Controlled Switching of Circuit Breakers: Project Report

COURSE PROJECT FOR EE 687

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1 Introduction

Circuit breakers need to be switched several times for certain components. The transients generated by such switchings can be detrimental for power system. Controlled switching helps to mitigate these effects by controlling the exact instat of closing or opening.

Controlled switching of circuit breakers refers to switching the circuit breakers ON (CLOSING of switch/CB) or OFF (OPENING of switch/CB) at a predefined instant. It can possibly have adaptive strategies employing statistical variation of switching instant and physical properties of circuit breakers like Rate of Decrease of Dielectric Strength (RDDS) [1, 2, 3]. This helps to minimize the transients in the the local power network as well as cascaded effects of such transients. An overview of this was given in the critique of the paper [1] and overview of the project submitted before. The transients are natural output of circuit configuration but these can be catastrophic to the devices connected in the network. Controlled switching of breakers enables the utilities to minimize the transients below the threshold level of devices.So this document conveys the simulation results which puts forth a clear view of the switching instants which can be beneficial to the utilities.

2 Controlled switching description

The transients generated in a network due to switching are determined by the connected load , load grounding configuration and grounding of the source. The Loads can be broadly classified into following four types -

1. Reactor banks (*independent reactor banks with air core*)
2. Capacitors
3. Transformers
4. Transmission lines

Similarly the grounding configuration of the load can be classified into three types.

1. Star grounded
2. Star ungrounded
3. Delta

Table 1 gives ideal switching instants for the load. The switching instants are written in angles(*degrees*) with respect to either reference current or voltage. If the load is delta connected or star ungrounded line-to-line voltage must be considered as reference voltage.

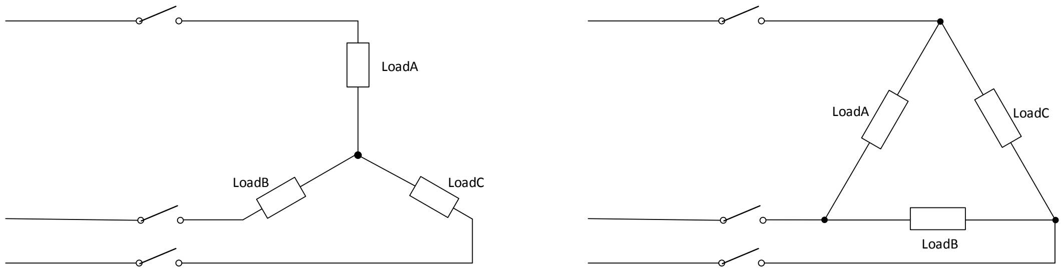
2.1 Outline and scope of project

In this work, following cases are considered -

1. Capacitor bank (star grounded) switching
2. Inductor bank (star grounded) switching

Device	Close	Open
Capacitor	Voltage 0	Current 0
Inductor	Current 0	Current 0
Transformer	Current 0	Current 0
Transmission line	Voltage 0	Current 0

Table 1: Ideal switching instants: in columns 2 and 3, the “0” refers to *zero crossing* of the respective parameters



(a) Star connected load

(b) Delta connected load

Figure 1: Load grounding configuration

Parameter	Description
Voltage source	11 kV (L-L rms), 3 phase grounded source, starting at t = -1 i.e. no ramp included in voltage
Switch type	SWIT-3XT, Switching instants are varied by parametric analysis
Frequency (Hz)	50

Table 2: Parameters used for transient simulation in EMTP-ATP

Only switching time is varied. Statistical variation not employed. The scope has also been limited to closing of the loads at different instants of voltage. The opening has not been considered due to absence of considerable RDDS (rate of decay of dielectric strength) information of breaker. Simulating a restrike/reignition requires detailed modelling of the circuit breaker.

Although, the work is limited to inductors and capacitors, it may be extended to transformers and transmission lines in certain cases. For example, transformers can be considered as reactors if there is no residual flux remaining in the core. This condition can be achieved by controlled opening of the transformer.

Similarly transmission lines can be considered as capacitors given that there are no trapped charges in the transmission line. The presence of trapped charge in the transmission lines greatly determines the voltage across the circuit breaker, its frequency and so its zero crossings. Also, although only star-connected grounded source and load are considered, the results from this work can be extended to delta connected loads. Fig.1 shows the positioning of the circuit breakers in a star and delta connected load. It shows that the voltage across the circuit breakers in delta connected load confronts the line to line voltage. A similar condition holds for a star ungrounded load. So during closing or opening of a circuit breaker in a delta or star ungrounded load , line to line voltage must be taken into consideration. And so obviously two circuit breakers must be closed or opened simultaneously in star ungrounded or delta load. However, there are few limitations to the extension of this work - for example -

- A transmission line *cannot* be considered as delta connected load due to a significant capacitance between the phase line and ground in comparison to inter-phase capacitance.
- An uncoupled, residual flux free transformer switching depends upon the connection of the primary winding.
- If source itself is ungrounded; it should always be considered as switching of ungrounded loads even if the load is physically star grounded.

