

Preparing for Power System Calculations

Power Factor Correction with Harmonic Analysis



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Power Line Problems in Industrial Environments

The College of Engineering
University of Wisconsin - Madison

Department of Professional Development

2000 Seminar

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Outline of a Manual Method

- Define the power system
- Calculate **p.u. impedance's** for each of the circuit elements.
- Calculate **total system impedance** at key points in the electrical system.

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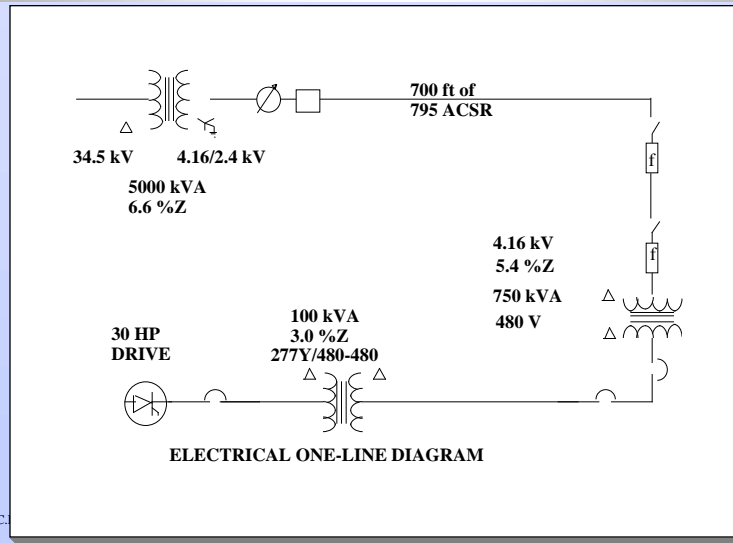
Outline of a Manual Method...

- Calculate available **short circuit currents** at key points in the electrical system.
- Calculate available **short circuit kVA** values at key points in the electrical system.

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Prepare a One Line Diagram of the Electrical System



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A1. Obtain Incoming Power Source Fault Current Data

Data required:

System Under Invest.

120, 240, 480 volt system
or above

4 kV to 138 kV system

Include Data On

Supplying system
at 4 kV

Supplying system
at next highest
voltage

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A2. Obtain Incoming Power Source Fault Current Data....

Data To Request from Utility:

- Present available three phase short circuit current in amps(sym) plus X/R ratio for present conditions.
- Future available three phase short circuit current plus X/R ratio for future conditions.

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A3. Obtain Incoming Power Source Fault Current Data....

Data we obtained for this example:

Base kV for pwr. supply = 34.5 kV

Present three phase short circuit current = 3200 A

X/R for present conditions = 5 (ratio)

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B1. Obtain Nameplate Data for Transformers

- Primary Connection (delta or wye)
- Primary Volts
- Secondary Connection (delta or wye)
- Secondary Volts
- Transformer Impedance (Z) in % (usually 1.8 to 7%)
- Transformer base rated kVA

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B2. Obtain Nameplate Data for Drives Transformers

- Primary Connection (delta or wye)
- Primary Volts
- Secondary Connection (delta or wye)
- Secondary Volts
- Transformer Impedance (Z) in % (usually 1.8 to 7%)
- Transformer base rated kVA

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B3. Transformer Data We Obtained for This Example

Transformer No. 1 Base rated kVA	5000	kVA
Transformer No. 1 Nameplate impedance in %	6.6	% Z
Transformer No. 1 Primary Winding in kV	34.5	kV
Transformer No. 2 Base rated kVA	750	kVA
Transformer No. 2 Nameplate impedance in %	5.4	% Z
Transformer No. 2 Primary Winding in kV	4.16	kV

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B5. Obtain Nameplate Data for Overhead Feeders

- Length of feeder in circuit feet
- Cable data:

Copper, aluminum, or ACSR (cu, al or ACSR)

Three or four wire system (3 or 4)

The above information will be used later to determine the actual Z at 60 Hz in Ohms for each cable section. The actual impedance will then be converted to p.u. Z.

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B6. Obtain Nameplate Data for Insulated Power Cables

- Length of feeder in circuit feet
- Cable data:
 - Copper or aluminum (cu or al)
 - Single or 3 conductor (1 or 3)
 - In magnetic duct (y/n)
 - In non-metallic duct (y/n)
 - Cable voltage rating INFO ONLY
 - URD or insulated power cable INFO ONLY

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B7. Obtain Nameplate Data for Capacitor Banks

- Capacitor kVAR rating in kVAR (3 phase)
- Connection (delta or wye)
- If wye connected, grounded? (y/n)
- Switched or fixed?
- If switched, mode of switching?
- (Time, voltage, current, PF)

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C1. Plan of Work

- Calculate **p.u. impedance's** for each of the circuit elements.
- Calculate **total system impedance at key points** in the electrical system.

