- Not all generated harmonic current flows through the harmonic filter
  - Some is absorbed by parallel load and some will go into the utility source
  - Worst case (highest current through filter) is with negligible parallel load and a high impedance (low fault current) source

			Harmonic order			
System	**Fundamental**		**5th**	**7th**	**11th**	**13th**
System voltage	34.5	kV (phase to phase)				
Short circuit current	10	kiloamperes				
Impedance	1.992	Ohms				
X/R ratio	10					
System reactance	1.982	Ohms				
System resistance	0.198	Ohms				
Filter						
Size	7420	rated kvar				
Current	124.2	Amperes				
Impedance	160.4	Ohms	4.4	29.2	68.4	86.0
Tuning	4.7	Harmonic order				
Capacitive reactance	168.0	Ohms $\frac{168}{5} \rightarrow$	33.6	24.0	15.3	12.9
Inductive reactance	7.6	Ohms $7.6 \times 5 \rightarrow$	38.0	53.2	83.7	98.9
Rectified load						
Total including factor of safety	30000	kva				
Current	502.0	Amperes $\frac{502}{5} \rightarrow$	100.4	71.7	45.6	38.6
System						
Parallel impedance		Ohms	3.07	9.45	16.61	19.92
Voltage (line to ground)	19918.6	Volts $100.4 \times 3.07 \rightarrow$	308.0	677.9	758.1	769.2
Filter Harmonic current		Amperes $\frac{308}{4.4} \rightarrow$	69.6	23.2	11.1	8.9
Total harmonic voltage	1311.7	Volts (rms)				
Voltage THD	6.59	Percent				

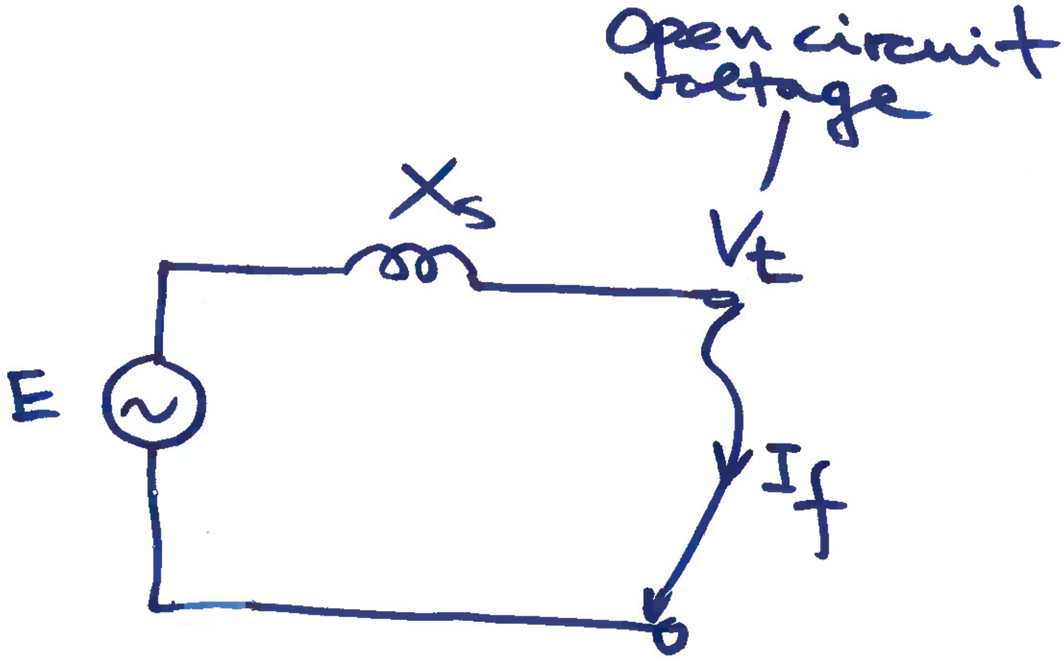
$S = \sqrt{3} V_L I_L$

$X_{eff} = X_C - X_L = 33.6 - 38$

$= \frac{34.5}{\sqrt{3}}$

$\frac{1311.7}{19918.6}$

$= \sqrt{308^2 + 677.9^2 + 758.1^2 + 769.2^2}$



$$I_f = \frac{E}{X_s}$$

Before the fault

$$E = V_t$$

$$\therefore I_f = \frac{V_t}{X_s}$$

$$\Rightarrow X_s = \frac{V_t}{I_f} = \frac{34.5/\sqrt{3}\ \text{kV}}{10\ \text{kA}} = 1.992\ \Omega$$

