Energization Study of 10.4 MVAR Capacitor Bank in 38KV System

C. Rivera (PREPA), and R. Baretty (PREPA)

***Abstract*--The southwestern region of the island of Puerto Rico has a high concentration of demand of electrical energy and experiences a considerable growth in demand of electrical energy by the development of new tourism and industrial projects. Lajas, that is part of the southwestern region, experiences problems of voltage regulation before situations of contingency. The problem of voltage regulation accentuates with the projections of growth of demand. In order to improve the conditions of voltage regulation before contingency situations, we studied the transient overvoltages created by the installation of a capacitor bank of 10.4 MVARs in Lajas substation. With ATP (Alternative Transient Program) we studied the overvoltages, the inrush currents and the inrush current frequency caused by the closing operation or energization of the 10.4 MVAR capacitor bank. This situation is called isolated capacitor switching. Also we evaluate the capability of the circuit breaker to handle the inrush current and the performance of the arresters in Lajas substation and near PREPA's stations.**

***Index Terms*—inrush current peak, inrush current frequency, arresters.**

I. INTRODUCTION

The Puerto Rico Electric Power Authority (PREPA) is the utility responsible for the generation, transmission and distribution of electrical energy of Puerto Rico that is essential for the economic and social development of the Island of Puerto Rico. The electric grid PREPA is made up of 230 kV, 115 kV and 38 kV circuits. Through the integration of the lines to different transmission centers, the electrical power is transmitted and the regulation of voltage the electrical system is controlled.

The 230 kV system provides capacity for the transmission with great blocks of energy from the generation plants located in the south of the island towards the main centers of demand of electrical energy in the north of the island.

The 115kV network is responsible for the transmission of power to areas of high density of electrical energy demand and the interconnection of the transmission centers of the electrical system. The 115 kV transmission system consists of an extensive network of lines and switchyards distributed throughout different regions. The 115 kV system is essential for the voltage regulation of the subtransmission system that covers extensive geographic zones. In addition, the transference capacity of the 115kV network is vital for the electrical system reliability on situations of contingency of 115 kV and 230 kV transmission lines.

The southwestern region of the island of Puerto Rico has a high concentration of demand of electrical energy and experiences a considerable growth in demand of electrical energy by the development of new tourism and industrial projects. The zone has serious limitations in the transference capacity and problems of overload and voltage regulation in the 38 kV system. This situation adversely affects the reliability of the electrical system

The zone of Lajas, that is part of the southwestern region, experiences problems of voltage regulation before situations of contingency in the 38 kV-line 13400. The problem of voltage regulation accentuates with the projections of growth of demand. In order to improve the conditions of voltage regulation before contingency situations we studied the installation of a capacitor bank of 10.4 MVARs in Lajas.

The installation of 10.4 MVAR three phase-Y-grounded capacitor bank will reduce significantly the reactive losses and improve the voltage regulation of the zone. This capacitor bank will be installed in a 38 kV sectionalizer in Lajas**.**

II. ISOLATED CAPACITOR BANK SWITCHING THEORY

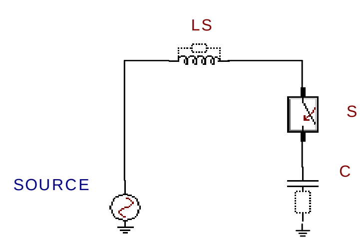


Fig 1 Isolated Capacitor Bank Configuration

A bank of shunt capacitors is considered isolated when the inrush current on energization is limited by the inductance of the source (LS) and the capacitance (C) of the bank being energized (as shown in Figure 1).

When the switch (S) is closed a current flows to energize the LC circuit [1]. Considering a discharged capacitor bank the current is given by

$$I(t) = (V_{source} / Z_0) \sin \omega_0 t \qquad (1)$$

where, $w_0 = 1/\sqrt{LC}$ (2) is the inrush current frequency

$Z_0 = \sqrt{L/C}$ (3) is the surge impedance

and V $_{source}$ is the peak of the source voltage.

