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L&T SWITCHGEAR
SAFE & SURE

—|VArticle|—

Volume - 1

Reactive Power Management




It gives us immense pleasure to present a compilation of the first twelve issues of –|VArticle|–, a technical write-up related to **Reactive Power Management**. Over the past twelve articles, we have tried our best to provide insights into selection of capacitors, filters, switchgear for capacitor switching and harmonics.

Our aim has been to create awareness on latest technology trends, and present some facts in the domain of Reactive Power Management. Some –|VArticle|– also give information about available product options to satisfy customer requirements.

Most of the information included in the –|VArticle|– is based on basic electrical engineering fundamentals and our on-field experience.

This compilation would be useful to consultants, end users and individuals interested in understanding current issues in Reactive Power Management.

Please feel free to get back to us with technical queries or requests for covering specific topics in future –|VArticle|–.

Regards,

Product Management - Reactive Power Management Products

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Harmonic Mitigation

The importance given to harmonics analysis in installation design is increasing these days. If any problem occurs due to harmonics, it results in major loss of material and money. International standardisation has been tackling these phenomena for many years, although the standards and recommendations in force are yet to produce significant results in India.

There are certain cases of malfunctions linked essentially to the above phenomena; some of these are illustrated below:

- Overloading of power factor correction capacitors
- Tripping of protection devices
- Overloads in neutral conductors due to third-order harmonics created by single-phase loads
- Overheating of cables
- Overloading of transformers or generators

The above malfunctions are not always felt immediately after the system is installed, but at times may be felt in the long term and are difficult to distinguish from the natural ageing of the equipment.

In harmonic rich environments, some of the following design considerations need to be incorporated in Automatic power factor correction system design:

1. Heavy duty capacitors (Capacitors having a higher overload and peak inrush current withstand) need to be used.
2. Depending on the nature of the non linear load, a suitable de-tuned reactor (5.67%, 7%, 14%) might have to be used.
3. When capacitors are used along with the de-tuned reactors, the voltage that appears across the capacitor increases (as it is the vector sum of the system voltage and the voltage across the reactor). Moreover to achieve a net output of the reactor capacitor combination, a higher kVAR capacitor needs to be used that will compensate for the reactive power used up by the de-tuned reactor.
4. To achieve the desired tuning frequency $1/(2\pi)\sqrt{LC}$ of the capacitor-reactor combination (In case of a de-tuned reactor, this frequency is well below the resonant frequency of the system), the inductance-capacitance combination is of crucial importance. If a lower value capacitor is used, the tuning frequency of the combination will increase and might even coincide with the resonant frequency of the system. This can be a very dangerous condition.

Thus the capacitor reactor combination has to be selected properly for successful harmonic mitigation. It is difficult to solve harmonics related problems, once the power factor correcting system is installed. It is important to incorporate Harmonic Mitigation techniques while the system is being designed.

Interpretation of Total Harmonic Distortion (THD)

It's a known fact that harmonics cause over loading of power capacitors and consequently reduce the life of power capacitors. Normally lot of emphasis is given only to %THD for assessing the harmonics level. But the frequency spectrum (5^{th}, 7^{th}, 11^{th}, 13^{th} and so on) of the harmonics are not given as much importance.

The over-current (and hence the stress on the capacitors) will not only depend on the %THD value but also on the magnitude of individual harmonics, which can be clearly seen in the frequency spectrum. Following calculations prove the above statement.

Case 1:

Assumptions:

1. V_{THD}: 25%
2. Harmonic frequencies considered: 5^{th} (250 Hz), 7^{th} (350 Hz)
3. V_5=20%V_1 and V_7=15%V_1
4. All other harmonic frequencies are negligible
5. The capacitors are delta connected hence will not provide a path for the third harmonic to flow

Important Formulae:

Xc=1/(2 x π x f x C), where X_c is the capacitive reactance, f is the frequency, C is the capacitance I_c=V_c/X_c, where Ic is the capacitive current, V_c is the voltage across the capacitor and X_c is the capacitive reactance

$V_{THD} = \sqrt{\Sigma(V_i^2)/V_1}$, where i=3 to 99

Calculations:

Using the superposition theorem, we can calculate the current contribution of individual harmonic voltages.

