Final Report

# POWER SYSTEM HARMONIC STUDY

# FOR

# PEACH BOTTOM NUCLEAR POWER PLANT

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## Section 1

## INTRODUCTION

The Peach Bottom Nuclear Power Plant, owned and operated by Philadelphia Electric Company (PECO), is comprised of two 1280 MW generating units. Each unit employs two 8000 hp variable speed recirculation pumps (total of 4 pumps) which have been powered by 9000 hp motor-generator (M-G) sets since the units were originally installed. Maintenance costs associated with the M-G sets are a matter of concern to PECO, resulting in their planned replacement by 8250 hp static adjustable speed drive (ASD) equipment. Since static motor drives do not draw purely sinusoidal load currents from the AC supply system, the issue of power system harmonic distortion arises.

Power system harmonics are sustained currents and voltages having frequencies which are whole number multiples of the base system operating frequency and come about as a result of the non-linear characteristics of power system loads. One major source of harmonics in modern industrial power systems is the solid state, phase controlled, line commutated, ac-dc converter, such as the rectifier portion of the proposed ASD equipment. A simplified view of such a device is that it creates dc by drawing power selectively on a phase-by-phase basis from the ac supply. Through the action of the full-wave rectifier, nonsinusoidal alternating current is typically drawn from the ac power system.

The waveform of the input current drawn by a static device depends upon the type of power converter employed. Dc motor controllers typically produce a constant dc output current, under steady load conditions, which results in a square wave input current. Although variable frequency ac output currents are generated by the proposed ASD drives, they typically draw nearly square wave input currents from the supply system, due to the smoothing effects of the dc link within the drive. Other types of variable frequency ac drives or dc drives which do not supply constant output current may draw heavily distorted input currents. In any case, Fourier analysis allows these steady state nonsinusoidal input currents to be described as the sum of a series of harmonic sinusoidal components. Since power system generators produce mainly the fundamental frequency and only the fundamental component carries usable energy, it is pretty accurate to describe nonlinear loads as sources of harmonic current injection into the system.

The typical square wave input current can be reduced into a Fourier series consisting of the fundamental plus all odd harmonics. In the most general case of balanced three phase drives, the third harmonic component and its multiples disappear leaving only the first, fifth, seventh, eleventh, etc. In more complex drive configurations (i.e., 12-pulse) some of these components can be reduced through cancellation. Since Kirchoff's laws always apply, harmonic currents which are injected into the system will circulate and must be dealt with by power systems engineers.

Although harmonic currents are injected by many types of loads, they are often not really harmful. It is true that the presence of harmonic currents causes the heating value current to be greater than the fundamental frequency load current, but the difference is normally small. The theoretical maximum value of each of the harmonic currents in a pure square wave is equal to the inverse of the harmonic order. Thus, on a typical three phase, six pulse, dc drive, the effective, or "root sum square (RSS)", current will be only 4% greater than the fundamental component:

$$I_e = SQRT(1^2 + (1/5)^2 + (1/7)^2 + (1/11)^2 + (1/13)^2 + \ldots) = 1.04$$

Such harmonics are unlikely to cause a conventional thermal problem unless power distribution equipment is loaded at near rated levels. In such cases, the effects of harmonic losses must be taken into account and power delivery equipment may need to be derated. However, major thermal problems are uncommon unless something happens to amplify some of the effects of one or more harmonic components.

The inclusion of capacitors for power factor improvement creates an RLC network which will exhibit one or more natural frequencies of oscillation. The previously mentioned harmonic currents may excite natural resonances in the system, thereby being amplified and possibly causing significant thermal problems. Two general types of resonant conditions may be encountered:

Series resonance - for which the equivalent impedance of the network approaches zero and excessive through currents can flow causing problems due to $I^2R$ heating of network elements.

Parallel resonance - for which the equivalent impedance of the network approaches infinity. Heavy currents build up within the system and severe voltage distortion can result from even a small injected harmonic current.

It is obvious that system resonance should be avoided at harmonic current injection frequencies. However, harmonic currents simultaneously injected by a number of sources can cause trouble when flowing into the system even in the absence of local resonance. For this reason, limits have been established regarding the voltage and current distortion present at the point of common coupling between industrial plants and host utilities. Industry experience has also led to recommended limits regarding the harmonic distortion of in-plant bus voltages to insure the proper operation of typical voltage sensitive load equipment.

