SHUNT CAPACITOR BANK SWITCHING TRANSIENTS: A TUTORIAL AND CASE STUDY

Govind Gopakumar, Huihua Yan, Dr. Bruce A. Mork
Michigan Technological University
Houghton, MI 49931

Kalyan K. Mustaphi
Northern States Power Company
Minneapolis, MN 55401

INTRODUCTION

Transient disturbances in power systems may damage key equipment, potentially having a great impact on system reliability. These transients may be introduced during normal switching operations, interruption of short circuits, lightning strikes, or due to equipment failure. Phasor analysis or other simplified analysis methods are usually inadequate due to system frequency dependencies and nonlinearities. Therefore, time-domain computer models are typically developed as a means of predicting the severity of the transient occurrences. The simulations are typically performed using simulation software such as the Electromagnetic Transient Program (EMTP). In this work, a royalty-free version of EMTP, called the Alternative Transients Program (ATP) was used.

During the switching of shunt capacitor banks, high magnitude and high frequency transients can occur [1, 5, 6, 7]. In earlier years, shunt capacitor banks have been more commonly installed at distribution and lower subtransmission levels. However, there has been a recent proliferation of new capacitor banks at transmission levels. Since larger higher-voltage capacitor banks have more stored energy and there is a higher system X/R ratio and less damping, this has raised concerns at Northern States Power Company (NSP) and other utilities regarding the vulnerability of their equipment.

Over the past several years, NSP has been installing a large number of capacitor banks at the 69-kV and 115-kV levels. This has been motivated by the need to provide steady-state voltage support, to provide reactive power support, and to increase power transfer capability. For example, area load growths and the Manitoba-Minnesota Transmission Upgrade (MMTU) Project have directly or indirectly required NSP and other utilities to add over 2 GVAR of capacitor banks in the region. At NSP, 80-MVAR banks at the 115-kV Elm Creek substation and 120-MVAR banks at the 115-kV Elliot Park substation provide reactive power support. Two 80-MVAR 115-kV capacitor banks at Split Rock are installed to provide steady state voltage support.

This paper provides an introduction to capacitor bank switching transients, illustrated using a simple single-phase system. A case study for capacitor bank switching at Split Rock is presented next, followed by a discussion and interpretation of some of the results.

CONCEPTUAL INTRODUCTION

The 34.5-kV per-phase system of Figure 1 is used to provide a conceptual introduction to some of the common transients involved in capacitor bank switching. It is built upon an example given in [1]. R_1 and L_1 represent the system source impedance. CB4 feeds two capacitor banks, represented by C_1 and C_2. S1 and S2 represent the circuit breakers used to switch the capacitor banks. L_B is the inductance of the bus spanning between the capacitor banks. R_2 and L_2 are the total impedance of the feeder and distribution transformer. A distribution-level capacitor bank is attached to the transformer secondary. CB3 can be used to initiate and interrupt a ground fault on the bus at some distance down the feeder, depending on location of the ground. Parameters are given in the Appendix. Using different portions of this system, five transients can be addressed: 1) energization inrush, 2) back-to-back energization, 3) outrush into a nearby fault, 4) voltage magnification, and 5) transient recovery voltage (TRV).

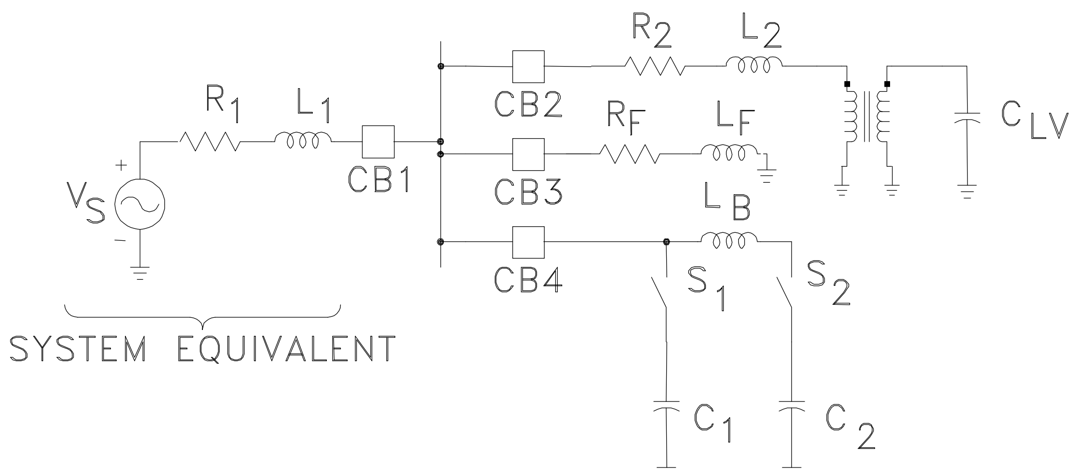

Figure 1. A simple 34.5-kV per-phase system used to illustrate capacitor bank transients.

1. Energization Inrush:

Energization inrush is a transient occurring when the first (or only) bank at the bus is energized. The transient is characterized by a surge of current having a high magnitude and a frequency as high as several hundred Hertz. There is also a transient overvoltage on the bus, caused by the surge of inrush current coming from the system source.