I_5 = V_5/X_{c5}

= $0.2V_1/[1/(2 \times \pi \times 5 \times f \times C)]$

= $0.2 \times 5 \times V_1/X_{c1}$

= $1 \times V_1/X_{c1}$

= I_1

Similarly,

I_7 = $1.05I_1$

The total current I will be a vector sum of I_1, I_5 and I_7

Thus $I = \sqrt{(I_1^2 + I_5^2 + I_7^2)}$

$= \sqrt{(1+1+1.1025)} \times I_1$

Net current, I = 1.8 I_1 ----------------------> (1)

Case 2:

Assumptions:

1. V_{THD}: 25%
2. Harmonic frequencies considered: 5^{th} (250 Hz), 7^{th} (350 Hz), 11^{th} (550 Hz), 13^{th} (650 Hz)
3. V_5=18%V_1, V_7=15%V_1, V_{11}=8%V_1 and V_{13}=4%V_1

Calculation:

I_5 = V_5/X_{c5}

= $0.18V_1/[1/(2 \times \pi \times 5 \times f \times C)]$

= $0.18 \times 5 \times V_1/X_{c1}$

= $0.9 \times V_1/X_{c1}$

= $0.9I_1$

Similarly,

I_7 = $1.05I_1$

I_{11} = $0.88I_1$ and

I_{13} = $0.52I_1$

The total current I will be a vector sum of I_1, I_5, I_7, I_{11} and I_{13}

Thus $I = \sqrt{I_1^2 + I_5^2 + I_7^2 + I_{11}^2 + I_{13}^2}$

$I = \sqrt{(1^2 + 0.9^2 + 1.05^2 + 0.88^2 + 0.52^2)} \times I_1$

Net current, I = 2 I_1,----------------------> (2)

Thus, in the above two cases, even the THD value remains same (25%), the over current (ref. Eq 1 and Eq 2) value is different depending upon the spectral values.

Hence THD value and detailed information of the frequency spectrum are necessary to predict the capacitor over-current. Harmonics study is the best way to get the frequency spectrum details and hence the exact over current value can be calculated.

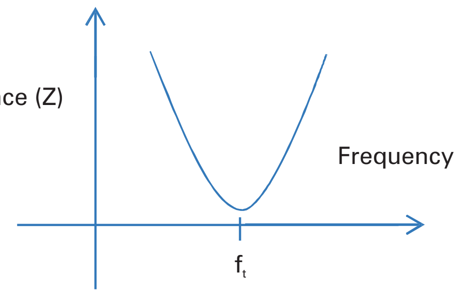
De-tuned Filters

What are De-tuned Filters?

De-tuned Filters are a combination of series inductors and power factor correction capacitors that are meant to:

1. Prevent resonance
2. Prevent harmonic amplification
3. Protect power factor correction capacitors from overload

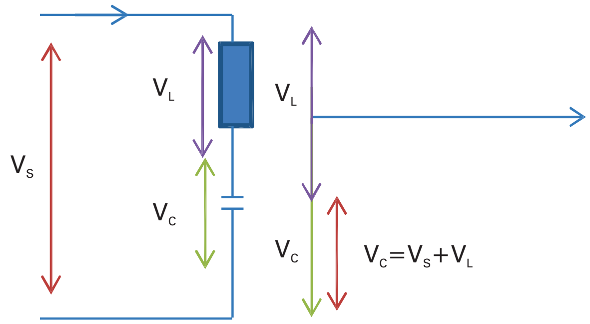
Every series LC combination behaves capacitive below its tuning frequency $f_t = 1/\left(2\pi\sqrt{(LC)}\right)$ and inductive above. The inductive element of the de-tuned filter is selected such that the tuning frequency of the filter is significantly lower than the lowest order harmonic frequency present in the system. The filter is thus de-tuned. The ratio of inductive reactance (X_L) and capacitive reactance (X_C) is defined as the tuning factor. Eg: A tuning factor of 7% implies X_L/X_C=0.07



As can be seen from the above graph, for all frequencies above the tuning frequency (f_t), the combination will provide increasing impedance. The combination will not provide a low impedance path for harmonics that the capacitor did earlier, thus preventing harmonic amplification. Further as the tuning frequency of the combination is lower than the lowest order harmonic in the system, there is no question of resonance. At 50 Hz the combination behaves capacitive and power factor correction is achieved

Can I add de-tuned filters in my existing panel?

