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POWER FACTOR CORRECTION and HARMONIC FILTERS AT THE AGS

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Technical Note

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Introduction

Power factor correction of a linear inductive load can be readily achieved by employing a bank of shunt capacitors to compensate the reactive component of load current. The lagging component of load current is compensated by an equal value of leading current. Basically the load and capacitors are (parallel) resonated at the power line frequency. A second resonance exists between the compensating capacitors and the inductance of the power distribution system. The second resonance is usually at a much higher frequency than the frequency of the power system, limiting the maximum level of power factor compensation. The limitation is due to voltage (harmonic) distortion introduced into the power system and to harmonic currents that are forced to flow through other loads that are connect to the power distribution system.

For non-linear loads the load current is distorted and consists of an infinite series of harmonic of the power line frequency. The harmonic currents are generated at the load and flows into the second resonant circuit. If any harmonic component of current excites a resonance response in the second resonant circuit than the line voltage will distort and the power distribution system can be adversely effected. In addition, the harmonic currents flowing in the transformer are enhanced by the resonance phenomenon and can be larger than the harmonic currents generated by the load. This can cause overheating of the affected transformer and further voltage distortion.

An interesting example of the resonant phenomena is the power factor correcting capacitor bank installed by LILCO at Substation 603 (Temple Place). The power system inductance is characterized by the short circuit capacity (SCC-VA) of the system and its capacitance by the on-line reactive compensation (Q-VAR's). The normalized resonant frequency is given by

$$n = \frac{F}{Fo} = \sqrt{\frac{SSC}{Q}}$$

It is customary in this area to express frequency in normalized units or harmonic number, that is normalized with respect to the power system frequency. The short circuit capacity at Temple Place is 1920 MVA; the LILCO capacitor bank is rated 16.2 MVAR. The resonance is at 10.9 and can be excited by the 11^{th} harmonic which is generated by both 6^{-} pulse and 12 pulse rectifiers. In addition, the 7^{th} and 13^{th} harmonics are enhanced by the resonant phenomena. From the theory of reactive networks the reactance, x, of a resonant circuit is

Many of the larger loads on site are non-linear. They are multi-phase rectifiers. The harmonic content of the line current for these loads are well known. The non-zero harmonics are at a frequency of nf_o, where

$$n = (mq \pm 1)$$

where q = total number of rectifier phases
m is any integer 1, 2, 3 ....

If commutation overlap is neglected than the magnitude of the harmonics are inversely proportional to the harmonic number n.

$$I_n = \frac{I_o}{n}$$

where I_o is the fundamental component of line current.

Thus, for a 6-phase rectifier the non-zero harmonic currents are

$$I_5 = \frac{1}{5}I_o$$
$$I_7 = \frac{1}{7}I_o$$
$$I_{11} = \frac{1}{11}I_o$$
$$I_{13} = \frac{1}{13}I_o,$$

and for a 12-phase rectifier

$$I_{11} = \frac{1}{11}I_o$$
$$I_{13} = \frac{1}{13}I_o.$$

Harmonic distortion of line current is reduced in value due to commutation overlap. Thus, by using these levels of distortion the design procedure is a worse case scenario. In designing a power factor correcting network the series resonant frequency of the branch is set to a value that is less than the lowest non-zero harmonic. This will ensure that the load harmonics cannot excite a resonant response. It should be pointed out that the 5^{th} and 7^{th} are generated in 12 pulse rectifiers do to various unbalance. These values are normally considered

Harmonic Loading

The maximum allowable harmonic loading of the filter is dependent on the voltage rating of the capacitors employed in the filter. For filters installed on the 480 volt distribution system both 480 volt and 600 volt power factor correcting capacitors have been evaluated. The maximum design values of current and voltage of the power capacitors are in accordance with IEEE Standard 18-1980. The limits are given as a percentage of the name-plate rating:

Peak Voltage	120%
RMS Voltage	110%
RMS Current	180%
KVA	135%

As an appropriate example consider a 480 volt installation of a 100 KVAR compensating network tuned to the 4.7th harmonic. A comparison of the name plating rating for 480 volt and for 600 volt capacitor are given in Table I.

