Capacitor switching comparison: the supremacy of diode technology

Capacitor switching transients

Shunt capacitor banks are required at a distribution level to guarantee power quality, in terms of voltage stability and network efficiency. Utilities normally need capacitors to be able to provide electrical power to their customers through a stable network, while industries need capacitors to increase the efficiency of their electric machines and to have an adequate power factor, thus avoiding penalties imposed by utilities.
However, switching capacitor banks is a delicate operation due to the nature of such particular network components. In fact, the basic characteristic of capacitors is that the voltage cannot change instantaneously; in other words, closing on a capacitor bank is almost like closing on a short-circuit initially. Therefore, when a capacitor is connected to the power network, the network voltage will be pulled down to nearly zero for a certain time interval. A high current peak, namely an inrush current, will then occur while the capacitor is charging. At the same time, the capacitor voltage will start to recover and overshoot the network voltage. The capacitor voltage will then tend to oscillate around the fundamental wave until it stabilizes with it after about one cycle. Such oscillations normally cause multi-zero crossing of the network voltage.
In the case in which a second capacitor bank is connected in parallel to the one already connected, namely back-to-back switching, the charged bank dumps a high frequency current peak into the uncharged bank. The inrush current resulting from a back-to-back closing is much higher in magnitude and frequency compared to single-bank closing.
In addition to such transients phenomena, switching capacitor banks with a vacuum technology presents the additional issues deriving from the nature of such technology. In fact, during a closing operation, an energy discharge may occur before the vacuum interrupter contacts are completely closed, namely a prestrike, resulting in system pre-ignition, higher inrush current and eventually vacuum contact welding which jeopardizes the next opening operation of the vacuum switch.

As far as the opening operation is concerned, vacuum technology suffers the risk of possible energy discharge after separation of the contacts, namely a restrike, which results in overvoltage and capacitor overcharge.
All these capacitor switching transients, voltage dips, voltage overshoots, high frequency inrush currents, prestrikes and restrikes undermine network stability as well as network reliability due to electrical equipment malfunctioning both for utilities and industries. Furthermore, capacitor switching transients affect the life of the capacitor itself and can cause sudden fatal damage.

Technology comparison

As mentioned above, capacitor switching transients are basically given by short circuit inductance (*L*) and the capacitance (*C*) of the bank which form an LC circuit. In particular, the inrush current peak (I_{peak}) is given by:

$$I_{peak} = U\sqrt{\frac{C}{L}}$$

Where *U* is the difference between network voltage and capacitor voltage. Considering that capacitor banks are almost always allowed to discharge once disconnected, capacitor voltage is assumed to be zero. Assuming then that *C* and *L* are constant, the magnitude of the inrush current peak depends on the network voltage at the time of connection. The worst case is when closing occurs at a network voltage peak.
In order to mitigate capacitor switching transients and therefore their effects on power quality, several methods for controlling the parameters of the equation presented exist, namely:
- Increasing the inductance of the circuit: inrush reactors or detuning reactors (the latter are usually used to avoid harmonic resonance).
- Decreasing the voltage difference at energization by inserting a resistor in series: pre-insertion resistor technology.
- Minimizing the network voltage at energization: synchronized switching (zero voltage crossing closing).

In order to assess the effectiveness of the switching technology of the methods listed, a single-phase model was built in PSCAD to simulate single-banks and back-to-back capacitor switching transients. The model is essentially composed of two 2.5 MVAR capacitors in parallel at 6.9 kVrms and 60 Hz, each of them operated by one switch (BRK1 and BRK2).

