

Power Quality & Harmonic Distortion on Distribution Systems

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Abstract - With the increase of non-linear loads on utility distribution systems, the voltage and current waveforms are becoming more distorted and the power quality is deteriorating. Since this is becoming a wide spread problem today, and new, more strict, distortion guidelines are under development, utility engineers are having to deal with analyzing and planning for the control of the distortion. This paper introduces some common harmonic analysis techniques and applies them to voltage waveforms recorded on a typical REA transmission and distribution system.

Introduction

The ideal power distribution system delivers, 100% continuous, real power at a constant voltage described by the following equation:

$$p(t) = v(t) i(t) = VI \sin^2(\omega t) \quad (1)$$

Where

$$v(t) = V \sin(\omega t); i(t) = I \sin(\omega t) \quad (2)$$

$$\omega = 120\pi = 377 \text{ rad/sec} \quad (3)$$

In the real world this will never happen. Why?

Factors which influence power quality:

- 1) Outages
- 2) Voltage drop
- 3) Power factor
- 4) Transients (lightning and switching surges)
- 5) Non-linear steady-state load conditions (harmonics).

Power system engineers have been dealing with outages, voltage drop, power factor, and transient conditions since the invention of the first AC distribution system back in the early 1900's. Adverse power system harmonics caused by the installation of non-linear type loads on the distribution system has become an increasing concern to utilities in the 1970's and 1980's. The following paper introduces power system harmonic analysis techniques and applies them to a typical REA transmission and distribution system.

Harmonics

Any steady-state periodic time domain waveform can be expressed by an infinite summation of sinusoidal waveforms at integer multiples of a fundamental frequency.

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(n\pi \frac{t}{L}) + b_n \sin(n\pi \frac{t}{L}) \quad (4)$$

$$a_n = \frac{1}{L} \int_{-L}^L f(t) \cos(n\pi \frac{t}{L}) dt \quad (5)$$

$$b_n = \frac{1}{L} \int_{-L}^L f(t) \sin(n\pi \frac{t}{L}) dt \quad (6)$$

where

$f(t)$ = Time Domain Function

n = Harmonic Index

L = Length of one Cycle in Seconds.

Joseph Fourier first used this idea to solve the heat conduction equation in 1807. But certain mathematicians in the French Academy of Sciences in Paris, such as Laplace, Lagrange, and Legendre, who reviewed Fourier's work rejected it because of lack of rigor and proof of convergence. Finally, in 1822, after two more revisions, Fourier published his *Theorie Analytique de la Chaleur* that contained, among other things, the Fourier series, and the Fourier integral [1].

The definition of power system harmonics is based on the application of the Fourier transform and superposition to voltage and current waveforms. As implied earlier in equation (1), an ideal power system contains only the first harmonic - 60 Hz. When non-linear load conditions exist, the distortion of the voltage and current waveforms can be explained and analyzed much easier using Fourier transforms.

Measuring and Calculating the Harmonics

There are many ways to obtain the Fourier transform of a voltage or current waveform on a power system. The easiest way is to use a spectrum analyzer and measure the harmonics.

directly in an on-line mode. Another popular method is to sample and store the time-domain waveforms as discrete data points and compute the harmonic components digitally using a microprocessor in an off-line type mode. With either method it is necessary to condition the signal properly by reducing the relative magnitudes of the waveforms to levels appropriate to the testing equipment being used and filtering out any high frequency components above the Nyquist frequency so that aliasing errors are not introduced into the output. Aliasing is a higher frequency component, above twice the sampling frequency, taking on the appearance of a lower frequency component. A popular technique for computing the harmonic magnitudes and phase angles of a sampled time domain waveform is a Discrete Fourier Transform (DFT):

$$F_n = \frac{1}{N} \sum_{k=0}^{N-1} f_k e^{-j2\pi kn/N} \quad (7)$$

where

- F_n = Fourier Coefficient of the n th Harmonic
- f_k = Data Point of the k th Sample
- N = Total Number of Samples per 60 Hz Cycle
- n = Harmonic Index
- k = Data Point Index.

Using a 5 kHz sample rate on a 60 Hz waveform means that 83.333 samples are taken for one complete cycle. Since the total number of samples (N) used in the DFT must be an integer, 83.333 must be rounded down to 83. Rounding in this fashion is referred to as windowing the time-domain function and it produces leakage errors in the output of the harmonic components when compared to the continuous-time Fourier transform [2], but the error is not significant compared to the levels of harmonics being measured. Also, the errors associated with the PT and CT circuits used to condition the signal vary but are usually higher than the leakage errors. The maximum relative error caused by leakage for any harmonic component is less than $\pm 0.6\%$ for 5 kHz and $\pm 0.3\%$ for 10 kHz sample rates on a 60 Hz waveform. This error can be reduced further by increasing the sample rate or increasing the window size. For harmonic analysis of voltage and current waveforms on a power system the 5 kHz sample rate produces very accurate results with a minimum amount of computational effort. On an 80386/387-33 MHz computer, the DFT takes less than 0.5 seconds to compute the harmonic magnitudes, phase angles, percent harmonic distortion of each component (HD), and total harmonic distortion (THD) out to the 41st harmonic. On an 80286/287-10MHz computer, it takes less than 2 seconds.

The HD and THD are defined as follows:

$$HD_n = \frac{|F_n|}{|F_1|} \quad (8)$$

$$THD = \frac{1}{|F_1|} \sqrt{\sum_{n=2}^{N/2} |F_n|^2} \quad (9)$$

THDv = Total Harmonic (voltage) Distortion
THDi = Total Harmonic (current) Distortion.