Parameters	480 Volt Capacitor	600 Volt Capacitor
Reactive Power	100 KVAR	150 KVAR @ 600 Volts 96 KVAR @ 480 Volts
Capacitance (y-equivalent)	1151 μF	1105 μF
Line Current	120.3 A	144.2 A @ 600 V 115.5 A @ 480 V
Line Voltage	480 Volts	600 Volts

TABLE I

Name Plate Ratings of 100 KVAR Compensating Network

The limits for current and voltage in the power capacitors are given in Table II

Parameters	Design Limits	
	480 Volt Capacitors	600 Volt Capacitors
Peak Voltage	576 Volts	720 Volts
RMS Voltage	528 Volts	660 Volts
RMS Current	216.5 A	259.6 A
VA	135 KVA	202.5 KVA

TABLE II

Design Limits For Power Capacitors

REACTIVE COMPENSATION	MAXIMUM LOAD
100 KVAR	1.28 MVA
200 KVAR	2.06 MVA
300 KVAR	2.76 MVA
400 KVAR	3.58 MVA
500 KVAR	4.30 MVA

TABLE III
Maximum Load with 600 Volt Capacitors Tuned to 4.7^{th} Harmonic

Two Frequency Harmonic Trap

Multiple harmonic filters are employed to trap a multiple number of harmonics of the load current and provide power factor correction. If the reactive compensation is fixed then the design requires an allocation of the fixed value of reactive compensation between the various filters. As an example, consider a 100 KVAR network consisting of a 5^{th} and 7^{th} harmonic trap, tuned to 4.7 and 6.6 respectively. If the division of the 100 KVAR compensation is allocated between the 5^{th} (Q_5) and 7^{th} (Q_7) such that the harmonic induced voltages are equal, then Q_5 and Q_7 are in the ratio of 2:1. This is seen as follows:

I_o is the fundamental component of line current,

$\frac{I_o}{n}$ is the harmonic current in the filter,

C is the capacitance of the filter,
ω is the radian frequency of the power system,

then the harmonic induced voltage is

$$\frac{I_o}{n} \frac{1}{\omega cn}.$$

For equality of the 5^{th} and 7^{th} harmonic voltages

$$\frac{I_o}{\omega C_5 (5)^2} = \frac{I_o}{\omega C_7 (7)^2}.$$

Thus $C_5 \approx 2\ C_7$ and $Q_5 = 2\ Q_7$. For the 100 KVAR network the 5^{th} harmonic filter employs

$$\sqrt{(\frac{1}{5})^2 + (\frac{1}{7})^2} = .246$$

or 24.6%.

The harmonic distortion has been calculated for the two filters and is given in Appendix E. For the single frequency filter, the 7th harmonic distortion is constant at $\frac{1}{7}$. All values for current harmonic distortion are normalized with respect to the fundamental component of line current. The results are given in Table V; D is the value of current distortion due to the 5th and 7th harmonics.

REACTIVE COMPENSATION	SINGLE FREQUENCY FILTER $D_7 = \frac{1}{7}$		TWO FREQUENCY FILTER		
	D_5	D	D_5	D_7	D
100 KVAR	.139	.199	.155	.109	.189
200	.107	.178	.126	.088	.153
300	.086	.167	.107	.075	.131
400	.073	.160	.092	.065	.113
500	.063	.156	.081	.057	.099

TABLE V

Current Harmonic Distortion with a 5th Harmonic Filter (tuned to 4.7)
and a 5th and 7th Harmonic Filter (tuned to 4.7 and 6.6)

Table V indicates that for the same capacitor bank the two frequency harmonic filter is more effective than a single frequency filter in reducing current harmonic distortion. For a single frequency filter the distortion cannot be reduced below that of the 7th harmonic, 14.3%.

