



Switching of capacitor banks using a SynchroTeq CSD

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Introduction

Controlled switching of capacitor banks using a SynchroTeq CSD product has been widely used since several years in order to reduce inrush current when closing the circuit breaker (CB) [1]. In this type of application, capacitor banks are used for voltage regulation and filter applications. Mechanically Switched Capacitor systems (MSC) are widely used in SVC and STATCOM applications with additional requirements for fast switching.

In wye-grounded capacitor bank applications (see Figure 1), Independent Poles Operated (IPO) CBs are typically closed when the source voltage is nearly equal to 0V. This zero crossing of each phase occurs at 0°, 120° and 60° relative to phase A and at every subsequent half-cycle (180°). Since there is a 120° electrical phase shift between the phases, optimum switching of capacitor banks cannot be optimized using a gang operated CB unless it is equipped with pre-insertion resistors or unless it has a staggered mechanism (one coil command but delayed operation for each phase).

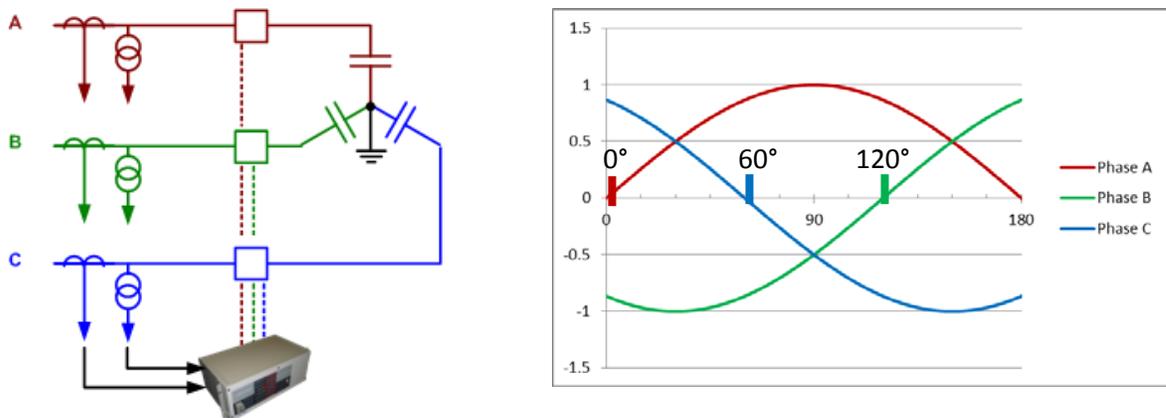


Figure 1 : Energization of a Yg capacitor bank

¹ Satendra , Transend Networks, Arthur Manolias, Areva T&D Australia, Robert Lees, Areva T&D Australia: "Control Philosophy of capacitor banks in Transend Networks"

When switching the CB at zero voltage, the current in the capacitor is established gradually to its nominal value within half a cycle: this switching strategy avoids high inrush current. Switching the CB at any other point would cause inrush current since capacitors oppose to sudden voltage changes.

Effects of switching the CB at the wrong moment

Figure 2 illustrates the switching of a wye-grounded capacitor bank at random moment (left) compared to closing at zero crossing of the source voltage (right). It can be seen on the left that the peak inrush current is almost 4 times the nominal current value. There is also switching transients on the voltage waveform during the first cycle that are propagated everywhere on the network. This could have been worst by switching the capacitor bank at maximum voltage. However, by switching the CB close to voltage zero crossing (right figure), the inrush current is eliminated and the switching transients on the voltage are minimized.