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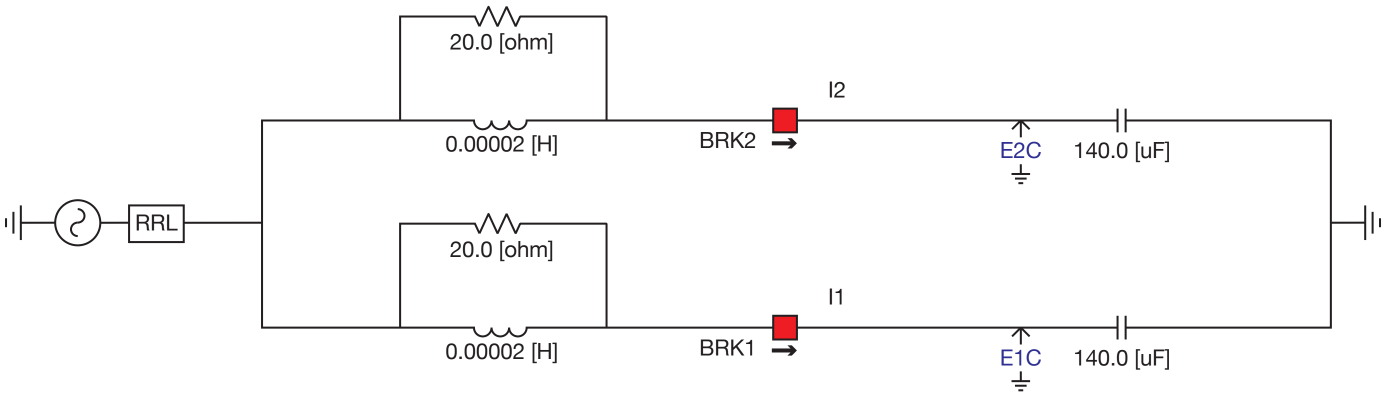
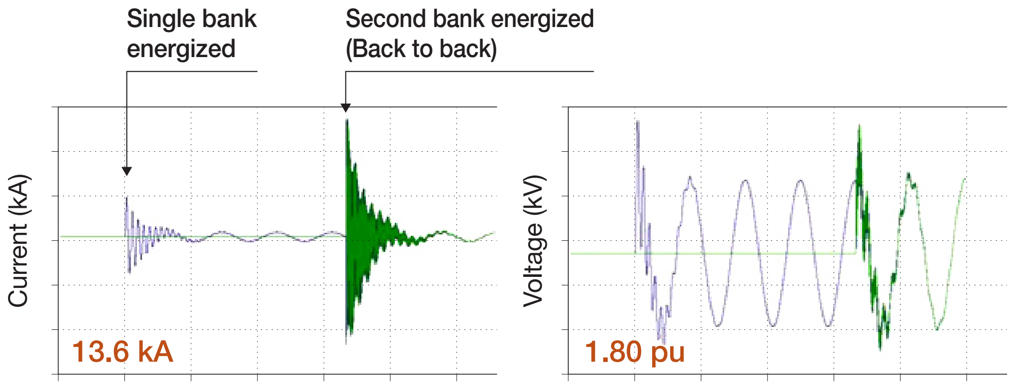


Figure 1 – PSCAD single-phase model.

The simulated switching technologies are:
A. Standard switching without damping
B. Standard switching with detuning reactors
C. Pre-insertion resistor
D. Synchronized vacuum
E. Diodes

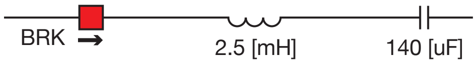
Configuration A: no damping

The transients described are clearly visible in the simulation graphs. In particular, the inrush current peak reaches its maximum at 13.6 kA when the second bank is energized, while the voltage overshoot reaches its maximum at 1.80 pu (per unit) when the first bank is energized.