Drives and other non-linear loads inexorably inject harmonics into the plant power system. The need is to control how these currents circulate within the system so as to minimize their adverse effects and meet harmonic distortion requirements. This control is usually achieved through the application of so-called "harmonic filters". Harmonic filters are shunt-connected power capacitors which have been "tuned" by the addition of a small series inductance so that the effective impedance of the shunt path at some harmonic frequency is very low. The low shunt impedance does two things:

- It provides a preferred, controlled path for harmonic current circulation thus reducing and/or minimizing the harmonic current flow in the principal circuit of the system.
- It greatly limits the range of harmonic frequencies over which harmonic resonance can occur with associated amplified harmonic currents and voltages.

At the same time, filters are designed such that fundamental frequency VAR requirements are also met.

For a capacitor bank to serve reliably in an harmonic filter, it must be specifically designed for that purpose; this requires that the capacitor bank have substantially higher voltage capability than a "standard" capacitor bank. Capacitors in an harmonic filter are subjected to more than nominal system voltage, and so existing unfiltered capacitors probably cannot be converted to harmonic filters. It is also generally the case that an harmonic filter designed to accomplish a power factor improvement objective will have a higher nominal VAR rating than one designed solely as an harmonic filter.

To control the propagation and effects of these currents, 13.8 kV harmonic filters are to be installed in parallel with each ASD unit. Each ASD installation will include one 2400 kVAr 5th, one 1800 kVAr 7th and one 1200 kVAr 11th harmonic filter. The design specifications for these filters as provided by General Electric Drive Systems Department (GEDS) are included in Appendix-1.

The present study investigates the performance of the proposed harmonic filters and the resulting degree of harmonic distortion expected under a variety of operating scenarios. Start-up and normal plant configurations are evaluated in addition to assessing the effects of filter outages on the harmonic distortion of plant voltages and currents.

## Section 2

## SYSTEM MODELING AND DATA

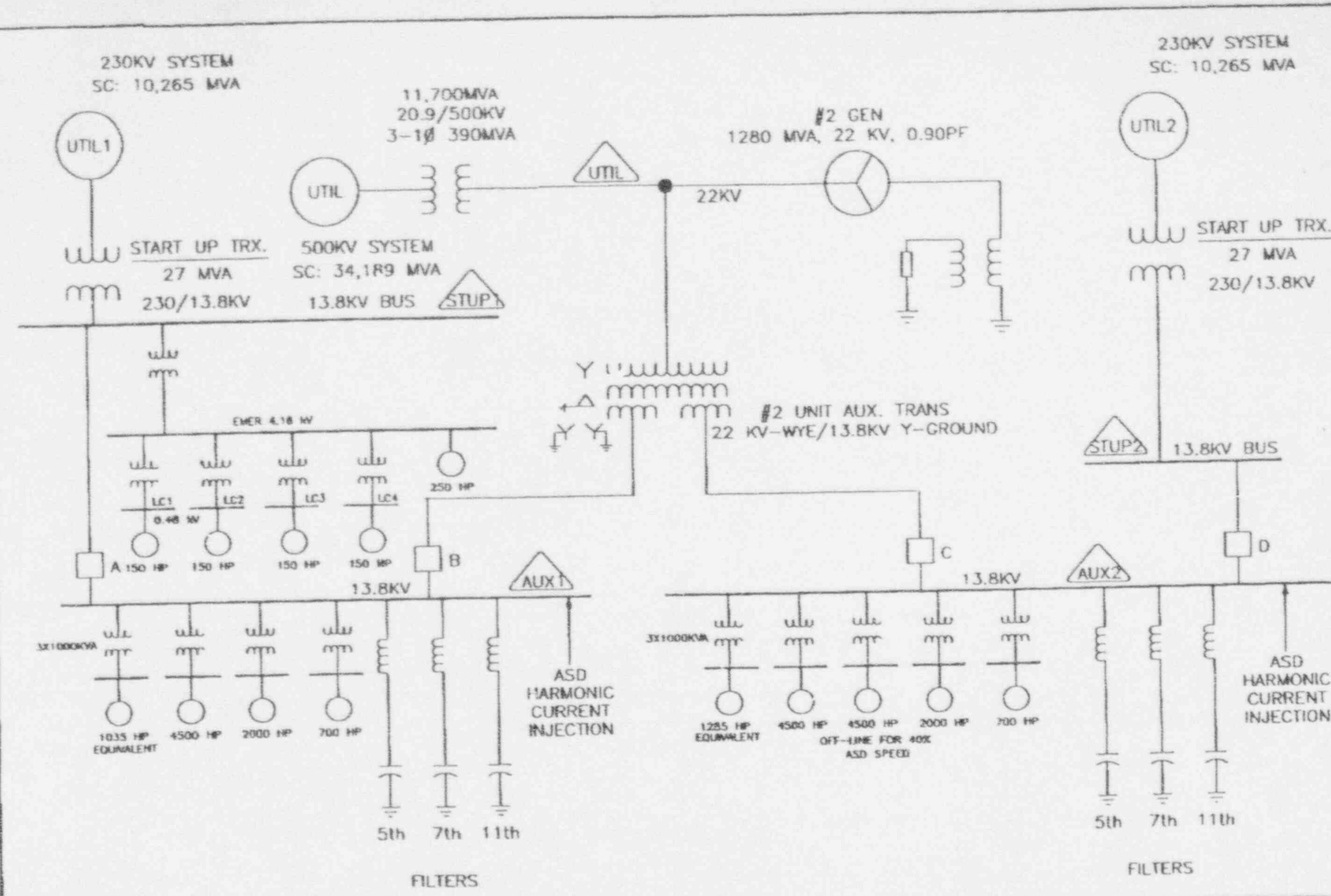
This report specifically studies the performance of the ASD units and harmonic filters associated with Generating Unit 2. As shown in Figure 2.1, the associated portion of the electrical distribution system includes Generating Unit #2, Start-Up Transformers #2 and #3, #2 Unit Auxiliary Transformer, #1 Auxiliary Bus and #2 Auxiliary Bus. The figure shows the bus numbers, ASD locations and harmonic filter arrangements examined in this report.

