

Standard Values: Selection Tables for Cables, Cable Cross Sections and Fuses

Selection table			
Power KVAr	Current A	Cross section mm ²	Fuse rating A
Rated voltage 230 V, 50 Hz			
2.5	6.3	1.5	10
5.0	12.6	4.0	25
7.5	18.8	6.0	35
10.0	25.1	10.0	50
12.5	31.4	16.0	50
15.0	37.7	16.0	63
20.0	50.2	25.0	80
25.0	62.8	35.0	100
30.0	75.8	50.0	125
40.0	100.4	70.0	160
50.0	125.5	95.0	200
75.0	188.3	185.0	315
100.0	251.0	2 x 120.0	400
125.0	-	-	-
150.0	-	-	-
175.0	-	-	-
200.0	-	-	-
Rated voltage 400 V, 50 Hz			
2.5	3.6	1.5	10
5.0	7.2	2.5	16
7.5	10.8	2.5	16
10.0	14.4	4.0	25
12.5	18.0	6.0	35
15.0	28.8	10.0	50
25.0	36.0	16.0	63
30.0	43.2	25.0	80
40.0	57.6	35.0	100
50.0	72.0	50.0	125
75.0	108.3	70.0	160
100.0	144.3	120.0	250
125.0	180.3	185.0	315
150.0	216.5	2 x 95.0	350
175.0	252.6	2 x 95.0	400
200.0	288.0	2 x 120.0	500
Rated voltage 440 V, 50 Hz			
2.5	3.3	1.5	10
5.0	6.6	2.5	16
7.5	10.0	2.5	16
10.0	13.2	4.0	25
12.5	16.8	4.0	25
15.0	19.8	6.0	35
20.0	26.4	10.0	50
25.0	33.0	16.0	63
30.0	39.6	25.0	80
40.0	52.8	35.0	100
50.0	66.0	50.0	125
75.0	99.0	70.0	160
100.0	132.0	95.0	200
125.0	165.0	185.0	315
150.0	198.0	2 x 95.0	350
175.0	231.0	2 x 95.0	400
200.0	264.0	2 x 120.0	500

The above mentioned values are guidelines for operation in normal conditions at ambient temperatures up to 35 °C. Upgrade accordingly if conditions differ, e.g. temperature or harmonics differ. The internal wiring of a capacitor bank is sometimes possible with a smaller cross section. Various parameters such as temperature inside the cabinet, cable quality, maximum cable insulation temperature, single or multi core cable, cable length and laying system have to be considered for a proper selection. The local panelbuilder/installer is responsible for a proper selection of the cable sizes and fuses according to the valid regulations and standards in the specific country where the PFC panels are installed.

Standard Values: Selection Tables for Cables, Cable Cross Sections and Fuses

Selection table			
Power KVAr	Current A	Cross section mm ²	Fuse rating A
Rated voltage 480 V, 50 Hz			
2.5	3.0	1.5	10
5.0	6.0	2.5	16
7.5	9.0	2.5	16
10.0	12.0	4.0	25
12.5	18.0	6.0	35
15.0	21.0	6.0	35
20.0	24.0	10.0	50
25.0	30.0	10.0	50
30.0	36.0	16.0	63
40.0	48.0	25.0	80
50.0	60.0	35.0	100
75.0	90.0	70.0	160
100.0	120.0	95.0	200
125.0	150.0	120.0	250
150.0	180.0	185.0	315
175.0	210.0	2 x 95.0	350
200.0	240.0	2 x 95.0	400
Rated voltage 525 V, 50 Hz			
2.5	2.7	1.5	10
5.0	5.5	1.5	10
7.5	6.9	2.5	16
10.0	11.0	2.5	16
12.5	13.7	4.0	25
15.0	16.5	4.0	25
20.0	22.0	6.0	35
25.0	27.5	10.0	50
30.0	33.0	16.0	63
40.0	44.0	25.0	80
50.0	55.0	35.0	100
75.0	82.5	70.0	160
100.0	110.0	95.0	200
125.0	137.5	95.0	200
150.0	165.0	185.0	300
175.0	193.0	2 x 95.0	350
200.0	220.0	2 x 95.0	350
Rated voltage 690 V, 50 Hz			
2.5	2.1	1.5	10
5.0	4.2	1.5	10
7.5	6.3	1.5	10
10.0	8.4	2.5	16
12.5	10.5	2.5	16
15.0	12.6	4.0	25
20.0	16.7	4.0	25
25.0	20.9	6.0	35
30.0	25.1	10.0	50
40.0	33.5	16.0	63
50.0	41.8	25.0	80
75.0	62.8	50.0	125
100.0	83.7	70.0	160
125.0	105.0	70.0	160
150.0	126.0	95.0	200
175.0	146.0	120.0	250
200.0	167.0	128.5	315

The above mentioned values are guidelines for operation in normal conditions at ambient temperatures up to 35°C. Upgrade accordingly if conditions differ, e.g. temperature or harmonics differ. The internal wiring of a capacitor bank is sometimes possible with a smaller cross section. Various parameters such as temperature inside the cabinet, cable quality, maximum cable insulation temperature, single or multi core cable, cable length and laying system have to be considered for a proper selection. The local panel builder/installer is responsible for a proper selection of the cable sizes and fuses according to the valid regulations and standards in the specific country where the PFC panels are installed.