3 Simulation results

All the simulation are performed in EMTP-ATP version 5.7. As described in previous section, only capacitor and inductor closing is considered for this work. The parameters used in simulations, common to both types (inductor and capacitor) of switchings is given in Table 2. Other parameters are given in the following sections. The subsections titled *Close* and *Open* refer to simulation studies related to closing and opening respectively.

3.1 Capacitor switching

3.1.1 Close

As described in previous section, the capacitor banks should be closed at voltage zero. If capacitor has zero charges prior to closing of switch, it acts simply as short circuit just after closing switch. Hence, it draws a huge inrush current which may exceed the rating of circuit breaker. This in turn may produce large overvoltages at

Parameter	Description
Capacitor bank	3 phase capacitor bank 5 μF per phase
Resistance in series with bank	1 Ω per phase
Line inductance	0.5 mH
Line resistance	1 Ω

Table 3: Parameters used for Capacitive Switching Simulation

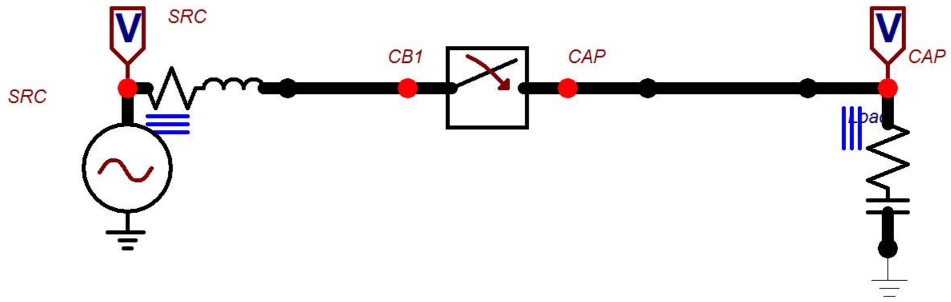


Figure 2: EMTP circuit for simulation of controlled switching of capacitor banks

the bus. These overvoltages in turn may trigger other transients at end of lines connected to banks and they are also harmful for sensitive loads [1]. A small resistance is taken in series with capacitor to imitate the effect of ESR (Equivalent Series Resistance) and that of any other parasitic effects. The transmission line is taken as a simple RL branch. The circuit is shown in Fig. 2. The parameters used for simulation are given in table 3. As described in [2], the three phases of the capacitor banks can be switched within 120°. With sequence A-C-B each separated by 60°. If they are switched at appropriate zero crossings, then transient voltages and currents through the banks are limited. This is shown in Fig. 3 and 4. However, for the sake of clear visualization, the switching of circuit breakers is spaced in time, by 120 electrical degrees. The switching of all the phases is shown in Fig. 5. This in a way represents a circuit breaker where operation of phases is staggered by 120°. The next figures i.e. Fig. 6 and 7 exhibit transient currents and voltages in phase A of the bus. It is obvious that the other two phases will also behave in similar fashion. From Figs. 6 and 7 it can be seen that when capacitor banks are closed at voltage zero crossing, the inrush current and hence transient overvoltages at the bus are minimal. However, when the bank is closed at a non-zero voltage points, very high transient currents can be seen. The transient overvoltages also touch almost 2 pu of their rated values. This is certainly harmful for the banks and can excite further transients in the circuit [1, 2]

Effect of closing all phases at same instant: If the circuit breaker closing is not even mechanically staggered, then it represents the case where all the phases close simultaneously. Effect of such closing on inrush currents is simulated and results are shown in Fig. 8. It can be seen that phases B and C extract a huge inrush current which comparable to peak voltage switching inrush current depicted in Fig. 6.

Thus, Figs. 3 through 8 illustrate various simulation results for controlled and uncontrolled switching of circuit breakers. It can be inferred that huge inrush currents of the order of 3 pu to 10 pu result from closing the capacitor banks at instants where voltages for respective phases is non-zero.

3.1.2 Open

As indicated in table 1, a capacitor bank should be switched OFF or OPENED only at zero current. A simple circuit as shown in 2 is simulated to see this phenomenon. The values of components are same as the ones used for the study of closing the switch.

For this study, the "T-cl" i.e. closing time for the switch is taken as -1; i.e., the switch is closed since long time and a steady state is reached. The marginal current below which the switch should not open is kept as 4 A. Two switching instants are chosen - 15 ms and 20 ms. These two instants correspond to current zero and current peak respectively.

The results for closing the switch at current zero are shown in Fig. 9. The figure shows that as the circuit breaker is opened the capacitor holds the charges and hence the bank voltage does not change. However, as the line current is interrupted, there is an envelope of high frequency transient voltage across the line (simulated as RL branch). As a result, the total TRV across the circuit breaker shows a high frequency envelope superimposed on the shifted voltage.

