Ultravar™
POWER FACTOR CORRECTION
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Savings and Application Guide

Power Factor Correction and Harmonic Solutions

For Industrial, Commercial, and Institutional Facilities

Savings and Application Guide

For Power Factor Correction and Harmonic Solutions

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Ultravar Power Factor Correction

GE Capacitor and Power Quality Produts

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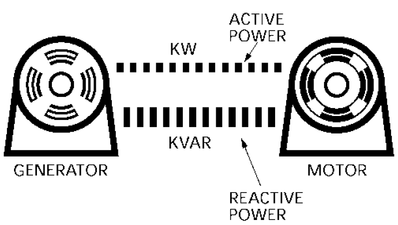
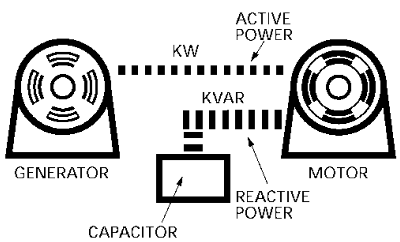


The figure above shows an induction motor operating under partially loaded conditions without Power Factor Correction. Here the feeder line must supply BOTH magnetizing (reactive) and active power.



The figure above shows the result of installing a capacitor near the same motor to supply the reactive power required to operate it. The total current requirement has been reduced to the value of the active power only, thus either reducing power cost or permitting the use of more electrical equipment on the same circuit.

Function of Capacitors

Electric power has two components:

Active power, which produces work.

Reactive power, which is needed to generate magnetic fields required for operation of inductive electrical equipment, but performs no useful work.

Active power is measured in KW (1000 Watts)

Reactive power is measured in KVAR (1000 Volt-Amperes Reactive)

Total power is measured in KVA (1000 Volts-Amperes)

The ratio of working power to total power is called Power Factor. The function of Power Factor Correction Capacitors is to increase the power factor by supplying the reactive power when installed at or near inductive electrical equipment.

Equipment Causing Poor Power Factor

A great deal of equipment causes poor power factor. One of the worst offenders is lightly loaded induction equipment. Examples of this type of equipment, and their approximate power factors follow:

- 80% power factor or better: Air conditioners (correctly sized), pumps, centerless grinders, cold headers, upsetters, fans or blowers.
- 60% to 80% power factor: Induction furnaces, standard stamping machines, and weaving machines.
- 60% power factor and below: Single-stroke presses, automated machine tools, finish grinders, welders.

When the above equipment functions within a facility, savings can be achieved by utilizing Ultravar industrial capacitors.

How Capacitors Save Money

Capacitors lower electrical costs two ways:

In many areas, the electrical rate includes a penalty charge for low power factor. Installation of power capacitors on the electrical distribution system within a facility makes it unnecessary for the utility to supply the reactive power required by inductive electrical equipment. The savings the utility realizes in reduced generation, transmission, and distribution costs are passed on to the customer in the form of lower electrical bills.

The second source of savings derived through the use of power factor correction capacitors is in the form of increased KVA capacity in the electrical distribution system. Installation of capacitors to furnish the non-productive current requirements of the facility makes it possible to increase the connected load by as much as 20 percent without a corresponding increase in the size of the transformers, conductors, and protective devices making up the distribution system which services the load.

Benefits of Power Factor Improvement

Power factor (PF) is the ratio of useful current to total current. It is also the ratio of useful power expressed in kilowatts (KW) to total power expressed in kilowatt-amperes (KVA). Power factor is usually expressed as a decimal or as a percentage.

$$PF = \frac{\text{Useful Power}}{\text{Total Power}}$$

Example: Kilowatts = 60 KW, KVA = 100 KVA

$$PF = \frac{60\ \text{KW}}{100\ \text{KVA}} = .60 = 60\%$$

The significant effect of improving the power factor of a circuit is to reduce the current flowing through that circuit which in turn results in the following benefits:

$$KVA = \sqrt{3} \times KV \times I$$

Benefit No. 1

Less Total Plant KVA for the Same KW Working Power.

Dollar savings are very significant in areas where utility billing is affected by KVA usage.

Example: 600 KW working power vs KVA required

POWER FACTOR	60%	70%	80%	90%	100%
ACTIVE POWER	600 KW	600 KW	600 KW	600 KW	600 KW
REACTIVE POWER	800 KVAR	612 KVAR	450 KVAR	291 KVR	0 KVAR
TOTAL POWER	1000 KVA	857 KVA	750 KVA	667 KVA	600 KVA

This allows for more efficient operation of plant transformers and “frees up” KVA for additional load. Cost avoidance can be significant.

$$KW = KVA \times PF$$

Benefit No. 2

More KW Working Power for the Same KVA Demand

Released system capacity allows for additional motors, lighting, etc. to be added without overloading existing distribution equipment.

Example: 600 KVA demand vs available KW

POWER FACTOR	60%	70%	80%	90%	100%
ACTIVE POWER	360 KW	420 KW	480 KW	540 KW	600 KW
REACTIVE POWER	480 KVAR	428 KVAR	360 KVAR	262 KVR	0 KVAR
TOTAL POWER	600 KVA	600 KVA	600 KVA	600 KVA	600 KVA

$$\text{\% voltage rise*} = \frac{KVAR \times \%Z_L}{\text{KVA of transformer}}$$

* with capacitor at the transformer

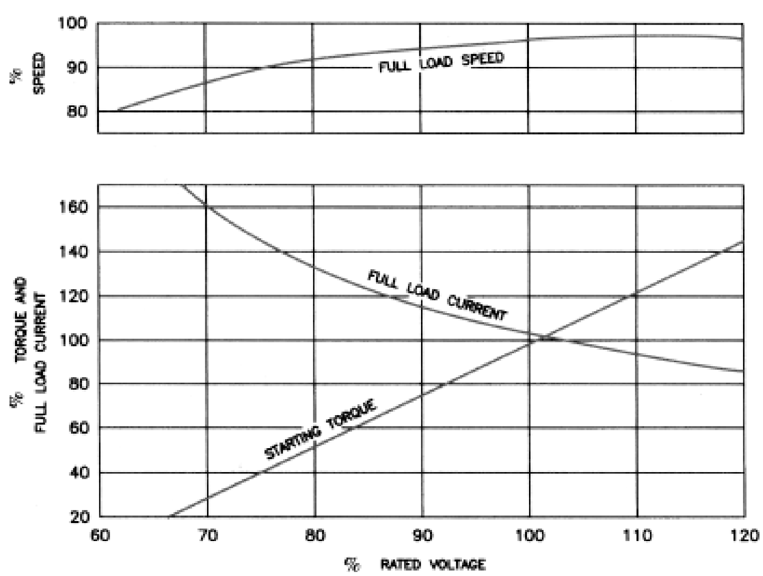
Z_L = transformer impedance % from nameplate

Benefit No. 3

Improved Voltage Regulation Due to Reduced Line Voltage Drop

This benefit will result in more efficient performance of motors and other electrical equipment.

Example: The graphs below depict what happens to the full load speed and starting torque of a motor at various levels of rated voltage.

