Low Voltage Products

Power factor improvement
Application guide

Power and productivity
for a better world™

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Basics of power factor

Basic concepts

Most load on an electrical distribution system can be categorized into three types - resistive, inductive and capacitive.

On modern systems, the most common load is the inductive type simply due to the nature of loads that consume electricity. Typical examples include transformers, fluorescent lighting and AC induction motors.

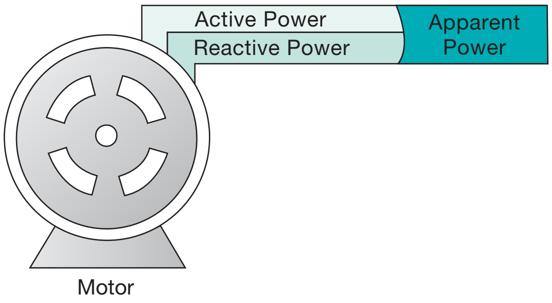


Figure 1

A common characteristic of all inductive loads from doorbells to transformers is that they comprise a winding of some kind. This winding creates an electromagnetic field that allows the motor or transformer to function. A certain portion of electrical power goes to maintain this electromagnetic field.

All inductive loads require two kinds of power to function properly:
- Active power (kW) which actually performs the work
- Reactive power (kVAR) that sustains the electromagnetic field

One common example of reactive power can be seen in an unloaded AC motor. When all load is removed from the motor, one might expect the no-load current to drop near zero. In truth, however, the no-load current will generally show a value between 25% and 30% of full load current. This is because of the continuous demand for magnetizing current by any inductive load. Active power is the power indicated on a wattmeter. Apparent power is simply the vector sum or geometrical sum of reactive and active power (Fig. 2).

What is power factor?

Power factor (p.f.) is the relationship between working (active) power and total power consumed (apparent power). Essentially, power factor is a measurement of how effectively electrical power is being used. The higher the power factor, the more effectively electrical power is being used.

A distribution system's operating power is composed of two parts: Active (working) power and reactive (non-working magnetizing) power. The **active power** performs the useful work... the **reactive power** does not. It's only function is to develop magnetic fields required by inductive devices.

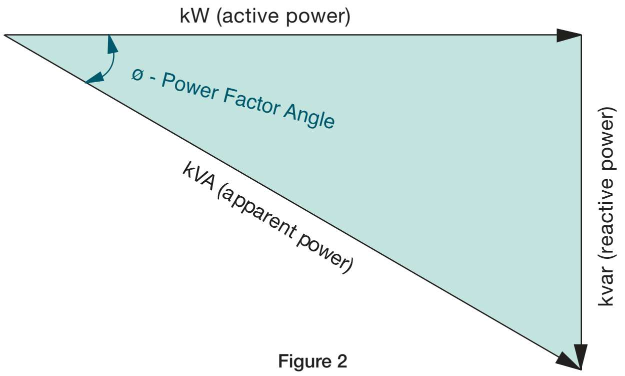


Figure 2

Generally, power factor decreases (angle Φ increases) with increased motor load. This geometric relationship of apparent power to active power is traditionally expressed by the right triangle (Fig 2) relationship of:

Cos Φ = p.f. = kW/kVA

Why improve low power factor?

Low p.f. simply means poor utilization efficiency. CosΦ varies between 0 and 1, hence a value between 0.9 and 1.0 is considered good power factor and essentially means that metered power and used power are almost equal. From a consumer's perspective, it simply means you are using what you paid for, with minimal wastage. When p.f. is low, the utility must provide the non-productive reactive power in addition to productive active power. For the utility that means larger generators, transformers, conductors and other system devices that pushes up their own capital expenditures and operating costs, which they simply pass on to industrial users in the form of power factor penalties. Hence, improved power factor helps avoid those penalties.

Key advantage of improved power factor = $$$ savings!!

1. Good p.f. minimizes or eliminates utility p.f. penalties
2. Good p.f. helps improve operating life of equipment
3. Good p.f. expands system capacity, hence facilitating partial deferrment of capital expenditures at plant level.

Basics of power factor

Figure 3 illustrates the relationship of power factor to total current consumed. With a p.f. = 1.0 given a constant load, the 100% figure represents the required useful current. As the power factor drops from 1.0 to 0.9, power is used less effectively. Therefore, 10% more current is required to handle the same load. A power factor of 0.7 requires approximately 43% more current; and a power factor of 0.5 requires approximately 200% (twice as much!!) current to handle the same load.

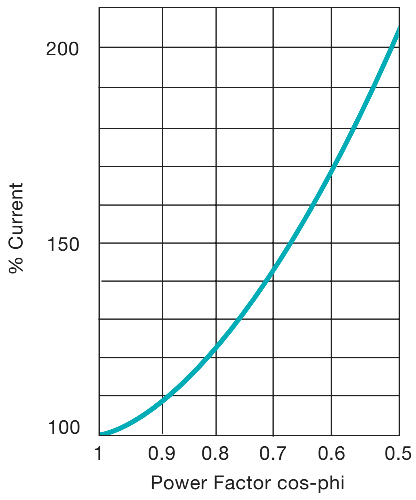


Fig. 3

How capacitors solve the problem of low p.f.

Low p.f. is a problem that can be solved by adding power factor improvement (PFI) capacitors to the plant distribution system. As illustrated in Fig. 4, capacitors work as reactive current generators “supplying” reactive power (kVAR) to the system. By generating their own reactive power, industrial users free the utility from having to supply it; therefore, the total apparent power (kVA) supplied by the utility will be less, which is immediately reflected in proportionately smaller bills. Capacitors also reduce the total current drawn from the distribution system and subsequently increase system capacity.

Capacitor rating

Power factor correction capacitors are rated in electrical units called “vars”. One VAR = one Volt Ampere of Reactive power. VARs are units of measurement for indicating how much reactive power the capacitor will supply. As reactive power is usually measured in thousands of vars, the prefix “k” (for “kilo”) is added to create the more familiar “kVAR” term. The capacitor kVAR rating shows how much reactive power the capacitor will supply. Each unit of kVAR supplied will decrease the inductive reactive power demand by the same amount.

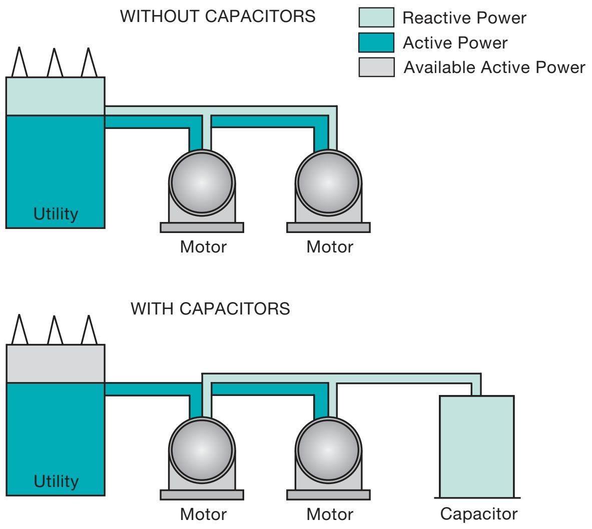


Fig. 4

Example (Fig. 5):
A low voltage network requires 410 kW active power at full load, and the power factor is measured to be 0.70. Therefore, the system’s full load consumption of apparent power is 579.5 kVA. If 300 kVAR of capacitive reactive power is installed, the power factor will rise to 0.96 and the kVA demand will be reduced from 579.5 to 424.3 kVA. Thus, savings can vary from 20~30% or even more in some cases, which cumulatively translates to considerable money savings with the PFI equipment often paying for itself in as little as 6 months.