The performance of the ASDs and harmonic filters associated with Generating Unit #3 are not evaluated since they are normally fed via different supply transformers from a stiff utility tie point. The result of the strong tie point is to reduce the harmonic common coupling between the Unit-2 and Unit-3 distribution systems. Since PECO has indicated that the Unit-2 and Unit-3 systems are nearly identical, only one is examined for the purpose of this study.

Several system configurations were examined based on the status of breakers A, B, C and D, noted in Figure 2.1. For each combination of breaker states, several plant load conditions were evaluated. Each scenario correlates the ASD load and harmonic current injection with the appropriate amount of 60 Hz motor load at each bus system model.

As shown in Figure 2.1, the short circuit stiffness at each 230 kV utility tie point is 10,265 MVA. The stiffness at the 500 kV tie point is 34,189 MVA.

The #2 Unit Auxiliary Transformer (3-winding type) shown in Figure 2.1 was modeled using an equivalent-T representation.

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PEACH BOTTOM NUCLEAR PLANT
HARMONIC STUDY

FIGURE 2.1
ONE-LINE

CONT. ON DRAWING:

DRAWING NO.: 1613-2

**Filter Impedance/Rating**

With age, the impedance of capacitors may be expected to increase slightly, thereby raising the tuning point of a harmonic filter. If the tuning point rises sufficiently, the filter may create parallel resonant conditions at the frequency for which it was originally tuned. To avoid this occurrence, it is desirable to tune the filter slightly below the target frequency, i.e., a 5th tuned to 4.9H, a 7th tuned to 6.85H or an 11th tuned to 10.9H. This arrangement gives good performance and avoids the possible amplification of harmonic currents due to the interaction between the filters. In accordance with the filter design specifications and normal manufacturing tolerances, the ASD harmonic filters are assumed to be tuned at the 4.89, 6.85, and 10.92 harmonic orders, respectively.

Table 2.1 documents the impedances of the filter capacitors and reactors used in this study. Per manufacturer's test data, the harmonic filter capacitors typically exhibit a kVAr output of 105% of their nameplate ratings. The capacitor impedances in Table 2.1 reflect these test results. Capacitor resistances are negligible. Filter reactor impedances are based upon the desired tuning point, in accordance with allowable manufacturing tolerances and available tap positions. The X/R ratios of the filter tuning reactors are assumed to equal 40. It is assumed that harmonic filter reactor cores will not saturate under the full spectra of harmonic filter current, thereby resulting in constant reactor inductance.

**Table 2.1**
**Filter Impedance Data Used in Harmonic Study**

| DESIRED TUNING POINT (N) | Filter kVAr Rating (14.41 kV) | CAPACITOR IMPEDANCE (PU) | REACTOR IMPEDANCE (PU) |
|---|---|---|---|
| 4.89 | 2400 | 0.0000 - j6.20127 | 0.00648- j0.25935 |
| 6.85 | 1800 | 0.0000 - j8.26838 | 0.00440 - j0.17618 |
| 10.92 | 1200 | 0.0000 - j12.40254 | 0.00260 - j0.10401 |

Note
1. PU unit on 10 MVA, 13.8 KV
2. Impedance data is not actual measured filter impedance data
3. Assumed reactor X/R ratio of 40
4. Capacitor impedance based on 105% kVAr nameplate rating

## Harmonic Current Injection

The magnitudes of the harmonic current components "injected" by the ASD units are related to the drive speed. As the drive speed and fundamental component of load current increase, the magnitudes of the lower harmonic components also tend to increase. Some of the higher frequency components reach maximum values at intermediate load levels, but the majority of the harmonic current components are greatest at full load.