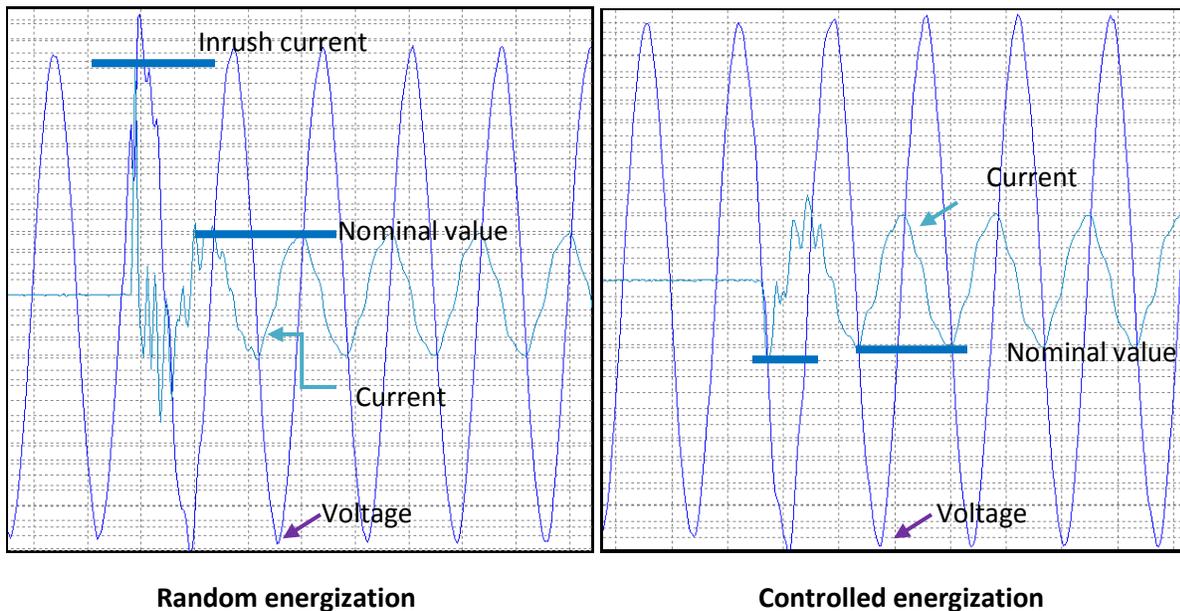


Figure 2 : Capacitor bank energization

Optimum closing time for delta connected capacitor banks

When switching a wye-floating or delta connected capacitor bank (Figure 3), the same principle of minimizing sudden voltage changes across capacitors is applicable. In the following example, phase A and C of a delta connected bank are closed simultaneously at 30° because they have equal amplitude. Since the same voltage is applied at points a and c simultaneously, there is no current flowing into C_{ca} or into the parallel branch made of C_{ab} and C_{bc} . At 120° relative to zero crossing of phase A, phase B is then closed. At that moment, the voltage at the b point is equal to 0 since phases A and C are opposite polarities at $\pm V$ and therefore, inrush current is avoided. This switching strategy repeats at every subsequent 60° phase shift.

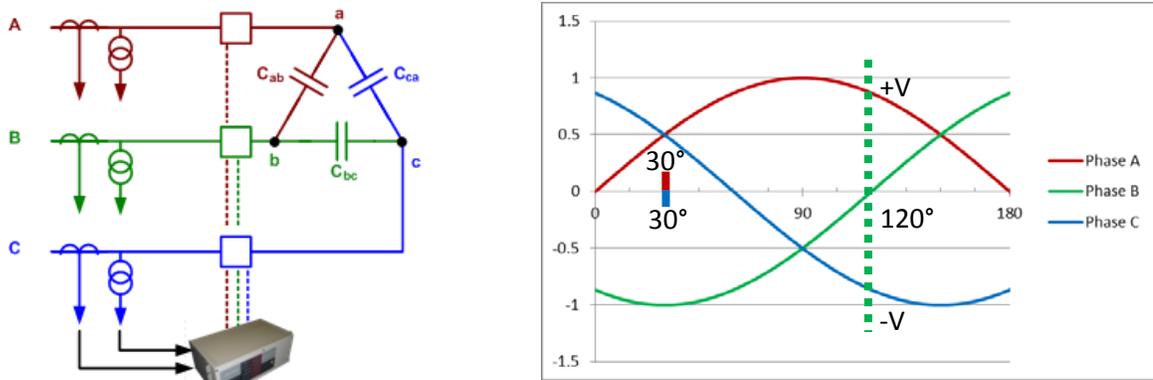


Figure 3 : Effects of the CB repeatability on the inrush current

Unfortunately, CBs are not perfect mechanical devices and their operating time has some scattering due to coupling of linkages, movement translators, cams, etc. In other words, for the same operating conditions, the CB operating time slightly varies, typically between $\pm 0.5\text{ms}$ up to several milliseconds. Figure 4 illustrates the measurement of the closing time of a CB (horizontal axis) versus the number of occurrence (vertical axis). A total of 21 operations were made on the CB in the same operating conditions. It can be seen that most of the time, the CB closing time is around 93.13ms (statistical average closing time), but it can vary between 92.25ms up to 94.10ms. The standard deviation of the operating time has been calculated to 0.51ms, meaning that 68% of the time, closing will occur within 93.13 ± 0.51 milliseconds and 95% of the time, closing will occur within 93.13 ± 1.02 milliseconds.

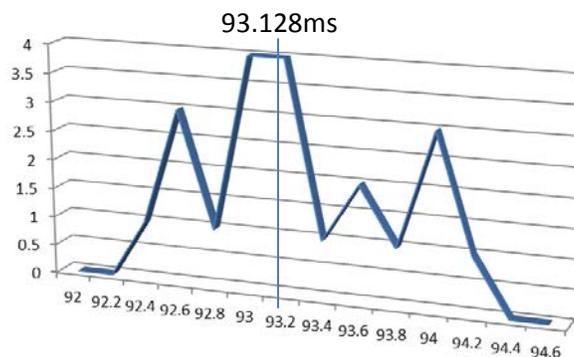


Figure 4 : Variation of the CB timing

According to Figure 5, using a capacitor bank operated in a 60Hz system, a ± 1 ms scattering time indicates that the CB may close while there is up to 37% of the nominal voltage present at the source (19% with a ± 0.5 ms scattering time). Therefore, most of the time, there will be no inrush current. The maximum inrush current expected from controlled switching will be 2.7 times lower than the one resulting from random switching.

As a conclusion, the better the repeatability of the CB, the lower the inrush current since the closing will occur closer to the optimum point. Ideally, CBs used for controlled switching of capacitor banks should have a repeatability varying from $\pm 0.5\text{ms}$ up to $\pm 1\text{ms}$.