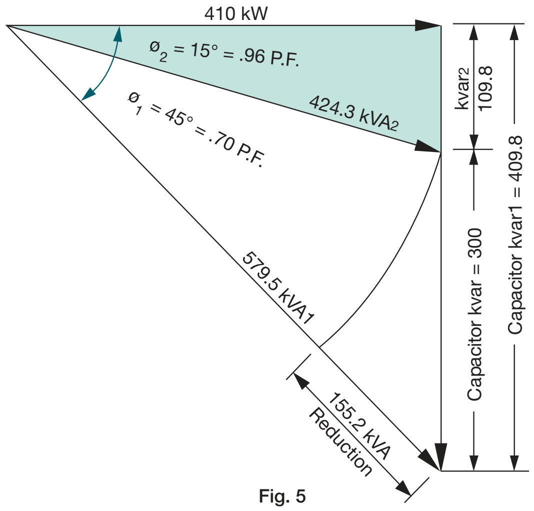


Fig. 5

Options and solutions

Options for improving power factor

The three main options for PFI are as follows:

- **Individual capacitor units** – One capacitor unit for each inductive load (in most cases a motor)
- **Banks of capacitor units** – Several capacitors grouped in an enclosure that is connected at a central point in the distribution system. Fixed capacitor banks comprise multiple capacitors racked in a common enclosure with no switching while automatic capacitor banks, also called “cap banks” have capacitors in a common enclosure with contactor or thyristor (SCR) switched by a controller.
- **Combination of above** – Where individual capacitors are installed on the larger inductive loads and banks are installed on main feeders or switchboards, etc.

Advantages of individual capacitors

- **Increased system capacity** – When active power compensation is closest to the load, it opens up system capacity and also minimizes line losses.
- **Cooler operation** – Voltage drops cause the current to increase, thereby cumulative heat losses occur due to marginally higher current flow. When voltage drops are corrected/addressed closest to the load itself, such temperature issues are prevented right from the start.
- **Simpler control** – Motor and capacitor can be switched ON and OFF together, which means simpler control logic and fewer control parts.
- **Precise compensation** – Since the individual capacitor is sized to the specific load and switches together with that load, there is no chance of over compensation.
- **Easier selection** – Selection of individual capacitors is simple and straight forward and requires no special calculations. See relevant charts on pages 11 and 13.

Low voltage capacitor construction

Advantages of fixed or automatic bank systems

- **More economical** – Cap banks are more economical than individual capacitor units when the key objective is to reduce utility power bills and/or reduce the current in primary feeders from a main generator or transformer. Being a single installation for power factor compensation simply adds to the convenience.
- **Lower installation costs** – The cost of installing one fixed or automatic capacitor bank unit can be less than installing a number of individual capacitors next to each inductive load.
- **Switching** – Automatic capacitor banks can switch all or part of the capacitance automatically depending on load requirements. This way, only as much power factor correction as needed for the given load is provided. (This switching capability is a primary advantage over fixed capacitor banks where over-capacitance, leading power factor and resulting overvoltages can occur should the load decrease.)
- **Single point of control** – It is easier to manage, monitor and operate the process when the power factor inprovement (PFI) equipment is in one physical location.

Combination of individual, fixed and automatic cap banks

A combination of individual and centralized cap banks is often the best. Individual capacitors are installed on larger motors and banks are installed on distribution systems. To determine the total power factor correction required, then, you need to know the total kVAR requirement for the facility and the desired power factor. By referring to the Power Factor Correction Chart, (Table 2), one can calculate the capacitance needed. See selection instructions on the following pages for more details.

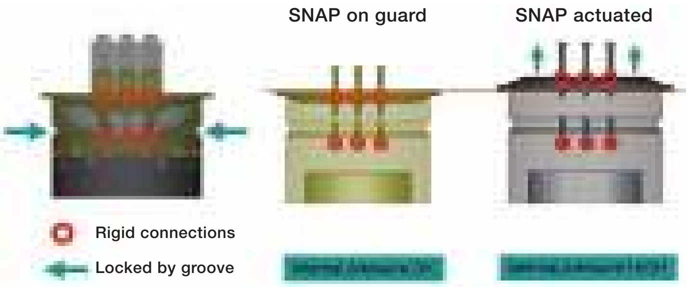
Options and solutions, applications and installation

Cylindrical capacitors

Functionally very similar to enclosed capacitors (rectangular), cylindrical capacitors are different in terms of physical dimensions and arrangement of internal parts. ABB cylindrical capacitors, also called **QCap**. Cylindrical capacitors are packaged very conveniently and are best suited to plain and detuned cap banks from 100 to 300 kVAR at 480V or 600V, 60Hz, standard design for use in commercial market segments in Canada.

QCap mechanical protection feature

A very simple but uniquely effective design feature provides mechanical protection to each Qcap unit. The device terminals are internally connected using three notched wires that break **together** when the lid rises due to gas pressure. To ensure the disconnection works reliably, the wires are indirectly anchored to the lid at one end and to the can at the other. The groove is designed to support this. The lid itself is has two stable positions – normal and expanded. When pressure pushes up the lid, all three wires break and the capacitor is entirely disconnected.



Logic of mechanical protection in QCap

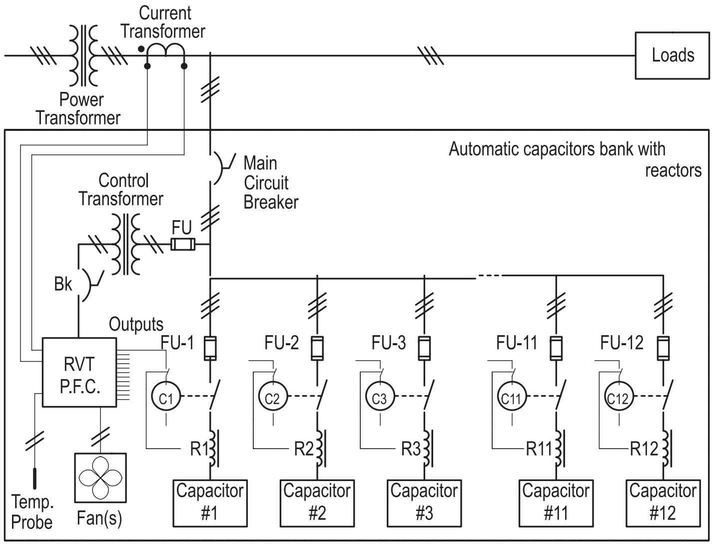
A low-impedence fault rapidly leading to a short-circuit, can be protected by a fuse. A high-impedance fault on the other hand may not lead to a current large enough to trip a fuse, it does cause cumulative resistive heating which increases the pressure in the sealed can, at a rate directly proportional to the rate of heating. Likewise, cumulative heating caused by self-healing action also slowly increases the pressure. Thereby the pressure threshold can be reached either by the long-term accumulation of gas released by self-healings (normal end of life) and/or by a high-impedance fault as described above.

Capacitors special applications

Care should be taken when power factor correction capacitors are used in the following applications:

- Frequent starts, plugging and jogging applications
- Regenerative loads where load may drive the motor (coasting, etc.)
- Multi-speed motors
- Motors involving open-transition reduced-voltage starting
- Reversing starters that switch more than once per minute
- Electronic thyristor (SCR) controlled softstarters

Typical wiring diagram (detuned)



Plain autobanks are exactly the same as above, only without the reactors R1, R2 and so on.

Application and installation

Where should power factor correction capacitors be installed in a distribution system?

Fig. 6 illustrates multiple options for locating PFI capacitors on a low voltage distribution system.