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C1. Plan of Work...

- Calculate available **short circuit currents** at key points in the electrical system.
- Calculate available **short circuit kVA** values at key points in the electrical system. This will be used to calculate probable resonance points for capacitors applied at various locations on the system.

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C2a. Convert Data to PER UNIT

- All field data will be converted to equivalent per unit data based on a 100 mVA base and the appropriate base voltage.
- The base mVA for calculations is arbitrary, the base voltage is usually the system voltage as transformed by system transformers.

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C2b. Convert Data to PER UNIT

- For the sample electrical system, the base mVA was selected as 100 mVA or 100,000 kVA. The base voltage was 34.5 kV, 4.16 kV and 0.48 kV respectively for each of the three electrical systems.
- Base mVA, base kV, base current, and base impedance values were calculated as follows :

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What are BASE values?

Base mVA = 100 mVA (Users Choice)

Base kV = System voltage as changed by xfmrs.

$$\text{Base Amps} = \frac{\text{Base mVA} * 1,000}{\text{Base kV} * 1.732} = \text{Amperes}$$

$$\text{Base Z} = \frac{\text{Base kV} * 1,000}{\text{Base Amps} * 1.732} = \text{Ohms}$$

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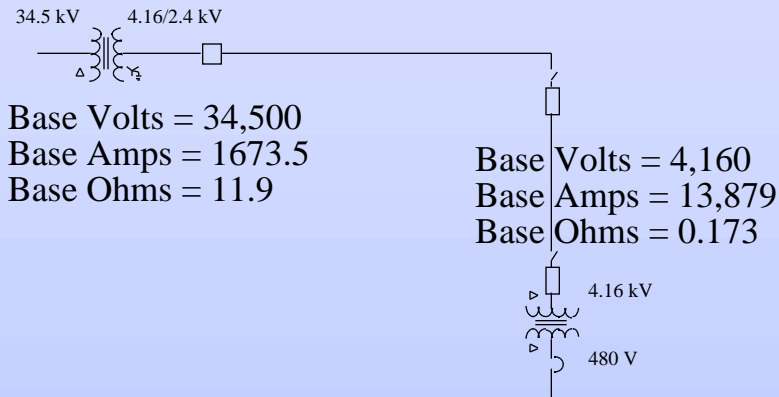
Base Values at 100 mVA

<i>Base kV</i>	<i>Base Current</i>	<i>Base Impedance</i>
0.12	481139.3	0.000144
0.24	240569.7	0.000576
0.48	120284.8	0.0023
2.4	24057.0	0.0576
4.16	13879.0	0.1731
12.47	4630.0	1.5550
24.9	2318.7	6.2001
34.5	1673.5	11.9025
69.0	836.8	47.6100
138.0	418.4	190.4400

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In a Pictorial Layout.....



Base Volts, Amperes and Impedance

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C3a. Utility Supply Data

- To Convert, use the following:

$$\text{Actual } Z_{\text{ (ohms)}} = \frac{\text{kV}_{(L-L)} * 1,000}{1.732 * I_{\text{ fault}}}$$

$$Z_{\text{ pu}} = \frac{\text{Actual } Z_{\text{ (ohms)}}}{\text{Base ohms}}$$

$$\text{X/R angle} = \arctan (\text{X/R ratio})$$

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C3b. Utility Data for Our Example

Base mVA selected for calculations	100	mVA
Base kV for power supply	34.5	kV
Present Three Phase Short Circuit Current	3200	Amperes
X/R ratio for present conditions	5	Ratio
Base Current	1673.48	Amperes
Base Ohms	11.90	Ohms
Actual Ohms impedance	6.2246	Ohms
Per unit impedance	0.5230	Ohms p.u.
X/R angle	78.69	degrees
	R	0.1026 Ohms p.u.
	X	0.5128 Ohms p.u.

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Use the “UTILITYZ” spreadsheet

The screenshot shows a spreadsheet titled 'UTILITYZ' with the following data:

	A	B	C	D	E	F
1	<i>Calculating Equivalent Utility Impedance</i>					
2						
3				Enter Data		
4	Base MVA selected for calculations			100	MVA	
5	Base kV for power supply			34.5	kV	
6						
7	Present Three Phase Short Circuit Current			3200	Amperes	
8	Present Phase to Ground Short Circuit Current			3200	Amperes	
9	X/R Ratio for present conditions			5	Ratio	
10						
11						
12	Calculated OUTPUT Data					
13				Answers		
14	Base Current			1673.48	Amperes	
15	Base ohms			11.90	Ohms	
16						
17	Positive and Negative Sequence Data					
18	Actual ohms impedance			6.2246	ohms	
19	Per Unit impedance			0.5230	ohms p.u.	
20	X/R angle			78.69	degrees	
21	R1 or R2			0.1026	ohms p.u.	
22	X1 or X2			0.5128	ohms p.u.	