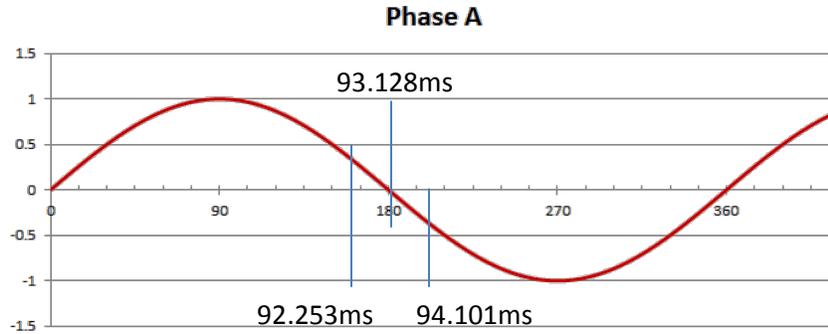


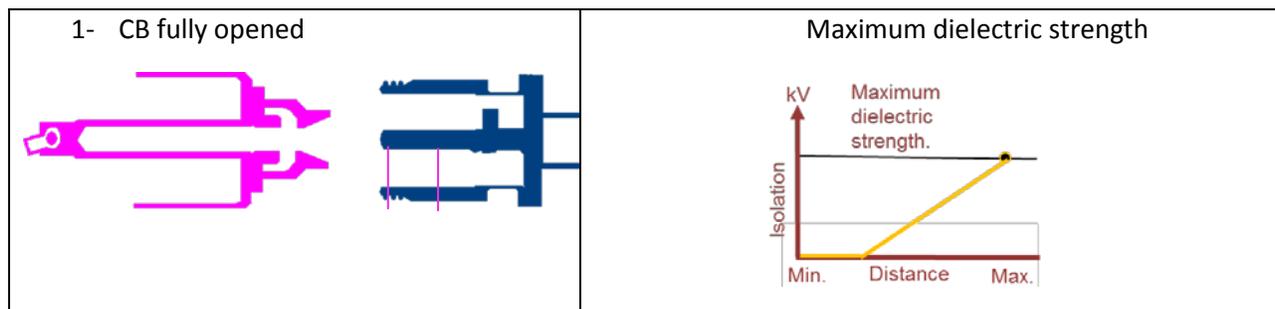
Figure 5 : Effects of the CB repeatability at 60Hz

The CB RDDS

As illustrated in the Figure 6, a single chamber CB has one mobile (left) and one stationary contact (right). It should be noted that multiple chambers CBs are used at higher voltage, but their operating principle remains the same.

In the opened position, the contacts are fully separated and the dielectric strength of the CB is determined by the distance between the contacts and the isolation media properties (SF6, air, vacuum, etc.). When closing the CB, the following sequence occurs:

- 1- The mobile contact is moved toward the fixed contact, reducing both the distance and the dielectric strength of the CB.
- 2- The contacts approach velocity determines the slope of the dielectric strength. This is called the **Rate of Decrease of Dielectric Strength (RDDS)**, which is normally expressed in kV/ms. This value is determined by the design of the CB.
- 3- As the contacts are moving toward each other, the voltage across them may exceed the dielectric strength determined by the contact separation distance. In this case, an arc will be produced and electrical conduction will start in the CB.
- 4- When the contacts are touching each other, the arc extinguishes and metallic conduction starts. The mobile contact will continue its motion until fully engaged in the stationary part.



