A Simulation Study on Capacitor Switching

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Abstract – **When a capacitor bank is energized, there is an immediate drop in system voltage towards zero, followed by a fast voltage recovery that can reach a peak of 2 per unit at frequencies between 300Hz and 1000Hz. These transients are not typically harmful to utility equipments. The most severe transients occurred when the uncharged capacitor is switched at the voltage peak. First peak of the transient are the most damaging one. The back-to-back capacitor switching is define as when energizing a capacitor bank with one or more already energized banks connected to the same bus. Energizing an uncharged capacitor bank at voltage peak is the worst case scenario for a typical capacitor switching. The overvoltage of the transients along with the high frequency inrush currents may be troublesome to some customer sensitive equipments.**

Keywords*–*capacitor switching, capacitor energization, back-to-back capacitor switching.

I. INTRODUCTION

Power systems usually contain lumped capacitors such as capacitor banks for voltage regulation or power factor improvement and capacitors that are part of filter banks to filter out higher harmonics. In addition, cable networks on the distribution level form a mainly capacitive load for the switching devices. Capacitive switching requires special attention because, after current interruption, the capacitive load contains an electrical charge and can cause a dielectric re-ignition of the switching device. When this process repeats, the interruption of capacitive currents causes high over-voltages [1], [4]. The interruption of a capacitive current can cause dielectric problems for the switching device, but when a capacitor bank is taken into service, large inrush currents can flow through the substation and can cause problems for the protection system. During closing a switch or circuit breaker in a dominantly capacitive network with capacitor banks or cable line, represented by its capacitance, the transient voltage oscillates along the line at a relatively low single frequency. It has amplitude that reaches a peak value approximately equal to twice the value of the system voltage that was present at the instant at which the closure of the circuit took place [3].

2. METHODOLOGY

This project is done using the Circuit Maker PRO to approach the model of the energization of a typical capacitor installation. Circuit Maker function is to design and to simulate a typical distribution substation circuit implemented in this project. Using this Circuit Maker PRO, fast and accurate simulation data can be obtained. For the beginning, section 2.1 explains on the basic capacitor switching transient theory. Then the one line diagram of distribution substation of factory is applied and the circuit is drawn using Circuit Maker PRO (shown in section 3). Then, the circuit was calculated and observed during the capacitor's initial energization and also during the back-to-back capacitor switching respectively. The data collected are explained in section 4 while section 5 concludes this paper.

2.1 CAPACITOR SWITCHING TRANSIENT

The problem of switching capacitor bank into another can be analyzed using simple circuit theory as figure 1 below.

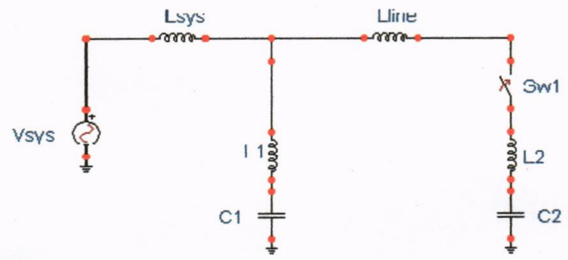

Figure 1: Equivalent circuit to analyzing the transient generated by back-to-back capacitor switching.

In this circuit C1 and C2 are the capacitance of the first and second banks, L1 and L2 are the inductance of each capacitor bank. Lline is equivalent inductance of the feeder segment between the bank and the Sw1 is the switch that closes in the controlled bank. For the moment we will neglect the source voltage into the equivalent circuit.

Assuming the first capacitor bank is charged to peak system voltage, the magnitude of the current that flow when the second capacitor are energized is:

$$I_{peak} = \frac{V_{peak}}{Z_0} \qquad (1)$$

Where $Z_0 = \sqrt{\frac{L}{C}}$ is referred to as the surge impedance; V is the magnitude of the voltage waveform driving the current during energizing; L stands for the inductance between the banks and the inductance found in the capacitor bank structure. If the second bank has an initial charge, then the magnitude of the voltage will be given by the voltage difference between banks. The transient arising from the energization of a capacitor bank will oscillate about the fundamental frequency waveform at a frequency typically in the hundreds of hertz. This frequency is given by;

$$f = \frac{1}{2\pi\sqrt{L_S C}} \qquad (2)$$

Where f the frequency of the oscillation is, L_S is the system inductance and C is the capacitance of the capacitor banks under evaluation.

3. SYSTEM REPRESENTATION

3.1.1.1 CIRCUIT DATA

The system under study is shown in a single line diagram as Figure 2 below. The system consists of a primary distribution system with a source of 33kV; 50Hz and a transformer with the parameters of 24MVA, 33/11kV (Y/Delta), and 750kcmil underground conductor cable section were 192m long. The configuration also shows two switched two capacitor bank sizes 1.2MVAR and 1.8MVAR ungrounded wye connection. The industry load was represented by R-L loop with constant impedance [2].

