Synchronous closing breakers for controlling 43.34 MVARs back-to-back 115 kV capacitor banks

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Abstract - The increase in electrical energy demand on the northern part of Puerto Rico, along with the fact that most of the generation is located in the southern part of the island forces the Puerto Rico Electric Power Authority (PREPA) to depend heavily on its transmission system capacity to transfer real and reactive power. The supply of reactive power to the north is essential to improve PREPA's margin of voltage stability when exposed to major transmission line outages. To face this situation PREPA is installing five (5) new 115 kV capacitor banks, 43.34 MVARs each, in the northern part of the island.

Two of these new capacitor banks will be installed on the same 115 kV bus (back-to-back operation) at the Sabana Llana Transmission Center. This Station serves many sensitive industrial loads. Due to the size of the new capacitor banks, a conventional breaker should not be used since the rate of change of inrush current exceeds its capacity. The Planning & Research Division of PREPA performed a series of ATP (Alternative Transient Program) simulations to evaluate the use of synchronous closing (zero voltage closing) breakers to control each of the capacitor banks on the back-to-back configuration. This evaluation not only guarantees a safe operation of both capacitor banks but also eliminates a potential power quality problem by minimizing the transient distortion in the voltage waveform during energization of the capacitor banks.

Keywords – Inrush current, synchronous closing, power quality, back-to-back operation

I. INTRODUCTION

PREPA is a public utility responsible for the generation, transmission and distribution of electrical energy in Puerto Rico. The installed generation capacity of PREPA is 4,922 MW. Of this total capacity approximately 3,500 MW (71%) is installed on the southern part of the island. On the other hand, the northern part of the island has the largest concentration of industries, pharmaceuticals and population. This situation, along with the fact that Puerto Rico is an island, forces our transmission system to play a vital role in the transfer of real and reactive power from south to north. Our transmission network is composed of a grid of 230 kV and 115 kV lines. Figure 1 shows a general map of the island with the distribution of major loads and electric power generation.

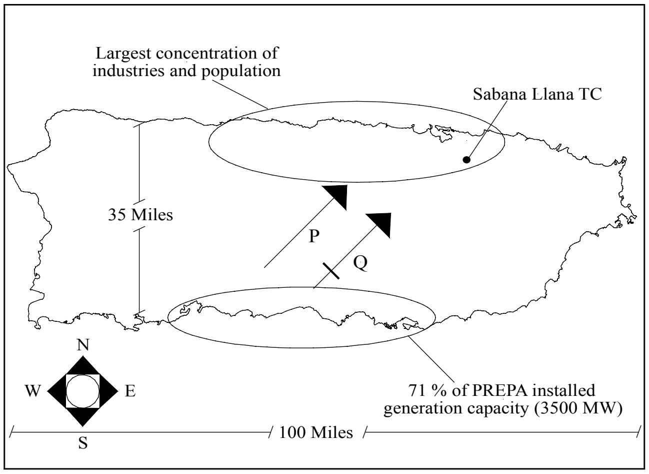

Figure 1. Map of Puerto Rico including major loads and electric power generation locations.

The installation of capacitor banks has been the most efficient and practical solution used by PREPA to complement the generation of reactive power in the northern part of the island. Five (5) new 115 kV capacitor banks, 43.34 MVARs each (Wye grounded), are being installed in major load transmission centers (TC) of the northern part of the island. These new capacitor banks will increase the reactive power dynamic reserve of the generating units in the north and improve the power factor of the system. As a consequence the generating units in the north will operate at a higher power factor increasing the margin of system voltage stability under contingency conditions of major transmission lines.

Also, the integration of these new capacitor banks will significantly decrease the reactive power losses in major transmission lines running from south to north, reducing the reactive power demand of the major generating units located in the south. The size and location of the new capacitor banks were optimized based on power flow analysis techniques to minimize the real and reactive power losses of the transmission system [1].

Two of these new 115 kV capacitor banks will be installed on the same 115 kV bus (back-to-back operation) at the Sabana Llana TC. This transmission center is one of PREPA's most important load centers. Many sensitive industrial, residential and commercial loads are supplied from Sabana Llana TC. It is also a major link between the north and south electrical systems.

