Power Factor Correction
A Practical Guide

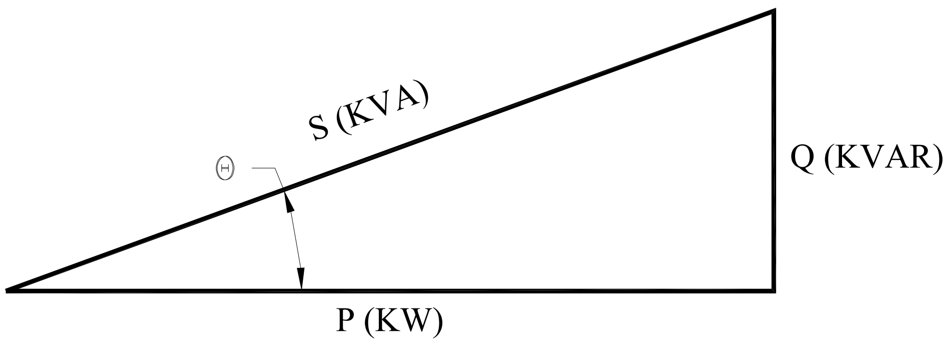
This guide was written to provide the maintenance engineer or plant engineer with a basic understanding of power factor. The guide also demonstrates that by correcting poor power factor loads with power capacitor banks, the capacity of the electrical system can be increased while simultaneously reducing the electric utility bills. The pitfalls of installing power capacitor banks on electrical systems that have non-linear loads are also presented.

A. Inductive Loads

The majority of the electrical loads found in modern facilities are inductive. The most common examples of inductive loads are motors and transformers.

Inductive loads require both active (P) and reactive power (Q). Active power is consumed by an inductive load to produce work. Active power is expressed in watts (W). Reactive power is consumed by an inductive load to produce the electromagnetic field. Reactive power is expressed in volt-amperes reactive (VAR). Reactive power circulates between the inductive load and the power source. This type of power places a heavier burden on the power source as well as on the power source's electrical distribution system.

Active power and reactive power make up apparent power (S). Apparent power is measured in volt-amperes (VA). The right triangle shown in Figure 1, also known as a power triangle, is often used to illustrate the relationship between active power, apparent power and reactive power.



Displacement Power Factor

The displacement power factor is the ratio of active power to apparent power at the fundamental frequency of the electrical system. The displacement power factor is often referred to as either the cosine (Θ) or power factor in a linear (non-harmonic producing) system.

The power factor is a measure of how effectively electricity is being used by a load. A high power factor means that the load is efficiently utilizing electrical power. The power factor can be determined from the following equation:

$$P_f = (\text{Active Power}) / (\text{Apparent Power})$$

For example, if a pump is consuming 200 KW of active power and 400 KVA of apparent power the power factor would be (200 KW) / (400 KW) or 0.50.

A low power factor means that you are not fully utilizing the electrical power that you are paying for. In the example above, the pump was only utilizing 50 % of the energy supplied to it to perform useful work.

The power triangles in Figure 2 demonstrate that the apparent power decreases as the power factor increases. The above-mentioned pump that is consuming 200 KW of active power would consume 250 KVA of apparent power at a power factor of 0.80.

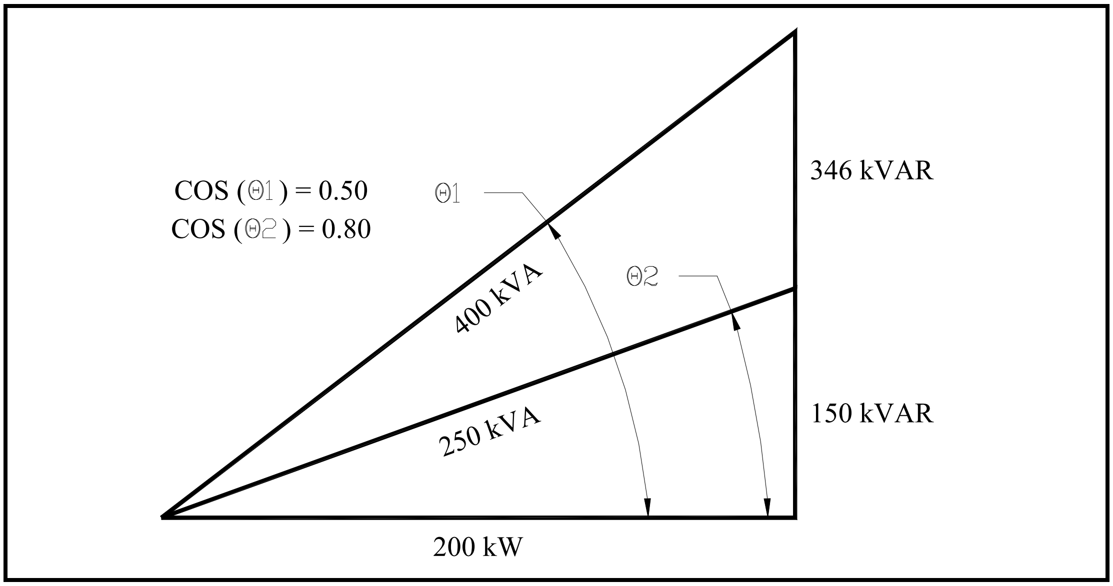
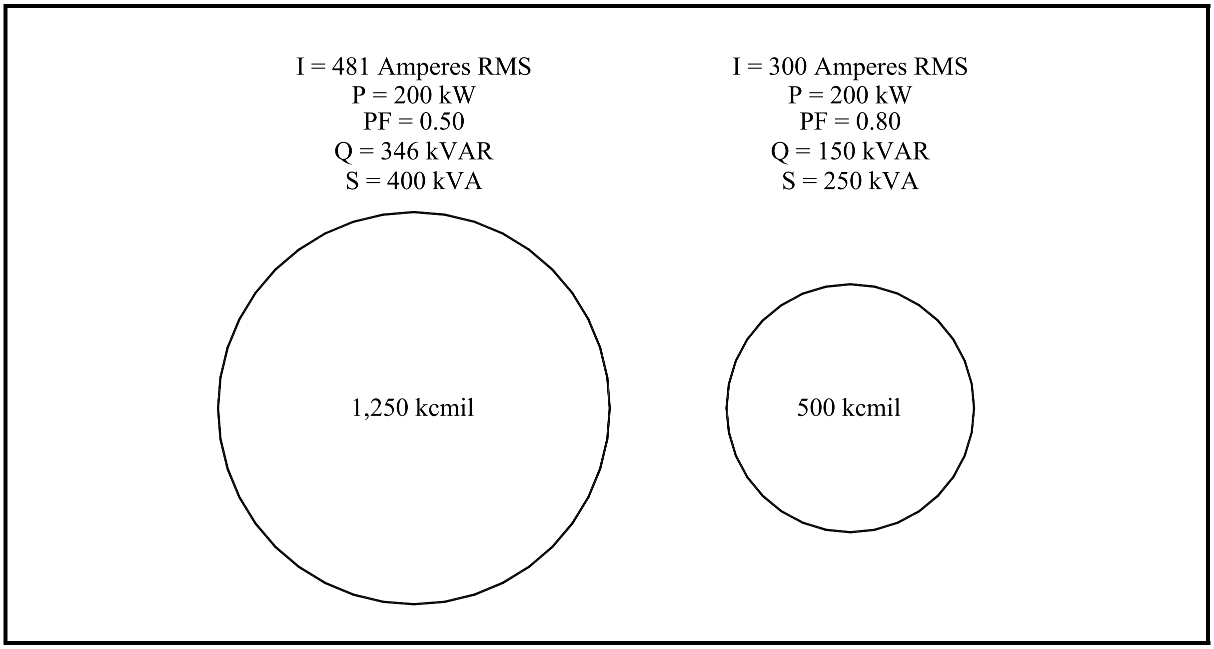
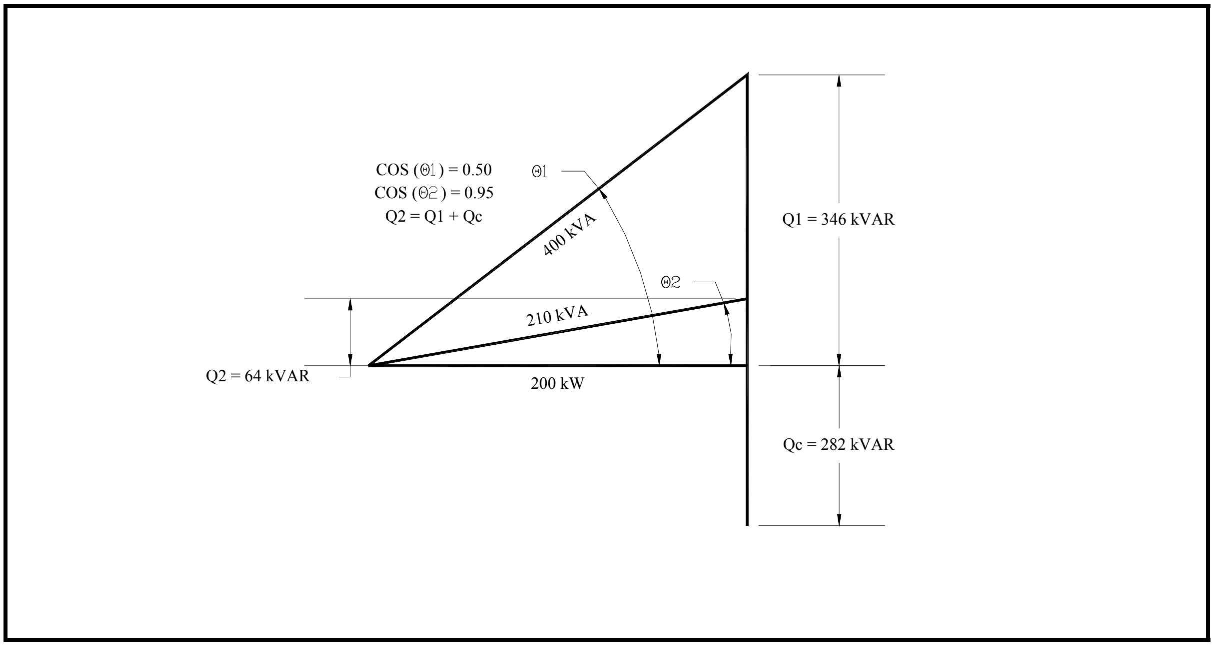