To illustrate, we begin with CB1 and CB4 closed, energizing C_1 by closing S1. The operative circuit consists of a Thevenin source in series with C_1. Analysis of switching transients typically makes use of superposition, breaking the transient into a) natural response caused by the switching and b) the forced response due to the 60-Hz system source. If we neglect system resistance, the natural response component of the inrush current into the capacitor may be approximated as:

$$i(t) = \frac{V(0)}{Z_0} \sin w_0 t \,, \tag{1}$$

where $Z_0 = \sqrt{\dfrac{L}{C_1}}\,, \quad w_0 = \dfrac{1}{\sqrt{LC_1}}\,,$

and V(0) is difference between the source voltage and the initial voltage of the capacitor at the instant of energization. It can be seen that as a capacitor bank size increases, peak inrush current increases and its frequency decreases. Reference [4] provides approximate methods of calculating the inrush, although it is recommended that an EMTP simulation be run to determine the effects of system damping.

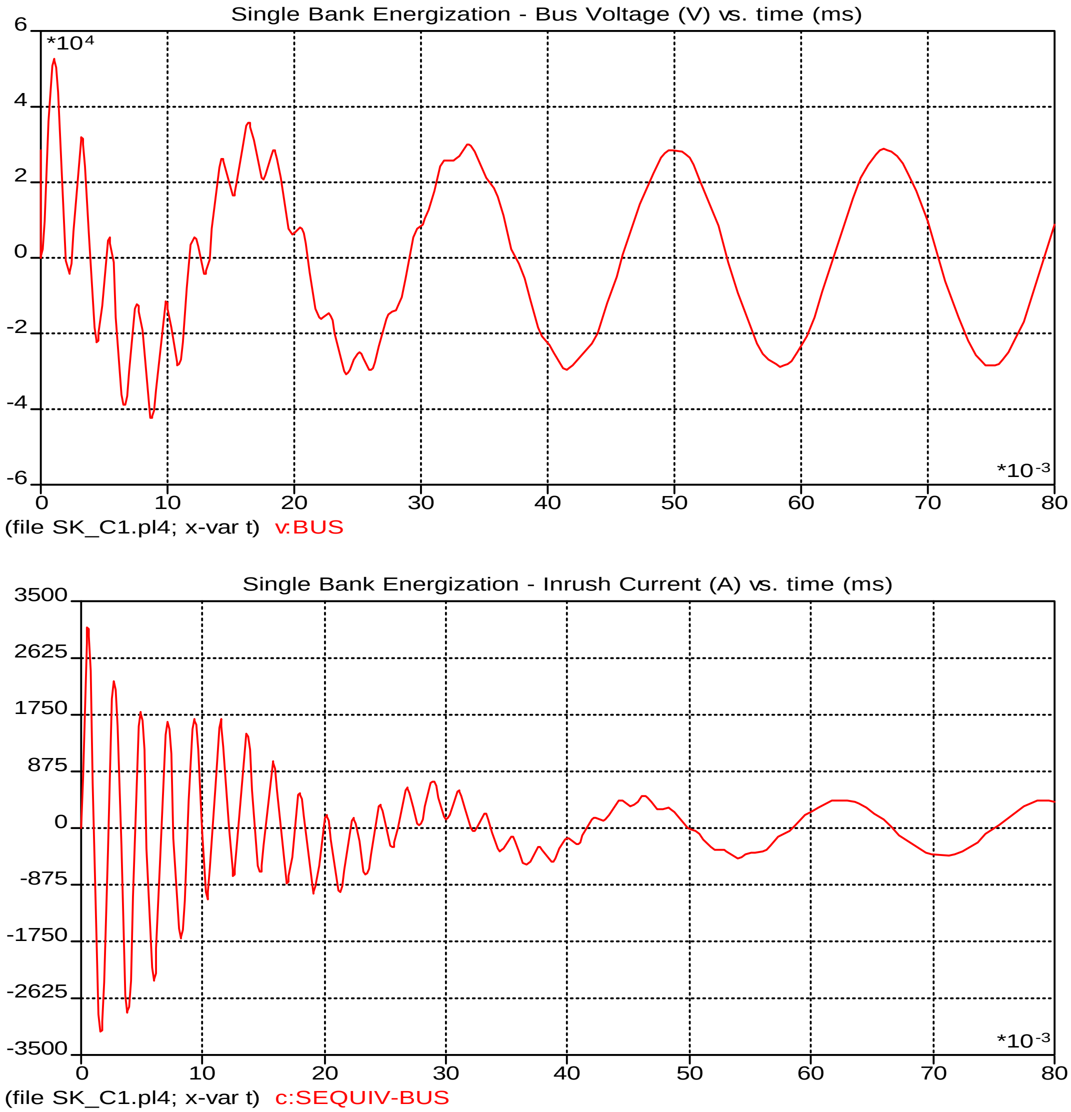

Figure 2. Energization inrush. Peak bus voltage = 1.87 pu. Peak current = 3041 Amps.

2. Back-to-back switching:

Energizing the second bank C_2 when the first bank C_1 is already energized is called back-to-back switching [5], and is simulated by closing switch S2 when C_1 is already operating in steady state. The resulting inrush to C_2 is a high-frequency transient which primarily involves the series combination of C_1, L_B, and C_2, driven by the voltage V(0) on C_1 at the instant S2 is closed. Just as with energization of a single bank, worst case occurs when the bus voltage is at its positive or negative peak value. This transient is typically in the kHz range. The expression for the high-frequency transient current riding on the steady-state 60-Hz response is [1]:

$$i(t) = \frac{V(0)}{Z_{01}} \sin w_{01} t \tag{2}$$

where, $Z_{01} = \sqrt{\frac{L_B}{C}}$, $w_{01} = \frac{1}{\sqrt{L_B C_{EQ}}}$, and $C_{EQ} = \frac{C_1 C_2}{C_1 + C_2}$.