The integration of these two new banks at Sabana Llana TC resulted in a very interesting and intensive study, not only because of the back-to-back operation, but also because there are existing 115 kV capacitor banks at nearby stations.

II. CAPACITOR BANK SWITCHING BASIC THEORY

Figure 2 shows a simplified circuit of an electrical system interacting with two capacitor banks in a back-to back configuration.

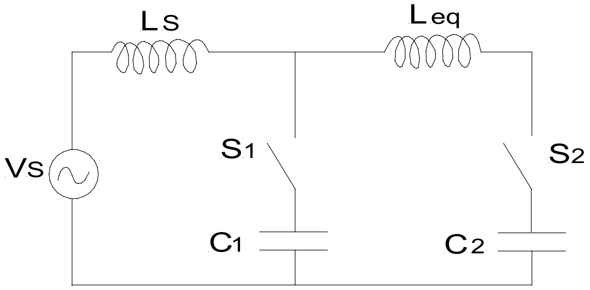

Figure 2. Simplified LC circuit with back-back configuration of capacitor banks

In general, the addition of an isolated shunt capacitor (closing S1 in Figure 2) to a predominantly inductive circuit, like an electric power system, results in a transient overvoltage at a natural frequency given by the following equation [2]:

$$f_{natural}\,(\text{Hz}) = \frac{1}{2\pi\sqrt{Ls \times C1}} \qquad (1)$$

Ls = equivalent system inductance (mH)
C_1 = Capacitance of bank 1 (μF)

This transient overvoltage can theoretically reach peak phase to ground values of 2.0 per unit and will oscillate in the system depending on the damping present [2].

The energizing current will oscillate at the same natural frequency and its peak value will depend on the driving voltage (system voltage at time of closing), the voltage trapped in the capacitor and the surge impedance of the circuit [2].

$$I_{peak}\,(\text{Amps}) = \frac{Vs - Vc1(0)}{Zo} = \frac{Vs - Vc1(0)}{\sqrt{\dfrac{Ls}{C1}}} \qquad (2)$$

Vs = peak value of system voltage at time of closing

$Vc1(0)$ = peak value of voltage in capacitor bank 1 prior to energization

$$Zo = \sqrt{\frac{Ls}{C1}} = \text{Surge impedance}$$

The natural frequency of the transient phenomena is generally greater than the system frequency (60 Hz in our case), hence the system voltage (Vs) may be considered a constant since its magnitude practically does not vary during the transient period. The amount of damping present in the circuit will determine the duration of the oscillation in the system.

In the particular case of a back-to-back energization of capacitor banks, one bank is energized near to another bank that was previously energized (Closing S2 with S1 already closed in Figure 2). The inductance limiting the inrush current in this case is the sum of the bus inductance, the inductance associated with the capacitor banks and the inductance of any aerial line or cable connecting them [3] (*Leq* in Figure 2). The value of this equivalent inductance is normally in the order of microHenries (μH). As a result, in the back-to back operation there will be a huge exchange of charge between the two capacitors during the transient period. The natural frequency and inrush current varies from the isolated capacitor bank case since capacitors 1 and 2 are now effectively in series and the inductance present during this transient is the equivalent inductance described before.

$$f_{natural}\,(\text{Hz}) = \frac{1}{2\pi\sqrt{Leq \times Ceff}} \qquad (3)$$

Leq = equivalent inductance; sum of inductances associated with bus, banks and lines or cables connecting both capacitor banks (μH).

C_{eff} = effective capacitance; Series combination of capacitance of banks 1 and 2 (μF).

The energizing current flowing from capacitor bank 1 into capacitor bank 2 will oscillate at the same natural frequency and again its peak value will depend on the driving voltage (capacitor bank 1 voltage at time of closing), the voltage trapped in the capacitor bank 2 and the new surge impedance of the equivalent circuit.

$$I_{peak}\,(Amps) = \frac{Vc1 - Vc2(0)}{Zo} = \frac{Vc1 - Vc2(0)}{\sqrt{\dfrac{Leq}{Ceff}}} \qquad (4)$$

$Vc1$ = peak value of bank 1 voltage at time of closing

$Vc2(0)$ = peak value of voltage in bank 2 prior to energization

$$Zo = \sqrt{\frac{Leq}{Ceff}} = \text{Surge impedance}$$

The system will also act to charge bank 2 but in a much smaller contribution than bank 1 does. Again, the natural frequency of the transient phenomena is greater than the system frequency (60 Hz in our case) hence the system voltage (Vs) may be considered a constant since its magnitude practically does not vary during the transient period.