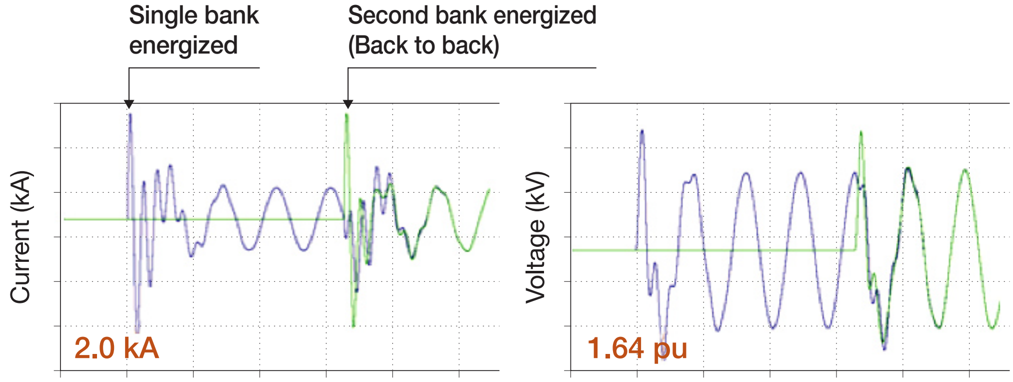


Configuration B: detuned reactors

To reduce the inrush peak and avoid resonance a reactor is connected in series with the capacitor to increase circuit inductance. This modifies the resonance frequency of the circuit and usually the reactors inductance is chosen to avoid 3rd and 5th harmonics. In this case, a 2.5 mH inductance is put in series on each capacitor.

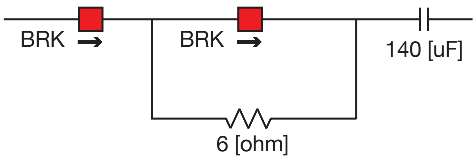


In this configuration the transient effects of the closing operations are reduced, both for the inrush current (2 kA peak) and the voltage overvoltage (1.64 pu).

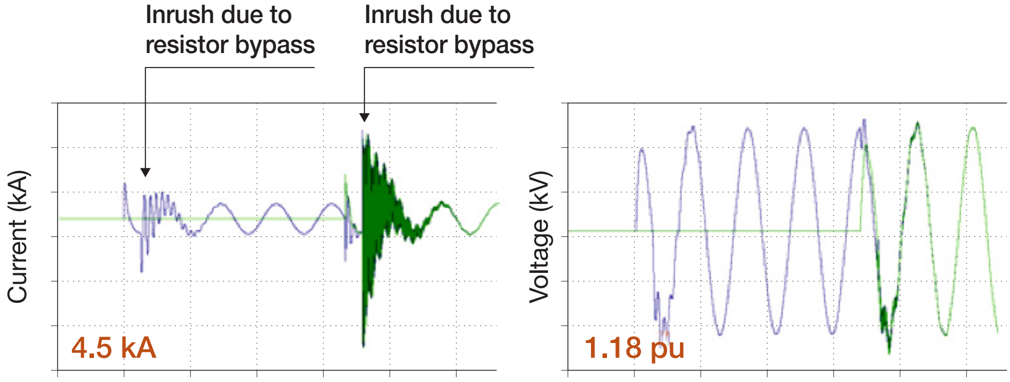


Configuration C: pre-insertion resistor

As described above , a resistor is inserted at energization to limit the inrush current, in this case a 6 Ohm resistor, and then bypassed (green BRK) to avoid power losses and overheating.



With the pre-insertion resistor technology the inrush at energization is greatly reduced; nevertheless, the bypass of the resistor causes a high inrush peak, especially when the second bank is energized (4.5 kA).
On the other hand, good results can be achieved on the voltage side with a peak of 1.18 pu.



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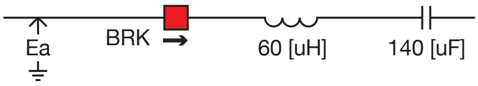
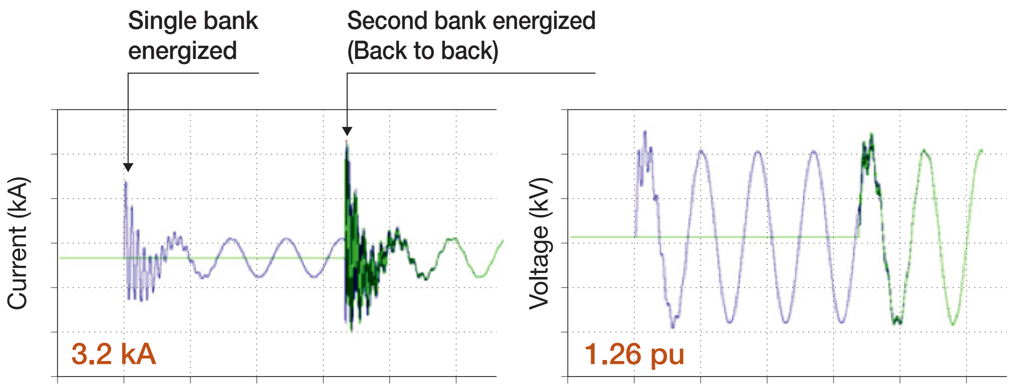
Configuration D: synchronized vacuum

