Technical information

Guidelines for selection of surge arresters for shunt capacitor banks
Shunt capacitor banks are used to an increasing extent at all voltage levels. There are a variety of reasons for this like the growing need for power transfer on existing lines while avoiding transfer of reactive power, better use of existing power systems, improving voltage stability, right-of-way and cost problems, voltage control and compensation of reactive loads.

Thyristor-controlled as well as breaker-switched capacitors are used. Breaker-switched capacitors are installed in distribution, HV and EHV systems.

Since detailed studies generally are justified for thyristor-controlled capacitors due to the large cost savings which are possible, the general guidelines in this publication deal only with the protection of breaker-switched equipment by ZnO arresters.

Three-phase capacitor bank sizes vary from a few tenths of MVAr to several hundreds of MVAr. Both ungrounded wye and grounded wye banks are in use. It is common practice to use "restrike-free" breakers. However, since many banks are switched on a daily basis, the probability of obtaining high transients associated with capacitor switching increases. Furthermore, the standardized procedure to verify that the breaker is restrike-free includes only a limited number of tests. The use of arresters not only gives protection if a restrike occurs but also decreases the probability of multiple restrikes since the trapped charge on the capacitors is reduced.

The aim of this brochure is to give guidance for selection of surge arresters for capacitor banks, when such protection is considered to be needed. The protection afforded by different arrester protection levels and positioning (such as phase-ground, phase-phase and phase-neutral) against switching overvoltages is dealt with. Arrester energies related to different protection levels and capacitor MVAr ratings are given and the guidance is summarized in a set of diagrams.

Resonance conditions are not discussed since the duty imposed is strongly affected by system conditions and components, grounding etc. It is assumed, therefore, that harmonic and dynamic overvoltages in general are and must be limited by system design and operating procedures.
Generally speaking, capacitor protection by surge arresters has been a difficult task before ZnO arresters became available. The high discharge currents and possible energies associated with an arrester operation at a capacitor bank heavily stressed the spark gaps in a SiC gapped arrester. The possible high energies could also result in overstressed SiC blocks. Once a sparkover occurred, the arrester which sparked-over had to discharge the whole energy stored in the capacitor and also carry a power-frequency follow current before a resealing at the next voltage zero was possible.

Paralleling of gapped arresters required complicated triggering systems and thus it was difficult to design arresters to meet very high energy requirements at low voltage levels. In practice, the gapped arresters in many cases served as "fuses".

With the introduction of ZnO surge arresters, it is possible to meet any energy demand by simply paralleling the necessary number of blocks even if the procedure to ensure current sharing is quite sophisticated.

Switching surges of different origins can occur but, in general, it is the restrike cases that result in the highest arrester duties. Even if it is desirable to select a breaker which minimizes the risk for restrikes, it is recommended to base the arrester energy rating on a restrike due to the reasons discussed above.

**Using surge arresters**

Many capacitor banks are operated without surge arresters. However, there are a variety of reasons to instal arresters:

- To prevent capacitor failures at a breaker restrike or failure.
- To limit the risk of repeated breaker restrikes.
- To prolong the service life of the capacitors by limiting high overvoltages.
- To serve as an "insurance" against unforeseen resonance conditions which otherwise would lead to capacitor failures.
- For overall limitation of transients related to capacitor bank switching which can be transferred further in the system and cause disturbances in sensitive equipment.
- For upgrading of capacitors by preventing high overvoltages and/or for increasing the service voltage.
- To serve as protection against lightning for capacitor banks connected to lines.
A series of computer calculations using the EMTP(DCG/EPRI version) have been carried out to study switching surge protection of capacitor banks installed on systems ranging from distribution levels up to 550 kV.

The banks have been assumed to be connected in an ungrounded wye and fed from a relatively strong system with a short-circuit current of 20 kArms. The ratio X/R in the source impedance has been selected to be 10 or more. Systems with neutrals both grounded and ungrounded have been considered. Different positioning of arresters such as phase-ground, phase-phase and phase-neutral have been taken into account.