There are empirical methods to calculate the expected transients [4]. However, this approach neglects the effects of the source and the rate of damping cannot be clearly determined. Such a high-order system cannot be solved using manual calculations. Numerical methods of solving the necessary differential equations have been developed, but the only practical means of solving it is with an EMTP-like program. Using our simple circuit as an example, we close S2 when the bus voltage is at its positive peak. The current inrush to C_2, shown in Figure 3, dies down in about 3 ms. However, it causes a dip in the bus voltage which causes a 300-Hz oscillation between L_1 and the capacitance of the now-paralleled banks $C_1 + C_2$ (Figure 4).

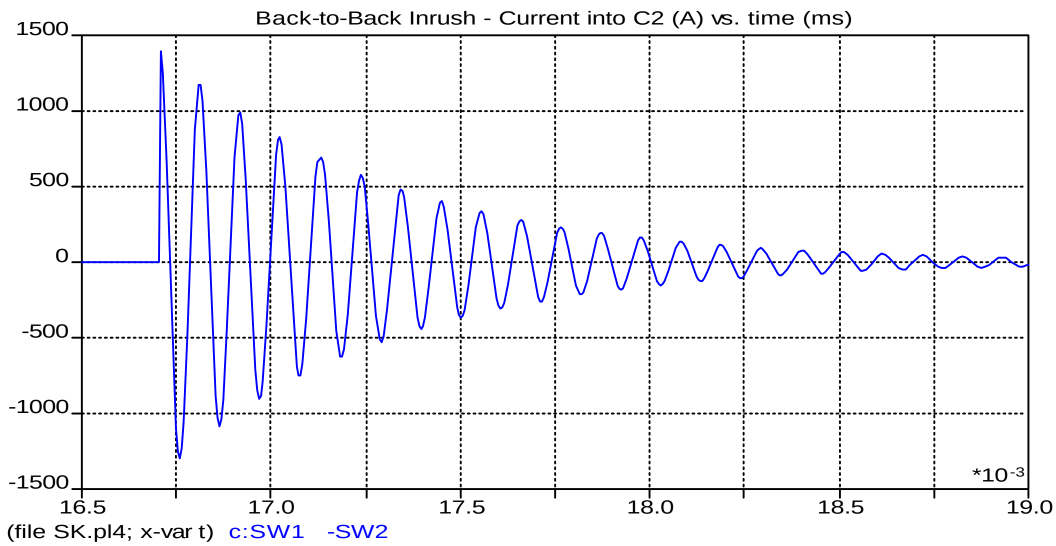

Figure 3. Back-to-back energization. Current inrush into C_2. Frequency = 9.4 kHz.

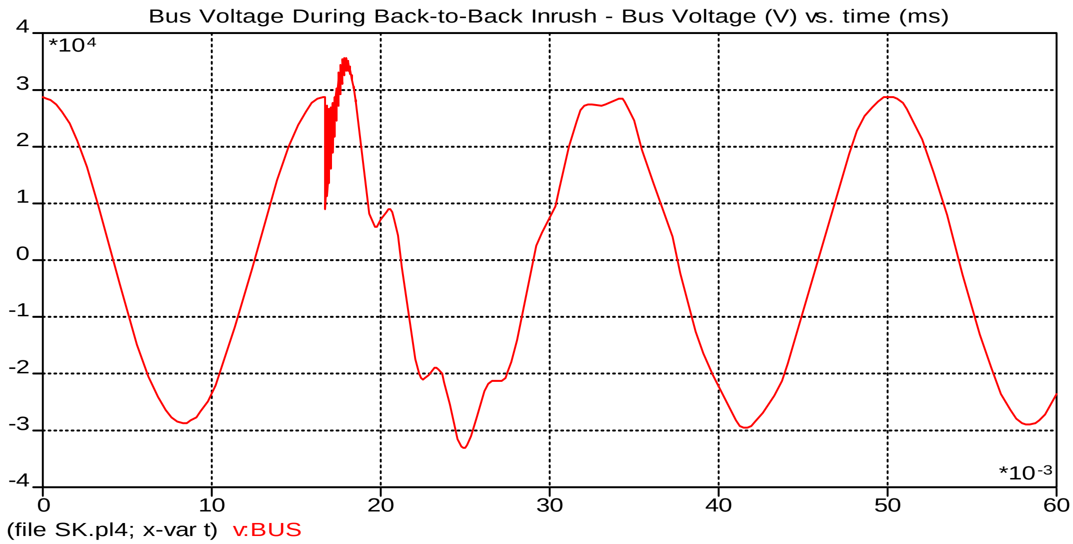

Figure 4. Transient in bus voltage following back-to-back switching.

3. <u>Outrush Transient:</u>

With capacitor bank C_1 operating in steady state, CB3 can be closed, simulating a fault at some distance down the local feeder. C_1 discharges into the fault, resulting in a damped oscillation with L_F. The outrush current from the capacitor is given by [1]:

$$i(t) = \frac{V(0)}{Z_{02}} \sin w_{02} t \tag{3}$$

where $Z_{02} = \sqrt{\frac{L_F}{C_1}}$, $w_{02} = \frac{1}{\sqrt{L_F C_1}}$, and

V(0) is the instantaneous magnitude of the voltage across capacitor C_1 at the instant of the fault. As the fault location is moved back toward the bus, L_F decreases, increasing the current magnitude and frequency of the outrush current. If a bus fault occurs, inductance is on the order of tens of micro-Henries, and outrush can be severe. Outrush-limiting reactors can be installed in series with each capacitor bank if necessary.