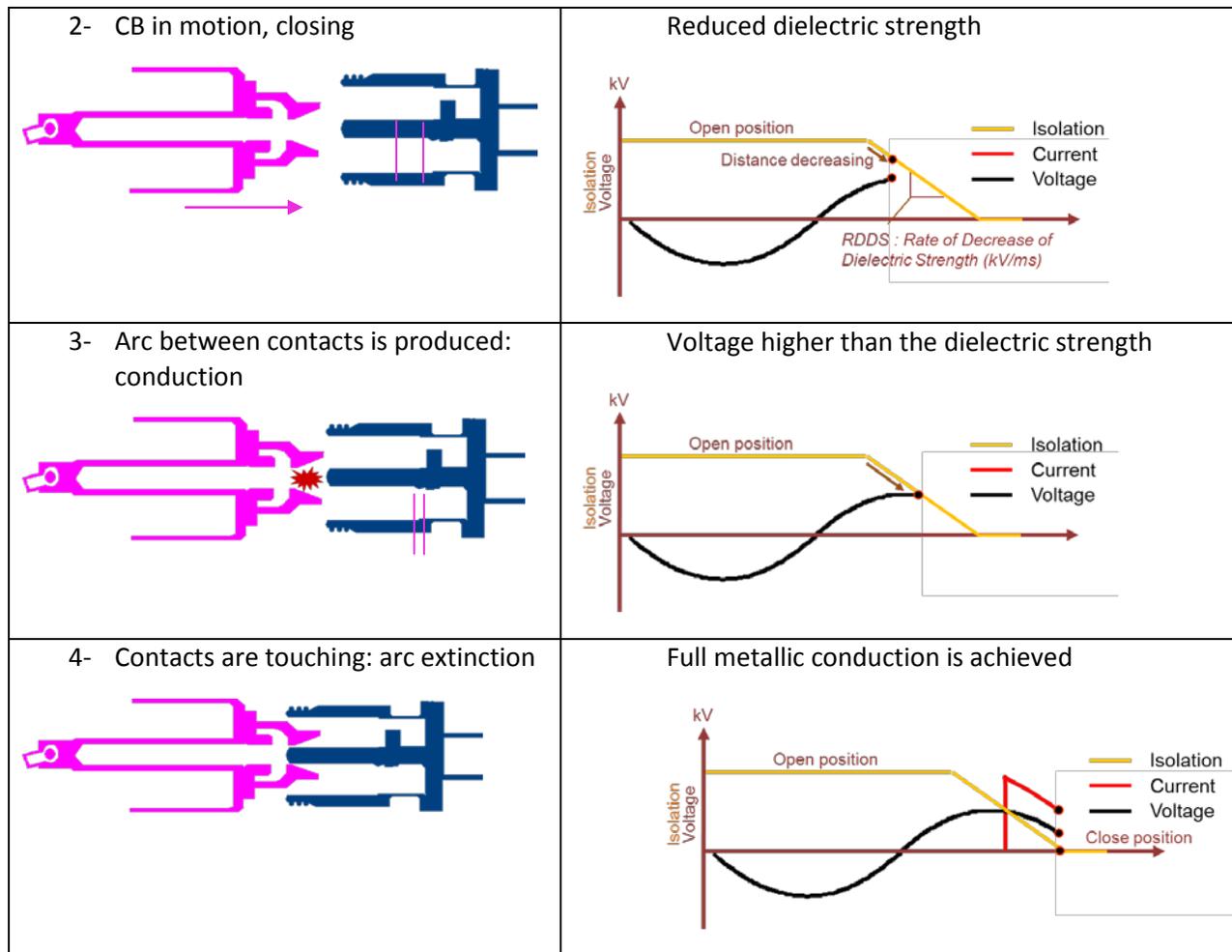


Figure 6 : CB closing

The pre-arc time

The review of the closing sequence reveals that the electrical conduction does not necessarily start when the contacts are touching each other (mechanical closure), but rather when the arc is established between both contacts. As illustrated in Figure 7, the pre-arc time varies according to the voltage across the contacts and the RDDS slope. In this example, the mechanical closing moment is selected to be 120° but the CB will start conducting around 33° sooner at 87° (left most). However, when the mechanical closing moment is selected to be 165° (center), the pre-arc time is reduced to 12° since the voltage is much lower.

The same pre-arc time variation occurs when the RDDS slope varies. For example, if the mechanical closure occurs at 225° (rightmost), the same RDDS will produce a 15° pre-arc time. As the RDDS slope is lowered, the pre-arc is increased to 23°.

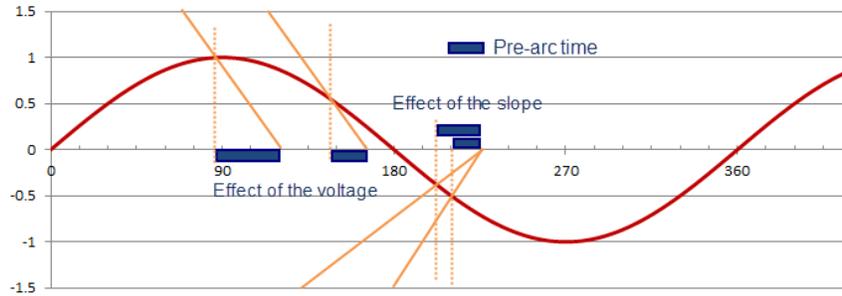


Figure 7 : Effects of the CB RDDS at 60Hz

Relationship between the CB RDDS and the system voltage

In order to determine the pre-arc time, the RDDS of the CB must be known. It is usually published as a kV/ms rating. As illustrated in Figure 8, the maximum voltage slope of a sinusoidal system occurs at zero crossing.

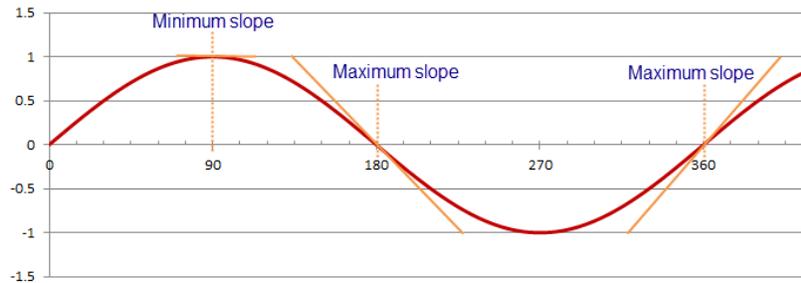


Figure 8 : Voltage slope

This voltage slope is computed as follows:

$$\text{Slope (kV/ms)} = V_{L-L} \cdot \frac{\sqrt{2}}{\sqrt{3}} \cdot \frac{2 \cdot \pi \cdot f}{1000}$$

where:

V_{L-L} is the line to line voltage (kV)

f is the network frequency (Hertz)

For example, the maximum voltage slope of a 230kV line at 60Hz is 70.79kV/ms. When the CB has the same RDDS value as the maximum voltage slope of the system, the RDDS is said to be equal to 1 PU. For example, if a CB has an RDDS value of 50kV/ms, the RDDS value in PU is equal to:

$$\text{RDDS (PU)} = \frac{\text{RDDS (kV/ms)}}{\text{Slope (kV/ms)}} = \frac{50\text{kV/ms}}{70.79\text{kV/ms}} = 0.7 \text{ PU}$$

Importance of the CB RDDS value

As illustrated in Figure 9, when the RDDS of the CB is greater than the maximum system voltage slope (RDDS ≥ 1 PU), it is possible to close the CB at any point on the wave. It should be noted that the zero crossing point is the hardest target to reach since the voltage slope is the highest at that time.