Capacitor (KVAR) selection chart

Current (ACTUAL) Tan φ	cos φ	achievable (TARGET) cos φ							Q _c	TARGET Cos φ = 0.96		
		Factor F								Cos φ ≤ 1		
		0.80	0.82	0.85	0.88	0.90	0.92	0.94		0.96	0.98	1.00
3.18	0.30	2.43	2.48	2.56	2.64	2.70	2.75	2.82	2.89	2.98	3.18	
2.96	0.32	2.21	2.26	2.34	2.42	2.48	2.53	2.60	2.67	2.76	2.96	
2.77	0.34	2.02	2.07	2.15	2.23	2.28	2.34	2.41	2.48	2.56	2.77	
2.59	0.36	1.84	1.89	1.97	2.05	2.10	2.17	2.23	2.30	2.39	2.59	
2.43	0.38	1.68	1.73	1.81	1.89	1.95	2.01	2.07	2.14	2.23	2.43	
2.29	0.40	1.54	1.59	1.67	1.75	1.81	1.87	1.93	2.00	2.09	2.29	
2.16	0.42	1.41	1.46	1.54	1.62	1.68	1.73	1.80	1.87	1.96	2.16	
2.04	0.44	1.29	1.34	1.42	1.50	1.56	1.61	1.68	1.75	1.84	2.04	
1.93	0.46	1.18	1.23	1.31	1.39	1.45	1.50	1.57	1.64	1.73	1.93	
1.83	0.48	1.08	1.13	1.21	1.29	1.34	1.40	1.47	1.54	1.62	1.83	
1.73	0.50	0.98	1.03	1.11	1.19	1.25	1.31	1.37	1.45	1.63	1.73	
1.64	0.52	0.89	0.94	1.02	1.10	1.16	1.22	1.28	1.35	1.44	1.64	
1.56	0.54	0.81	0.86	0.94	1.02	1.07	1.13	1.20	1.27	1.36	1.56	
1.48	0.56	0.73	0.78	0.86	0.94	1.00	1.05	1.12	1.19	1.28	1.48	
1.40	0.58	0.65	0.70	0.78	0.86	0.92	0.98	1.04	1.11	1.20	1.40	
1.33	0.60	0.58	0.63	0.71	0.79	0.85	0.91	0.97	1.04	1.13	1.33	
1.30	0.61	0.55	0.60	0.68	0.76	0.81	0.87	0.94	1.01	1.10	1.30	
1.27	0.62	0.52	0.57	0.65	0.73	0.78	0.84	0.91	0.99	1.06	1.27	
1.23	0.63	0.48	0.53	0.61	0.69	0.75	0.81	0.87	0.94	1.03	1.23	
1.20	0.64	0.45	0.50	0.58	0.66	0.72	0.77	0.84	0.91	1.00	1.20	
1.17	0.65	0.42	0.47	0.55	0.63	0.68	0.74	0.81	0.88	0.97	1.17	
1.14	0.66	0.39	0.44	0.52	0.60	0.65	0.71	0.78	0.85	0.94	1.14	
1.11	0.67	0.36	0.41	0.49	0.57	0.63	0.68	0.75	0.82	0.90	1.11	
1.08	0.68	0.33	0.38	0.46	0.54	0.59	0.65	0.72	0.79	0.88	1.08	
1.05	0.69	0.30	0.35	0.43	0.51	0.56	0.62	0.69	0.76	0.85	1.05	
1.02	0.70	0.27	0.32	0.40	0.48	0.54	0.59	0.66	0.73	0.82	1.02	
0.99	0.71	0.24	0.29	0.37	0.45	0.51	0.57	0.63	0.70	0.79	0.99	
0.96	0.72	0.21	0.26	0.34	0.42	0.48	0.54	0.60	0.67	0.76	0.96	
0.94	0.73	0.19	0.24	0.32	0.40	0.45	0.51	0.58	0.65	0.73	0.94	
0.91	0.74	0.16	0.21	0.29	0.37	0.42	0.48	0.55	0.62	0.71	0.91	
0.88	0.75	0.13	0.18	0.26	0.34	0.40	0.46	0.52	0.59	0.68	0.88	
0.86	0.76	0.11	0.16	0.24	0.32	0.37	0.43	0.50	0.57	0.65	0.86	
0.83	0.77	0.08	0.13	0.21	0.29	0.34	0.40	0.47	0.54	0.63	0.83	
0.80	0.78	0.05	0.10	0.18	0.26	0.32	0.38	0.44	0.51	0.60	0.80	
0.78	0.79	0.03	0.08	0.16	0.24	0.29	0.35	0.42	0.49	0.57	0.78	
0.75	0.80		0.05	0.13	0.21	0.27	0.32	0.39	0.46	0.55	0.75	
0.72	0.81			0.10	0.18	0.24	0.30	0.36	0.43	0.52	0.72	
0.70	0.82			0.08	0.16	0.21	0.27	0.34	0.41	0.49	0.70	
0.67	0.83			0.05	0.13	0.19	0.25	0.31	0.38	0.47	0.67	
0.65	0.84			0.03	0.11	0.16	0.22	0.29	0.36	0.44	0.65	
0.62	0.85				0.08	0.14	0.19	0.26	0.33	0.42	0.62	
0.59	0.86				0.05	0.11	0.17	0.23	0.30	0.39	0.59	
0.57	0.87					0.08	0.14	0.21	0.28	0.36	0.57	
0.54	0.88					0.06	0.11	0.18	0.25	0.34	0.54	
0.51	0.89					0.03	0.09	0.15	0.22	0.31	0.51	
0.48	0.90						0.06	0.12	0.19	0.26	0.48	
0.46	0.91						0.03	0.10	0.17	0.25	0.46	
0.43	0.92							0.07	0.14	0.22	0.43	
0.40	0.93							0.04	0.11	0.19	0.40	
0.36	0.94								0.07	0.16	0.36	
00..33	95									0.13	0.33	

$Q_c = PA \times (\tan \phi_1 - \tan \phi_2)$
 $Q_c \text{ (KVAR)} = PA \times F = \text{active power (kW)} \times \text{factor "F"}$
 $PA = S \times \cos \phi = \text{apparent power} \times \cos \phi$
 $\tan \phi_1 + \phi_2$ according to $\cos \phi$ values ref. Table

Example:
 ACTUAL motor power P = 100 kW
 Actual $\cos \phi$ 0.61
 TARGET $\cos \phi$ 0.96
 Factor F from table 1.01

Capacitor reactive power Q_c
 $Q_c = 100 \times 1.01 = 101.0 \text{ KVAR}$

Individual PFC for Motors

Approximate values (specified by the German Electricity Association VDEW) for fixed PFC of motors			
Motor nominal rating	Capacitor power rating (1500 r.p.m.*) KVAr	Capacitor power rating (1000 r.p.m.*) KVAr	Capacitor power rating (750 r.p.m.*) KVAr
1 ... 1.9	0.5	0.5	0.6
2 ... 2.9	1	1	1.2
3 ... 3.9	1.5	1.6	1.7
4 ... 4.9	2	2.1	2.3
5 ... 5.9	2.5	2.6	2.9
6 ... 7.9	3	3.2	3.5
8 ... 10.9	4	4.2	4.6
11 ... 13.9	5	5.3	5.8
14 ... 17.9	6	6.3	6.9
18 ... 21.9	7.5	8.0	8.6
22 ... 29.9	10	10.5	11.5
30 ... 39.9	approx. 40% of the motor power		
40 and above	approx. 35% of the motor power		

*r.p.m.: revolutions per minute

The capacitor output should be approx. 90% of the apparent power of the motor when idle.

This means a power factor of 0.9 at full load and 0.95...0.98 during idling.

Important: The capacitor output must not be rated too high for individual compensated machines where the capacitor is directly connected with the motor clamp.

This especially applies when the machine has a big oscillating weight and still continues to rotate after switching off. The capacitor placed in parallel may act as generator for the motor which will cause serious overvoltages.

The consequence could be heavy damage to the capacitor as well as to the motor.

Individual PFC for Transformers

Standard values for transformers power factor correction		
Rated apparent power of transformer KVAr	Rated capacitor power for oil immersed transformer KVAr	Rated capacitor power for cast resin transformer KVAr
10	1.0	1.5
20	2.0	1.7
50	4.0	2.0
75	5.0	2.5
100	5.0	2.5
160	7.0	4.0
200	7.5	5.0
250	8.0	7.5
315	10.0	8.0
400	12.5	8.5
500	15.0	10.0
630	17.5	12.5
800	20.0	15.0
1000	25.0	16.7
1250	30.0	20.0
1600	35.0	22.0
2000	40.0	25.0
2500	50.0	35.0
3150	60.0	50.0

For an exact calculation of the right capacitor value, following formula can be used:

$$Q_c = I_0\% \cdot \frac{AN}{100}$$

Q_c = needed capacitor (KVAr)

$I_0\%$ = magnetising current of the transformer

AN = apparent rated power of the transformer in KVA

There are regional differences in the guidelines of power suppliers concerning the admissible size of capacitors directly connected with a transformer. Therefore a consultation with the respective power supplier is recommended

before installation of a compensation bank. Modern transformers have laminations which only need low capacity to reverse the magnetism. In case the capacitor output is too high, stress increase may occur during idling.

Detuned PFC in General

When installing capacitors for PFC purpose, the problem of dealing with harmonics has to be faced. They have to be taken into account when designing the PFC system in order to prevent parallel and /or series resonance conditions that would damage the whole electrical system.