Computing the harmonics using a Fast Fourier Transform (FFT) is widely used when computational time is important, but the sample rate must be adjusted to produce integer powers of two (ie. 32, 64, 128, 256 etc.) data samples per 60 Hz cycle. It is also possible to use zero padding at the end of the sample set to adjust the number of samples to equal an integer power of two when the sample rate cannot be adjusted easily in the test equipment [2]. Yet, this technique affects the magnitudes and phase angles of the harmonic components and additional computational effort must be expended to rescale the values.

Sources of Harmonics

Since harmonic distortion is caused by non-linear elements connected to the power system, anything that has non-linear characteristics will cause harmonic distortion. There are many kinds of harmonic producing loads available; it can be argued that most loads have some degree of non-linearity, but in most cases their effect on the distribution system can safely be neglected. Here are some examples of common sources of power system harmonics some of which never cause serious problems [3]:

- 1) Transformer saturation
- 2) Transformer inrush
- 3) Transformer neutral connections
- 4) MMF distributions in AC rotating machines
- 5) Electric arc furnaces
- 6) Fluorescent lighting
- 7) Computer switch mode power supplies
- 8) Battery chargers
- 9) Imperfect AC sources
- 10) Static VAR compensators
- 11) Variable frequency motor drives (VFD)
- 12) DC converters
- 13) Inverters
- 14) Television power supplies.

One of the strongest sources of harmonic distortion are large VFD type loads. These loads not only produce a lot of harmonic distortion, the amount varies with time. It is because of these large harmonic producing loads and the effect they have on power systems that harmonic distortion limits are being developed.

IEEE Voltage Distortion Limits [4]

	[2.3kV-69kV]	[69kV-138kV]	>138kV
HD	3.0%	1.5%	1.0%
THDv	5.0%	2.5%	1.5%

Note that the term HD references the relative Harmonic Distortion (HD) of a single harmonic frequency component to the fundamental frequency component - see (8).

Harmonic Distortion Examples

The following examples show how harmonic distortion produced on a distribution system from VFD type loads can affect the voltage waveforms and the overall performance and quality of power delivered to all customers on the system.

Referring to the one-line diagram in Fig.1, a REA transmission and distribution system is serving several substations, one of which supplies four customer owned 24.94 Kv distribution feeders connecting to several large

VFD loads. Three of the feeders have power factor correction capacitor banks that total 3.6 MVAR.

Fig.2 shows a time-domain voltage waveform taken on the supply side of a 600 KVA, 480 V, VFD under a 350 A load. The data was collected using a digital oscillograph recorder set on a 5 kHz sample rate and connected to the secondary of a single phase, 480-120 VAC, control power transformer. Also shown in Fig.2 is the frequency domain magnitude and phase harmonic components.

Fig.3 was taken at the same VFD but all three distribution capacitor banks were switched off-line during the measurement. Though the THDv is approximately the same for both waveforms, there is a very noticeable difference in appearance between the two. When the capacitors are on-line, Fig.2, the high frequency harmonic components are not as pronounced, the peak voltage is greater than the nominal 170 V level, and the 5th harmonic component is 135% greater in magnitude. The reduction of the high frequency components also can be seen in the time domain waveform of Fig.2 by noting the absence of the many fine voltage spikes contained in Fig.3.

At bus #1, two 24.94 kV feeders are serving approximately 5 MVA of connected VFD loads and 1 MVA of miscellaneous induction motor loads. Fig.4 and Fig.5 were taken while the distribution capacitor banks were on and off-line, respectively. The measurement was taken on the secondary of a 14.4 kV to 120 V set of PT's used for the protective relaying and metering circuits of the main substation. When the capacitor banks were on-line, the PT secondary voltage was approximately 200 V peak or a 18% over-voltage. Note that the 5th harmonic voltage is adding to the peak of the fundamental to cause the over-voltage condition. The additive property of the 5th harmonic voltage is not typical at all points on the distribution system.

While the 24.94 kV capacitor banks were on-line, Fig.6 was recorded at a common 120 Vrms, single phase, wall outlet serving an office building computer room. The office building transformer bank is connected to Feeder #4. Since the 5th harmonic is negative sequence in nature for a balanced set of sequence component harmonics, it is shifted by a positive 30 electrical degrees through a Wye-Delta transformer bank (high-voltage to low-voltage) instead of the negative 30 degree shift for positive sequence harmonics. The 30 degree shift can align the harmonic sequence components so that the peak of the 5th subtracts from the peak of the fundamental and causes a pronounced notch in the waveform. It is possible to approximate the waveform in Fig.6, since the only predominant harmonics are the 1st and the 5th, from the DFT harmonic magnitudes and phase angles as follows:

$$v(t) = 2|F_1|\sin(\omega t) + 2|F_5|\sin(5\omega t + \phi_5) \quad (10)$$

where

$$\begin{aligned} \omega &= 377 \text{ rad/sec} \\ F_1 &= 86.3 \text{ V}; F_5 = 10.1 \text{ V}; \\ \phi_5 &= \theta_5 - 5\theta_1 = [166.8^\circ - 5(-82.7^\circ)]\pi/180^\circ \\ &= 508.3^\circ. \end{aligned}$$

The exact method for calculating the time-domain discrete data points from a modified

version of the harmonic magnitudes and phase angles is the inverse DFT:

$$f_k = \sum_{n=0}^{N-1} F_n e^{j2\pi kn/N}. \quad (11)$$

Harmonic Penetration

So far, the example waveforms have been associated with the 24.94 kV distribution system. The harmonic voltage distortion will propagate back into the transmission system and diminish in magnitude as the ratio of harmonic load current to non-harmonic load current diminishes. Also, as the voltage measurements are taken closer to a voltage source (ie. very high short circuit level; very low equivalent impedance) the harmonic voltage distortion will approach zero. This is true only when the system distributed capacitance or other power factor correction capacitor banks are not in a parallel resonant condition at another location in the system.