$$Z_s = \frac{34.5\ kV/\sqrt{3}}{10\ kA}$$

$$= 1.992\ \Omega$$

$$Z_s = \sqrt{R_s^2 + X_s^2}$$

$$= \sqrt{0.198^2 + 1.982^2}$$

$$= 1.992\ \Omega$$

where R_s, X_s are given

$$\frac{X}{R} = \frac{1.982}{0.198} = 10$$

$$S = \sqrt{3}\, V_L I_L$$

$$7420 = \sqrt{3}\, V_L I_L$$

$$\therefore\ I_L = \frac{7420}{\sqrt{3} \times 34.5}$$

$$= \underline{124.2\,A}$$

$$S = \sqrt{3}\, V_L I_L$$

$$30000 = \sqrt{3} \times 34.5 \times I_L$$

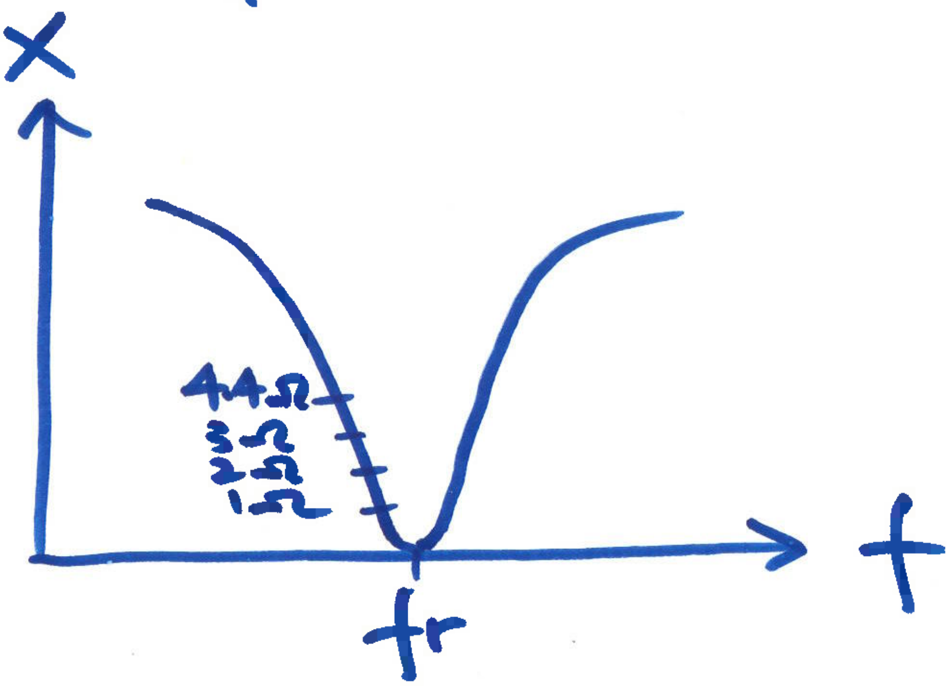
$$\therefore\ I_L = \frac{30000}{\sqrt{3} \times 34.5}$$

$$= \underline{502.4\,A}$$

At $f_r = 300$ Hz, $X_C = X_L$

At 6% below $f_r = 300$ Hz

$$X_{eff} = X_C - X_L$$



Due to system impedance variation filter reactance variation, component variation, etc.

$$4.4\,\Omega \xrightarrow{\text{Shift}} 0\,\Omega$$

- Total harmonic voltage across the capacitor,

$$V_C(1) = I_f(1)\,X_C = 124 \times 168 = 20{,}832\ \text{V}$$

$$V_C(h) = \sum_h I_f(h)\left(\frac{X_C}{h}\right) = 69.6 \times \frac{168}{5} + 23.2 \times \frac{168}{7} + 11.1 \times \frac{168}{11} + 8.9 \times \frac{168}{13} = 3{,}180\ \text{V}$$

- Voltage rating of the capacitor,

$$V_r = V_C(1) + V_C(h) = 20{,}832 + 3{,}180 = 24{,}012\ \text{V}$$

- Design should rate capacitor voltage at 100%, and reserving the 110% rms voltage and 120% peak voltage margins for contingency operation
- Based on line-to-line rated voltage and its impedance, the rated three-phase MVAr of the capacitor bank,

$$Q_{\text{rated}} = \frac{\left(\sqrt{3}V_r\right)^2}{X_C} = \frac{\left(\sqrt{3} \times 24.012\right)^2}{168.4} = 10.27\ \text{MVAr}$$

  - Capacitor rated MVAr is significantly larger than the filter effective reactive power (7.4 MVAr) because capacitor voltage rating is higher than nominal system voltage

- Nominal capacitor current based on rated voltage and MVAr,

$$I_{\text{nom}} = \frac{Q_{\text{rated}}}{\sqrt{3}V_{\text{rated}}} = \frac{10.27\ \text{MVAr}}{\sqrt{3} \times \left(\sqrt{3} \times 24\ \text{kV}\right)} = 142.6\ \text{A}$$

$$= \frac{144.8}{142.6} = 101.5\%$$

The calculated filter current of 144.8 A is only 101.5% of this nominal current, and thus complying with IEEE Std 18 (<135%)

- Dielectric heating of the capacitor must be acceptable,

$\frac{69.6\times168}{5}$ $\frac{23.2\times168}{7}$

$$\left|\sum_h \left(V(h)I(h)\right)\right| \le \left|1.35Q_{\text{rated}}\right|$$

$$\left|3\times(20.83\times124+2.34\times69.6+0.56\times23.2+0.17\times11.1+0.12\times8.9)\right| \le \left|1.35\times10270\right|$$

$$8{,}285 \le 13{,}865$$

- Filter capacitor is conservatively designed and meets all requirements
- Good to build certain contingency for harmonics from unidentified sources or new non-linear loads

- Filter reactor can be located at the source side of the capacitor or the neutral side
- If located at the source side, it should be rated to withstand a short circuit to ground at the junction between reactor and capacitor,

$$X_S = \frac{V_{\text{ll,nom}}}{\sqrt{3}I_{\text{SCBUS}}} = \frac{34.5\text{ kV}}{\sqrt{3}\times10\text{ kA}} = 1.99\ \Omega$$

$$I_{SC} = \frac{V_{\text{ll,nom}}}{\sqrt{3}(X_S+X_L)} = \frac{34.5\text{ kV}}{\sqrt{3}\times(1.99+7.63)} = 2.07\text{ kA}$$