When PFC capacitors are connected, the inductance of the transformer together with the capacitors forms a resonant circuit that could be excited by a harmonic current generated by the load. This resonant circuit has a resonance frequency, and if a harmonic current of this frequency (or close to it) exists, it will lead the circuit into a resonance condition where high current will flow through the branches (L: the transformer, and C: the capacitor bank), overloading them and raising the voltage across them and across the whole electrical system that is connected in parallel.

PFC detuned filtering is a technique to correct the power factor avoiding the risk of resonance condition performed by shifting the resonance frequency to lower values where no harmonic currents are present.

This is achieved by modifying the basic LC circuit formed by the transformer and the capacitor bank, introducing a filter reactor in series with the capacitors, making this way a more complex resonant circuit but with the desired feature of having a resonance frequency below the first existing harmonic. This way it's not possible to have a real resonance condition.

Besides this main objective, the reactor connected in series with capacitors form a series resonant circuit with a certain tuning frequency at which the branch will offer a low impedance path. Filtering of harmonic currents and "cleaning" of the grid will be achieved.

Components for PFC detuned filters must be carefully selected according to the desired PFC purpose, to the harmonics present in the system, to some features of the system like short circuit power and impedances, to the desired filtering effect and to the characteristics of the resonant circuit configured.

For example, the voltage across the capacitors will be higher than the nominal grid voltage when they have a reactor connected in series.

The reactors must be selected in line with the inductance value to obtain the desired tuning frequency and current capability high enough for the harmonic current absorption that can be expected. The tuning frequency is usually indirectly referred to as the detuning factor p and expressed as percentage.

$$p = 100 \cdot \frac{X_L}{X_C} = \left(\frac{f}{f_{RES}} \right)^2 \cdot 100$$

f : fundamental frequency
 f_{RES} : tuning frequency

PFC detuned filtering is an engineering speciality that takes experienced know-how to implement it in a satisfying and safe way.

The design instructions for detuned PFC systems on page 87 to 90 have to be followed to ensure an optimum performance of the PFC system.

Note: The recommendations given in the selection tables are meant as a support tool. EPCOS does not take over any responsibility for the design, as apart from the theoretical conditions the prevailing circumstances in the application have to be taken into account.

Detuned PFC: Important Facts and Instructions

Important design instructions to be followed for detuned PFC Systems

- 1 Determine the necessary effective power (kvar) of the capacitor bank in order to obtain the desired PF.
- 2 Design the capacitor stages in such a way that the sensibility of the bank is around 15–20% of the total available power. It's not useful to have a more sensitive bank that reacts with a 5 or 10% of the total power because this would lead to a high amount of switching operations, wasting the equipment unnecessarily when the real objective is to have a high average PF.
- 3 Try to design the bank with standard kvar values of effective power steps, preferably multiples of 25 kvar.
- 4 Measure the presence of harmonic currents in the main feeder cable of the system without capacitors at all possible load conditions. Determine frequency and maximum amplitude for every harmonic that could exist.

Calculate the Total Harmonic Distortion of Current $THD-I = 100 \cdot \sqrt{[(I_3)^2 + (I_5)^2 + \dots + (I_N)^2]} / I_1$
Calculate every existing value for $THD-I_N = 100 \cdot I_N / I_1$
- 5 Measure the presence of harmonic voltages that might come from outside your system, if possible measure the HV side. Calculate the Total Harmonic Distortion of Voltage $THD-V = 100 \cdot \sqrt{[(V_3)^2 + (V_5)^2 + \dots + (V_N)^2]} / V_1$
- 6 Are there harmonics such as $THD-I > 10\%$ or $THD-V > 3\%$ (measured without capacitors)?
If YES → use PFC-DF and go to consideration 7.
If NO → use standard PFC and skip considerations 7, 8 and 9.
- 7 Is there 3rd harmonic content, $I_3 > 0.2 \cdot I_5$?
If YES → use PFC-DF with $p = 14\%$ and skip consideration 8.
If NO → use PFC-DF with $p = 7\%$ or 5.67% and go to consideration 8.
- 8 THD-V is:
 $3-7\% \rightarrow$ use PFC-DF with $p = 7\%$
 $> 7\% \rightarrow$ use PFC-DF with $p = 5.67\%$
 $> 10\% \rightarrow$ ask for special filter design
- 9 Select the proper components using EPCOS tables for PFC-DF and standard values for effective power, the voltage and frequency of your grid, and the determined detuned factor p .
- 10 Always use genuine EPCOS application-specific designed components for PFC-DF. Please observe that reactors are specified for their effective power at grid voltage and frequency. This power will be the real effective power of the whole LC set at fundamental frequency. Capacitors for PFC-DF must be selected for a higher rated voltage than the grid's because of the overvoltage caused by the series connection with the reactor. Contactors for capacitors are designed as application-specific to reduce inrush capacitor currents and to handle capacitive loads in a reliable way.

Capacitor Voltage Rating selection guideline for a Detuned Capacitor Bank

General

It is necessary to understand the importance of choosing the right voltage rating while using capacitors in a 'Detuned' system. In commonly accepted technical parlance, we say 'voltage drop across the reactor', however, notice that a capacitor and reactor are electrical components with opposite signs, i.e., $=jX_L$ and $-jX_C$

Hence, when you apply a basic voltage divider formula to these impedances, it's obvious that there exists a steady state voltage 'rise' across the capacitor in the circuit. Now the steady state voltage across the capacitor shall be as follows:

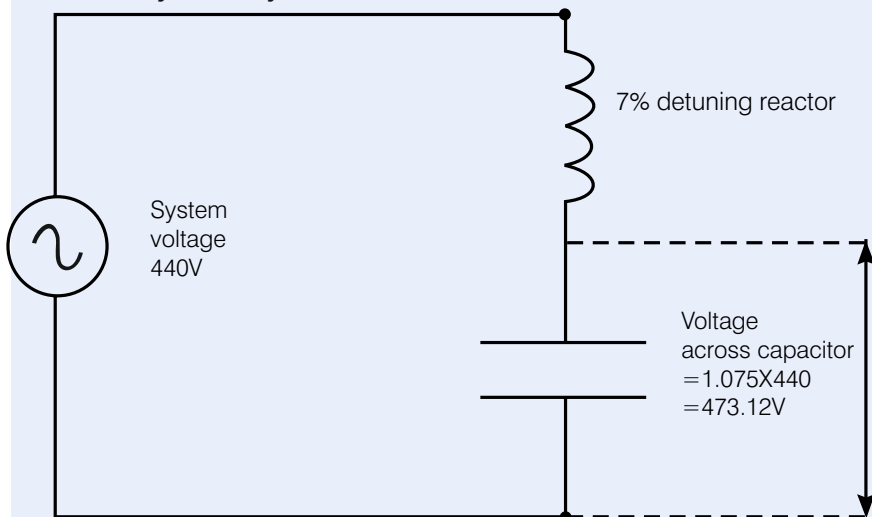
$$V_{cap} = \frac{-j X_C}{-j X_C + j X_L} \times 1pu$$