Fig.7 and Fig.8 were recorded approximately 12 miles from the customer owned VFD feeders under the conditions of the three capacitor banks on and off-line, respectively. The measurements were made on the secondary of 7.2 kV to 120 V relaying PT's. Similar properties can be detected in these waveforms as can be detected in the others:

- 1) When the capacitors are on-line, the high frequency harmonic components are not as pronounced.
- 2) The peak voltage is greater than the nominal 170 V level.
- 3) The 5th harmonic component is greater in magnitude.
- 4) The THDv is significantly higher.

This effect is caused by the interaction of the three power factor correction capacitors on the 24.94 kV distribution feeders and the equivalent transmission system inductance.

Parallel Resonance

For a capacitance and inductance connected in parallel, resonance between the elements occurs when the driving frequency is such that the equivalent impedance is a maximum. Under linear conditions, when no harmonics are being generated in the system, there is no frequency above the fundamental that can excite the system into parallel resonance. When non-linear conditions exist, such as those caused by VFD's, frequencies may be present at or near the resonant frequency. If this occurs, the voltage waveform magnitudes in the system can be amplified well above the nominal levels.

$$\frac{f_R}{f_1} = \sqrt{\frac{1}{LC}} = \sqrt{\frac{S_{sys}}{Q_c}} \quad (12)$$

where

$$\begin{aligned} f_R &= \text{Parallel Resonant Frequency (Hz)} \\ f_1 &= \text{Nominal System Frequency (60 Hz)} \\ L &= \text{System Equivalent Inductance (H)} \\ C &= \text{System Equivalent Capacitance (C)} \\ S_{sys} &= \text{System Fault Level (VA)} \\ Q_c &= \text{System Connected Capacitance (VAR)}. \end{aligned}$$

Since this equation is only good for one of each kind of element, it should not be expected that it will give the correct resonant harmonic frequencies for systems containing a complex inter-connection of many capacitances and inductances. Still, making some reasonable simplifying assumptions and using common sense, the dominate resonant harmonic frequency can be approximated fairly well.

As an example, the approximate short circuit level range at the 24.94 kV buses in Fig.1 when the bus tie switch is closed is 89 MVA to 107 MVA depending on whether the co-generator is on-line. The total connected capacitance on the combined feeders is 3.6 MVAR. Using (12), the parallel resonant frequency falls in the range from 298 Hz to 327 Hz. Since 6-pulse type VFD's generate harmonic frequencies according to

$$6k \pm 1, \quad (13)$$

where

$$k = 1, 2, 3, \dots$$

the predominate frequencies are

300 Hz, 420 Hz, 660 Hz, 780 Hz, ... etc.

For this example, the 5th harmonic (300 Hz) frequency component generated by the VFD's is exciting the 24.94 kV distribution system into parallel resonance. Since parallel resonance occurs at an impedance maximum, the 5th harmonic voltage is amplified by the 5th harmonic current flowing through the high 5th harmonic impedance of the network; this effect is causing the 18% overvoltage recorded on Bus #1: Fig.5.

To examine the system impedance at the fifth harmonic, it helps to see what the impedance frequency response looks like with the capacitor banks on and off-line. Fig.9 shows the system impedance magnitude as a function of frequency. When the capacitor banks are connected on-line, the frequency response changes to that shown in Fig.10. Note that the impedance maximum point corresponds closely to the 5th harmonic. Since the VFD is essentially a current source at harmonic frequencies given by (13), the fifth harmonic current must flow through the 5th harmonic impedance; therefore, the 5th harmonic voltage drop on the system is a maximum when the capacitor banks are on-line. It appears to be amplified.

At frequencies above the 5th harmonic, the parallel combination of the system impedance with the capacitor impedance is dominated by the capacitor. When the capacitor banks are on-line, the high frequency components produced by the VFD's flow mostly through the low impedance of the capacitor banks. This helps explain why the waveforms (Fig.2 and 4) appear to be much smoother when the banks are on-line. It also explains why capacitor banks experience higher heating effects when exposed to harmonic producing loads. Premature fuse melting on capacitor banks occurs from the long-time heating effects of the harmonic current components, above the parallel resonant frequency, flowing through the fuse elements.

Concerns for Distortion

Since the voltage amplification on the system is on the order of 18%, increased insulation stress on equipment will 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 20%. If capacitors are subjected to prolonged voltage peaks above their rated values, reduced insulation life as well as total failure is very likely to occur. Electric motors and generators are affected in the same way.

The transformer banks in the system that have to conduct the harmonic currents will have higher heating losses. Since this will cause higher temperatures, the insulation life will be degraded compared to an equivalent 60 Hz load current.

Since the 5th, 11th, 17th, 23rd, etc. harmonic components are negative sequence, additional heating losses and negative sequence harmonic torques will be present in all rotating machinery connected to the system where the harmonic distortion is significant.

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, and the PT and CT coil 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 aliasing, 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 crossing points. The waveforms shown in Figs.2 and 3 are good examples of this. An electronic power factor or VAR switching control on a distribution capacitor bank is a typical example of a device that depends on normal, 60 Hz, zero crossings.