It is important to notice that the new surge impedance (Zo) is much smaller for the back-to-back operation than for the energization of an isolated bank. This is true since Leq << Ls and Ceff is smaller than C_1. With these changes there will be a huge inrush current flowing between the banks at a much higher natural frequency.

This high frequency – high magnitude transient current can produce excessive mechanical stresses to system components. For circuit breaker applications, ANSI Standard C37.06-2000 establishes rated inrush currents and rated inrush current frequency for back-to-back operation of capacitor banks [4].

According to ANSI Standard C37.06-2000: "The rated inrush current peak is the highest magnitude of current that the circuit breaker shall be required to close at any voltage up to the rated maximum voltage. The rated transient inrush current frequency is the highest frequency that the circuit breaker shall be required to close at 100% rated back-to-back capacitor switching inrush current rating".

"For applications below 100% of rating, the product of the inrush current peak and the natural frequency shall not exceed the product of rated inrush current peak and rated transient inrush current frequency". This product establishes the maximum rate of change of inrush current with respect to time (di/dt in Amperes/μseconds).

Traditional techniques used to minimize the transient overvoltages and inrush currents include metal oxide varistor (MOV) arresters, current limiting reactors and preinsertion resistors. A MOV arrester clips the transient overvoltage to a certain level while discharging the surge. A current limiting reactor increases the surge impedance and as a result lowers the inrush current of the capacitor bank and a preinsertion resistor damps the oscillations of the transient wave [5].

A more recent and efficient method called *synchronous closing* or *Zero voltage closing* (ZVC) performs the energization of the capacitor bank at a specific point in the voltage waveform. Theoretically, by measuring the bus voltage and using a control algorithm, the synchronous closing breaker can energize the capacitor bank (Wye grounded) when the voltage is at zero potential (*Zero voltage closing* breakers). This would minimize both the transient overvoltage and the related inrush current [6].

III. CASE STUDY

Figure 3 shows a simplified one line diagram of the study area. In addition to the two new 43.34 MVARs 115 kV capacitor banks in Sabana Llana TC, there is an existing 31.7 MVARs 115 kV capacitor bank at Canóvanas TC (7.4 miles away from Sabana Llana TC). There is another 43 MVARs 115 kV existing capacitor bank 10 miles from Sabana Llana TC at the Hato Rey TC. A future 43.34 MVARs 115 kV capacitor bank will be installed at Berwind TC (3.3 miles away form Sabana Llana TC)

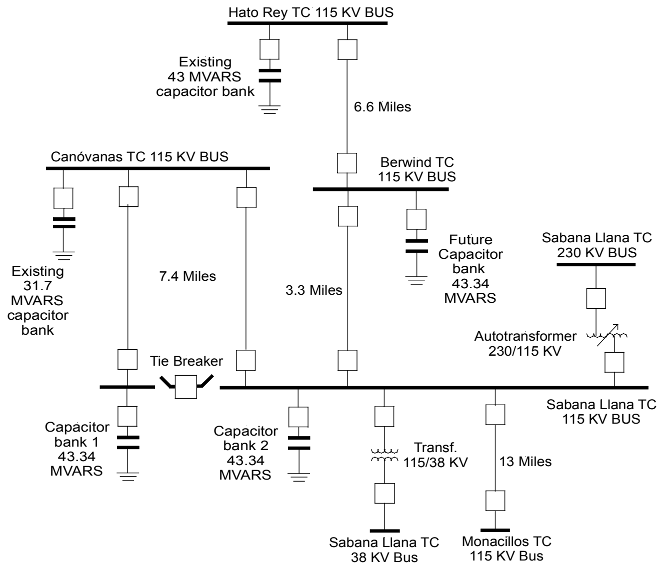

Figure 3. One line diagram of the study area of Sabana Llana TC

In the back-to-back configuration at Sabana Llana TC there would be two 43.34 MVARs capacitor banks separated only by the bus inductance as mentioned before. The corresponding capacitances and inductances involved are:

$C1$ = 9.39 μFarads; 43.34 MVARs

$C2$ = 9.39 μFarads; 43.34 MVARs

Leq = 178 μHenries; bus, line and banks inductances

Using equations (3) and (4) and considering energizing bank 2 (uncharged) at peak system voltage, the expected peak transient inrush current and frequency are:

$f_{natural}$ (kHz) = 5.5

I_{peak} (kAmps) = 15.3

Using ATP [7] and its graphical preprocessor ATPDraw [8] we were able to simulate the back-to-back energization of capacitor bank 2 (capacitor bank 1 previously energized) at different system conditions.

A. Back-to-Back closing at Peak System Voltage

Figures 4 and 5 show inrush current and frequency for both capacitor banks during back-to-back energization at peak system voltage. In Figure 6 we can see the exchange of charge between both banks during the transient period. Figure 7 shows the phase voltages distortion at Sabana Llana TC during this operation.

Existing capacitor banks at remote Stations (Canóvanas and Hato Rey) also act to charge capacitor bank 2 but in a much smaller contribution than capacitor bank 1 does in the back-to-back configuration at Sabana Llana.

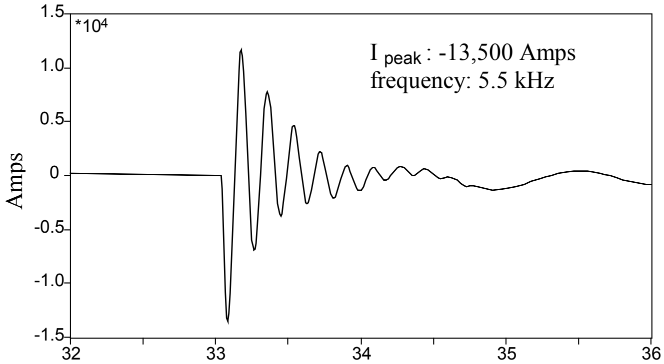

Figure 4. Capacitor bank 1 phase "A" current during back-to-back energization at peak system voltage.

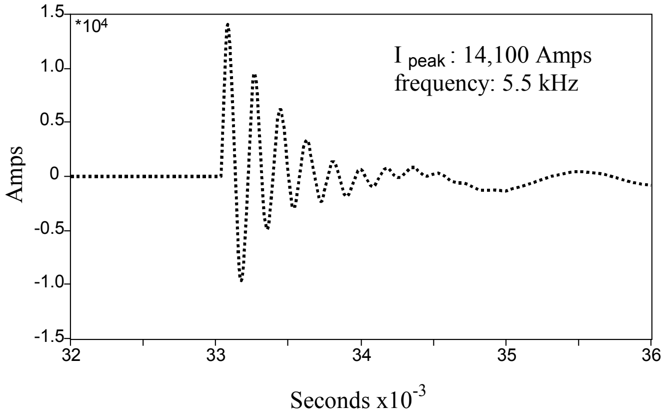

Figure 5. Capacitor bank 2 phase "A" current during back-to-back energization at peak system voltage.

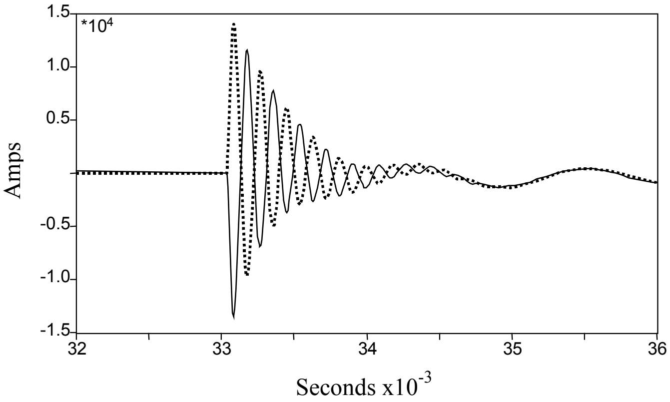

Figure 6. Capacitor banks 1 and 2 phase "A" currents during back-to-back energization at system peak voltage.