Where $X_L = p \cdot X_C$

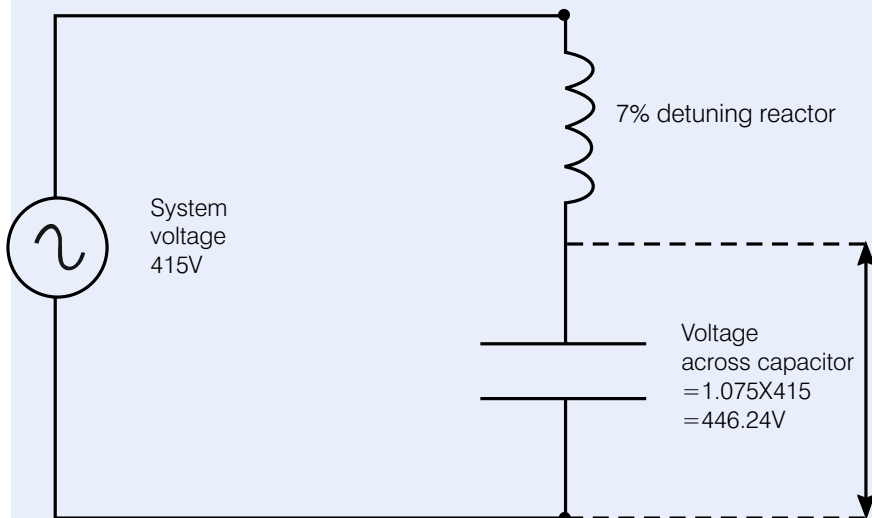
$p =$ Detuning percentage

Example with $p=7\%$ detuning reactor, $X_C=100\Omega$ and $X_L=7\Omega$

$$V_{cap} = \frac{-j 100}{-j 100 + j 7} \times 1pu = 1.075 pu$$



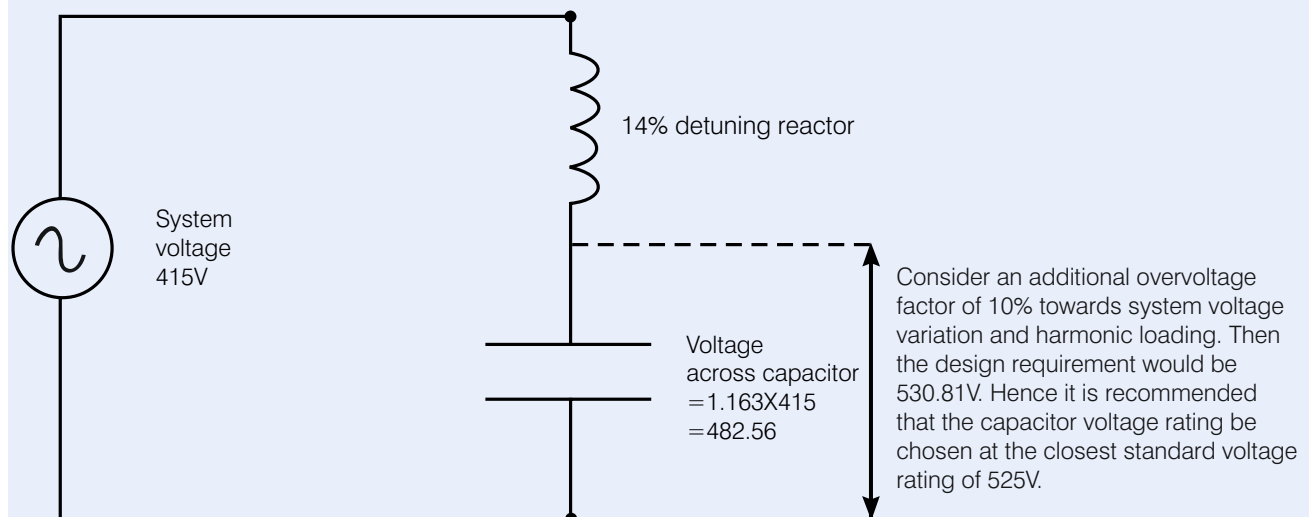
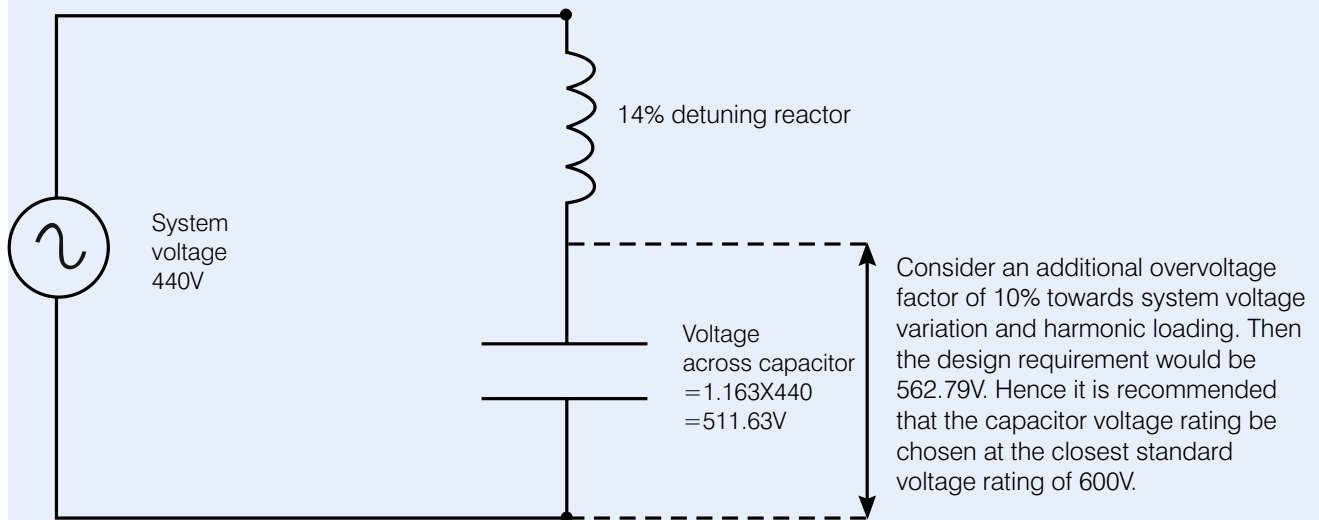
Consider an additional overvoltage factor of 10% towards system voltage variation and harmonic loading. Then the design requirement would be 520.43V. Hence it is recommended that the capacitor voltage rating be chosen at the closest standard voltage rating of 525V.



Consider an additional overvoltage factor of 10% towards system voltage variation and harmonic loading. Then the design requirement would be 490.86V. Hence it is recommended that the capacitor voltage rating be chosen at the closest standard voltage rating of 500V, or atleast 480V.

Capacitor Voltage Rating selection guideline for a Detuned Capacitor Bank

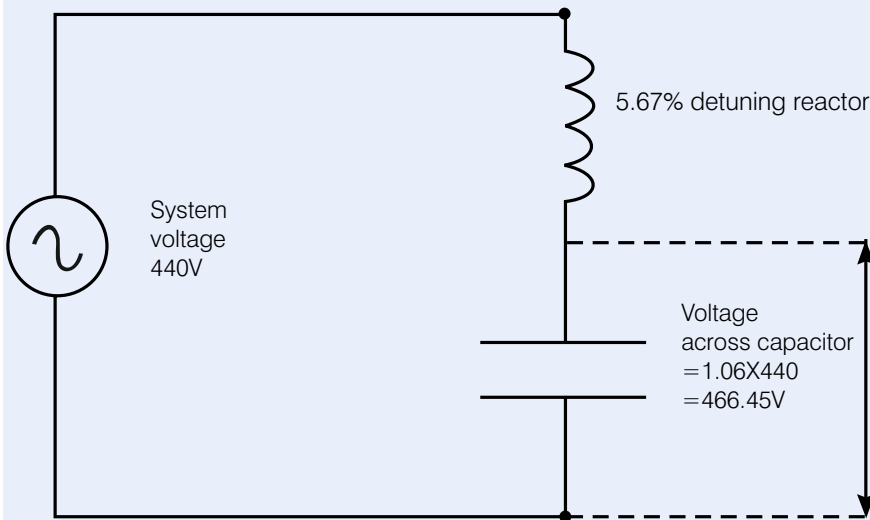
Example with $p=14\%$ detuning reactor, $X_c=100\Omega$ and $X_L=14\Omega$



