Power Factor Correction and Harmonic Control for dc Drive Loads

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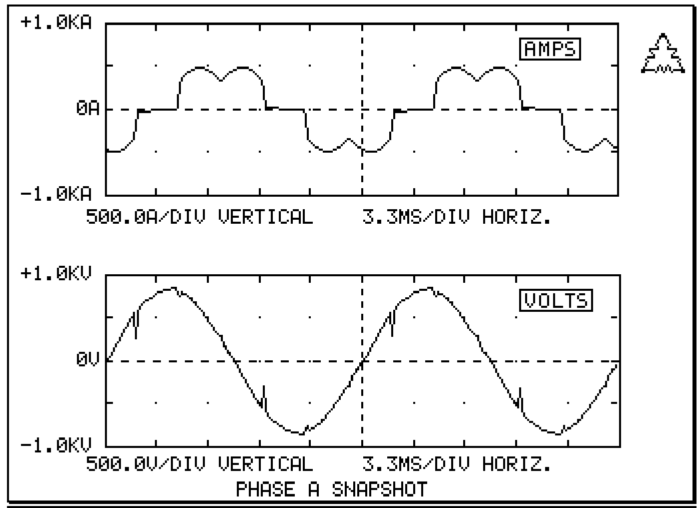
ABSTRACT

This paper describes the design of power factor correction and harmonic control equipment for loads at a plastic film manufacturing plant. Measurements were performed to characterize the harmonic generation and power factor requirements of the load. The electric utility supplying the new facility is requiring that the plant meet the harmonic current limits specified in the new IEEE 519. Harmonic filters which can meet the IEEE 519 guidelines for the specific load characteristics were designed. General filter design guidelines for this type of application are presented.

INTRODUCTION

DC drives can be a significant percentage of plant load in many industrial facilities. They are commonly used in the plastics, rubber, paper, textile, printing, oil, chemical, metal, and mining industries. These drives are still the most common type of motor speed control for applications requiring very fine control over wide speed ranges with high torques.

Power factor correction is particularly important for dc drives because phasing back of the SCRs results in relatively poor power factor, especially when the motor is at reduced speeds. Additional transformer capacity is required to handle the poor power factor conditions (and the harmonics) and more utilities are charging a power factor penalty that can significantly impact the total bill for the facility.



PHASE A CURRENT SPECTRUM 2:51:53 PM
Fundamental amps: 346.2 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	-43°	2nd	0.3%	68°
3rd	0.4%	-126°	4th	0.2%	30°
5th	25.3%	-30°	6th	0.1%	61°
7th	5.5%	-122°	8th	0.2%	10°
9th	0.6%	37°	10th	0.2%	-45°
11th	8.2%	-102°	12th	0.1%	-37°
13th	3.9%	170°	14th	0.2%	-65°
15th	0.3%	-40°	16th	0.2%	-119°
17th	5.0%	-179°	18th	0.1%	-126°
19th	2.9%	93°	20th	0.2%	-136°
21st	0.3%	-44°	22nd	0.2%	167°
23rd	3.4%	109°	24th	0.1%	162°
25th	2.1%	14°	26th	0.2%	150°
27th	0.2%	-144°	28th	0.2%	100°
29th	2.7%	39°	30th	0.1%	86°
31st	1.9%	-59°	32nd	0.2%	74°
33rd	0.2%	99°	34th	0.2%	29°
35th	2.1%	-35°	36th	0.1%	6°
37th	1.7%	-135°	38th	0.2%	3°
39th	0.3%	41°	40th	0.2%	-42°
41st	1.8%	-110°	42nd	0.2%	-72°
43rd	1.5%	150°	44th	0.2%	-70°
45th	0.5%	-30°	46th	0.3%	-113°
47th	1.7%	177°	48th	0.2%	-146°
49th	1.4%	70°	50th	0.2%	-142°

ODD	28.9%	EVEN	1.0%
THD:	28.9%		

Figure 1. Example dc Drive Current Waveform and Harmonic Spectrum

The dc drives also generate significant harmonic currents. Figure 1 is an example current waveform and harmonic spectrum for a dc drive load. The harmonics make power factor correction more complicated. Power factor correction capacitors can cause resonant conditions which magnify the harmonic currents and cause excessive distortion levels [1,2]. This paper describes the design of power factor correction to avoid harmonic problems.