  - $V_{\text{ll,nom}}$ nominal system line-to-line voltage
  - I_{SCBUS} available short-circuit current at bus
  - I_{SC} symmetrical short-circuit rating of reactor

- The quality factor Q (X/R ratio) of harmonic filter is not critical in most application, but is usually above 50

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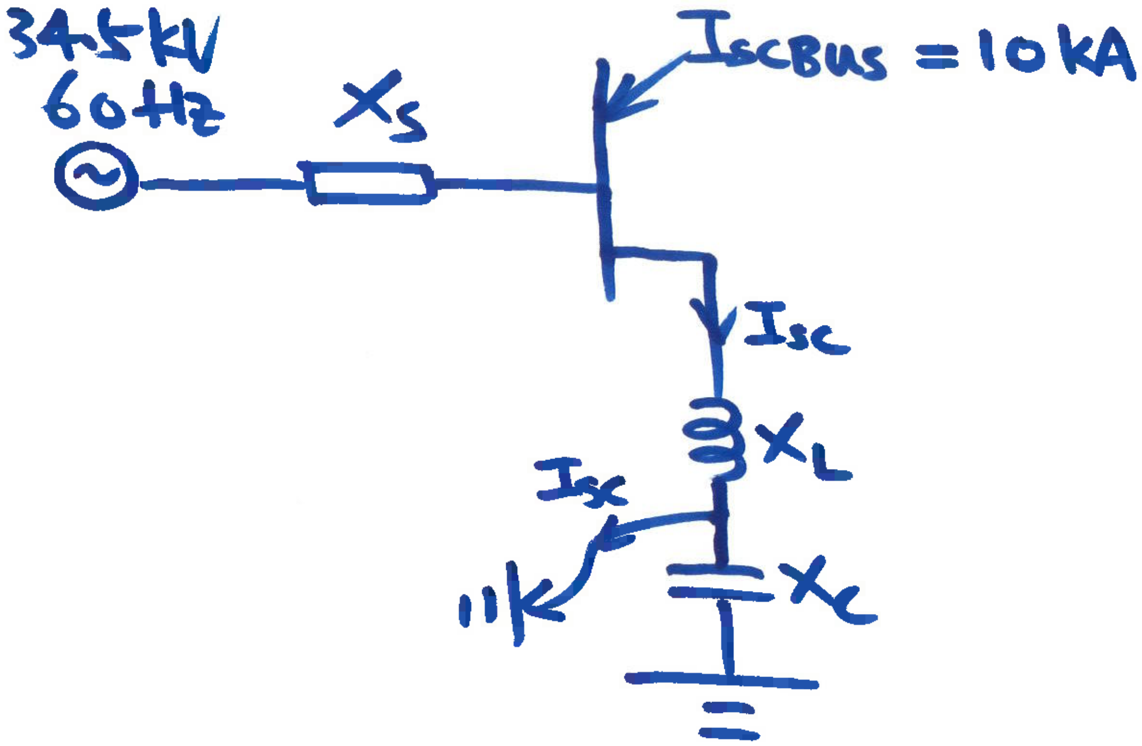
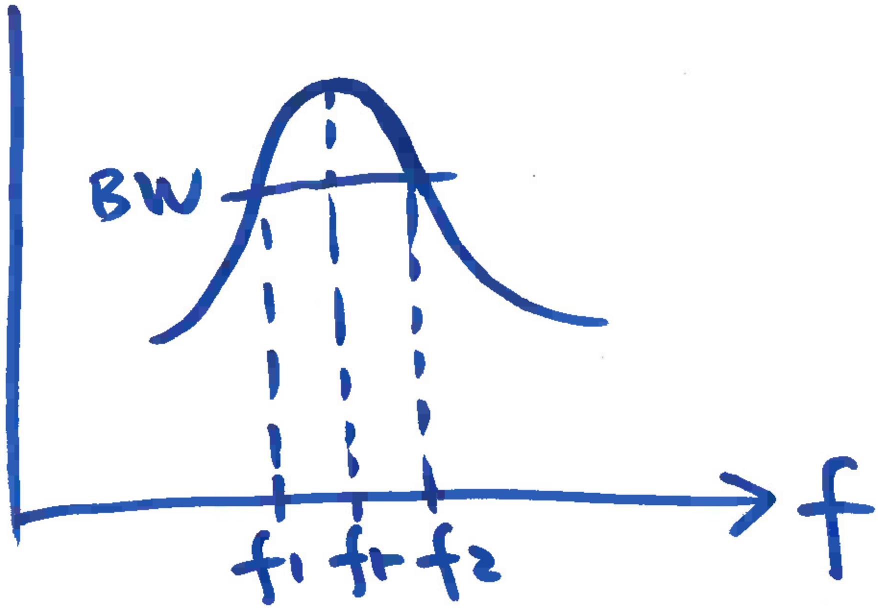
XR



$$X_S = \frac{V_L/\sqrt{3}\ \text{kV}}{I_{scBus}\ \text{kA}}\ \Omega$$

$$I_{sc} = \frac{V_L/\sqrt{3}\ \text{kV}}{(X_S + X_L)}\ \text{kA}$$

(19)



Q > 50, more selective

high Q affects the filter "selectivity" which means more selective.

$$BW = \frac{f_r}{Q} \Rightarrow Q\uparrow = \frac{f_r}{BW\downarrow}$$

The smaller the BW, the higher the circuit selectivity.