Option A: Downstream of the overload relay

Advantages: this is the most efficient location since the reactive power (kVAR) compensation is produced right where it is consumed. Line losses and voltage drop are minimized. The capacitor is switched automatically by the motor starter, so it is only energized when the motor is running. No separate switching device or overcurrent protection required. Also, thermal overload needs to be set carefully, since the capacitor will cause a reduction in amps through the overload, hence lower trip setting for the same level of motor protection (see Table1 for line current reduction as a percent of FLA).
Note: this works only with contactor starters. Special care needs to be taken in cases where softstarters are used.

Option B: Between the contactor and the overload relay

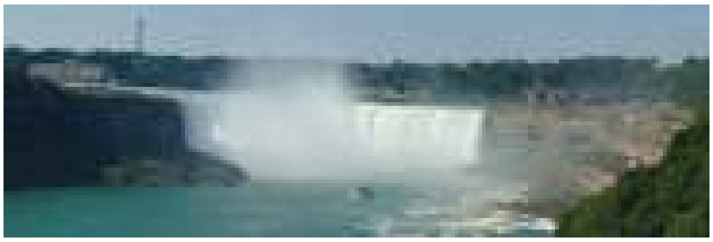
Advantages: same as Option A except that the overload relay can be set to the full load amps as per motor nameplate. This location is often preferred by panel builders as overload trip setting is simplified.

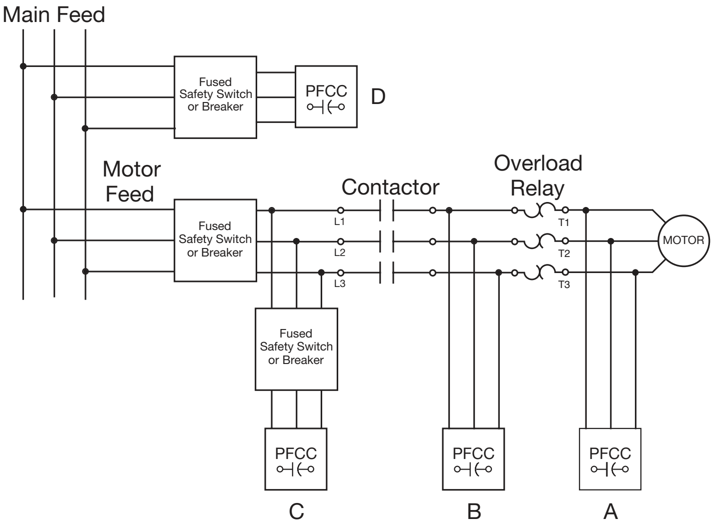
Option C: Between the circuit breaker and the contactor

Advantages: The capacitor can act as a central kVAR source for multiple motors fed by the same circuit breaker. Recommended for frequent jogging & reversing applications. Disadvantage: as the capacitor stays energized even when the motor(s) are not running, there is a risk of overcompensation and leading p.f. at light load. Also, line losses are higher than with Options A & B as the reactive current is carried further.

Option D: As a central compensation source (cap bank) connected to the main distribution bus

Advantages: Of the four options,this is the most cost-effective as it uses a few large kVAR capacitors rather than many small units. Also, it is a single installation, hence easier to operate, monitor and control. A power factor controller switches the capacitors in and out to ensure the correct level of compensation on the network.





Locations for capacitors in motor circuits
Fig. 6

Temperature and ventilation

Low voltage capacitors should be located in adequately ventilated areas with ambient temperature below 40°C. As capacitors always operate at full load and generate heat of their own, the better the heat dissipation, the longer the operating life of the capacitor. Frequency and voltage are key factors that can cause capacitor temperature to rise.

- **Line frequency** – variations in mains frequency can result in temperature stress in the capacitor, though modern power system frequencies tend to be increasingly stable.
- **Operating voltage** – if operating voltage exceeds 110% of the capacitor rating, then overheating and cumulative damage can occur. In such a case, the voltage must be corrected or the capacitor must be taken offline in the shortest time possible.

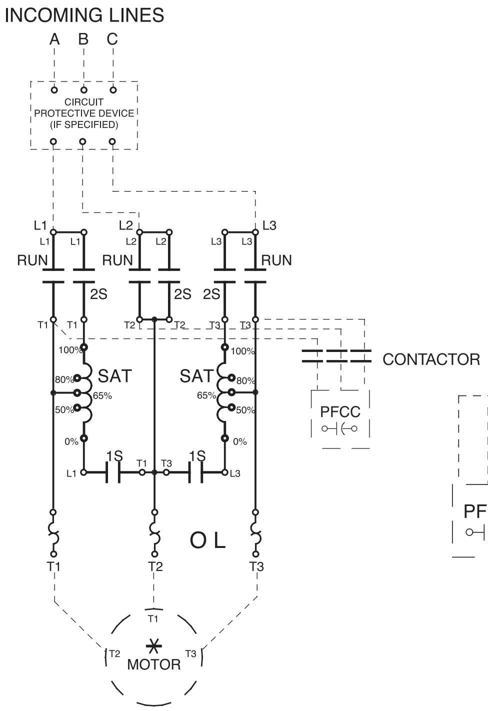
Note: This overvoltage problem is exactly why it is always recommended to “undersize” a capacitor’s kVAR rating during selection. Too much capacitance causes overvoltage and overvoltage in turn causes excessive heat, the cumulative effects of which can result in damage to the capacitor itself.

Discharging time

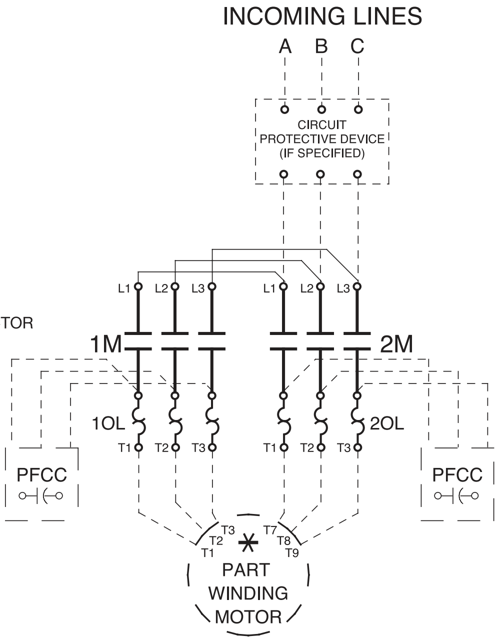
Low voltage capacitors need a full minute to discharge through the resistors, but it is still recommended that the terminals be short-circuited to ground after the 1-minute has elapsed and prior to human contact.