DESCRIPTION OF EXAMPLE SYSTEM

Klockner Pentaplast manufactures heavy duty plastic film. The process uses calenders which are driven by dc motor drives. As a result, there is significant harmonic current generation and the plant power factor without compensation is quite low. Shunt capacitors can be added to partially correct the power factor but this can cause harmonic problems due to resonance conditions and transient problems during capacitor switching by the utility [3].

Klockner Pentaplast is building a new facility in Rural Retreat, VA to manufacture plastic film. This facility will include two calender lines similar to lines at their existing facility in Gordonsville, VA. Measurements performed at the Gordonsville facility are used to characterize these dc drive loads and additional analysis is described to determine power factor correction and filtering requirements for the new facility.

Klockner would like to correct the power factor to 0.95 with power factor correction equipment (capacitors). However, the power factor correction must take into account the potential for resonance which could magnify the harmonic currents generated by the dc drive loads. This usually means that harmonic filters are required. In addition, the electric utility supplying the new facility has required that Klockner meet the proposed limits in the revised version of IEEE 519. [4] This results in a need for harmonic filters to reduce the harmonic current components injected onto the utility system.

The plant electrical system consists of two sets of 480 Volt switch gear fed from a common 480 Volt bus. A 3750 kVA transformer steps down from a 34.5 kV distribution line for the entire facility. Figure 2 is a one line diagram illustrating the Rural Retreat facility.

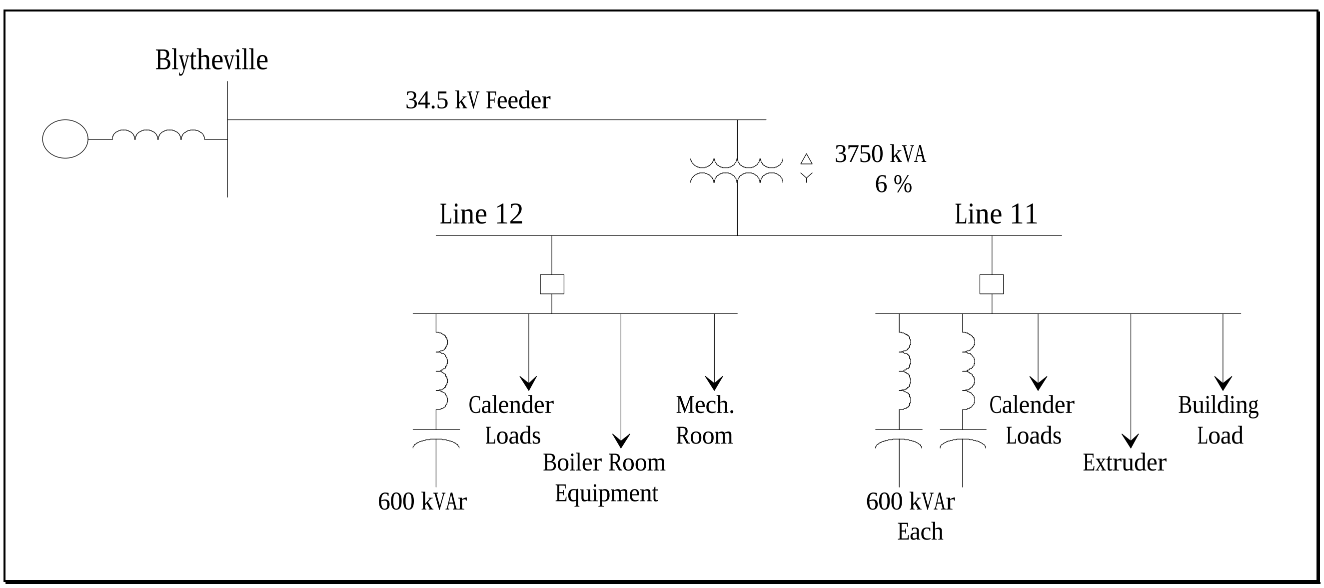


Figure 2. One Line Diagram for Rural Retreat Facility

CALCULATING POWER FACTOR CORRECTION REQUIREMENTS

The new calender lines at Rural Retreat will be similar to existing lines at the Gordonsville facility. Therefore, measurements at the existing facility are used to estimate the power factor correction that will be needed at Rural Retreat. Since all of the load will essentially be connected to the same 480 Volt bus at Rural Retreat, the important consideration is the total power factor for the two switchgear lines.