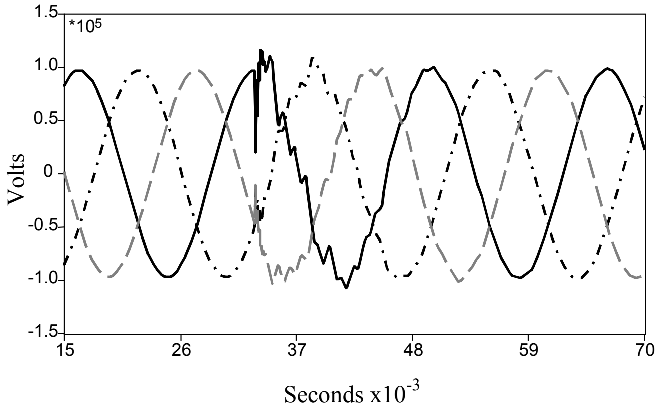

Figure 7. Phase voltages distortion in Sabana Llana 115 kV bus during back-to-back energization at system peak voltage.

Table I summarizes the results obtained during the back-to-back energization at peak system voltage. A conventional breaker back-to-back rated values for inrush current and frequency, according to ANSI Standard C37.06-2000, are included for comparison. It is important to notice that both breakers exceed their capacity of rate of change of inrush current when energized at voltage peak in the back-to-back operation.

Table I. Rate of change of inrush current with respect to time for breakers of both capacitor banks during energization of bank 2 at peak system voltage.

	Peak Current (Amps)	**Frequency (kHz)**	**Rate of change (di/dt) (Amps/μsec)**
Breaker - Bank 1	13,500	5.5	467
Breaker - Bank 2	14,100	5.5	487
ANSI C37.06-2000 Conventional Breaker	16,000	4.25	427

B. Back-to-Back Synchronous Closing

The Planning and Research Division of PREPA recommended synchronous closing technology for the breakers of both capacitor banks to be installed in Sabana Llana TC. In addition to the safety and reliability issues related with the results summarized in Table I, the recommendation was based on PREPA's concern on the power quality of the load centers at Sabana Llana TC.

Figures 8 and 9 show inrush current and frequency for both capacitor banks during back-to-back energization at system voltage zero (Zero Voltage Closing). Figure 10 shows the phase voltages distortion at Sabana Llana TC during this operation.

These Figures illustrate the advantage of using synchronous closing technology for minimizing voltage distortion and limiting the rate of change of inrush current with respect to time experienced by both breakers.

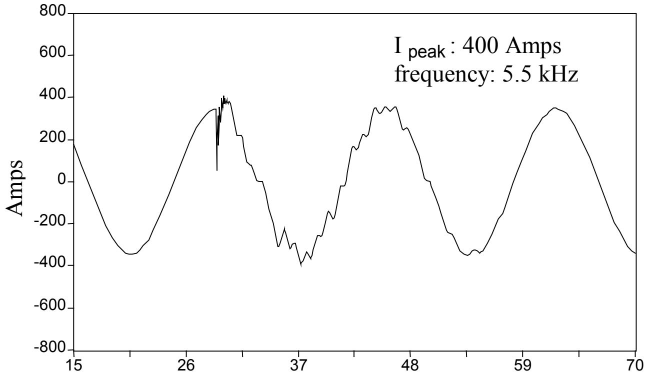

Figure 8. Capacitor bank 1 phase "A" current during back-to-back energization at system zero voltage.

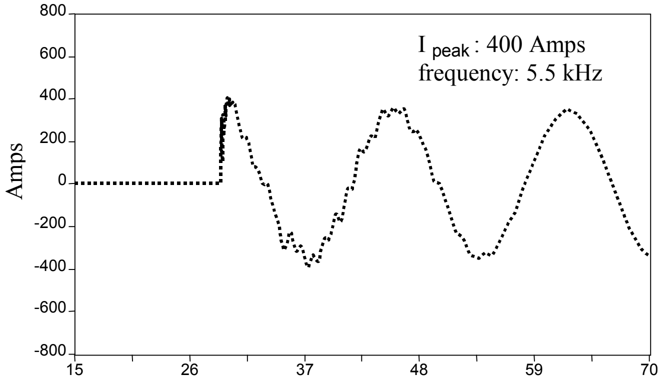

Figure 9. Capacitor bank 2 phase "A" current during back-to-back energization at system zero voltage.