The case selected as decisive has been a two-phase restrike with full charge on capacitors due to a previous break. For this case the protection levels and the three-phase MVar rating of the banks have been varied in order to determine the resulting capacitor voltage as function of arrester protective level and bank size. The arrester energy stress as function of the same parameters is also obtained.

The three main cases considered with different positioning of the arresters are illustrated in Figures 1 to 3.

In the Figures $U_g$ is the phase-ground voltage of the feeding system, $R$ and $L_1$ resistance and inductance respectively of feeding system, $L_2$ possible series reactor of shunt capacitor, $C$ capacitance of shunt capacitor and $Z_{ng}$ system grounding impedance which has been set to either zero or infinite.

The arrows in the circuit diagrams indicate the modelled fault sequence of a three-phase break followed by a two-phase breaker restrike.

Since the expected arrester currents related to capacitor transients are high, the nominal protection levels for the arrester have been taken at 3kA switching surge. These levels are generally given in the catalogues for well-qualified surge arresters.
Effect of series reactors
Many capacitor banks are supplied with series reactors to either limit the current when switching-in with parallel banks connected or for nearby external faults or to form a filter with the capacitors. It may be common practice, for instance, to tune the reactor-capacitor circuit to a specific harmonic in order to avoid problems with unforeseen harmonics in the system. To cover one such case and check its influence on protection and energy demands on surge arresters, capacitors with series-reactors tuned to the 7th harmonic have been considered. It has been found that the main influence is that arrester currents are lower and energies higher.

It must also be pointed out that if the primary aim is to protect the capacitors, arresters positioned in front of the reactors will not protect the capacitors. The voltage may very well be twice as high at the capacitors than at the arresters.

Furthermore, when selecting the continuous operating voltage \((U_{c,\text{c}})\) of the arresters, it must be taken into account that the voltage phase-ground will be higher at the capacitor than at the reactor.

Summary of computer analyses
The results of the parametric analyses are summarized in a set of diagrams, one for each method of arrester positioning. To limit the number of diagrams for practical purposes, some approximations have been necessary. However, the resulting capacitor voltages are generally conservative which means that calculations for a specific case may result in 5% to 10% lower values. Note that 1 p.u. is defined as usual i.e. the peak value of the line-to-ground voltage. Therefore, to use the diagrams for a specific arrester protective level, the arrester voltage taken from the catalogues must be recalculated to p.u. value as defined above.

The calculations have been performed for a power frequency of 50 Hz. For 60 Hz the diagrams can be used if the actual 3-phase MVAr rating of the bank is multiplied with 0.83 before the diagrams are consulted. (The factor 0.83 will give the same capacitance as used for the calculations with 50 Hz).

Note that for capacitor banks connected grounded wye the diagrams for arresters phase-neutral could be used.

Also note that cases with ground faults within the capacitor banks preceding a breaker restrike have not been considered. For a capacitor with directly grounded neutral such fault may lead to even higher arrester duties due to a capacitor voltage in excess of 1 p.u. at the instant of the restrike. However, if this case should be considered the arrester energy could be estimated by multiplying the diagram values with the factor \((2+U)^2/9\) where \(U\) is the expected voltage (in p.u.) on sound phases at ground fault.

Arresters phase-ground
• Protection considerations
  The same capacitor voltage is obtained for grounded as well as ungrounded systems. With a series reactor a few percent lower voltages are obtained due to lower arrester currents. The given values in Figure 4 are for the case with directly grounded neutral without a series reactor and are generally on the safe side (conservative).
Energy considerations
Figure 5 and 6 give the energy for the case with directly-grounded system neutral. If the system neutral is ungrounded, the arrester energy will be 30% to 40% less since, in that case, the total energy is equally shared between the two arresters in series phase-to-phase. If a series reactor with a reactance of approximately 2% i.e. tuned to the 7th harmonic is connected in series with the capacitors, the energy will be 15% to 30% higher than shown in Figures 5 and 6.

Arresters phase-neutral

Protection considerations
The same capacitor voltage is obtained for grounded as well as ungrounded systems. With a series reactor up to 5% lower voltages are obtained due to lower arrester currents. The given values in Figure 7 are for the case with directly grounded neutral without a series reactor and generally on the safe side (conservative).

