at a depth of approximately 3000 meters. During the design phase, a decision was made to utilize variable frequency drives (VFD's). In order to minimize the power system distortion on the platform due to the VFD's, a further decision was made to minimize system harmonics. As such a number of actions were taken in the design and installation of the VFD's to minimize the generation of harmonics.

To prove that the project would work, a decision was made to install one 1000 kVA VFD on the platform as a prototype to supply a 600 hp ESP. A second, similar drive was installed approximately 6 months later. In order to minimize distortion on the platform, a decision was made to install 12 pulse drives in place of the standard, less expensive 6 pulse drives. A special, three winding transformer was used consisting of a delta primary, closed polygon secondary, closed polygon tertiary. This transformer allows the connection of either a 6 pulse or 12 pulse drive. See fig. 9. For a six pulse drive, the secondary and tertiary windings are operated in parallel with no phase shift, and for a 12 pulse drive, the secondary and tertiary winding provide the necessary 30 degree phase shift.

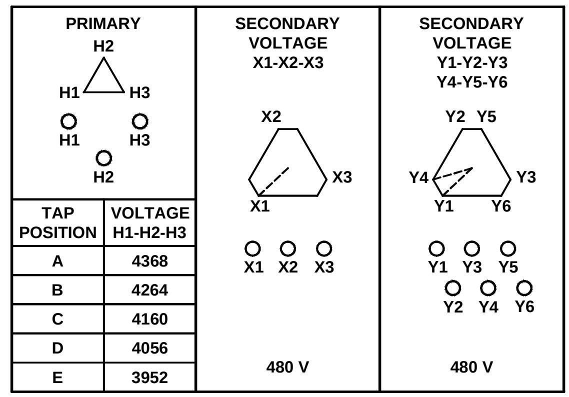


Fig. 9 – Closed Polygon Transformer

Harmonic voltage and current measurements were taken on the platform. Measurements were taken at the point of the generators to see what the effect of the harmonic distortion impact was on the curve produced on the generator and the voltage on the generator bus. The installation of the two, twelve pulse drives was a success. The THDi measured at the generator was found to be in the 1.3% range. See Fig. 10.

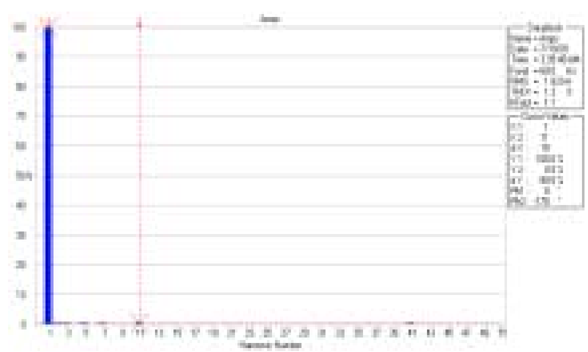


Fig. 10 – Harmonic Current Profile with two drives

The harmonic current distortion from the generators without the drives is shown in Fig. 11 and is surprisingly higher at approximately 1.7%.

The harmonic voltage distortion THDv of the platform with the two drives on line is shown in fig. 12 and was found to be 1.2%.

To show a comparison of the voltage profile from the platform, see Fig 13 which is the Harmonic voltage profile of an office 120 Volt outlet which is located on a system powered by an investor owned electric utility. The THDv from that profile is 3.7%.