Figure 3 illustrates the effects of various power factors on the electrical system with an active power consumption of 200 KW at 480 Volts RMS. As the figure shows, the conductor size required for the 0.80 power factor load is 500 kcmil and the conductor size required for the 0.50 power factor load is 1,250 kcmil. The relative diameters of the two conductors are shown in the figure.

You can improve the power factor of a load by adding power capacitor banks to the electrical system. The source must supply reactive power to the load, when the apparent power (KVAR) is greater than the active power (KW). A power capacitor bank acts like a reactive power source. The power capacitor bank will reduce the amount of apparent power that has to be supplied by the source.



The power triangles of Figure 4 show the apparent power demands made on the electrical system before and after the addition of a power capacitor bank. By installing a power capacitor bank and increasing the power factor to from 50 % to 95 % the apparent power has been reduced from 400 KVA to 210 KVA, a reduction of 47.5 %.



Power capacitor banks provide the following benefits:

- Improved Voltage Stability
  A poor power factor load creates an excessive current requirement on the electrical distribution system. As the power factor of the load decreases, the line current requirements of the load increase resulting in reduced voltage at the load. The addition of a power capacitor bank at the low power factor load will reduce the current requirements of the load and thus increase the voltage at the load.

- Increased Electrical System Capacity
  A power capacitor bank can free up electrical system capacity. Consider the following example. A 200 KW load operating at a 0.40 power factor is connected to a 500 KVA step-down transformer. The load consumes 500 KVAR of apparent power, 458 KVAR of reactive power and the transformer is operating at a load factor of (500 KVA) / (500 KVA) or 1. If the power factor of the load is corrected to 0.95 then the load consumes 200 KW of active power, 210 KVA of apparent power and 64 KVAR of reactive power. The load factor of the step-down transformer is now (210 KVA) / (500 KVA) or 0.42.

  The capacitive reactive power required to correct the power factor to 0.95 can be determined from the following equation:

$$\text{Capacitive Reactive Power Required (KVAR)} = \\ (200\ \text{KW}) * [\text{TAN}(\text{COS}^{-1}(0.4)) - \text{TAN}(\text{COS}^{-1}(0.95))]$$

$$\text{Capacitive Reactive Power Required} = 393\ \text{KVAR}$$

- Reduced Electrical System Losses
  A poor power factor load produces additional power losses (I^2R) in the electrical conductors because the electrical conductors have additional current, reactive current, flowing in them. These losses can be reduced by adding a power capacitor bank to the electrical system. The following equation can be used to calculate the reduction in losses:

$$\text{Reduction} = 1 - [(\text{Original Power Factor}) / (\text{Corrected Power Factor})]^2$$

- Reduced Electric Utility Bills
  Your electric utility provides active and reactive power to you facility in the form of apparent power. While the reactive power does not register on the utilities power demand or watt-hour meters, the utilities distribution and transmission systems must be large enough to handle the load. Electric utilities have various ways of recovering their cost for larger cables, generators, switches and transformers. The following case studies show how much money can be saved by adding power capacitor banks to your electrical system.

Case Study Number 1

The electric utility measures and bills for apparent power at the rate of $4.50 per KVA demand. Your facility's uncorrected apparent power demand is 500 KVA at a service voltage of 480 Volts RMS and the average power factor in your facility is 0.70.

Determine the monthly savings and the equipment payback period if the power factor of the facility is corrected to 0.95.