Energy considerations
Figure 8 and 9 give the energy for the case with directly-grounded system neutral. If the system neutral is
ungrounded the arrester energy will be approximately the same. For a series reactor tuned to the 7th harmonic the energy will be slightly higher approximately 5%.

Arresters phase-phase

- **Protection considerations**

  The same capacitor voltage is obtained for grounded as well as ungrounded systems. With a series reactor up to 5% lower voltages are obtained due to lower arrester currents. The given values in Figure 10 are for the case with directly grounded neutral without a series reactor and generally on the safe side (conservative).

- **Energy considerations**

  Figure 11 and 12 give the energy for the case with directly-grounded system neutral. If the system neutral is ungrounded the arrester energy will be approximately the same. For a series reactor tuned to the 7th harmonic the energy will be slightly higher, approximately 5%.
Selection of arrester parameters

Continuous operating voltage
Where the capacitor is installed, the maximum permissible operating voltage allowed under normal conditions is usually 5% to 10% above the nominal voltage level. This must be considered when selecting the $U_c$ of an arrester.

If phase-phase arresters are considered, the required $U_c$ is the phase-to-phase maximum operating voltage.

In case of harmonics it is important to notice that the $U_c$ of the arrester must be higher than or equal to the expected crest voltage across the arrester divided by $\sqrt{2}$.

Rated voltage
The rated voltage ($U_r$) is a measure of the overvoltage capability of the arrester and is selected based on temporary overvoltages, TOV. A recommended selection procedure is found in Ref. (11) for phase-ground arresters. Special attention should be paid to overvoltages caused by backfeed for arresters on a distribution system with ungrounded wye-delta transformers.

In case of earth fault, phase-neutral arresters will be subjected to lower TOV than phase-ground arresters. The same selection procedure as for phase-ground arresters thus results in a safety margin. Only if it is problematic to find an arrester with sufficiently low protective level connected phase-neutral and with a rated voltage based on this selection procedure, it will be necessary to consider more carefully the possible TOV for phase-neutral applications.

Phase-phase arresters are not subjected to TOV during earth faults. For any ABB high voltage arrester and for a normal choice of $U_c$ of less than or equal to 0.8 times rated voltage the resulting TOV capability will be, as a minimum, as follows:

- $1.42 \times U_m$ for 1 s or shorter times
- $1.35 \times U_m$ for 10 s or shorter times
- $1.27 \times U_m$ for 100 s or shorter times

The $U_c$ of the arrester shall be equal to or higher than $U_m$ which is the highest system voltage. Such selection usually will be sufficient to cover possible phase-phase TOV.

Energy capability
The energy capability of ZnO varistors may be somewhat dependent on the discharge current amplitude i.e. for shorter durations of an impulse, the energy capability is less. Usually the duration of arrester discharge currents resulting from capacitor transients is much shorter and the currents higher than obtained in the long-duration current withstand test as per IEC, which is the most relevant standardized test to define the energy capability. Some caution, therefore, is recommended when selecting an arrester type which will meet the energy requirements. A derating regarding energy capability may be necessary if given rated energy is based on existing IEC standard tests or even much longer current impulses.

The derating factor is not generally mentioned in manufacturers' standard catalogues and should be requested.

If the probability of a breaker
restrike (the considered decisive case) is assumed to be very low, one choice could also be to accept an arrester failure and not select an arrester to withstand this case. Of course the protection level of the arresters must always be selected in order to ensure that the capacitors are not subjected to voltages in excess of their withstand capability.

Examples

Example 1
- System voltage: 36 kV
- Fault clearing time: 10 s or less
- System grounding: Ungrounded
- Capacitor bank connection: Ungrounded wye
- Rated 3-phase power: 18 MVAr
- Desired protective level: 2.4 p.u.

For arresters installed phase-ground:

\[ U_c \] of the arrester must be higher than or equal to \( 36\sqrt{3} = 20.8 \text{ kV} \)

Following the procedure in Ref. (11) and for a particular arrester type, it is found that the rated voltage must be higher than or equal to 33 kV which is a "standard" value. For 33 kV rated voltage a usual \( U_c \) is 26.4 kV which is sufficient even if the operating voltage at the capacitor is 5-10% above the given 36 kV.