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C4. Xfmr Nameplate to P.U.

To convert use the following formulas:

Per Unit Z (p.u.) =

$$\text{Nameplate } Z * \frac{1,000}{\text{Transformer kVA rating}}$$

X/R angle = arctan (X/R ratio) = ϕ

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Some Useful Information

An X/R ratio has to be assumed for the transformer.

Some typical X/R ratios are:

kVA Size	X/R Ratio	kVA Size	X/R Ratio
-----	-----	-----	-----
0	5	750	7
150	5	1000	8
225	5.5	1500	9
300	6	2000	12
400	6	2500	12
500	6		

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Remember, these are the xfmr's

Transformer No. 1 Base rated kVA	5000	kVA
Transformer No. 1 Nameplate impedance in %	6.6	% Z
Transformer No. 1 Primary Winding in kV	34.5	kV
Transformer No. 2 Base rated kVA	750	kVA
Transformer No. 2 Nameplate impedance in %	5.4	% Z
Transformer No. 2 Primary Winding in kV	4.16	kV

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And Here is the P.U. Data

	Transformer No. 1 =====	Transformer No. 2 =====
Base kVA	5000	750
Z in %	6.6	5.4
Primary	34.5	4.16
X/R Ratio	12	7
Z in p.u.	1.32	7.20
Z angle	85.24	81.87
R in p.u.	0.1096	1.0182
X in p.u.	1.3154	7.1276

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How Did We Get the Xfmr P.U.?

Formulas used for the above calculations are as follows:

Per Unit Z (p.u.) =

$$\text{Nameplate } Z \text{ (in\%)} * \frac{1,000}{\text{Transformer kVA rating}}$$

$$\text{X/R angle} = \arctan(\text{X/R ratio}) = \phi$$

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Use the "TRANSFZ" spreadsheet

	A	B	C	D	E	F	G	H
1	<i>Calculating Equivalent Transformer Impedance</i>							
2						kVA	X/R	
3						Size	Ratio	
4				Enter Data		0	5	
5	Base MVA selected for calculations	100	MVA			150	5	
6						225	5.5	
7	Transformer No. 1 Base rated kVA	5000	kVA			300	6	
8	Transformer No. 1 Nameplate impedance in %	6.6	% Z			400	6	
9	Transformer No. 1 Primary Winding in kV	34.5	kV			500	6	
10						750	7	
11	Transformer No. 2 Base rated kVA	750	kVA			1000	8	
12	Transformer No. 2 Nameplate impedance in %	5.4	% Z			1500	9	
13	Transformer No. 2 Primary Winding in kV	4.16	kV			2000	12	
14						2500	12	
15	Transformer No. 3 Base rated kVA	100	kVA			Lookup Table		
16	Transformer No. 3 Nameplate impedance in %	3	% Z					
17	Transformer No. 3 Primary Winding in kV	0.48	kV					
18	Calculated OUTPUT Data							
19		Transformer	Transformer	Transformer				
20								

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C5. Converting Cables to P.U.

- Converting cables and other circuit element impedance's to per unit impedance's at the base mVA is accomplished using the following formula.

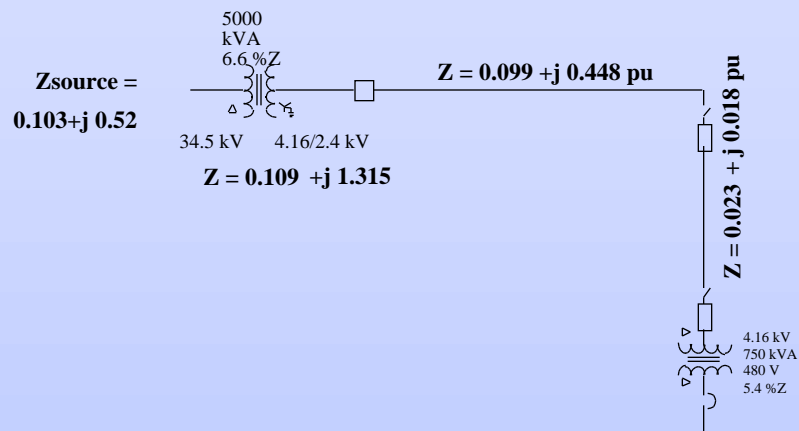
Per Unit Z (of item) =

$$\frac{\text{Actual imped. in ohms} * 100}{(\text{Base volts in kV})^2}$$

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The Impedance Diagram



Impedance Diagram

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D1. Calculating Source to Point Z's

- The impedance from each point of the system to the point of incoming supply must be known to calculate short circuit currents and short circuit kVA. Later this data will be used to evaluate the placement of drives and other harmonic producing equipment.
- I recommend summing impedance's using complex numbers and then converting to polar coordinates for final calculations.