The value of the maximum rate of change, with respect of time, of transient inrush current on energizing an uncharged bank is given by:

$$(di_i / dt)\max = 2\pi f_i i_{peak} \quad A/\mu s \qquad (4)$$

where $(di_i / dt)\max$ is the maximum rate of change of inrush current (A/ μ s)

i_{peak} is the peak transient inrush current (A)

f_i is the inrush current frequency (Hz)

This rate of change should not exceed the capability of circuit breakers to handle inrush current [2]. The rate of change of the circuit breaker-rms short circuit is given by:

$$(di / dt)\max = 2\pi f_s I_{sc}\sqrt{2} \quad A/\mu s \qquad (5)$$

where $(di / dt)\max$ is the rate of change of the rated short circuit breaker (A/ μ s)

I_{sc} is the rated rms short circuit breaker (A)

f_s is the power system frequency (Hz)

A. Surge Arresters Application

A surge arrester is a protective device for limiting surge voltages by diverting surge current and returning the device to its original status. In this study we considered the metal oxide varistor arrester (MOV). The very important characteristic of a MOV is the maximum continuous operating voltage (MCOV). The MCOV of the arrester is typically in the range of 75% to 85% of the duty cycle voltage rating. At MCOV, the arrester current is usually not more than 10 mA. On the arrival of a surge, the increasing surge current is accompanied by a rise in arrester voltage to a maximum level determined by volt-ampere characteristics. As surge decreases, the discharge voltage will decrease back towards the pre-surge level [3].

The arresters must fulfill standard insulation levels BIL (Basic Lightning Impulse Insulation) and BSL (Basic Switching Impulse Insulation Level). For a 38 kV (line-line) system the standard withstand voltage with a maximum voltage of 48.3 kV, the BIL is 250 kV [4]. The BSL is nearly a 83% of the BIL (207.5 kV). For a duty cycle voltage rating of 48.3 kV or 27.9 kV line to ground, the standard rms duty cycle voltage rating is 30 kV and the corresponding MCOV is 24.4 kV [5].

In the study we simulated the arresters electrical characteristics from the *T & D Product Digest* [6].

The next important characteristic of a surge arrester is its energy capability, which is measured in kJ/kV. For the arrester below of 550 kV, it is recommended that no more than the 85% of 10 kA be dissipated in a single such event [5]. The energy consideration is important because the design of the MOV arresters pays much attention to the transfer of the heat generated from the ZnO disks to the housing and hence to the ambient air [1]. In this catalog the arrester energy capability in a single impulse of 4 ms is 4.5 kJ/kV [6].

III. Case Study

The Figure 2 shows a simplified one line diagram study area with the 10.4 MVAR capacitor bank in Lajas. The corresponding inductance and capacitance involved are:

C=19.068 μ F and L_s = *10.41 mH*

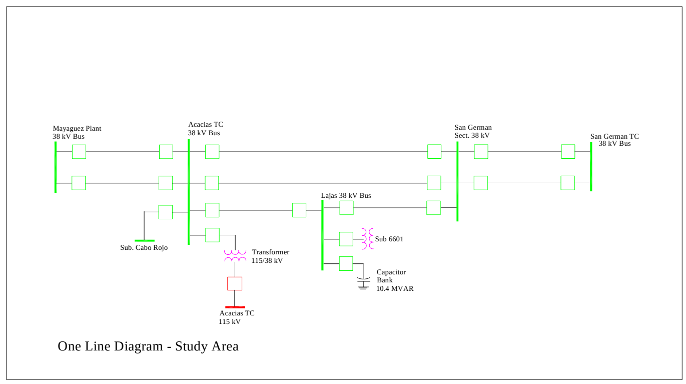


Fig. 2 One Line Diagram Lajas Study Area

Using *(1)* , the peak inrush current is 1.395 kA and tusing (2), the inrush current frequency is 357.22 Hz (6 times higher than power frequency).

Using ATP [7] and its graphical processor ATPDraw [8] we simulated the closing operation of the capacitor bank. Figure 3 shows the ATP model.

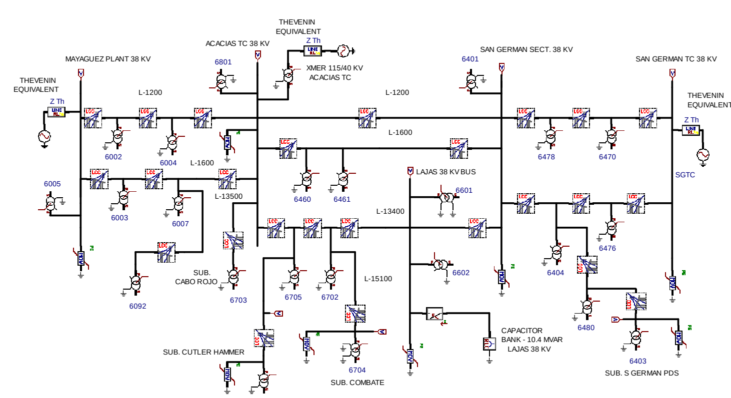


Fig. 3 ATP Draw Model - 10.4 MVARs Lajas 38 kV Capacitor Bank

A. ATP Model Validation

The equivalent model in ATP was validated using PSS/E (Power System Simulator for Engineers). To validate the model we simulate three-phase fault in the Lajas 38 kV, which is the connecting bus of the proposed capacitor bank. We compared the fault contribution of the adjacent buses (Acacias 38 kV and San German Sect. 38 kV). In Table I shows the respective values.