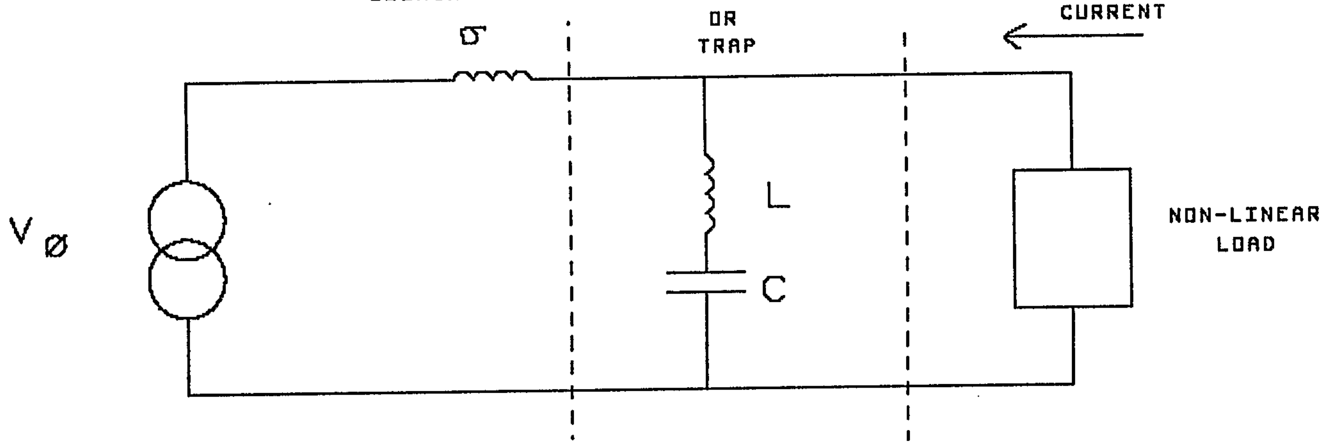


Figure 1

Basic Power Factor Correction Network

$V_\emptyset$ = Phase Voltage

σ = Output Source Inductance

C = Compensating Capacitor

L = Tuning Inductor

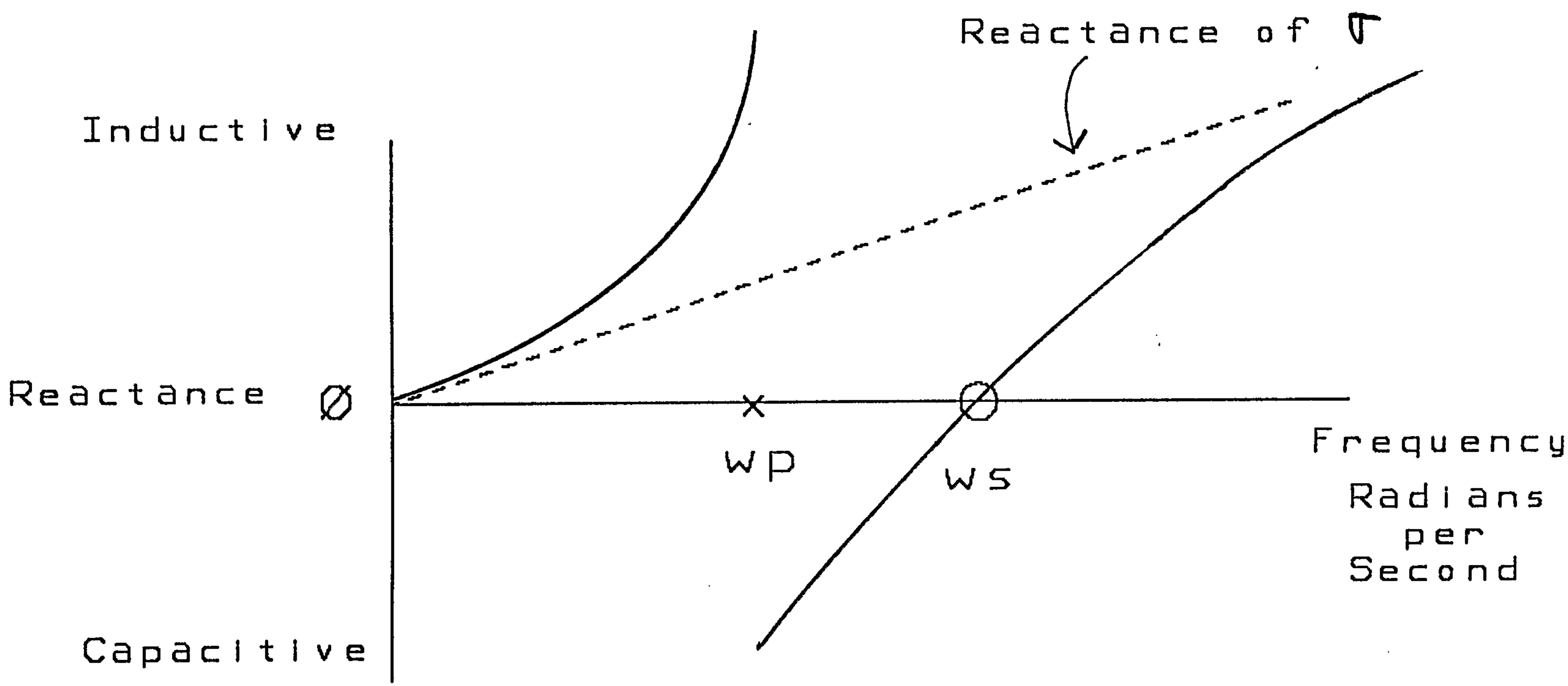


Figure 2

Reactance Plot of

Power Factor Corrective Network

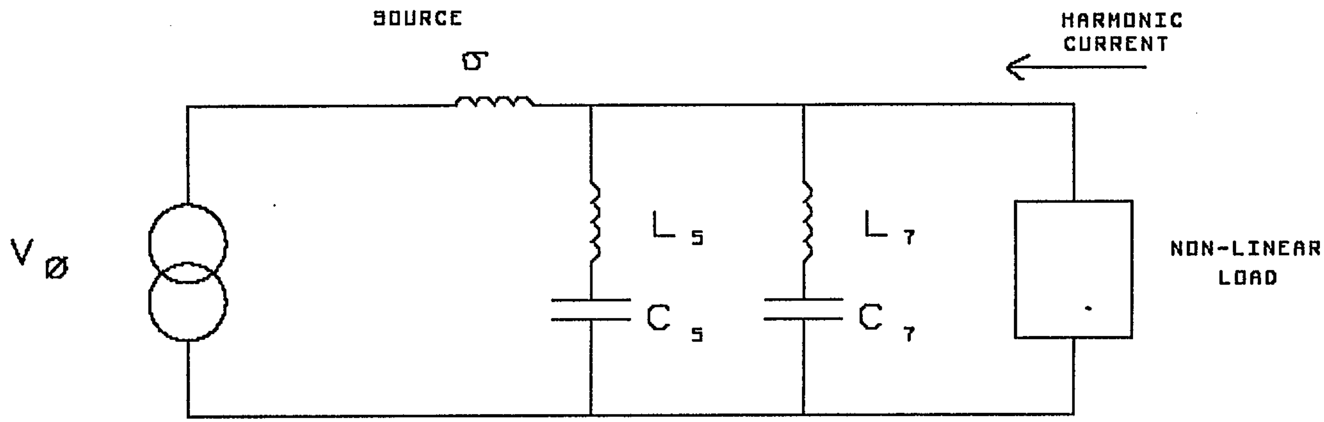


Figure 3

Power Factor Correcting Network

with Two Harmonic Traps

5th & 7th

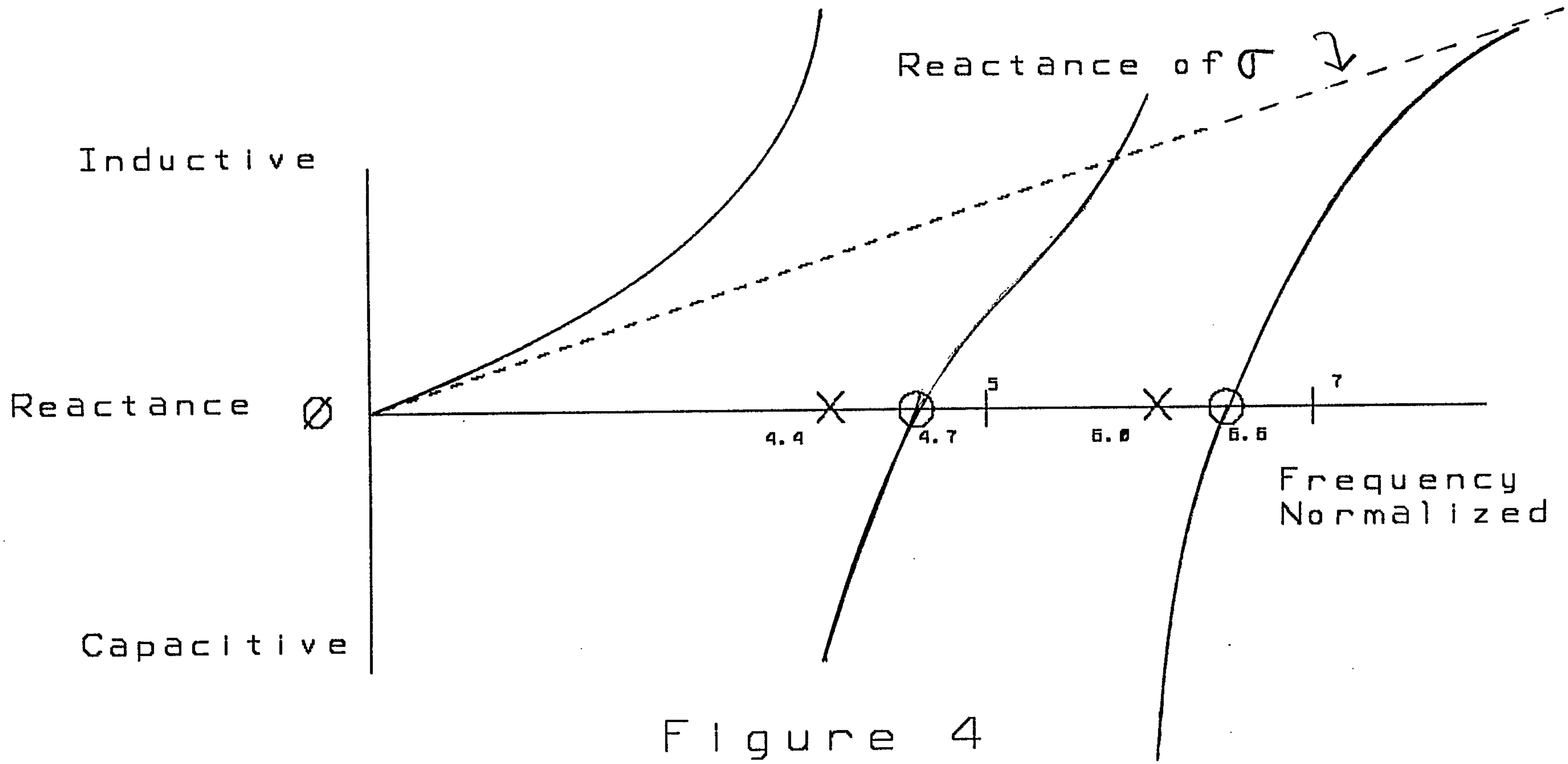


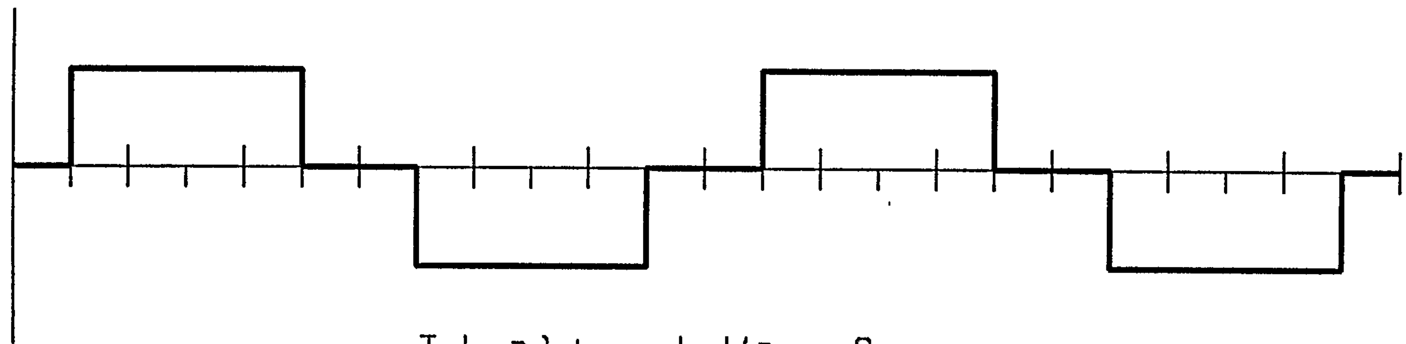
Figure 4

Reactance Plot of

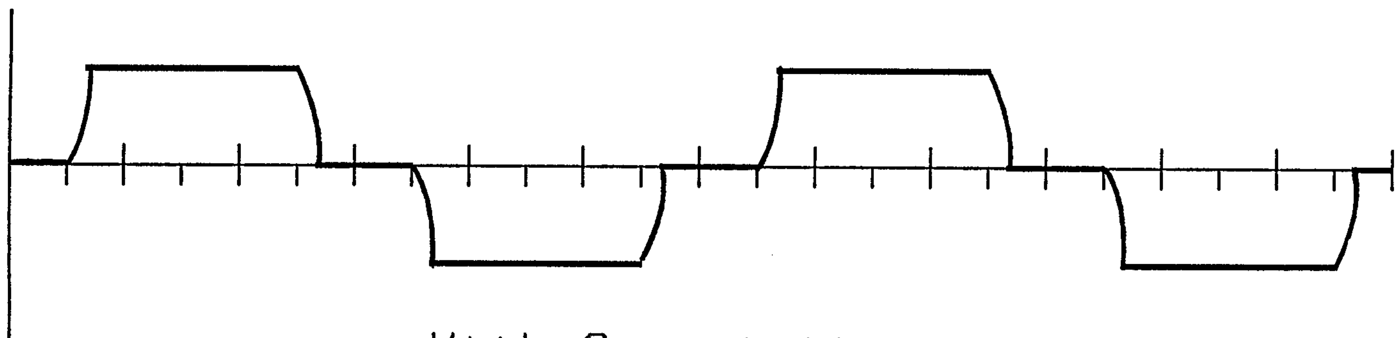