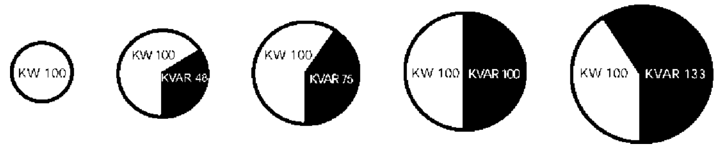


$$I = \frac{KVA \times 10^3}{\sqrt{3}V}$$

Benefit No. 4

Reduction in Size of Transformers, Cables and Switchgear in New Installations – Thus Less Investment

Example: The figure below represents the increasing size of conductors required to carry the same 100 KW at various power factors.



KVA-100	KVA-111	KVA-125	KVA-141	KVA-167
PF-100%	PF-90%	PF-80%	PF-70%	PF-60%

$$\% \text{ reduction of power losses} = 100 - 100\left(\frac{\text{original PF}}{\text{new PF}}\right)^2$$

Benefit No. 5

Reduced Power Losses in Distribution Systems, Since These Losses are Proportional to the Square of the Current

Since the losses are proportionate to the square of the current, the formula at left applies.

Example: Improve power factor from 65 percent to 90 percent

$$\text{Reduction of power losses} = 100 - 100\left(\frac{.65}{.90}\right)^2 = 48\%$$

Facts and Formulas

1. $PF = \cos\theta = \frac{KW}{KVA}$ (motor input)

2. $KW \text{ (motor input)} = \frac{hp \times .746}{\% \text{ Eff.}}$

3. $KVA = \frac{\sqrt{3} \times V \times I}{10^3}$ (three phase)

4. $KVA = \frac{V \times I}{1000}$ (single phase)

5. $KVA = \frac{KW}{PF} = \sqrt{(KW)^2 + (KVAR)^2}$

6. $I = \frac{KVA \times 10^3}{\sqrt{3}\ V}$ (three phase)

7. $I = \frac{KVA \times 10^3}{V}$ (single phase)

8.. $KVAR = \frac{2\pi f C (KV)^2}{10^3}$

9. $C = \frac{KVAR \times 10^3}{(2\pi f)(KV)^2}$

10. $X_C = \frac{10^6}{(2\pi f)C}$

Legend:

K = 1000
W = watts
V= volts
A = amperes
hp = horsepower
PF = power factor

I = line current (amperes)
I_c = capacitor current (amperes)
C = capacitance (microfarads)
f = frequency

Derating for V & f

$$KVAR_E = KVAR_R \left(\frac{V_A}{V_R}\right)^2 \left(\frac{f_A}{f_R}\right)$$

$KVAR_E$ = Effective KVAR

$KVAR_R$ = Rated KVAR

V_A = Applied Voltage

V_R = Rated Voltage

f_A = Applied frequency

f_R = Rated frequency

Examples:

- Reduced KVAR when operating 60 Hz unit @ 50 Hz

  Actual KVAR = Rated KVAR $\left(\frac{50}{60}\right)$ = 83% rated KVAR

- Reduced KVAR when operating @ below rated voltage

  Actual KVAR = rated KVAR $\left(\frac{\text{operating voltage}}{\text{rated voltage}}\right)^2$

i.e.: 240 V @ 208 V = .75 rated KVAR

Degree of Power Factor Improvement

As noted on page 3, power capacitors lower costs two ways. To determine how much improvement should be made to the existing power factor, one must analyze the potential benefits to be gained in each situation.

If utility bill savings are a factor, it is recommended that the past 12 months' billings be reviewed and compared to potential billings at improved power factor levels. Since there are a variety of rate structures in existence, each case must be investigated separately. In general, where penalty clauses exist, the power factor should be raised to at least 95 percent.

Where relief of an overloaded distribution system is the major consideration, the degree of correction will depend upon the amount of relief required. In some instances, correction to unity may be economical.

Size of Capacitor Bank

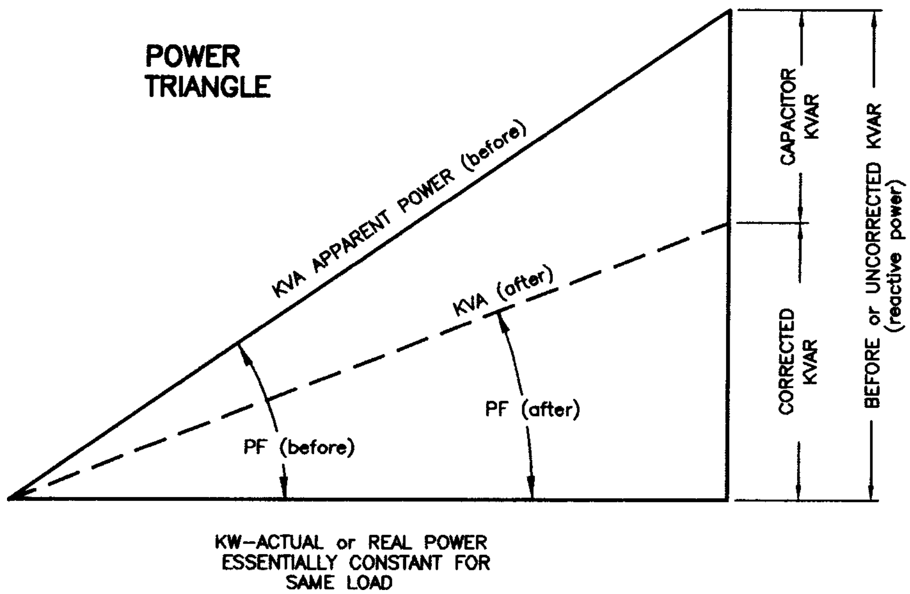
Where the size of the capacitor bank needed to improve power factor to the desired level (usually 95%) is not readily available from Motor Tables or by graphic determination, it can be calculated as shown on page 9 or by these formulae.

TO FIND	WHEN YOU KNOW	THREE-PHASE
Watts input to anything	Output, efficiency	$\frac{\text{Watts output}}{\text{\% efficiency}}$
Watts input to a motor	Horsepower, efficiency	$\frac{\text{hp x .746 x LF}}{\text{\% efficiency}}$
Horsepower (Output)	Current, voltage efficiency, power factor	$\frac{\text{1.73 x E x I x \%eff. x PF}}{.746}$
Kilovolt-amperes	Current, voltage	$\frac{\text{1.73 x E x I}}{1000}$
Kilowatts	Current, voltage, power factor	$\frac{\text{1.73 x E x I x PF}}{1000}$
Amperes	Horsepower, voltage, efficiency, power factor	$\frac{\text{hp x .746 x LF}}{\text{1.73 x E x \%eff. x PF}}$
Amperes	Kilowatts, voltage, power factor	$\frac{\text{kw x 1000}}{\text{1.73 x E x PF}}$
Amperes	Kilovolt-amperes, voltage	$\frac{\text{kva x 1000}}{\text{1.73 x E}}$
Power factor	Watts, voltage, current	$\frac{\text{Watts}}{\text{1.73 x E x I}}$
Power factor	Kilowatts, voltage, current	$\frac{\text{kw x 1000}}{\text{1.73 x E x I}}$

PF = power factor E = volts LF = load factor I = current in amperes

Determining Your Capacitor Requirements

The total KVAR rating of capacitors required to improve a facility's power factor to any desired value may be calculated very easily by using several basic formulas and by applying the appropriate multiplier selected from Table 1 on page 11.