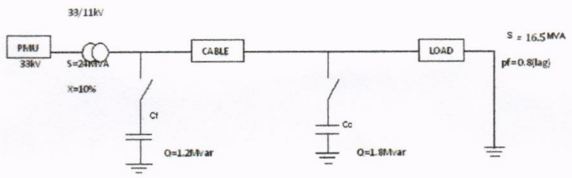

Figure 2: Single line diagram of substation under study

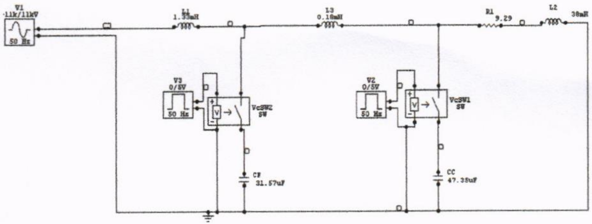

Figure 3: System represented of the Base Case in Circuit Maker PRO

4. SIMULATION RESULT

4.1 BASE CASE

The controllable capacitor bank switched was closed at peak voltage (45.29ms). Figure 4 shows the waveform for the voltage at the controllable capacitor bank before and after the switching operation. The peak voltage reached almost twice its steady state value during energization.

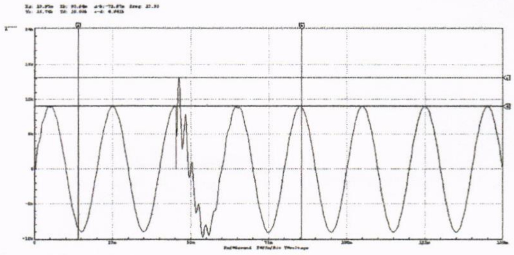

Figure 4: Voltage at the controllable capacitor bank when energizing at the peak value system voltage.
Vpeak =15.74kV(1.499pu)

Phenomenon called back-to-back switching is when the energization of controllable capacitor bank and having a nearby fixed capacitor bank already in service. This phenomenon will generated high frequency inrush current in which the fixed capacitor bank charged the controlled capacitor bank. This inrush current was also of big concern. Based on the theoretical, with equation (1) and (2) the peak inrush current and the frequency of this transient are:

$$I_{peak} = \frac{V_{peak}}{Z_o}$$

$$Z_o = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.18mH}{47.35\mu F}} = 1.9497\Omega$$

Therefore;

$$I_{peak} = 4.6066\text{kA}$$

and

$$f = \frac{1}{2\pi\sqrt{LC}} = 1.7239 \text{ kHz}$$

The transient analysis concentrates on phenomena occurring between the capacitor banks as the exchange of energy occurred between these components. Figure 5 shows the current between the capacitor banks with a peak value of $3.2kA$ at $f = 2.28kHz$.

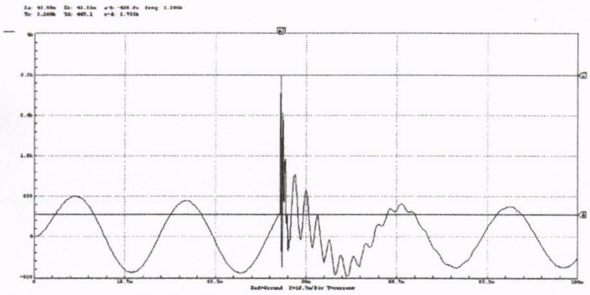

Figure 5: Current between banks when energizing at the peak system voltage. $I_{peak} = 3.2kA$; $f = 2.28kHz$

The charging of the controllable capacitor bank after the switching operation can be appreciated in figure 6 below. The controllable capacitor bank was discharged until the switch was closed at 45.49ms (peak system voltage). The current remain zero until the switch was closed. Then, the inrush current from the fixed capacitor bank charged the controllable capacitor bank. It happen when the frequency established by the inductance of the conductor between the bank and the capacitance of the capacitor bank. The transient disappeared approximately after 85.64ms and the current reached its steady state value.

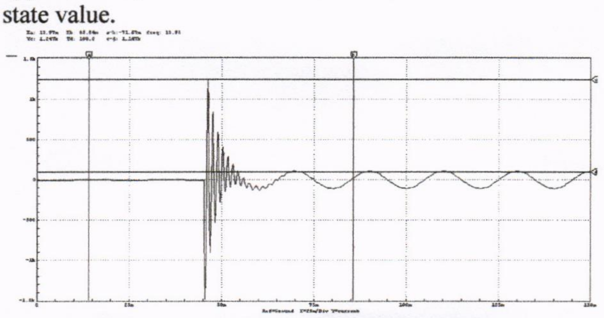

Figure 6: Current through the controllable capacitor bank when energizing at the peak system voltage.
$I_{peak} = 1.247kA$

The energization of the controllable capacitor bank did not affect considerably the current at the industrial load as Table 1 show the peak inrush current reached only 820A. Concentration is given on the high frequency inrush current between the capacitor banks.

	Location	Peak Value
Voltage	11kV Bus at Transformer	15.8kV
	Fixed Capacitor Bank	15.87kV
	Control Capacitor Bank	16.33kV
	Industrial Load	16.53kV
Current	Feeder Output from Substation	1.872kA
	Between Capacitor Bank	3.387kA
	Controlled Capacitor Bank	1.09kA
	Industrial Load	726.7A

Table 1: Peak voltages and current at different Location in the Base Case Circuit.