Measurement Results

Measurements were performed characterizing typical calender line conditions at the existing Gordonsville facility. There were two very important findings from these measurements:

1. Displacement power factor for the calender line loads (almost exclusively dc drives) ranged from 0.65-0.70. This displacement power factor determines the capacitor/filter sizes required for the loads.

2. There is significant cancellation of harmonic currents resulting from the different dc drives fed from the main bus. Whereas the total harmonic distortion in the current for a single drive is approximately 30% (see Figure 1), the total harmonic distortion for the total current at the bus was usually on the order of 15%, not including the effect of resonances caused by capacitor banks. This is an important consideration when determining the filter rating requirements and the ability to meet IEEE 519 harmonic current limits.

Power Factor Calculations for the New Facility

The power factor requirements for the new facility are calculated based on the total expected load. Table 1 calculates the power factor correction requirements at estimated minimum and maximum load levels. The estimated power factor of the loads is based on the measurement results. Based on these estimates of plant loading, a total compensation of 1800 kVAr should be sufficient to maintain a power factor exceeding 0.95 for all load conditions.

Table 1. Calculation of Power Factor Correction for Total Plant Loading

Total Load Power Factor Calculations		
Bus:	**Total 480 Volt Bus Loading**	
Voltage L-N	277.00	
L-L	479.78	
	Min	Max
Load Range (Amps):	2400	4000
Power Factor	0.65	0.67
Load kVA	1995	3326
Load kW	1297	2228
KVAr	1516	2469
Existing Capacitors	0	0
Load kVAr	1516	2469
Load Power Factor	0.65	0.67
Additional kVAr Recommended	1200	1800
Expected Power Factor	0.97	0.96

ANALYSIS OF HARMONIC DISTORTION CONCERNS

For the purposes of harmonic analysis, the dc drive loads can be represented as sources of harmonic currents. The system looks stiff to these loads and the current waveform illustrated in Figure 1 is relatively independent of the voltage distortion at the drive location. This assumption of a harmonic current source permits the system response characteristics to be evaluated separately from the dc drive characteristics. The representation of the drives as harmonic current sources is shown in Figure 3.

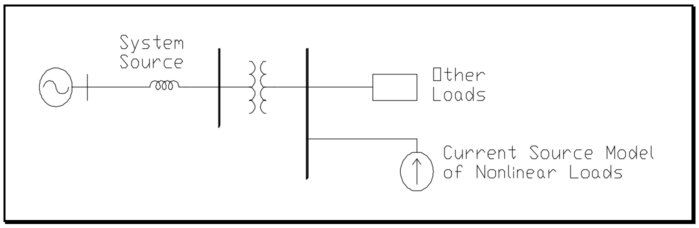


Figure 3. Representation of the DC Drives as Harmonic Current Sources

Analysis of the system response is important because the system impedance vs. frequency characteristics determine the voltage distortion that will result from the dc drive harmonic currents. A simplified version of the situation is shown in Figure 4.

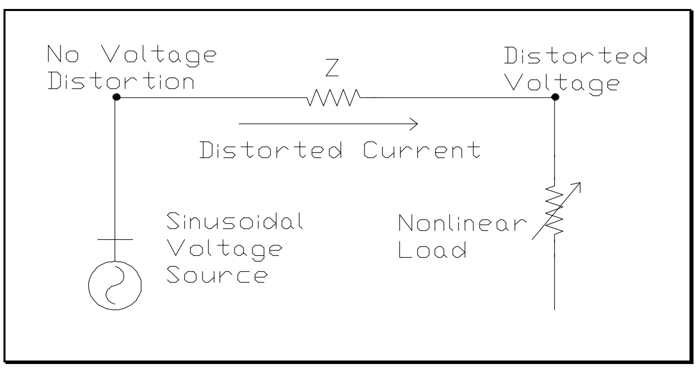


Figure 4. Voltage Distortion Caused by Harmonic Currents and System Impedance

If the system is infinitely strong (no impedance), there will never be any voltage distortion. It is the harmonic currents generated by the dc drives passing through the system impedance that causes voltage distortion. Filters are the means used to control the system response.