Table 2.2 shows the harmonic currents injected into the 13.8 kV bus by each ASD unit for a variety of drive speeds. Since the separate ASD units are located at different points within the electrical distribution system and operate independently, the harmonic currents generated by the separate drives will not generally occur at the same phase angles. As the separate currents combine in the power system, they will add vectorily and some degree of cancellation may expected to occur. For the purposes of this study, it is assumed that the harmonic currents injected by the separate drives are actually in phase and add arithmetically. This assumption leads to a conservative calculation of the total harmonic distortion (THD) since cancellation due to unequal phase angels is ignored.

**Table 2.2**
**Harmonic Current Injection per Each ASD**

| | DRIVE % SPEED | | | | |
|---|---|---|---|---|---|
| H | 100.00 | 80.00 | 60.00 | 40.00 | 20.00 |
| 1 | 335.0 | 214.4 | 113.9 | 63.7 | 63.7 |
| 5 | 66.0 | 43.2 | 23.1 | 13.0 | 13.0 |
| 7 | 44.6 | 29.8 | 15.9 | 8.9 | 8.9 |
| 11 | 26.6 | 19.3 | 10.6 | 6.0 | 6.0 |
| 13 | 20.4 | 15.1 | 8.3 | 4.6 | 4.7 |
| 17 | 14.4 | 11.9 | 6.9 | 4.0 | 4.0 |
| 19 | 10.7 | 9.5 | 5.5 | 3.1 | 3.1 |
| 23 | 7.6 | 8.2 | 5.1 | 3.0 | 3.0 |
| 25 | 5.3 | 6.4 | 4.0 | 2.3 | 2.3 |
| 29 | 3.4 | 5.8 | 4.0 | 2.4 | 2.4 |
| 31 | 2.1 | 4.5 | 3.1 | 1.8 | 1.8 |
| 35 | 0.8 | 4.2 | 3.3 | 2.0 | 2.0 |
| 37 | 0.4 | 3.1 | 2.5 | 1.4 | 1.4 |
| 41 | 0.9 | 2.9 | 2.7 | 1.7 | 1.7 |
| 43 | 0.8 | 2.1 | 2.0 | 1.2 | 1.2 |
| 47 | 1.6 | 2.0 | 2.3 | 1.5 | 1.5 |
| 49 | 1.2 | 1.4 | 1.7 | 1.0 | 1.0 |
| I-THD % | 26.5 | 28.7 | 29.8 | 30.2 | 30.2 |

### Section 3

## HARMONIC ANALYSIS AND RESULTS

To evaluate the effects of injected harmonic currents on the Peach Bottom Nuclear Plant electrical distribution system, a computer based harmonic analysis was performed. The analysis method basically determines harmonic current flows and bus voltages using a system of nodal admittance equations. Ideal voltage or current sources at individual frequencies represent harmonic sources. Inductances, capacitances and transformers are assumed to be ideal elements within the frequency range of interest. Eddy current factors are employed in modeling the resistances of each type of device. The solution of multiple source systems uses the superposition principle disregarding phase angle relationships. Thus, the current or voltage distortion at any point is the algebraic sum of the distortion due to each source. This renders the calculation method conservative. Actual measurements are expected to be less than the calculated values. However, this method is a valid means of assessing the boundaries of the harmonic performance of an actual industrial power system. The following equations are useful in assessing the extent of harmonic current and voltage distortion.

$THD_V = SQRT( SV_h^2 ) / V_1$ for h = 2 to n        $V_h$ = Voltage @ Harm. Order h

$I_{rss} = SQRT( SI_h^2 ) / I_1$ for h = 2 to n        $I_h$ = Current @ Harm. Order h

$V_{sum} = S\ V_h = S\ I_h * Z_h$ for h = 1 to n        $Z_h$ = Impedance. @ Harm. Order h

The response of the electrical distribution system to the harmonic currents injected by the ASD equipment was evaluated under sixty four (64) different operating scenarios. As illustrated in Tables 3.1 through 3.4, analyses were performed under four switching configurations involving circuit breakers A, B, C and D (see Figure 2.1). Under each configuration, four combinations of harmonic filter states were evaluated. For each combination of circuit breaker and harmonic filter switching conditions, four ASD speeds (40, 60, 80 & 100 %) were evaluated. Tables 3.1 through 3.4 summarize the conditions and key results of each scenario. The output for each scenario is provided in Appendix-3.