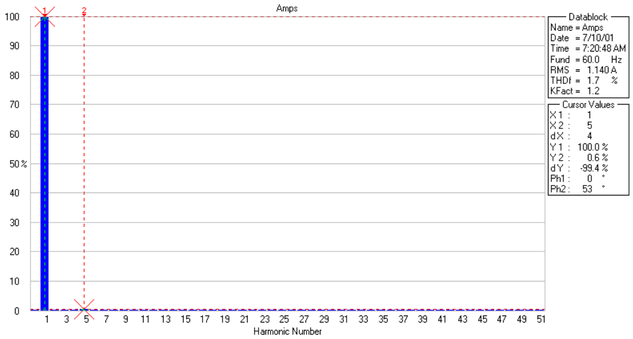


Fig. 11 – Harmonic Current Profile w/o drives

Fig. 12 – Harmonic Voltage Profile with Drives

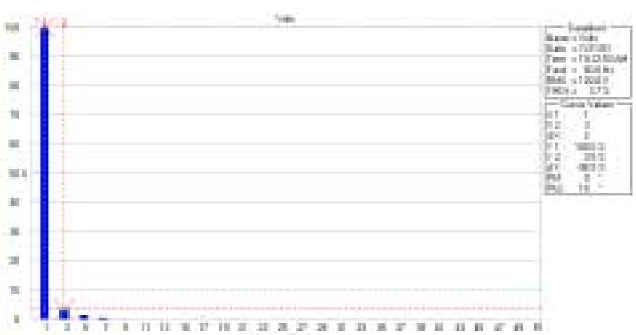


Fig. 13 – Harmonic Voltage Profile of Office Outlet

Additional waveforms and harmonic profiles were taken once drives 3, 4 and 5 were installed. They are shown in appendix 2.

Fig. A2-1 shows the current waveform for one half of VSD1 which was tapped at negative 7.5 degrees. The appearance is that of a typical 6 pulse drive. The harmonic spectrum is shown in Fig. A2-5. The harmonic distortion is 36%.

Fig. A2-2 shows the current waveform for the other half of VSD1 which was tapped at 22.5 degrees. The appearance is also that of a typical 6 pulse drive. The harmonic spectrum is shown in Fig. A2-6. The harmonic distortion is 36.2 %.

Fig. A2-3 shows the composite current waveform for the 12 pulse drive of VSD1. Note the improvement in the current waveform from that of the standard 6 pulse drive. The harmonic spectrum is shown in Fig. A2-7. The harmonic distortion is 8.3% and shows the improvement from the two six pulse drives.

Fig. A2-4 shows the composite waveform for the total upper ESP room which provides some cancellation similar to a 24 pulse drive. The improved current waveform is shown in Fig. 4 with the harmonic spectrum shown in Fig. A2-8. The harmonic distortion is 2.5% and shows the improvement from the single 12 pulse drive of 8.3%.

The following is a summary of harmonic distortion for the various readings:

Measurement Location	THDi
VSD1 – (-7.5 degree)	36%
VSD1 – (+22.5 degrees)	36.2%
VSD1	8.3%
ESP Room Total	2.5%

CONCLUSIONS

While many of the issues discussed in this paper pertain to the petrochemical industry, the results and conclusions can be used in other industries. In particular, the following general conclusions can be made:

- Power systems are designed for a specific frequency, 50 or 60 Hz. The introduction of harmonic currents and voltages into this system will create power system distortions.
- Power system harmonics create additional power system losses and decrease system efficiency which may result in loss of life and premature failure to system equipment.
- The petrochemical industry must understand the sources of power system harmonics and take appropriate actions to minimize harmonic distortion. IEEE 519 is an excellent standard and reference. Following this standard will help minimize problems associated with the generation of harmonic currents.
- Harmonics due to saturable magnetic circuits can be minimized by limiting the nominal operating voltage to a value at or below the knee of the saturation curve.
- Harmonics on variable speed drives can be limited by using drives with more than six pulses. The higher the number of pulses, 12, 18, 24, etc, the greater the reduction in the number and size of harmonic currents.