Power Factor Corrective Network

for

Figure 3



Idealized Waveform



With Commutation
Overlap

Figure 5
Line Current with
and without
Commutation Overlap

Appendix A

Maximum Fifth Harmonic Loading

Consider a 100 KVAR reactive compensating network turned to 4.7. Justification of the maximum harmonic loading for capacitors rated at 480 volts and 600 volts is included. With 480 volt capacitors the value of capacitance (y equivalent) is 1151 μF and the reactance to the fundamental current is 2.304 ohms; to the 5th harmonic current, .461 ohms. The fundamental current is 126A and the 5th harmonic current is 87.7A. This is depicted in Figure A-1. Using linear superposition the peak and RMS value of capacitor voltage, RMS current, and KVA is calculated and normalized with respect to the name plate rating. The maximum 5th harmonic loading is determined by the KVA rating of the power capacitors and is 87.7A.

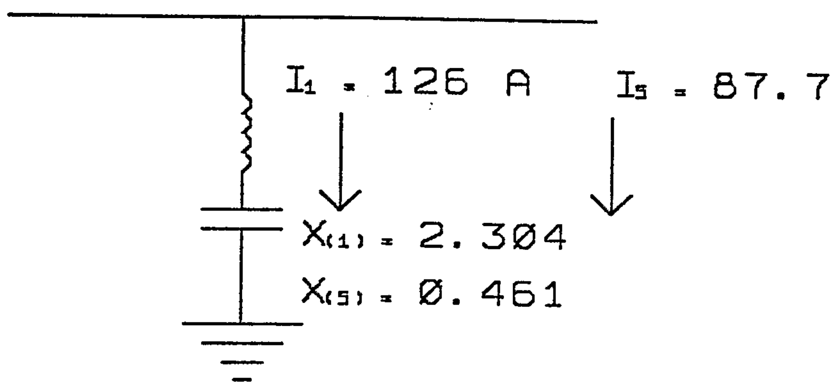


Figure A-1

$v(1) = 290.3$ V (ϕ) $= 502.82$ V (L-L)

$v(5) = 40.41$ V (ϕ) $= 70$ V (L-L)

$V_{RMS} = \sqrt{(502.8)^2 + (70)^2} = 507.65$ (106%)

$V_{peak} = 502.8 + 70 = 572.8$ (119%)