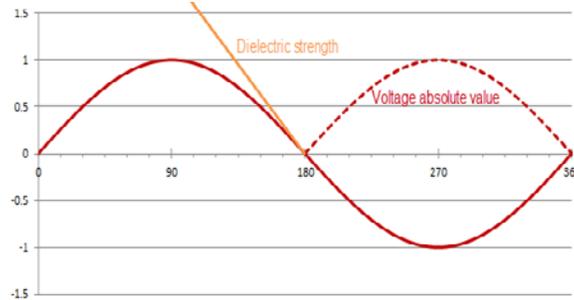


Figure 9 : Importance of the RDDS for capacitor banks

In Figure 10 example, the CB RDDS is lower than 1 PU. If the CB was controlled to do a mechanical closure at the zero crossing, an important pre-arc time would occur since the dielectric strength of the CB would be lower than the system voltage. Therefore, the target point must be moved later (by around 45°) until the dielectric slope clears the system voltage. The pre-arc will cause the CB to start conducting earlier at around 15° and therefore, it will not be possible to avoid inrush current.

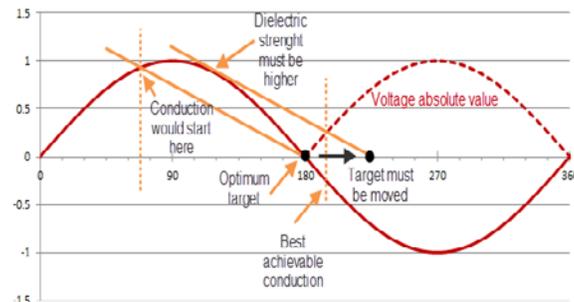


Figure 10 : Effects of the RDDS on the switching point

When the RDDS of the CB is lower than 1 PU, it is therefore not possible to reach target points around the zero crossing, which is the optimum switching point for a wye-grounded capacitor bank. In this type of application, a fast CB with an RDDS higher than 1 PU should be selected.

Calculating the optimum target point and the arc time

The optimum closing time for a wye-grounded discharged capacitor bank is 0° since at this moment, there won't be sudden voltage change across the capacitor. However, this target is only reachable when the RDDS of the CB is greater than 1 PU. When lower than 1 PU, trigonometric calculations must be done to determine the minimum reachable closing time. Furthermore, the repeatability of the CB should also be taken in account in this calculation.

In Figure 11 example, if the minimum closing angle is selected to be the target point, the CB mechanical scattering may ignite an electrical arc almost ½ cycle sooner than the objective: rather than closing the CB at an angle close to 0°, the arc cause the CB to close near the peak of the voltage, causing a very high inrush current in the capacitor bank.