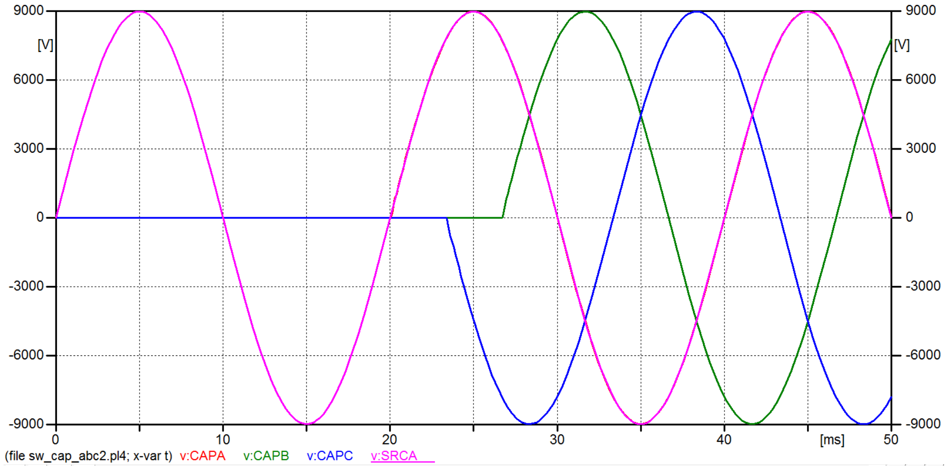


Figure 3: Bus voltages for closing of three phase capacitor banks within 120°: v:CAPA, v:CAPB, v:CAPC correspond to bus voltages for phases A, B and C respectively. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

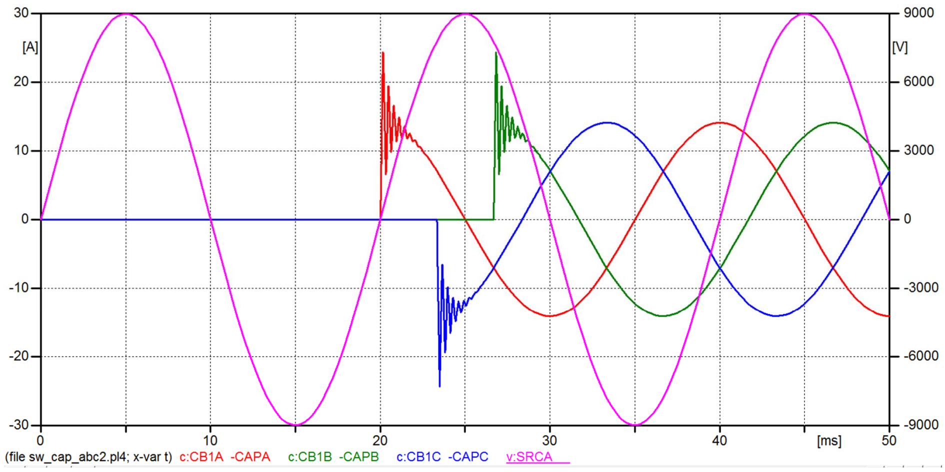


Figure 4: Inrush currents for Closing of three phase capacitor banks within **120°**: c:CB1A -CAPA, c:CB1B -CAPB, c:CB1C -CAPC correspond to bus voltages for phases A, B and C respectively. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

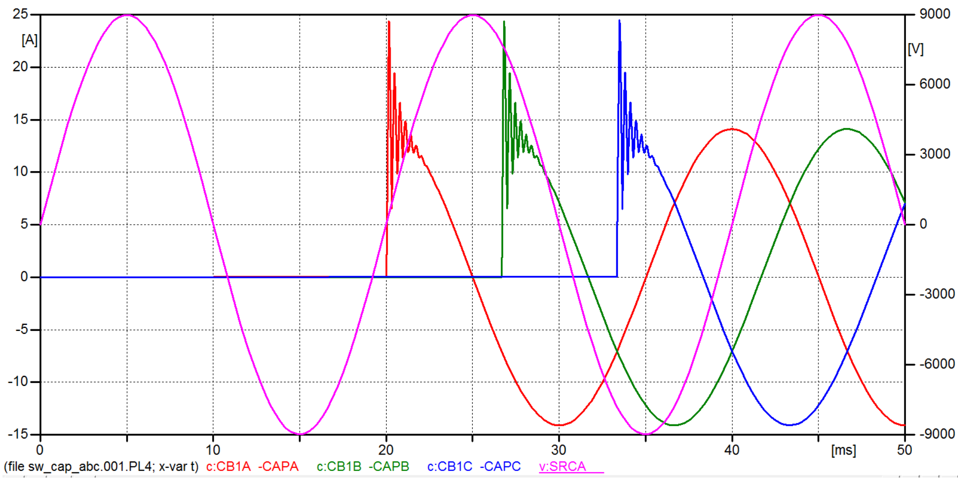


Figure 5: Inrush currents for Closing of three phase capacitor banks within **240°**: c:CB1A -CAPA, c:CB1B -CAPB, c:CB1C -CAPC correspond to bus voltages for phases A, B and C respectively. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