Conclusion

There have been many papers and publications written on power system harmonic related issues. The information presented in this paper is by no means new or unique. The purpose of this paper was to introduce harmonics in the light of power quality and give an introduction of power system harmonics to engineers who have had little exposure. Basic definitions on computing harmonics, harmonic distortion, and parallel resonances were given to help support the discussion of the example waveforms taken on a typical REA transmission and distribution system. Common harmonic producing sources and basic concerns for the distortion produced by non-linear loads has also been given.

References

- [1] P. O'Neil, "Advanced Engineering Mathematics," 2nd ed. Wadsworth, Belmont, CA, 1987.
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- [3] J. Arrillaga, D. A. Bradley, P. S. Bodger, "Power System Harmonics," 1st ed. Wiley, New York, 1985.
- [4] C. K. Duffey, R. P. Stratford, "Update of Harmonic Standard IEEE-519: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems." IEEE Transactions on Industry Applications, Vol. 25, No. 6, November/December, 1989.

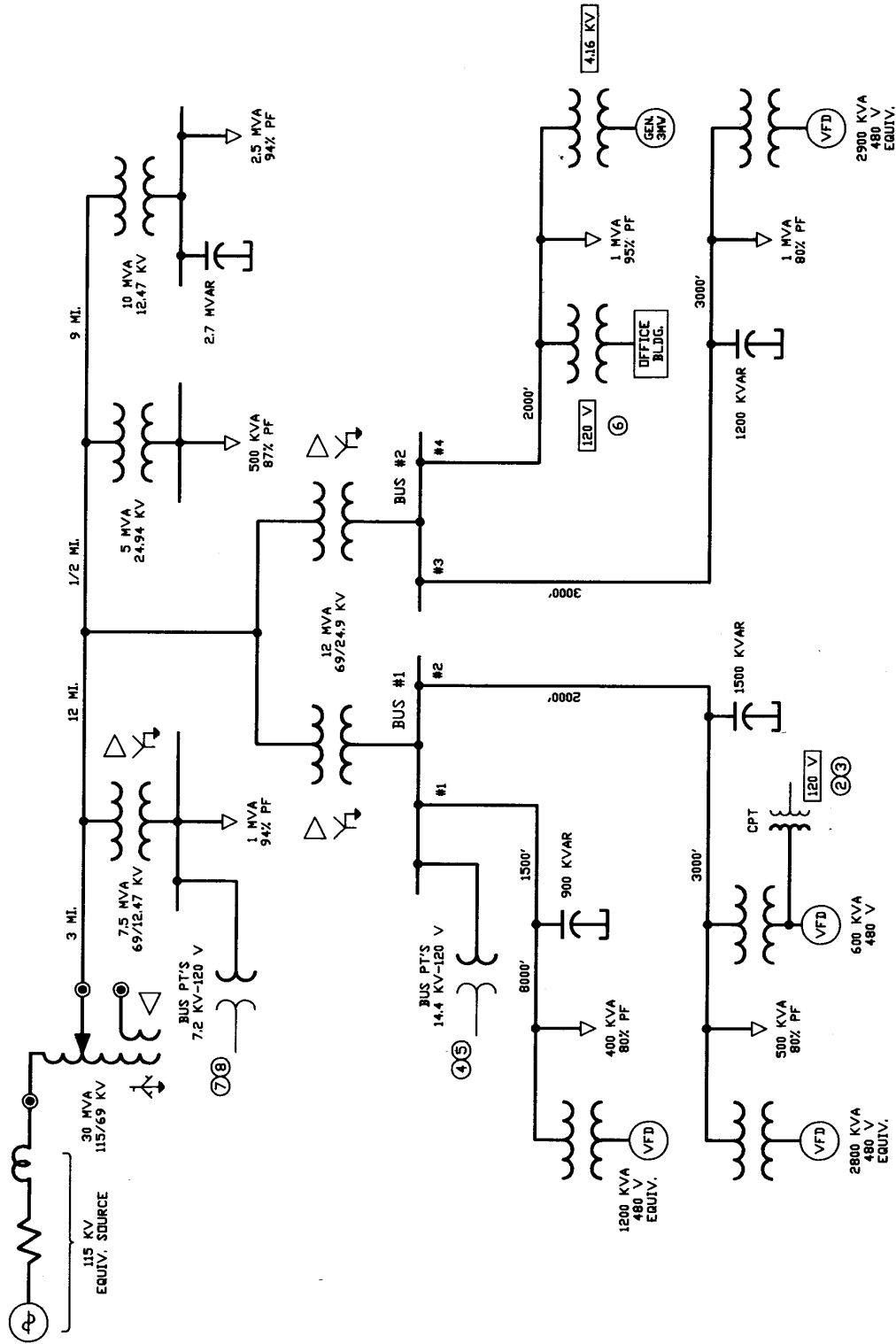


Figure 1
 REA transmission and distribution system serving
 customer owned VFD loads. The voltage waveforms
 shown in the following figures were measured at
 the indicated locations.