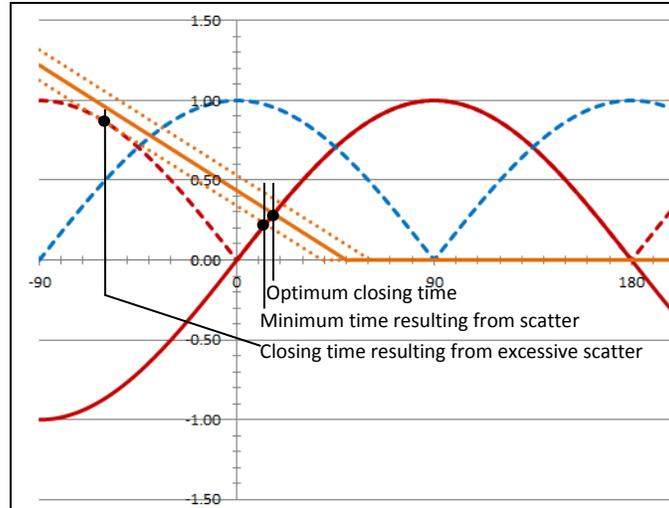


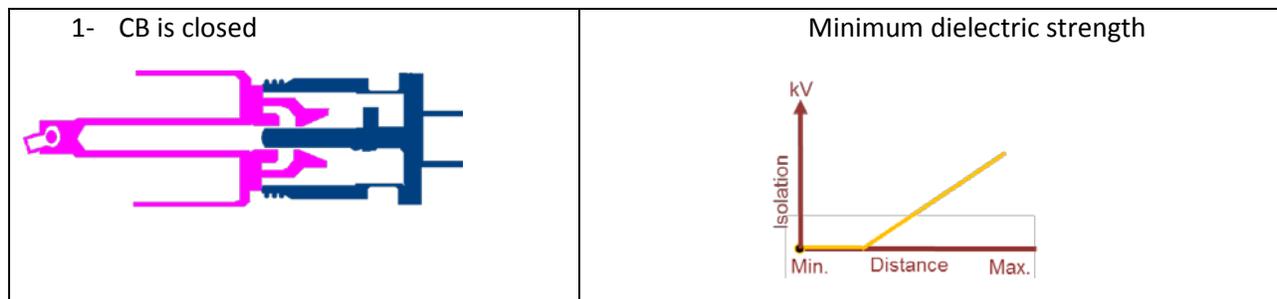
Figure 11 : Choosing the closing moment

The “Optimum angle calculator.xls” MS Excel™ spreadsheet available from Vizimax provides a tool for calculating the optimum electrical closing target angle and the pre-arc time, taking in account the RDDS and the mechanical scattering time of the CB.

Opening the CB on a capacitor bank

When opening the CB on a capacitor bank, the following sequence occurs (see Figure 12):

- 1- The mobile contact is pulled away from the fixed contact, but still maintaining the metallic conduction.
- 2- When the contacts are separated, an arc is produced because the voltage is higher than the dielectric strength of the CB. In the capacitor bank, the current is leading the voltage by 90°.
- 3- As the contacts are moving away, the current continues flowing by arc as the contacts are separated, even if the voltage becomes lower than the dielectric strength of the CB due to ionization.
- 4- The current is interrupted (CB opened) when:
 - a. the current becomes equal to 0 (the arc extinguish)
 - b. the voltage at that moment is lower than the dielectric strength of the CB



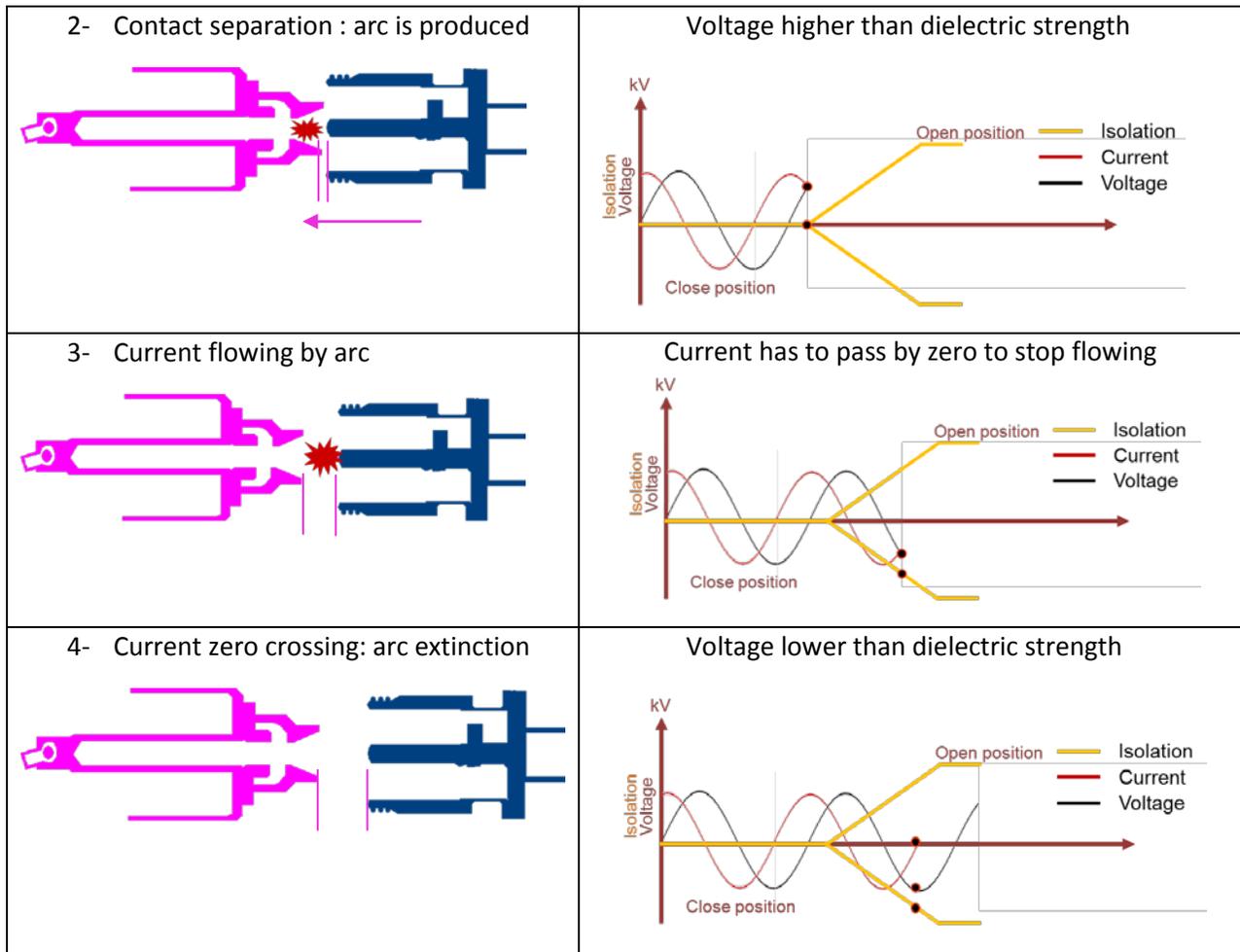


Figure 12 : CB opening

In Figure 12 opening example, the CB electrical opening (interruption of current) will occur when the voltage is at peak because the voltage is lagging the current by 90°. This means that the load capacitor will stay charged at peak maximum voltage, leaving a maximum difference voltage of 2 PU across the CB after opening. This is illustrated in the Figure 13 where an opening of the CB occurs at +90°.