$I_{RMS} = \sqrt{(126)^2 + (87.7)^2} = 153.5A$ (128%)

$VA = \sqrt{3} \, x \, 507.65 \, x \, 153.5 = 135 \, KVA$ (135%)

With 600 volt capacitors the value of capacitance is 1105 μF, the reactance to the fundamental is 2.4 ohms, and to the fifth harmonic is 0.48 ohms. The fundamental current is 121A and the fifth harmonic current is 186 A and is depicted in Figure A-2.

Appendix B

Utility Generated - Fifth Harmonic Current

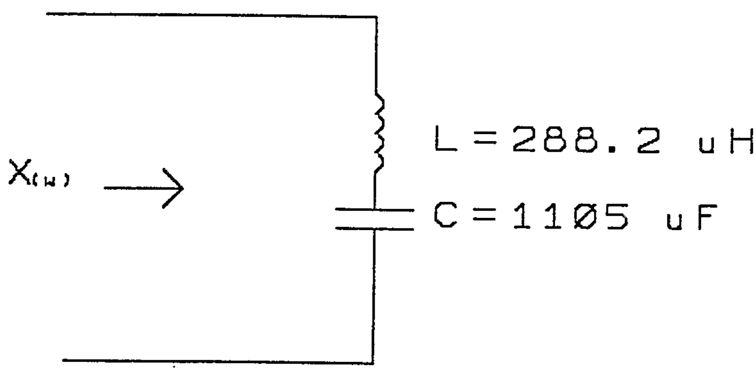
Specifications of the sub-station transformer required to calculate the 5th harmonic current due to the source (utility) voltage distortion.