Harmonic Distortion Levels at the Existing Facility

Initial power factor correction procedures for the Gordonsville facility involved installation of capacitor banks for each calender line. One or two 600 kVAr banks were used for each line. This resulted in problems with high voltage distortion levels in the plant and also caused transient voltage magnification when the utility company switched a higher voltage transmission system capacitor bank. To prevent these problems, the 600 kVAr capacitor banks are being configured as harmonic filters rather than just capacitors. The configuration is shown in Figure 5.

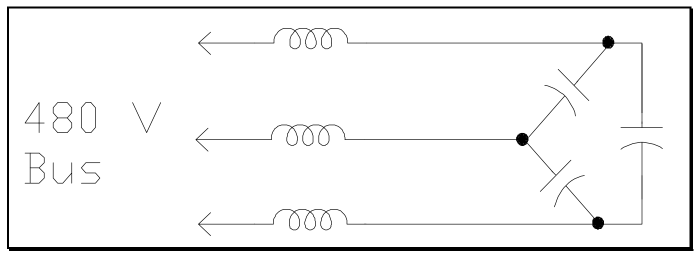


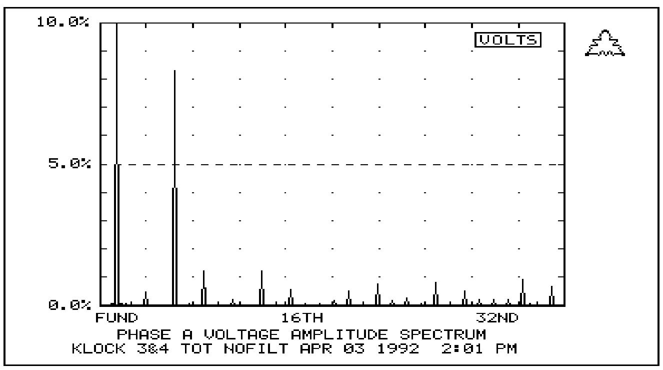
Figure 5. Basic Configuration for a 480 Volt Harmonic Filter Bank

The filter is tuned below the fifth harmonic. This limits the additional harmonic current which must be absorbed from the utility system and also allows for tolerances in the filter components.

The addition of a single 600 kVAr filter significantly improved voltage distortion levels at the 480 Volt bus. Figure 6 compares the voltage harmonic spectrum with and without the filter in service.

KLOCK 3&4 TOT NOFILT Apr 03 1992 (Fri)
PHASE A VOLTAGE SPECTRUM 2:00:57 PM
Fundamental volts: 265.8 Vrms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	0°	2nd	0.1%	−161°
3rd	0.5%	127°	4th		
5th	8.3%	107°	6th		
7th	1.2%	146°	8th	0.1%	114°
9th	0.2%	19°	10th		
11th	1.2%	−144°	12th		
13th	0.5%	116°	14th		
15th			16th	0.1%	22°
17th	0.5%	−47°	18th		
19th	0.8%	107°	20th	0.2%	−136°
21st	0.2%	−48°	22nd		
23rd	0.8%	−146°	24th	0.1%	101°
25th	0.5%	25°	26th	0.2%	67°
27th	0.2%	141°	28th	0.2%	−120°
29th	0.9%	124°	30th	0.1%	58°
31st	0.7%	−2°	32nd		
33rd	0.3%	−81°	34th	0.4%	73°
35th	0.4%	−123°	36th	0.2%	−26°
37th	0.5%	105°	38th	0.2%	78°
39th	0.1%	135°	40th	0.3%	−24°
41st	0.7%	110°	42nd	0.1%	−91°
43rd	1.0%	−18°	44th	0.4%	18°
45th			46th	0.4%	−105°
47th	0.5%	85°	48th		
49th	0.7%	−64°	50th	0.5%	−46°
ODD	8.9%		EVEN	1.0%	
THD:	8.9%				