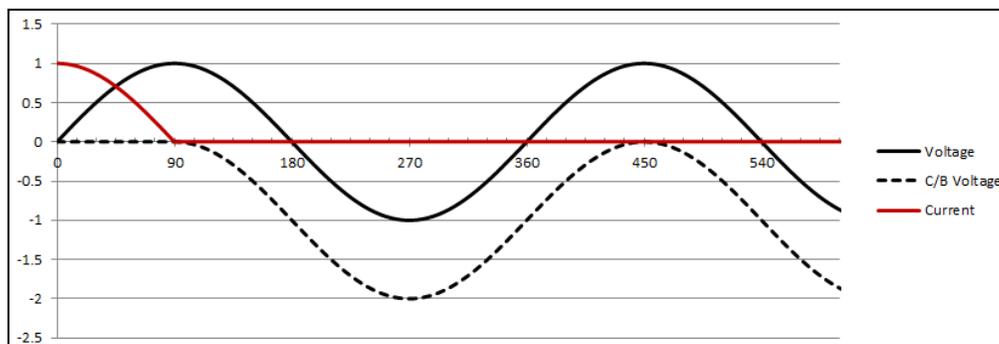


Figure 13 : Voltage across de CB

However, since capacitors are not perfect devices, they will gradually self-discharge to 0V after usually a period of 15 minutes (see Figure 14 with exaggerated discharge). Typically, the discharge time constant “ τ ” is in the minute range, meaning that it would take 1 minute for the capacitors to discharge to 36.8% of their initial voltage. After 5 time constants, the capacitor bank is considered to be fully discharged.

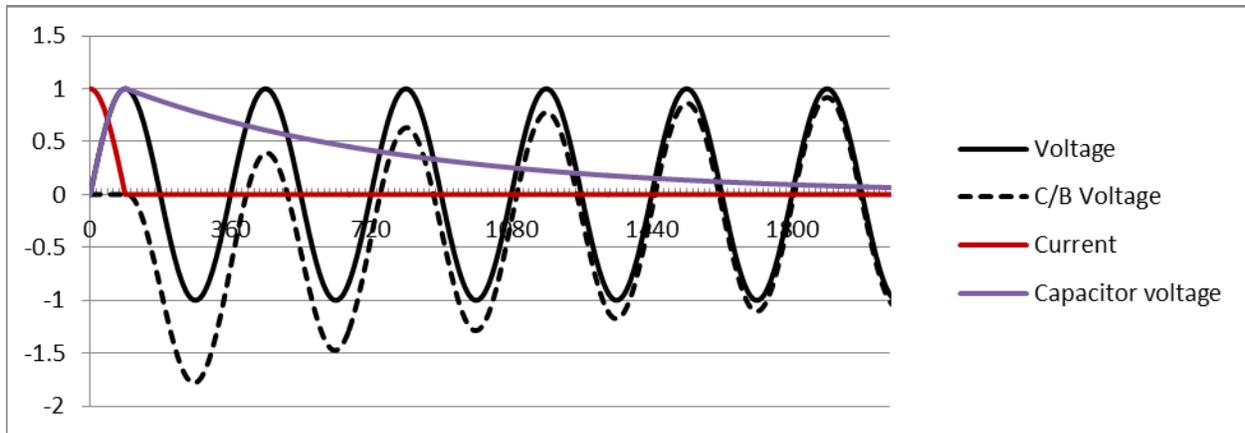


Figure 14 : Capacitor discharge

When controlling a capacitor bank switching using a CSD, it is important to account for the residual voltage that exists on the capacitor bank. In many cases, a blocking timer is used to control the CB closing. The timer is armed each time the CB is opened and it blocks the closing of the CB.

Fast switching of capacitor banks

SynchroTeq products are perfectly adapted for fast switching of capacitor banks and filters. In many applications such as static VAR compensation (SVC) and STATCOM (static compensators), very rapid switching sequences are required where the operation of the CB cannot be blocked due to the presence of residual charges. In these applications, the CSD must account for the capacitor/filter residual charge and the self-discharge characteristics of the capacitor bank to determine the optimum switching point. For example, immediately after opening the CB, the optimum closing time is at peak voltage. However, 15 minutes after opening, the optimum closing moment is at zero crossing of the voltage. The optimum closing moment becomes dynamic and varies according to the residual charge from 90° gradually to 0°.

Using patented algorithms, the latest VIZIMAX CSD products (SynchroTeq Plus and SynchroTeq MV) have the capability of switching the capacitor banks according to the residual voltage and self-discharge characteristics. Each time the CB is switched, (by a protection trip or a voluntary command), the current and voltage waveforms are captured thus determining the residual voltage trapped in each phase of the capacitor bank. The capacitor bank residual voltage is constantly evaluated by the CSD in order to dynamically compute the optimum closing angle according to the source voltage and the network frequency.