The voltage that appears across the terminals of a capacitor increases the moment you connect an inductor in series with it. This can be illustrated by the below phasor:



V_S: System Voltage; V_C : Voltage across the capacitor; V_L : Voltage across the inductor; I:current.

As can be seen $V_C>V_S$ by an amount V_L. Thus if reactors are to be added to an existing APFC panel, the capacitors will have to be replaced with those capable of withstanding higher voltages. Moreover the output of the capacitors will have to compensate for the reactive power that will be consumed by the reactor.

Reactors are a major source of heat and existing panel may not have sufficient space or cooling arrangement to handle the heat generated by the newly installed reactors.

For these reasons, it is not advisable to add de-tuned reactors to existing APFC panels.

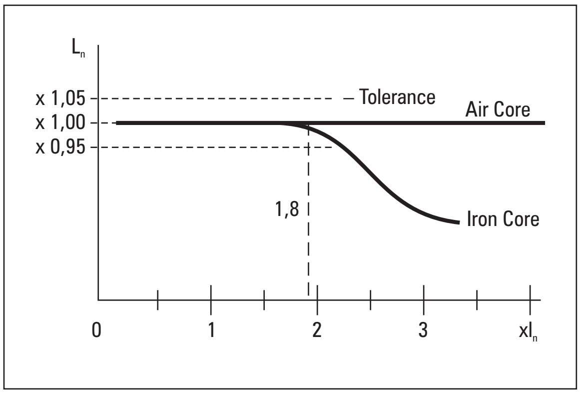
Reactor tuning factor	Tuning frequency	Application (harmoic orders)	Typical loads
7%	189 Hz	5th harmonic (250 Hz) and above	6 pulse drives (AC / DC), 3 phase UPS, frequency converters
14%	133 Hz	3rd harmonic (150 Hz) and above	Single phase UPS, CFL lamps, SMPS, dimmers

Linearity of Reactor

An industry whose load includes a high proportion of non-linear load (harmonic generating loads), and has poor power factor, requires capacitor with de-tuned filter. This would perform the function of power factor improvement while preventing harmonic amplification.

Normally, the inductance of the series reactor (of de-tuned filter) connected is chosen such that the tuning frequency of the de-tuned filter is 10% below the lowest harmonic frequency with considerable current/voltage amplitude. Therefore, resonance will not happen in the system and reactor offers high impedance for higher frequency harmonics.

Normally, 7% detuned reactors are designed considering typical industrial loads such as drives that have the following harmonic voltages: V_3=0.5% V_N, V_5=6% V_N, V_7=5% V_N and so on. However, if the individual harmonic voltages increase, the following phenomenon happens:



Relation between inductance (L_N) and inductor current (I_N)

- The magnitude of net current (through LC) increases.
- If the current increases beyond certain limit, the reactor will be driven into its saturation region.
- Once the reactor saturates, inductance value (L, in henry) of the reactor starts decreasing (as $L = N\phi/I$).
- Therefore, the resonant frequency (F_R) of the LC will rise [as Resonant frequency $= 1/2\pi\sqrt{LC}$]
- As the resonant frequency rises, the capacitor-reactor combination will offer lower impedance to the fifth harmonic component and the current through the combination will increase further.
- Thus, the resonant frequency of the reactor capacitor combination will increase continuously resulting in a thermal runaway.
- The new resonant frequency may match the fifth harmonic frequency and can results in resonance.

Normally, reactors are designed with predefined linearity. A reactor having a higher linearity will not saturate for higher harmonic currents and will prevent the system from a thermal run-away as described above.

Q-factor of Reactor

The quality factor or Q-factor is a dimensionless parameter that characterizes a resonator's bandwidth relative to its center frequency. It also describes the damping nature of a resonant circuit. Higher Q indicates a lower rate of energy loss relative to the stored energy of the oscillator; the oscillations die out more slowly. For example, a pendulum suspended from a high-quality bearing, oscillating in air, has a high Q, while a pendulum immersed in oil has a low one. Oscillators with high quality factors have low damping so that they ring longer.