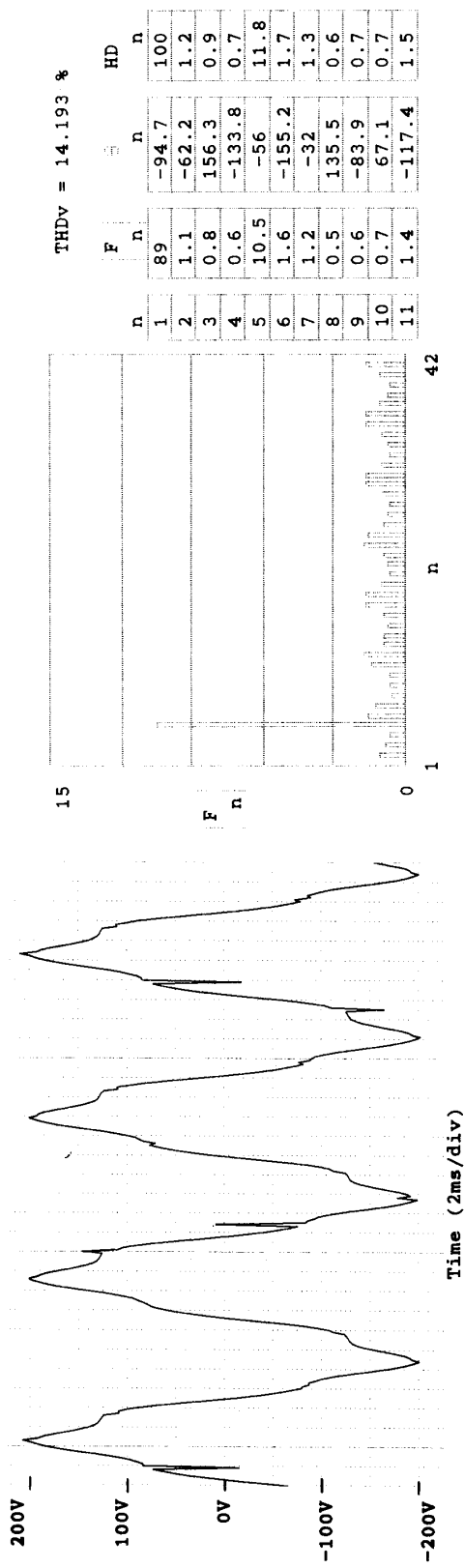


Figure 2
120Vrms waveform taken on the 480-120V CPT on a 600 kVA, 480 V VFD. Distribution capacitor banks on-line. Note, the 60 Hz frequency component is not shown.

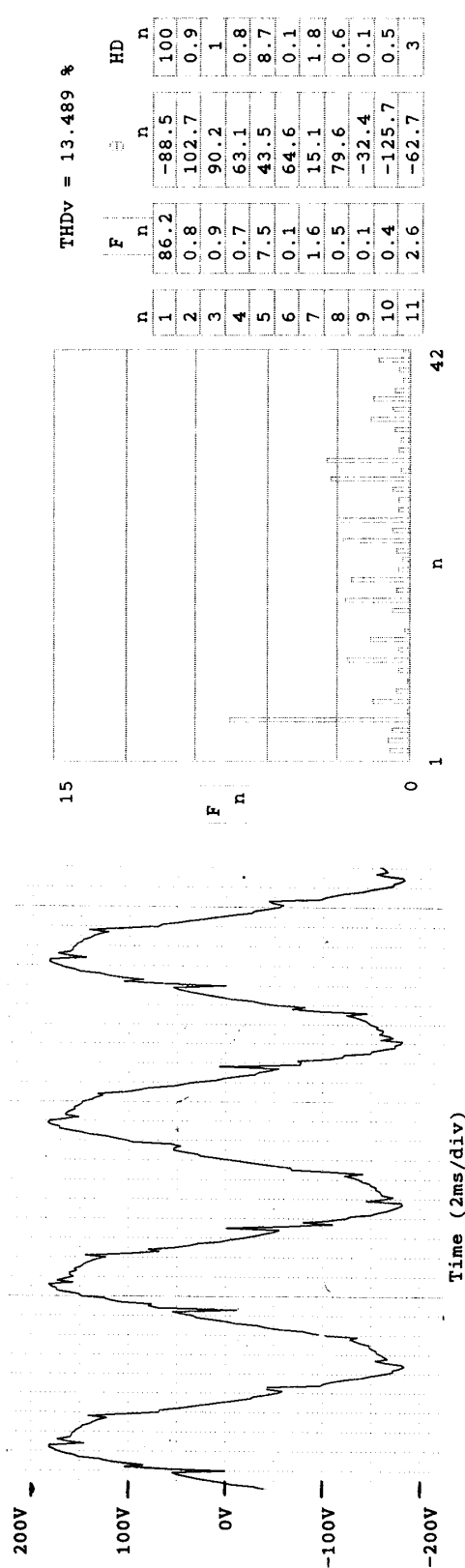


Figure 3
Same as Fig. 2, but distribution capacitor banks off-line.