Recommended wiring schematics with starter combinations

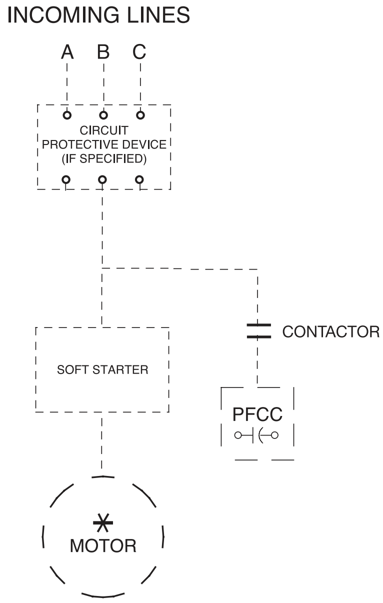
Autotransformer



Part-winding

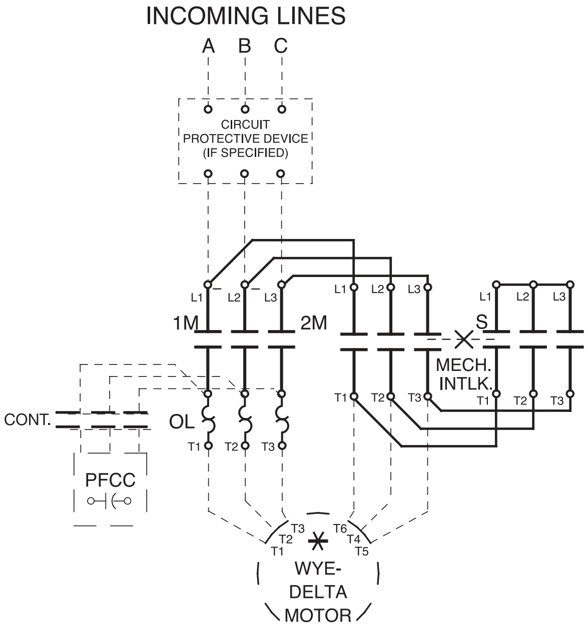


Softstarter

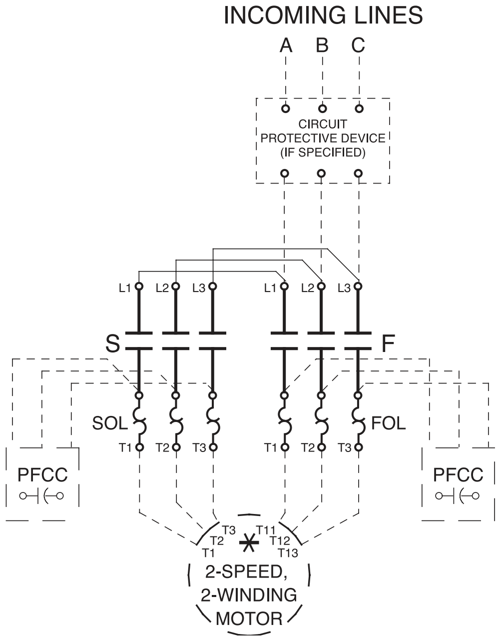


Note: for softstart wiring, see page 12

Wye-Delta



2 speed/2 winding



Note: standard applicable guidelines and practices shall be used for installation.

Low voltage capacitor construction

Principal components of a 3-phase capacitor

The principal components of a 3-phase ABB capacitor include:

1. **Sequential protection system:**
   - **Self-healing capacitor elements**
     Self-healing means that in case of dielectric breakdown, the fault is cleared by evaporation of the metalized layer.
   - **Modularity due to multiple elements**
     Since the average capacitor comprises multiple elements wired in Y or Δ, the end-of-life failure of one element does not affect the continued operation of the capacitor, though the overall capacitance may be reduced slightly.
   - **Nonflammable dry vermiculite filler**
     Vermiculite is a dry, granular, inert and non-flammable insulating material filled around the elements and compacted down to displace oxygen in the enclosure.
2. **Discharge resistors**
   Discharge resistors (one per phase) are sized for safe capacitor discharge (<50V in <1 min), as per NEC.
3. **Terminal studs**
   Large terminal studs are located inside the enclosure at the top of the capacitor for quick and easy cable connections.
4. **Enclosure**
   All ABB enclosures are made of welded heavy gauge steel. Available enclosure types include Nema 1, 12 and 3R.

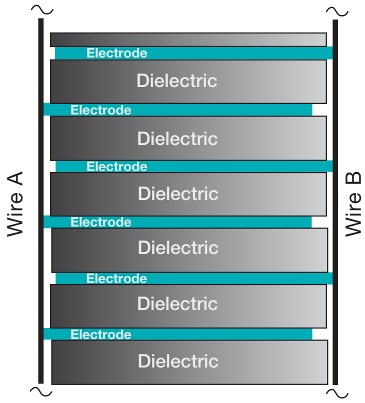
What is a metallized-film element?

Zinc metallized polypropylene film comprises a very thin layer of conducting material (electrode) vapour-coated onto a layer of capacitor grade insulating film. The electrode thickness averages ~0.01 microns while the film is 5~10 microns thick depending on design voltage (higher the voltage rating, thicker the film). The capacitance of an element is inversely proportional to the separation between electrodes. Hence, if the electrode separation is halved, the capacitance is doubled and element size is halved. Two electrode layers separated by one layer of insulating film are tightly wound around a core, effectively forming thousands of layers, such that the edge of one electrode is exposed on one side of the element and the edge of the other electrode is exposed on the other side (Fig. 12 & 13). Wires are then connected to each side of the element. The element is enclosed in a plastic canister and sealed.

Key advantages are:

1. **Self-healing design** (see Fig. 14 & 15)
2. **Low internal losses** (<0.5 Watt/kVAR including resistors)
3. **Small element size** but powerful capacitors
4. **Smaller environmental footprint** at end of life cycle

Fig. 12



Partial cutaway view of capacitive element layers
Fig. 13

More about self healing elements

"Self-healing" is a characteristic which is unique to metallized electrode capacitors. All capacitor normally experience insulation breakdown as a result of the accumulated effect of temperature, voltage stress, impurities in the insulating medium, etc. When this happens in a non-"metallized" design, the electrodes are shortcircuited and the capacitor ceases its production of reactive power.

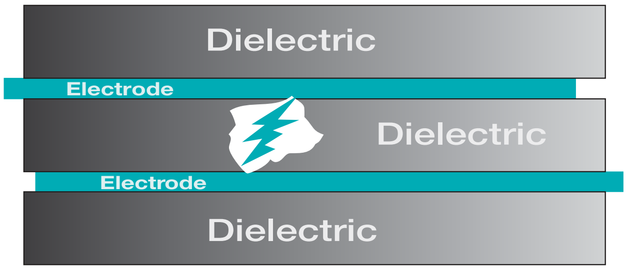


Figure 14. Two electrodes short circuit through a fault in a dielectric layer.

In an ABB metallized-film unit, however, these individual insulation breakdowns do not mean the shutdown of the capacitor. The faults self-heal themselves and the capacitor continues operation. The conducting electrode is very thin; when a short circuit develops as a result of a fault in the insulating dielectric, the thin electrode vaporizes around the area of the fault. This vaporization continues until sufficient separation exists between the faulted electrodes to overcome the voltage level. Fig. 15 illustrates the process of self-healing. The entire process of self-healing takes "microseconds" and the amount of electrode which is lost is negligible in comparison to the total surface area of the element. The result is the metallized-film unit may self-heal hundreds of times during its long life and still retain virtually all of its rated capacitance.

Low voltage capacitor construction

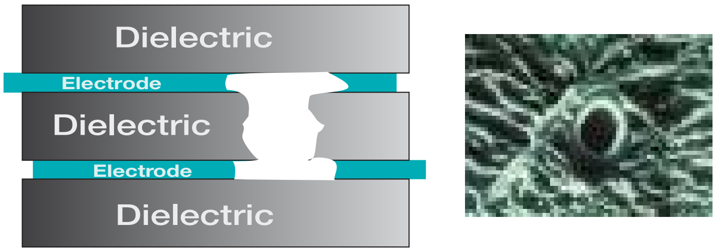


Figure 15 and the real picture illustrates "self-healing" where electrode layers around the short circuit (<1µm) are vaporized, hence contained.

The IPE sequential protection system

ABB's metallized-film self-healing capacitor elements have a longer life than conventional foil design. However, the effects of time, temperature, voltage stress and frequency, cumulatively effect capacitor life. ABB's sequential protection system with patented Internally Protected Element (IPE) design provides the highest possible protection to equipment and personnel. This proven design ensures maximum reliable service and protection in each element, which includes an internal fuse link (See Fig. 16) for individual disconnection in short-circuit conditions.