Examples:

1. A plant with a metered demand of 600 KW is operating at a 75% power factor. What capacitor KVAR is required to correct the present power factor to 95%?
   a. From Table 1, Multiplier to improve PF from 75% to 95% is .553
   b. Capacitor KVAR = KW x Table 1 Multiplier
      Capacitor KVAR = 600 x .553 = 331.8 say 330

2. A plant load of 425 KW has a total power requirement of 670 KVA. What size capacitor is required to improve the present power factor to 90%?
   a. Present PF = $\frac{KW}{KVA} = \frac{425}{670}$ .634 = 63.4% say 63%
   b. From Table 1, Multiplier to improve PF from 63% to 90% is .748
   c. Capacitor KVAR = KW x Table 1 Multiplier = 425 x .748 = 317.9 say 320 KVAR

3. A plant operating from a 480 volt system has a metered demand of 258 KW. The line current read by a clip-on ammeter is 420 amperes. What amount of capacitors are required to correct the present power factor to 90%?
   a. KVA = 1.73 x KV x I = 1.73 x .480 x 420 = 349 KVA
   b. Present PF = $\frac{KW}{KVA} = \frac{258}{349}$ = 73.9 say 74%
   c. From Table 1, Multiplier to improve PF from 74% to 90% is .425
   d. Capacitor KVAR = KW x Table 1 Multiplier = 258 x .425 = 109.6 say 110 KVAR

Table 1 - Sizing Capacitors for Electrical Systems

This table gives multipliers for KW to get the capacitor KVAR needed to increase from original to desired corrected power factor. Use the multipliers to size auto-switched or fixed capacitors for large loads.

DESIRED CORRECTED POWER FACTOR (%)

ORIGINAL POWER FACTOR (%)	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
50	0.982	1.008	1.034	1.060	1.086	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
51	0.937	0.963	0.989	1.015	1.041	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
52	0.893	0.919	0.945	0.971	0.997	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
53	0.850	0.876	0.902	0.928	0.954	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
54	0.809	0.835	0.861	0.887	0.913	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
55	0.768	0.794	0.820	0.846	0.873	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
56	0.729	0.755	0.781	0.807	0.834	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
57	0.691	0.717	0.743	0.769	0.796	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
58	0.655	0.681	0.707	0.733	0.759	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
59	0.618	0.644	0.670	0.696	0.723	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
60	0.583	0.609	0.635	0.661	0.687	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
61	0.549	0.575	0.601	0.627	0.653	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
62	0.515	0.541	0.567	0.593	0.620	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
63	0.483	0.509	0.535	0.561	0.587	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
64	0.451	0.477	0.503	0.529	0.555	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
65	0.419	0.445	0.471	0.497	0.523	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
66	0.388	0.414	0.440	0.466	0.492	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
67	0.358	0.384	0.410	0.436	0.462	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
68	0.328	0.354	0.380	0.406	0.432	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
69	0.299	0.325	0.351	0.377	0.403	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
70	0.270	0.296	0.322	0.348	0.374	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
71	0.242	0.268	0.294	0.320	0.346	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
72	0.214	0.240	0.266	0.292	0.318	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
73	0.186	0.212	0.238	0.264	0.290	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
74	0.159	0.185	0.211	0.237	0.263	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
75	0.132	0.158	0.184	0.210	0.236	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
76	0.105	0.131	0.157	0.183	0.209	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
77	0.079	0.105	0.131	0.157	0.183	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
78	0.052	0.078	0.104	0.130	0.156	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
79	0.026	0.052	0.078	0.104	0.130	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
80	0.000	0.026	0.052	0.078	0.104	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
81		0.000	0.026	0.052	0.078	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
82			0.000	0.026	0.052	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
83				0.000	0.026	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
84					0.000	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
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
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
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
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
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
90											0.000	0.029	0.058	0.089	0.121	0.156	0.193	0.234	0.281	0.342	0.484
91												0.000	0.030	0.060	0.093	0.127	0.164	0.205	0.253	0.313	0.456
92													0.000	0.031	0.063	0.097	0.134	0.175	0.223	0.284	0.426
93														0.000	0.032	0.067	0.104	0.145	0.192	0.253	0.395
94															0.000	0.034	0.071	0.112	0.160	0.220	0.363
95																0.000	0.037	0.078	0.126	0.186	0.329
96																	0.000	0.041	0.089	0.149	0.292
97																		0.000	0.048	0.108	0.251
98																			0.000	0.061	0.203
99																				0.000	0.142
100																					0.000

Example: Total KW input of load from wattmeter reading 100 KW at a power factor of 60%. The leading reactive KVAR necessary to raise the power factor to 90% is found by multiplying the 100 KW by the factor found in the table, which is .849. Then 100 KW x 0.849 = 84.9 KVAR. Use 85 KVAR

Power Bill Savings

Poor power factor necessitates increased generation and transmission costs to provide the required amount of real power (KW). In order to equitably distribute these costs to the end user, many utilities utilize a rate structure that penalizes poor power factor.

To illustrate the power bill savings that can be obtained through capacitor installation, it is assumed that the utility serving a facility has the following rate schedule:

Sample Rate Schedule:
The billing demand is calculated such that a penalty is incurred for power factors below 90%.

$$\text{Billing Demand} = \frac{\text{KW demand} \times .90}{\text{Actual PF}}$$

Demand Charge per Month:

First 10 KW	$5.25/KW
Next 40 KW	$4.00/KW
Next 100 KW	$3.50/KW
Excess KW	$2.75/KW

Utility Demand Charges Before Improvement:
see page 9, example 2

$$\text{Billing Demand} = \frac{425 \text{ KW} \times .90}{.63} = 607.1 \text{ KW}$$

Therefore our KW demand charges would be:

10 x $5.25	$ 52.50
40 x $4.00	$ 160.00
100 x $3.50	$ 350.00
457.1 x $2.75	$1,257.03
	$1,819.53

Utility Demand Charges After Improvement:

$$\text{Billing Demand} = \frac{425 \text{ KW} \times .90}{.90} = 425 \text{ KW}$$

10 x $5.25	$ 52.50
40 x $4.00	$ 160.00
100 x $3.50	$ 350.00
275 x $2.75	$ 756.25
	$1,318.75

Savings per month = $1,819.53 – $1,318.75 = $500.78

Annual saving = $6,009.36

Payback Analysis:

Automatic Correction: 325 kvar, 480 volts, 25 kvar per step = AVC7325F25
list price = $13,034 ÷ $6,009.36 = approximately a two year payback (based on list price)

Fixed Correction: 325 kvar, 480 volts = ICS4325F333F
list price = $3,158 ÷ $6,009.36 = approximately a six month payback (based on list price)

NOTES:

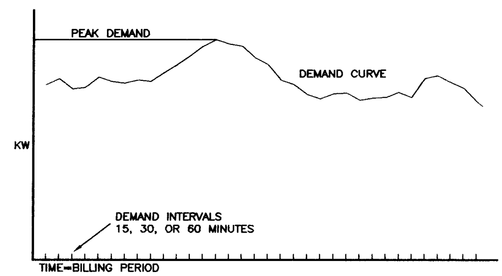
1. KWH charges are not shown since the significant dollar savings in this example are in the demand rate structure.