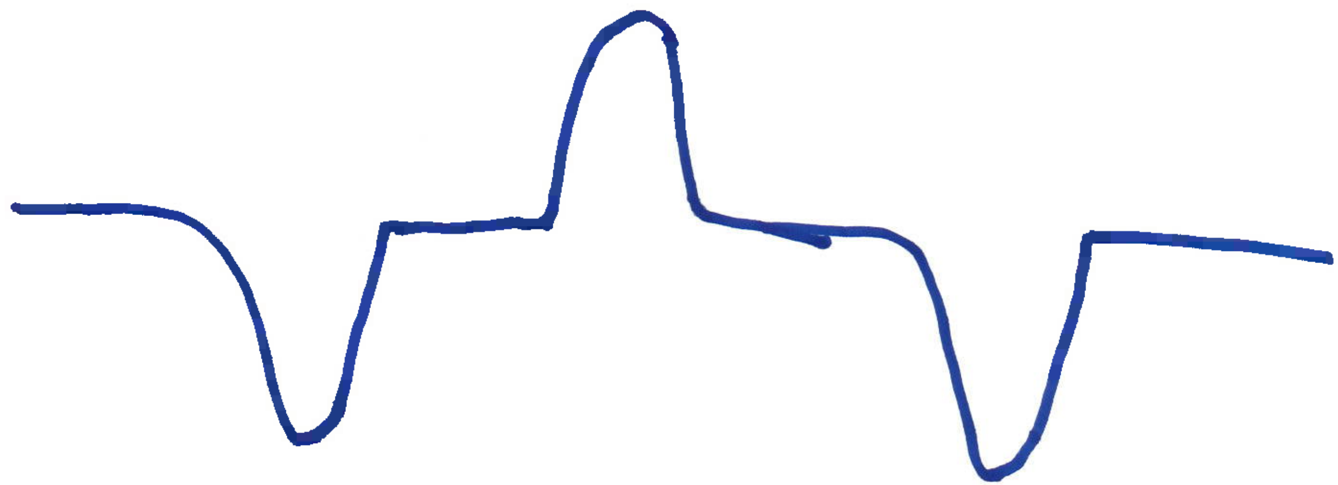
(1) 12-pulse system

$12k \pm 1$

(2) 24-pulse system

$24k \pm 1$

At PCC, voltage distortion



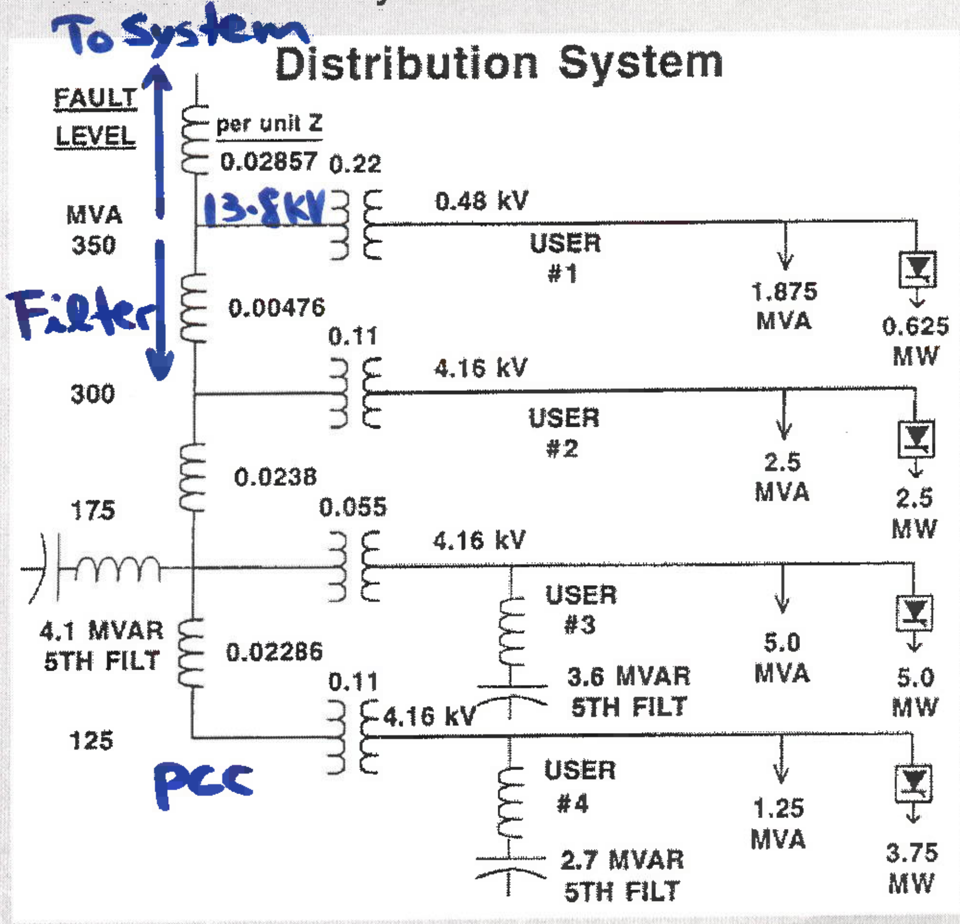
1. $$\downarrow SCR = \frac{I_{sc}}{I_L \uparrow}$$