Figure 15 illustrates a rapid C-O-C sequence on a capacitor bank with residual charges. When the CB is first closed, the residual charge is around -0.7 PU and the CB is closed when the line voltage is equal to the residual charge. The CB is opened 3 cycles later. At the moment of current interruption, the instantaneous voltage is measured by SynchroTeq and calculations are done to evaluate the capacitor residual voltage during its self-discharge. When the second closing command is received by SynchroTeq, the closing angle is dynamically adjusted so that the source voltage matches the residual charge at around 0.8 PU. It can be noted that there is no inrush current resulting from the two close operations.

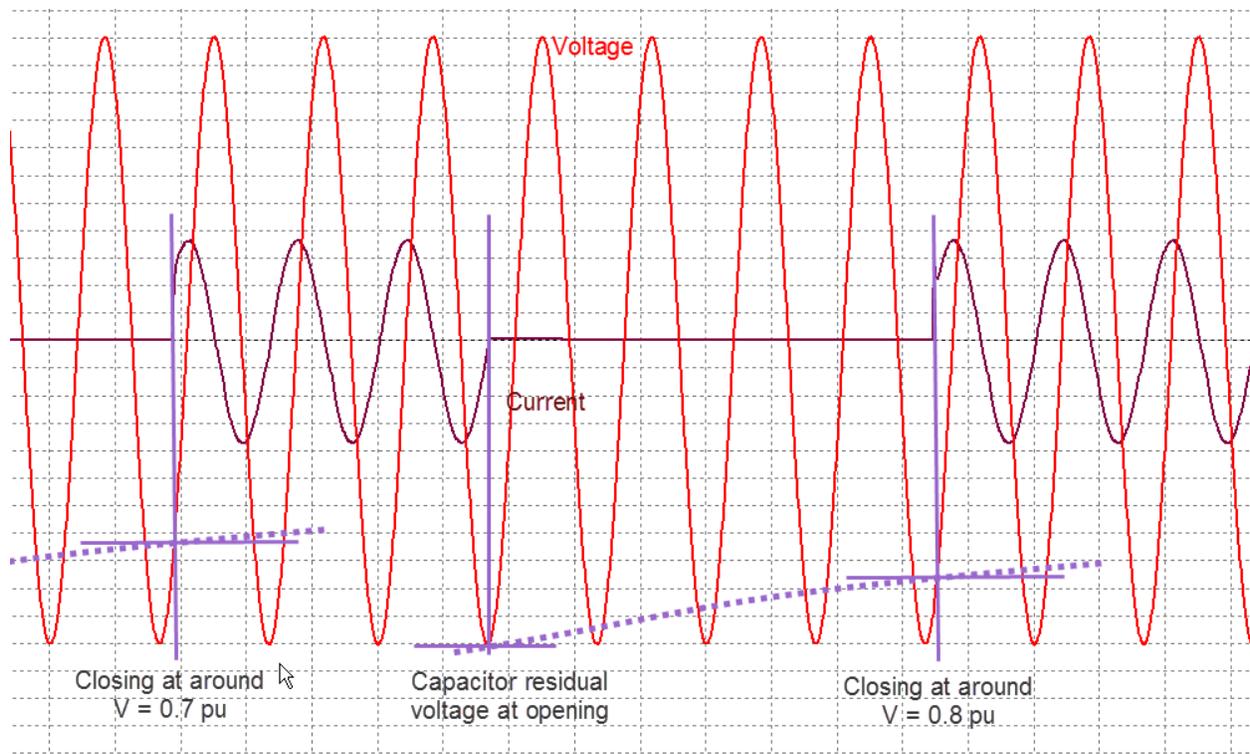


Figure 15 : Rapid C – O – C sequence

When receiving a close command, SynchroTeq is ready to close the C/B at the optimum angle, minimizing the latency between the reception and the completion of the command. Using a 60ms closing time circuit breaker, the 100ms response time to command completion is guaranteed at 50Hz.

Conclusion

This document has presented the controlled switching of capacitor banks. It has been seen that the best moment to close the CB depends on the configuration of the capacitor bank (wye-grounded, delta). When switching the CB at the optimum time, inrush current is eliminated and voltage switching transients are minimized, improving the quality of the waveform and reducing the stress on the electrical apparatus. In order to provide a good control on the target angle, the CB must have a good repeatability (± 0.5 to ± 1.0 ms) and must also have a high Rate of Decrease of Dielectric Strength (RDDS ≥ 1 PU).

When opening the CB, the arc is interrupted at zero crossing of the current, and therefore the capacitors remain charged at full voltage. For rapid switching of capacitor banks, the residual voltage on the capacitor bank must be taken in account before closing the CB, which is the case for the SynchroTeq Plus which provides advanced controlled switching functions for almost every type of load and extensive CB monitoring functions.

With the approach presented in this paper, power system operators are capable of switching on and off capacitor banks as needed. No longer is it required to wait for capacitor discharge since SynchroTeq accounts for the residual voltage.