In this configuration the vacuum switch is fitted with a synchronization relay able to measure the network voltage and to trigger contacts closing to achieve complete closing at zero voltage. However, the contacts should not move overly before the voltage zero crossing since this would cause a prestrike compromising the vacuum contacts. A certain delay is therefore required which usually is about 1 ms. In this case of a 6.9 kVrms and 60 Hz system, the voltage difference at 1 ms after the zero crossing is about 3.6 kV, which would then cause an inrush peak. In order to mitigate it, a 60 μH inductance is added to the circuit.

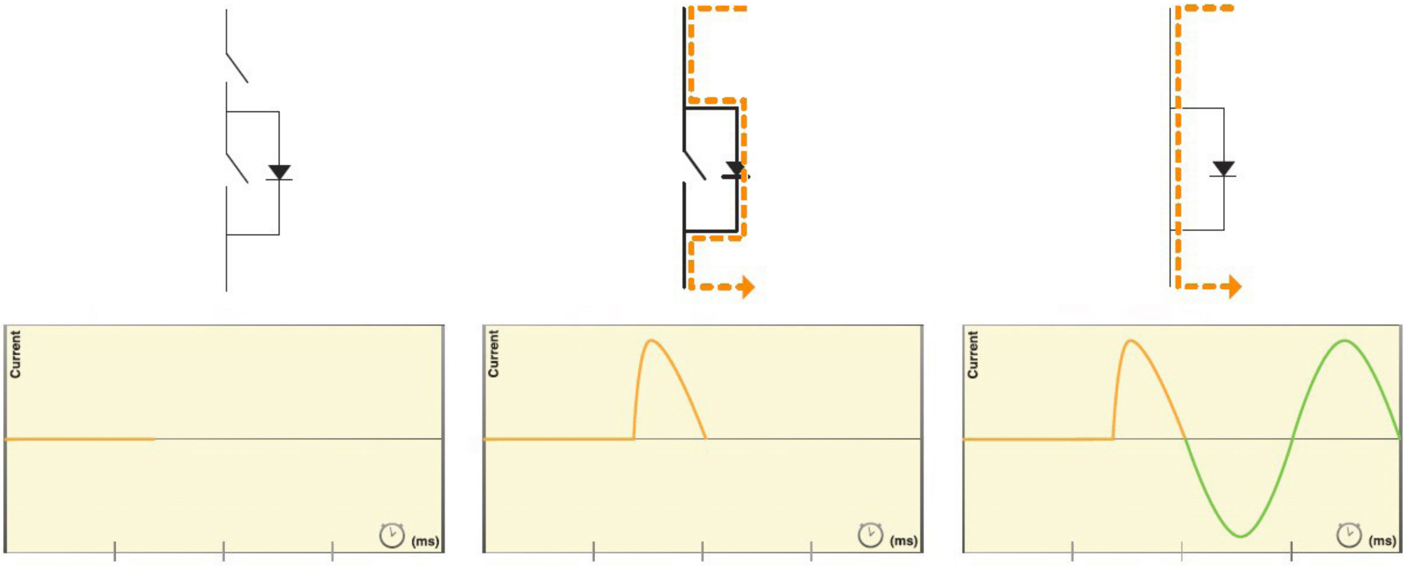


The synchronized vacuum mitigates the inrush current peak (3.2 kA) slightly more than the pre-insertion resistor technology, while the overvoltage is higher (1.26 pu).