The Q-factor is the ratio of the reactance to the resistance in the circuit. In other words, it is the absolute value of the ratio of reactive power to real power

$$\tilde{z} = R + jX$$

$$Q = \left|\frac{X}{R}\right|$$

Thus, we can also calculate the Q-factor, just by knowing the power factor of the circuit

$$Q = \frac{|\sin\phi|}{|\cos\phi|} = \frac{\sqrt{1-PF^2}}{PF} = \sqrt{\frac{1}{PF^2} - 1}$$

or just the tangent of the phase angle

$$Q = |\tan\phi|$$

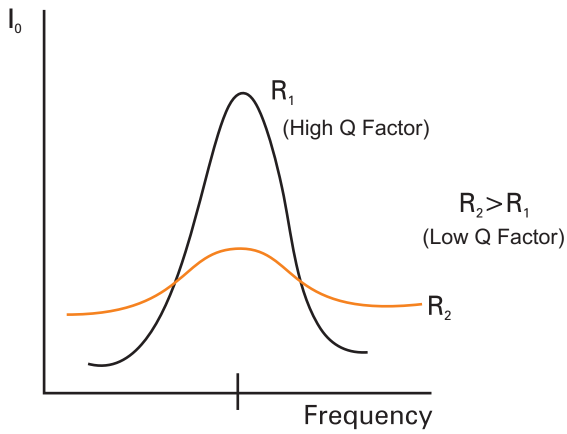
While selecting a detuned filter, it is important to give due consideration to its band-width. The bandwidth will decide the extent of impendence the filter offers to higher order harmonics. The bandwidth of the filter is a function of the resistance of the system. The resistance largely depends upon material and construction of the filter inductor.

Bandwidth = F_2-F_1 = F_r/Q

Where, F_2 is the upper cut off frequency

F_1 is the lower cut off frequency and

F_r is the resonant frequency



For an electrically resonant system, the Q-factor represents the effect of electrical resistance, as shown in the above figure. When resistance is low (R_1), the system will have a low bandwidth. When the resistance is increased gradually (say to R_2), its bandwidth increases. Thus while selecting De-tuning reactors, care should be taken that the Q factor of the same is adequate.

K-factor Transformers

Harmonic currents are generated whenever non-linear loads are connected to the mains supply. The problems caused by harmonic currents include increased losses and overheating of transformers, over heating of cables, especially the neutral conductor, overheating and vibration in induction motors and premature failure of power factor correction capacitors. This article discusses the effects of harmonics specifically on transformers and a method to ensure the reliability of transformers in harmonics rich environments.

Losses in transformers are due to eddy current losses and stray magnetic losses in the core and resistive losses in the windings. Of these, eddy current losses play an important role in harmonic rich environments. These losses are directly proportional to the square of the frequency. Higher harmonic content would lead to higher eddy current losses. This in turn would increase the operating temperature of the transformer that could result in a premature failure.

In order to overcome the above ill effects, a special transformer called as k-factor transformer has been developed. This is a specifically de-rated transformer that is designed keeping in mind harmonic loads.

- K-factor will account for the increase in eddy current losses, because of non-linear loads, along with normal losses in the transformers.
- This special transformer also has 200% neutral or more for triplen harmonics.
- Moreover, it also has stranded conductors for reducing skin effect, low loss steel in the core for reducing eddy current loss.

K-factor is defined as the ratio of total eddy current loss to the eddy current loss at the fundamental frequency.

$$K = \frac{P_t}{P_f} = \sum_{h=1}^{n} I_h^2 h^2$$

Where, P_f is the eddy current loss at the fundamental frequency, f

P_h is the eddy current loss at h^{th} harmonic

P_t is the total eddy current loss

I_h is the h^{th} harmonic current

Hence, if we know the harmonics spectrum, we can easily arrive at the amount of de-rating or the k-factor of the transformer.

K-Factor transformers available, are designed to take care of the increased stresses on account of Harmonics. Depending on the nature of the non linear load, suitable K-Factor transformers can be selected.

Following are the typical K-Factor for non-linear loads connected:

% non-linear load	K-Factor
<5%	K-1
<35%	K-4
<50%	K-7
<75%	K-13
<100%	K-20

Hence choosing K-Factor transformers for modern building loads, industries with more non-linear loads, would result in better performance and long life of the transformers.

