A DIODE BASED CAPACITOR SWITCH - A NOVEL SOLUTION FOR POWER QUALITY IMPROVEMENT

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ABSTRACT

Capacitor bank switching is required when providing compensating reactive power for power systems. However, high inrush currents and voltage transients from capacitor bank switching not only affect the performance of the capacitor banks themselves and their switching devices, they can also cause nuisance tripping of nearby electrical equipment such as drives and other sensitive loads. This paper describes how a novel solution using diodes for capacitor switching reduces these negative effects and enables a more optimized power factor correction of the electrical distribution system.

INTRODUCTION

In the CIRED session 2007 [1] a new capacitor switch concept was introduced that offered a major step forward in capacitor switching technology. The concept takes advantage of the known fact that diodes change their conducting state at sinusoidal voltage zero crossing points and combines it with a fast operating mechanical switch to create a new diode capacitor switch device. The diodes are used for the actual closing and opening operations, whereas the fast mechanical switch carries the rated current in the closed state and provides an isolating gap in the open state. This gives a perfect switching performance from the semiconductors, eliminating their drawbacks relating to power losses and limited impulse voltage withstand strength. As a result, a very smooth switching event, free of pre-strikes, re-ignitions or re-strikes, is achieved reducing electrical stresses on the capacitor bank and other nearby equipment and loads.
The energizing of the capacitor bank occurs with almost no inrush current irrespective of the charging state of the bank. Furthermore, tests have shown that the inrush current does not exceed twice the nominal current on single-bank or back-to-back capacitor bank switching operations.
As a next step in the development of this novel solution and to gain more field experience, a pilot has been installed. This paper describes the functionality of the switch and presents new experimental results including various laboratory tests and the performance data collected from the pilot installation. The paper closes with a comparison of capacitor bank switching performance using different technologies and emphasizing the advantages of the capacitor switch against other available equipment on the market.

DIODE CAPACITOR SWITCH

A detailed description of the medium voltage diode capacitor switch is made in [1]. Basically, each phase of the switch consists of three contacts and two anti-parallel diode stacks, one for opening and one for closing, see figure 1.
During an opening sequence contact 3 is opened first to commutate current to the opening diode. When the diode interrupts the current at the next current zero, contact 2 is opened to finalize the open operation. The diodes are at that point disconnected from the circuit and do not need to be rated for the impulse voltage stresses.
A closing sequence starts with all contacts open. First contact 3 is closed. Then contact 2 is closed at a time when the closing diode is in blocking mode. When the voltage difference between the source and load becomes zero the closing diode starts to conduct with minimal inrush current and during the diode conduction phase, contact 1 closes. With all contacts closed, the diodes are by-passed for the entire duration that the switch stays in the closed position.

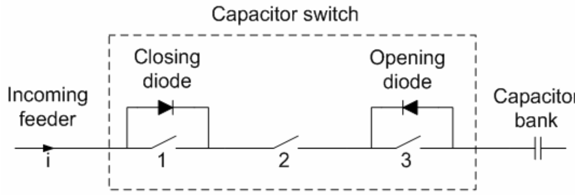

Figure 1. Medium voltage diode capacitor switch.

To achieve this sequence a synchronizing relay is used to send a start command to the operating mechanism at the correct phase angle of the source voltage. The diodes are not sensitive to scatter in synchronizing error and ensure that energization is always made at voltage zero.
The switch has one single operating mechanism with the three phases mechanically connected together with a common shaft and a built-in mechanical offset between the phases. The shaft is operated by a digitally controlled servomotor operating mechanism, MotorDrive™ [2]. The operating mechanism consists of a converter that provides current to a permanent magnet servo motor. A resolver

attached to the motor, which provides feedback to a closed loop controller, maintains a pre-determined trajectory for each close or open operation. The energy needed for an operation is provided by electrolytic capacitors.

EXPERIMENTAL RESULTS

A number of laboratory tests have been performed in order to verify the diode capacitor switch performance. In the ABB high power laboratory in Ratingen, Germany, single bank and back to back tests have been performed at 12 kV system voltage at 50 Hz frequency with a capacitive current of 420 Arms. A short circuit generator provided the current during the test and a total of about 80 close / open operations have been performed in loose accordance with IEC 62271-100 clause 6.111.

Figure 2 shows an example when the switch energizes the capacitor bank with another identical capacitor bank already energized on the same bus. The inrush current is < 900 A, thanks to the optimal closing at voltage zero.