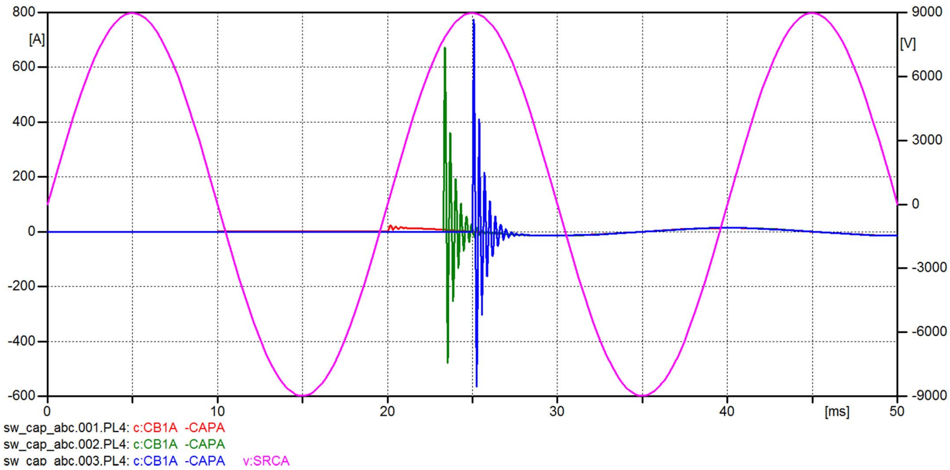


Figure 6: Inrush currents (phase A) for closing of three phase capacitor banks: c:CB1A -CAPA represents current. red, green and blue plots correspond to closing of circuit breakers at voltage zero, voltage 60° and peak voltage point in time respectively. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

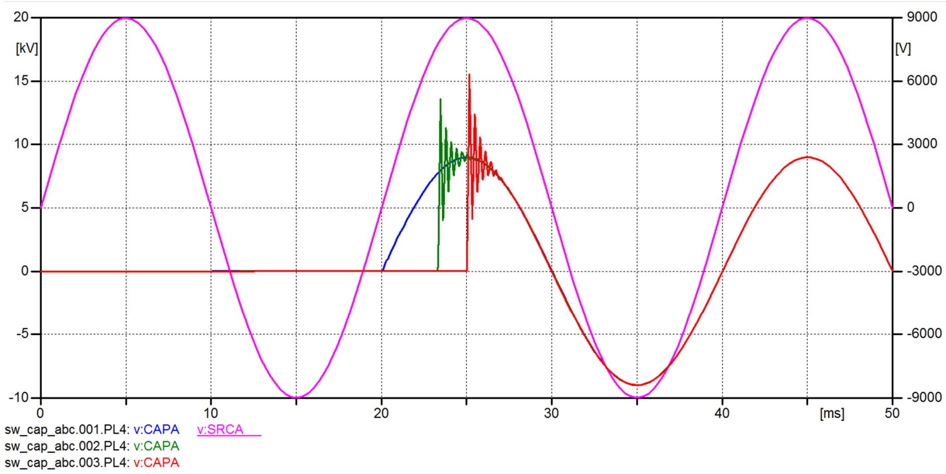


Figure 7: Bus voltages (phase A) for closing of three phase capacitor banks: v:CAPA represents bus voltage - red, green and blue plots correspond to closing of circuit breakers at voltage zero, voltage 60° and peak voltage point in time respectively. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

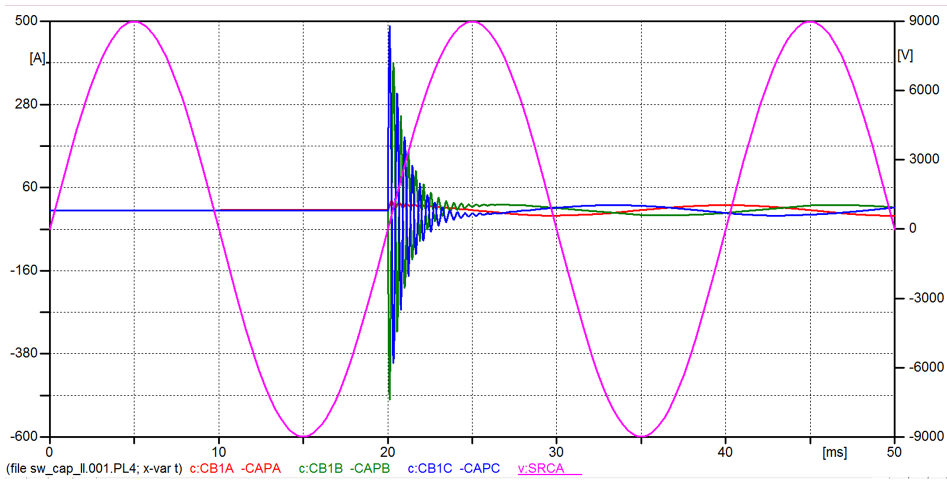


Figure 8: Inrush currents for closing of three phases of a capacitor bank simultaneously: c:CB1A -CAPA, c:CB1B -CAPB, c:CB1C -CAPC correspond to bus voltages for phases A, B and C respectively. Phase A is closed at voltage zero. At the same instant, phases B and C are closed. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