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D2. Impedance in Each Section

Base mVA selected for calculations 100 mVA

	R in p.u. -----	X in pu -----	Base kV for the section -----
Section 1	0.103	0.513	34.5
Section 2	0.109	1.315	4.16
Section 3	0.099	0.448	4.16
Section 4	0.023	0.018	4.16

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D3. Imp. from Source to Point

	Subtotal R	Subtotal X
	-----	-----
Section 1	0.103	0.513
Section 2	0.212	1.828
Section 3	0.311	2.276
Section 4	0.334	2.294

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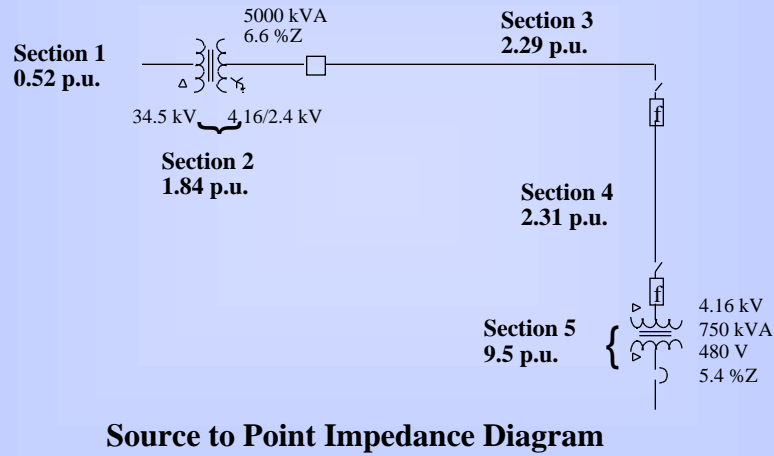
D3. Imp. from Source to Point

	Subtotal Z	Angle Z (deg)
	-----	-----
Section 1	0.5232	78.6
Section 2	1.8403	83.4
Section 3	2.2971	82.2
Section 4	2.3182	81.7

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D4. Imp. from Source to Point



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Use the “SOURCEPT” spreadsheet

SOURCEPT					
	A	B	C	D	E
1	<i>Calculating Source-to-Point Impedance</i>				
2					
3		Base MVA selected for calculations	100	MVA	
4					
5					
6			R in pu	X in pu	
7		Section 1	0.103	0.513	<i>Input</i>
8		Section 2	0.109	1.315	<i>Data</i>
9		Section 3	0.099	0.448	
10		Section 4	0.023	0.018	
11		Section 5	1.02	7.13	
12		Section 6	5.88	29.4	
13					
14					
15			Subtotal R	Subtotal X	
16		Section 1	0.103	0.513	<i>Rectangular</i>
17		Section 2	0.212	1.828	<i>Components</i>
18		Section 3	0.311	2.276	
19		Section 4	0.334	2.294	
20		Section 5	1.754	12.424	
21		Section 6	5.88	29.4	

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E. Calc. Short Ckt. Amps & kVA

- The impedance from each point of the system to the point of incoming supply is used to calculate short circuit currents and short circuit kVA.
- Using the per unit data calculated above, the short circuit currents and short circuit kVA at each point may be calculated.

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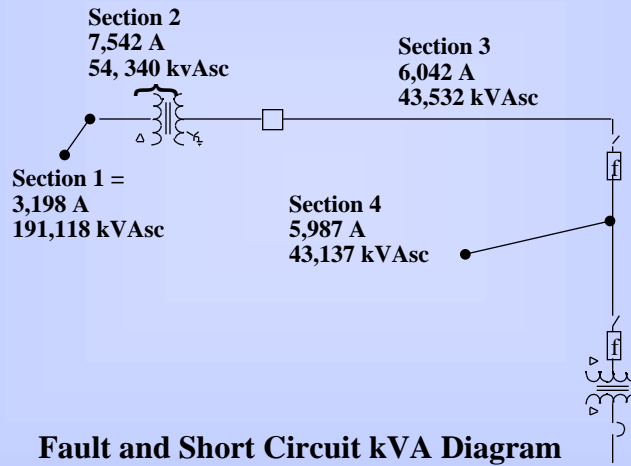
The following is a summary of the short circuit current and short circuit kVA for each point in our sample problem.