2. $$\uparrow SCR = \frac{I_{sc}}{I_L \downarrow}$$

3. $$\downarrow SCR = \frac{I_{sc} \downarrow}{I_L}$$

Example of meeting harmonic limits

- A utility distribution feeder with four users along the feeder
  - Evaluate if meeting limit requirements and effectiveness of harmonic filter
  - Each user sees a different short circuit level or system size
  - User 1 @ I_{sc} / I_L ratio of 140
    - 350MVA, 14.6kA system
    - 2.5MVA, 104A load
    - 25% is converter with 26A
  - User 2 @ I_{sc} / I_L ratio of 60
    - 300MVA, 12.55kA system
    - 5MVA, 209A load
    - 50% is converter with 105A
  - User 3 @ I_{sc} / I_L ratio of 17.5
    - 175MVA, 7.32kA system
    - 10MVA, 418A load
    - 50% is converter with 209A
  - User 4 @ I_{sc} / I_L ratio of 25
    - 125MVA, 5.2kA system
    - 5MVA, 209A load
    - 75% is converter with 157A



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User #1

$$I_{sc} = \frac{350\,\text{MVA}}{\sqrt{3} \times 13.8\,\text{kV}} = \underline{\underline{14.6\,\text{kA}}}$$

$$I_1 = \frac{2.5\,\text{MVA}}{\sqrt{3} \times 13.8\,\text{kV}} = \underline{\underline{104\,\text{A}}}$$

$$SCR = \frac{I_{sc}}{I_1} = \underline{\underline{140}}$$

$$25\% \times 104\,\text{A} = \underline{\underline{26\,\text{A}}}$$

$$\text{Converter Load} = \frac{0.625}{2.5}$$

$$= 0.25 \text{ or } 25\%$$

User #1

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	4.99 /104	3.43	1.90	1.48	0.91	0.70	0.52	0.42	0.36	0.31	0.29	
% Distortion	4.80	3.33	1.83	1.42	0.87	0.67	0.50	0.40	0.35	0.30	0.28%	6.42%
Case B To System	2.49 /104	2.49	1.49	1.18	0.73	0.56	0.42	0.34	0.29	0.25	0.23	
To Filter	2.49	0.94	0.40	0.30	0.18	0.14	0.10	0.08	0.07	0.06	0.05	
% Distortion	2.39	2.39	1.43	1.13	0.70	0.54	0.40	0.33	0.28	0.24	0.22%	4.00%
Case C To System	3.50 /104	2.67	1.53	1.20	0.74	0.57	0.43	0.34	0.30	0.25	0.24	
To Filter	1.48	0.76	0.37	0.28	0.17	0.13	0.09	0.08	0.06	0.06	0.05	
% Distortion	3.77	2.57	1.47	1.15	0.71	0.55	0.40	0.33	0.29	0.24	0.23%	4.76%
Case D To System	2.50 /104	2.36	1.42	1.12	0.70	0.53	0.40	0.32	0.28	0.24	0.22	
To Filter	2.49	1.08	0.48	0.36	0.22	0.16	0.12	0.10	0.08	0.07	0.07	
% Distortion	2.40	2.26	1.36	1.07	0.67	0.51	0.38	0.31	0.27	0.23	0.21%	3.04%
IEEE Std 519 Limits	12%		5.5%		5.0%		2.0%				1.0%	15%

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User #2

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	20.2 209	13.9	7.66	5.99	3.68	2.84	2.10	1.68	1.47	1.26	1.16	
% Distortion	9.67	6.65	3.67	2.87	1.76	1.36	1.00	0.80	0.70	0.60	0.56%	13.0%
Case B To System	8.42	9.44	5.76	4.56	2.84	2.20	1.63	1.31	1.14	0.98	0.90	
To Filter	11.8	4.41	1.90	1.43	0.84	0.64	0.47	0.37	0.32	0.28	0.25	
% Distortion	4.03	4.52	2.76	2.18	1.36	1.05	0.78	0.63	0.55	0.47	0.44%	7.35%
Case C To System	13.2	10.3	5.94	4.68	2.89	2.24	1.66	1.33	1.16	1.00	0.92	
To Filter	7.01	3.6	1.72	1.31	0.79	0.60	0.44	0.35	0.31	0.26	0.24	
% Distortion	6.32	4.93	2.84	2.24	1.38	1.07	0.79	0.64	0.56	0.48	0.45%	9.1%
Case D To System	8.43	8.79	5.38	4.27	2.66	2.06	1.53	1.23	1.07	0.92	0.85	
To Filter	11.8	5.07	2.28	1.72	1.02	0.78	0.57	0.45	0.39	0.34	0.31	
% Distortion	4.03	4.21	2.57	2.04	1.27	0.99	0.73	0.59	0.51	0.44	0.41%	7.0%
IEEE Std 519 Limits	10%		4.5%		4.0%		1.5%				0.7%	12%