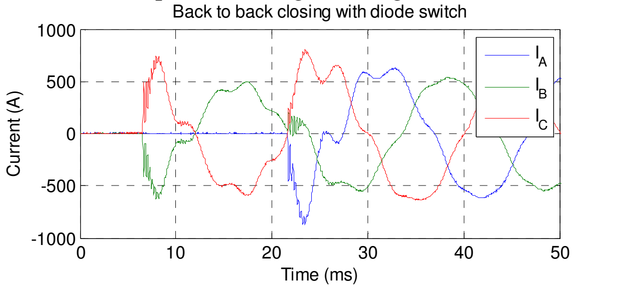

Figure 2. Back to back, three phase closing at ABB, 50 Hz.

This inrush current can be compared with a back to back energization of the same capacitor bank, using a non-synchronized standard vacuum circuit breaker, see figure 3. In this case the inrush current reaches 17 000 A or almost 20 times higher than the diode capacitor switch inrush current during back to back switching.

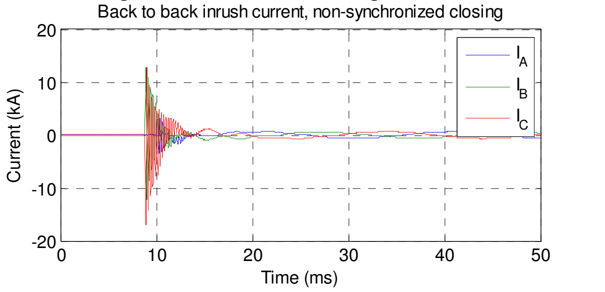

Figure 3. Back to back non-synch closing at ABB, 50 Hz.

In order to also test the 60 Hz capability of the switch at 15.5 kV system voltage, tests have been performed at the Powertech high power laboratory in Vancouver, Canada. Powertech uses direct testing from the transmission system and 400 close / open operations with single bank configuration have been performed with a capacitive current of 404 Arms. The inrush current at closing is < 1000 A, see figure 4.

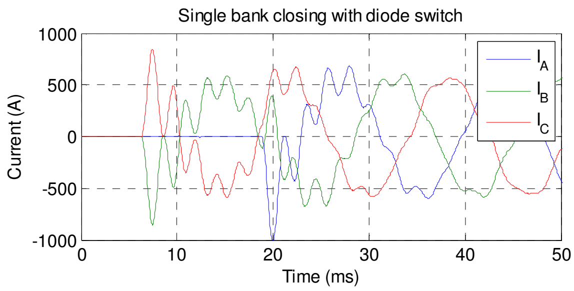

Figure 4. Single bank closing at Powertech, 60 Hz.

Almost 500 operations performed during the high power tests have shown that the switch is able to perform both single bank and back to back switching at 50 and 60 Hz up to 15.5 kV system voltage with very low inrush currents without any inrush limiting reactors included in the circuits.

PILOT INSTALLATION

In order to gain real life experience, a diode capacitor switch has been installed in a 13.8 kV / 60 Hz urban power system in New York, USA. The switch was installed in a completely new substation capable of providing 170 MW of electricity for midtown Manhattan. The substation is part of ConEdison's electric power system, which supplies more than 3 million customers through the world's largest underground cable system in the New York metropolitan area.

The substation has six capacitor banks, 10 Mvar each, connected back to back. The capacitor banks, ungrounded double wye, are normally equipped with inrush limiting reactors, 60 μH / phase, and operated by synchronized vacuum switches with individual pole operating mechanisms. One of these capacitor banks has been equipped with the diode capacitor switch instead. Each capacitor bank, see figure 5 (left), consists of (from right) incoming cable compartment, control cubicle, switch compartment and capacitor compartment - all in a metal enclosed encapsulation.

An instrumentation system was installed to monitor and evaluate the performance of the switch. The phase currents are measured with Rogowski coil sensors. Voltages upstream and downstream of the switch are measured with resistive voltage dividers. That gives a total of nine channels using 10 kHz sampling frequency on each channel. Every operation was captured with a data acquisition board connected to a laptop. The MotorDrive™ operating mechanism was also monitored and travel curves, phase currents to the servo motor and voltage at the converter's DC-link logged. Another feature within the operating mechanism is its capability to carry out a self-diagnostic test of the entire mechanism by making a micro-motion. A micro-motion is a small rotation (a few degrees) of the switch shaft, while the switch is still in service in either opened or closed position. The self diagnostic feature checks the integrity and the condition of the converter, resolver and capacitor energy storage. In the pilot

installation this is performed once a day.
Figure 5 (right) shows the installed pilot switch in the switch compartment. Inrush limiting reactors can be seen under the roof. They are needed for standard installations when synchronized vacuum switches are used and for reasons of simplicity they have been kept in this installation. Rogowski coils for current measurements are installed at the incoming busbar (top right). Resistive voltage sensors are located on both sides of the switch. The black boxes standing on post insulators contain the diodes. The local control panel and synchronizing relay are located below the switch.