4. <u>Voltage Magnification:</u>

This transient manifests itself as a voltage increase when a capacitor bank is energized. A common scenario is the interaction between a distribution-level capacitor bank and another nearby bank on the transmission system. To reproduce it with our simple circuit of Figure 1, we close CB2 with C_1 already energized. If the natural frequency of L_1 and C_1 matches the natural frequency of L_2 and the distribution capacitor bank C_{LV}, then voltage magnification may occur.

$$w_0 = \frac{1}{\sqrt{L_2 C_{LV}}} = \frac{1}{\sqrt{L_1 C_1}} \quad (4)$$

Under such a condition, voltage magnification transients can be experienced at the distribution level capacitor (Figure 5). This could lead to severe overvoltages, which could ultimately lead to the failure of the capacitor bank. When a capacitor bank is added at the transmission level, it is important to rule out or mitigate any interaction with local distribution banks.

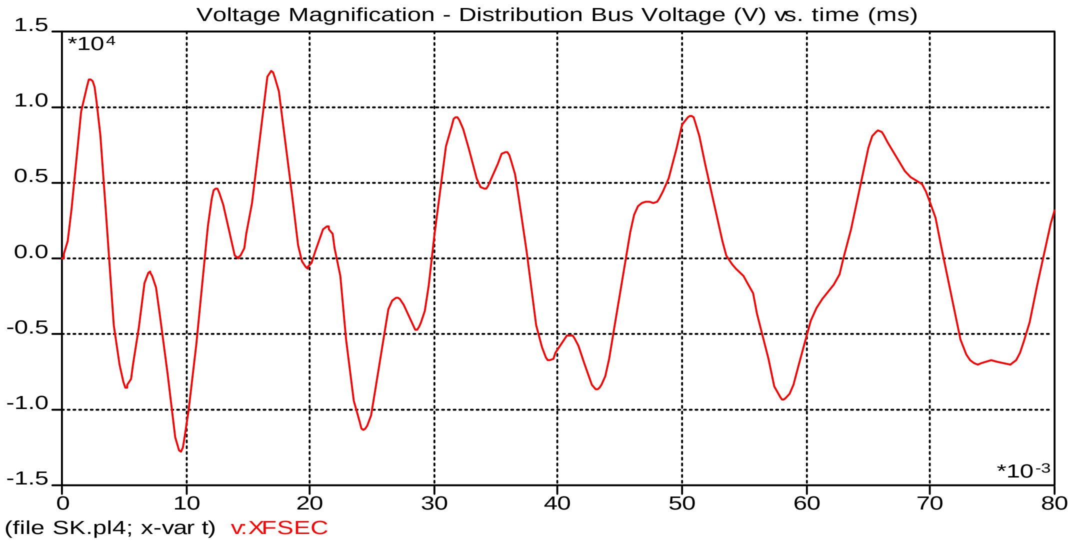

Figure 5. Voltage magnification at distribution bus. Peak voltage is 1.76 pu.

5. <u>Transient Recovery Voltage (TRV):</u>

This is the transient voltage that appears across the poles of a circuit breaker upon interrupting a circuit. This can be simulated in Figure 1 by considering the voltage across the contacts of CB1 after clearing a fault on the feeder or on the bus. During the fault, the voltage at the bus is very low or zero. When the breaker contacts open, the voltage on the source side "recovers" or jumps back up to rated system voltage.

However, the voltage on the source side of the circuit breaker recovers by charging up the bushing capacitance of the circuit breaker. Additional shunt capacitances may also be present in the form of stray capacitance or capacitor banks on the source side of the circuit breaker. The total shunt capacitance present, as it is charged, resonates with the source inductance L_1.

If there is only bushing capacitance, the natural frequency is very high. If there is little damping (i.e. if R_1 is small), the peak voltage across the circuit breaker can reach 2.0 pu. The results of a simulation using our simple system are shown in Figure 6. In this case, peak recovery voltage reaches 1.4 pu, and the frequency is over 5 kHz.

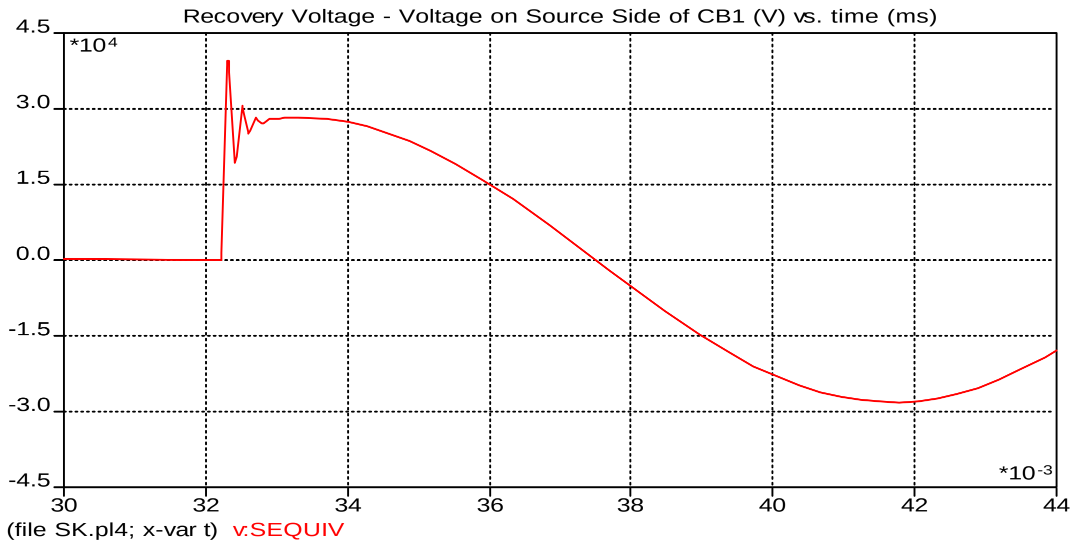

Figure 6. Transient recovery voltage.