User #3

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	40.1 / 4.18	27.6	15.3	11.9	7.31	5.64	4.18	3.34	2.93	2.5	2.3	
% Distortion	9.59	6.60	3.66	2.85	1.75	1.35	1.00	0.80	0.70	0.60	0.55%	12.8%
Case B To System	0.01	12.5	8.78	7.03	4.44	3.45	2.58	2.07	1.82	1.56	1.44	
To Filter	40.1	15.1	6.52	4.87	2.87	2.19	1.60	1.27	1.11	0.94	0.86	
% Distortion	0.00	2.99	2.10	1.68	1.06	0.83	0.62	0.50	0.44	0.37	0.34%	4.37%
Case C To System	0.02	9.73	7.10	5.73	3.64	2.83	2.12	1.70	1.50	1.28	1.18	
To Filter	40.1	17.9	8.20	6.17	3.67	2.81	2.06	1.64	1.43	1.22	1.12	
% Distortion	0.00	2.33	1.70	1.37	0.87	0.68	0.51	0.41	0.36	0.31	0.28%	3.48%
Case D To System	0.04	10.3	7.50	6.05	3.84	2.99	2.24	1.80	1.58	1.35	1.25	
To Filter	40.1	17.3	7.80	5.85	3.47	2.65	1.94	1.54	1.35	1.15	1.05	
% Distortion	0.00	2.46	1.79	1.45	0.92	0.72	0.54	0.43	0.38	0.32	0.30%	3.68%
IEEE Std 519 Limits	4%		2.0%		1.5%		0.6%				0.3%	5.0%

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User #4

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	30.1 /209	20.7	11.5	8.95	5.50	4.24	3.14	2.51	2.20	1.88	1.72	
% Distortion	14.4	9.90	5.50	4.28	2.63	2.03	1.50	1.20	1.05	0.90	0.82%	19.3%
Case B To System	0.00	9.39	6.60	5.30	3.34	2.59	1.94	1.56	1.37	1.17	1.07	
To Filter	30.1	11.3	4.90	3.66	2.16	1.64	1.20	0.96	0.83	0.71	0.65	
% Distortion	0.00	4.49	3.16	2.54	1.60	1.24	0.93	0.75	0.66	0.66	0.51%	6.57%
Case C To System	0.01	6.17	4.64	3.76	2.40	1.87	1.40	1.12	0.99	0.85	0.78	
To Filter	30.1	14.5	6.86	5.19	3.10	2.37	1.74	1.39	1.21	1.03	0.94	
% Distortion	0.00	2.95	2.22	1.81	1.14	0.89	0.67	0.54	0.47	0.41	0.37%	4.50%
Case D To System	0.03	7.72	5.64	4.55	2.89	2.25	1.68	1.35	1.19	1.02	0.93	
To Filter	30.1	13.0	5.86	4.40	2.61	1.99	1.46	1.16	1.01	0.86	0.79	
% Distortion	0.01	3.69	2.70	2.18	1.38	1.08	0.80	0.65	0.57	0.49	0.45%	5.53%
IEEE Std 519 Limits	7%		3.5%		2.5%		1.0%				0.5%	8.0%

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Meeting harmonic voltage limits

User	Case	V_5	V_7	V_{11}	V_{13}	V_{17}	V_{19}	V_{23}	V_{25}	V_{29}	V_{31}	V_{35}	THD
#1	A	3.26	3.14	2.73	2.51	2.02	1.74	1.56	1.36	1.38	1.26	1.31	7.13
	B	0.37	1.62	1.70	1.60	1.32	1.14	1.03	0.90	0.92	0.84	0.87	3.93
	C	0.57	1.18	1.24	1.18	0.97	0.85	0.77	0.67	0.68	0.62	0.65	2.94
	D	0.38	1.39	1.50	1.42	1.17	1.02	0.92	0.80	0.82	0.75	0.78	3.48
#2	A	3.77	3.63	3.16	2.91	2.34	2.02	1.81	1.57	1.60	1.46	1.51	8.25
	B	0.41	1.86	1.96	1.85	1.52	1.32	1.19	1.04	1.06	0.97	1.01	4.53
	C	0.64	1.34	1.43	1.35	1.12	0.97	0.88	0.77	0.78	0.72	0.75	3.37
	D	0.41	1.60	1.72	1.63	1.35	1.17	1.06	0.92	0.94	0.86	0.90	3.99
#3	A	5.77	5.55	4.84	4.45	3.58	3.08	2.77	2.40	2.44	2.23	2.31	12.62
	B	0.00	2.52	2.78	2.63	2.18	1.89	1.71	1.49	1.52	1.39	1.44	6.39
	C	0.39	1.64	1.87	1.78	1.49	1.29	1.17	1.03	1.05	0.96	1.00	4.34
	D	0.00	2.07	2.37	2.26	1.88	1.64	1.48	1.29	1.32	1.21	1.26	5.47
#4	A	6.59	6.35	5.53	5.09	4.09	3.52	3.16	2.75	2.79	2.55	2.64	14.43
	B	0.82	3.31	3.47	3.27	2.69	2.33	2.10	1.03	1.87	1.71	1.77	8.02
	C	0.33	1.73	2.02	1.94	1.62	1.41	1.28	1.12	1.14	1.04	1.09	4.69
	D	0.83	2.86	3.07	2.90	2.39	2.08	1.88	1.64	1.67	1.53	1.59	7.12

A = System with no filters
B = System with 4.1 Mvar fifth harmonic filter at User #3, 13.8 kV bus
C = System with fifth harmonic filter at User #3 and #4, 4.16 kV bus
D = System with 5.8 Mvar fifth harmonic filter at User #3, 13.8 kV bus