Solution

Active Power Demand = (0.70) * (500 KVA)
Active Power Demand = 350 KW

Corrected Apparent Power Demand = (350 KW) / (0.95)
Corrected Apparent Power Demand = 368.4 KVA

Existing Monthly Utility Charge = ($4.50 per KVA) * (500 KVA)
Existing Monthly Utility Charge = $2,250

Corrected Monthly Utility Charge = ($4.50 per KVA) * (368.4 KVA)
Corrected Monthly Utility Charge = $1,687.60

Monthly Savings = Existing Monthly Utility Charge - Corrected Monthly Utility Charge
= $592.20

Yearly Savings = (12) * (Monthly Savings)
= $7,106.40

Capacitive Reactive Power Required (KVAR) =
(350 KW) * [TAN (COS^{-1} (0.70)) – TAN (COS^{-1} (0.95))]

Capacitive Reactive Power Required (KVAR) = 242 KVAR, use 250 KVAR

The list price for a fixed, 250 KVAR, 480 volt RMS, and three-phase power capacitor bank is $4,827. The equipment payback period is ($4,827) / ($7,106.40) or 0.68 years.

Case Study Number 2

The electric utility bill for active power demand and adds a surcharge for the power factor. The surcharge is a multiplier applied to the active power demand. The following formula demonstrates a utility billing based on a 0.90 power factor:

[(0.90) / (Actual Power Factor)] * (Active Power Demand)

Some utilities charge for poor power factor but they will also give a credit for power factor above a certain level.

Your electric utility measures and bills for active power at the rate of $3.50 per KW demand. Your facility’s uncorrected active power demand is 500 KW at a service voltage of 480 Volts RMS and the average power factor in your facility is 0.70.

Determine the monthly savings and the equipment payback period if the power factor of the facility is corrected to 0.90.

Solution

Adjusted Active Power Demand = [(0.90) / (0.70)] * (500 KW)
= 643 KW

Existing Monthly Demand Charge = ($3.50 per KW) * (643 KW)
= $2,250

Corrected Active Power Demand = [(0.90) / (0.90)] * (500 KW)
= 500 KW
Corrected Monthly Demand Charge = ($3.50 per KW) * (500 KW)
= $1,750

Monthly Savings = Existing Monthly Demand Charge - Corrected Monthly Demand Charge
= $500

Yearly Savings = (12) * (Monthly Savings)
= $6,000

Capacitive Reactive Power Required (KVAR) =
(500 KW) * [TAN (COS^{-1} (0.70)) – TAN (COS^{-1} (0.90))]

Capacitive Reactive Power Required (KVAR) = 267 KVAR, use 300 KVAR

The list price for a fixed, 300 KVAR, 480 volt RMS, and three-phase power capacitor bank is $5,508. The equipment payback period is ($5,508) / ($6,000) or 0.92 years.

B. Industries with Poor Power Factor Loads

Poor power factor most often occurs when motors are operated at less than full load. Examples of devices equipped with motors that would be operated in this manner are: compressors, conveyors, grinders, punch presses and saws. In these devices, the motors are sized to enable the device to perform at a published maximum level. These devices are seldom operated continuously at this maximum level.

The following industries typically exhibit low power factors.

Facility	Uncorrected Power Factor
Brewery	0.65-0.75
Chemical	0.65-0.75
Foundry	0.70-0.80
Granary	0.70-0.80
Hospitals	0.70-0.80
Machine Shop	0.60-0.70
Plastics Extruding	0.55-0.70
Plating	0.65-0.75
Saw Mill	0.45-0.60
Stamping	0.60-0.70
Textile	0.65-0.75

C. Power Capacitor Bank Placement

Fixed power capacitor banks can be installed in a non-harmonic producing electrical system at the feeder, load or service entrance.

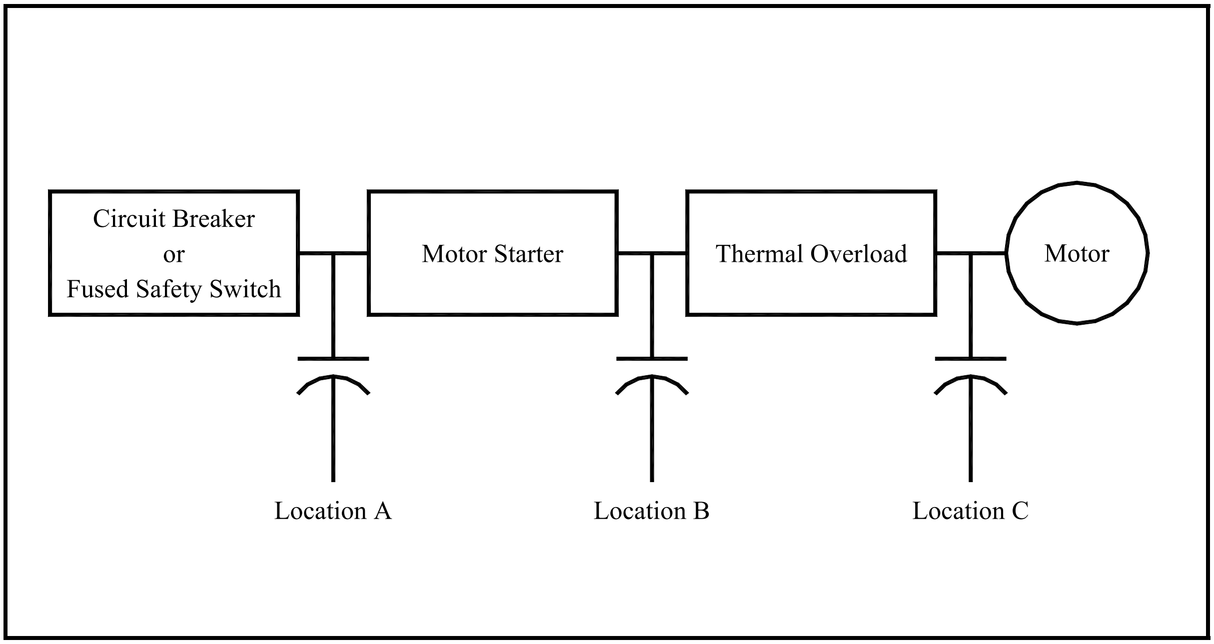
Since power capacitor banks are reactive power generators, the most logical place to install them is directly at the load where the reactive power is consumed. Three options exist for installing a power capacitor bank at the motor.