TABLE I
COMPARISON OF THREE PHASE CONTRIBUTIONS OF ADJACENT BUSES

THREE PHASE FAULT LAJAS 38 KV	ATP	PSSE
FAULT CONTRIBUTIONS (A)		
SAN GERMAN SECT 38 KV	4,360	4,462
ACACIAS TC 38 KV	1,018	1,524
TOTAL FAULT CURRENT LAJAS 38 KV (rms)	5,375	6,062

The model was effectively validated. The values obtained in ATP model were comparable to those calculated in PSS/E program. We calculated a 12% difference between PSS/E and ATP values.

B. Analysis of Breaker Interruptive Capacity for10.4MVAR Capacitor Bank - Mathematical Analysis and ATP Simulation Results

As previously discussed, the capability of circuit breakers to handle inrush current is given by equation 5:

$$(di/dt)\max = 2\pi fsIsc\sqrt{2} \quad A/\mu s \quad (5)$$

In the case of the selected breaker:

$$\frac{di}{dt}(\max) = 377(60)(40k)(A/s)$$

$$\frac{di}{dt}(\max) = 21.3A/\mu s$$

To calculate the rate of inrush current with respect to time (di/dt) to which the breaker is exposed, we use equation (4) :

$$\frac{di}{dt} = 2\pi fii_{peak}(A/s)$$

where:

$$\text{I}\,peak = \sqrt{2}\sqrt{IccIrated}\,(Amperes)$$

$$fi = fs\sqrt{\frac{Icc}{Irated}}(Hertz)$$

Icc = system short circuit current at point of connection
Irated= rated current of capacitor bank
fs = power system frequency (60Hz)
fi = inrush current frequency

In determining the inrush current and frequency, the increase in current due to applied voltage and the capacitance tolerance should be considered. The increase in current at maximum rated voltage is (48.3/38)= 1.27. The positive tolerance of capacitors is 10% for a factor of 1.1.

In this case, we calculate the parameters fi and Ipeak:

$$\text{I}\,rated = 10.4M/(38K\sqrt{3})$$

$$Irated = 158.01Amperes$$

$$Icc = 6062A$$

$$\text{I}\,peak = \sqrt{2}\sqrt{(6062)(1.27)(1.1)(158)}\,(Amperes)$$

$$\text{I}\,peak = 1637.1(Amperes)$$

$$fi = 60\sqrt{\frac{6062}{(1.1)(1.27)(158)}}(Hertz)$$

$$fi = 314.2(Hertz)$$

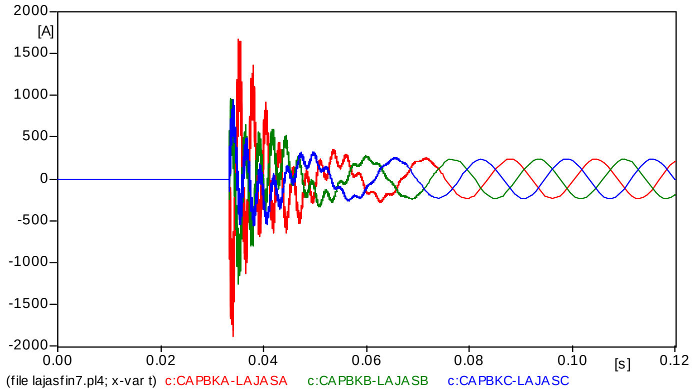
Finally:

$$\frac{di}{dt} = 2\pi(314.2)(1637.1)(A/\mu s)$$

This gives us:

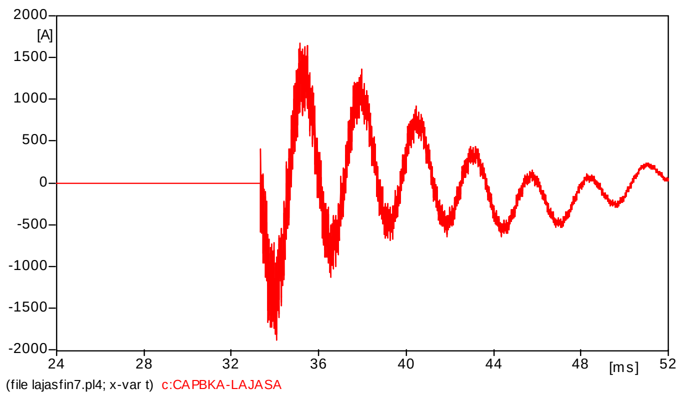
$$\frac{di}{dt} = 3.23(A/\mu s)$$

Our simulation in the ATP system shows the following values for the inrush current and the inrush current frequency :