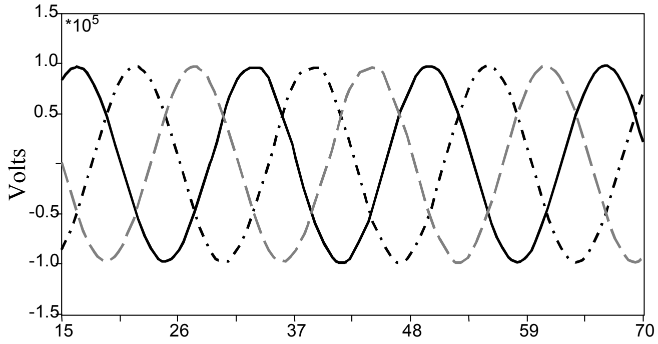

Figure 10. Phase voltages distortion in Sabana Llana 115 kV bus during back-to-back energization at system voltage zero.

The control systems and mechanisms related with synchronous closing technology typically have a tolerance of one millisecond (+/-1 msec). This situation was also evaluated using ATP [7] and its graphical preprocessor ATPDraw [8] to guarantee a safe and reliable operation of both breakers controlling the banks. Figures 11 and 12 show inrush current and frequency for both banks during back-to-back energization at one (1) millisecond after system voltage zero. Figure 13 shows the phase voltages distortion at Sabana Llana TC during this operation.

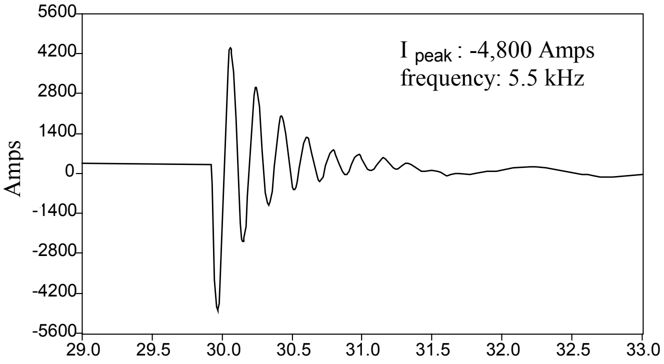

Figure 11. Capacitor bank 1 phase "A" current during back-to-back energization at 1 millisecond after system zero voltage.

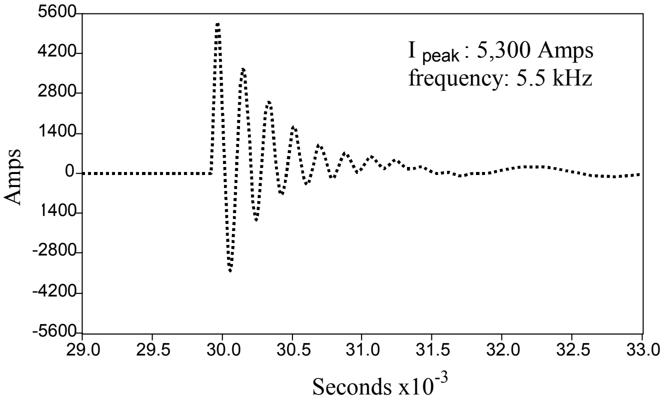

Figure 12. Capacitor bank 2 phase "A" current during back-to-back energization at 1 millisecond after system zero voltage.

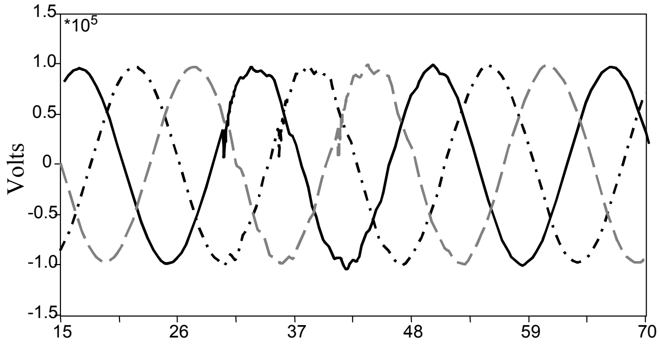

Figure 13. Phase voltages distortion in Sabana Llana 115 kV bus, back-to-back energization at 1 millisecond after zero voltage.