CASE STUDY

A case study of the capacitor bank switching at the 115-kV Split Rock Substation is provided here. The motivation behind this project was the proposed increase in capacity of the capacitor banks at split rock. NSP was concerned about the possibility of high magnitude transients due to an upgrade to larger capacitor banks. This project was undertaken as a part of the research collaboration between NSP and Michigan Technological University (MTU). The transient model was developed in 1998.

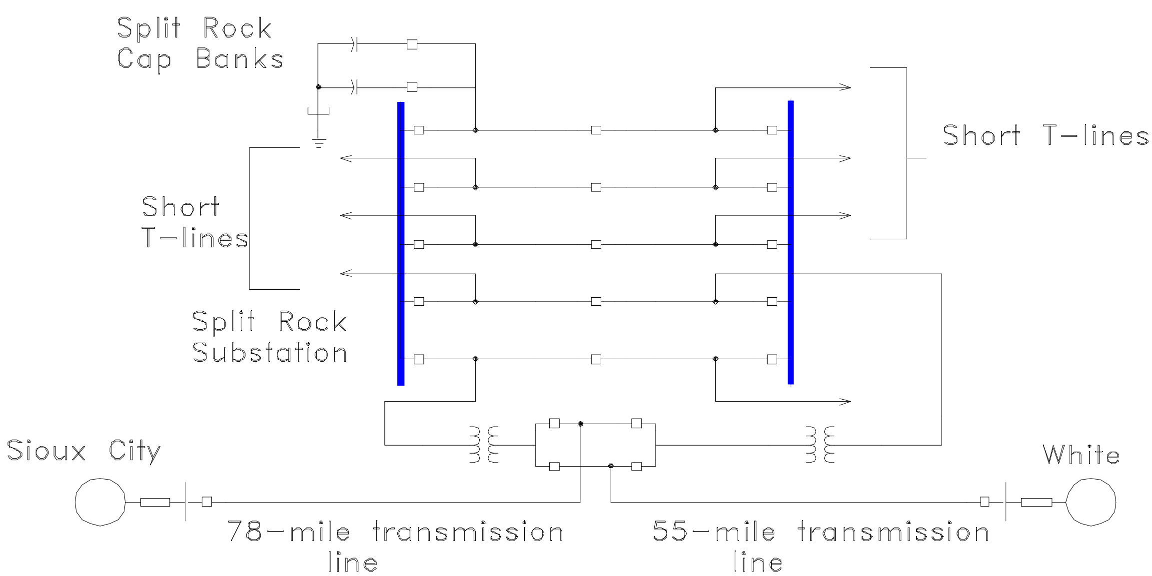

Figure 7. Elementary one-line of the 115-kV Split Rock substation.

This is a breaker-and-a-half scheme, with five bus bays. Shunt capacitor banks are connected to one of the bus bays. An important feature, from the modeling aspect, is the presence of two long 345-kV transmission lines connected to this substation. These lines greatly reduce the system source impedance and increase its X/R ratio.

The system model can be divided into the following sub-categories: (a) Bus work, (b) Transmission lines, (c) Transformers, (d) Capacitors & loads, (e) System equivalents.

(a) Bus work modeling: All buswork is divided into short sections according to the actual conductor configuration [3]. Coupling effects between the parallel bus bays are taken into account.

(b) Transmission lines: The transmission lines connected to the Split Rock substation consist of two long 345-kV transmission lines from Sioux City and White, and a number of shorter 115-kV transmission lines.

(c) Transformers: Two 345/115-kV transformers are present in the system.

(d) Capacitor, reactor & load modeling: Capacitors and reactors are modeled using simple lumped capacitances. The loads in the system are modeled using lumped elements.

(e) System Equivalents: The area of concern is modeled in detail. As it is not possible to model the entire power system, the system outside of the bounds for the model are decided are represented by a 60-Hz system short-circuit equivalent.