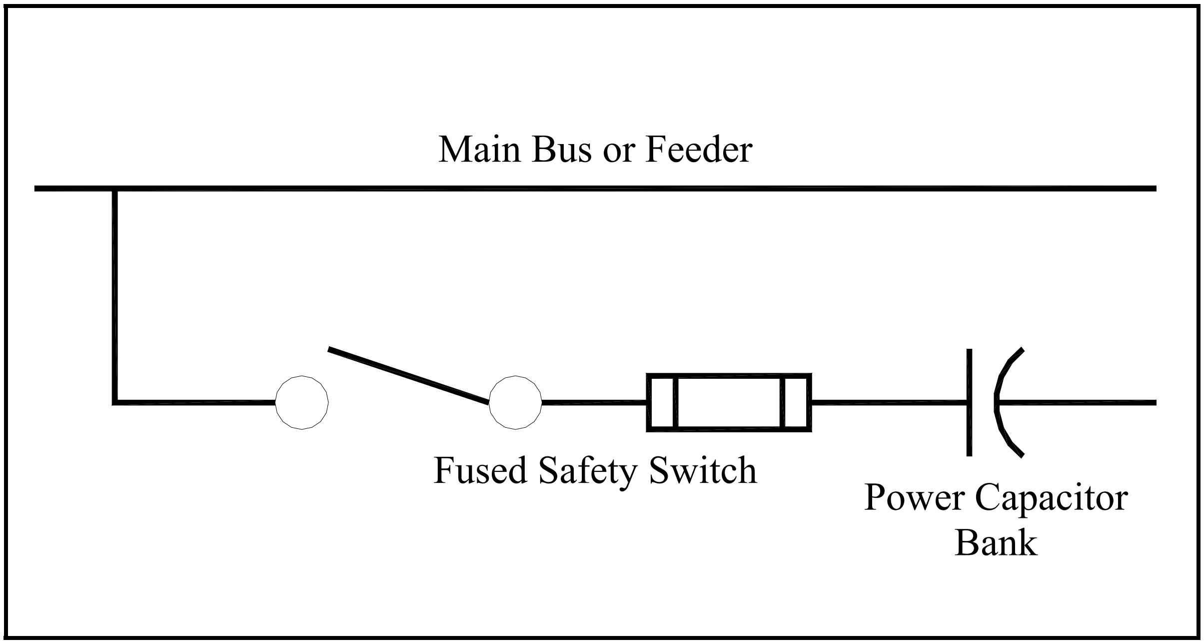
Location A: The line side of the starter. This location should be used for the following: motor loads with high inertia, where disconnecting the motor with the power capacitor bank can turn the motor into a self excited generator; motors that are jogged, plugged or reversed; motors that start frequently; multi-speed motors; starters that disconnect and reconnect capacitor units during cycling and starters with open transition.

Location B: Between the overload relay and the starter. This location can be used in existing installations when the overload ratings surpass the National Electrical Code requirements.

Location C: The motor side of the overload relay. This location can be used in existing installations when no overload change is required and in new installations in which the overloads can be sized in accordance with reduced current draw.

When correcting the power factor for an entire facility, fixed power capacitor banks are usually installed on feeder circuits or at the service entrance. Fixed power capacitor banks should only be used when the facility's load is fairly constant. When a power capacitor bank is connected to a feeder or service entrance a circuit breaker or a fused disconnect switch must be provided.





D. Power Capacitor Bank Sizing

The capacitive reactive power provided by a power capacitor bank is expressed in kilo-volt-amperes-reactive (KVAR).

To size a power capacitor bank for an individual motor load, use Tables 1 and 2. Simply look up the type of motor frame, RPM and horsepower. The charts indicate the capacitor size in KVAR required to correct the power factor to 0.95. The charts also indicate how much the current is reduced when the power capacitor bank is installed.

To size a power capacitor bank for an entire facility you need to know the active power consumption (KW), current power factor and target power factor. With these three quantities known, you can use Table 3 to determine the size of the power capacitor bank.

Table 1
Recommended, Capacitive Reactive Power for High Efficiency Induction Motors and Pre T-Frame Induction Motors to Raise the Full Load Power Factor to Approximately 95 %

Poles	2		4		6		8		10		12	
RPM	3600		1800		1200		900		720		600	
hp	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %
3	1.5	14	1.5	15	1.5	20	2	27	2.5	35	3	41
5	2	12	2	13	2	17	3	25	4	32	4	37
7.5	2.5	11	2.5	12	3	15	4	22	5	30	6	34
10	3	10	3	11	4	14	5	21	6	27	7.5	31
15	4	9	4	10	5	13	6	18	8	23	9	27
20	5	9	5	10	6	12	7.5	16	9	21	12.5	25
25	6	9	6	10	7.5	11	9	15	10	20	15	23
30	7	8	7	9	9	11	10	14	12.5	18	17.5	22
40	9	8	9	9	10	10	12.5	13	15	16	20	20
50	12.5	8	10	9	12.5	10	15	12	20	15	25	19
60	15	8	15	8	15	10	17.5	11	22.5	15	27.5	19
75	17.5	8	17.5	8	17.5	10	20	10	25	14	35	18
100	22.5	8	20	8	25	9	27.5	10	35	13	40	17
125	27.5	8	25	8	30	9	30	10	40	13	50	16
150	30	8	30	8	35	9	37.5	10	50	12	50	15
200	40	8	37.5	8	40	8	50	10	60	12	60	14
250	50	8	45	7	50	8	60	9	70	11	75	13
300	60	8	50	7	60	8	60	9	80	11	90	12
350	60	8	60	7	75	8	75	9	90	10	95	11
400	75	8	60	6	75	8	85	9	95	10	100	11
450	75	8	75	6	80	8	90	9	100	9	110	11
500	75	8	75	6	85	8	100	9	100	9	120	10

Table 2
Recommended, Capacitive Reactive Power for T-Frame NEMA Design B Induction Motors to Raise the Full Load Power Factor to Approximately 95 %

Poles	2		4		6		8		10		12	
RPM	3600		1800		1200		900		720		600	
hp	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %	Capacitor Size kVAR	Current Reduction %
2	1	14	1	24	1.5	30	2	42	2	40	3	50
3	1.5	14	1.5	23	2	28	3	38	4	40	4	49
5	2	14	2.5	22	3	26	4	31	5	40	5	49
7.5	2.5	14	3	20	4	21	5	28	6	38	6	45
10	4	14	4	18	5	21	6	27	7.5	36	8	38
15	5	12	5	18	6	20	7.5	24	8	32	10	34
20	6	12	6	17	7.5	19	9	23	10	29	12.5	30
25	7.5	12	7.5	17	8	19	10	23	12.5	25	17.5	30
30	8	11	8	16	10	19	15	22	15	24	20	30
40	12.5	12	15	16	15	19	17.5	21	20	24	25	30
50	15	12	17.5	15	20	19	22.5	21	22.5	24	30	30
60	17.5	12	20	15	22.5	17	25	20	30	22	35	28
75	20	12	25	14	25	15	30	17	35	21	40	19
100	22.5	11	30	14	30	12	35	16	40	15	45	17
125	25	10	35	12	35	12	40	14	45	15	50	17
150	30	10	40	12	40	12	50	14	50	13	60	17
200	35	10	50	11	50	11	70	14	70	13	90	17
250	40	11	60	10	60	10	80	13	90	13	100	17
300	45	11	70	10	75	12	100	14	100	13	120	17
350	50	12	75	8	90	12	120	13	120	13	135	15
400	75	10	80	8	100	12	130	13	140	13	150	15
450	80	8	90	8	120	10	140	12	160	14	160	15
500	100	8	120	9	150	12	160	12	180	13	180	15