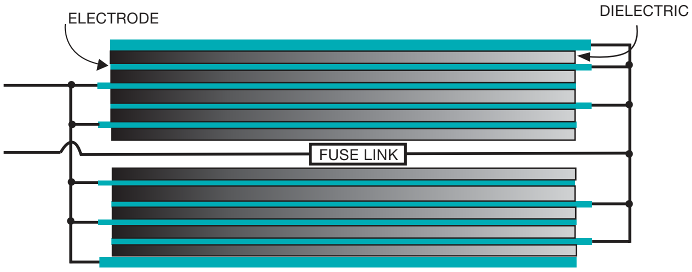


Figure 16

What are discharge resistors?

As the capacitor elements store electrical charges like a battery, the capacitor will maintain a near full charge even off power. As this is a potential safety issue (dangerous on human contact), discharge resistors are connected between all of the terminals. When the capacitor is pulled off power, these resistors drain the stored electrical charge, in the form of heat. It is recommended, however, that capacitor terminals should **always** be shortcircuited before touching the terminals.

What is the significance of dry type design?

ABB low voltage capacitors – both box type and cylindrical – contain no free liquids. Environmental and personnel concerns associated with leakage or flammability of conventional oil-filled units are eliminated while kVAR for kVAR, dry-type units weigh 30% to 60% less than their oil filled counterparts.

Cylindrical capacitors design (QCap)

QCaps comprice 3 rolls of metallized film stacked vertically and sealed off with a thermosetting plastic, much like the IPE described earlier. The sealing not only protects from oxidation of the electrode, but also provides mechanical rigidity to the capacitor unit. Discharge resistors are integrated with the cage-clamp terminals at the top. One fixing bolt at the bottom is suitable for vertical or horizontal mounting.

Enclosed or QCap - which to select?

While both designs are functionally very similar, each is better suited to certain applications primarily due to design and construction, availability, etc.

Enclosed/rectangular capacitors are best suited to **industrial** applications in Canada for the following reasons:

1. Fully customizable – 208~750V, 50/60 Hz, 2~100kVAR
2. Modular design – longer operating life under stress
3. Servicable, repairable
4. Standalone design, with options (fuse, indications, etc.)
5. Made in ABB Canada

Cylindrical capacitors are best suited to **commercial** applications in Canada for the following reasons:

1. Single can size with 6 ratings, 12.5~30 kVAR
2. Suitable for detuned banks (660V available on request)
3. Compact design suitable for smaller cap banks
4. Easy to stock, hence ideal for integrators
5. Made in ABB Belgium

Please contact **pqs_rfq@ca.abb.com** for more information.

Sizing capacitors
Selection chart based on motor HP and rpm

Table 1. Suggested maximum capacitor ratings for T-frame EEMAC class B motors (600V and below)

Induction motor rating (HP)	Enclosure type											
	3600 R/MIN		1800 R/MIN		1200 R/MIN		900 R/MIN		720 R/MIN		600 R/MIN	
	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	12	25	18	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	120	12	160	12	180	13	180	15

WARNING
In order to avoid any complications with the motor or capacitor, never oversize capacitors or exceed 1.0 power factor.

Problems caused by overcompensation

Overcompensation causes p.f. to cross 1.0, also called as leading power factor, which must be avoided at all costs. The main issue is that leading power factor causes overvoltage, which puts stress on the capacitor, causing it to heat up and eventually burn out. Also, power factor exceeding 0.95 leading on generator supply can cause the genset to hunt, enough to trip circuit breakers and also affect operation of other equipment on the network.

Example based on motor HP and rpm: A manufacturer needs to determine the proper capacitors required for a 1200 RPM, 75HP T-Frame EEMAC class B motor.

1. First look up 75 in the horsepower column (Table 1)
2. Then locate the 1200 RPM capacitor rating (kVAR) column. The result is 25 kVAR. That should improve the power factor to around 0.95
3. Now refer to the appropriate brochure for capacitor part number or contact ABB on **pqs_rfq@ca.abb.com**

Note: while selecting individual capacitors or fixed banks, always select the calculated kVAR rating or a size lower. On the other hand, for auto cap banks, selecting a size higher than the calculated value helps to factor in future expansions or load additions. That is because an auto cap bank always has the flexibility to adjust its kVAR output within its range, based on real-time demand.

Sizing capacitors
Selection methods and examples

Simple thumb-rule calculations based on motor data:
90% of no-load motor amps gives approximate kVAR Hence, if no-load motor amps = 50A, then capacitor rating shall be 50 x 0.9 = 45 kVAR or less.

If only full-load motor amps is known, then no load amps can be calculated as 30% of full load amps. Hence, if full load motor amps = 100A, then no-load amps = 100 x 0.3 = 30A, then capacitor rating shall be 30 x 0.9 = 27 kVAR or less.

A very rough estimation would be 30% of motor HP, hence for a 100HP motor, 30 kVAR would be an approximate.

Calculation based on motor kW (see Table 2 next page)

- Starting p.f. = 0.75 and target p.f. = 0.90
- Corresponding factor from table = 0.398
- Motor HP = 100, hence 100 x 0.745 = 74.5 kW
- Required capacitor size = 74.5 x 0.398 = 29.65, rounded to 30 KVAR
- Part number for 600V, 3-ph network would be C603G30 if installed inside a panel or C605G30 if standalone

What if existing power factor cannot be determined because kVA is unknown?

Metered demand = 700kW. Ammeter reading indicates 900A. Existing power factor and apparent power (kVA) are unknown. How to calculate existing system power factor and capacitance required to improve p.f. to 0.92 level?

1. kW is known (700kW) apparent power
   kVA = (VOLTS x AMPS x √3) ÷ 1000
2. The volts and amps of the distribution system are known so for 600V and 900A, we have
   (600 x 900 x 1.732) ÷ 1000 = 935.28 kVA
3. Now power factor is = 700kW/935.28kVA = 0.746 pf => 0.75
4. Look up Table 2 next page against existing p.f. of 0.75 and target p.f. of 0.92. Hence multiplier = 0.398
5. Multiply this factor with the kW value.
   Hence, 700 x 0.456 = 319.2 kVAR

The general rule as mentioned earlier in this document is to select a rating below the calculated value if a fixed capacitor bank is used and to select a rating above the calculated value if an auto cap bank is uesd. Practically, the best option in this particular case is an auto cap bank.

Note: in the last example, reactive power compensation of 319.2 kVAR is required to reach a target power factor of 0.92. Fixed banks always carry the risk of overcompensation in light load conditions so unless the capacitor is assigned to and switched with a single load, it is recommended to use automatic cap banks that can switch the capacitors in stages, especially for larger values, that is 100 kVAR and above.

Note on using capacitors with softstarters

If individual power factor correction is to be provided to motors controlled by softstarters, care muct be taken to use correct interlocking in the control wiring such that the capacitor and SCR's are not in the circuit at the same time. Inappropriate wiring or control logic may result in damage to the softstarter and equipment. Please consider the following guidelines/logic while designing the control circuit:

1. Capacitor shall **always be located upstream** of the softstarter as indicated in the power schematic on page 8
2. Capacitor shall be switched by a contactor in order to ensure isolation when required
3. Control logic shall ensure that the capacitor is isolated from the circuit while the SCR's in the softstarter are ramping up as well as when ramping down. **That means the capacitor shall be active only when softstarter's bypass contactor is switched ON**
4. Most ABB softstarters have a top-of-ramp (TOR) dry contact that can be used to switch the capacitor contactor

Please contact ABB on **lvp.support@ca.abb.com** for more information or suggestions on wiring capacitors together with softstarter motor control.