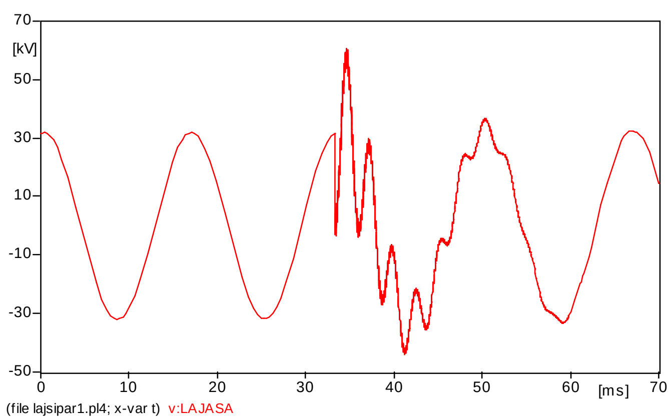
Seconds

Figure 4. Capacitor Bank Inrush Current Phases A,B,C



Seconds

Figure 5. Capacitor Bank Inrush Current (Phase A only)



Milliseconds

Figure 6. Capacitor Bank Voltage (Phase A only)

From the capacitor bank inrush current (phase A) Figure 5, we can calculate the actual di/dt from the simulation.

ATP simulated di/dt max = 3.23 A/µs
Δi= -1.808-1.423 kA
Δt= 0.034-0.035.

From Figure 6, we can observe the resonant frequency obtained from the ATP simulation:
ATP Simulated fi= 387Hz

This results from the simulation are consistent with our previous mathematical calculations.
Calculated di/dt max = 3.23 A/µs
Calculated fi = 314.2 Hz

The ATP Simulation value as well as the calculated value of current with respect to time (di/dt) to which the breaker is exposed are both below the limiting value of the selected breaker. We can therefore affirm that the breaker should operate seamlessly in the studied system.

In breakers with SF6 insulation (as the one specified for this analysis) the rate of current with respect to time (di/dt), which it is exposed, is not the deciding factor in its selection process. The focus should be instead in verifying that the magnitude of the inrush current is less than the rated short circuit current of the breaker. In this case, from Table 2 of ANSI/IEEE C37.06-2000 [9] we obtain that for this breaker, the rated short circuit current is 40000A. This value is far greater than the inrush current for the capacitor bank .

Capacitor Bank Inrush Current (Simulated) = 1881A
Capacitor Bank Inrush Current (Calculated)= 1637A
Breaker Rated Short Circuit Current = 40000A

This concludes that the breaker is well suited for this application.

C.. Effects of Overvoltages on Contiguous Buses and Substations due to Energization of 10.4MVAR Capacitor Bank in Lajas Bus

The last part of our discussion deals with the analysis of the overvoltages reflected on nearby elements by energizing the capacitor bank. Emphasis is placed on evaluating the effects on the immediate connection bus (Lajas 38KV) and the next buses (Acacias and San German Secc. 38KV). The effects on radial substations in the same subtransmission circuit are also simulated. These include substations 6703-Cabo Rojo 38KV, 6704-Combate 38KV and 6774-Cutler Hammer 38KV.

The detail to which the elements in the system have been represented, allows us to calculate the transient overvoltages in these points of interest. Figures 7 through 24 illustrate the surge phenomena in the above-mentioned points along with the energy dissipated by the arresters. Analysis of the overvoltages at each point is done considering two conditions (with and without arresters). The dissipating energy capability of the simulated arresters is 4.5 KJ/KV at rated voltage. The Switching Surge Protective Level is 58KV. The Maximum Continous Operating Voltage is 24.4KV and the Voltage rating is 30KV. For this application, the total maximum dissipated energy capability is 135KJ. As observed, arresters prove to dissipate energy in the greater overvoltage conditions present in the system.