Figure 5. 10 Mvar capacitor bank and detailed view of switch.

The pilot installation has been in service for more than six months and during that period 87 close / open operations have been made. Usually, the capacitor bank is energized on weekdays during early morning hours and de-energized in the evening in order to follow the reactive power demand of the system. Peak loads occur during the summer due to the high air conditioning loads. During hot periods there are some cases where the capacitor bank could therefore be energized for weeks. On the other hand, if there is a requirement for faster load response, it would be possible to divide capacitor banks into smaller units and switch them more frequently since the electrical and mechanical endurance of the switch can reach 100 000 operations.
To check the accuracy of the operating mechanism, the contact separation time was measured. Contact separation of one of the contacts is made at 29.0 degrees rotation of the shaft connected to the servo motor. The contact separation time has been measured for each operation and figure 6 shows how the contact separation time varied for the first 87 open operations. The opening time ranges from 20.03 to 20.25 ms giving a 220 µs spread.

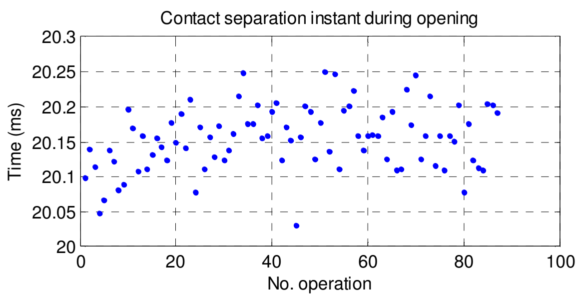

Figure 6. Contact separation time at 29.0 degrees rotation.

The load current of a 10 Mvar capacitor bank at 13.8 kV is 418 Arms. During energization the inrush current is below 1000 A, irrespective of the bank being energized as the first bank or switched in a back to back configuration. This can be compared with a theoretical worst case scenario with a non synchronized switch, where the inrush current can easily reach 20 000 A. Figure 7 shows an example for a bank energized with the diode capacitor switch with other banks already in service.

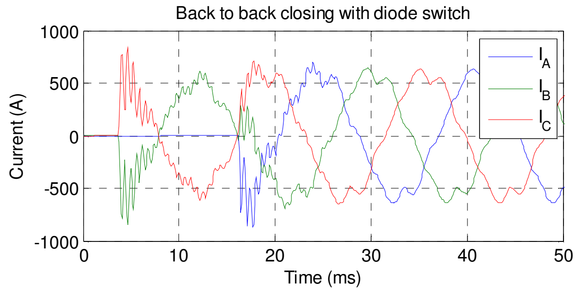

Figure 7. Back to back, three phase closing in pilot installation.

Another effect of the reduced inrush current is of course the reduced voltage transients during the closing event. Figures 8 and 9 show the busbar voltage during closing with the diode switch and during closing with a synchronized vacuum switch that is not perfectly synchronized at voltage zero. As the contacts start to close, the voltage is still sufficiently high to cause pre-arcing across the vacuum contacts. Both measurements are made in the same substation on two identical capacitor banks. For clarity, the black dots in figure 8 indicate the closing instant for the different phases since voltage transients can hardly be detected with the diode switch. Voltage transients are easily seen for the closing with the vacuum switch.

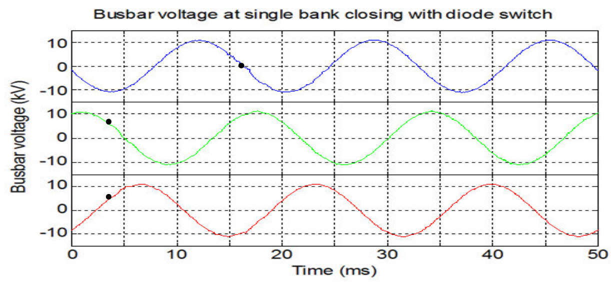

Figure 8. Very small voltage disturbance at the busbar during closing with diode switch.

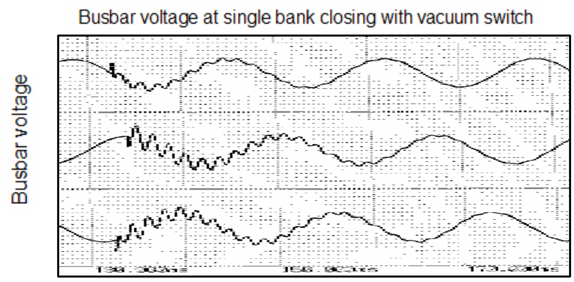

Figure 9. Significant voltage disturbance during closing with synchronized vacuum switch due to pre-arcing.