## Table 3.1
## Total Harmonic Distortion Results
## Adjustable Speed Drive at 100% Speed

| Case # | System Configuration Breaks-Closed | Bus-3 Filters AUX-1 | Bus-2 Filters AUX-2 | THD AUX-1 13.8 kV | THD AUX-2 13.8 kV | THD EMER 4.16 kV | THD E-LC 480V | THD Non-1E 480V | THD - Voltage Criteria |
|---|---|---|---|---|---|---|---|---|---|
| 1 | B & C | Off | Off | 5.4 | 5.3 | - | - | 4.5 | >5.0 |
| 2 | B & C | On | On | 2.1 | 2.1 | - | - | 1.8 | |
| 3 | B & C | Off | On | 5.3 | 2.1 | - | - | 4.5 | >5.0 |
| 4 | B & C | On | Off | 2.1 | 5.2 | - | - | 1.8 | >5.0 |
| 5 | A & D | Off | Off | 6.7 | 6.2 | 6.5 | 6.0 | 5.6 | >5.0 |
| 6 | A & D | On | On | 2.3 | 2.3 | 2.3 | 2.1 | 2.0 | |
| 7 | A & D | Off | On | 6.7 | 2.3 | 6.5 | 6.0 | 5.6 | >5.0 |
| 8 | A & D | On | Off | 2.3 | 6.2 | 2.3 | 2.1 | 5.1 | >5.0 |
| 9 | A & C | Off | Off | 6.7 | 5.2 | 6.5 | 6.0 | 5.6 | >5.0 |
| 10 | A & C | On | On | 2.3 | 2.1 | 2.3 | 2.1 | 2.0 | |
| 11 | A & C | Off | On | 6.7 | 2.1 | 6.5 | 6.0 | 5.6 | >5.0 |
| 12 | A & C | On | Off | 2.3 | 5.2 | 2.3 | 2.1 | 4.2 | >5.0 |
| 13 | B & D | Off | Off | 5.2 | 6.2 | - | - | 5.1 | >5.0 |
| 14 | B & D | On | On | 2.1 | 2.3 | - | - | 1.9 | |
| 15 | B & D | Off | On | 5.2 | 2.3 | - | - | 4.4 | >5.0 |
| 16 | B & D | On | Off | 2.1 | 6.2 | - | - | 5.1 | >5.0 |

## Table 3.2
## Total Harmonic Distortion Results
## Adjustable Speed Drive at 80% Speed

| Case # | System Configuration Breaks-Closed | Bus-3 Filters AUX-1 | Bus-2 Filters AUX-2 | THD AUX-1 13.8 kV | THD AUX-2 13.8 kV | THD EMER 4.16 kV | THD E-LC 480V | THD Non-1E 480V | THD - Voltage Criteria |
|---|---|---|---|---|---|---|---|---|---|
| 1 | B & C | Off | Off | 4.8 | 4.7 | - | - | 4.0 | |
| 2 | B & C | On | On | 2.3 | 2.3 | - | - | 2.0 | |
| 3 | B & C | Off | On | 4.7 | 2.3 | - | - | 4.0 | |
| 4 | B & C | On | Off | 2.3 | 4.6 | - | - | 3.8 | |
| 5 | A & D | Off | Off | 5.9 | 5.5 | 5.8 | 5.3 | 5.0 | >5.0 |
| 6 | A & D | On | On | 2.6 | 2.5 | 2.6 | 2.3 | 2.2 | |
| 7 | A & D | Off | On | 5.9 | 2.5 | 5.8 | 5.3 | 5.0 | >5.0 |
| 8 | A & D | On | Off | 2.6 | 5.5 | 2.6 | 2.3 | 4.5 | >5.0 |
| 9 | A & C | Off | Off | 5.9 | 4.6 | 5.8 | 5.3 | 5.0 | >5.0 |
| 10 | A & C | On | On | 2.6 | 2.3 | 2.6 | 2.3 | 2.2 | |
| 11 | A & C | Off | On | 5.9 | 2.3 | 5.8 | 5.3 | 5.0 | >5.0 |
| 12 | A & C | On | Off | 2.6 | 4.6 | 2.6 | 2.3 | 3.7 | |
| 13 | B & D | Off | Off | 4.7 | 5.5 | - | - | 4.5 | >5.0 |
| 14 | B & D | On | On | 2.3 | 2.5 | - | - | 2.1 | |
| 15 | B & D | Off | On | 4.7 | 2.5 | - | - | 4.0 | |
| 16 | B & D | On | Off | 2.3 | 5.5 | - | - | 4.6 | >5.0 |