Table 3
Multipliers to Determine the Capacitive Reactive Power Required for Power Factor Correction

	Corrected Power Factor															
PFe	0.85	0.86	0.87	0.88	0.89	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
0.50	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.306	1.337	1.369	1.403	1.440	1.481	1.529	1.590	1.732
0.51	1.067	1.093	1.120	1.147	1.174	1.202	1.231	1.261	1.291	1.324	1.358	1.395	1.436	1.484	1.544	1.687
0.52	1.023	1.049	1.076	1.103	1.130	1.158	1.187	1.217	1.247	1.280	1.314	1.351	1.392	1.440	1.500	1.643
0.53	0.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397	1.458	1.600
0.54	0.939	0.965	0.992	1.019	1.046	1.074	1.103	1.133	1.163	1.196	1.230	1.267	1.308	1.356	1.416	1.559
0.55	0.899	0.925	0.952	0.979	1.006	1.034	1.063	1.092	1.123	1.156	1.190	1.227	1.268	1.315	1.376	1.518
0.56	0.860	0.886	0.913	0.940	0.967	0.995	1.024	1.053	1.084	1.116	1.151	1.188	1.229	1.276	1.337	1.479
0.57	0.822	0.848	0.875	0.902	0.929	0.957	0.986	1.015	1.046	1.079	1.113	1.150	1.191	1.238	1.299	1.441
0.58	0.785	0.811	0.838	0.865	0.892	0.920	0.949	0.979	1.009	1.042	1.076	1.113	1.154	1.201	1.262	1.405
0.59	0.749	0.775	0.802	0.829	0.856	0.884	0.913	0.942	0.973	1.006	1.040	1.077	1.118	1.165	1.226	1.368
0.60	0.714	0.740	0.767	0.794	0.821	0.849	0.878	0.907	0.938	0.970	1.005	1.042	1.083	1.130	1.191	1.333
0.61	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.157	1.299
0.62	0.646	0.672	0.699	0.726	0.753	0.781	0.810	0.839	0.870	0.903	0.937	0.974	1.015	1.062	1.123	1.265
0.63	0.613	0.639	0.666	0.693	0.720	0.748	0.777	0.807	0.837	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.581	0.607	0.634	0.661	0.688	0.716	0.745	0.775	0.805	0.838	0.872	0.909	0.950	0.998	1.058	1.201
0.65	0.549	0.576	0.602	0.629	0.657	0.685	0.714	0.743	0.774	0.806	0.840	0.877	0.919	0.966	1.027	1.169
0.66	0.519	0.545	0.572	0.599	0.626	0.654	0.683	0.712	0.743	0.775	0.810	0.847	0.888	0.935	0.996	1.138
0.67	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.966	1.108
0.68	0.459	0.485	0.512	0.539	0.566	0.594	0.623	0.652	0.683	0.715	0.750	0.787	0.828	0.875	0.936	1.078
0.69	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.907	1.049
0.70	0.400	0.427	0.453	0.480	0.508	0.536	0.565	0.594	0.625	0.657	0.692	0.729	0.770	0.817	0.878	1.020
0.71	0.372	0.398	0.425	0.452	0.480	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.344	0.370	0.397	0.424	0.452	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.316	0.343	0.370	0.396	0.424	0.452	0.481	0.510	0.541	0.573	0.608	0.645	0.686	0.733	0.794	0.936
0.74	0.289	0.316	0.342	0.369	0.397	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.262	0.289	0.315	0.342	0.370	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.235	0.262	0.288	0.315	0.343	0.371	0.400	0.429	0.460	0.492	0.526	0.563	0.605	0.652	0.713	0.855
0.77	0.209	0.235	0.262	0.289	0.316	0.344	0.373	0.403	0.433	0.466	0.500	0.537	0.578	0.626	0.686	0.829
0.78	0.183	0.209	0.236	0.263	0.290	0.318	0.347	0.376	0.407	0.439	0.474	0.511	0.552	0.599	0.660	0.802
0.79	0.156	0.183	0.209	0.236	0.264	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.634	0.776
0.80	0.130	0.157	0.183	0.210	0.238	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.608	0.750
0.81	0.104	0.131	0.157	0.184	0.212	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82	0.078	0.105	0.131	0.158	0.186	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.556	0.698
0.83	0.052	0.079	0.105	0.132	0.160	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.530	0.672
0.84	0.026	0.053	0.079	0.106	0.134	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85	0.000	0.026	0.053	0.080	0.107	0.135	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86		0.000	0.027	0.054	0.081	0.109	0.138	0.167	0.198	0.230	0.265	0.302	0.343	0.390	0.451	0.593
0.87			0.000	0.027	0.054	0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88				0.000	0.027	0.055	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
0.89					0.000	0.028	0.057	0.086	0.117	0.149	0.184	0.221	0.262	0.309	0.370	0.512
0.90						0.000	0.029	0.058	0.089	0.121	0.156	0.193	0.234	0.281	0.342	0.484
0.91							0.000	0.030	0.060	0.093	0.127	0.164	0.205	0.253	0.313	0.456
0.92								0.000	0.031	0.063	0.097	0.134	0.175	0.223	0.284	0.426
0.93									0.000	0.032	0.067	0.104	0.145	0.192	0.253	0.395
0.94										0.000	0.034	0.071	0.112	0.160	0.220	0.363
0.95											0.000	0.037	0.078	0.126	0.186	0.329
0.96												0.000	0.041	0.089	0.149	0.292
0.97													0.000	0.048	0.108	0.251
0.98														0.000	0.061	0.203
0.99															0.000	0.142
1.00																0.000

Instructions

1. Find the existing power factor in the column labeled PFe.
2. Read across to the desired corrected power factor.
3. Multiply the number by the active power in KW to determine the effective capacitive reactive power required in KVAR.

Example

If your facility consumed 1,000 KW with an existing power factor of 0.500 and you wanted a corrected power factor of 0.95, you would:

- find 0.50 in the column labeled P_f e
- read across to the 0.95 corrected power factor column to find 1.403
- multiply 1,000 KW by 1.403 to obtain 1,403 KVAR and round this value up to 1,500

Tables 4, 5 and 6 present the recommend conductor sizes and current ratings for fuses and switches. The conductor sizes are based on:

- ambient temperature of 35 °C
- insulation temperature rating of 90 °C
- three (3) current-carrying conductors in a: cable, conduit, earth (directly buried) or raceway

Please consult the National Electrical Code for aluminum, copper-clad aluminum and different insulation temperature ratings.