Transformer Compensation

Background:

With increased emphasis on power quality and significant incentives / penalties associated with power factor improvement, most customers are trying to operate their plant electrical system at near unity power factor.

In order to achieve near unity power factor, all sources of reactive power need to be identified and fully compensated. One such element that consumes reactive power is the transformer. Reactive power is consumed by transformers through the no load magnetizing current and through the leakage reactance. This issue is aimed at helping customers size capacitor banks for transformer compensation.

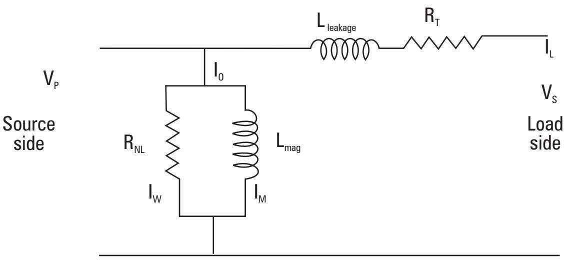
Basics:

The power factor on the HT side (source side) of a transformer depends upon the following:

- LT side (Load side) power factor
- Real power consumed by transformer
- Reactive power consumed by transformer

The load side power factor is compensated by employing APFC panels or/and by providing individual compensation to connected loads. Transformer compensation on the other hand is not as well understood.

The equivalent circuit of a transformer is as shown below:



Where: V_P is the source Voltage, V_S is the load Voltage, I_O is the no load current, I_W is the no load watt loss current, I_M is the magnetizing current, R_{NL} is the no load resistance, L_{mag} is the magnetizing inductance, $L_{leakage}$ is the leakage inductance, R_T is the winding resistance.

As can be seen from the equivalent circuit, the inductive elements, namely L_{mag} and $L_{leakage}$ contribute to the VAR consumption of the transformer.

Magnetizing VAR requirement of a transformer:

The magnetizing VAR consumption is a function of the rated voltage and the magnetizing current of the transformer. The no load current of a transformer varies between 0.5 % and 2.5% of the full load current depending on the design of the transformer and the operating flux level. The magnetizing current is around 80% of the no load current and thus varies between 0.4% and 2%. It is safe to assume a value of 1-1.2% for distribution transformers.

Thus the VAR required to compensate for the magnetizing current of the transformer is around 1-1.2% of the transformer kVA rating.

VAR requirement due to leakage reactance

The VAR requirement due to leakage reactance is a function of the square of the current and the leakage reactance. At full load the voltage drop across the leakage reactance is equal to the impedance voltage (%Z impedance). The reactive VAR consumption is equal to the product of impedance voltage and load current.

$$Q_X = I_L^2 \times X_{Leakage};$$

Where I_L is the load current and $X_{Leakage}$ is the leakage reactance; Q_x is the kVAR

Power requirement:

Typically, for a 3 phase transformer,

$$X_{leakage} = \frac{V_2^2}{kVA} \times (\%Z) ;$$

Where V_2 is the secondary voltage.

$$Q_X = (\% Z) \times (KVA) \times (\% load)^2$$

% loading is assumed to be 50% to 75%. Thus for %Z=5%, Q_X works out to 5%* $(75\%)^2$ i.e. 3%

Thus the VAR requirement to compensate for the leakage reactance of the transformer is around 3% of the kVA rating of the transformer

The total VAR required to compensate for the reactive power consumed by the transformer is around 4% to 4.25% of the kVA rating of the transformer.