2. Due to variations in rate schedules throughout the country, it is impossible to provide an example of each schedule. Please check with your power company and local representative to determine your potential savings through power factor correction.

Factors That Affect Your Electric Bill

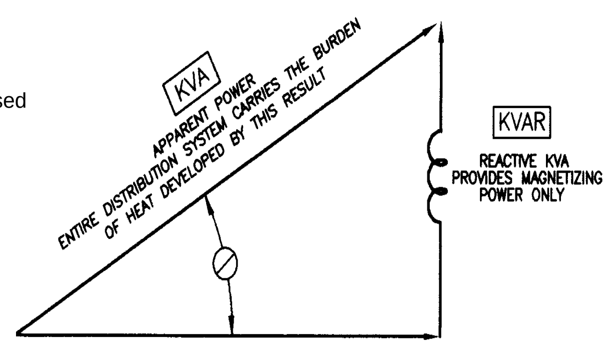
1. **Energy Charge -**
   Number of kilowatt-hours used during the billing period.
   Number of kilovolt amperes (KVA) used during the billing period

2. **Demand Charge -**
   This charge compensates the utility for the capital investment required to serve the facility's peak load. Demand charges may be a large portion of the total electric bill, sometimes as high as 75%. Demand charges can be reduced by reducing energy peaks, reducing KVA, and improving power factor.



1 - Uncorrected KVA
2 - Corrected KVA

3. **Power Factor Penalty Charge -**
   A penalty imposed to encourage the user to improve power factor. Power companies usually impose a billing penalty when power factor (P.F.) drops below 90% - although this figure could be as high as 95%. In nearly all cases, the least expensive and most efficient method to reduce this charge is by adding capacitors.



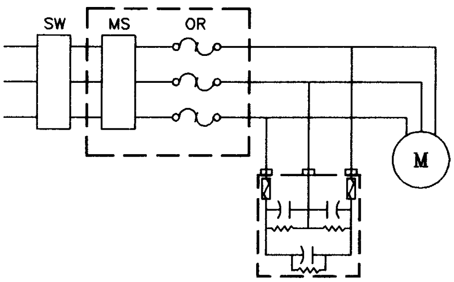


Figure 1: For new motor installations
Capacitors are connected on motor side of thermal-overloaded relay. Relay should be selected with rating less than motor nameplate full-load current, commensurate with reduced line current effected by the capacitors. This reduction in line current, if not available from tables, may be determined by measuring line current with and without capacitors, or by calculation.

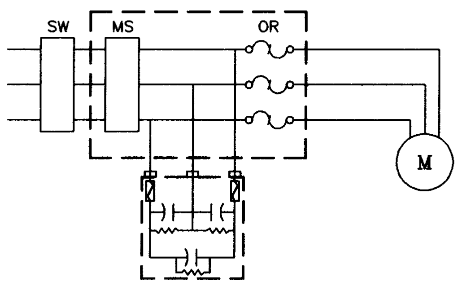


Figure 2: For existing motor installations
Capacitors are connected to line side of thermal-overload relay. In this case the overload relay does not have to be resized.

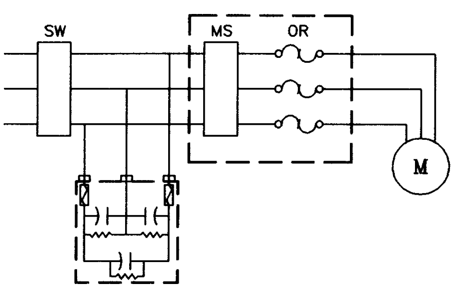


Figure 3:
Capacitors are permanently connected to line, but with protection of a fusible safety switch or circuit breaker which eliminates separate capacitor switch. To avoid nuisance blowing of the capacitor fuses, install the capacitors at this location when the motors are multiple speed, reversing, jogging, inching, or reduced voltage start.

Legend:
- **SW** Fusible safety switch or breaker.
- **MS** Motor Starter. OR Motor thermal-overload relay.
- **C** Dust-tight capacitor unit.
- **M** Motor.
- **F** Removable, high IC, one-time current limiting indicating fuses.
- **R** Discharge resistors.

Note: In Figures 2 and 3, the thermal-overload relay does not require replacement since full motor current continues to flow through it.

Location of Power Capacitors

Methods of Wiring to Induction Motor Circuits –

Capacitors may be connected to each motor and switched with it, as in Figures 1 and 2, in which case they are energized only when the motor is in operation, or they may be permanently connected to the line ahead of motor starters as in Figure 3.

Power Capacitors afford Kilovar relief from their point of installation toward the power source.

1. The most economical location is directly across the terminals of larger motors thereby eliminating the cost of a separate switch. The capacitor ratings may be selected directly from Table 2 or Table 3, which require knowing only the type, horsepower rating, and speed of the motor. Reference to Figure 1 or 2 indicates the recommended location for new and existing motors. These capacitor ratings normally correct the motor no-load power factor to unity which in turn generally results in a full-load power factor of 94%-96%.

2. Where there are multiple motors with low horsepower ratings, or motors which do not run continuously, the capacitors should be connected directly to feeders in the facility through an appropriate switching device to serve as a disconnect for servicing, or light loads. Locations should be as far downstream in the facility as possible for maximum benefit.

3. Installations may be made at load centers when it is difficult to connect the capacitors directly across motor terminals or to feeders. Again, switching is a recommended practice.

4. If only power bill penalties are to be offset, the total capacitor requirement can be installed on the load side of metering equipment. Such a location does not increase the capacity of the facility distribution system.