Table 4
Recommended Conductor Sizes, Fuse Ratings and Switch Ratings for 240 Volts RMS, 60 Hertz, Three-Phase Power Capacitor Banks

KVAR	Rated Current (Amperes RMS)	Conductor Size	Fuse Rating (Amperes RMS)	Switch Rating (Amperes RMS)
0.5	1.2	14 AWG	3	30
1	2.4	14 AWG	6	30
1.5	3.6	14 AWG	6	30
2	4.8	14 AWG	10	30
2.5	6.0	14 AWG	10	30
3	7.2	14 AWG	15	30
4	9.6	14 AWG	20	30
5	12	14 AWG	20	30
6	14	14 AWG	25	30
7.5	18	12 AWG	30	30
8	19	10 AWG	35	60
10	24	10 AWG	40	60
12.5	30	8 AWG	50	60
15	36	8 AWG	60	60
17.5	42	6 AWG	80	100
20	48	6 AWG	80	100
25	60	4 AWG	100	100
30	72	3 AWG	125	200
35	84	2 AWG	150	200
40	96	1 / 0	175	200
45	108	1 / 0	200	200
50	120	2/ 0	200	200
60	144	3/ 0	250	400
70	168	250 kcmil	300	400
80	192	300 kcmil	350	400
90	217	350 kcmil	400	400
100	241	400 kcmil	400	400
125	301	(2) 3 / 0	500	600
150	361	(2) 250 kcmil	600	600
175	421	(2) 350 kcmil	750	800
200	481	(2) 400 kcmil	800	800

The rated current is based on 240 Volts RMS, 60 Hertz.
Multiply the KVAR by 0.7511 and the rated current by 0.8667 when the power capacitor banks are operated on 208 Volts RMS, 60 Hertz.

Table 5
Recommended Conductor Sizes, Fuse Ratings and Switch Ratings for 480 Volts RMS, 60 Hertz, Three-Phase Power Capacitor Banks

KVAR	Rated Current Amperes RMS	Conductor Size	Fuse Rating Amperes RMS	Switch Rating Amperes RMS
1	1.2	14 AWG	3	30
1.5	1.8	14 AWG	3	30
2	2.4	14 AWG	6	30
2.5	3.0	14 AWG	6	30
3	3.6	14 AWG	6	30
4	4.8	14 AWG	10	30
5	6.0	14 AWG	10	30
6	7.2	14 AWG	15	30
7.5	9.0	14 AWG	15	30
8	10	14 AWG	20	30
10	12	14 AWG	20	30
12.5	15	14 AWG	25	30
15	18	12 AWG	30	30
17.5	21	10 AWG	40	60
20	24	10 AWG	40	60
25	30	8 AWG	50	60
30	36	8 AWG	50	60
35	42	6 AWG	80	100
40	48	6 AWG	90	100
45	54	4 AWG	100	100
50	60	4 AWG	125	100
60	72	2 AWG	150	200
70	84	1 / 0	175	200
80	96	1 / 0	200	200
90	108	1 / 0	200	200
100	120	2 / 0	200	200
125	150	3 / 0	250	400
150	180	250 kcmil	300	400
175	210	350 kcmil	400	400
200	241	400 kcmil	400	400
250	301	(2) 3 / 0	500	600
300	361	(2) 250 kcmil	600	600
350	421	(2) 350 kcmil	750	800
400	481	(2) 500 kcmil	800	800

The rated current is based on 480 Volts RMS, 60 Hertz.

Table 6
Recommended Conductor Sizes, Fuse Ratings and Switch Ratings for 600 Volts RMS, 60 Hertz, Three-Phase Power Capacitor Banks

KVAR	Rated Current Amperes RMS	Conductor Size	Fuse Rating Amperes RMS	Switch Rating Amperes RMS
1	1.0	14 AWG	3	30
1.5	1.4	14 AWG	3	30
2	1.9	14 AWG	6	30
2.5	2.4	14 AWG	6	30
3	2.9	14 AWG	6	30
4	3.8	14 AWG	10	30
5	4.8	14 AWG	10	30
6	5.8	14 AWG	10	30
7.5	7.2	14 AWG	15	30
8	7.7	14 AWG	15	30
10	9.6	14 AWG	20	30
12.5	12	14 AWG	20	30
15	14	14 AWG	25	30
17.5	17	12 AWG	30	30
20	19	10 AWG	35	60
25	24	10 AWG	40	60
30	29	8 AWG	50	60
35	34	8 AWG	60	100
40	38	6 AWG	80	100
45	43	6 AWG	90	100
50	48	6 AWG	100	100
60	58	4 AWG	100	100
70	67	3 AWG	125	200
80	77	3 AWG	150	200
90	87	1 AWG	150	200
100	96	1 AWG	175	200
125	120	2 / 0	200	400
150	144	3 / 0	250	400
175	168	250 kcmil	300	400
200	192	300 kcmil	350	400
250	241	400 kcmil	400	400
300	289	(2) 3 / 0	500	600
350	337	(2) 250 kcmil	600	600
400	385	(2) 300 kcmil	650	800

The rated current is based on 600 Volts RMS, 60 Hertz.

E. Harmonic Rich Electrical Systems

Lately, non-linear devices, devices that draw current in a non-sinusoidal fashion, have increased dramatically. Examples of both linear and non-linear devices are as follows:

Linear Devices	**Non-Linear Devices**
Incandescent Lighting	Arc Furnaces
Heating Loads	Arc-Type Lighting
Motors	DC Drives
	Induction Furnaces
	Personal Computers
	Programmable Controllers
	Uninterruptible Power Supplies (UPS)
	Variable Frequency Drives (VFD)

The increase usage of non-linear devices has led to harmonic distortion in electrical distribution systems. **Although power capacitor banks do not cause distortion they can aggravate the situation.** The existence of harmonic currents is a site-specific problem. Harmonic currents are transformed into harmonic voltages by the impedance of the electrical system.

Power capacitor banks and transformers can create harmful resonance conditions. When this occurs harmonic currents produced by non-linear loads can be amplified many times. The following equation can be used to estimate the resonant frequency:

$$F_r = F * [KVA_{sc} / KVAR]^{½}$$

where:

F_r	resonant frequency (Hertz)
F	fundamental frequency (Hertz)
KVA_{sc}	short circuit capacity of the electrical system at the location where the power capacitor bank is installed (KVA)
KVAR	effective capacitive reactive power for the power capacitor bank

The following example demonstrates the effects of resonance. A load consumes 346 KW with a power factor of 0.50. The plant manager would like to correct the power factor to 0.95 or better using a fixed power capacitor bank on the secondary winding of the transformer. The short circuit capacity of the electrical system is 15,000 KVA with an $X_{sc} / R_{sc} = 10$ at the location where the power capacitor bank will be installed. The line-to-line voltage is 480 Volts RMS and the system frequency is 60 Hertz. The power capacitor bank losses are estimated at 0.5 Watts per KVAR.

