# COMPARISON OF SHUNT COMPENSATION SYSTEMS IN MEDIUM VOLTAGE NETWORKS

## Abstract

An analysis of four shunt reactive power compensation configurations is presented. The performance of the banks is compared in terms of the level of absorption of load control signals, exposure to damage from background harmonic distortion levels, and sensitivity to switching transients. In each case component tolerances, fault and load levels are varied to determine performance under a wide range of network conditions.

It is concluded that inrush current limited banks with audio frequency blocking filters effectively avoid absorption of load control signals, but these systems are exposed to damage from harmonic distortion and switching transients in the network. Detuned capacitor banks are not exposed to harmonic resonance or network switching events, while optimum performance is obtained from detuned banks with blocking filters.

A brief description of the approach to design component ratings in detuned capacitor banks is presented.

## Introduction

Distribution network capacity is stretched to the limit in many electricity markets. Shunt reactive power compensation is installed at all levels of the networks to improve the voltage profile, free up generation and transmission capacity and reduce system losses.

The configuration and functionality of compensation systems are determined to a large extent by local preferences and requirements for flexibility, noise levels and availability. As a result design and implementation of systems vary widely internationally, or even within a single country.

Selecting the most suitable configuration for a given application can be challenging in the face of this variety. The physical conditions behind selection of a particular implementation in one network may not exist in another network, and the reasoning behind the selection will most likely be unknown to buyers.

The purpose of this paper is to investigate the performance of different power factor correction topologies in the context of a practical application.

It is vitally important that all systems connected to the network are capable of operating successfully regardless of network fault level, size of load and component drift within manufacturers' tolerance limits. Typical variations have been used in this paper to construct a number of operating scenarios to evaluate the performance of each configuration.

The performance of each configuration will be reviewed in terms of attenuation of audio frequency control signals, performance in avoiding amplification of harmonic distortion, and susceptibility to network switching transients.

Once a configuration is selected, it is necessary to determine the correct rating for the critical components.

A brief description of a suitable design approach is included to assist in the detailed specification of shunt reactive power plant.

## Configuration

The network used as the basis of analysis is shown below.

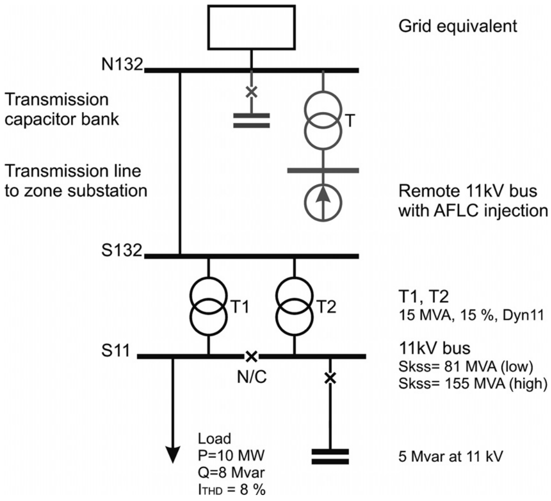


*Figure 1: Network section used in analysis*

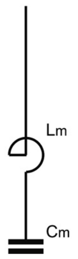
A Thevenin equivalent of the complete utility system feeds a zone substation via a short overhead transmission line. The zone substation contains a 132 kV busbar, two transformers, and a number of loads. These loads are lumped together in this analysis to form a single load of 12.8 MVA at a power factor of 0.78, connected to the 11 kV busbar of the zone substation. The transformers are intended for operation in N-1 redundancy, but it is possible for both transformers to feed the load via the normally closed bus coupler. Parallel operation of the transformers results in a significantly higher fault level at 11 kV (155 MVA) than with a single transformer in service (81 MVA.)

Audio frequency load control signals are injected upstream from the zone substation. The injection equipment is connected to a remote zone substation shown shaded in the figure above. The injection frequency has been taken as 1045 Hz.

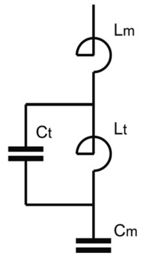
It has been decided for operational purposes to connect a shunt capacitor bank at the zone substation. This may consist of multiple steps, but for purposes of this analysis, the power factor correction system has been lumped into a single step of 5 Mvar at 11 kV.

Four configurations were considered for the application. The single line diagram below indicates the two different circuits for the four configurations.