Table 2 - Suggested Maximum Capacitor Ratings for
U-Frame NEMA Class B. Motors
NEMA Motor Design A or B, Normal Starting Torque, Normal Running Current

H.P. Rating	3600 RPM		1800 RPM		1200 RPM		900 RPM		720 RPM		600 RPM	
	KVAR	%AR	KVAR	%AR	KVAR	%AR	KVAR	%AR	KVAR	%AR	KVAR	%AR
3	1.5	14	1.5	15	1.5	20	2	27	2.5	35	3.5	41
5	2	12	2	13	2	17	3	25	4	32	4.5	37
7.5	2.5	11	2.5	12	3	15	4	22	5.5	30	6	34
10	3	10	3	11	3.5	14	5	21	6.5	27	7.5	31
15	4	9	4	10	5	13	6.5	18	8	23	9.5	27
20	5	9	5	10	5	11	7.5	18	10	20	10	25
25	5	6	5	8	7.5	11	7.5	13	10	20	10	21
30	5	5	5	8	7.5	11	10	15	15	22	15	25
40	7.5	8	10	8	10	10	15	16	15	18	15	20
50	10	7	10	8	10	9	15	12	20	15	25	22
60	10	6	10	8	15	10	15	11	20	15	25	20
75	15	7	15	8	15	9	20	11	30	15	40	20
100	20	8	20	8	25	9	30	11	40	14	45	18
125	20	6	25	7	30	9	30	10	45	14	50	17
150	30	6	30	7	35	9	40	10	50	17	60	17
200	40	6	40	7	45	8	55	11	60	12	75	17
250	45	5	45	6	60	9	70	10	75	12	100	17
300	50	5	50	6	75	9	75	9	80	12	105	17

Suggested Maximum Capacitor Ratings for T-Frame Motors When Switched with Capacitors

Table 3: Suggested Maximum Capacitor Ratings for T-Frame NEMA Class B. Motors

Applies to three-phase, 60 HZ motors when switched with capacitors as a single unit.

	NOMINAL MOTOR SPEED											
	3600 R/MIN		1800 R/MIN		1200 R/MIN		900 R/MIN		720 R/MIN		600 R/MIN	
Induction Motor Rating (HP)	Capacitor Rating (KVAR)	Line Current Reduction (%)	Capacitor Rating (KVAR)	Line Current Reduction (%)	Capacitor Rating (KVAR)	Line Current Reduction (%)	Capacitor Rating (KVAR)	Line Current Reduction (%)	Capacitor Rating (KVAR)	Line Current Reduction (%)	Capacitor Rating (KVAR)	Line Current Reduction (%)
3	1.5	14	1.5	23	2.5	28	3	38	3	40	4	40
5	2	14	2.5	22	3	26	4	31	4	40	5	40
7.5	2.5	14	3	20	4	21	5	28	5	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	30
25	7.5	12	7.5	17	8	19	10	23	12	25	18	30
30	8	11	8	16	10	19	14	22	15	24	22.5	30
40	12	12	13	15	16	19	18	21	22.5	24	25	30
50	15	12	18	15	20	19	22.5	21	24	24	30	30
60	18	12	21	14	22.5	17	26	20	30	22	35	28
75	20	12	23	14	25	15	28	17	33	14	40	19
100	22.5	11	30	14	30	12	35	16	40	15	45	17
125	25	10	36	12	35	12	42	14	45	15	50	17
150	30	10	42	12	40	12	52.5	14	52.5	14	60	17
200	35	10	50	11	50	10	65	13	68	13	90	17
250	40	11	60	10	62.5	10	82	13	87.5	13	100	17
300	45	11	68	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

Percent AR is the percent reduction in full-load line current due to capacitors. A capacitor located on the motor side of the overload relay reduces current through the relay. Therefore, a smaller relay may be necessary. The motor-overload relay should be selected on the basis of the motor full-load nameplate current reduced by the percent reduction in line current (percent AR) due to capacitors.

The capacitor size specified in the above table will increase the full load power factor to 95% and larger sizes should not be used without consulting the factory.

To calculate required kvar for energy efficient motors (or any motor) use the following formula:

$$\text{kvar} = \frac{\text{H.P. x .746}}{\text{\% efficiency}} \left(\sqrt{\frac{1 - PF_0^2}{PF_0^2}} - \sqrt{\frac{1 - PF_1^2}{PF_1^2}} \right)$$

PF_0	Original Power Factor (supplied by manufacturer)
PF_1	Target Power Factor
H.P.	Motor Horsepower from nameplate
% efficiency	Motor manufacturer nameplate

Points to Consider when Sizing Capacitors

Two limiting factors must be considered when capacitors are to be switched with a motor as a unit. The first is overvoltage due to self-excitation, and the second is transient torques.

Self-excitation voltage: When a motor is disconnected from the line, it will normally rotate for a short time before coming to rest. A capacitor connected to this motor will still be supplying magnetizing current, which will excite the motor. Under these conditions, the motor and capacitor act like a generator and produce a certain voltage because of this "self-excitation." The magnitude of the voltage that can be produced is determined by two things—the rating of the capacitor being used and the speed of the motor involved. It is not uncommon for this "self-excitation" voltage to reach 150% of rated voltage if too large a capacitor is being used.

Transient torques: Perhaps even more important than overvoltage is the transient torques that can occur if the motor happens to close back into the line before coming to a complete rest. If the motor is still rotating and acting as a generator, the resulting transient torque may be as much as 20 times the full load torque.

Because of transient torque and overload considerations, most motor manufacturers provide recommendations concerning the maximum capacitor KVAR that should be switched with a given motor. These recommendations are conservative enough to avoid endangering the motor, and will ordinarily result in a corrected power factor of approximately 95-98% at full load.

To avoid nuisance blowing of fuses when capacitors are connected directly across the motor terminals:

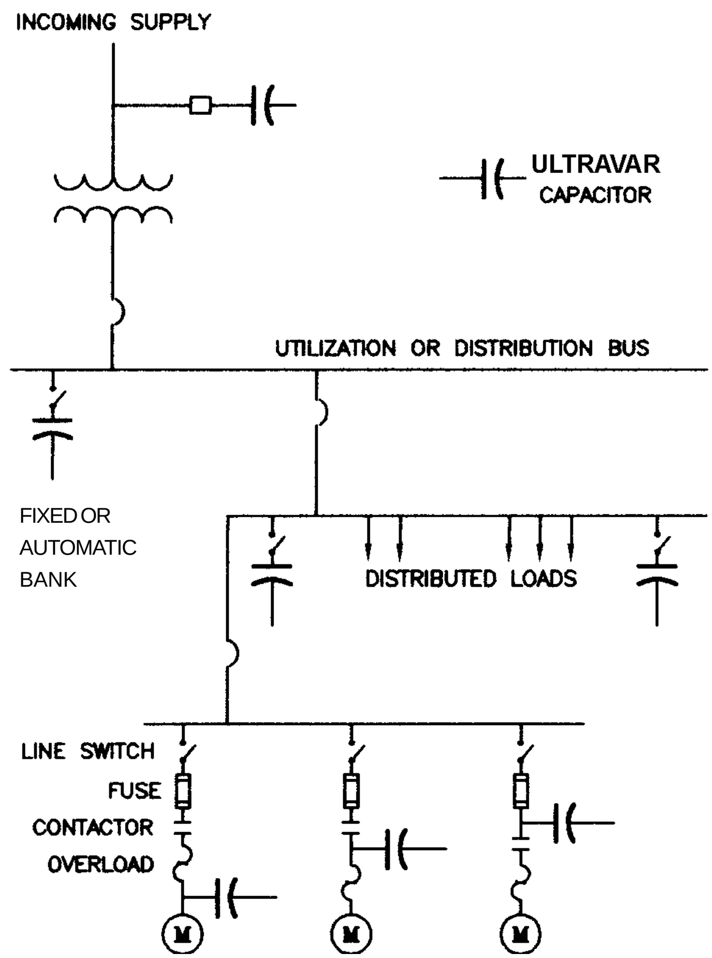
1. Motors should not be subject to plugging or reversing duty.
2. Motors should not be operated such that rapid restarting occurs.