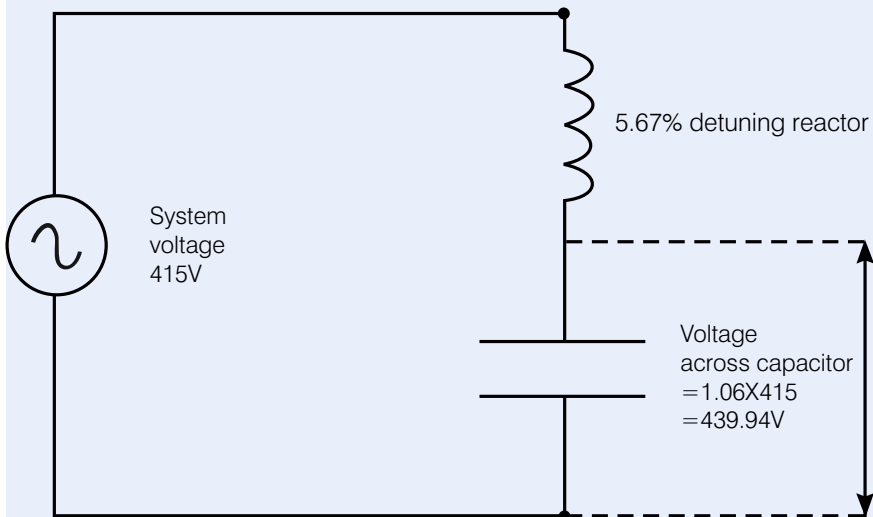
Capacitor Voltage Rating selection guideline for a Detuned Capacitor Bank

Example with p= 5.67% detuning reactor, $X_c=100\Omega$ and $X_L=5.67\Omega$

$$V_{cap} = \frac{-j 100}{-j 100 + 5.67} \times 1pu = 1.06 pu$$



Consider an additional overvoltage factor of 20% towards system voltage variation and harmonic loading. Notice the difference between the previous considerations of detuning. This is due to the fact that the detuning frequency has shifted upwards, more closer towards the 5th Harmonic frequency. This behaves like a partially tuned filter for the 5th Harmonic frequency. Then the design requirement would be 559.74V. Hence it is recommended that the capacitor voltage rating be chosen at the closest standard voltage rating of 600V. It is also preferred that the type of capacitor chosen is one which has a reasonably larger overcurrent capability as well.



Consider an additional overvoltage factor of 20% towards system voltage variation and harmonic loading. Notice the difference between the previous considerations of detuning. This is due to the fact that the detuning frequency has shifted upwards, more closer towards the 5th Harmonic frequency. This behaves like a partially tuned filter for the 5th Harmonic frequency. Then the design requirement would be 527.93V. Hence it is recommended that the capacitor voltage rating be chosen at the closest standard voltage rating of 525V. It is also preferred that the type of capacitor chosen is one which has a reasonably larger overcurrent capability as well.

Dynamic PFC: Important Facts and Instructions

General

Conventional PFC systems quickly reach their limits when they have to deal with fast changing loads. Applications like rolling mills, steel presses, wind turbines, container cranes and large buildings include a huge amount of electric consumers that require a reactive power adjustment on the ms scale. Production equipment, elevators, chillers, and other electric devices not only require such dynamic reactions of the power factor compensation equipment, they also lead very soon to a total number of switchings that exceeds the specifications of standard electromechanical contactors by far.

In conventional PFC systems, standard capacitor contactors are used to switch capacitor steps on and off. These electromechanical devices offer between 100 000 and 200000 switching operations in total during their life time which means that in such an application they reach their life expectancy after 1 to 2 years already. It has to be mentioned that capacitors are much stricter limited with regard to the permitted annual number of switching operations (IEC 60831). This typically results in destruction of their inrush current damping capability and may also damage the contacts in the main power circuit. Burnt main contacts may produce oscillation or "unclean" (re-bouncing) switching operations. This massive overload not only

shortens the life expectancy of the capacitor, but also increases the risk of premature failure and in the worst case represents a potential safety risk.

But furthermore the capacitor itself is specified for a limited number of switching operations per year. The standard IEC 60831 gives an acceptable value of 5 000 switching operations per year, a value far below switching numbers up to 100 000 that may be required per year in dynamic applications. Such large switching numbers and the respective overvoltages and overcurrents during each switching operation are likely to damage the capacitor and may lead to a very early capacitor failure.

In dynamic PFC systems, the capacitor contactors are replaced by thyristor modules that are suitable for a nearby unlimited number of switching operations as there is no mechanical wear-off. Thyristor modules feature electronic semiconductor switches that are able to react to a changing reactive power demand on the ms scale and that can switch capacitors without additional stress. The EPCOS TSM-thyristor switches keep the capacitors at the peak value of the grid voltage and connect them only when the grid reaches this peak voltage value. Thus the capacitors are switched current free and inrush currents that can reach values of 200 times the nominal current for conventional contactors are avoided. Additionally capacitor dis-

charge times up to 50 sec as necessary for conventional PFC is not required here.

In summary dynamic PFC does not only prevent wear-off of the capacitors and the switches and increases thus the lifetime of a PFC system and its safety. It also increases the power quality in the grid essentially as it can almost react in real time to reactive power demands. Fast enough for example, to take care of motor start up effects or spot welding requirements.

EPCOS offers all necessary key components to set up a dynamic PFC systems as the thyristor modules (TSM, see page 51), the required fast transistor output controllers (BR6000-T, page 39), and the EPCOS standard reactor (page 55) and of course capacitor series (page 12).

PFC Basic Formulae

The following electrical formulas may be used to calculate basic PFC values.

Active power

The amount of input power converted to output power is the active power.

$$P = \sqrt{3} \cdot V \cdot I \cdot \cos \varphi \quad (\text{W})$$

Formula 1

Power factor

The power factor of an AC electrical power system is defined as the ratio of the real (active) power to the apparent power.

$$\text{Power factor} = \frac{\text{Active power}}{\text{Apparent power}} = \frac{P}{S}$$

Formula 4

Reactive power

The reactive power is the power consumed in an AC circuit due to the expansion and collapse of magnetic (inductive) and electrostatic (capacitive) fields.

$$Q = \sqrt{3} \cdot V \cdot I \cdot \sin \varphi \quad (\text{VAr})$$

Formula 2

Power Factor Correction

When the AC load is partly capacitive or inductive, the current waveform is out of phase with the voltage. This requires additional AC current to be generated that is not consumed by the load, creating I²R losses in power cables. Capacitors are used to supply reactive energy to inductive loads. Reactive energy must be produced as closely as possible to the loads to prevent unnecessary flow of current in the network. This is known as power factor correction.

$$Q_C = P \cdot (\tan \varphi_1 - \tan \varphi_2) \quad [\text{VAr}]$$

Formula 5

Q_C: reactive power needed

P : total active power

φ₁: actual angle of cos φ actual

φ₂: target angle of cos φ actual

Apparent Power

The apparent power is the power delivered to an electric circuit.