Inrush limited and detuned bank configuration



Inrush limited and detuned banks with blocking circuit



The four configurations can be described as inrush current limited, inrush current limited with audio frequency blocking, detuned, and detuned with audio frequency blocking.

The table below indicates the nominal values of inductance and capacitance for an 11 kV, 5 Mvar step. The detuned banks include a 7 % reactor, and the audio injection frequency is 1045 Hz.

| | $L_m$ (mH) | $L_t$ (mH) | $C_m$ (µF) | $C_t$ (µF) |
|---|---|---|---|---|
| Inrush current limited | 0.15 | - | 131 | - |
| Inrush current limited with blocking circuit | 0.15 | 1 | 131 | 23 |
| Detuned | 5.8 | | 122.3 | |
| Detuned with blocking circuit | 5.22 | 0.58 | 122.3 | 39.6 |

Inrush current limited capacitor banks consist of a main capacitor circuit, with a small series reactor. The purpose of the reactor is to limit the current transient that occurs when the capacitor is energised, or when a capacitor bank close by is energised. The purpose is to restrict the peak current to within what switchgear and capacitor units can withstand. The reactors are generally small, in the order of 150µH.

A blocking circuit can be added to the inrush current limited bank, by inserting an additional series reactor, and placing a capacitor in parallel with this tuning reactor. The values of the tuning circuit are selected such that the bank has a high impedance at the injection frequency.

Detuned capacitor banks also consist of a capacitor bank and a series connected reactor. In this case, the reactor is chosen such that the combination of reactor and capacitor has low impedance at a frequency where no harmonic distortion is expected. This frequency is generally less than the fifth, and occasionally less than the third harmonic. To achieve this tuning frequency, the reactor has to be substantially larger than in the case of the inrush current limited bank.

A blocking circuit can be added in the same manner as before to detuned banks, to present high impedance at the audio injection frequency.

## Network variables

Three network parameters were varied for the purposes of this analysis - the fault level at the 11 kV busbar, the load and the actual value of components in the capacitor bank.

Parallel operation of the transformers results in a significantly higher fault level at 11 kV (155 MVA) than with a single transformer in service (81 MVA).

The load was changed between high (or full load) and low load, which was taken as 10 % of full load. Load level variation results in variation of the damping in the network.

Variation in component values resulted in the tuning frequency of any blocking circuit to be at minimum, nominal and maximum values. The minimum tuning frequency occurs at maximum component values.

IEC 60289 and AS1089 state the tolerance range for reactors in tuned circuits as -3 – +3 %. IEC 60871-1 requires capacitor banks between 3 and 30 Mvar to fall within 0 – +10%. This tolerance spread was used for inrush current limited banks as well as detuned banks.

The values of the main components of the bank - the capacitor banks and inrush or detuning reactor - were varied according to the same tolerance limits. The variations in component values, load and fault level result in twelve scenarios of unique network conditions.

## Audio frequency load control

Ripple control, or audio frequency load control, is commonly used to control single phase domestic loads, typically hot water systems. The carrier frequency for the control signal varies widely.

Power networks are designed for optimal performance at power frequency, and therefore attenuation of control signals is a concern in all applications. Since capacitor impedance is inversely proportional to frequency, capacitor banks tend to absorb much of these signals. Special capacitor bank design measures are generally required to avoid this, such as the blocking filters discussed above.

Component mismatch - due to deviations within the tolerance limits from nominal value and component drift - are serious concerns in the application of these filters. The following charts describe the impact of the above-mentioned tolerance spread, changes in fault level and variations in load level on the tuning frequency and impedance at the carrier frequency.

In the analysis carried out below a carrier signal at 1045 Hz is injected at a busbar remote from the 11 kV busbar where the power factor correction is applied. The current flowing into the source impedance sets up a voltage at the carrier frequency at all busbars in the network.

It is clear from the charts below that the tolerance variations permissible for capacitors and reactors result in wide variations in tuned frequency.

Most utilities specify tuning reactors with multiple tap positions so that the tuning frequency can be varied somewhat on blocking filters consisting of capacitors and reactors with the standard tolerance spread.