RESULTS

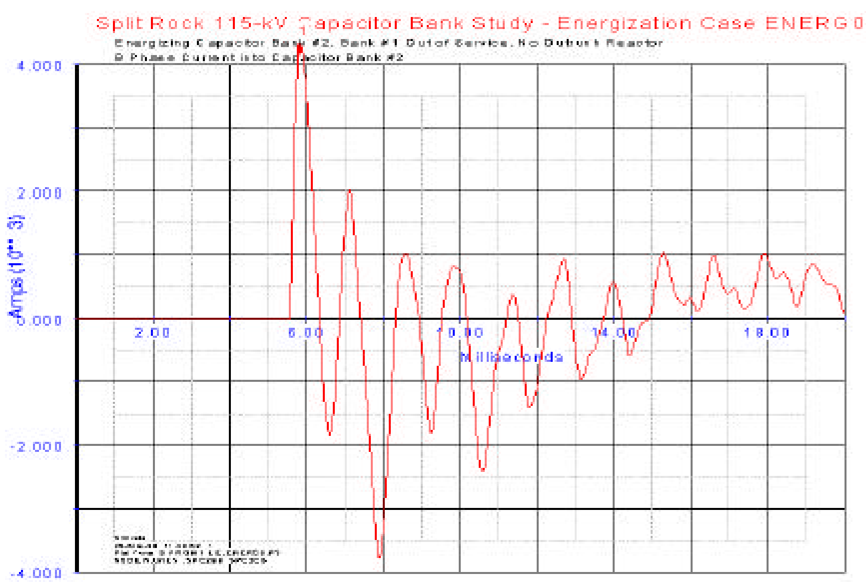

Figure 8. Inrush current into a single capacitor bank, without any reactor.

Inrush Transient: The capacitor bank was energized at the peak of the B-phase voltage. A plot of the inrush case with no inrush reactor is shown in Figure 8. Capacitor transients can have a damaging effect on circuit breakers. Figure 9 shows the variation of the inrush for different inrush reactor sizes. It can be seen that with the increase in reactor size, the inrush current decreases.

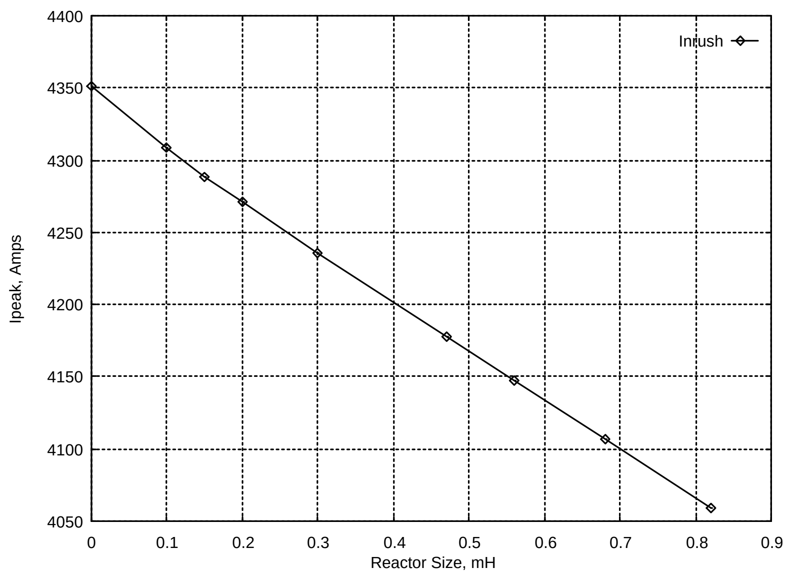

Figure 9. Peak Inrush currents for different reactor sizes.

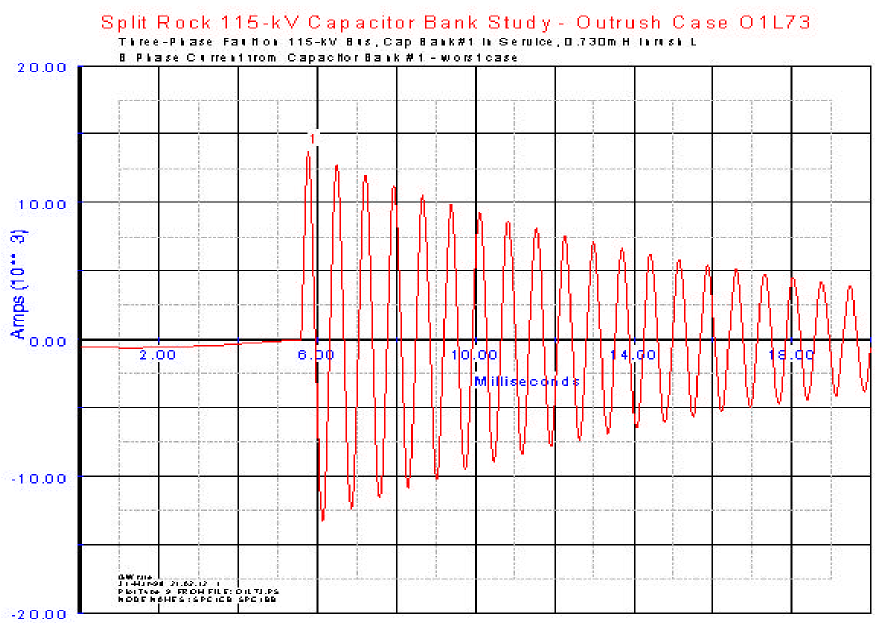

Figure 10. B-phase transient outrush current from Cap Bank #1 for a three phase fault at the 115-kV bus at Split Rock, with 0.73mH reactor.

Outrush Transient: The outrush transient is simulated by introducing a three-phase fault at the capacitor bank bus with only one of the capacitor banks in service. The fault is simulated at the peak of the B-phase voltage in order to simulate the worst case. Figure 10 shows the plot of the outrush current with a reactor of 0.73mH.

The product of the peak transient current and the peak transient frequency is an important factor of merit for circuit breakers in this context. General-purpose circuit breakers have a maximum limit of 2×10^7 while special purpose circuit breakers have a maximum limit of 6.9×10^7 [4]. Figure 11 shows the variation of the product of the peak transient frequency with the peak transient current. From the plot it can be seen that a general purpose circuit breaker can be employed only with an inductor of 0.8 mH. A special purpose breaker can be used when the size of the inductor is 0.15mH or larger.