Capacitor Switching in APFC Panels

The switching of capacitor banks is a special and challenging application in Automatic Power Factor Correction (APFC) panels. The selection of appropriate switching device for such applications is based on two criteria:

- Ability to carry rated capacitor current continuously
- Ability to make the peak-inrush current of capacitor

It is simple to calculate the capacitor rated current and select the switching device to be able to carry rated capacitor current (2.5 to 3 times the capacitor rated current to take care of overload, harmonics, supply voltage variation and capacitor value tolerance). However, it is a little difficult to select the switching device which is able to make the peak-inrush current. This is because the peak inrush current for capacitor switching application depends upon various factors such as:

- The inductance of the network (including cables, switchgears and transformer)
- The transformer power rating and % impedance
- Methods used for power factor correction:
  - fixed capacitor bank
  - multi-stage capacitor bank with steps of equal ratings
  - multi-stage capacitor bank with steps of unequal ratings
- In multi-stage capacitor bank, the nos. and rating of steps already switched on

In most of the installations, the multi-stage capacitor banks are used with steps of unequal ratings. The bigger steps of higher kVAr ratings being switched on initially and smaller steps are switched on periodically, for achieving the targeted power factor. In such cases, the value of inrush-current peak will be far higher and hence the smaller capacitors will be heavily stressed.

Capacitor switching can be done by various ways such as:

Power contactor:

- Normal power contactors will simply allow the inrush current to flow through them and because of this, contactors and capacitors are heavily stressed. Contactor selection should be such that it withstands the heavy inrush current for which some amount of derating would be required.
- Power contactors should be used along with inrush current limiting reactors, which will increase the cost and size of the APFC panel.
- Instead of de-rating power contactors and using current limiting reactors, capacitor duty contactors shall be used.

Capacitor duty contactor:

- MO C range of capacitor duty contactors can be used to limit the inrush current to less than $10*I_N$.
- Capacitor duty contactors have pre-contacts with current limiting resistors (of 4 Ω).
- Capacitor duty contactors are employed where the frequency of switching is less i.e., the load fluctuation is not often. The capacitor requires atleast 60 seconds to discharge to a nominal value (50 V). So capacitor duty contactors cannot be used when load fluctuation is heavy.
- MO C contactors can be used for switching capacitors upto 80 kVAr in each branch.

Thyristor switching module:

- TSM is used for dynamic power factor correction i.e., wherever the load fluctuation is heavy (welding, steel rolling, etc.)
- Rapid switching (5 ms) is possible with TSM along with Quick Discharge Resistor (QDR). Existing discharge resistor in capacitors shall be replaced with QDR.
- There will be no inrush current while using TSM (zero voltage switching and zero current switching). So frequent switching will not affect the life of capacitors and there may not be a need to use extra current limiting reactors.
- TSM has thermal cutoff, which will switch off when temperature exceeds beyond a certain limit. It will automatically switch on when optimum temperature is attained.
- Panel design becomes critical while using TSMs and adequate cooling arrangements need to be employed.

Fuse Selection for APFC Panels

For any APFC panel, fuses are required for faster short circuit protection and overload protection of capacitors. Fuse selection for capacitive load is critical because of heavy inrush current, high overload capacity and continuous full load. These inherent traits of a capacitor, complicates the selection process. Hence the selection should be such that even during these permissible abnormalities, the fuse should not blow.

Normally, the maximum permissible current in a capacitor branch is **2 times** the rated current. This factor is comprised of the following:

- Harmonics overload and over voltage – 30%
- Capacitance tolerance – 10%
- Frequency variation – 2%
- Fuse deration factor – 35%

The fuse used for branch protection must be capable of carrying this current continuously. Hence the fuse should be sufficiently rated so as to avoid the deterioration of the fuse element. Further the fuse should not blow during switching of the capacitors because of the inrush current (more than 100 times the rated capacitor current under normal conditions). In order to prevent nuisance operation of fuse, its time-current characteristic should cover the peak inrush current of the capacitor. Hence for the optimal selection of fuses, the inrush current must be limited by using either **capacitor duty contactor** or **inrush current limiting reactor**.

The following table** shows the selection of Fuses and Capacitor switching contactors for an APFC panel:

kVAr	Rated current+ (A)	O/C factor	Allowed O/C for capacitor (A)	Recommended Contactor+	Fuse rating (A)
10	13.12	2	26.24	MO C12	32
15	19.68	2	39.36	MO C15	40
20	26.24	2	52.48	MO C20	63
25	32.80	2	65.60	MO C25	80
30	39.37	2	78.74	MO C30	80
50	65.61	2	131.22	MO C50	160

**Selection principle is same for other family of fuses*
***The table is valid only for L&T switchgear and capacitors*
+at 440 V

The rated current of a capacitor can be calculated as.

$$\frac{1000 \times kVAr}{\sqrt{3} \times V}$$

For any capacitor bank, permissible overload is **2** times rated capacitor current. Hence, fuses should be rated to carry continuous overcurrent as given in the above table. In case Thyristor Switching Modules are used instead of capacitor duty contactors, it is highly recommended to use **High Speed Fuses** (semiconductor fuse).