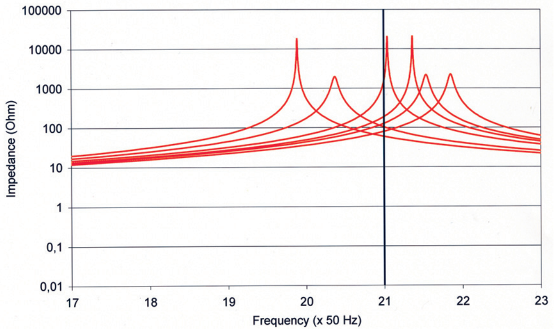


*Figure 2: Impedance vs frequency for inrush current limited bank with blocking filter*

It is clear from Figure 2 that good rejection of the carrier frequency (shown as the solid vertical line) will be achieved if all components are at nominal values. However, the impedance at the carrier frequency can vary by more than an order of magnitude.

Figure 3 shows that the situation is also potentially serious in the case of detuned banks with blocking filters.

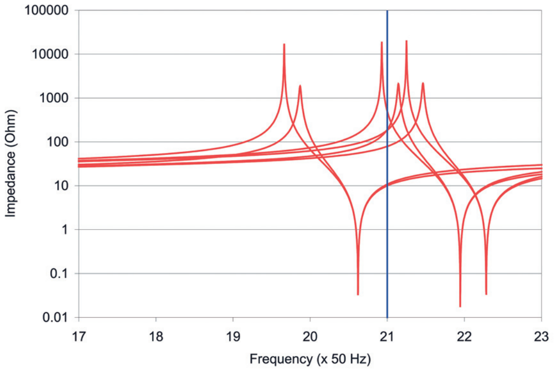


*Figure 3: Impedance vs frequency for detuned bank with blocking filter*

Multiple tap positions on reactors are costly, require additional maintenance, and unless the filters are carefully tuned, do not permanently solve the problem of increased attenuation when component values drift.

It is recommended that tuning components are matched during design and manufacture. If the above analysis is repeated with typical component variations instead of the tolerance range allowed for by the standards, the spread of tuning frequencies and impedance at the blocking frequency is greatly reduced, as shown in Figure 4.

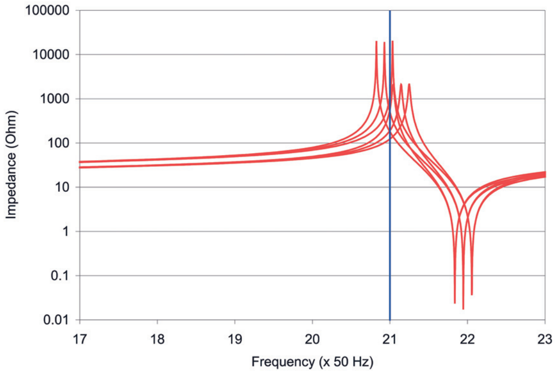


*Figure 4: Impedance vs frequency for detuned bank with blocking filter, matched components*

The table below indicates the level of carrier frequency signal that remains on the 11 kV busbar after the power factor correction is applied. A value of 80 %, for example, indicates that the signal strength when the particular configuration of power factor correction is applied is 80 % of what it would be without any power factor correction.

The minimum, average and maximum values obtained under all network conditions are presented for each bank configuration.

Values in italics indicate the outcome with typical manufacturing tolerances, i.e. when the capacitor and reactor components are manufactured to match the application.

*Table 1: Audio frequency signal remaining after connection of capacitor bank*

| | Min | Avg | Max |
|---|---|---|---|
| Inrush current limited | 1% | 2% | 3% |
| Inrush current limited with blocking | 90% | 101% | 117% |
| | 94% | 96% | 99% |
| Detuned | 73% | 77% | 81% |
| | 73% | 77% | 81% |
| Detuned with blocking circuit. | 48% | 81% | 100% |
| | 94% | 99% | 103% |

Most specifications require that signal levels must remain between 90 % and 130 % of the level without any PFC connected, under all network conditions. Inrush current limited banks alone absorb virtually all the control signal, while the same banks fitted with suitable blocking filters perform adequately, and are not very susceptible to changes in fault level and component tolerances.

Detuned banks with blocking filters perform very well provided that the components of the filter are matched during manufacturing, or adjusted to match during construction.

Detuned banks without any blocking filters tend to absorb more than the acceptable amount of control signal, but are the least influenced by network conditions, especially variations in component values.

## Exposure to harmonic distortion

The traces below indicate the impedance of the network in Figure 1, as seen from the 11 kV busbar. In each case, the effects of changes in load, fault level, and equipment tolerance are shown.

In the case of the inrush current limited banks, irrespective of the presence of blocking filters, the network presents high impedance close to 250 Hz.