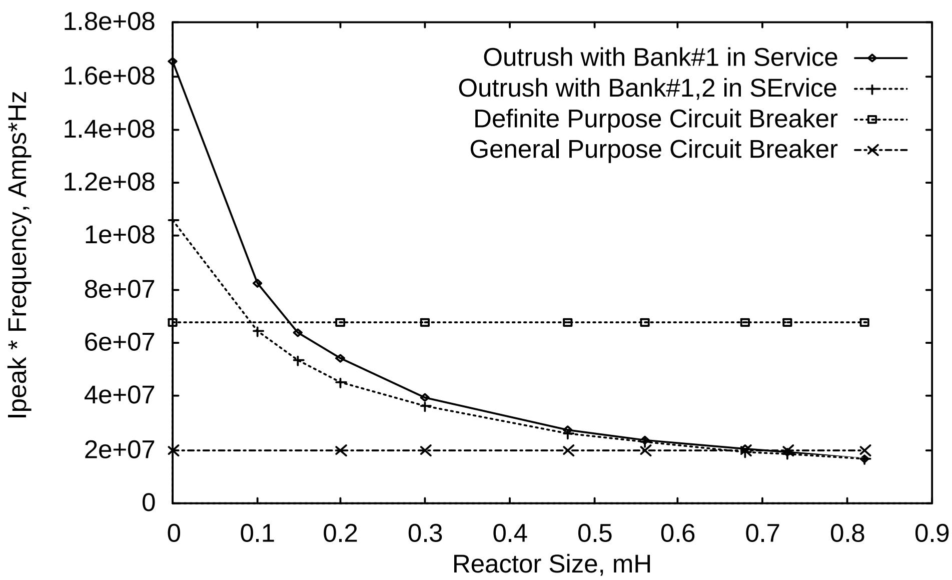

Figure 11. Product of peak outrush current & frequency for various reactor sizes.

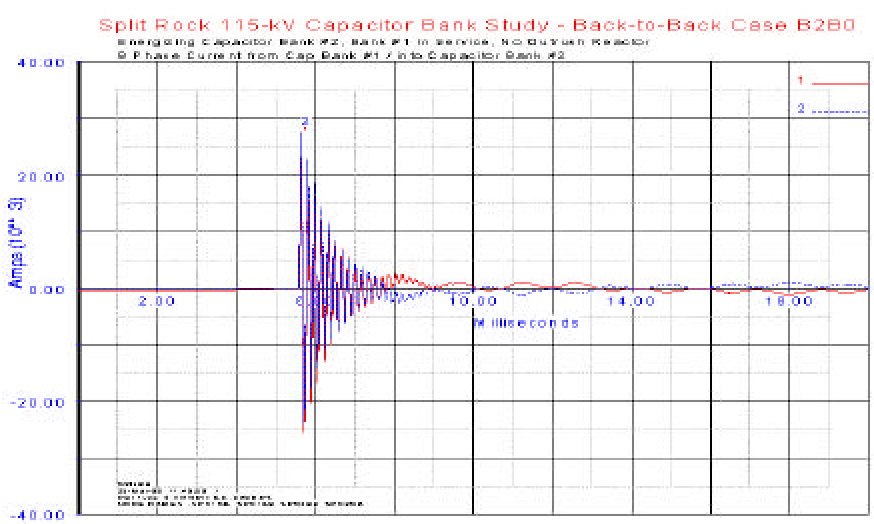

Figure 12. Inrush current from/into capacitor banks in back-to-back switching.

Back-to-back cases: As in the case of the inrush transient, the switching takes place at the peak of the B-phase voltage. A plot of the inrush current, resulting from energizing the second capacitor bank in the presence of the first, is presented in Figure 12. The peak current was seen to be 28.1-kA, with an oscillation frequency of 5.6 kHz.

Voltage Magnification: For this study, there were seven distribution capacitor banks at the nearby West Sioux Falls Substation, rated 1300-kVAR, 13.8-kV. Three of them are located on the feeders on one bus section, while the other four are located on feeders on another bus section. There are two 115-kV/13.8-kV distribution transformers at the substation, one for each 13.8-kV bus section. Each distribution capacitor bank can be operated independently. This creates a total of 13 combinations of operations. To investigate all possible voltage magnification cases, 26 cases were simulated considering possible operations of two 115-kV capacitor banks at Split Rock substation. To find worst cases, statistical simulations were run for each capacitor banks configuration. No surge arresters were included in this study.

Highest peak voltage on the 13.8-kV bus at West Sioux Falls Substation is 20.66kV, or 1.83 pu, occurring during single-bank energization at Split Rock when only the four capacitor banks on one bus section are in service. Table I presents highest peak voltage on 13.8-kV bus at West Sioux Falls with all possible operating configurations. Figure 13 is the visual plot of Table I.