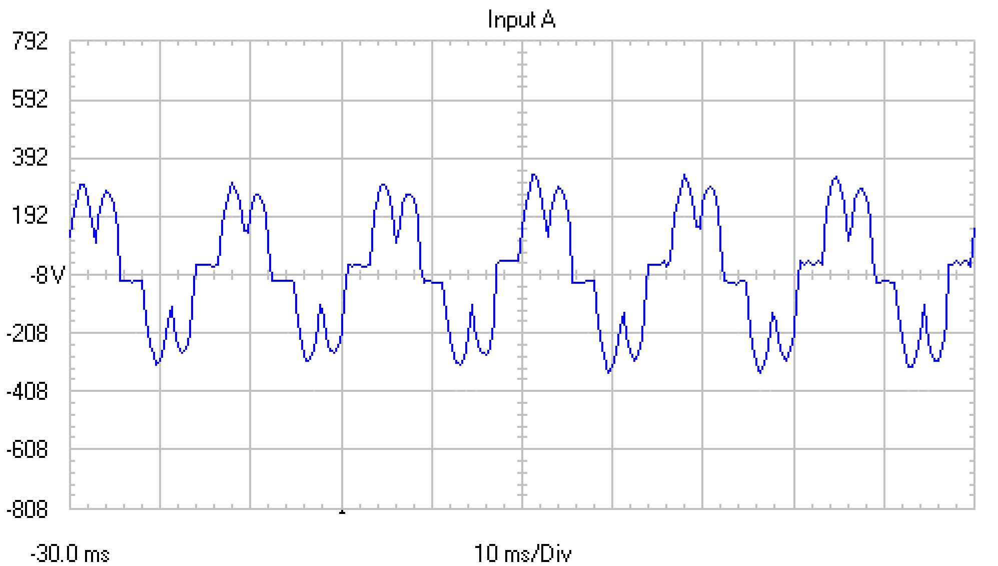
APPENDIX I

Table A1 lists the first 15 harmonics showing its respective classification as a positive, negative or zero sequence component. As mentioned in the main text, positive sequence provides positive torque, negative sequence provides negative torque and zero sequence provides no torque to electrical machinery. The harmonics in bold are the ones normally found in a three phase power system. As previously stated, even harmonics are not normally found in a three phase power system.

TABLE A1
HARMONICS AND SYMMETRICAL COMPONENTS

Harmonic	Symmetrical Component
Fundamental	**Positive sequence (P1)**
Second	Negative sequence (N2)
Third	**Zero sequence (Z3)**
Fourth	Positive sequence (P4)
Fifth	**Negative sequence N5)**
Sixth	Zero sequence (Z6)
Seventh	**Positive sequence (P7)**
Eighth	Negative sequence (N8)
Ninth	**Zero sequence (Z9)**
Tenth	Positive sequence (P10)
Eleventh	**Negative sequence (N11)**
Twelfth	Zero sequence (Z12)
Thirteenth	**Positive sequence (P13)**
Fourteenth	Negative Sequence (N14)
Fifteenth	**Zero Sequence (Z15)**

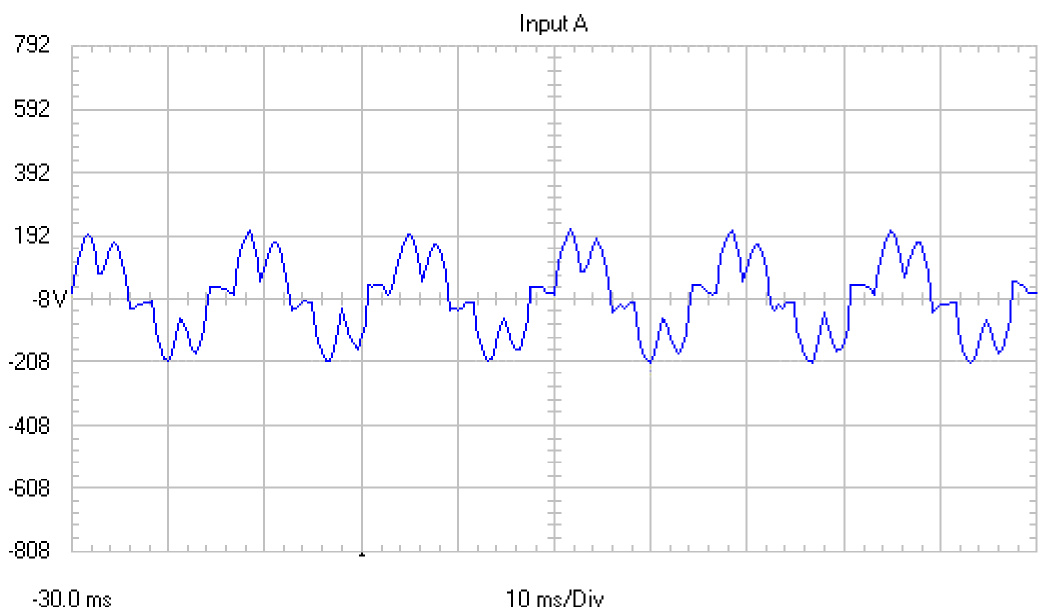
APPENDIX II



VSD1 - "A" Phase Secondary - Negative 7.5 Degrees

Fig A2-1 – Current Waveform of VSD3 @ -7.5 Degrees

Fig. A2-1 shows the current waveform for one half of VSD1 which was tapped at negative 7.5 degrees. The harmonic spectrum is shown in Fig. A2-5 with a THDi of 36%.