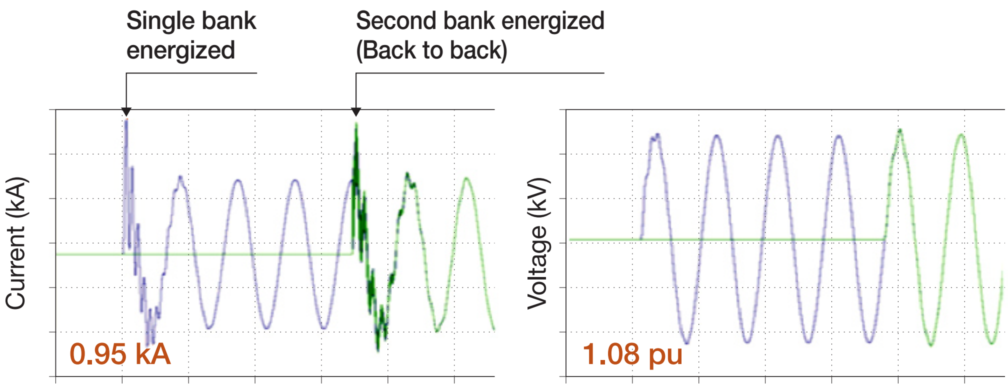


Configuration E: diodes

Diode technology uses power diodes to naturally energize the capacitor banks with the network voltage, starting exactly from the zero crossing thanks to network voltage synchronization. The diodes are then bypassed after a quarter of cycle, namely at zero current crossing, to avoid power losses and overheating.



The diode-based switch is able to drastically reduce the switching transients, limiting the inrush current peak to less than 1 kA and the overvoltage to less than 10%.



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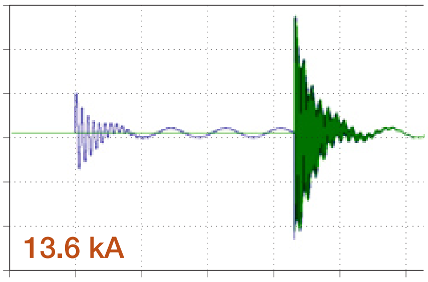
Conclusions

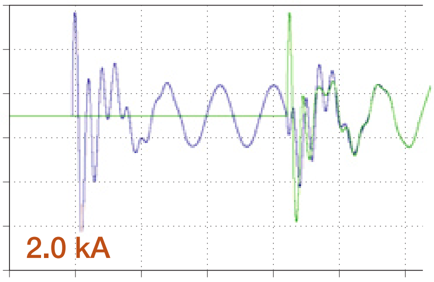
A comparison of capacitor switching technologies was performed by means of simulations of a single-phase model. Single step and back-to-back closing operations were simulated for each technology. The results are summarized below.