Figure 4 shows that an arrester protective level at 3 kA of 2.2 p.u. (64.7 kV) or less is needed to ensure a capacitor voltage less than or equal to 2.4 p.u.

Summary of required arrester data for connection phase-ground:
- Rated voltage: 33 kV or more
- Protective level at 3 kA: 64.7 kV or less (switching surge)
- Energy capability for capacitor discharges: 2.8 kJ per kV rated voltage or more

Note that if a selected arrester has a lower protective level than 64.7 kV it must be rechecked that this does not lead to considerably higher energy demands. The selection procedures thus contain an iterative process.

The minimum guaranteed protective level of the arrester thus is also of importance if calculated energies are close to arrester capability. Usually for 10 and 20 kA surge arresters a minimum characteristics could be estimated as approximately 5% below maximum guaranteed values or the manufacturer should be consulted for more accurate figures. For 5 kA arresters, due to manufacturing tolerances, the spread could be much higher.
For arresters installed phase-neutral:
$U_c$ of the arrester must be the same as for arresters phase-ground.

At ground fault the voltage will be less than for the arresters connected phase-ground. Here is a possibility therefore to decrease the rated voltage. However this means higher energy and less safety margins. Therefore, first check what the same rated voltage will result in.

Figure 7 shows that an arrester protective level of 2,35 p.u. is sufficient and the Figure 8 shows that the energy will be 105 kJ for an arrester with a protective level of 2,35 p.u. or higher at 3 kA which means 3,2 kJ/kV rated voltage.

Summary of required arrester data for connection phase-neutral:
- Rated voltage: 33 kV or more
- Protective level at 3kA: 69 kV or less (switching surge)
- Energy capability for capacitor discharges: 3,2 kJ per kV rated voltage or more

If an arrester with protective level of 64,7 kV is selected, the same as for the phase-ground case, the required energy capability as per Figure 8 would be about 120 kJ or 3,6 kJ per kV rated voltage.

Example 2
- System voltage: 245 kV
- Temporary overvoltages (duration 1s or less)
  - phase-ground: 1,55 p.u.
  - phase-phase: 2,45 p.u.
- System grounding: Directly grounded
- Capacitor bank connection: Ungrounded wye
- Rated 3-phase power: 80 MVAr
- Desired protective level: 2,2 p.u.

For arresters installed phase-ground:
$U_c$ of the arrester must be higher than or equal to $245\sqrt{3}=142$ kV

Rated voltage, following the procedure in Ref. (11) and for a particular arrester, must be higher than or equal to 193 kV.

Next higher "standard" value is 198 kV. For 198 kV rated voltage, the $U_c$ for this particular arrester is 156 kV which is sufficient even if the operating voltage at the capacitor is 5-10% above the given 245 kV.

Figure 4 shows that an arrester protective level at 3 kA of 1,8 p.u.(360 kV) or less is needed to ensure a capacitor voltage less than or equal to 2,2 p.u.

According to Figure 6 80 MVAr and 1,8 p.u. protective level result in an arrester energy of 820 kJ which means $820/198 = 4.1$ kJ/kV rated voltage.

Summary of required arrester data for connection phase-ground:
- Rated voltage: 198 kV or more
- Protective level at 3kA: 360 kV or less (switching surge)
- Energy capability for capacitor discharges: 4,1 kJ per kV rated voltage or more

A protective level of 360 kV at 3 kA for a rated voltage of 198 kV is extremely low even for 20kA arresters of line dis-
charge class 4 and 5. It certainly will require multiple column arresters if the TOV amplitude could not be reconsidered to a lower value which makes it possible to select a lower rated voltage for the arrester. However, if the given TOV’s are realistic, connection of the arresters phase-neutral could be an alternative or even installation of phase-phase arresters.