The amount of capacitive reactive power required to correct the power factor of the 346 KW load from 0.50 to 0.95 is:

$Q_C = 346 \text{ KW} * [\text{TAN} (\text{COS}^{-1} (0.50)) – \text{TAN} (\text{COS}^{-1} (0.95))]$

$Q_C = 485$ KVAR, use 500 KVAR

The estimated resonant frequency of the electrical system is:

$F_r = F * [KVA_{sc} / KVAR]^{½}$

$F_r = 60 \text{ Hertz} * [15{,}000 \text{ KVA} / 500 \text{ KVAR}]^{½}$

$F_r = 329$ Hertz

The following are the calculations that must be performed in order to determine the impact of harmonic currents.

The assumptions that were made in performing these calculations are:

- the resistances of the power capacitor bank and the source are not a function of frequency
- the reactance (X_c) of the power capacitor bank is modeled as a pure capacitor
- the reactance (X_{sc}) of the source is modeled as a pure inductor

The magnitude of the source impedance (Z_{sc}) at 60 Hertz is:

$Z_{sc} = (V^2) / (KVA_{sc})$
$Z_{sc} = (480 \text{ Volts RMS})^2 / (15{,}000{,}000 \text{ VA})$
$Z_{sc} = 0.0154 \text{ Ohms}$

The resistance (R_{sc}) of the source at 60 Hertz is:

$Z_{sc}^2 = R_{sc}^2 + X_{sc}^2$
$X_{sc} = (10) * R_{sc}$
$Z_{sc}^2 = R_{sc}^2 + (10 * R_{sc})^2$
$Z_{sc}^2 = 101 * R_{sc}^2$
$R_{sc} = Z_{sc} / (10.05)$
$R_{sc} = 0.0015 \text{ Ohms}$

The reactance (X_{sc}) of the source at 60 Hertz is:

$X_{sc}^2 = Z_{sc}^2 - R_{sc}^2$
$X_{sc} = 0.0153 \text{ Ohms}$

The impedance ($\mathbf{Z}_{sc}$) of the source at 60 Hertz is:

$\mathbf{Z}_{sc} = 0.0015 + 0.0153 \text{ j, Ohms}$

The impedance ($\mathbf{Z}_{sc}$) of the source at 300 Hertz is:

$\mathbf{Z}_{sc} = 0.0015 + [(5) * (0.0153)] \text{ j, Ohms}$
$\mathbf{Z}_{sc} = 0.0015 + 0.0766 \text{ j, Ohms}$
$\mathbf{Z}_{sc} = 0.0766 \text{ Ohms}, 88.88^\circ$

The admittance ($\mathbf{Y}_{sc}$) of the source at 300 Hertz is:

$\mathbf{Y}_{sc} = 1 / \mathbf{Z}_{sc}$
$\mathbf{Y}_{sc} = 13.05 \text{ mho}, -88.88^\circ$

The magnitude of the power capacitor bank impedance (Z_c) at 60 Hertz is:

$Z_c = V^2 / KVAR$
$Z_c = 480 \text{ Volts RMS}^2 / 500{,}000 \text{ VAR}$
$Z_c = 0.4608 \text{ Ohms}$

The active power dissipated (P_c) in the power capacitor bank at 480 Volts RMS and 60 Hertz is:

$P_c = 0.5 \text{ Watts per KVAR} * 500 \text{ KVAR}$
$P_c = 250 \text{ Watts}$

The nominal power capacitor bank line current (I_c) at 480 Volts RMS and 60 Hertz is:
I_c = 500,000 KVA / [$\sqrt{3}$ * 480 Volts RMS]
I_c = 601.4 Amperes RMS

The resistance (R_c) of the power capacitor bank is:
$R_c = P_c / I_c^2$
R_c = 0.000691 Ohms

The reactance (X_c) of the power capacitor bank at 60 Hertz is:
$X_c = (Z_c^{\,2} - R_c^{\,2})^{1/2}$
X_c = 0.46079 Ohms

The impedance ($\mathbf{Z}_c$) of the power capacitor bank at 60 Hertz is:
$\mathbf{Z}_c$ = 0.000691 - 0.46079 j, Ohms

The impedance ($\mathbf{Z}_c$) of the power capacitor bank at 300 Hertz is:
$\mathbf{Z}_c$ = 0.000691 – [(0.46079) / (5)] j, Ohms
$\mathbf{Z}_c$ = 0.000691 - 0.09216 j, Ohms
$\mathbf{Z}_c$ = 0.092163 Ohms, -89.57°

The admittance ($\mathbf{Y}_c$) of the power capacitor bank at 300 Hertz is:
$\mathbf{Y}_c = 1 / \mathbf{Z}_{sc}$
$\mathbf{Y}_c$ = 10.85 mho, 89.57°

The admittance of the system ($\mathbf{Y}_s$) at 300 Hertz is:
$\mathbf{Y}_s = \mathbf{Y}_c + \mathbf{Y}_{sc}$
$\mathbf{Y}_s$ = [(10.85 mho * COS (89.57°)) + (13.05 mho * COS (-88.88°))] +
[(10.85 mho * SIN (89.57°)) + (13.05 mho * SIN (-88.88°))] j
$\mathbf{Y}_s$ = [0.0814 mho + 0.2551 mho] + [10.8497 mho – 13.0475 mho] j
$\mathbf{Y}_s$ = 0.3365 - 2.1978 j, mho
$\mathbf{Y}_s$ = 2.22 mho, -81.30°

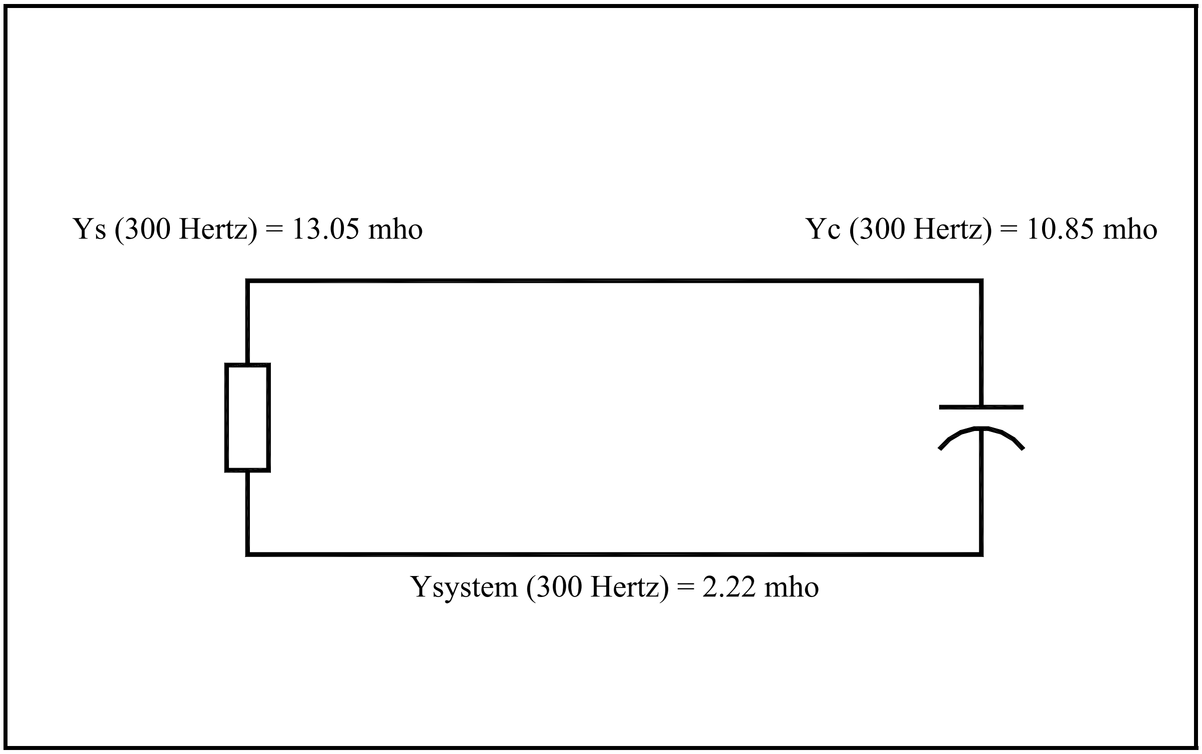
Let's see what happens if one (1) ampere RMS of fifth (5-TH) harmonic current is injected into the electrical system by a non-linear load.