When the network impedance is high at or close to a frequency at which non-linear loads, such as variable speed drives or arc furnaces inject current into the network, a high voltage appears across the network impedance.

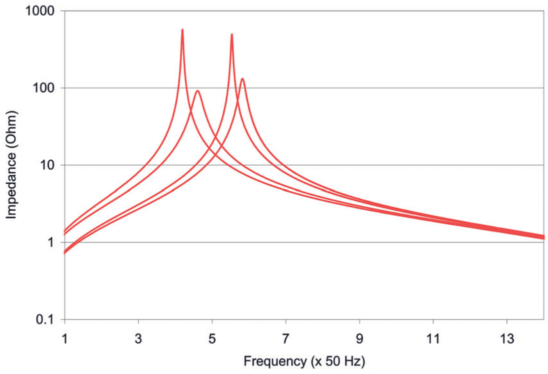


*Figure 5: Impedance of an inrush current limited bank*

When this occurs, a comparatively small non-linear load can cause high levels of voltage distortion. The phenomenon is referred to as amplification of voltage distortion due to parallel resonance.

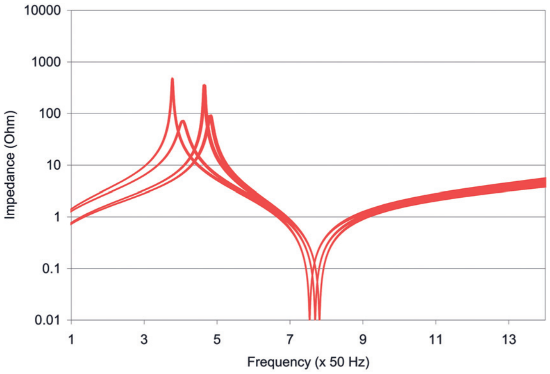


*Figure 6: Impedance of an inrush current limited bank with blocking filter*

The effect of a detuning reactor in the capacitor bank is shown clearly in the trace below. The characteristic is independent of the presence of a blocking circuit.

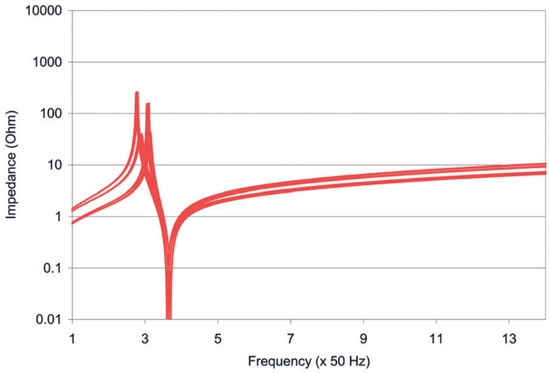


*Figure 7: Impedance of a detuned bank*

The network has low impedance at the tuned frequency. This frequency is selected to be below the fifth harmonic, and is entirely a function of the components of the capacitor bank. The capacitor bank is inductive at frequencies above the tuned frequency, and therefore resonance is impossible.

The table below presents a summary of the outcomes under all network and load conditions, for each of the configurations.

A nonlinear load with a total current harmonic distortion of 8 % was used in this analysis, to indicate an industrial load with a low level of harmonic distortion.

The voltage harmonic distortion at the 11 kV busbar is just below the IEC 61000-3-6 compatibility limit of 8 % without PFC connected. This occurs when the fault level is low and the full load is connected.

*Table 2: Harmonic distortion at 11 kV busbar*

| | Min | Avg | Max |
|---|---|---|---|
| No PFC connected | 0.4% | 3.1% | 7.8% |
| Inrush current limited | 1.1% | 8.2% | 16.8% |
| Inrush current limited with blocking | 0.4% | 4.8% | 14.0% |
| Detuned | 0.2% | 1.3% | 2.9% |
| Detuned with blocking circuit | 0.2% | 1.4% | 3.2% |

The voltage harmonic spectra for the maximum distortion level in each configuration are presented in Figure 8.

It is very clear from this graph that detuned banks provide protection against harmonic amplification, with harmonic levels somewhat reduced compared with distortion without any power factor correction connected.

Inrush current limited banks do not provide any protection against harmonic resonance. The predicted distortion levels, even with low level load current distortion, far exceed compatibility levels according to IEC 61000.