	Section Base kV -----	Section Base(A) -----	3 Phase Fault(A) -----	3 Phase SC kVA -----
Section 1	34.5	1,673	3,198	191,118
Section 2	4.16	13,878	7,542	54,340
Section 3	4.16	13,878	6,042	43,532
Section 4	4.16	13,878	5,987	43,137

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In a Pictorial Layout.....



Fault and Short Circuit kVA Diagram

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Use the "SCKVA" spreadsheet

The screenshot shows the SCKVA spreadsheet with the following data:

Section	R1 in pu	X1 in pu	Base kV for the section
Section 1	0.103	0.513	34.5
Section 2	0.109	1.315	4.16
Section 3	0.099	0.448	4.16
Section 4	0.023	0.018	4.16
Section 5	1.02	7.13	0.48
Section 6	5.88	29.4	0.48

Additional spreadsheet data:

- Base MVA selected for calculations: 100 MVA
- Subtotal R1: 0.212
- Subtotal X1: 1.828

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This Is What We Are Here For!!!!

Calculate Resonance Circuits In the Electrical Power System:

$$\frac{f_o}{60} = \sqrt{\frac{\text{kVA sc}}{\text{kVAR cap}}}$$

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Resonant Points of System Impedance and a Capacitor Bank

In our sample problem we will consider installing capacitors at various locations in the system. Using available short circuit kVA data:

	kVA Short Circuit -----
Section 1	191,118
Section 2	54,340

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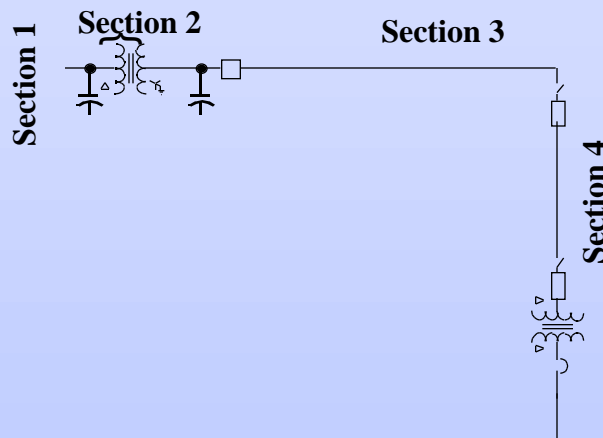
With Assumed kVARs of Power Factor Correction, the Following Results..

kVAR's of Capacitors	Resonant Harmonic Section 1 34.5 kV	Resonant Harmonic Section 2 4.16 kV
-----	-----	-----
150	35.7	19.0
300	25.2	13.5
450	20.6	11.0
600	17.8	9.5
750	16.0	8.5
900	14.6	7.8
1050	13.5	7.2
1200	12.6	6.7

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This is Where The Caps Are Located



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Use the “RESCALC” spreadsheet

RESCALC					
	A	B	C	D	E
1	<i>Calculating Resonance Points</i>				
2					
3					
4		kVA Short Circuit			
5	Section 1	191,118			
6	Section 2	54,340			
7	Section 5	10,503			
8	Section 6	2,532			
9					
10	kVAR's	Resonant Har	Resonant Har	Resonant Har	Resonant Har
11	of Capacitors	Section 1	Section 2	Section 5	Section 6
12	150	35.7	19.0	8.4	4.1
13	300	25.2	13.5	5.9	2.9
14	450	20.6	11.0	4.8	2.4
15	600	17.8	9.5	4.2	2.1
16	750	16.0	8.5	3.7	1.8
17	900	14.6	7.8	3.4	1.7
18	1050	13.5	7.2	3.2	1.6
19	1200	12.6	6.7	3.0	1.5
20	1350	11.9	6.3	2.8	1.4
21	1500	11.3	6.0	2.6	1.3

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Comments and Considerations

In this case notice how installing the same kVAR value of capacitors near the incoming supply reduced the likelihood of resonating with lower frequency harmonics. This is important since the 5th and 7th harmonics are usually significantly stronger than the 11th and the 13th. Of course it is possible for other harmonics to be present, which can only be determined by a frequency survey of the electrical system.

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A More Detailed Analysis May Be Required

- If there is more than one capacitor bank or adjacent customers that contribute to the problem, a more in-depth computer analysis is required.
- I combine a detailed computer analysis with a survey of the system voltage and load currents.
- The survey may include long term monitoring.

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