## Table 3.3
## Total Harmonic Distortion Results
## Adjustable Speed Drive at 60% Speed

| Case # | System Configuration Breaks-Closed | Bus-3 Filters AUX-1 | Bus-2 Filters AUX-2 | THD AUX-1 13.8 kV | THD AUX-2 13.8 kV | THD EMER 4.16 kV | THD E-LC 480V | THD Non-1E 480V | THD - Voltage Criteria |
|---|---|---|---|---|---|---|---|---|---|
| 1 | B & C | Off | Off | 3.1 | 3.1 | - | - | 2.6 | |
| 2 | B & C | On | On | 1.7 | 1.6 | - | - | 1.4 | |
| 3 | B & C | Off | On | 3.1 | 1.6 | - | - | 2.6 | |
| 4 | B & C | On | Off | 1.7 | 3.0 | - | - | 2.5 | |
| | | | | | | | | | |
| 5 | A & D | Off | Off | 3.9 | 3.6 | 3.8 | 3.5 | 3.3 | |
| 6 | A & D | On | On | 1.9 | 1.8 | 1.8 | 1.7 | 1.6 | |
| 7 | A & D | Off | On | 3.9 | 1.8 | 3.8 | 3.5 | 3.3 | |
| 8 | A & D | On | Off | 1.9 | 3.6 | 1.8 | 1.7 | 2.9 | |
| | | | | | | | | | |
| 9 | A & C | Off | Off | 3.9 | 3.0 | 3.8 | 3.5 | 3.3 | |
| 10 | A & C | On | On | 1.9 | 1.6 | 1.8 | 1.7 | 1.6 | |
| 11 | A & C | Off | On | 3.9 | 1.6 | 3.8 | 3.5 | 3.3 | |
| 12 | A & C | On | Off | 1.9 | 3.0 | 1.8 | 1.7 | 2.4 | |
| | | | | | | | | | |
| 13 | B & D | Off | Off | 3.1 | 3.6 | - | - | 2.9 | |
| 14 | B & D | On | On | 1.6 | 1.8 | - | - | 1.5 | |
| 15 | B & D | Off | On | 3.1 | 1.8 | - | - | 2.6 | |
| 16 | B & D | On | Off | 1.6 | 3.6 | - | - | 2.9 | |

## Table 3.4
## Total Harmonic Distortion Results
## Adjustable Speed Drive at 40% Speed

| Case # | System Configuration Breaks-Closed | Bus-3 Filters AUX-1 | Bus-2 Filters AUX-2 | THD AUX-1 13.8 kV | THD AUX-2 13.8 kV | THD EMER 4.16 kV | THD E-LC 480V | THD Non-1E 480V | THD - Voltage Criteria |
|---|---|---|---|---|---|---|---|---|---|
| 1 | B & C | Off | Off | 1.8 | 1.9 | - | - | 1.6 | |
| 2 | B & C | On | On | 1.0 | 1.0 | - | - | 0.8 | |
| 3 | B & C | Off | On | 1.8 | 1.0 | - | - | 1.5 | |
| 4 | B & C | On | Off | 1.0 | 1.9 | - | - | 1.6 | |
| | | | | | | | | | |
| 5 | A & D | Off | Off | 2.3 | 2.3 | 2.2 | 2.0 | 1.9 | |
| 6 | A & D | On | On | 1.1 | 1.1 | 1.1 | 1.0 | 0.9 | |
| 7 | A & D | Off | On | 2.3 | 1.1 | 2.2 | 2.0 | 1.9 | |
| 8 | A & D | On | Off | 1.1 | 2.3 | 1.1 | 1.0 | 1.9 | |
| | | | | | | | | | |
| 9 | A & C | Off | Off | 2.3 | 1.9 | 2.2 | 2.0 | 1.9 | |
| 10 | A & C | On | On | 1.1 | 1.0 | 1.1 | 1.0 | 0.9 | |
| 11 | A & C | Off | On | 2.3 | 1.0 | 2.2 | 2.0 | 1.9 | |
| 12 | A & C | On | Off | 1.1 | 1.9 | 1.1 | 1.0 | 1.5 | |
| | | | | | | | | | |
| 13 | B & D | Off | Off | 1.8 | 2.3 | - | - | 1.9 | |
| 14 | B & D | On | On | 1.0 | 1.1 | - | - | 0.9 | |
| 15 | B & D | Off | On | 1.8 | 1.1 | - | - | 1.5 | |
| 16 | B & D | On | Off | 1.0 | 2.3 | - | - | 1.9 | |

Tables 3.1 through 3.4 compare the expected total harmonic distortion of bus voltage (THDv) with the acceptable levels recommended in IEEE Stnd. 519 - 1993. The standard has been developed to establish guidelines concerning the distortion of system voltage and current waveforms due to the behavior of non-linear load devices. The standard primarily concerns itself with conditions at the point of common coupling (PCC) between an industrial customer and the local utility system. Within an industrial plant, the PCC is considered to be the point between the non-linear load and other loads. For the purposes of this study, the PCC is considered to be the 13.8 kV Auxiliary bus supplying a given ASD.