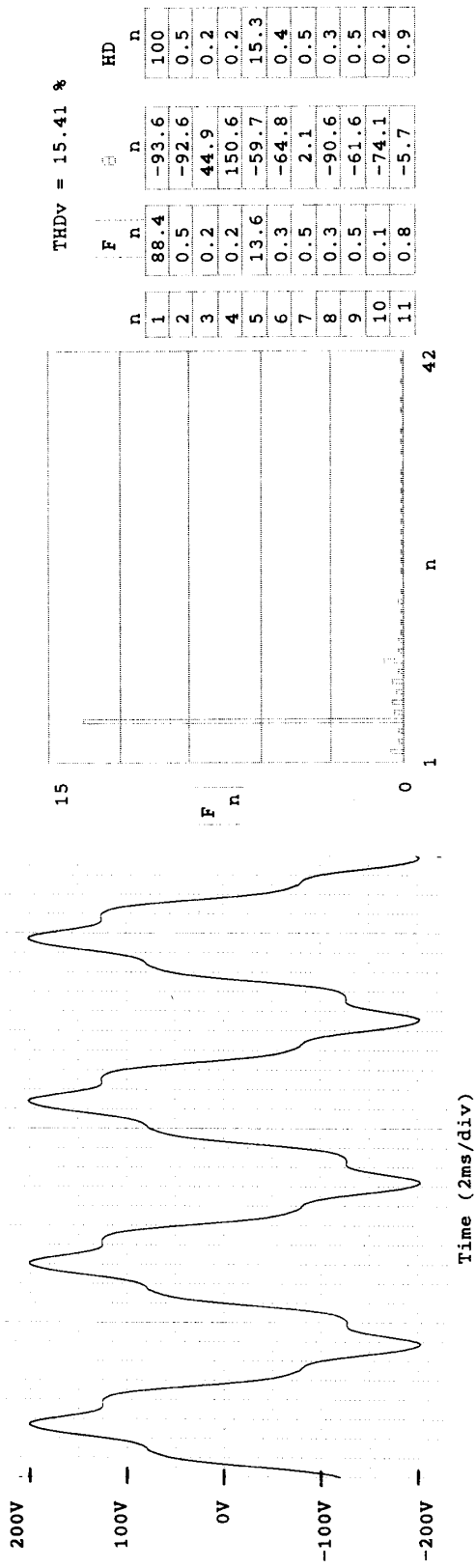


Figure 4
120Vrms waveform taken at the 14.4kV-120V PT's connected to Bus #1. Distribution capacitor banks on-line.

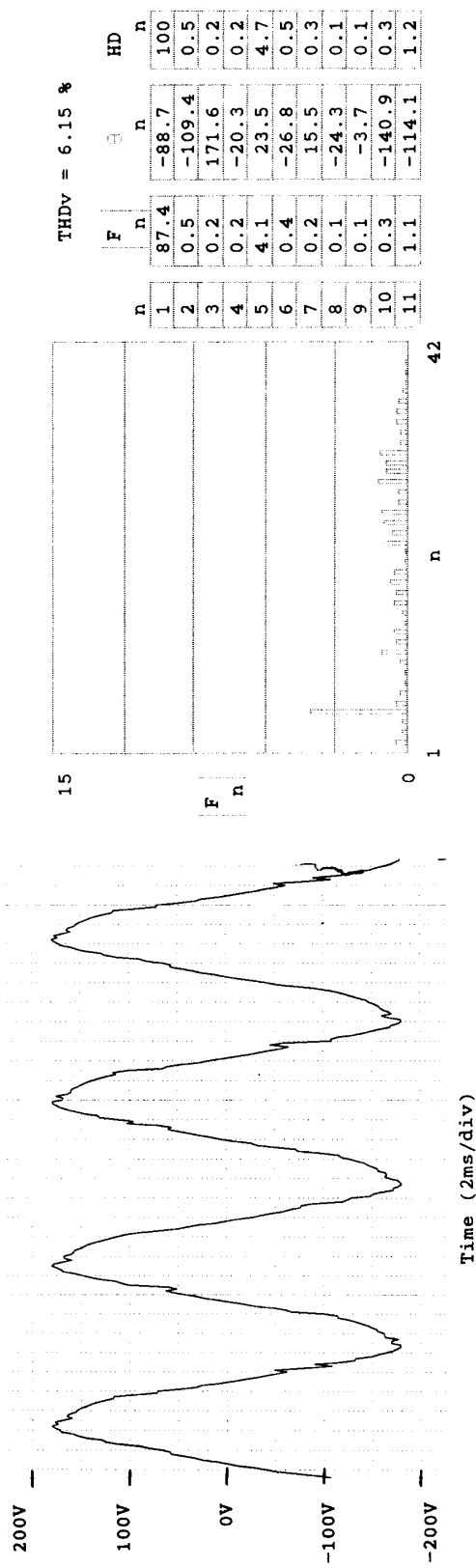


Figure 5
Same as Fig. 4, but distribution capacitor banks off-line.