VSD1 - "A" Phase Secondary +22.5 Degrees

Fig. A2-2 – VSD3 Current Harmonic Waveform @ -22.5 Degree

Fig. A2-2 shows the second half of VSD 1 which was tapped at the 22.5 position. The harmonic spectrum is shown in Fig. A2-6 with a THDi of 36.2%.

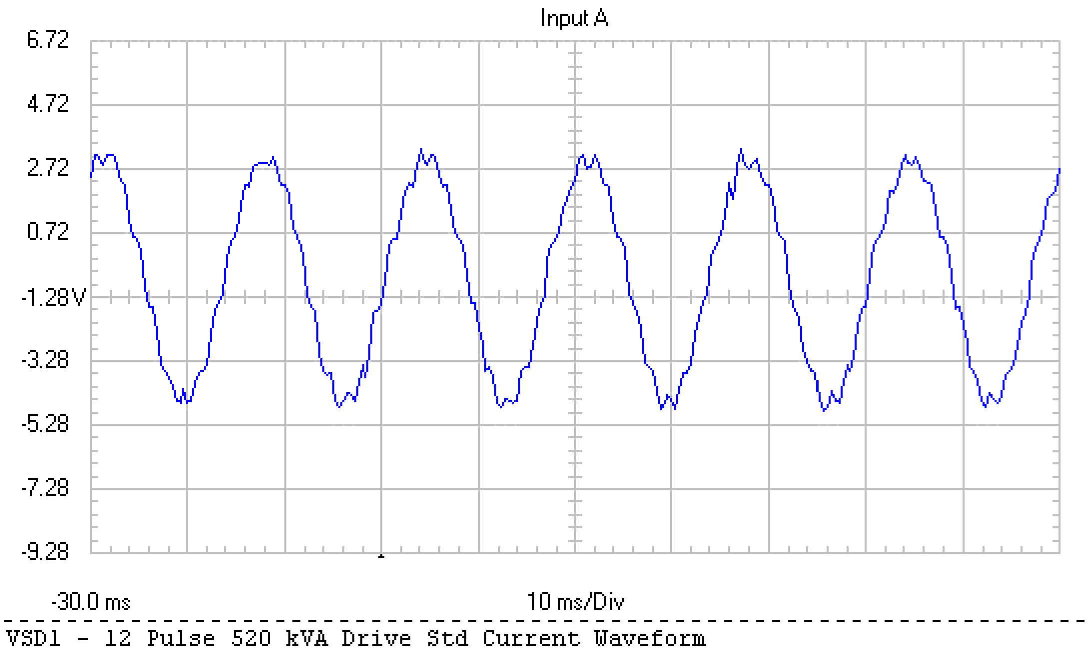


Fig. A2-3

Fig. A2-3 shows the total current input for VSD3 which is a 12 pulse drive. The harmonic spectrum is shown in Fig. A2-7 with a THDi of 8.3%.