$$S = \sqrt{3} \cdot V \cdot I \quad (\text{VA})$$

Formula 3

Connection and rating of capacitors

The reactive power of the capacitor is a function of its rated voltage and current.

$$Q_C = V_C \cdot I_C \quad [\text{VAr}]$$

Formula 6

$$Q_C = \frac{V_C \cdot V_C}{X_C} = \frac{(V_C)^2}{X_C}$$

Formula 7

$$X_C = \frac{1}{\omega \cdot C} = \frac{1}{2\pi \cdot f \cdot C}$$

Formula 8

f: frequency of network

X_C: impedance of capacitor

C: capacitance value

Formula (7) and (8) together

$$Q_C = (V_C)^2 \omega \cdot C = (V_C)^2 2\pi \cdot f \cdot C$$

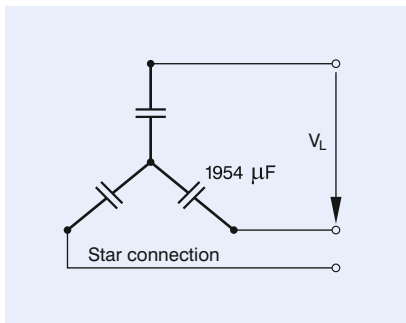
Formula 9

PFC Basic Formulae

Capacitor in three-phase PFC application

Three-phase PFC applications have two types of capacitor connections: star and delta.

- STAR connection



$$Q_{TOT} = 3 \cdot Q_C$$

Formula 10

$$V_C = V_L / \sqrt{3}$$

Formula 11

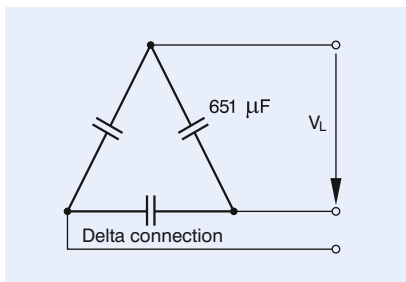
From formulae (9), (10) and (11)

$$Q_{TOT} = 3 \cdot \frac{(V_L)^2}{(\sqrt{3})^2} \cdot \omega \cdot C_{STAR}$$

$$C_{STAR} = \frac{Q_{TOT}}{(V_L)^2 \cdot \omega} = \frac{Q_{TOT}}{(V_L)^2 \cdot 2\pi \cdot f}$$

Formula 12

- DELTA connection



$$V_C = V_L$$

Formula 13

From formulae (9), (10) and (13)

$$Q_{TOT} = 3 \cdot (V_L)^2 \cdot \omega \cdot C_{DELTA}$$

$$C_{DELTA} = \frac{Q_{TOT}}{3 \cdot (V_L)^2 \cdot \omega} = \frac{Q_{TOT}}{3 \cdot (V_L)^2 \cdot 2\pi \cdot f}$$

Formula 14

As a conclusion formula (12) and (14)

$$C_{DELTA} = \frac{C_{STAR}}{3}$$

Formula 15

Capacitor output kvar:

From the formula (9), if we find the Q_{new} with ratio: C will be constant.

$$Q_{New} = \left(\frac{V_{New}}{V_R} \right)^2 \cdot \frac{f_{New}}{f_R} \cdot Q_C$$

Formula 16

These values are operating conditions:
 Q_{new} : new reactive power
 V_{new} : new voltage
 f_{new} : new frequency

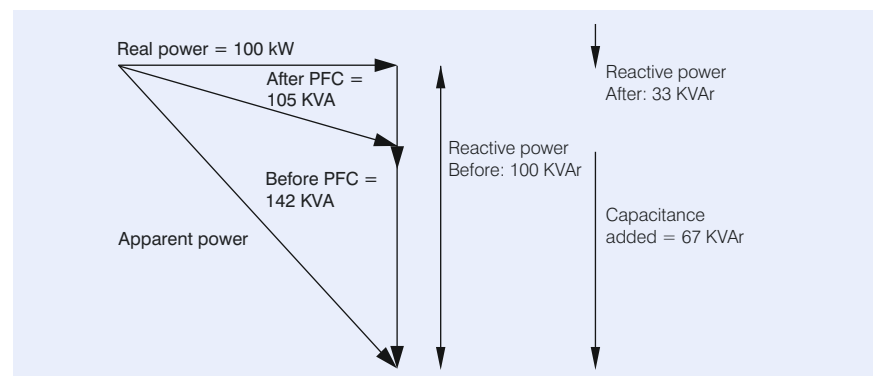
These values are the values capacitor is designed:
 Q_C : rated capacitor reactive power
 V_C : rated capacitor voltage
 f_R : rated frequency

Calculation examples

Example 1:

The relationship between active, reactive and real power and $\cos \phi$

In the diagram below, the power triangle shows an initial power factor of 0.70 for a 100 kW (real power) inductive load. The reactive power required by the load is 100 KVAR. By installing a 67-KVAR capacitor, the apparent power is reduced from 142 to 105 KVA, resulting in a 26% reduction in current. The power factor is improved to 0.95.



Formulas used (1), (2), (3) and (4).

Power factor calculations:

Before PFC: $100/142 = 0.70$ or 70%

After PFC: $100/105 = 0.95$ or 95%

PFC Basic Formulae

Example 2:

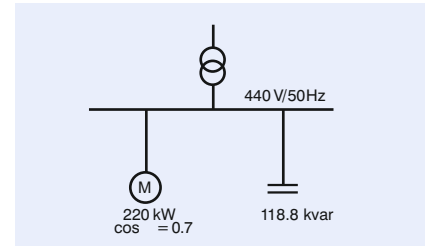
Calculation of capacitor rating for industrial installation

- Given parameters:

Induction motor	220 kW
Network	440 V AC,
(line delta)	3-phase
Frequency	50 Hz
Power factor	
- Current cos ϕ	0.7
- Target cos ϕ	0.9

Target to correct the power factor to 0.9:

$$\begin{aligned} \cos \phi_1 &= 0.7 & \tan \phi_1 &= 1.02 \\ \cos \phi_2 &= 0.9 & \tan \phi_2 &= 0.48 \\ Q_C &= P (\tan \phi_1 - \tan \phi_2) \\ &= 220 \cdot 1000 (1.02 - 0.48) \\ &= 118.8 \text{ KVAR} \end{aligned}$$



Example 3:

Calculating capacitor ratings for DELTA and STAR connections in example 2

STAR connection:

$$V_C = \frac{V_L}{\sqrt{3}} = \frac{440}{\sqrt{3}} = 254 \text{ V}$$

$$C_{STAR} = \frac{Q_{TOT}}{(V_L)^2 \cdot \omega} = \frac{Q_{TOT}}{(V_L)^2 \cdot 2\pi \cdot f}$$

$$\begin{aligned} C_{STAR} &= \frac{118.8 \cdot 1000}{(440)^2 \cdot 2\pi \cdot 50} \\ &= 1954 \text{ } \mu\text{F} / \text{Line (phase)} \end{aligned}$$

$$C_{TOT} = 5862 \text{ } \mu\text{F}$$

DELTA connection:

$$V_C = V_L = 440 \text{ V}$$

$$C_{DELTA} = \frac{Q_{TOT}}{3 \cdot (V_L)^2 \cdot \omega} = \frac{Q_{TOT}}{3 \cdot (V_L)^2 \cdot 2\pi \cdot f}$$

$$\begin{aligned} C_{DELTA} &= \frac{118.8 \cdot 1000}{3 \cdot (440)^2 \cdot 2\pi \cdot 50} \\ &= 651 \text{ } \mu\text{F} / \text{Line (phase)} \end{aligned}$$

$$C_{TOT} = 1954 \text{ } \mu\text{F}$$

Example 4:

Calculating apparent power reduction (S1-S2) in example 2

$$\begin{aligned} S_1 &= P / \cos \phi_1 = 220 / 0.7 \\ &= 314 \text{ kVA} \end{aligned}$$

$$\begin{aligned} S_2 &= P / \cos \phi_2 = 220 / 0.9 \\ &= 244 \text{ kVA} \end{aligned}$$

$$S_1 - S_2 = 70 \text{ kVA}$$

Thus, additional power of $70 \cdot (0.9) = 63 \text{ kW}$ can be supplied and transferred via the existing network.