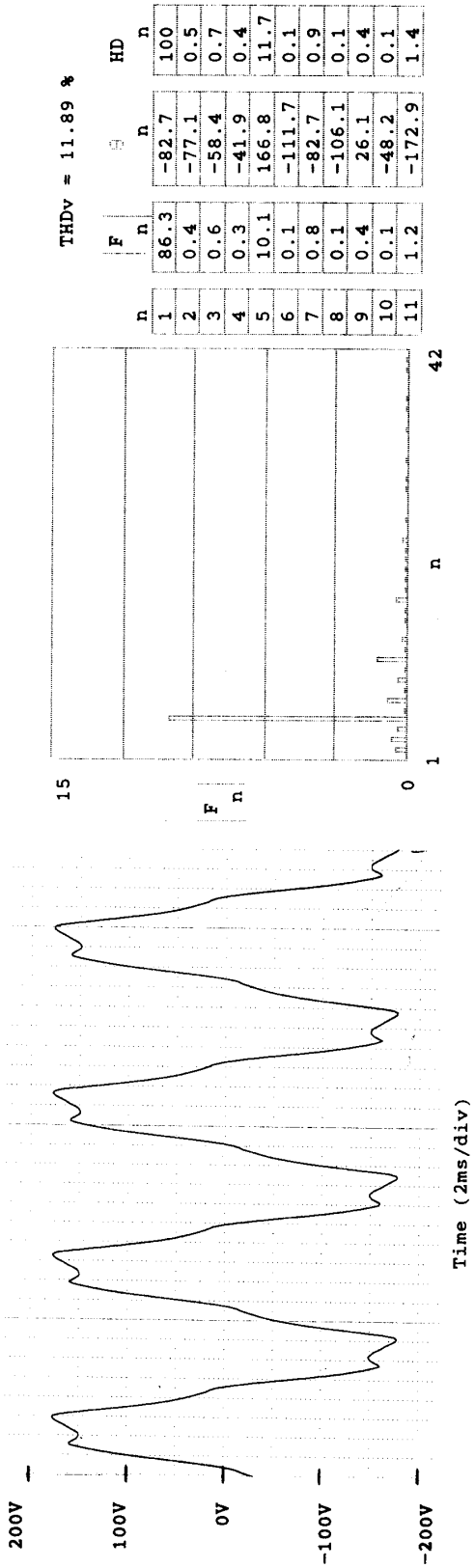


Figure 6
 120Vrms waveform take at a common wall outlet
 serving an office building computer room.
 Distribution capacitor banks on-line.

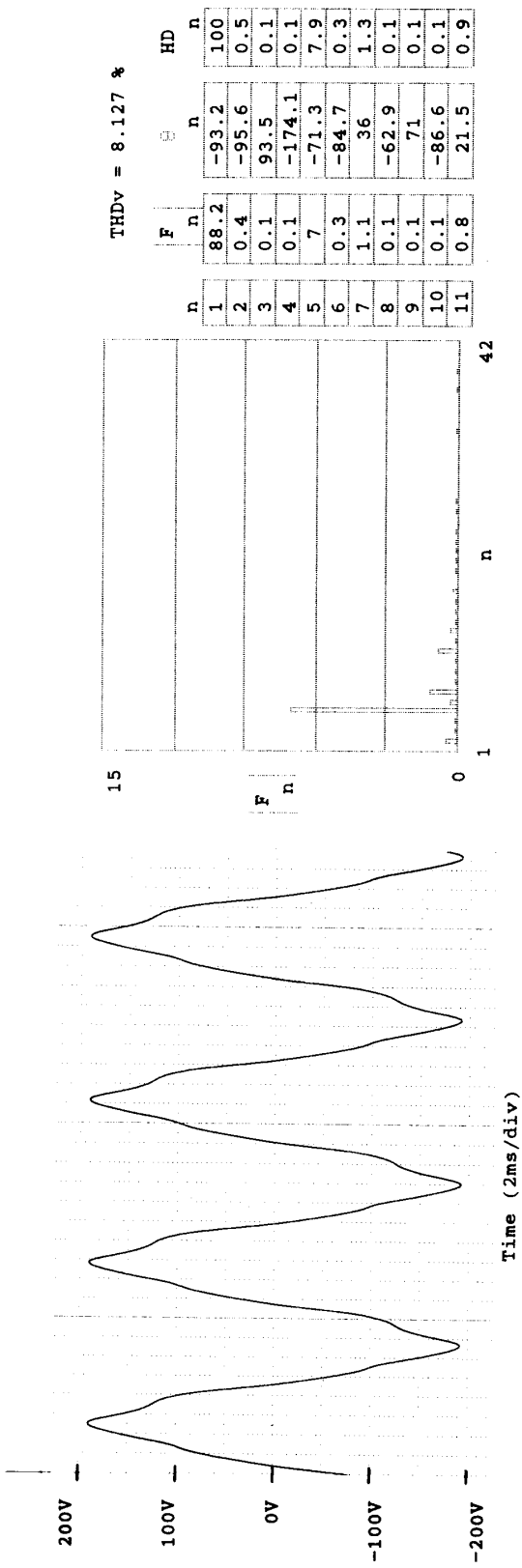


Figure 7
 120Vrms waveform taken at the 7.2kV-120V PT's connected to a distribution bus located 12 miles away from the harmonic source. Distribution capacitor banks on VFD feeders on-line.

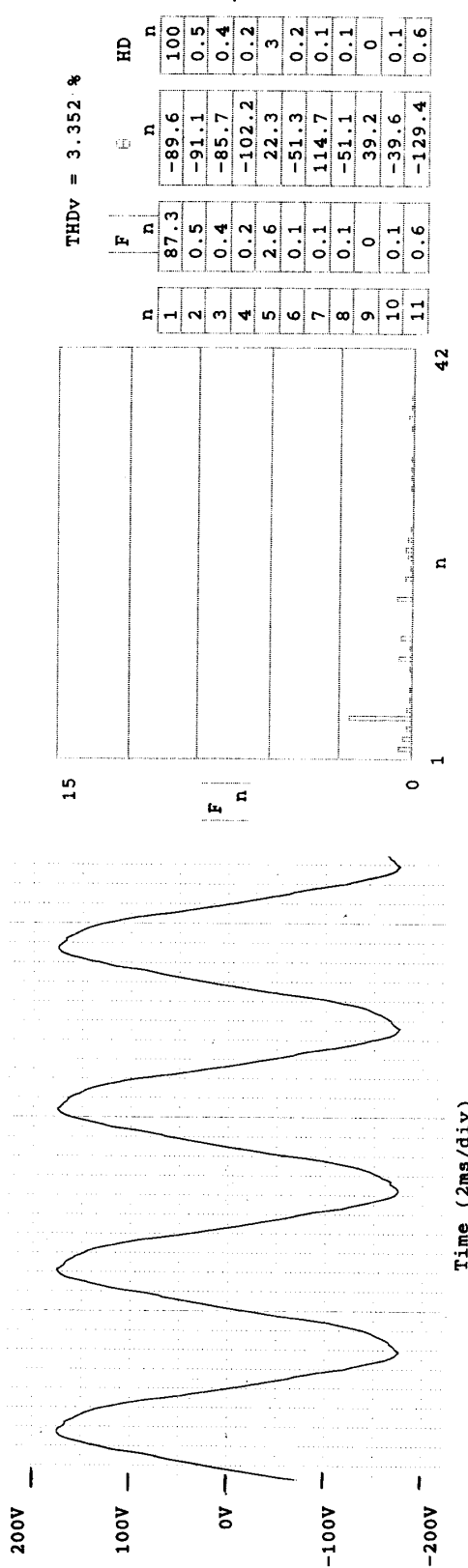


Figure 8
 Same as Fig. 7, but distribution capacitor banks off-line.