Inrush current

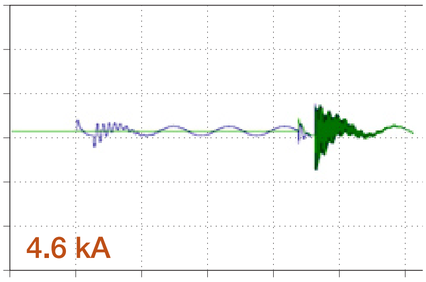
A) No damping



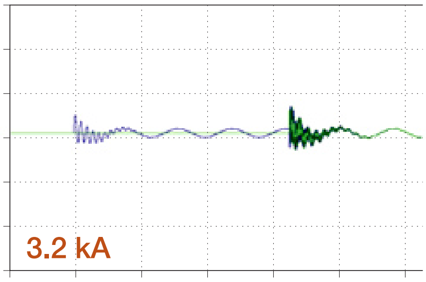
B) Detuning reactors



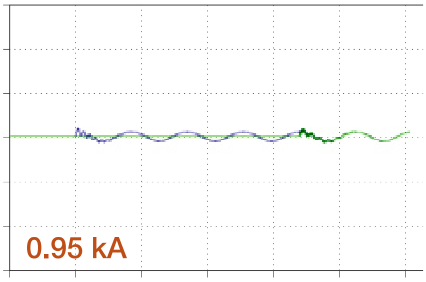
C) Pre-insertion resistor



D) Synchronized vacuum

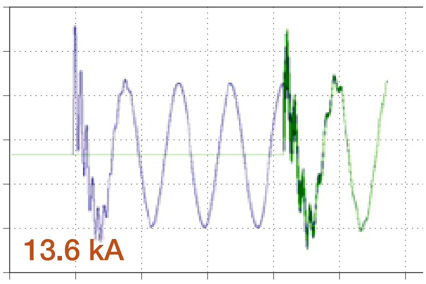


E) Diodes

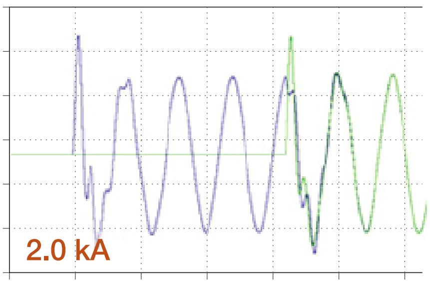


Overvoltage

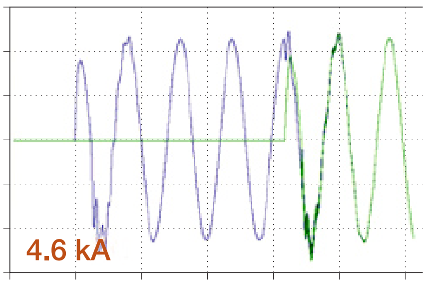
A) No damping



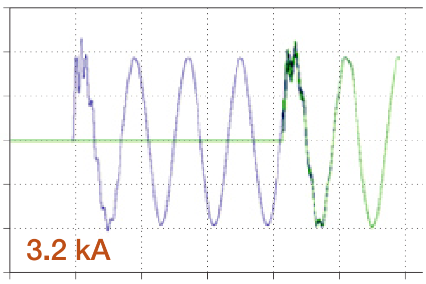
B) Detuning reactors



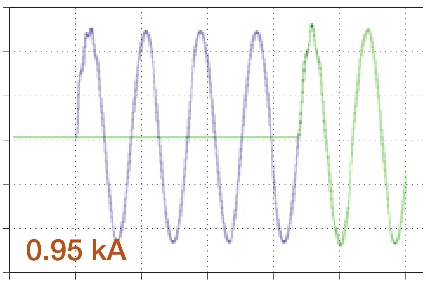
C) Pre-insertion resistor



D) Synchronized vacuum



E) Diodes



Configuration	Added inductance	Max Inrush current peak [kA]	Max Overvoltage peak [pu]
No damping	–	13.60	1.80
Detuning reactors	2.5 mH	2.00	1.64
Pre-insertion resistor	–	4.50	1.18
Synchronized vacuum	60 µH	3.20	1.26
Diodes	–	0.95	1.08

Despite the quite low rated voltage (6.9 kV rms) and capacitor power (2.5 MVAR), switching capacitor banks with standard technologies and without any damping results in high inrush current and overvoltage, which are likely to cause network instability.

For this reason, a common solution is to add detuning reactors between the switch and the capacitors. This solution gives much better results in terms of inrush current, while the overvoltage is still critical for network stability. Detuning reactors also occupy space and are the cause of high power losses.
Considering the transient-mitigating solutions, the pre-insertion resistor technology provides good results in terms of overvoltage, but the inrush current is even higher than that resulting from the solution with detuning reactors. This is mainly due to the required bypass of the resistor to avoid power losses and overheating. Consequently, network stability is improved compared to other solutions but the stress on the switch and on the capacitor is still high.
The synchronized vacuum technology is able to decrease the inrush current slightly compared to the pre-insertion resistor, but is in any case critical due to the issue of contacts welding. The overvoltage level is again quite high.
Diode technology provides the best results both in terms of inrush current and overvoltage, and is consequently the best solution for switching capacitor banks. In fact, thanks to its ability to perform switching smoothly, diode technology is able to protect both network stability and capacitor life.

It is important to note that in case of larger capacitor banks or higher network voltage, the transients phenomena are usually greater and thus cause more critical issues to both utilities and industries. However, the switching capacity of diode technology is not affected by capacitor power and network voltage. Hence, the benefits of diode technology are greater with bigger capacitors and higher voltage levels.

Please see the DS1 diode-based transient-free capacitor switch webpage to find out more about ABB’s application of diode technology!

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