Cable cross section calculation

Line current drawn by the motor:

I_1 uncompensated load (0.7):

$$I_1 = \frac{220 \cdot 1000}{\sqrt{3} \cdot 440 \cdot (0.7)} = 412 \text{ A}$$

I_2 compensated load (0.9):

$$I_2 = \frac{220 \cdot 1000}{\sqrt{3} \cdot 440 \cdot (0.9)} = 320 \text{ A}$$

Thus, the cable can carry an additional load of 92 A, or the designer can reduce the cable cross section.

Cautions

Temperature class of capacitors (according IEC 60831-1)			
Temperature class	Temperature of capacitor surrounding air		
	Maximum	Maximum mean for 24 h	Maximum mean for 1 year
B	45 °C	35 °C	25 °C
C	50 °C	40 °C	30 °C
D	55 °C	45 °C	35 °C

Enclosure of capacitors (IPxx)			
Enclosure	First digit		Second digit
Ip00		No protection against finger touch and ingress of solid foreign bodies	No protection against ingress of water
Ip20		protection against finger touch and solid foreign bodies ≥ 12.5 mm diameter	No protection against ingress of water
Ip41		protection against tool touch and solid foreign bodies ≥ 1 mm diameter	Deep-water protection
Ip54		protection against tool touch and solid foreign bodies ≥ 1 mm diameter, protection against dust deposit	Splash-water protection

Maximum admissible overvoltage			
Frequency (50/60 Hz)	Ma x. voltage (V_{rms})	Max. duration	Remarks
Line frequency	$1.00 \cdot V_R$	Continuous duty	Highest mean during entire operating time of capacitor; exceptions (see below) are admissible for times of < 24 h
Line frequency	$1.10 \cdot V_R$	8 h daily	Line voltage fluctuations
Line frequency	$1.15 \cdot V_R$	30 min daily	Line voltage fluctuations
Line frequency	$1.20 \cdot V_R$	5 min daily	Line voltage fluctuations
Line frequency	$1.30 \cdot V_R$	1 min daily	Line voltage fluctuations
Line frequency with harmonics	Such that current does not exceed maximum admissible figure ($I_{max.} = 1.3 \cdot I_R$)		

Temperature class of capacitors to standard IEC 60831-1

Capacitors are divided into temperature classes. Each class is represented by a number followed by a letter, e.g. –40/D. The number is the lowest ambient temperature at which a capacitor may operate. The upper limit temperature is indicated by the letter (see table above).

The useful life of a capacitor depends very much on temperature. Proper cooling of a capacitor must ensure that the maximum temperature is not exceeded, otherwise useful life is degraded. When configuring a circuit, one should make sure that capacitors are not subjected to heat from

adjacent components (reactors, bus bars, etc). Forced cooling is preferable for compact designs. And it is highly inadvisable to arrange capacitors directly above reactors. Exceeding specified temperature limits may set in worst case the safety device out of operation.

Cautions

Enclosure of capacitors (IPxx)

For different models there are different types of enclosure. The type of enclosure is indicated by a designation consisting of the two letters IP followed by two digits.

Current rating /maximum admissible overcurrent

The rated current (I_R) is the current resulting for rated voltage (V_R) and frequency (in Hz), excluding transients. Maximum permitted rms current for each particular capacitor is specified in the data sheet. Continuously exceeding of the nominal current will lead to increased self-heating of the capacitor and reduce life time. The maximum admissible overcurrent (I_{max}) of $1.3 \cdot I_R$ to IEC 60831 standard is maintained or overachieved by all capacitors in this catalog. The figures for overcurrent allow for the combined effects of harmonics, over voltage and capacitance tolerance.

Maximum admissible overvoltage

Capacitors from EPCOS are suitable for operation on overvoltages quoted by IEC 60831 (see table). Overvoltages higher than $1.15 \cdot V_R$ reduce life time of the capacitor and must not occur more than 200 times during life time of capacitor. Overvoltages above $1.3 \cdot V_R$ must not occur at all, appropriate overvoltage protection (e.g. against lightning strikes) must be ensured.

Mean life expectancy

The mean life expectancy of power capacitors is mainly governed by the following factors:

- duration of overload,
- ambient temperature and the resulting case temperature,
- maximum rms current and the resulting case temperature,
- voltage height and duration.

The calculated life expectancy of the various series is stated for nominal operating conditions. If components are stressed less than the IEC 60831 factors, longer useful life can be expected, and a correspondingly shorter one or increased failure rate if nominal parameters are exceeded.

Fuse protection

Power capacitors have to be protected against short circuits by fuses or thermal magnetic overcurrent relays. Slow-blow, low-voltage high-breaking-capacity fuses (HRC) are preferable. The fuse rating should be 1.6 to 1.8 times the rated current of the capacitor. Magnetic short circuit relays should be set to between 9 and 12 times rated current to prevent them responding to high inrush currents. Maximum allowed fault current of 10 000 A in accordance with UL 810 standard must be ensured by the application design.

⚠ HRC fuses must not be used for switching. Resulting electric arcing can cause death! It may also cause capacitor failures, and result, worst case, in capacitor bursting and fire.

Cautions

Switching of capacitors

When a capacitor is switched to an AC system, the result is a resonant circuit damped to a greater or lesser degree. In addition to the rated current, the capacitor accepts a transient current that is a multiple of (up to 200 times) its rated current. Fast switching, low-bounce contactors should be used, and have the switching capacity for capacitive currents stated by the producer. Special capacitor contactors with leading contacts that feature precharging resistors to damp inrush currents are recommended. As per IEC 60831 standard, a maximum of 5 000 switching operations per year is acceptable. Before considering a higher number of switching operations, please contact EPCOS.

Discharging

Capacitors must be discharged to a maximum of 10% of rated voltage before they are switched in again. This prevents an electric impulse discharge in the application, influences the capacitor's useful life in PFC systems, and protects against electric shock. The capacitor must be discharged to 50 V or less within 1 min. There must not be any switch, fuse or any other disconnecting device in the circuit between the power capacitor and the discharging device. EPCOS supplies capacitor discharge resistors to all series, alternatively discharge reactors are available.

⚠ Caution: Discharge and short circuit capacitor before handling!