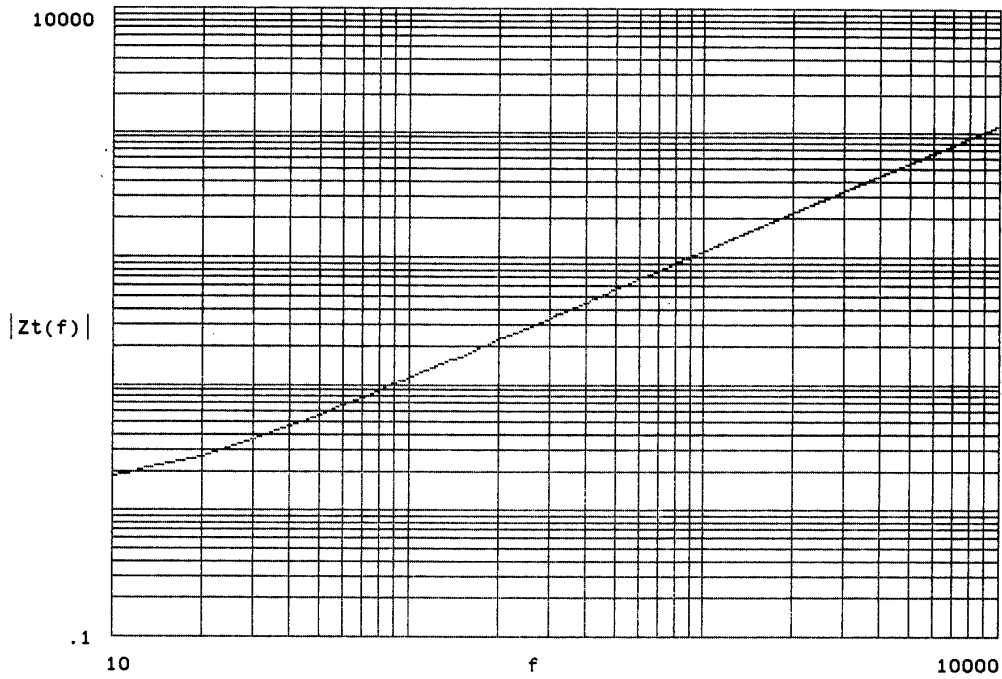


Figure 9
 Equivalent system impedance vs. frequency looking into the 69kV transmission system from the 24.94kV distribution buses with bus tie switch closed and capacitor banks off-line.

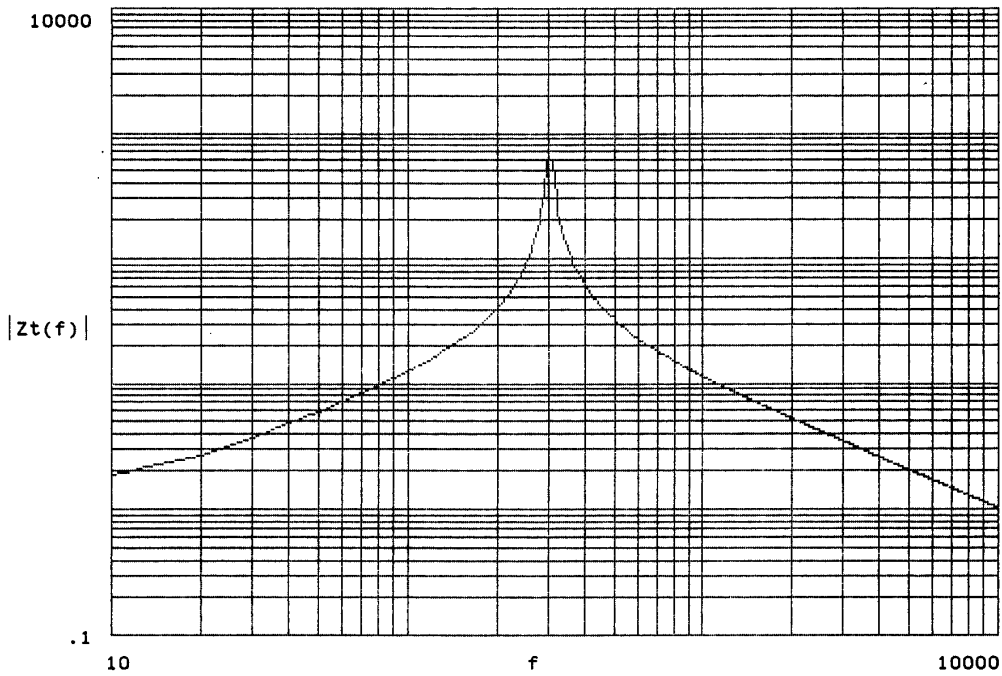


Figure 10
 Same as Fig.9, but capacitor banks on-line.

Conference Paper



POWER QUALITY & HARMONIC DISTORTION ON DISTRIBUTION SYSTEMS

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