Table II summarizes the results of the synchronous closing energization of capacitor bank 2 during the back-to-back operation. This table presents results of energization at system voltage zero, energization at plus or minus one (1) millisecond of system voltage zero and plus or minus two (2) milliseconds of system voltage zero. Again, a conventional breaker back-to-back rated values of inrush current and frequency according to ANSI Standard C37.06-2000 are included for comparison.

Table II. Rate of change of inrush current with respect to time for breakers of both capacitor banks during energization of bank 2 using synchronous closing technology.

	Peak Current (Amps)	**Frequency (kHz)**	**Rate of change di/dt (Amps/μsec)**
Closing at System Zero Voltage			
Breaker - Bank 1	400	5.5	13.6
Breaker - Bank 2	400	5.5	13.6
Closing at +1msec of Zero Voltage			
Breaker - Bank 1	4,800	5.5	166
Breaker - Bank 2	5,300	5.5	184
Closing at -1msec of Zero Voltage			
Breaker - Bank 1	5,200	5.5	180
Breaker - Bank 2	5,200	5.5	180
Closing at +2msec of Zero Voltage			
Breaker - Bank 1	9,150	5.5	315
Breaker - Bank 2	9,700	5.5	335
Closing at -2msec of Zero Voltage			
Breaker - Bank 1	9,450	5.5	327
Breaker - Bank 2	9,520	5.5	329
ANSI C37.06-2000 Conventional Breaker	16,000	4.25	427

VI. CONCLUSIONS

- A conventional breaker should not be used to control the capacitor banks in the back-to-back configuration at Sabana Llana TC since the rate of change of inrush current may exceed the breakers capacity when closing near peak system voltage.

- The synchronous closing technology limits the rate of change of inrush current with respect to time allowing a safe, reliable and flexible operation of the new capacitor banks at Sabana Llana TC.

- The synchronous closing technology eliminates a potential power quality problem by minimizing the transient distortion in the voltage waveform during energization of the capacitor banks.

- The results of the simulation prove that even energizing capacitor bank 2 during the back-to-back operation at one (1) millisecond (+/- 1 msec) of system voltage zero (tolerance of the synchronous closing control system and mechanism), we guarantee a safe operation of both capacitor banks.

- Although synchronous closing technology with a tolerance of two (2) milliseconds (+/- 2msecs) also results in an safe operation for both breakers in our case study (di/dt < 427 Amps/μsec), there is technology today that offers better synchronous closing accuracy (+/- 1 msec). This value of tolerance for the control system (+/- 1 msec) is preferred since it results in a lower rate of change of inrush current and less distortion in the voltage waveform.

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REFERENCES

[1] Anazagasty, A., Torres, W., "Evaluation of Alternatives for the Integration of Reactive Power in the Northern Part of Puerto Rico," Planning & Research Division – Puerto Rico Electric Power Authority

[2] Greenwood, A., "Electrical Transients in Power Systems, 2nd edition," Wiley & Sons, 1991.

[3] ANSI / IEEE C37.012-1979, "IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis"

[4] ANSI C37.06-2000, "AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis Preferred Ratings and Related Required Capabilities

[5] Grebe, T.E., Gunther, E.W., "Application of the EMTP for Analysis of Utility Capacitor Switching Mitigation Techniques," 8th International Conference on Harmonics and Quality of Power ICHQP 1998 Athens, Greece

[6] IEEE Working Group on Switching Surges, "Switching Surges: Part IV- Control and Reduction on AC Transmission Lines," IEEE Transactions on Power Apparatus. and Systems, Vol. PAS-101, No. 8 August 1982

[7] *Alternative Transient Program Rule Book*, Can/ Am EMTP User Group, USA, 1997

[8] Prinkler, L., H∅idalen, H.K.: ATPDraw version 3.5 for Windows9x/NT/2000/XP- User's Manual, SINTEF Energy Research AS, Norway, TR F5680, ISBN 82-594-2344-8, Aug 2002