Note: All values are in percent

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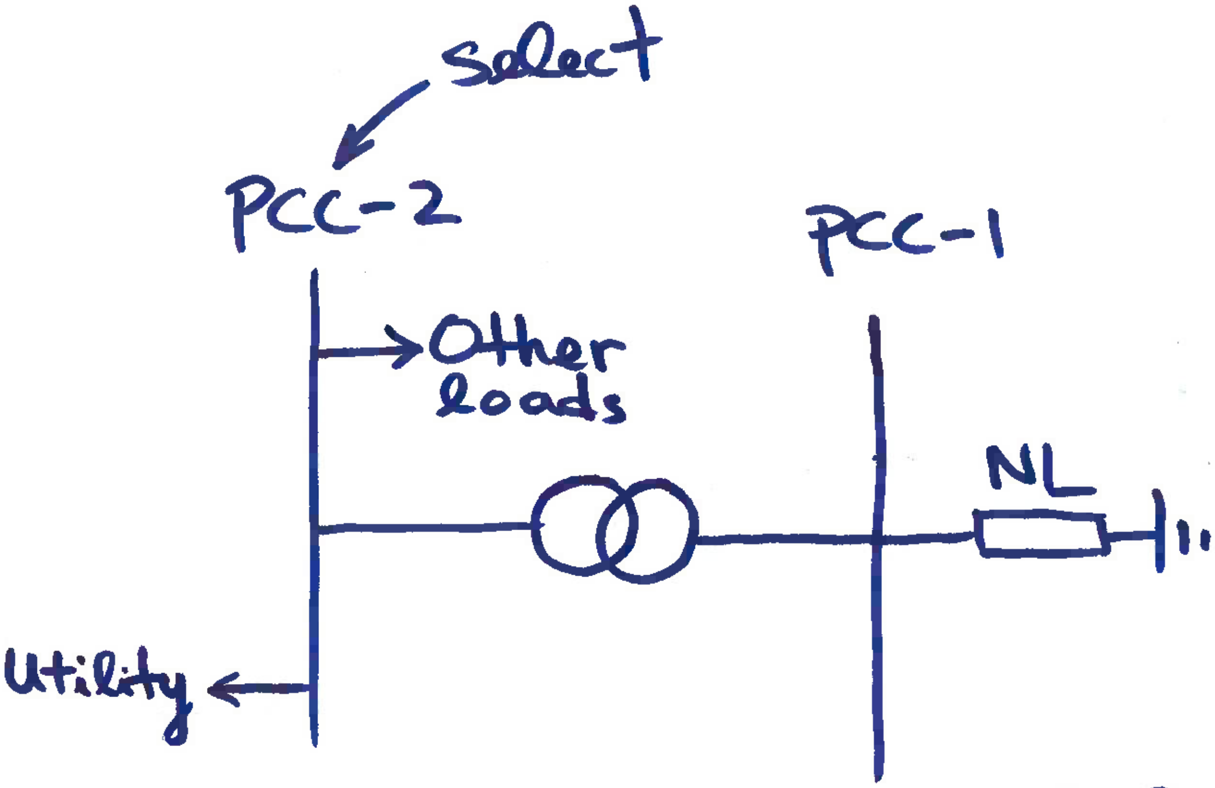
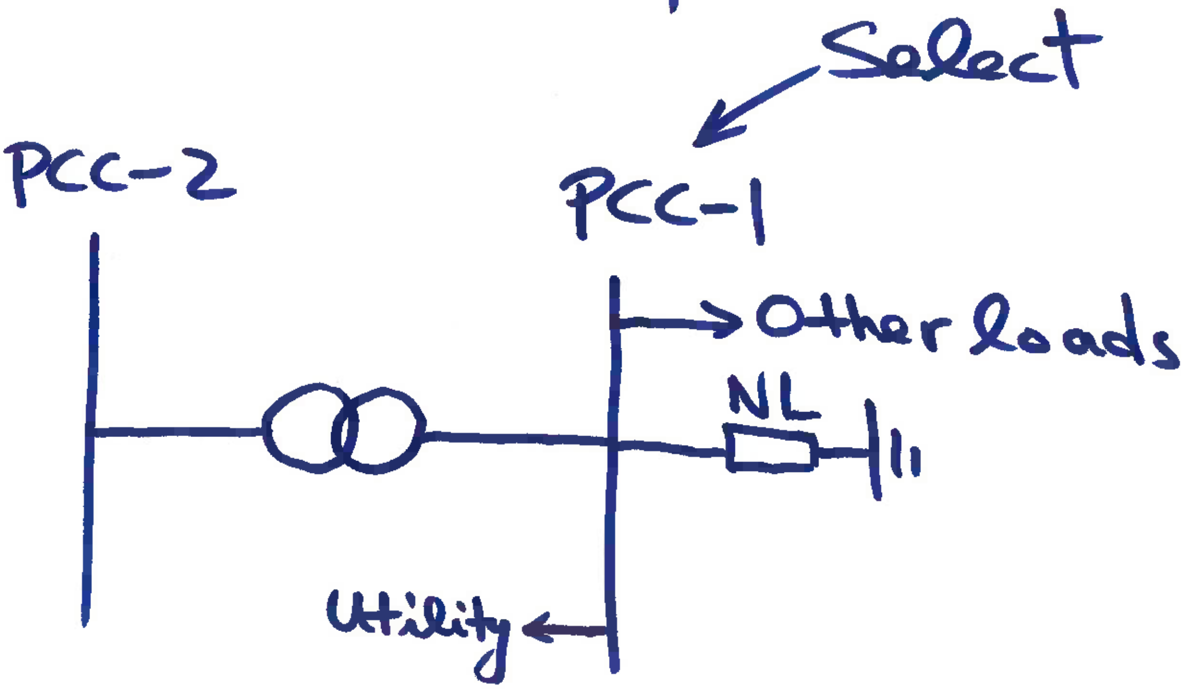
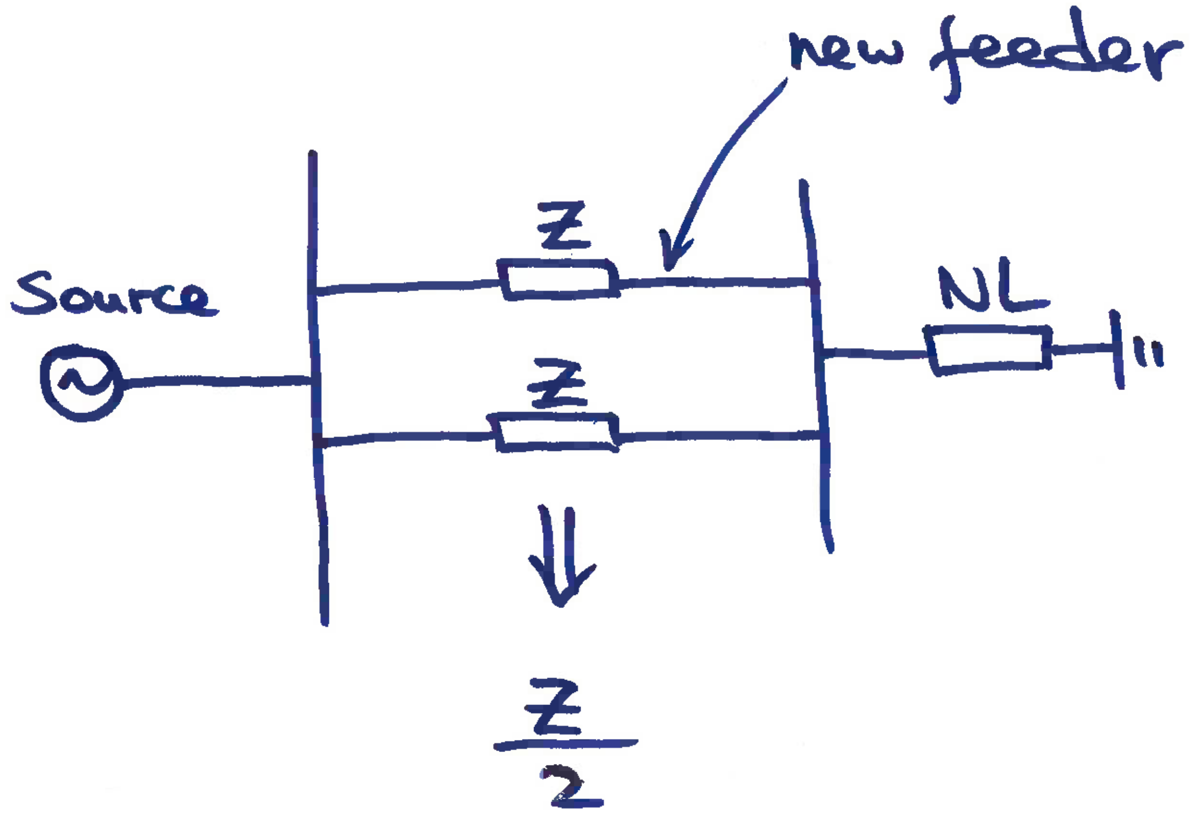