Switching Capacitors

The National Electrical Code requires that power capacitors, other than those directly connected across motor terminals, have separate disconnecting means to permit their removal from the circuit as a regular operating procedure, or for maintenance purposes. The Code also requires that the continuous current carrying capacity of the disconnecting device and of the capacitor circuit conductors shall be not less than 135 percent of the rated current of the capacitor.

Since power capacitors for industrial service are designed for use in an ambient temperature of 46°C (115°F) maximum, the cables and disconnecting devices should also be selected for this ambient operation.

The data in Table 4 on page 15 is predicated on these conditions.



Suggested Wire Sizes for Capacitor Installations Table 4

The cable sizes indicated in this table are based on 135% of rated current in accordance with NEC 460.

240 Volt, 3 Phase

Cap. Rating KVAR	75°C Min.Cable Sizes k	90°C Min.Cable Sizes k	Safety Switch Rating AMPS	Safety Switch Fuse AMPS
0.5	14	14	30	3
1	14	14	30	5
2	14	14	30	10
2.5	14	14	30	10
3	14	14	30	15
4	12	12	30	20
5	12	12	30	20
6	10	10	30	25
7.5	10	10	30	30
8	8	8	60	35
10	8	8	60	40
12.5	8	8	60	50
15	6	6	60	60
17.5	4	6	100	75
20	4	4	100	80
22.5	3	4	100	90
25	3	3	100	100
27.5	1	2	200	125
30	1	2	200	125
35	1/0	1	200	150
40	2/0	2/0	200	175
45	3/0	3/0	200	200
50	3/0	3/0	200	200
60	250	4/0	400	250
75	350	300	400	300
100	2x3/0	3x3/0	400	400
125	2x250	2x4/0	600	500
150	2x350	2x300	600	600
175	2x500	2x350	800	700
200	2x600	2x500	800	800
225	3x350	3x300	1,200	900
250	3x350	3x350	1,200	1,000
275	4x300	3x400	1,200	1,100
300	4x350	3x500	1,200	1,250

480 Volt, 3 Phase

Cap. Rating KVAR	75°C Min.Cable Sizes k	90°C Min.Cable Sizes k	Safety Switch Rating AMPS	Safety Switch Fuse AMPS
0.5	14	14	30	1
1	14	14	30	3
1.5	14	14	30	3
2	14	14	30	6
2.5	14	14	30	6
3	14	14	30	6
4	14	14	30	10
5	14	14	30	10
6	14	14	30	15
7.5	14	14	30	15
8	12	12	30	20
10	12	12	30	20
12.5	10	10	30	25
15	10	10	30	30
17.5	8	8	60	35
20	8	8	60	40
22.5	8	8	60	50
25	8	8	60	50
27.5	6	6	60	60
30	6	6	60	60
35	4	6	100	70
40	4	4	100	80
45	3	4	100	90
50	3	3	100	100
60	3	3	200	110
75	1/0	1	200	150
100	3/0	2/0	200	200
125	250	4/0	400	250
150	350	300	400	300
175	500	350	400	350
200	2x3/0	2x3/0	400	400
225	2x3/0	2x3/0	400	400
250	2x250	2x4/0	600	500
275	2x250	2x4/0	600	500
300	2x350	2x300	600	600
325	2x500	2x350	800	700
350	2x500	2x350	800	700
375	2x600	2x500	800	800
400	2x600	2x500	800	800
425	2x350	2x300	1,200	900
450	2x350	2x300	1,200	900
475	2x350	2x300	1,200	900
500	3x400	3x350	1,200	1,000
525	3x400	3x350	1,200	1,000
550	4x300	3x400	1,200	1,100
575	4x350	3x500	1,200	1,200
600	4x350	3x500	1,200	1,200

600 Volt, 3 Phase

Cap. Rating KVAR	75°C Min.Cable Sizes k	90°C Min.Cable Sizes k	Safety Switch Rating AMPS	Safety Switch Fuse AMPS
0.5	14	14	30	1
1	14	14	30	3
1.5	14	14	30	3
2	14	14	30	3
2.5	14	14	30	5
3	14	14	30	5
4	14	14	30	6
5	14	14	30	10
6	14	14	30	10
7.5	14	14	30	15
8	14	14	30	15
10	12	12	30	20
12.5	12	12	30	20
15	10	10	30	25
17.5	10	10	30	30
20	8	8	60	35
22.5	8	8	60	40
25	8	8	60	40
27.5	8	8	60	45
30	8	8	60	50
35	6	6	60	60
40	4	6	100	70
45	4	4	100	80
50	4	4	100	80
60	3	3	100	100
75	1	2	200	125
100	1/0	1	200	150
125	3/0	3/0	200	200
150	250	4/0	400	250
175	350	300	400	300
200	500	350	400	350
225	2x3/0	2x3/0	400	400
250	2x3/0	2x3/0	400	400
275	2x4/0	2x3/0	600	450
300	2x250	2x4/0	600	500
325	2x250	2x4/1	600	500
350	2x350	2x300	600	600
375	2x350	2x300	600	600
400	2x500	2x350	800	700
425	2x500	2x350	800	700
450	2x500	2x400	800	750
475	2x500	2x400	800	750
500	2x600	2x500	1,200	800
525	2x600	2x500	1,200	800
550	3x350	2x600	1,200	900
575	3x350	2x600	1,200	900
600	3x400	3x350	1,200	1,000

* Not more than three single conductors are allowed in a raceway with 30°C ambient. For higher ambient temperatures, consult the National Electrical Code Table 310-16 (correction factor for ambients over 30°C). Rated current is based on operation at rated voltage, frequency, and KVAR.

Understanding Harmonics

Harmonics are multiples of the fundamental frequency distortions found in electrical power, subjected to continuous disturbances. In a 60 Hz electrical system, 300 Hz is the 5th harmonic, 420 Hz is the 7th harmonic, and so on. These harmonics are created by the increased use of non-linear devices such as UPS systems, solid state variable speed motor drives, rectifiers, welders, arc furnaces, fluorescent ballasts, and personal computers. The source of these harmonics may be internal or external. Individual harmonic frequencies will vary in amplitude and phase angle, depending on the harmonic source. Variable speed drives are usually referred to by the number of rectifiers in the system. The most common are six (rectifiers) and twelve (rectifiers) pulse drives.