Table I. Peak Voltages under Different Operation Configurations

Transient Type		1 feeder	2 feeders	3 feeders	4 feeders
Single-Bank Energization	0 feeder ON	17.92kV	19.16kV	19.37kV	20.66kV
	1 feeder ON	17.91kV	19.26kV	19.50kV	20.52kV
	2 feeders ON		18.88kV	19.23kV	20.75kV
	3 feeders ON			18.85kV	20.04kV
Back-to-Back Switching	0 feeder ON	16.32kV	17.50kV	17.91kV	17.93kV
	1 feeder ON	16.38kV	17.63kV	18.04kV	18.05kV
	2 feeders ON		17.40kV	17.90kV	17.98kV
	3 feeders ON			17.62kV	17.74kV

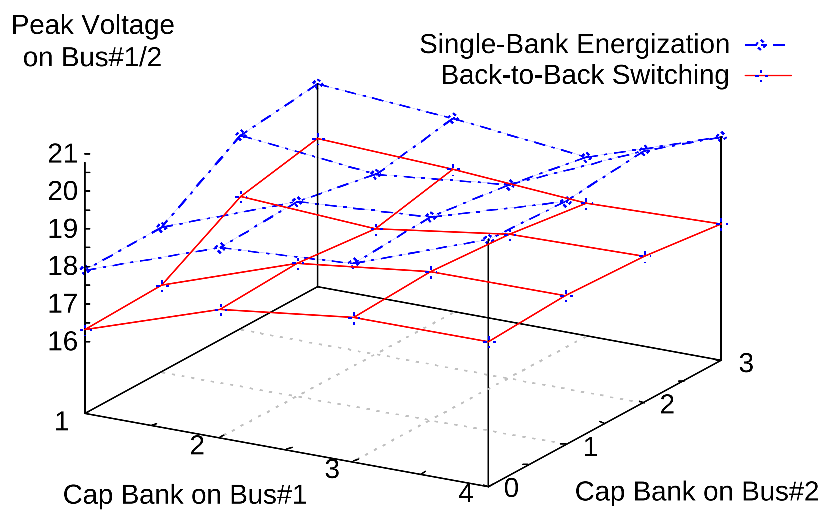

Figure 13. Peak transient voltages at 13.8 kV bus at West Sioux Falls with different capacitor configurations.

Capacitor Bank Reclosing cases: In the absence of any discharging device, the capacitor bank retains the trapped charge. This can lead to extremely high transient voltages at the re-energization of the capacitor. Either surge arresters or voltage transformers are employed to provide voltage discharge prior to reclosing. For the study, a voltage transformer/surge arrester was connected across the energized capacitor and the re-energization transient was examined under normal and half load conditions. The capacitor bank was re-energized at the voltage peak opposite in polarity with the trapped voltage to simulate the maximum transient. Table II shows the transient voltages for different combinations.

Table II. Transient peak voltages for capacitor bank re-energization

Cap. Voltages→	Maximum Charge	With Voltage Xfmr.	With Surge Arrester
50 % load	**Aϕ=219kV** **Bϕ=191kV** **Cϕ=194kV**	**Aϕ=174.9kV** **Bϕ=179.6kV** **Cϕ=160.7kV**	**Aϕ=177kV** **Bϕ=179kV** **Cϕ=165kV**
25 % load	**Aϕ=245kV** **Bϕ=200kV** **Cϕ=235kV**	**Aϕ=224kV** **Bϕ=184kV** **Cϕ=207kV**	**Aϕ=189kV** **Bϕ=180kV** **Cϕ=182.5kV**

CONCLUSION

Although some estimations of capacitor bank switching transients can be made by hand calculations, an EMTP study is really required to properly model the complex behaviors of the power system. Once the model has been developed, many scenarios can be simulated, and detailed statistical studies can be performed.

The study outlined in this paper is by no means a comprehensive and complete representation of the work carried out. Rather, it is meant to give the reader an appreciation for the basic behaviors observed and the types of things to be concerned about.

There are other complex interactions between capacitor banks and system nonlinearities that have not been mentioned here. These include phenomena like nonlinear ring-down of capacitor banks involved in reclosing schemes [8]. Also, adding capacitor banks to the system can change the frequency response of the system, which is particularly a concern in the vacinity of a DC terminus.

APPENDIX – CIRCUIT PARAMETERS

R_1 = 0.5 Ohms L_1 = 3 mH R_2 = 0.001 Ohms L_2 = 12 mH

C_1 = 40.1 μF (18 MVAR) C_2 = 22.3 uF (10 MVAR) C_{LV} = 601 μF

Dist. Transformer: 4:1 ratio L_B = 19 μH C_{BUSH} = 300 pF

REFERENCES

[1] A. Greenwood, *Electrical Transients in Power Systems*, 2nd Edition, John Wiley & Sons Inc., 1991.

[2] H. W. Dommel, *EMTP Theory book*, Microtran Power System Analysis Corporation, Vancouver, British Columbia, May 1992.

[3] H. Yan, B.A. Mork, K.K. Mustaphi, “Shunt Capacitor Transient Inrush/Outrush Currents on the 115-kV Bus at Split Rock Substation,” Internal Study, May 1998.

[4] IEEE Standard C37.012-1979 - Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers.

[5] *IEEE Standards Collection on Power Capacitors*, ISBN 1-55937-416-0, 1994.

[6] John H. Brunke, “Application of Power Circuit Breakers for Capacitive and Small Inductive Current switching,” *Application of Power Circuit Breakers*, IEEE Tutorial Course 93 EHO 388-9-PWR, 1993.

[7] *Modeling and Analysis of System Transients Using Digital Programs*, IEEE PES Special Publication TP-133-0 (Ch.4 – Modeling Guidelines for Switching Transients).

[8] L. Ganatra, P. Mysore, K. Mustaphi, A. Mulawarman, B.A. Mork, G. Gopakumar, “Application of Reclosing Schemes in the Presence of Capacitor Bank Ringdown,” Proceedings of American Power Conference, Chicago, IL, April 1999.