Select
PCC-2
PCC-1
Other loads
NL
Utility



Select
PCC-2
PCC-1
Other loads
NL
Utility


new feeder
Z
Source
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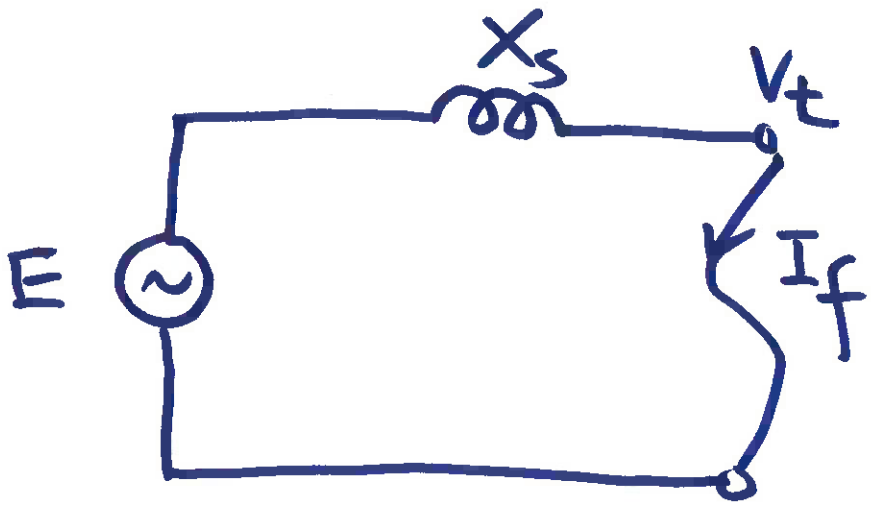
2



$$I_{fpu} = \frac{\overset{1\,pu}{E_{pu}}}{X_{spu}}$$

$$I_{fpu} = \frac{1}{X_{spu}} \; pu$$

$$I_{f\,actual} = \frac{1}{X_{spu}} \times I_b \; A$$

$$I_b = I_{rated}$$