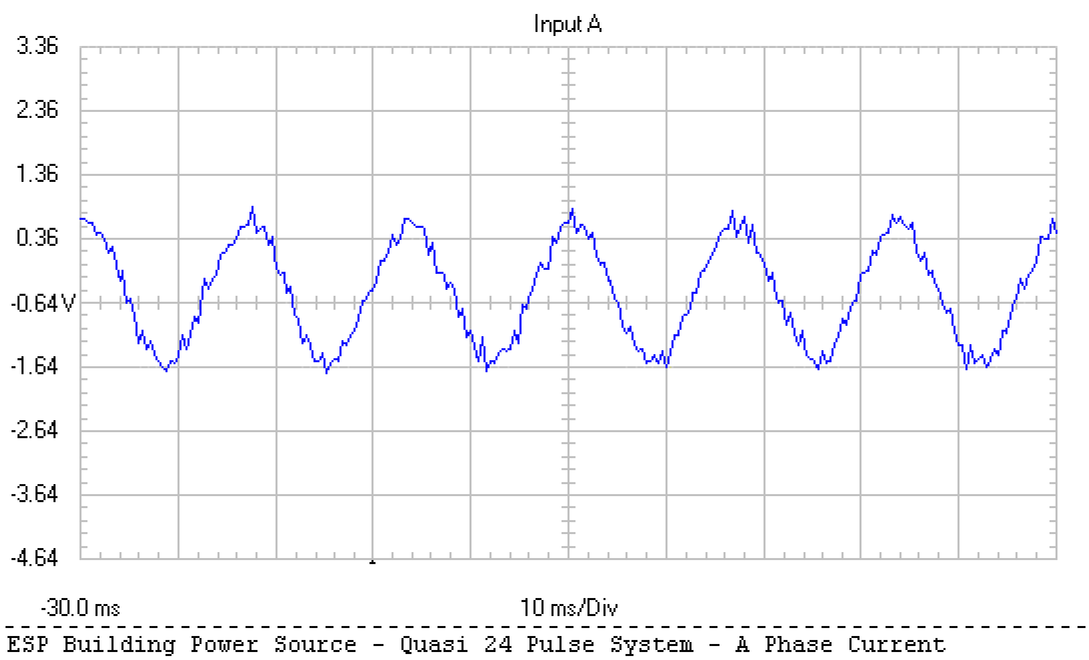
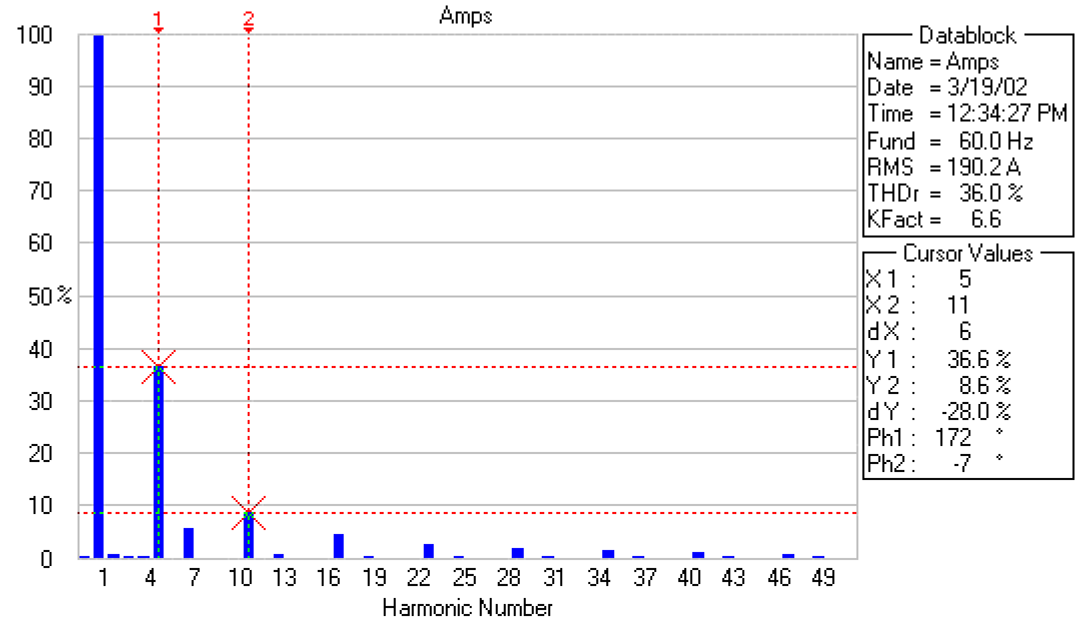