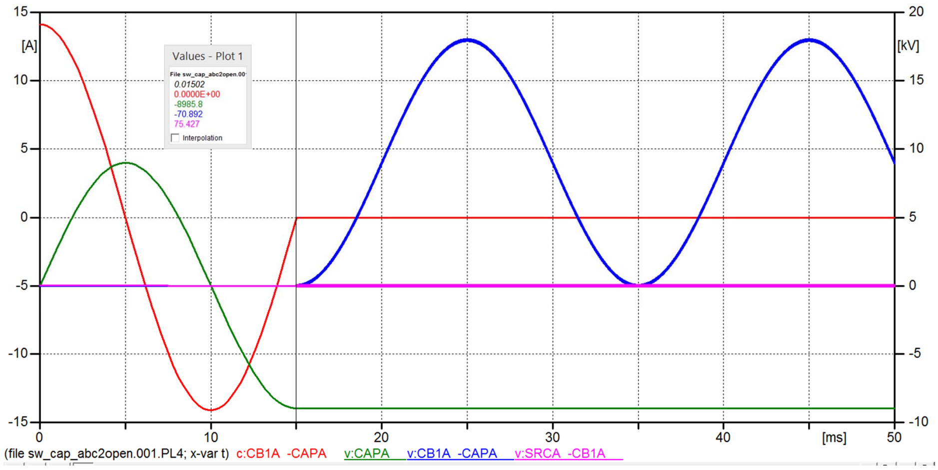


Figure 9: Opening of three phase capacitor banks at current 0 (15 ms): c:CB1A -CAPA is current through the bank and hence the circuit breaker. v:CAPA, v:CB1A -CAPA and v:SRCA -CB1A are voltages (phase A) across capacitor bank, circuit breaker and line inductor respectively. All voltages are plot on right Y axis.

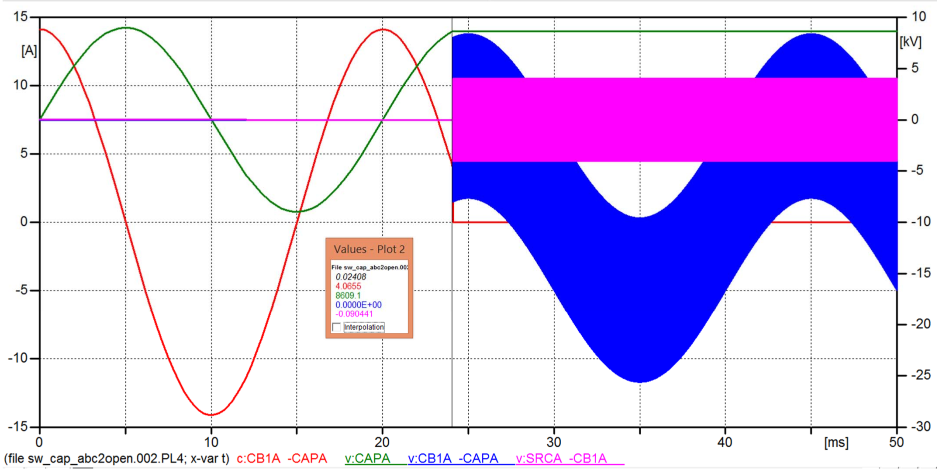


Figure 10: Opening of three phase capacitor banks at current peak (20 ms): c:CB1A -CAPA is current through the bank and hence the circuit breaker. v:CAPA, v:CB1A -CAPA and v:SRCA -CB1A are voltages (phase A) across capacitor bank, circuit breaker and line inductor respectively. All voltages are plot on right Y axis.

Effect of opening a switch at current peak is shown in Fig. 10. It should be noted that the circuit breaker does not open at 20 ms because the marginal current is set to be 4 A. Hence the switch opens at 4 A. The TRV is more severe in this case. This might result in chopping of current in practical scenario.

3.2 Inductor switching

3.2.1 Close

The waveforms given below coveys the impact of closing inductors at different instants of voltage. A random switching instant might lead to heavy inrush current being drawn by the inductor which in turn might lead false fault detection by the protection relays and also heavy inter-turn forces in the windings of the inductor.The circuit considered for simulation is shown in Fig.11. The different values of the parameters are provided in Table.4. The inductor load has been closed at different angles of voltage waveform which are as shown below:

1. Angle 0°: The 0°is with respect to the voltage positive zero crossing. Under a normal steady state condition the inductor current lags the voltage . So at the instant of voltage positive zero crossing current will be at its negative peak. As soon as the circuit breaker is closed the circuit expects a peak level current. So it starts drawing a heavy current into the load which is termed as the inrush current. Fig.12 shows the three phase current at the instant of switching. As seen from the waveform there is a flow of heavy inrush current into the circuit. The peak current reaches to a value which is two times the normal peak current. Such heavy currents could lead to false tripping of protective relays.