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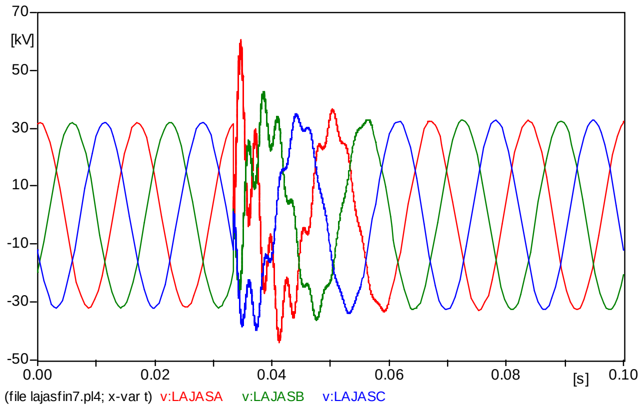

Seconds

Figure 7. Lajas 38KV Bus (Without Arresters)

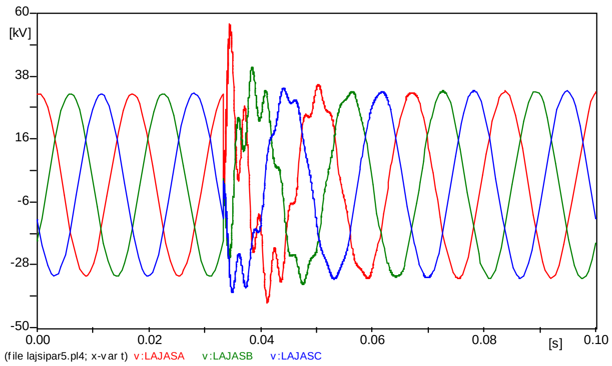

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Figure 8. Lajas 38KV Bus (With Arresters)

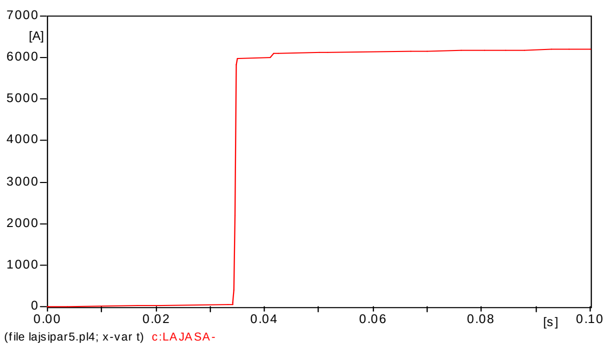

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Figure 9. Lajas 38KV Bus Arresters Dissipated Energy

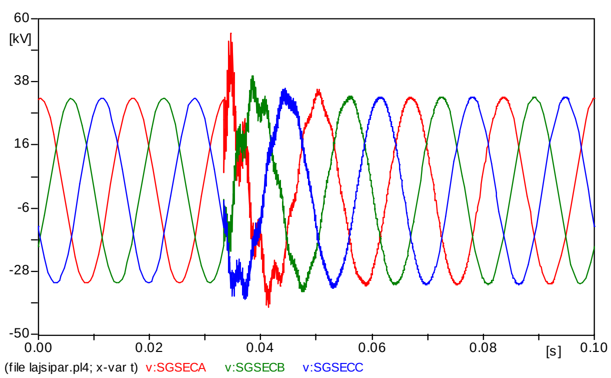

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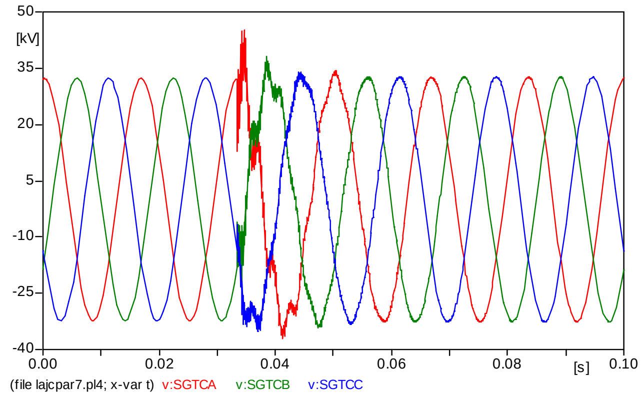
Figure 10. San German Secc. 38KV Bus (Without Arresters)



Seconds

Figure 11. San German Secc 38KV Bus (With Arresters)

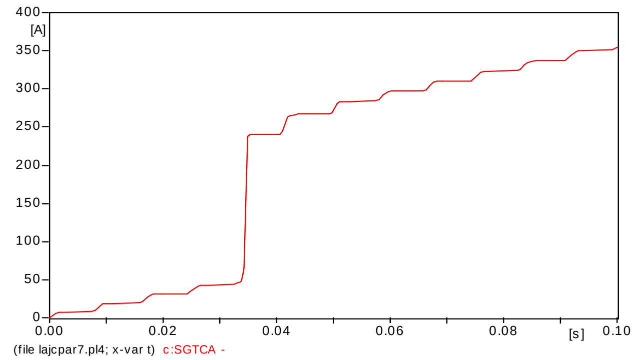


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Figure 12. Lajas 38KV Bus Arresters Dissipated Energy