Above selection chart is valid only if fuses are used along with capacitor duty contactor or inrush current limiting reactor (0.2% reactor). Please consider the above table purely as a guideline for selection. Actual selection needs to be done based on considerations of connected load and the electrical network properties.

MCCB Selection for APFC Panels

For any APFC panel, MCCBs are required for short circuit protection, overload protection and for isolation of capacitors. MCCB selection for capacitive load is tricky because of heavy inrush current, high overload capacity and continuous full load. These inherent traits of a capacitor, complicates the selection process. The selection should be such that the MCCB should not nuisance trip during inrush current and should withstand continuous flow of overload current.

Whenever we use MCCB in an APFC panel, proper measures need to be taken against the ill effects of the inrush current. Normally the inrush current (more than 100 times the rated capacitor current) will remain for a few micro-seconds and will not be sensed by the MCCB. However the contacts of MCCB may repel and bounce because of the current limiting feature, causing micro-arcs between the contacts of MCCB. This multiple bounce can result in premature failure of MCCB contacts. In order to reduce the magnitude of the peak inrush current, MCCBs must be used along with c**apacitor duty contactors** or **inrush current limiting reactors**.

The maximum permissible current in a capacitor branch is 1.46 times the rated current. This factor is comprised of the following:

- Harmonics overload and over voltage – 30%
- Capacitance tolerance – 10%
- Frequency variation – 2%

The branch MCCB must be capable of carrying this current continuously. The following table** shows the selection of MCCBs and Capacitor switching contactors for an APFC panel:

kVAr	Rated current⁺(A)	O/L factor	Permissible capacitor O/L (A)	Recommended Contactor+	MCCB*	Thermal Setting (A)		**Magnetic setting** (6 to 10*I_R)
						I_N	I_R (100% I_N)	
10	13.12	1.46	19.16	MO C12	DH / DU / DN	19	19	171
15	19.68	1.46	28.74	MO C15	DH / DU / DN	29	29	261
20	26.24	1.46	38.32	MO C20	DH / DU / DN	38	38	342
25	32.80	1.46	47.90	MO C25	DH / DU / DN	48	48	432
30	39.37	1.46	57.47	MO C30	DH / DU / DN	58	58	513
50	65.61	1.46	95.79	MO C50	DH / DU / DN	96	96	864

**Selection principle is same for other family of MCCBs*
***The table is valid only for L&T switchgear and capacitors*
+at 440 V

The rated current of a capacitor can be calculated as

$$(1000 \times \text{kVAr}) / (\sqrt{3} \times V)$$

For any capacitor bank, permissible overload is 1.46 times rated capacitor current. Hence, MCCB should be rated to carry continuous over current as given in the above table.

Above selection chart is valid only if MCCB is used along with capacitor duty contactor or inrush current limiting reactor (0.2% reactor). Please consider the above table purely as a guideline for selection. Actual selection needs to be done based on considerations of connected load and the electrical network properties.

Life of Power Capacitors

The life of a capacitor is influenced by the following three parameters:

- Temperature
- Voltage
- Current

Temperature:

For a capacitor, the temperature depends upon the following parameters:

- Ambient temperature in which capacitor is being operated
- Amount of over current that flows through the capacitor
- Power loss of the capacitor (dielectric power loss and resistive power loss)

The increase in temperature results in faster degradation of the dielectric. For every 10°C rise in temperature, the life of the capacitor is halved. Faster the degradation of the dielectric, lower will be the life of the capacitor.

Increase in temperature beyond a certain limit may result in expansion of impregnation and dielectric material. This may result in bulging of capacitors. In worst case, capacitor may even burst, if it does not have an over-pressure disconnector.

The capacitor must thus be operated at rated ambient temperature for a longer operating life.