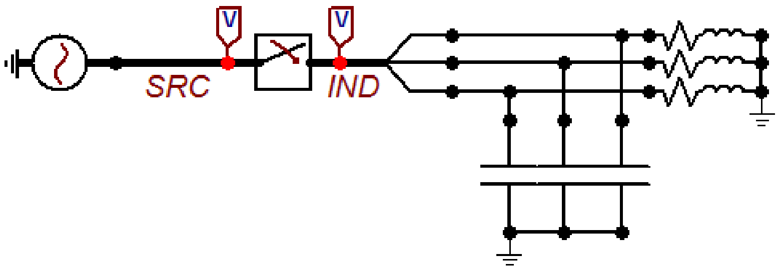


Figure 11: EMTP circuit for simulation of controlled switching of reactor banks

Component	Specifications
Inductor	L=105mH
ESR reseistance	R=0.1Ω
Shunt Capacitor	C=1.0nF

Table 4: Parameters used for Inductive Switching Simulation

2. Angle 30°: At 30°although the prospective current might be below the negative peak but its still much higher than the zero current level. So the current waveform seems to be in a better position than the previous current but still there is a significant DC offset present. The currents are as shown in Fig.13.

3. Angle 60°: The currents are as shown in Fig.14.

4. Angle 90°:This is the most favorable instant for switching of the inductor load.The prospective current is zero at this instant.So there won't be any inrush current being drawn into the load. The currents are as shown in Fig.15.

5. Angle 120°: The currents are as shown in Fig.16.

6. Angle 150°: The currents are as shown in Fig.17.

7. Angle 180°: The currents are as shown in Fig.18.

3.2.2 Open

The opening sequence of the reactor is similar to that of opening the capacitor. The inductor must ideally be closed at current zero condition. And the present day circuit breakers mechanism even enable breaking of the circuit at current zero instant. The problem arises whenever there is small inductive currents flowing in the circuit and the circuit is to be tripped. As the current level is too low, there are chances that the opening arc might get extinguished before the current reaches its natural zero. This condition is known as **current chopping** and the circuit breakers are termed as *overzealous circuit breakers*. This might lead to conditions like re-strike and re-ignitions. As the current was chopped before its current zero condition there are chances that the current might re-strike in the next cycle initial time span due to insufficient distance between the circuit breaker contacts. So the most favorable condition is to open the circuit breaker at current zero instant with sufficient arcing time as per given by the circuit breaker manufacturer. Fig.19 shows the opening operation of the inductor.

4 Conclusion

Controlled switching of circuit breakers is studied in this course project by simulating examples of switching of inductor banks and capacitor banks. All the simulations are using EMTP-ATP. The study is limited to observing effects of various switching instants on voltage and current transients. The effect of RDDS and statistical variation is not implemented.

In particular, effects of closing capacitor banks at instants when the voltage is not zero is observed to produce large inrush currents and consequent overvoltages. These voltages are harmful for local equipment as well as they can excite transients at far end of transmission lines also [1, 2]. The results are similar to that shown in [1].

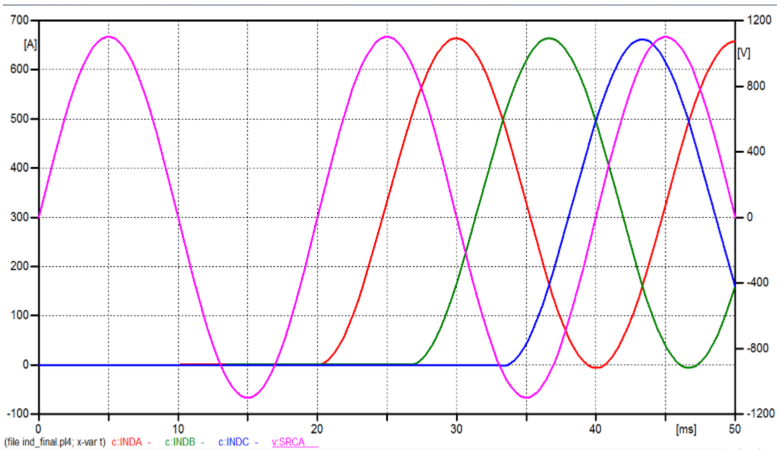


Figure 12: Inrush currents for closing of three phase inductor banks due to switching at voltage zero: c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

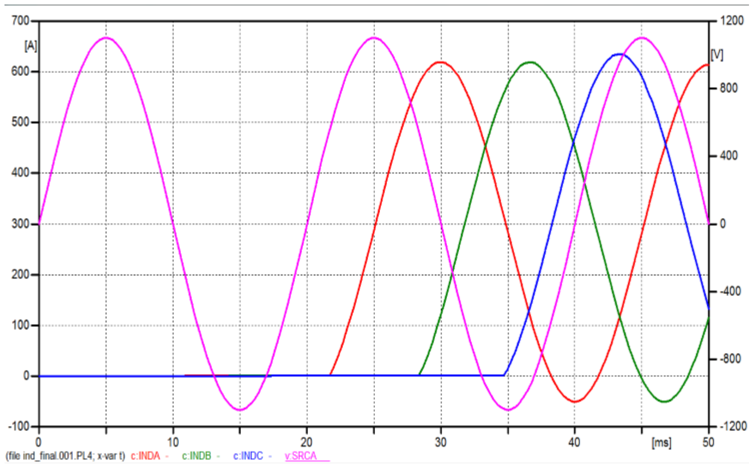


Figure 13: Inrush currents for closing of three phase inductor banks due to switching at voltage 30°: c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