Fig. A2-4

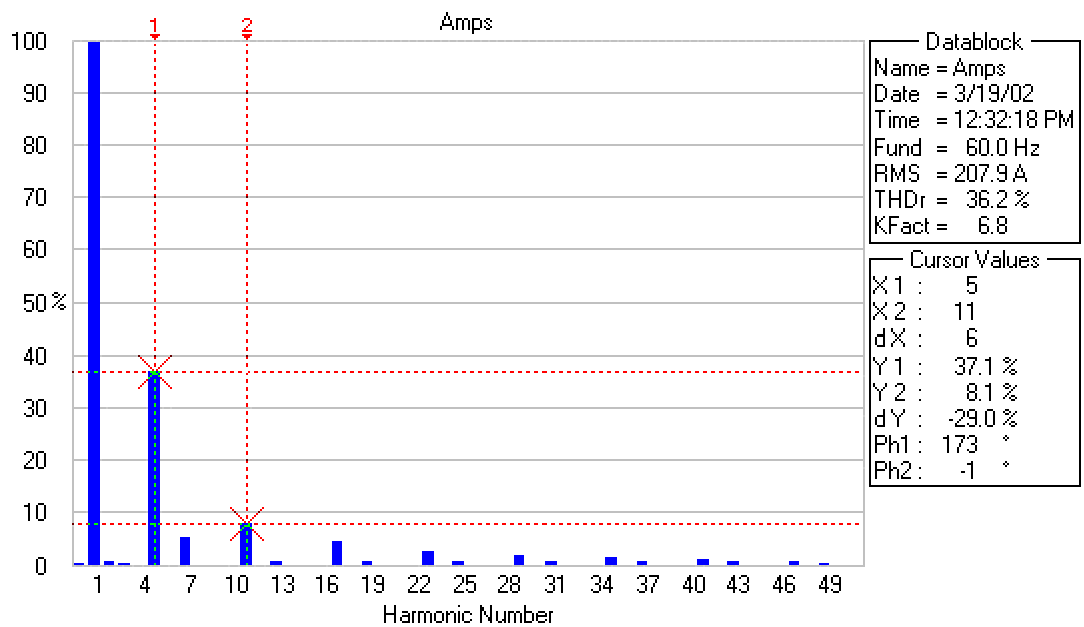
Fig. A2-4 is a measurement of the current going to the upper ESP room. The measurement is for the total current of VD1, VSD2 and VSD3. VSD1 and VSD3 are connected similarly and the connection of VSD2 is such that it provides 24 pulse type of harmonic cancellation. The upper ESP room is set up as a quasi 24 pulse system. The harmonic spectrum is shown in Fig. A2-8 with a THDi 2.5%.



VSD1 - "A" Phase Secondary - Neg 7.5 Degrees

Fig. A2-5

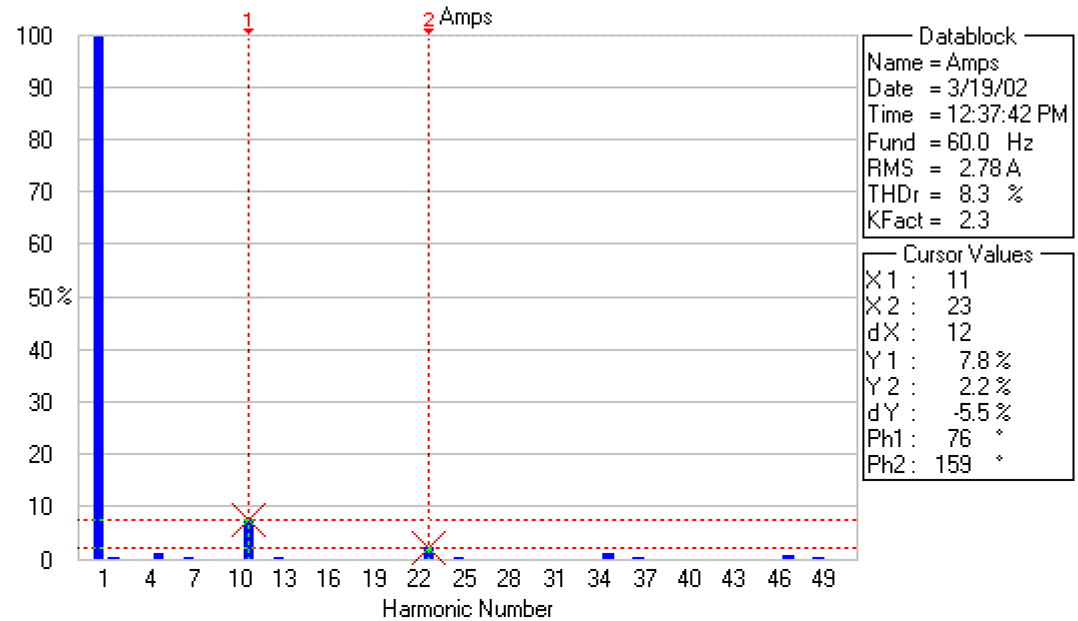
Fig. A2-5 is the harmonic spectrum for the current waveform in Fig. A2-1.