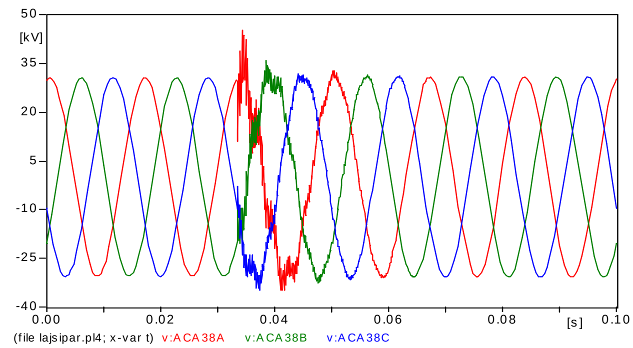

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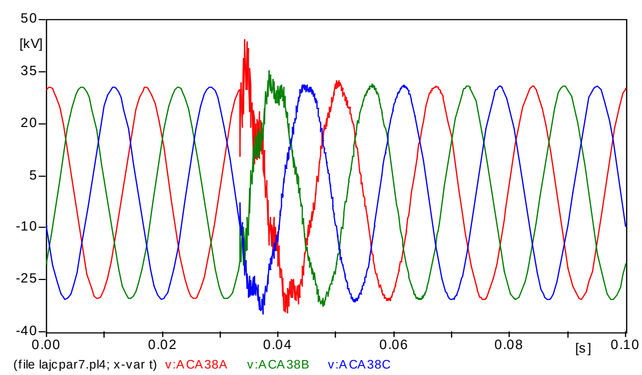
Figure 13. Acacias 38KV Bus (Without Arresters)



Seconds

Figure 14. Acacias 38KV Bus (With Arresters)

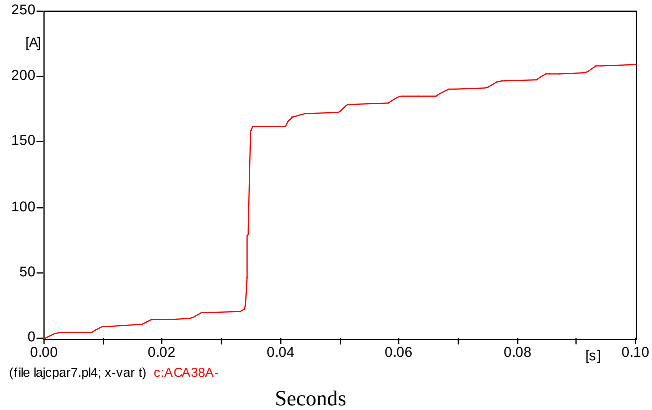


Figure 15. Acacias 38KV Bus Arresters Dissipated Energy

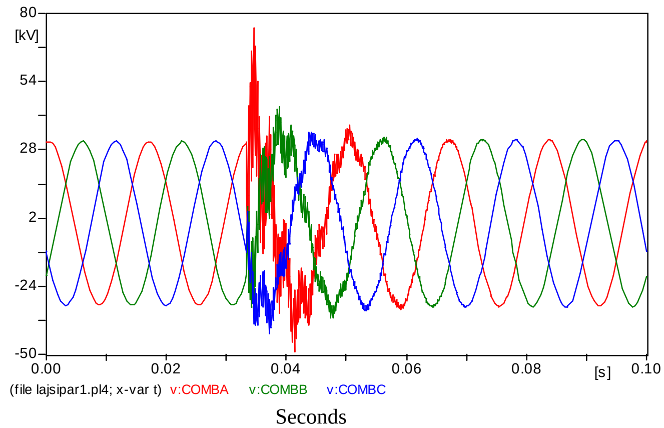


Figure 16. Combate Substation 6704 38KV (Without Arresters)

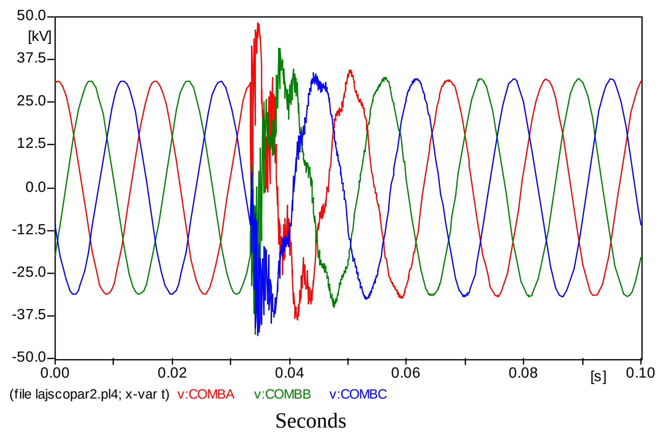


Figure 17. Combate Substation 6704 38KV (With Arresters)