The standard recommends that the THDv at a general purpose bus be maintained at or below 5% while 10% THDv may be allowed at a bus serving solid state drive equipment. These limits are not analytically derived, but are based upon many years' experience within the electrical industry.

Table 3.1 summarizes the results of the harmonic analysis assuming the ASDs are operating at 100% speed. As seen in the table, the THDv at a given 13.8 kV Auxiliary Bus is expected to exceed 5% under this drive load when the local harmonic filters are turned off. The THDv is expected to exceed 6% when the 13.8 kV bus is supplied via its start-up transformer and to only slightly exceed 5% when the larger, generator auxiliary transformer is employed.

Table 3.2 summarizes the results of the harmonic analysis assuming the ASDs are operating at 80% speed. As seen in the table, the THDv at a given 13.8 kV Auxiliary Bus is not expected to exceed 5% when supplied via the generator auxiliary transformer regardless of the state of the local harmonic filter. If a given 13.8 kV bus is supplied via the associated start-up transformer, the local harmonic filter will be required to hold the THDv below 5%. However, without the local filter, the THDv is expected to only slightly exceed 5%.

Tables 3.3 and 3.4 illustrate that the THDv is not expected to exceed 5% at any bus under any switching condition if the ASD speeds are at or below 60%.

Case 5 in Table 3.2 indicates that THDv may approach 6% under start-up configuration with both filter sets turned off and the ASD speeds at 80%. Case 5 in Table 3.3 indicates a THDv approaching 4% under similar conditions with the drive speeds at 60%. By interpolation, it may be assumed that the THDv may approach 5% at approximately 70% ASD speed.

The harmonic analysis results, contained in Appendix 3, indicate the current and voltage duties impressed upon the harmonic filter reactors and capacitors. When compared with the filter design ratings, contained in Appendix 1, it is clear that the harmonic filter capabilities will not be exceeded under any operating scenario evaluated.

Although solid state drives often constitute the major source of harmonic currents in an industrial system, other non-linear loads are also present. Some common examples are fluorescent lighting, personal computers and battery chargers. Although the effects of such devices do not equal those created by high power drives and rectifiers, they may be of significant magnitudes when considering a low voltage distribution circuit. Such is the case at the Peach Bottom Nuclear Plant.

Per recent measurements performed by PECO, the ambient bus voltage distortion present at 480V Load Center #1 falls between 1 and 2%. Although negligible in itself, this ambient voltage distortion will add to the distortion levels predicted in the aforementioned harmonic analysis. The voltage components at each frequency will add vectorily, thus the total voltage at any one frequency will be less than the arithmetic addition of the individual components. Since the various phase angle relationships of these voltage components are unknown, a conservative approach should be taken in estimating the possible total harmonic distortion at a given bus.

Table 3.5 conservatively estimates the THDv at 480V Load Center #1. The voltage components predicted by the harmonic analysis with circuit breakers A and D closed and both harmonic filters turned off are added arithmetically to the ambient voltage components noted in the PECO measurements. The resulting THDv at the load center bus is indicated at the bottom of the table for ASD speeds of 40, 60, 80 and 100%. By interpolation, it may be assumed that the THDv at Load Center #1 may approach 5% at approximately 65% ASD speed. Thus, the inclusion of ambient harmonic distortion results in a 5% reduction in ASD speed if the THDv at the 480V Load Center #1 is to be maintained at or below 5%.

Finally, it must be remembered that the preceding analysis is conservative. Variability introduced by system damping effects and harmonic source phase angle relationships should result in lower harmonic distortion levels than those predicted herein. Although the IEEE recommendations concerning bus voltage distortion are only meant to apply at the point of common coupling between a static load and power supply system, PECO intends to apply the 5% guideline throughout the Peach Bottom Nuclear Plant distribution system. Before final plant operating guidelines based on harmonic distortion limits are

established, a thorough measurements program should be undertaken to verify the actual distortion levels experienced within the plant under various operating conditions.