For arresters installed phase-neutral:
Figure 7 shows that for a capacitor voltage of 2,2 p.u. an arrester protective level of 2 p.u. (400 kV) is sufficient. Figure 9 shows that 2 p.u. will give 600 kJ in the arrester or 3 kJ per kV rated voltage.

Summary of required arrester data for connection phase-neutral:
- Rated voltage: 198 kV or more
- Protective level at 3kA: 400 kV or less (switching surge)
- Energy capability for capacitor discharges: 3,0 kJ per kV rated voltage or more

For arresters installed phase-phase:
$U_c$ of the arrester must be higher than or equal to 245 kV.

Rated voltage for any ABB arrester as per the discussion above (page 8, Selection of $U_r$) must be higher than or equal to $(2,55/\sqrt{3}) / (1,25/1,42) \times 245 \text{ kV} = 318 \text{ kV}$. Next higher "standard" value is 330 kV.

An arrester rated 330 kV is usually applied on 420 kV systems and the $U_c$ for that type of arrester is usually 264 kV which is sufficient even if the operating voltage at the capacitor is 8% above the given 245 kV.

Figure 10 shows that for a capacitor voltage of 2,2 p.u. an arrester protective level of 3,6 p.u. (720 kV) is sufficient. Figure 12 shows that 3,6 p.u. will give 1250 kJ in the arrester or 3,8 kJ per kV rated voltage.

Summary of required arrester data for connection phase-phase:
- Rated voltage: 330 kV or more
- Protective level at 3kA: 720 kV or less (switching surge)
- Energy capability for capacitor discharges: 3,8 kJ per kV rated voltage or more

The protective level for the minimum required rated voltage is not particularly low. With arresters phase-phase, therefore, it is possible to improve the protection further, which on the other hand leads to higher requirements on arrester energy capability. For an arrester protective level of 670 kV which could be met by 20 kA arresters of line discharge class 4 and 5 the voltage across the capacitors, phase-neutral, will be as low as 2,05 p.u.
Step-by-step procedure

To determine possible protective levels and arrester data the following step-by-step procedure is suggested:

• Decide upon a maximum capacitor voltage for switching surges. Consult Figures 4, 7 or 10 for necessary arrester protective levels at 3kA.

• Compare the efficiency of different arrester connection schemes phase-ground, phase-phase or phase-neutral.

• Determine necessary \( U_c \) and rated voltage of the arrester taking into account possible harmonics, enhanced voltage at the capacitor as well as TOV.

• Consult ABB’s Buyers Guide for protective levels of arresters fulfilling requirements on \( U_c \) and rated voltage. If necessary reconsider desired capacitor maximum voltage and/or arrester positioning.

• If desired capacitor voltage still is not met, check what paralleling of arresters will result in i.e. check the protective levels for lower currents than 3 kA.

• Consult Figures 5, 6, 8, 9, 11 and 12 regarding energy demand. Adjust the choice of arrester type concerning energy due to capacitor discharges. For ABB high voltage arresters use 80% of the “single impulse energy” as the energy capability for capacitor discharges. If the energy is not met by catalogued arresters, consider using the arresters with parallel columns.

• For actual arrester protective level, recheck that the energy demand is fulfilled.

Conclusions

There are many well-justified reasons to install arresters to limit overvoltages at capacitor banks, and in general it is possible to obtain an efficient protection of even relatively large shunt capacitor banks with commonly-used arresters. Only at lower voltage levels, the need for multiple column arresters exists. This is because the energy demand is approximately a linear function of capacitor MVAr rating independent of system voltage.

It is important to consider the installation. Arresters across capacitor or between phases give a superior protection compared with arresters phase-ground.

In case of arresters between phases or phase-neutral, the insulation phase-ground may be protected by an extra
set of arresters or existing phase-ground arresters in the station if found necessary due to the exposure to lightning surges.

**Note!** The guidelines do not discuss resonances which can result in even higher duties than listed. On the other hand it is difficult in practice to foresee resonances and, if they do occur, an arrester failure may be acceptable instead of trying to design for every possible case. It must be noted that the main aim with provision of arresters, i.e. the protection of the capacitors, is still fulfilled even if the arrester fails.

### References