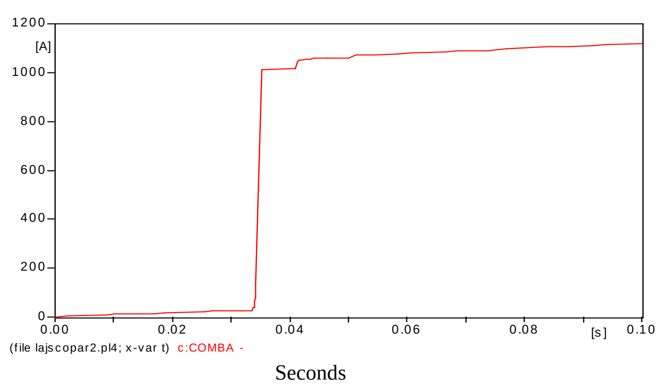


Figure 18. Combate Substation 6704 38KV Arresters Dissipated Energy

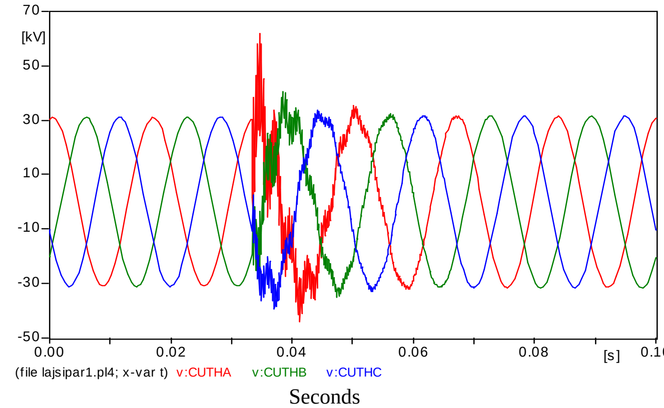


Figure 19. Cutler Hammer Sub. 6774 38KV (Without Arresters)

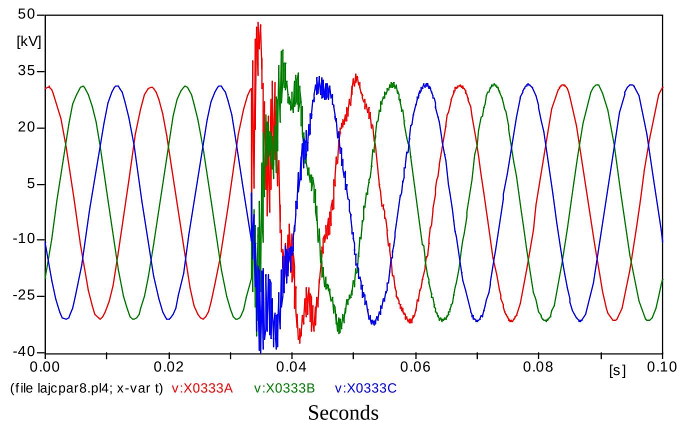


Figure 20. Cutler Hammer Sub.38KV (With Arresters)