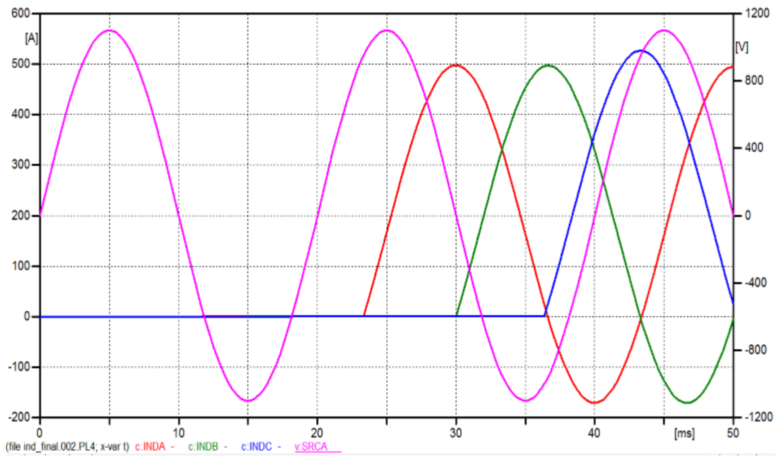


Figure 14: Inrush currents for closing of three phase inductor banks due to switching at voltage 60°: c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

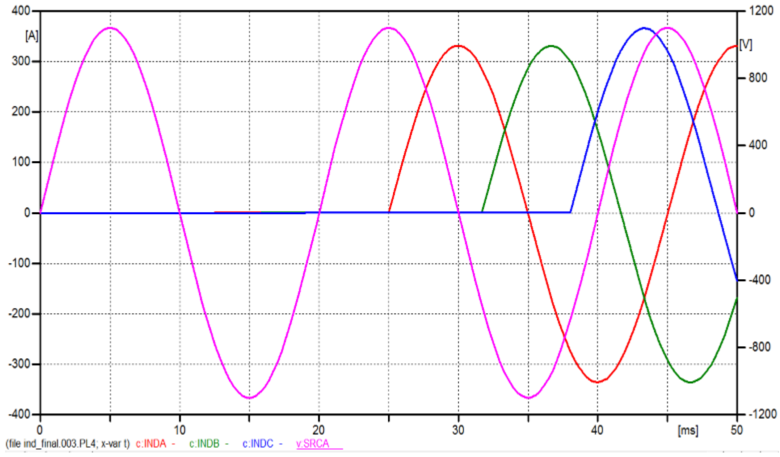


Figure 15: Inrush currents for closing of three phase inductor banks due to switching at voltage 90°: c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

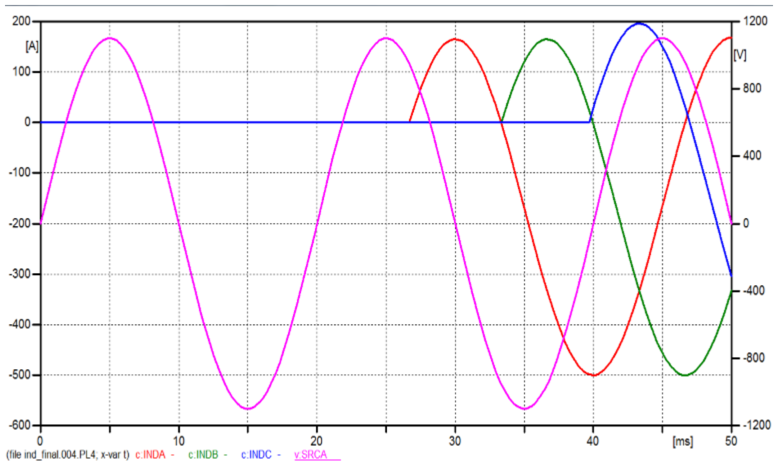


Figure 16: Inrush currents for closing of three phase inductor banks due to switching at voltage 120°: c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