Line Voltage = 480 Volts
Phase Voltage = 277.1 Volts
Rating = 2.5 MVA
Maximum Symmetrical Fault Current = 50,000 A
High Voltage Distoration:
    5th Harmonic = 3%
    7th Harmonic = 2%
Calculation of the transformer reactance

$$x = \frac{277.1}{50,000} = 5.542 \, milliohms \ at \ 60hZ$$

$= .0277$ Ohms @ 5th harmonic

Reactance of harmonic filter



$$X(\omega) = -\frac{1}{\omega C}\left[1-\left(\frac{\omega}{\omega_o}\right)^2\right]$$

where ω = frequency variable
ω_o = resonant frequency, normalized value of 4.7

at the 5th harmonic

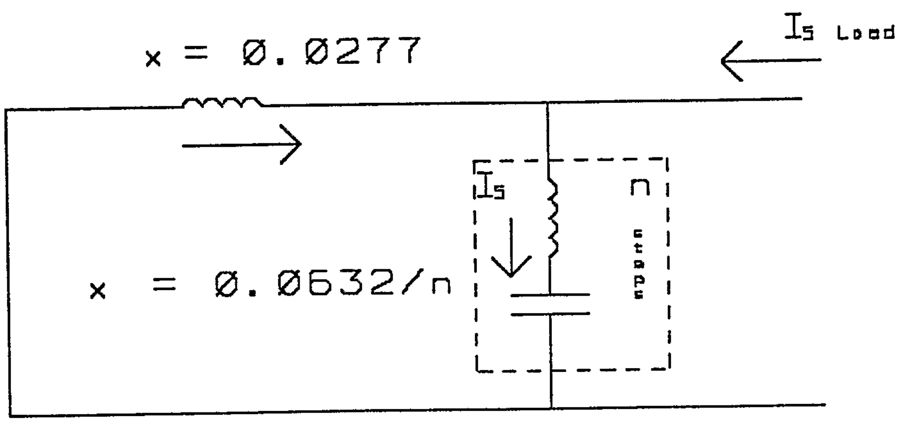
Number of Steps, n	Total Maximum Allowable 5th Harmonic Current	I_5 From Utility	I_5 From Load
1	186 A	91.4 A	94.6 A
2	372	140.2	231.8
3	548	170.5	377.5
4	744	191.	553.
5	920	206.	714.

Table B-1
Distribution of 5^{th} Harmonic Current

Appendix C

Attenuation of Load Generated Fifth Harmonic Current

The equivalent circuit developed in Appendix B can be used to calculate the fraction of load generated 5th harmonic current trapped by the harmonic filter



$$\frac{I_5}{I_{5LOAD}} = \frac{.0277}{.0277 + \frac{.0632}{n}}$$

This ratio is tabulated in Table C-1. In addition, this table contains the maximum allowable fifth harmonic current in the filter that is attributable to the load (from Appendix B). From this information the maximum allowable fifth harmonic current generated by the load and the KVA rating of the load can be calculated. For example, with a one-step harmonic filter the fraction of current trapped by the filter is .305. The maximum harmonic current of the filter is 186A; 91.4A is due to the 3%-3rd harmonic voltages distortion of the utility. Thus, 94.6A is due to the load. The load generated 5th harmonic current, is 310A, 94.6/.305. With 20% fifth harmonic current the fundamental component of load current is 1550A and the load is calculated

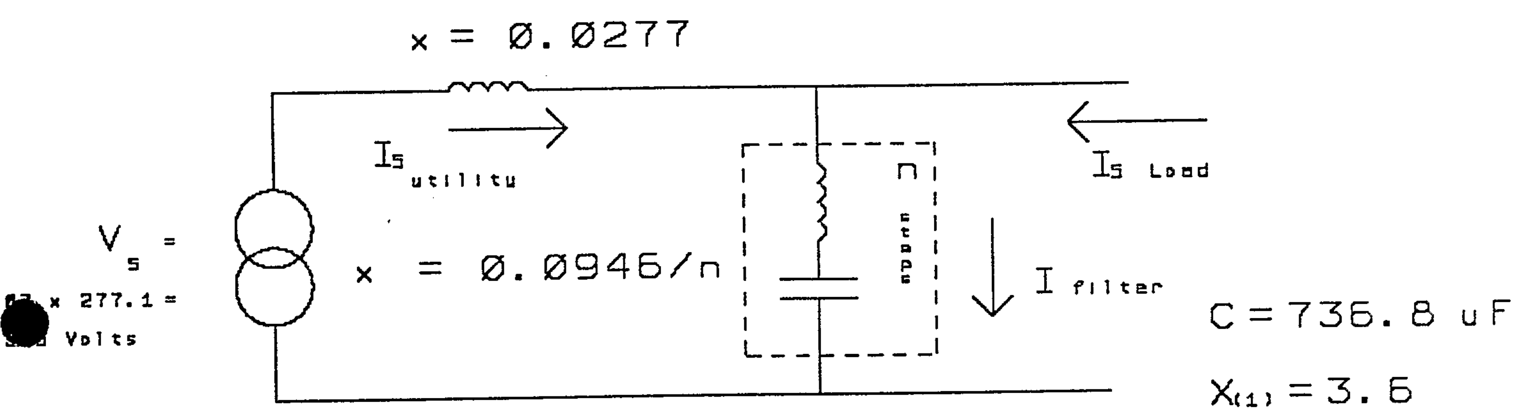
as $\sqrt{3} \; x \; 1550 \; x \; 480 = 1.28 \; MVA.$