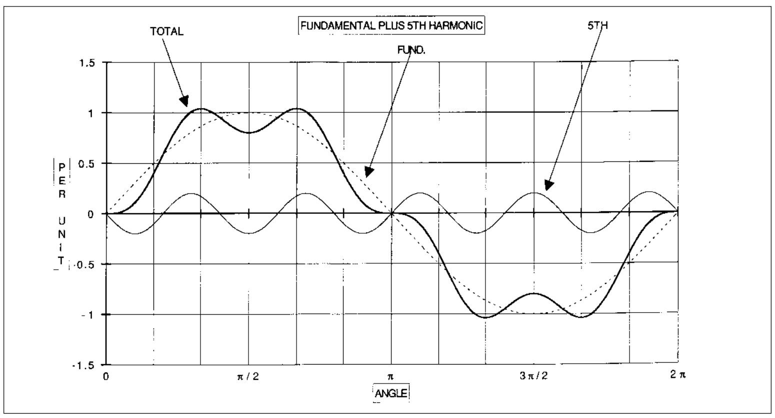


Figure 1

Harmonic Resonance occurs when the capacitor reactance and the system reactance are equal. If this occurs, large harmonic currents will circulate between transformer and capacitor. These currents will result in greater voltage distortion. This provides a higher voltage across the capacitor and potentially harmful currents through all capacitor equipment. Harmonic resonance may occur at any frequency but the 5th, 7th, 11th and 13th are the frequencies with which we are most concerned. If total bus load exceeds 15-20% of harmonic generation load, the potential for a resonance condition is high. Some indicators of resonance are overheating, frequent circuit breaker tripping, unexplained fuse operation, capacitor failure, electronic equipment malfunction, flicking lights and telephone interference.

Conquering Harmonic Resonance can be accomplished by:
(1) adding or subtracting capacitance from the system to move the parallel resonance frequency to one that is not deleterious;
(2) adding tuned harmonic suppression reactors in series with the capacitor to prevent resonance; (3) altering the size of non-linear devices. It is important that the tuned frequency, for the 5th harmonic, be at approximately the 4.7th harmonic to account for tolerance in manufacturing and to remove the largest offending portion of the 5th harmonic. Parallel resonance will occur around the 4th harmonic, at a much lower amplitude and in an area that does no harm to the system or capacitor. Tuning lower than 282 Hz is not efficient in removing large portions of the offending harmonic.

Considerations of how power factor correction capacitors affect a system are of utmost importance. In systems with more than 15-20% of harmonic loads, a harmonic survey should be performed to indicate potential problem areas. Readings taken over changing load conditions at potential capacitor locations are most useful in determining the types of systems best employed to accomplish the ultimate harmonic suppression, power factor improvement, KVA reduction and other goals.

Applying Power Factor Correction in a Harmonic Environment

The use of capacitors has long been accepted as the most practical solution to low power factor problems in power systems. Modern capacitors are a reliable, maintenance free, inexpensive source of VAR's needed in inductive circuits to synchronize the voltage and current waveforms.

In the past, the application of capacitors was straightforward; all that was required was a knowledge of KW (or KVA), existing power factor, and target power factor. In recent years, however, this practice has been complicated by the proliferation of non-linear loads.

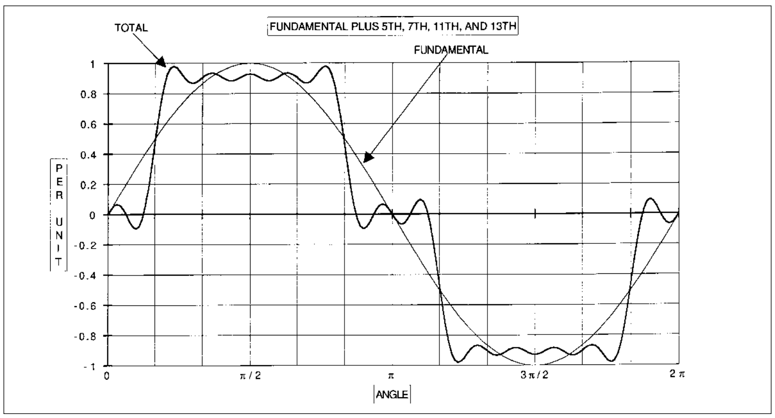


Figure 2

The Source of the Problem

One of the most widely used solid state motor controls is the six-pulse drive. These devices represent a non-linear impedance to the power source, drawing a quasi-square wave alternating current rich in harmonics.

For six-pulse drives, the characteristic harmonics are: 5, 7, 11, 13, 17, 19, . . . ; the higher order harmonics are not usually troublesome because their magnitude is progressively smaller. **Figures 1 and 2** show the total distortion when one or more harmonics are added to the fundamental.

Harmonic Resonance

When a capacitor bank is added to a power system, it is effectively connected in parallel with the system's impedance, which is primarily inductive. As far as the harmonic source is concerned, it sees a capacitor in parallel with an inductor. **Figure 3** shows the model circuit for this system on a per phase basis. Resistor 'R' represents the inevitable system losses. The harmonic source is represented as a constant current source, since it behaves as such.

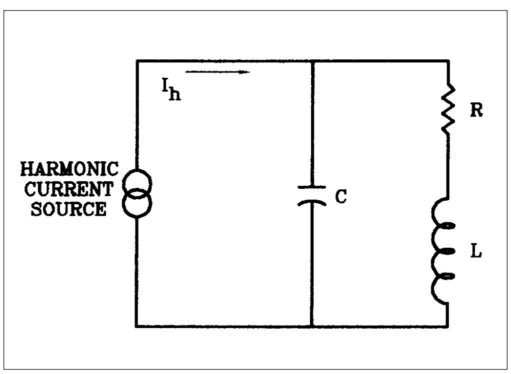


Figure 3

Since the capacitive (X_C) and inductive (X_L) reactances are frequency dependent (as frequency increases, X_C decreases and X_L increases), there is a frequency at which these two parameters will be equal; this frequency is called the system's natural resonant frequency.

At this frequency, the system's impedance appears to the harmonic source to be very large. Therefore, a harmonic current at the resonant frequency flowing through this impedance will result in a very large harmonic voltage as derived by Ohm's Law ($V_h = I_h Z_h$).

A large harmonic voltage will in turn result in a much larger harmonic current exchange between the capacitor bank and the system impedance. This secondary harmonic current may be many orders of magnitude larger than the generated harmonic current, resulting in nuisance operation of circuit breakers or fuses that happen to be in the path of this current.

The degree of magnification is determined by the system resistance.

Since the generated harmonic current is considered to be constant for a given frequency, then the harmonic voltage will be proportional to the impedance. Consequently, the frequency response of the impedance is a good indication of the system's susceptibility to harmonic resonance.

Figure 4 is the impedance plot, as seen by the harmonic source in figure 3, for a typical system consisting of 500 KVAR connected to a 1500 KVA, 480 volt transformer. (While impedance magnitudes are dependent on system resistance, resonant frequency is primarily a function of inductance (L) and capacitance (C).)

The quick and simple way to calculate the system's harmonic resonance is through the following relationship derived from the system's reactances:

$$h = \sqrt{\frac{KVAsc}{KVAR}}$$

where: h = harmonic order

$KVAsc = \frac{KVA}{Zpu}$ = available short circuit at point of capacitor bank installation

KVAR = capacitor bank size

This calculation, even though it does not take into account upstream system impedance, is reasonably accurate for most applications since the bulk of the impedance is contributed by the transformer itself.