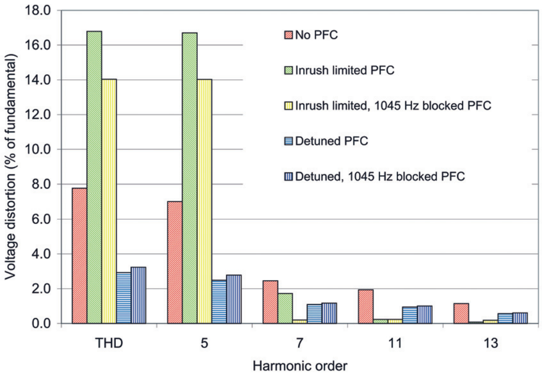


*Figure 8: Maximum voltage distortion*

Apart from non-compliance to statutory requirements, such high levels of harmonic distortion could result in premature failure of capacitors, reactors, switchgear and electronic systems.

The chart below indicates the harmonic spectrum of the current into the capacitor bank. The inrush current limited banks have very high levels of fifth harmonic distortion, exceed the 84 % distortion limit imposed by the requirement for reactors to be rated to 1.43 x $I_{nom}$, with an overload factor of 10 % for fundamental frequency over current, and 30 % in total for harmonic current.

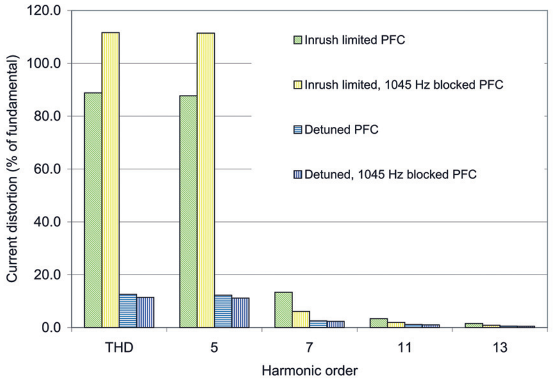


*Figure 9: Capacitor bank current distortion*

## Switching transients

Voltage transients may arise from any number of events in the network, and propagate through the network. One such event is the energisation of a capacitor bank. In this analysis, a large capacitor bank is energised at the 132 kV busbar N132, shown shaded in Figure 1.

Two alternatives have been reviewed in this analysis: where the inrush current into the bank is restricted by means of inrush current limiting reactors, and where the bank is supplied with a detuning reactor.

The voltage transient at the 132 kV bus is shown below.

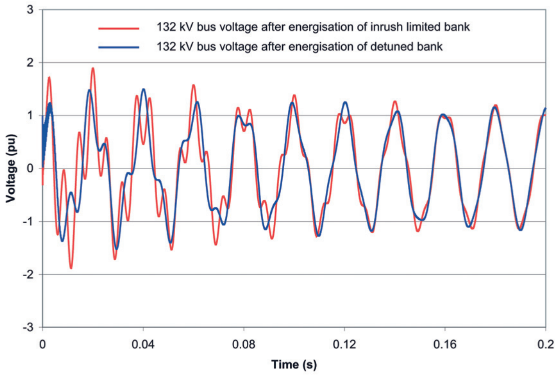


*Figure 10: 132 kV bus transients due to transmission capacitor bank energisation*

Figure 10 illustrates that the voltage transient propagating through the network is significantly more severe - higher frequency and peak values - when inrush current limiting reactors are used.

The chart below indicates the voltage transient at the 11 kV busbar when the inrush current limited bank is connected. The transient event at this busbar without any capacitor banks at 11 kV is shown as a reference.

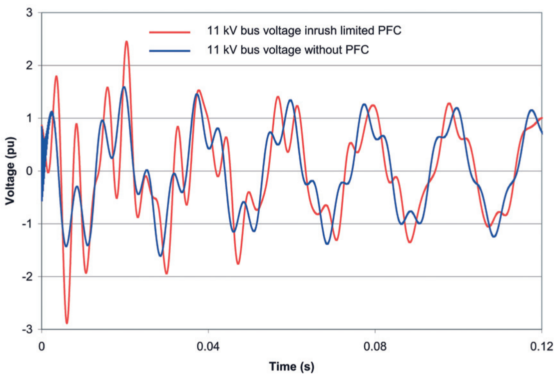


*Figure 11: Voltage transient at 11 kV bus with inrush current limited bank connected*

The peak transient value is significantly amplified when the inrush current limited 11 kV capacitor bank is already connected - to a peak value of close to 3 p.u.