Sizing capacitors
Selection based on existing and target cos phi values

Generic calculations

Step 1 – Know your starting power factor ($\cos \Phi_1$) and Target power factor ($\cos \Phi_2$)

Step 2 – Take inverse cosines of both $\cos \Phi_1$ and $\cos \Phi_2$, to obtain the angles Φ_1 and Φ_2

Step 3 – Take the tangents of the angles Φ_1 and $\cos \Phi_2$ and subtract one from the other ($\tan \Phi_1 - \tan \Phi_2$)

Step 4 – Finally, capacitor size in kVAR = $P * (\tan \Phi_1 - \tan \Phi_2)$, where P = load power in KW

Using the tables

To make it easy, the ($\tan \Phi_1 - \tan \Phi_2$) factors are already listed in Table 2 below, so simply multiply that value with P (the actual kW load) to directly obtain the kVAR value of the capacitor.

Note: As we normally use horse power values in North America, the simple relationship is 1HP = 0.745kW

Table 2: Power factor correction chart

Starting cos Φ	Target cos Φ											
	0.85	**0.90**	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**0.99**	**1.00**
0.60	0.714	0.849	0.878	0.907	0.938	0.970	1.005	1.042	1.083	1.130	1.191	1.333
0.61	0.679	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.157	1.299
0.62	0.646	0.781	0.810	0.839	0.870	0.903	0.937	0.974	1.015	1.062	1.123	1.265
0.63	0.613	0.748	0.777	0.807	0.837	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.581	0.716	0.745	0.775	0.805	0.838	0.872	0.909	0.95	0.998	1.058	1.201
0.65	0.549	0.685	0.714	0.743	0.774	0.806	0.840	0.877	0.919	0.966	1.027	1.169
0.66	0.519	0.654	0.683	0.712	0.743	0.775	0.810	0.847	0.888	0.935	0.996	1.138
0.67	0.488	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.966	1.108
0.68	0.459	0.594	0.623	0.652	0.683	0.715	0.750	0.787	0.828	0.875	0.936	1.078
0.69	0.429	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.907	1.049
0.70	0.400	0.536	0.565	0.594	0.625	0.657	0.692	0.729	0.770	0.817	0.878	1.020
0.71	0.372	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.344	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.316	0.452	0.481	0.510	0.541	0.573	0.608	0.645	0.686	0.733	0.794	0.936
0.74	0.289	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.262	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.235	0.371	0.400	0.429	0.460	0.492	0.526	0.563	0.605	0.652	0.713	0.855
0.77	0.209	0.344	0.373	0.403	0.433	0.466	0.500	0.537	0.578	0.626	0.686	0.829
0.78	0.183	0.318	0.347	0.376	0.407	0.439	0.474	0.511	0.552	0.599	0.660	0.802
0.79	0.156	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.634	0.776
0.80	0.130	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.608	0.750
0.81	0.104	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82	0.078	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.556	0.698
0.83	0.052	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.530	0.672
0.84	0.026	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85	–	0.135	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86	–	0.109	0.138	0.167	0.198	0.230	0.265	0.302	0.343	0.390	0.451	0.593
0.87	–	0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88	–	0.055	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
0.89	–	0.028	0.057	0.086	0.117	0.149	0.184	0.221	0.262	0.309	0.370	0.512
0.90	–	–	0.029	0.058	0.089	0.121	0.156	0.193	0.234	0.281	0.342	0.484

Harmonics

Problems created by harmonics

- – Excessive heating and failure of capacitors, capacitor fuses, transformers, motors, fluorescent lighting ballasts, etc.
- – Nuisance tripping of circuit breaker or blown fuses
- – Presence of the third harmonic & multiples of the 3rd harmonic in neutral grounding systems may require the derating of neutral conductors
- – Noise from harmonics that lead to erroneous operation of control system components
- – Damage to sensitive electronics (eg. ECG in hospitals)
- – Electronic communications interference

Origins of harmonic distortion

Any device with non-linear operating characteristics can produce harmonics. “Non-linear loads” are simply those where the current does not follow the sinusoidal pattern of the voltage waveform. An ever increasing demand for stability and precision in electrical control and protection equipment has led to a proliferation of diodes, diacs, triacs, thyristors (SCRs), IGBT’s and similar semiconductor devices in power applications. Although these solid state devices have brought significant improvements in control design and efficiency, they do produce harmonic currents due to their high switching frequency in operation. Such rapid switching breaks the current waveform down to a point where it is no longer sinusoidal. Such currents not only cause a disturbance on the supply network but also adversely affect the operation of other equipment on the network, including PFI equipment and capacitors. While we focus our discussions on harmonics sources associated with solid-state power electronics, there are other sources of harmonic currents as well, grouped as follows:

1. Power electronic equipment: Variable Frequency Drives (AC VFD’s, DC drives, PWM drives, etc.), UPS’s, rectifiers, switched power supplies, static converters, SCR systems, diode bridges, IGBT controlled systems, etc.
2. Arcing equipment: furnaces, welding, lighting (CFL, etc.)
3. Saturable devices: Transformers, motors, generators, etc. The harmonics from such devices are relatively insignificant compared to power electronics and arcing equipment.

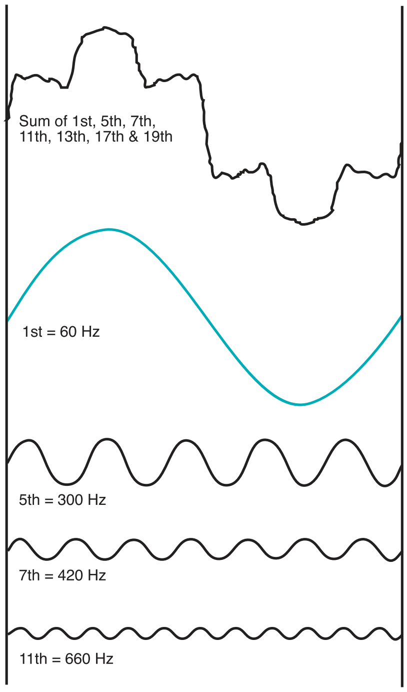
Waveform

Harmonics are defined as integer multiples of the fundamental 60 Hz waveform (i.e., 3rd harmonic = 180 Hz; 5th harmonic = 300 Hz, etc). Multiple waveforms at various frequencies result in a non-sinusoidal, distorted waveform. Harmonics are continuous (steady-state) disturbances on the electrical network and very different from transient disturbances like surges, spikes, sags, impulses, etc.

Transient problems are usually solved by installing surge capacitors, isolation transformers or MOVs. These devices help solve the transient problems but will not affect the mitigation of low order harmonics or solve harmonic resonance problems.

Harmonic content

IGBT/SCR based converters are often identified by the number of DC current pulses they produce per cycle. The most common ones are 6 and 12 pulse types. Several factors influence harmonic content but some significant harmonic currents, shown as a percentage of the fundamental current, are listed below (Fig 7).



Order of harmonic	Typical percentage of harmonic current	
	6 Pulse	12 Pulse
1	100	100
5	35	-
7	14	-
11	9	9
13	8	8
17	6	-
19	5	-
23	4	4
25	4	4

Figure 7

Harmonic overloading of capacitors

The impedance of a circuit dictates the current flow in that circuit. As supply impedance is generally considered to be inductive, the network impedance increases proportionally with frequency while the capacitor impedance decreases, hence varying inversely. This causes most of the higher frequency currents to be absorbed by the capacitor, and other equipment associated with the capacitor. In certain cases, harmonic currents can exceed the fundamental (60 Hz) capacitor current. They can also cause an increased voltage across the dielectric of the capacitor which could exceed its voltage rating, resulting in premature capacitor failure.