I_l (5) = 1 Ampere RMS

The amount of fifth harmonic current flowing into the power capacitor banks is:
I_c (5) = I_l (5) * (Y_c / Y_s)
I_c (5) = (1 Ampere RMS) * (10.85 mho / 2.22 mho)
I_c (5) = 4.89 Amperes RMS

The amount of fifth harmonic current flowing into the source is:
I_{sc} (5) = I_l (5) * (Y_{sc} / Y_s)
I_{sc} (5) = (1 Ampere RMS) * (13.05 mho / 2.22 mho)
I_{sc} (5) = 5.88 Amperes RMS

The installation of a power capacitor bank to this particular electrical system will cause approximately a six-fold increase in the amount of fifth (5-TH) harmonic current that flows to the source. Figure 7 is the simplified model for the electrical system.



Generally speaking, power factor correction should be applied in the form of either a harmonic filter bank or a protected power capacitor bank in electrical systems that have non-linear loads.

F. Formulas and Nomenclature

Symbol	**Description**	**Units**
B	susceptance	mho
C	capacitance	farads
I	line current	amperes RMS
F	system frequency	Hertz
G	conductance	mho
L	inductance	Henry
P	active power	watts
P_c	capacitor unit power dissipation	watts per KVAR
P_f	power factor	none
Q	reactive power	volt-amperes reactive
R	resistance	Ohm
R_f	reactive factor	none
S	apparent power	volt-amperes
V	voltage	Volts RMS
Y	absolute value or modulus of the admittance	mho
Y	**admittance vector**	**mho**
Z	absolute value or modulus of the impedance	Ohm
Z	**impedance vector**	**Ohm**
X	reactance	Ohm
X / R	inductor quality factor	none

Capacitor Formulas

- **reactance**
  $X_c = 1 / [2 * C * F * \pi]$
- **resistance**
  $R = (P_c * V^2) / (1000 * Q_c)$, single-phase
  $R = (3 * P_c * V^2) / (1000 * Q_c)$, three-phase
- **reactive power**
  $Q_c = 2 * C * F * \pi * V^2$
- **units connected in a parallel circuit**
  $C_t = C_1 + C_2 + C_3 + \ldots + C_n$
- **units connected in a series circuit**
  $C_t = (C_1 * C_2) / (C_1 + C_2)$, two units
  $C_t = 1 / [(1/C_1) + (1/C_2) + (1/C_3) + \ldots + (1/C_n)]$, more than two units

Inductor Formulas

- **reactance**
  $X_l = 2 * F * L * \pi$
- **resistance**
  $R = X_l / (X/R)_{ratio}$
- **reactive power**
  $Q_l = V^2 / (2 * f * L * \pi)$
- **units connected in a series circuit**
  $L_t = L_1 + L_2 + L_3 + \ldots + L_n$
- **units connected in a parallel circuit**
  $L_t = (L_1 * L_2) / (L_1 + L_2)$, two units
  $L_t = 1 / [(1/L_1) + (1/L_2) + (1/L_3) + \ldots + (1/L_n)]$, more than two units

Miscellaneous Formulas

- **admittance**
  $\mathbf{Y} = 1 / \mathbf{Z}$
  $\mathbf{Y} = G + B\,j$: $B > 0$ Capacitive, $B = 0$ Non Reactive, $B < 0$ Inductive
  $\mathbf{Y} = Y, \Phi_y$: $Y = \sqrt{[G^2 + B^2]}$, $\Phi_y = TAN^{-1} (B / G)$
- **impedance**
  $\mathbf{Z} = 1 / \mathbf{Y}$
  $\mathbf{Z} = R + X\,j$: $X < 0$ Capacitive, $X = 0$ Non Reactive, $X > 0$ Inductive
  $\mathbf{Z} = Z, \Phi_z$: $Z = \sqrt{[R^2 + X^2]}$, $\Phi_z = TAN^{-1} (X / R)$
- **line current**
  general formula: $I = S / V$, single phase
  $I = S / [\sqrt{3} * V]$, three phase
  inductor: $I_l = Q_l / V$, single phase
  $I_l = Q_l / [\sqrt{3} * V]$, three phase
  power capacitor bank: $I_c = Q_c / V$, single phase
  $I_c = Q_c / [\sqrt{3} * V]$, three phase
- **power factor**
  $P_f = P / S$
- **power triangle**
  $S = \sqrt{[P^2 + Q^2]}$
- **reactive factor**
  $R_f = Q / S$
  $R_f = \sqrt{[1 - P_f^{\,2}]}$

Operation of Power Capacitor Banks at other that at Nameplate Frequency and Nameplate Voltage

- Given the nameplate capacitive reactive power ($KVAR_n$), nameplate frequency (F_n) and nameplate voltage (V_n):
  the capacitive reactive power at frequency (F): $KVAR = (F / F_n) * (KVAR_n)$
  the capacitive reactive power at voltage (V): $KVAR = (V / V_n)^2 * (KVAR_n)$

Examples

Determine the capacitive reactive power output when a 60 Hertz, 100 KVAR, 4.16 KV RMS, power capacitor bank is operated at 50 Hertz and 4.16 KV RMS.

Effective KVAR = (50 Hertz / 60 Hertz) * (100 KVAR) = 83.3

Determine the capacitive reactive power output when a 60 Hertz, 100 KVAR, 4.16 KV RMS, power capacitor bank is operated at 60 Hertz and 2.4 KV RMS.

Effective KVAR = $(2.400 \text{ KV RMS} / 4.16 \text{ KV RMS})^2 * (100 \text{ KVAR}) = 33$

Conversion Factors

1 farad = 1,000,000 μf
1 Henry = 1,000,000 μh
1 KVA = 1,000 volt-amperes