KLOCK 3&4 TOT W FILT Apr 03 1992 (Fri)
PHASE A VOLTAGE SPECTRUM 1:56:14 PM
Fundamental volts: 270.8 Vrms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	0°	2nd		
3rd	0.4%	124°	4th		
5th	3.0%	118°	6th		
7th	0.6%	147°	8th		
9th			10th		
11th	0.6%	−108°	12th		
13th	0.5%	129°	14th	0.1%	146°
15th	0.2%	178°	16th	0.1%	−16°
17th	0.5%	−157°	18th		
19th	0.6%	18°	20th		
21st			22nd	0.2%	−122°
23rd	0.5%	71°	24th		
25th	0.8%	−106°	26th	0.1%	−19°
27th	0.2%	124°	28th		
29th	0.3%	45°	30th		
31st	0.4%	1°	32nd		
33rd	0.2%	−38°	34th	0.2%	170°
35th	0.3%	−50°	36th		
37th	0.9%	−147°	38th	0.2%	−100°
39th	0.2%	54°	40th	0.2%	110°
41st	0.6%	−38°	42nd	0.1%	67°
43rd	0.3%	120°	44th	0.2%	173°
45th	0.3%	−74°	46th	0.2%	57°
47th	0.7%	−134°	48th	0.1%	−43°
49th			50th		
ODD	3.8%		EVEN	0.6%	
THD:	3.8%				

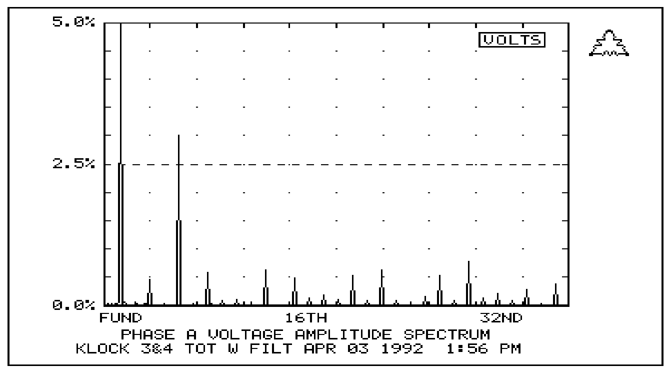


Figure 6. Comparison of Bus Voltage Distortion With and Without Harmonic Filter in Service

Filter Design for the New Facility

The switchgear lineups at the new facility are being configured with 1200 Amp switchgear. For this reason, the individual power factor correction steps are being limited to 600 kVAr. Based on the power factor correction estimates, two steps will be installed initially and a third step will be added in the future if it is warranted based on actual plant loading.

Each 600 kVAr step will be configured as a harmonic filter tuned to approximately 4.7 times the fundamental frequency (60 Hz). 600 Volt capacitors will be used for these filters to prevent overloading due to voltage rise across the reactor and harmonics from the power system. In order to accomplish this, capacitors with a nominal rating of 900 kVAr at 600 Volts will be required. Figure 7 provides the specifications for the recommended filter configuration. The specifications are based on two filters sharing the maximum load at the Rural Retreat plant.

Low Voltage Filter Calculations:

Klockner Pentaplast - Rural Retreat (each 600 kVAr filter bank)

SYSTEM INFORMATION:

Filter Specification:	5 th	Power System Frequency:	60 Hz
Capacitor Bank Rating:	900 kVAr	Capacitor Rating:	600 Volts 60 Hz
Nominal Bus Voltage:	480 Volts	Derated Capacitor:	576 kVAr
Capacitor Rated Current:	866.0 Amps	Total Harmonic Load:	1500 kVA
Filter Tuning Harmonic:	4.7 th	Filter Tuning Frequency:	282 Hz
Cap Impedance (wye):	0.4000 W	Cap Value (wye):	6631.5 uF
Reactor Impedance:	0.0181 W	Reactor Rating:	0.0480 mH
Filter Full Load Current:	725.7 Amps	Supplied Compensation:	603 kVAr
Transformer Nameplate: *(Rating and Impedance)*	3750 kVA 6.00 %	Utility Side Vh: *(Utility Harmonic Voltage Source)*	2.00 % THD
Load Harmonic Current:	25.00 % Fund	Load Harmonic Current:	451.1 Amps
Utility Harmonic Current:	191.5 Amps	Max Total Harm. Current:	642.6 Amps

CAPACITOR DUTY CALCULATIONS:

Filter RMS Current:	969.3 Amps	Fundamental Cap Voltage:	502.8 Volts
Harmonic Cap Voltage:	89.0 Volts	Maximum Peak Voltage:	591.8 Volts
RMS Capacitor Voltage:	510.6 Volts	Maximum Peak Current:	1368.3 Amps

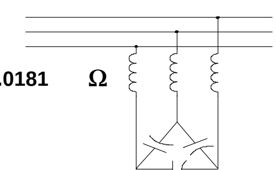
CAPACITOR LIMITS: (IEEE Std 18-1980)

	Limit		Actual
Peak Voltage:	120%	←——→	99%
Current:	180%	←——→	112%
KVAr:	135%	←——→	95%
RMS Voltage:	110%	←——→	85%

FILTER CONFIGURATION:

480 Volt Bus

Xl = 0.0181 Ω



900 kVAr @
600 Volts

Xc(wye) = 0.4000 Ω

FILTER REACTOR DESIGN SPECIFICATIONS:

Reactor Impedance:	0.0181 W	Reactor Rating:	0.0480 mH
Fundamental Current:	725.7 Amps	Harmonic Current:	642.6 Amps

Figure 7. 600 kVAr Filter Specifications

Figure 8 shows the frequency response of the system looking from the 480 Volt bus when there are two 600 kVAr filters in service. There should always be at least two filters in service during normal load conditions to share the harmonic loading. The filters prevent any resonances near the characteristic harmonics of the dc drive (5th and above).

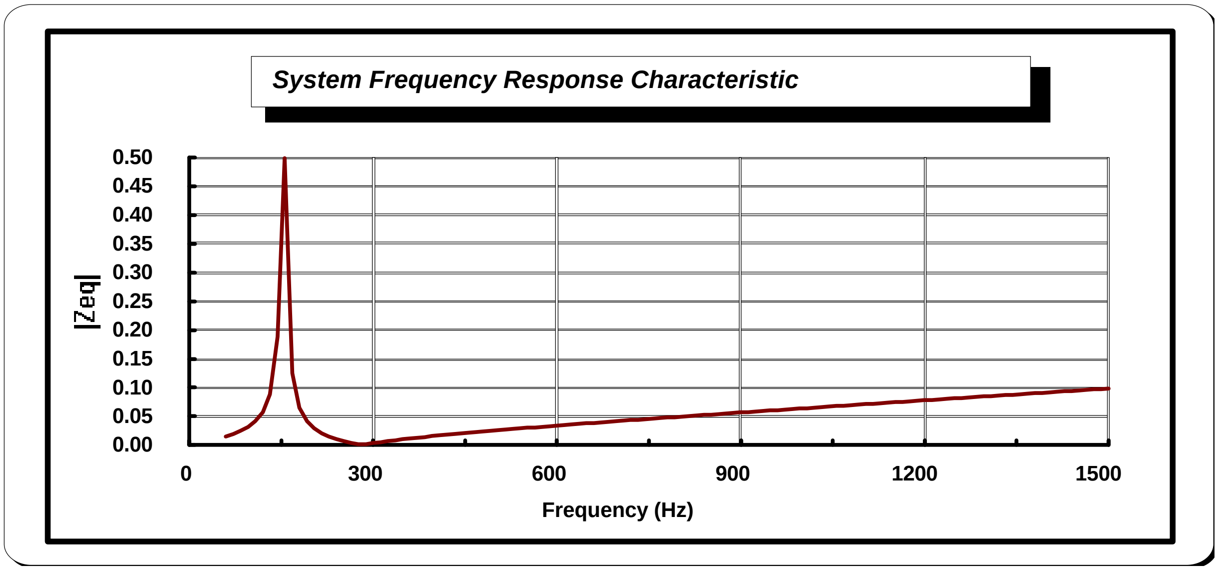


Figure 8. Frequency Response Looking from 480 Volt Bus with Two 600 kVAr Filters in Service

Evaluation of Current Limits in IEEE 519

The newest version of IEEE 519, "Recommended Practice for Harmonic Control in Electric Power Systems", provides recommended harmonic current limits for individual customers at the point of common coupling with the electric utility. The utility supplying the new facility has specified these harmonic current limits in the contract with Klockner-Pentaplast. Therefore, it is important to make sure that the specified harmonic filters will adequately limit the harmonic currents injected onto the utility system.