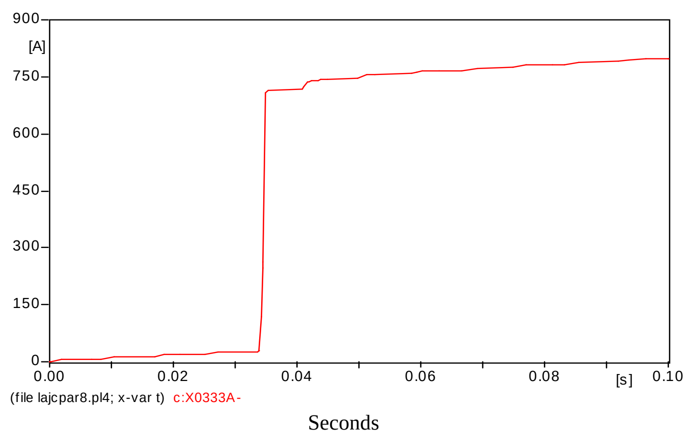


Figure 21. Cutler Hammer Sub 38KV Arresters Dissipated Energy

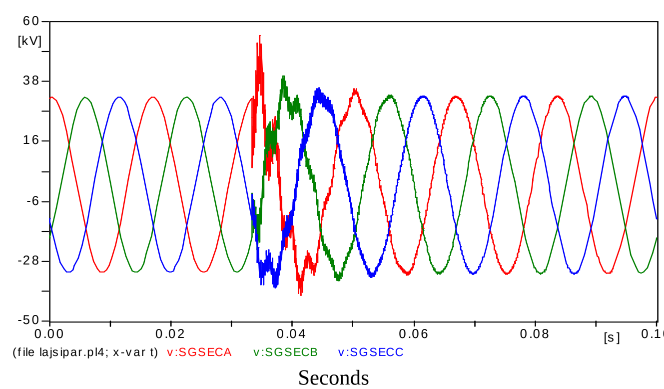
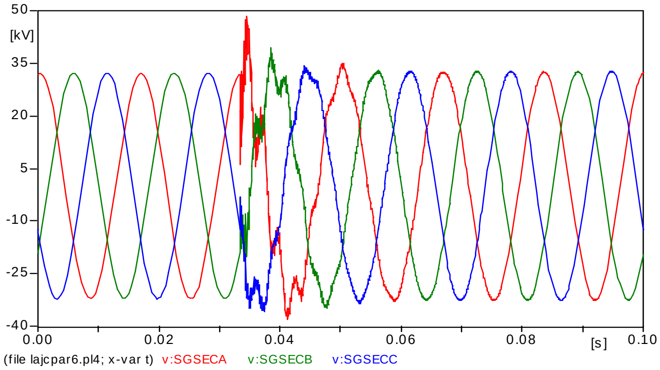
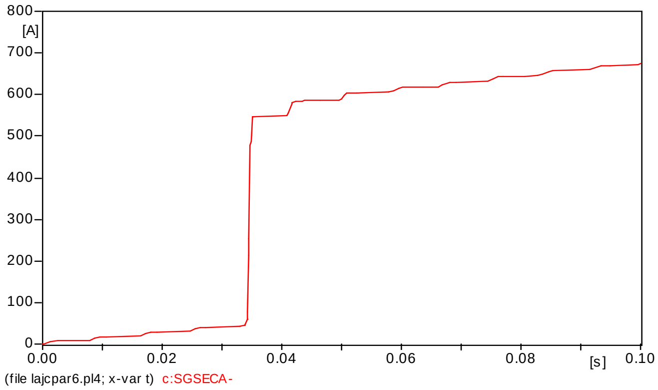


Figure 22. San German PDS 38KV Sub 6403 (Without Arresters)



Seconds

Figure 23. San German PDS 38KV Sub 6403 (With Arresters)



Seconds

Figure 24. San German PDS 38KV Sub. Arresters Dissipated Energy

Table II summarizes the reduction of overvoltages in the test points evaluated with the ATP Simulation (as viewed in Figures 7 through 24) due to the presence of arresters:

Table II. Effect of Arresters on the Overvoltages on test points due to the energization of the capacitor bank in Lajas bus.

Bus (or Substation)	Voltage Without Arresters (KV)	Voltage With Arrester s (KV)	Energy Dissipated by Arrester (KJ)
Lajas 38KV Bus	60.17	55.0	6.2
Acacias 38KV Bus	43.3	42.8	0.2
San German Secc.38KV Bus	50.6	48	0.7
Combate 38KV Substation	73.2	47.8	1.1
Cutler Hammer 38KV Substation	61.3	47.3	0.8
San German PDS 38KV Substation	52.5	46.3	0.5

All the voltages recorded in the simulation were below the Basic Insulation Level (250KV) and Basic Surge Level (200KV) for 38KV equipment. The system is therefore protected against the overvoltages generated by the energization of the capacitor bank.

IV. CONCLUSIONS:

1. The circuit breaker has proven to be effective for the selected application. Analysis of both the rate of current change per time (di/dt) and the rated interrupting current validate this conclusion.
2. The arresters evaluated in the study area simulated in ATP have the energy dissipating capability to withstand the overvoltages generated by closing the capacitor bank in Lajas.
3. Effects of transient overvoltages are higher in radially connected substations such as Combate and Cutler Hammer. The general damping of the system impedance lessens the effects of the overvoltages in the adjacent buses.
4. Further analysis should consider case scenarios including, but not limited to:
    A. Analysis of Overvoltages during the disconnection of the capacitor bank (followed by a restrike)
    B. Analysis of Overvoltages during the energization of the capacitor bank with single or multiple transmission line contingencies.
    C. Analysis of phase to phase voltages generated at delta connected transformers.

V. Acknowledgment

The authors gratefully acknowledge the contributions of the engineer Larry Marini from PREPA for his support and time during the development of this study.

VI. References

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VII. Biographies

Caroline Rivera graduated from the University of Puerto Rico in Mayaguez in 1990 with degree of bachelor science in electric engineering.

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