TECHNOLOGY COMPARISON

A simple one phase circuit with two back to back capacitor banks has been modeled to simulate the effect of using different technologies to reduce inrush currents during capacitor bank closing. The network is simulated in PSCAD with a phase to ground voltage of 6.9 kV. The prospective short circuit current is 35 kA with a DC decay time constant of 45 ms. To provide high frequency damping, 20 ohms are connected across the source impedance and stray inductances, see figure 10. Stray inductance in each phase is 20 μH.

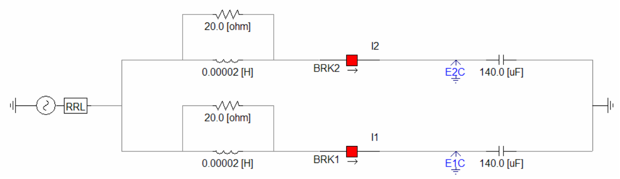

Figure 10. Basic simulation model.

The system is set so that the first capacitor bank is closed at 0.1 s and the second bank is closed at 0.1667 s. The simulation results for the non-damped circuit show that for the worst case (closing at peak voltage) the over voltage at the capacitor becomes 1.80 pu and peak inrush current is 13.6 kA, see figure 11.

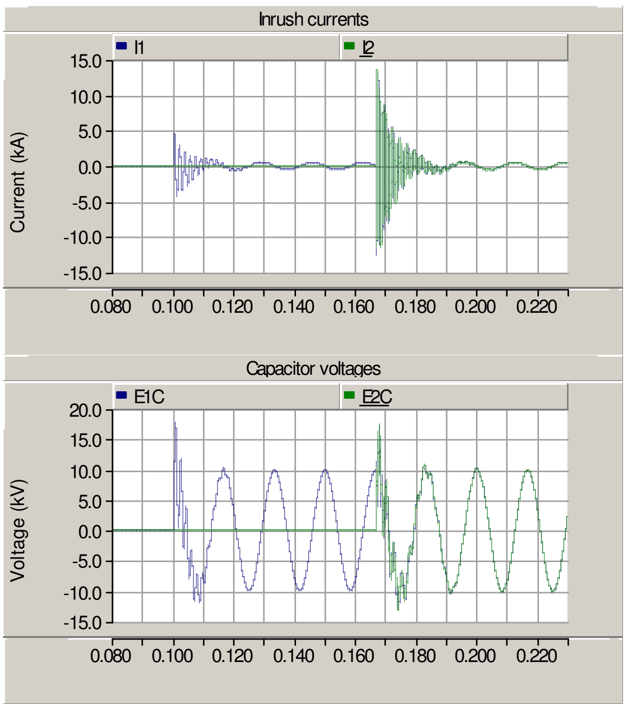

Figure 11. Simulation results, no damping, worst case for conventional non-synchronized switch.

In addition, four configurations have been modeled and compared in Table 1 together with the measurement results from the pilot installation. The four circuit configurations are:

- Detuned capacitor bank. 2.5 mH added in series with each bank (4.5 detuning)
- Voltage zero closing assuming 1 ms closing error. 60 μH current limiting reactor added.
- 6 Ohm pre-insertion resistor.
- Diode switching using the inherent conduction start at voltage zero.

Simulation case	Added inductance	Max inrush current	Peak Voltage
No damping	-	13.6 kA	1.80 pu
Detuned capacitor bank	2.5 mH	2.0 kA	1.64 pu
Voltage zero closing with 1 ms error	60 μH	3.2 kA	1.26 pu
6 Ohm pre-insertion resistor	-	4.5 kA	1.18 pu
Diode switching, simulation	-	0.95 kA	1.08 pu
Diode switching, measurement	60 μH	0.9 kA	1.05 pu

Table 1. Comparison of different capacitor switching methods.

The table shows clearly how the diode switching method both reduces the maximum inrush current and at the same time provides the most reduction in the peak over voltage.

CONCLUSIONS

This paper describes a novel method for the switching of capacitor banks in medium voltage systems by utilizing the inherent diode conduction starting at voltage zero. The concept has been verified by both high power tests and in a pilot installation with good results. The inrush currents so much reduced that they are only about 50% higher than the nominal load current and the voltage distortion is almost not detectable.

The high mechanical and electrical endurance (arc free switching) can also enable more frequent operations of capacitor banks to allow a timely reactive power compensation and thus optimize the power factor correction and thereby reduce system losses and increase distribution capacity.

A comparison of other available technologies shows that the diode switching is superior for capacitor switching in both inrush mitigation and over voltage reduction.

REFERENCES

[1] Backman et. al, "A diode based transient free capacitor switch", *CIRED 2007*

[2] A. Bosma, F.J. Koerber, R. Cameroni, R. Thomas, 2002, Motor Drive with Electronic Control for HVAC Circuit-Breakers, *CIGRÉ Report 13-203, 2002*