Capacitors in networks with harmonics

Harmonics are produced in the operation of electric loads with a nonlinear voltage/current characteristic (e.g. rectifiers and inverters for drives, welding apparatus and uninterruptible power supplies). Harmonics are sinusoidal voltages and currents with higher frequencies of a multiple of the 50 or 60 Hz line frequency. In low-voltage three-phase systems the 5th and 7th harmonics are especially troublesome. Detuned PFC should be used in systems subject to harmonics. This represents a series resonant circuit of power capacitor and reactor. The circuit is tuned so that the series resonant frequency is below the lowest harmonics

appearing in the system. This produces an inductive response to all frequencies above the series resonant frequency, avoiding resonances with system inductances. Depending on the selected series resonant frequency part of the harmonic current is taken up by the detuned PFC system. The remainder of the harmonic current flows into the superordinate system. The use of detuned PFC thus contributes to reducing voltage distortion through harmonics and lessens the disturbing effect on proper operation of other electric loads.

Most international standards limit THD-V on LV side to 5%. However it has to be noted that in many grids these levels are exceeded and even lower distortion, e.g. 3–4% THD-V can generate extreme overcurrents in case of resonance condition.

Maximum overcurrents as specified under technical data of each series must not be exceeded.

Resonance must be avoided by appropriate panel design. Resonance may cause very high overcurrents which can lead to capacitor failures, and worst case, to explosion and fire.

Cautions

Mechanical damage

In case of dents or any other mechanical damage, capacitors must not be used at all.

Vibration resistance

The resistance to vibration of capacitors corresponds to IEC 68, part 2-6.

Max. test conditions:

Test duration	2 h
Frequency range	10 ... 55 Hz corresponding to max. 0.7 g
Displacement amplitude	0.75 mm

Because the fixing and the terminals may influence the vibration properties, it is necessary to check stability when a capacitor is built in and exposed to vibration. Irrespective of this, you are advised not to locate capacitors where vibration amplitude reaches the maximum in strongly vibrating equipment.

Connection

Make sure connection cables are of flexible type or flexible copper bands are used. This is mandatory to allow the overpressure disconnecter work and avoid mechanical stress on the terminals and feedthroughs.

The connection cables to the capacitor should be designed for a current of at least 1.5 times the rated current so that no heat is conducted into the capacitor. If reactors are used in an application, the distance between reactor and capacitor must be great enough so that no heat of the reactors, which are operating at a much higher temperature level, is conducted via connection cable to the capacitors.

Avoid bending cable lugs, cables or other mechanical force on the terminals. Otherwise leakages may set the safety device out of operation.

Ensure firm fixing of terminals, fixing torque to be applied as per individual specification.

Maximum specified terminal current (please refer to technical data of specific series) must not be exceeded at any case.

Grounding

The threaded bottom stud of the capacitor has to be used for grounding. In case grounding is done via metal chassis that the capacitor is mounted to, the layer of varnish beneath the washer and nut should be removed.

Storage and operating conditions

Do not use or store capacitors in corrosive atmosphere, especially where chloride gas, sulfide gas, acid, alkali, salt or the like are present. In dusty environments regular maintenance and cleaning especially of the terminals is required to avoid conductive path between phases and/or phases and ground.

Installation

Specifications like IEC 61921, VDE 0100, VDE 0101, VDE 0560 part 4 and 46, EN 60831 and IEC60831 apply to the installation and operation of power capacitors. Capacitors should be sited in cool and well ventilated locations away from other heat-radiating elements. Natural heat dissipation is generally sufficient for cooling purposes if enough air is able to flow to and away from them and the capacitors are spaced at least 20 mm apart. Otherwise, in a less well ventilated environment, forced cooling (fans) will be necessary, scaled so that the maximum admissible ambient temperature is not exceeded.

Keep at least 20 mm space above the capacitor and do not attach any component on the top. This gap will allow a longitudinal extension of can in order to ensure that over-pressure disconnecter can fully extend.

Useful life of capacitors strongly depends on the operating temperature (refer to page 95, temperature classes of capacitors).

Exceeding maximum allowed temperature may set the safety device out of operation.

Please read the Installation and Maintenance Instructions on the internet at www.epcos.com/pfc.

Note

Products shown in this catalog reflect typical specifications. You are kindly requested to approve our product specifications or request our approval for your specification before ordering.

Cautions

Reactors- Antiresonance harmonic filter

During operation, all electrically active parts of this equipment such as windings, electronic components, leads, fuses and terminals carry a dangerous voltage which can lead to burns or electric shock.

Covers which protect these electrically active parts from being touched must not be opened or removed during operation.

Before any assembly or maintenance work is started, all installations and equipment must be disconnected from the power source.

Noncompliance with these instructions may lead to death, serious injury or major damage to equipment.

In order to exclude impermissible temperatures and thus overload of the insulation system, the following directions must additionally be observed:

1. Only those protective devices specified on the type plates, such as fuses and motor protection switches, may be used. It is mandatory to observe the set values specified for the motor protection switches. Any temperature-sensitive protective devices such as temperature switches and temperature sensors must be connected in accordance with the installation instructions.
2. High temperatures are permissible for the surfaces under rated operating conditions, and especially in the event of overload. Depending on the temperature class and type of loading, these may attain values of up to 260°C and may also affect adjacent components which have been packed too densely.

3. The insertion position should be selected so that any cooling ducts present within the winding are arranged vertically and that the current of cooling air is not impeded by adjacent components, connecting leads etc.
4. The maximum voltage of the insulating system specified on the type plate must not be exceeded.

Noncompliance with these instructions may lead to considerable damage to equipment or fire due to impermissibly high temperatures.

Thyristor modules (TSM-series)

- Live parts in the PFC equipment must not be touched!
- Warning signs in the PFC systems are required!
- Wait 10 minutes after the main switch is turned off – until the voltage in the system has dropped to an uncritical value.
- In non-detuned systems (400 V grid) capacitors with a higher voltage rating (e.g. 440 V) are needed.
- In detuned systems (400 V grid) capacitors with a voltage of 525V are needed.
- For discharging the capacitors, special high-voltage resistors type EW-22 are required. Standard resistors cannot be used!
- In dynamic PFC systems discharge reactors cannot be used (this would be a short circuit of the highvoltage DC)!
- In PFC systems without filter circuit reactors current limiting reactors are required (e.g. BD-series) for the TSM.
- For short circuit protection, super-fast electronic fuses for protection of the thyristor are required, standard HRC fuses are not suitable. See selection table on pages 89 and 90.
- Failure to follow cautions may result, worst case, in premature failures or physical injury.

Capacitor contactors

In case auxiliary contacts are used for switching of discharge resistors (not in accordance with IEC60831 standard), make sure that the current of the discharge resistors is not higher than the rated current of the auxiliary contacts.

Only flame-resistant and self-extinguishing materials may be used in the proximity of capacitor contactors because abnormal temperatures cannot be ruled out in the area near the resistance spirals.

Capacitor contactors N110/N230 may only be used in PFC systems with reactors.

PF controllers (BR604, BR6000 and BR7000 series)

Controller hunting: When putting the capacitor bank into operation, it is required to avoid needless switching cycles (means permanent switching on and off of steps without significant change of consumer loads). This so called “controller hunting” would increase the number of switching operations of the connected contactors and capacitors, decrease the expected life cycle (wear out) and result, in worst case, in bursting and fire etc. This can be avoided by a proper programming of the PFcontrollers with the actual system parameters (current transformer prim. and sec., first KVAR step, control series, switching time).

The “ZVEI General safety recommendations for power capacitors” must be observed in addition to the safety instructions given in this catalogue and in the particular data-sheets. They are available on the EPCOS website in the various product groups. They may also be called up from the ZVEI website.