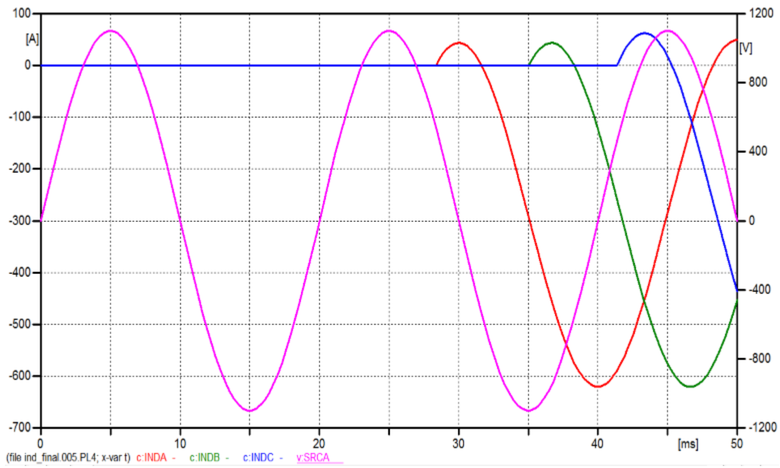


Figure 17: Inrush currents for closing of three phase inductor banks due to switching at voltage 150°: c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

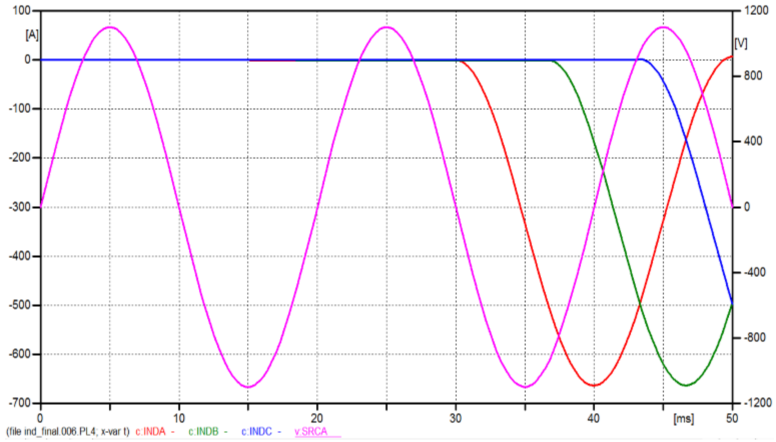


Figure 18: Inrush currents for closing of three phase inductor banks due to switching at voltage 180°: c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

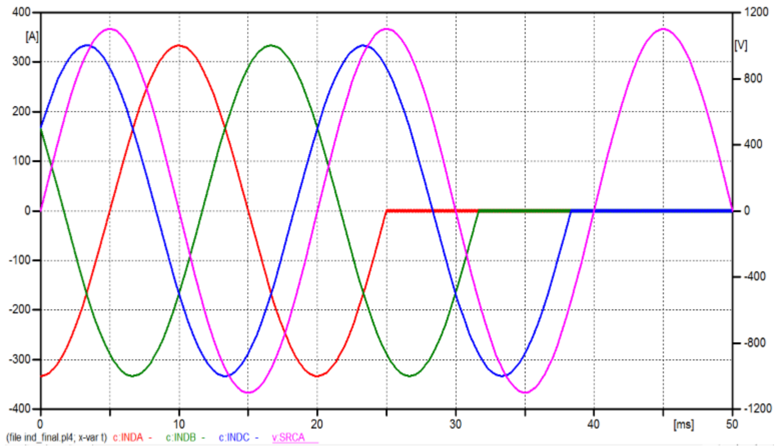


Figure 19: Currents in the respective phases during an open operation of the reactor : c:INDA represents current in Phase A, c:INDB represents current in Phase B and c:INDC represents current in Phase C. v:SRCA represents source voltage of phase A. Source voltage is on the right Y axis

Similarly, opening of capacitor bank at non-zero currents results high frequency TRV across the breaker. The magnitude of TRV varies depending on the switching instant and margin of current at which the circuit breaker actually opens.

Closing of reactor banks is quite common in utilities to avoid Ferranti effect. An uncontrolled closing of these banks might lead to heavy inrush current being injected into the load. These can trigger fault level tripping by the protection relays and heavy inter-turn forces among the inductor windings.So it is always favourable to switch the reactive load at current zero instant[1, 2].

Similarly opening of reactor is quite a crucial operation in terms of circuit breakers healthiness.If sufficient arcing time is not provided and the switching is not controlled to open at current zero instant re-strikes and re-ignitions might occur.

Thus, controlled switching of capacitors involves opening at current zero and closing at voltage zero. Controlled switching for inductor and capacitor banks is hence certainly useful reliability and safety of power systems.

References

[1] D. Goldsworthy, T. Roseburg, D. Tziouvaras, and J. Pope, "Controlled switching of hvac circuit breakers: Application examples and benefits," in *Protective Relay Engineers, 2008 61st Annual Conference for*, April 2008, pp. 520–535.

[2] "Controlled switching of hvac circuit-breakers (Ist part): Guide for application lines, reactors, capacitors, transformers," *CIGRE WG 13.07*, pp. 1–50, Sep 1998.

[3] "Controlled switching of hvac circuit-breakers (IInd part): Guidance for further application including unloading transformer switching, load and fault interruption and circuit breaker uprating," *CIGRE WG A3.07*, pp. 1–52, Sep 2004.