Harmonic resonance

The circuit or selective resonant frequency is reached when the capacitor reactance and the supply reactance are equal. Whenever power factor correction capacitors are applied to a distribution network, which combines capacitance and inductance, there will always be at least one frequency at which the capacitors are in parallel resonance with the supply. If this condition occurs at, or very close to, one of the significant harmonics generated, then large currents can oscillate between the supply network and capacitors. These currents are limited only by the damping resistance in the circuit. Such currents will add to the harmonic voltage disturbance in the network causing increased voltage distortion. This results in a higher voltage across the capacitor and excessive current through all capacitor components. Resonance can occur on any frequency, but the common ones are 5th, 7th, 11th and 13th harmonics or close to that, for 6 pulse systems. See Fig.8.

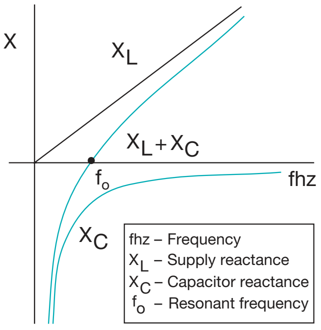


Fig. 8

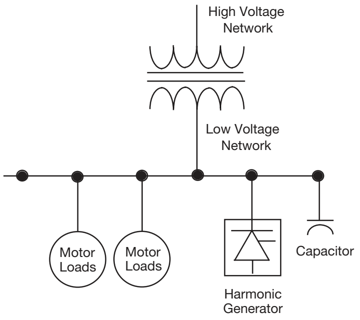


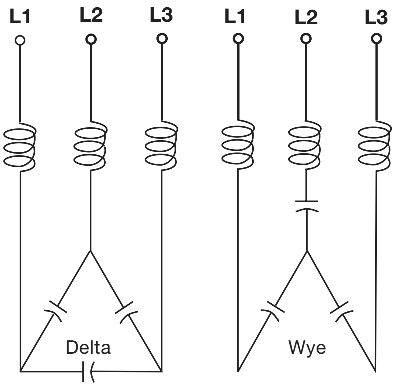
Fig. 9

Avoiding resonance

In older systems it used to help to install capacitors in a part of the system (Fig. 9) with the least probablility of parallel resonance with supply. Realistically though, with harmonics increasingly prevalent on most networks these days, avoiding resonance is not an option anymore as opposed to overcoming it.

Preventing resonance conditions

There are several ways to overcome resonance. The simplest solution to overcome resonance is to connect a reactor in series with each capacitor to ensure the reactance is inductive at the critical resonant frequencies but capacitive at the fundamental frequency. For this, the capacitor and reactor must have a tuning frequency below the lowest critical order of harmonic, which is usually the 5th, which translates to the 175 Hz to 270 Hz range, depending on the magnitude and order of harmonics present. The addition of a reactor in the capacitor circuit increases the fundamental voltage across the capacitor, hence the voltage rating of the capacitor needs to be higher. See Fig. 10.



Detuned Capacitor/Reactor Systems
Fig. 10

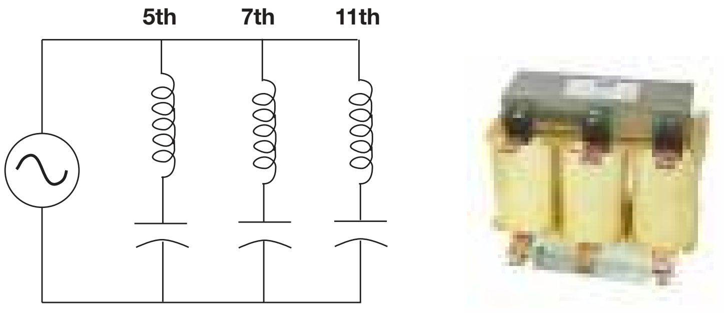
Eliminating harmonic distortion

Harmonic currents can be reduced by using a basic passive harmonic filter, often packaged with VFD's mainly to address the 5th harmonic. In order to eliminate harmonics however, it is necessary to employ more sophisticated filter technology, especially active harmonic filtering as described on the next page.

Harmonics filtering

Types of filters

Filtering technology has evolved to address harmonics caused by a proliferation of semiconductor based, electronically switched devices. Filters in the past involved precisely calculated LC circuits tuned to different frequencies (see Fig.11) that addressed a limited number of harmonic orders. Such combinations were almost always a precarious balance, so any change in load would necessitate a re-design and modification to the existing filter. **Also, increasingly complex non-linear loads on modern networks result in higher order harmonics which are beyond the capabilities of older, reactor based technologies.**



Shunt Filters
Fig. 11

ABB solutions for harmonics mitigation

While old filters primarily depended on reactors, newer Insulated Gate Bipolar Transistor-based (**IGBT**) solutions are best suited to actively eliminate harmonics with far greater precision, which is why ABB only promotes active filtering technology.

Active harmonic filters (**AHF**) are recommended where harmonic distortion already exists or if the harmonic distortion is above the 5% limits recommended in IEEE 519-1992, “Guide for Harmonic Control and Reactive Compensation of Static Power Converters”. AHF are IGBT-based and can be used in conjunction with tuned filters and are specifically designed to eliminate harmonics up to the 50th, thereby improving power quality across the entire network. ABB has a full range of cULus approved active harmonic filters (PQFM and PQFI versions) for a variety of applications and environments - commercial, industrial and even marine. PQFI and PQFM both, have the additional capability of load balancing as well providing a limited amount of reactive compensation to augment the power factor correction of standard fixed or automatic PFI equipment. Full support is provided on request for product sizing and selection based on the specific requirements of every application. For more information, please refer to the AHF brochures or simply contact ABB on **pqs_rfq@ca.abb.com.**

Harmonic studies

The first step in solving harmonic related problems is to perform an analysis to determine the specific needs of the network. To determine capacitor and filter requirements, it is necessary to establish the impedance of the supply network and the value of each harmonic current.

ABB Canada's full offering for low voltage power quality

- Individual capacitor units, fully assembled in Montreal
- Cylindrical capacitors, made in Belgium, with modules and cap banks assembled in Montreal
- Fixed or automatic capacitor banks, plain or detuned as required, fully assembled in Montreal
- Dynacomp SCR-switched detuned capacitor banks, fully assembled in Montreal
- Active harmonic filters, made in Belgium
- All products above are fully **cULus** approved
- On-site power factor and harmonic studies
- On-site commissioning and startup offerred
- Complete pre-sales and after-sales support