VSD1 - "A" Phase Secondary - 22.5 Degrees Positive

Fig. A2-6

Fig. A2-6 is the harmonic spectrum for the current waveform in Fig. A2-2.



VSD1 - "A" Phase Primary - 45 Amps Primary

Fig. A2-7

Fig. A2-7 is the harmonic spectrum for the current waveform in Fig. A2-3

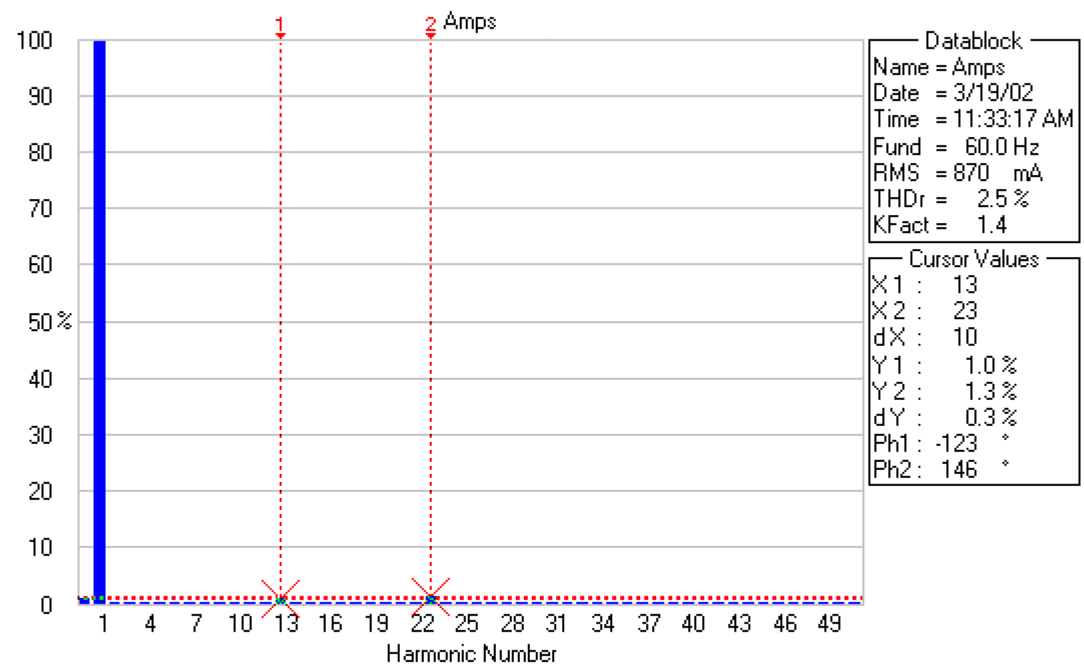


Fig. A2-8

Fig. A2-8 is the harmonic spectrum for the current waveform in Fig. A2-4.

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VITA

John P. Nelson received a BSEE in 1970 from the University of Illinois and an MSEE in 1975 from the University of Colorado. Mr. Nelson performed post graduate studies in business administration at the University of Colorado. From 1969 to 1979, Mr. Nelson was employed by Public Service Company of Colorado (now Xcel Energy) and 1979-1984 by Power Line Models. In 1984, Mr. Nelson founded NEI Electric Power Engineering where he is presently president and principle engineer.

Mr. Nelson has been active with PCIC for over twenty years and has authored or co-authored numerous papers including three prize winning papers. Mr. Nelson has specialized in power system design, system grounding and power system protection. He has taught both undergraduate and graduate courses in electric power engineering as an adjunct professor at the University of Colorado. He has also taught several tutorials for PCIC. He is a registered professional engineer in the states of Colorado, Arizona, California, Louisiana, New Mexico, Utah, Wisconsin and Wyoming.