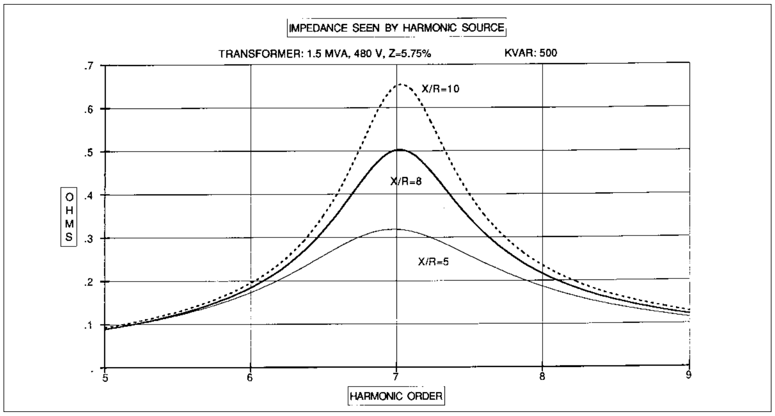


Figure 4

Detuning the Circuit

The most effective solution to this problem consists of series tuning the capacitor bank to the lowest offending harmonic, usually the 5th. This is done by introducing an inductor in series with the capacitor as shown in **figure 5.**

The impedance versus frequency plot, as seen by the harmonic source, is shown in **figure 6**; the original impedance response (untuned) is shown for comparison.

The minimum impedance occurs at the series resonant point, the 4.7th harmonic, while the peak represents a parallel resonance due to the capacitor and the two inductors. Harmonic currents generated at or near the series resonant frequency (such as the 5th) will flow to the trap harmlessly, provided the capacitor and reactor are sized properly to withstand the additional stresses. These currents are simply following the path of least impedance. The system will not resonate above this frequency since it is inductive. This approach will accomplish two objectives. On the line side of the capacitor filter bank, system power factor is corrected and harmonic voltage distortion is reduced, Harmonic voltage (V_h) is the result of a harmonic current (I_h) flowing through the system impedance (Z_h), i.e. Ohm's Law ($V_h = I_h Z_h$).

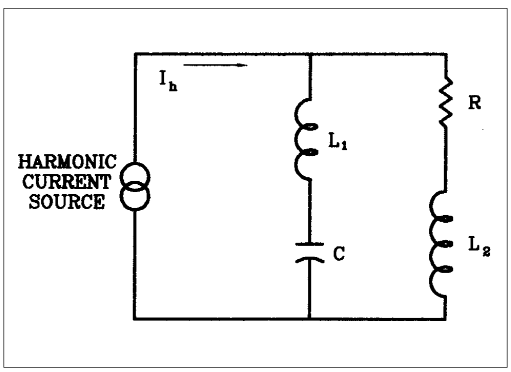


Figure 5

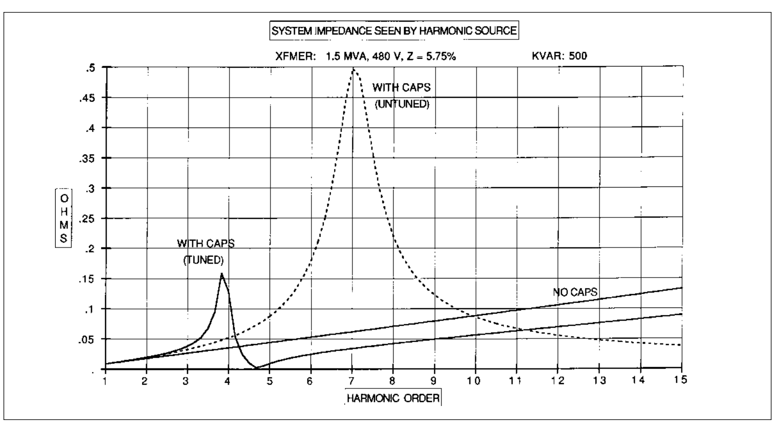


Figure 6

By reducing the system impedance (Z_h) we can reduce the harmonic voltage (V_h) even though the harmonic current (I_h) remains the same.

When the main objective is to reduce harmonic distortion, the engineer will consider the use of more filter stages, each tuned to the next higher harmonic (7th, 11th, . . .). In some cases, where harmonic currents are excessive, the use of capacitors rated at the next higher voltage may be required. In most cases, Ultravar capacitors are run at rated voltage and will maintain their twenty year life expectancy.

The Ultravar Power Quality Engineering Department is available to assist you with system analysis.

Harmonic Survey Data Form

for Low Voltage Harmonic Filter Capacitor Equipment

Company Name

Address

City

State Zip

Contact

Title

TEL

FAX

System Characteristics

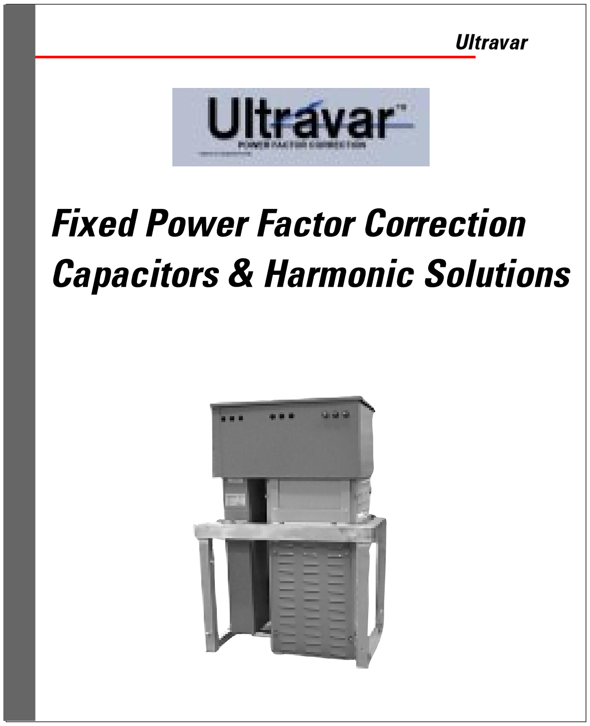
(Include a one line diagram, if available):

- Power distribution transformer ________ KVA
- Transformer impedance (or reactance) _ %
- Transformer resistance* ________ %
- Transformer primary voltage (line to line) Volts
- Transformer secondary voltage ________ Volts
- Primary three phase fault current (RMS)* KA
  or secondary fault current* ________ KA
- Primary system X/R ratio* ________
- Total system load (demand) ________ KW
- Power factor (at peak load):
  Existing ________ %
  Desired ________ %
- Capacitors to be added:
  voltage ____ KVAR __
  voltage ____ KVAR __
  voltage ____ KVAR __
- Existing capacitors on your distribution system
  Service Entrance __________ voltage __ KVAR
  Primary Side voltage ____ KVAR __
  Individual voltage ____ KVAR __
  Equipment/Motors
- Describe any existing capacitor problems:

* Typical values will be assumed if the actual values are not known.

Return completed form to your Ultravar representative.

Other available Ultravar™ publications:



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