**Table 3.5**
**Projected Percent Harmonic Distortion at 480V Load Center #1**
**Including the Effects of Ambient Voltage Distortion**

| H | Ambient | ASD Speed (%) | | | | H | Ambient |
|---|---|---|---|---|---|---|---|
| | | 100 | 80 | 60 | 40 | | |
| 1 | 100 | 100 | 100 | 100 | 100 | 2 | 1.1 |
| 3 | 0.7 | 0 | 0 | 0 | 0 | 4 | 0.4 |
| 5 | 0.8 | 2.7 | 1.8 | 0.9 | 0.5 | 6 | 0.2 |
| 7 | 0.6 | 2.5 | 1.7 | 0.9 | 0.5 | 8 | 0.2 |
| 9 | 0.2 | 0 | 0 | 0 | 0 | 10 | 0.2 |
| 11 | 0.2 | 2.4 | 1.7 | 0.9 | 0.5 | 12 | 0.2 |
| 13 | 0.1 | 2.2 | 1.6 | 0.9 | 0.5 | 14 | 0.1 |
| 15 | 0.2 | 0 | 0 | 0 | 0 | 16 | 0.1 |
| 17 | 0.1 | 2 | 1.6 | 1 | 0.6 | 18 | 0.1 |
| 19 | 0 | 1.6 | 1.5 | 0.8 | 0.5 | 20 | 0.1 |
| 21 | 0.1 | 0 | 0 | 0 | 0 | 22 | 0.1 |
| 23 | 0.2 | 1.4 | 1.5 | 1 | 0.6 | 24 | 0.2 |
| 25 | 0 | 1.1 | 1.3 | 0.8 | 0.5 | 26 | 0.1 |
| 27 | 0.1 | 0 | 0 | 0 | 0 | 28 | 0.1 |
| 29 | 0.1 | 0.8 | 1.4 | 0.9 | 0.6 | 30 | 0.1 |
| 31 | 0.1 | 0.5 | 1.1 | 0.8 | 0.5 | 32 | 0.1 |
| 33 | 0.2 | 0 | 0 | 0 | 0 | 34 | 0.1 |
| 35 | 0.6 | 0.2 | 1.2 | 0.9 | 0.6 | 36 | 0.6 |
| 37 | 0.1 | 0.1 | 0.9 | 0.8 | 0.4 | 38 | 0.2 |
| 39 | 0.1 | 0 | 0 | 0 | 0 | 40 | 0.1 |
| 41 | 0 | 0.3 | 1 | 0.9 | 0.6 | 42 | 0 |
| 43 | 0.1 | 0.3 | 0.7 | 0.7 | 0.4 | 44 | 0.1 |
| 45 | 0.1 | 0 | 0 | 0 | 0 | 46 | 0.1 |
| 47 | 0.1 | 0.7 | 0.8 | 0.9 | 0.6 | 48 | 0.1 |
| 49 | 0 | 0.5 | 0.8 | 0.7 | 0.4 | 50 | 0.1 |

THDv @ 100% ASD Speed = 7.10
THDv @ 80% ASD Speed = 6.46
THDv @ 60% ASD Speed = 4.68
THDv @ 40% ASD Speed = 3.46

Section 4

## CONCLUSIONS

The following conclusions may be drawn from the foregoing analysis:

1. The harmonic filters as specified by GEDS are adequate to meet the system requirements per IEEE-std. 519-1993 and performance requirements per PECO.

2. For the system conditions investigated, the operation of the ASD equipment, including harmonic filters, will create less than 3% additional harmonic distortion of system voltage (THDv).

3. To maintain THDv below 5% at the 13.8 kV bus with a set of harmonic filters out of service, the associated ASD should not be operated above 70% speed.

4. To maintain THDv at lower voltage buses below 5% under similar conditions while including the effects of ambient distortion may require the reduction of the ASD speed to 65%.

5. Before final plant operating guidelines based on harmonic distortion limits are established, a thorough measurements program should be undertaken to verify the actual distortion levels experienced within the plant under various operating conditions.

### Section 5

## RECOMMENDATIONS

The following recommendations are made based on the results reported herein:

1. For each filter installation the optimal tuning points should be as follows:

| | | | | |
|---|---|---|---|---|
| 5th filter | n = 4.89 | range | < 5 | n = tuning point |
| 7th filter | n = 6.85 | range | < 7 | i.e. 60 Hz * n |
| 11th filter | n = 10.92 | range | < 11 | |

   Note that exact tuning of the filters is not possible due to the discrete nature of the filter reactor taps, but should be tuned as nearly as possible to the tuning points shown above.

2. At the time of installation, 13.8 kV bus voltage and filter current measurements should be performed to ensure that distortion levels are within PECO voltage distortion criteria and that the filters are operating within their design limits.

3. The filters should be checked periodically (i.e. annually) to ensure their proper condition and fitness to serve.

4. The installation of future drives or capacitor banks may effect the duties impressed upon the harmonic filters. Filter duties should be investigated following any such plant modification.

5. To maintain THDv levels at or below 5%, a given ASD should not be operated above 70% speed while the associated harmonic filters are off line. The effects of ambient harmonic distortion may lower this limit to 65%.

6. Before final plant operating guidelines based on harmonic distortion limits are established, a thorough measurements program should be undertaken to verify the actual distortion levels experienced within the plant under various operating conditions.