Appendix

Typical recommended cable sizes and protection device ratings

1503- phase capacitor kVAR	Rated current per phase (amps)	Minimum copper cable size for 75 °C insulation	Minimum copper cable size for 90 °C insulation	Recommended fuse amps	Recommended disc switch amps	Recommended MCCB trip amps
240 Volt						
2.5	6	#14	#14	10	30	15
3.5	8.4	#14	#14	15	30	15
5	12	#12	#12	20	30	20
7.5	18	#10	#10	30	30	30
10	24	#8	#8	40	60	40
15	36	#6	#6	60	60	60
20	48	#6	#6	80	100	80
25	60	#4	#4	100	100	90
30	72	#3	#3	125	200	110
40	96	#1	#1	175	200	150
50	120	00	00	200	200	200
60	144	000	000	250	400	225
75	180	250 kcmil	250 kcmil	300	400	300
100	241	400 kcmil	400 kcmil	400	400	400
125	301	(2) - 0000	(2) - 000	500	600	500
150	361	(2) - 250 kcmil	(2) - 250 kcmil	600	600	600
200	481	(2) - 400 kcmil	(2) - 350 kcmil	800	800	750
250	601	(3) - 300 kcmil	(3) - 300 kcmil	1000	1000	900
300	722	(3) - 400 kcmil	(3) - 350 kcmil	1200	1200	1100
480 Volt						
1.5	1.8	#14	#14	3	30	15
2	1.8	#14	#14	3	30	15
2.5	3	#14	#14	6	30	15
3	3.6	#14	#14	6	30	15
3.5	4.2	#14	#14	10	30	15
4	4.8	#14	#14	10	30	15
5	6	#14	#14	10	30	15
6	7.2	#14	#14	15	30	15
6.5	7.8	#14	#14	15	30	15
7.5	9	#14	#14	15	30	15
10	12	#12	#12	20	30	20
15	18	#10	#10	30	30	30
20	24	#8	#8	40	60	40
25	30	#8	#8	50	60	50
30	36	#6	#6	60	60	60
35	42	#6	#6	70	100	70
40	48	#6	#6	80	100	80
45	54	#4	#4	90	100	90
50	60	#4	#4	100	100	90
60	72	#3	#3	125	200	110
70	84	#2	#2	150	200	150
75	90	#1	#1	150	200	150
80	96	#1	#1	175	200	150
90	108	0	0	200	200	175
100	120	00	00	200	200	200
150	180	350 kcmil	350 kcmil	300	400	300
200	241	400 kcmil	400 kcmil	400	400	400
250	301	(2) - 0000	(2) - 000	500	600	500
300	361	(2) - 250 kcmil	(2) - 250 kcmil	600	600	600
350	421	(2) - 300 kcmil	(2) - 300 kcmil	700	800	650
400	481	(2) - 400 kcmil	(2) - 350 kcmil	800	800	750
500	601	(3) - 300 kcmil	(3) - 300 kcmil	1000	1000	900

Appendix

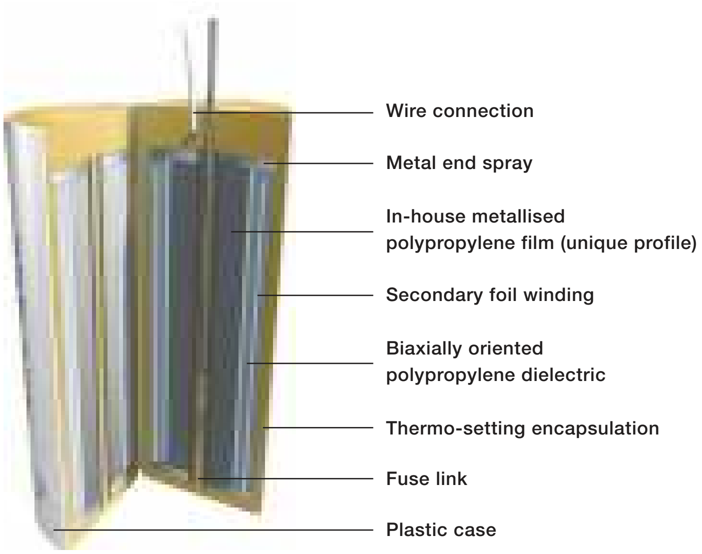
Typical recommended cable sizes and protection device ratings

3- phase capacitor kVAR	Rated current per phase (amps)	Minimum copper cable size for 75 °C insulation	Minimum copper cable size for 90 °C insulation	Recommended fuse amps	Recommended disc switch amps	Recommended MCCB trip amps
600 Volt						
2	2	#14	#14	3	30	15
3	3	#14	#14	6	30	15
4	4	#14	#14	6	30	15
5	5	#14	#14	10	30	15
7.5	7	#14	#14	15	30	15
10	10	#14	#14	20	30	15
15	14	#12	#12	25	30	25
20	19	#10	#10	35	60	30
25	24	#8	#8	40	60	40
30	29	#8	#8	50	60	50
35	34	#6	#6	60	60	60
40	38	#6	#6	70	100	60
45	43	#6	#6	80	100	70
50	48	#6	#6	80	100	80
60	58	#4	#4	100	100	90
70	67	#3	#3	125	200	110
80	77	#2	#3	150	200	125
90	87	#1	#2	150	200	150
100	96	#1	#1	175	200	150
150	144	3/0	3/0	250	400	225
200	192	300 kcmil	250 kcmil	350	400	300
250	241	400 kcmil	400 kcmil	400	400	400
300	289	(2) - 3/0	500 kcmil	500	600	450
350	337	(2) - 4/0	(2) - 4/0	600	600	550
400	385	(2) - 300 kcmil	(2) - 250 kcmil	600	600	600
500	481	(2) - 400 kcmil	(2) - 350 kcmil	800	800	750

The above table gives recommended ratings of cables, disconnect switches, and/or molded case circuit breakers for use with capacitor loads. For requirements not covered in the table, the following application guidelines may be used for capacitor switching duty:

– Power cable sizing	135% of capacitor current
– Disconnect switch	150% of capacitor current
– Molded case circuit breaker	150% of capacitor current

The above ratings are based on the CE code handbook. ABB assumes no responsibility for inappropriate ratings.



Cut-away view of an Internally Protected Element

Installation requirements

For any installation requirements on capacitors, refer to section 26-200 to 26-222 of the Canadian Electrical Code, or consult ABB Control's technical support department.

Separate overcurrent protection

A separate overcurrent device is not necessary when an ABB capacitor is electrically connected on the load side of the motor starter fused safety switch or breaker. Personnel and facility short circuit protection is provided within the capacitor by ABB's patented Sequential Protection System. Short circuit protection between the main feed and the capacitor is provided by the motor starter fused safety switch or breaker. A disconnect switch can be provided when the capacitor is connected as illustrated in Option C (See Fig. 6, page 7). When the capacitor is connected as in Option C, it remains energized even when the motor is off. The optional disconnect helps avoid this condition.

Additional information

1. Improved voltage @ transformer due to capacitor addition:

$$\%\text{ voltage rise} = \frac{\text{kVAR of capacitors x \% reactance of transformer}}{\text{kVA of transformer}}$$

Note: System reactance should be added to the transformer reactance if available.

2. Reduced power losses in the distribution system due to capacitor addition:

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

3. Reduced kVAR when operating 60 Hz unit @ 50 Hz

$$\text{Actual kVAR} = \text{rated kVAR}\left(\frac{50}{60}\right) = .83\text{ rated kVAR}$$

4. Reduced kVAR when operating @ below rated voltage

Actual kVAR = rated kVAR

i.e.
240 V @ 208V = .751 rated kVAR $\left(\frac{\text{operating voltage}}{\text{rated voltage}}\right)^2$

i.e.
660 V @ 600V = .826 rated kVAR $\left(\frac{\text{operating voltage}}{\text{rated voltage}}\right)^2$

Common formulae:

$$\cos \Phi = \frac{kW}{kVA} \qquad \cos \Phi\text{ (average)} = \frac{kWh}{\sqrt{(kWh^2 + kVARh^2)}}$$

$$kVAR = kW * \tan\Phi = kW * \tan(\cos^{-1}\Phi)$$

$$kVA = \frac{\sqrt{3} * V * I}{1000} \qquad kVAR = \frac{V^2 * 2 * \pi * f * C}{1000000/1000}$$

$$I_{line} = \frac{kVA * 1000}{\sqrt{3} * V} \qquad kW = \frac{\sqrt{3} * V * I * \cos\Phi}{1000}$$

Abbreviations and notations:

V = voltage, I = current in Amps, kW = real power
kVA = apparent power, kVAR = reactive power
C = capacitance in microFarad, f = frequency in Hertz
HP = horsepower, k = kilo, π = 3.14159

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