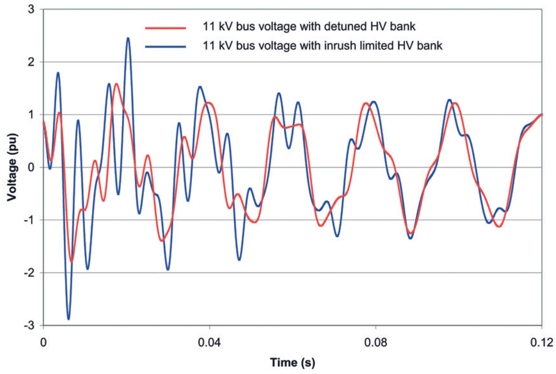


*Figure 12: Effect of detuned transmission bank on inrush current limited capacitor bank.*

The outcome with the same configuration at the 11 kV bus, but with a detuning reactor used in the 132 kV bank is shown in Figure 12. The transient with the 132 kV bank fitted with inrush current limiting reactors only is shown as a reference.

The peak voltage transient at the 11 kV busbar is significantly reduced by the use of detuning reactors at 132 kV.

Figure 13 demonstrates that transient amplification also takes place in capacitor banks with blocking filters, in this case due to a switching operation of a 132 kV bank with inrush current limiting reactors.

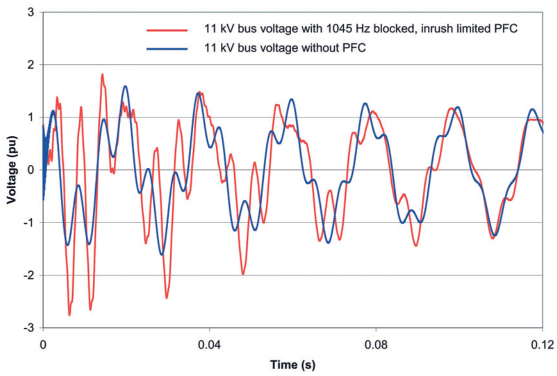


*Figure 13: Voltage transient at 11 kV bus with inrush current limited and blocking bank connected*

This transient amplification can be largely avoided by making use of detuned banks at 11 kV, independent of whether a blocking filter is required.

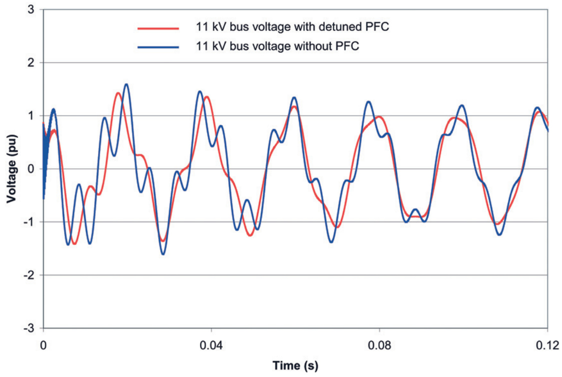


*Figure 14: Voltage transient at 11 kV bus with detuned bank connected*

The traces in Figure 14 compare the voltage transient at the 11 kV busbar when a 132 kV bank is energised, and a detuned bank is connected to the 11 kV with the transient when there is no 11 kV bank connected.

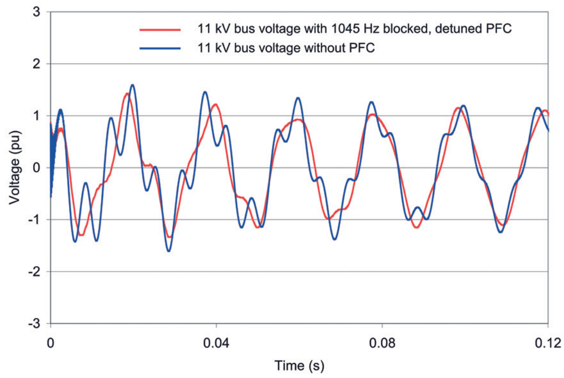


*Figure 15: Voltage transient at 11 kV bus with detuned, blocking bank connected*

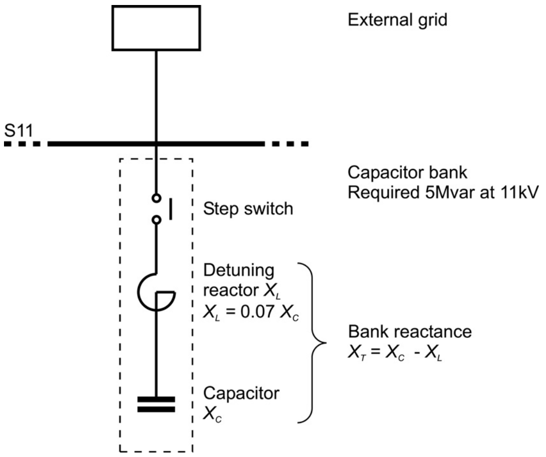
The situation is not altered to any significant extent by the presence of a blocking filter in the detuned bank, as shown in Figure 15. The detuned bank has a small damping effect on the voltage transient, and no amplification takes place.