A few assumptions are required to make this evaluation. A short circuit capacity at the transformer high side of 23 MVA is assumed. This is relatively low because the plant is supplied from a long 34.5 kV feeder circuit. Worst case harmonic generation levels are assumed which do not include significant cancellation from the different drives. The IEEE 519 evaluation is based on an "average maximum demand current" defined as the average of the monthly maximum demand values for twelve months. For a new plant this must be estimated. 3000 kVA was used for this evaluation.

Figure 9 evaluates the expected current distortion levels with respect to the IEEE 519 limits for the case without compensation or harmonic filters. The limits are exceeded at almost every individual harmonic frequency and for the total demand distortion (TDD).

Figure 10 illustrates the effect of the proposed 600 kVAr filters on the expected harmonic current levels being injected onto the utility system. These values were obtained from a simulation of the system response. The limits are not exceeded at any individual frequency or for the total demand distortion. There should be no problem with the IEEE 519 limits for the proposed filter configuration.

System Data:	**KLOCKNER-PENTAPLAST - Rural Retreat**				
Conditions:	**No Filters**				
Transformer =	3750	kVA			
Impedance =	6.00	%	Total Z =	0.0137	Ohms
Source Strength =	23	MVA	Low Side Strength =	16.81	MVA
Max. Avg. Demand kVA =	3000	kVA	Short Circuit Ratio =	5.60	
Max. Avg. Dem. Current=	3613	Amps			

Harmonic Number	Frequency (Hz)	Load Harmonics (Amps)	IEEE Current Limit (%)	IEEE Current Limit (Amps)	Exceeds Limit
1	60	3613	N/A	N/A	N/A
3	180		4.00%	145	OK
5	300	995	4.00%	145	**Exceeds**
7	420	198	4.00%	145	**Exceeds**
11	660	274	2.00%	72	**Exceeds**
13	780	78	2.00%	72	**Exceeds**
17	1020	76	1.50%	54	**Exceeds**
19	1140	38	1.50%	54	OK
TDD:	>>>>>>>>>>>>>>>	29.26%	5.00%		**Exceeds**

Figure 9. IEEE 519 Evaluation Without Filters

System Data:	**KLOCKNER-PENTAPLAST - Rural Retreat**				
Conditions:	**Two 600 kVAr Filters**				
Transformer =	3750	kVA			
Impedance =	6.00	%	Total Z =	0.0137	Ohms
Source Strength =	23	MVA	Low Side Strength =	16.81	MVA
Max. Avg. Demand kVA =	3000	kVA	Short Circuit Ratio =	5.60	
Max. Avg. Dem. Current=	3613	Amps			

Harmonic Number	Frequency (Hz)	Load Harmonics (Amps)	IEEE Current Limit (%)	IEEE Current Limit (Amps)	Exceeds Limit
1	60	3613	N/A	N/A	N/A
3	180		4.00%	145	OK
5	300	47	4.00%	145	OK
7	420	38	4.00%	145	OK
11	660	72	2.00%	72	OK
13	780	22	2.00%	72	OK
17	1020	22	1.50%	54	OK
19	1140	11	1.50%	54	OK
TDD:	>>>>>>>>>>>>>>>	2.76%	5.00%		OK

Figure 10. IEEE 519 Evaluation With Two 600 kVAr Filters

SUMMARY

DC Drive loads can have a low displacement power factor, resulting in a need for power factor correction. The power factor correction can be sized based on the displacement power factor of the load but all of the compensation should be installed as harmonic filters to avoid harmonic resonance problems and excessive voltage distortion levels. Filters tuned below the fifth harmonic will usually be adequate to keep voltage distortion levels below 5% and current harmonics injected onto the utility system below the levels specified in IEEE 519.

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[2] T. Grebe, "Why Power Factor Correction Capacitors May Upset Adjustable Speed Drives," Power Quality, May/June, 1991.

[3] M.F. McGranaghan, R.M. Zavadil, G. Hensley, T. Singh, M. Samotyj, "Impact of Utility Switched Capacitors on Customer Systems - Magnification at Low Voltage Capacitors," Presented at the 1991 IEEE T&D Show, Dallas, TX, September, 1991.

[4] Revised Standard IEEE 519, submitted for approval Spring, 1992.