Voltage:

The increase in system voltage has the following effects on the capacitor:

- **Dielectric degradation:** If the voltage increases beyond a certain limit, the dielectric material will breakdown. This critical voltage is called the dielectric breakdown voltage. Breakdown can result in an internal short circuit causing the capacitor to fail permanently.
- **Increase in current flow through the capacitor:** (as capacitors are linear in nature) As the voltage increases, the capacitor current also increases because X_c remains constant ($I_c = V/X_c$). This results in overloading of the capacitor, which may reduce the life of the capacitor.

  Over-voltage limits of the capacitors are +10% for 12 hrs in 24 hrs, +15% for 30 min in 24h, +20% for 5 min in 24 hrs and +30% for 1 min in 24 hrs.

Current:

The parameters that are related to current, which affect the life of the capacitor are:

- **Inrush current**

  Inrush current (100 times rated current) is like a momentary short circuit. Frequent switching of the capacitor without proper inrush current limiting devices will affect the life of the capacitor as it is heavily stressed during each switching operation.

  Switching frequency thus limits the life of the capacitor.

- **Over-load current**

  Continuous overload of capacitor is mainly because of harmonics and continuous over voltage. Overloading results in local hot spots and may lead to an internal short circuit.

A generally accepted formula for estimating life of capacitor is:

$$L = L_R \left(\frac{E_R}{E_0} \right)^7 x2^{(\Delta T/10)}$$

Where:
L = operating life under stated temperature and voltage
L_R = life at rated temperature and voltage
E_R = rated voltage limit
E_O = operating voltage
ΔT = difference between rated operating temperature and capacitor core temperature in C.

To conclude, all the above parameters should be within the rated value in order to exploit the maximum life of the capacitor.

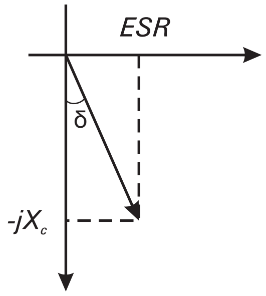
Capacitor Power Loss Calculation

A capacitor is a passive device which has two conductors separated by a dielectric of infinite resistance, ideally. Hence, this would offer only capacitive reactance, with zero resistance and zero inductance values. But practically, the dielectric of the capacitor will offer a finite resistance along with the capacitance. This finite resistance is called as **Equivalent Series Resistance (ESR)**, and its equivalent circuit can be represented as below:

The ESR in the capacitor causes the leakage current to flow through the dielectric of the capacitor. This results in real power loss (I^2 * ESR) called as dielectric loss. Higher the ESR, higher will be the power loss, and hence the heat generated by the capacitor will also be more. The heat generated should be dissipated properly; otherwise it may result in significant temperature rise. A good quality capacitor will have very low ESR value.

In a lossless (ideal) capacitor, the current leads the voltage by exact 90°. But there will be a small shortfall in the lead angle from 90°, because of the dielectric loss. The difference in angle is called as loss angle (δ). The following diagram represents the loss angle (δ) in the impedance plane.

Impedance plane



The tangent of the loss angle (loss tangent) is defined as the ratio of the capacitor's equivalent series resistance (ESR) to the capacitive reactance (X_c). From the above diagram,

$$\tan\delta = \frac{ESR}{[Xc]} \longrightarrow \text{(Eq 1)}$$

Power loss = I^2 x ESR

= (ωCV) x (ωCV) x ESR where, ω = 2πf

= (ωC) x (ωCV^2) x ESR

= (ωC) x Q x ESR

= Q x ESR / X_c

Power loss = Q tan δ [from Eq 1]

Where, Q is the reactive power rating of the capacitor (in VAr).

Typically, for good quality power capacitors, tan δ value would be less than 0.0002. Power loss of any capacitor can be computed if tan δ value is known. An example calculation is given below:

For a 10 kVAr capacitor, consider the value of tan δ as 0.0002

Total watt loss = 10 x 1000 x 0.0002

= 2 watts

Per kVAr power loss = Total watt loss / kVAr

= 2/10

= 0.2 watts per kVAr

Hence, power loss of any power capacitor can be calculated from the tan δ value. Normally, the tan δ value is available in the routine test certificate of the power capacitor.

The life of a power capacitor is largely dependent upon the temperature. Hence, it is a good practice to do the thermal design of APFC panel after computing the capacitor power loss.

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