Appendix D

Analysis of Two Harmonic Filter

This analysis combines the procedure developed in Appendices A, B, and C for a fifth and seventh harmonic filter with n sections. Each section is rated 100 KVAR @ 600 V (67 KVAR @ 480 V) and 50 KVAR @ 600 (33 KVAR @ 480 V). The filters are tuned to 4.7 and 6.6.

The equivalent circuit for the 5^{th} harmonic filter is



$$I_{5UTILITY} = \frac{8.313}{.0277 + \frac{.0945}{n}}$$

$$\frac{I_{5FILTER}}{I_{5LOAD}} = \frac{.0277}{.0277 + \frac{.0948}{n}} \qquad x(5) = \frac{-3.6}{5}\left[1-\left(\frac{5}{4.7}\right)^2\right] = .0948\,ohms$$

The results of the analysis is given in Table D-1.

n	Maximum Value of I_5 in Filter	$I_{5UTILITY}$	$I_{5FILTER}$	$\frac{I_{5FILTER}}{I_{5LOAD}}$	I_{5LOAD}	I_o I_{LOAD} Fundamental	Load
1	124A	67.9 A	56.1 A	.226	248.2 A	1241 A	1.03 MVA
2	248	110.7	137.3	.369	372.1	1861	1.55
3	372	140.2	231.8	.467	496.4	2482	2.06
4	496	161.7	334.3	.539	620.2	3101	2.58
5	620	178.2	441.8	.594	743.8	3719	3.09

Table D-1
Analysis of 5th Harmonic Filter

n	Maximum Value of I_7 in Filter	$I_{7UTILITY}$	$I_{7FILTER}$	$\frac{I_{7FILTER}}{I_{7LOAD}}$	I_{7LOAD}	I_o Load Fundamental	Load
1	66 A	33.1A	32.9A	.232	141.8A	992.6A	.83MVA
2	132	53.8	78.2	.381	205.2	1436.	1.19
3	198	67.9	130.1	.475	273.9	1917.	1.59
4	264	78.1	185.9	.547	339.9	2379.	1.98
5	330	85.9	244.1	.601	406.1	2842.	2.36

Table D-2
Analysis of 7th Harmonic Filter

Appendix E

Harmonic Distortion in Line Current

Using the data in Tables C-1, D-1, and D-2 the reduced value of harmonic distortion in the line current can be estimated. As an example, for the single frequency filter with 3-100 KVAR steps the fifth harmonic current diverted by the filter is .568 of the fifth harmonic component of load current. The fifth harmonic is 0.2 of the fundamental load current I_o. Thus, the fifth harmonic current that is flowing in the power systems is .432 x 0.2 I_o or .086 I_o. The seventh harmonic current in the power system is .143 I_o. The harmonic distortion due to the 5th and 7th harmonic is $\sqrt{(.086)^2 + (.143)^2} = .167 \; or \; 16.7\%$.

Table E-1 gives the result of this calculation. In a similar manner the harmonic distortion of the two frequency filter is calculated; the reduction of the 5th and 7th is individually calculated and combined. The results of this calculation is given in Table E-2.

Number of Steps n	$\frac{I_{5FILTER}}{I_{5LOAD}}$	$\frac{I_{5SYSTEM}}{I_{5LOAD}}$	$I_{5SYSTEM}$	Harmonic Distortion
1	.305	.695	$.139I_o$	19.9%
2	.467	.533	$.108I_o$	17.8%
3	.568	.432	$.086I_o$	16.7%
4	.637	.363	$.073I_o$	16.0%
5	.687	.313	$.063I_o$	15.6%

Table E-1
Harmonic Distortion of Line Current Single Frequency Filter