## Recommended ratings

A detuned filter arrangement is selected to simplify the bank design and to avoid the problems of resonance and exposure to switching transients. The design approach assumes that network conditions with the bank connected are known, or that values published as worst case figures in network distribution codes are to be used.

The nominal output   of the capacitor bank is 5 Mvar at nominal voltage $V_N$ of 11 kV. The reactor rating is 7 % of the capacitor. The busbar voltage can be expected to operate at 10 % above nominal voltage for substantial periods, including the voltage rise as a result of the capacitor bank.

It is assumed that the voltage total harmonic distortion $V_{TDH} = 5\%$. It is assumed that this arises from 5th and 7th harmonic voltages only where $V_{N,5} = 4\%$ and $V_{N,7} = 3\%$, in percentage of the fundamental frequency nominal voltage.



The total bank reactance can be calculated from the nominal reactive power requirement of the bank at nominal voltage, $X_T = V_N^2/Q_N$ .This value and the relationships indicated in the figure above result in values of capacitance 122.3 µF and inductance of 5.8 mH.

The combination of inductor and capacitor is capacitive at frequencies less than the tuning frequency of 189 Hz, and inductive at frequencies greater than 189 Hz. Resonance between the capacitor bank and the network impedance is therefore impossible above this tuning frequency.

AS 2897 and IEC 60871-1 require that the voltage rating of the capacitor be determined as the arithmetic sum of fundamental and harmonic voltages.

The fundamental frequency voltage across the bank is determined by considering the current $I_N$ flowing through the bank at 50 Hz, and then using the capacitor reactance $X_{C,50}$ at 50 Hz to determine the voltage across the capacitor, $V_{C,1} = I_1 \times X_{C,1}$, where $I_1 = V_{N,1} \times 1.1/X_{T,1}$ .

The current at each harmonic is determined in a similar fashion: $I_n = V_{N,n}/X_{T,n}$ and $V_{C,n} = I_n \times X_{C,n}$.

| $n$ | $V_{N,n}$ (V) | $X_{T,n}$ (Ω) | $I_n$ (A) | $V_{C,n}$ (V) |
|---|---|---|---|---|
| 1 | 12100 | 24 | 287 | 7512 |
| 5 | 440 | 4 | 65 | 339 |
| 7 | 330 | 9 | 21 | 78 |

These results lead directly to the required voltage rating of the capacitors and the current rating of the reactor:

$$V_{C,rating} = \sum_{n=1}^{\infty} V_{C,n} \quad \text{and} \quad I_{L,rating} = \sqrt{\sum_{n=1}^{\infty} I_n^2}$$

$$= 13.7 \text{ kV} \qquad = 297 \text{ A}$$

The rated output of the capacitor at rated voltage is 7.25 Mvar.

## Conclusion

The table below presents a summary of the outcomes obtained above.

*Table 3: Overall outcome for configurations*

| | Absorption of signal | Sensitivity to harmonic distortion | Sensitivity to upstream transients |
|---|---|---|---|
| Inrush current limited | 👎 | 👎 | 👎 |
| Inrush current limited with blocking | 👍 | 👎 | 👎 |
| Detuned | – | 👍 | 👍 |
| Detuned with blocking circuit. | 👍 | 👍 | 👍 |

Capacitor banks with inrush limiting reactors are not suitable for applications where audio frequency control signals are present, where any level of harmonic distortion may be present, or where switching transients may occur.

The addition of a blocking circuit ensures that audio frequency signals are not attenuated, but harmonic resonance remains likely and amplification of transients in the network may still occur.

Detuned banks do absorb audio frequency signals to a certain extent, but are not susceptible to harmonic resonance and switching transients. Improved performance of detuned banks can be obtained where required by the addition of a blocking circuit, especially when matched components are used.