4.2 MITIGATION OF CAPACITOR INRUSH TRANSIENT

The value of reactor that has been used with the controlled capacitor bank is an inductance with 539.97µH/phase. This inductance is used to limit the peak inrush current between the banks to half the base case value. Figure 7 represent the system using current limiting reactor.

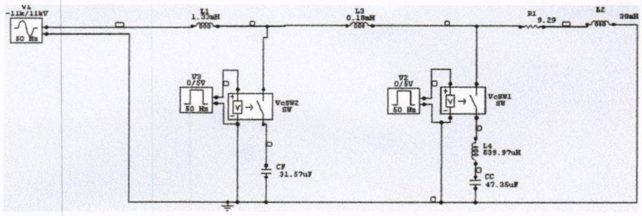

Figure 7: System representation including the current limiting reactor for the controlled capacitor bank

Using the result from base case inrush current and the surge impedance of the circuit, the sizes of the reactor was calculated. The equation used:

$$I_{peak,new} = \frac{1}{2}(I_{peak,old}) \qquad (3)$$

$$= \frac{4.6066kA}{2} = 2.3033kA$$

$$Z_{O\ total,new} = \frac{V_{peak}}{I_{peak,new}} \qquad (4)$$

$$= \frac{11k(\sqrt{\frac{2}{3}})}{2.3033k} = 3.8994\Omega$$

$$L_{total,new} = (C_{eq})(Z_{O\ total,new})^2 \qquad (5)$$

$$= (47.35\mu)(3.8994)^2 = 719.97\mu H$$

$$L_{reactor} = L_{new} - L_{old} \qquad (6)$$

$$= 719.97\mu - 0.18m = 539.97\mu H$$

Increasing the inductance between the fixed capacitor bank and controllable capacitor bank reduced the peak inrush current to the desired value. The simulated peak inrush current was reduced to 1.933kA as shown in figure 8 below. The value is nearly half of the base case value. Based on previous assumption, it confirms that increasing the surge impedance of the circuit would reduce the high frequency transient. The frequency of the transient inrush current also reduced to 1.147 kHz.

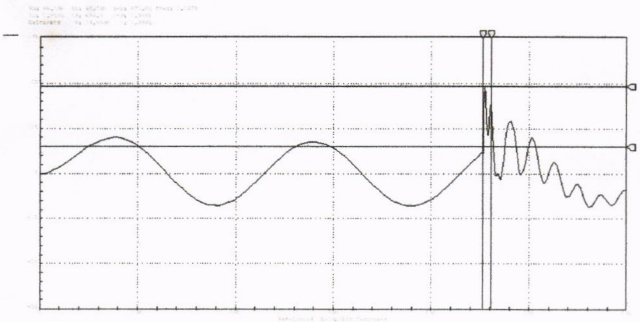

Figure 8: current between banks when energizing the controllable capacitor bank and the current limiting reactors. $I_{peak} = 1.933kA;\ f = 1.147kHz$

From the result obtained, it shows restore the current to the steady state value. This restoring transient event can also be observed at the controlled capacitor bank voltages. Figure 9 shows, how the voltage peak at 14.72kV and then reaches the steady state value after the restoring frequency transient.

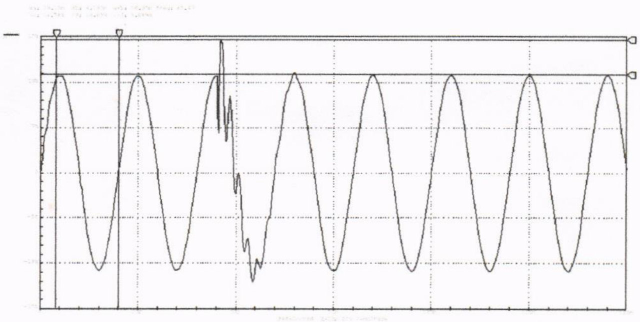

Figure 9: Voltage at the controllable capacitor bank when energizing it along with the current limiting reactors. $V_{peak} = 14.72kV$

Table 2 below shows the peak current and the peak voltage at different location in the circuit.

	Location	Peak Value
Voltage	11kV Bus at Transformer	14.88kV
	Fixed Capacitor Bank	15.07kV
	Control Capacitor Bank	14.72kV
	Industrial Load	14.67kV
Current	Feeder Output from Substation	2.133kA
	Between Capacitor Bank	1.933kA
	Controlled Capacitor Bank	861.10A
	Industrial Load	803A

Table 2: Peak currents and voltages at different location in the circuit using the reactor

5. CONCLUSIONS

The energization of capacitor banks in distribution circuits can cause transients in the voltage and current wavefroms. This problem is aggravated by switching a capacitor bank close to another bank already in service. The resulting transient overvoltage can reach a peak value close to two per unit, and the inrush current can reach magnitudes of several kilo amperes. Furthermore, a high magnitude with high frequency transient that arise, will lead to several problems, mainly to the consumers sensitive electronics equipments. Further research should be carried out to mitigate this kind of problems without compromising the power quality assurance.

There are several technologies available to mitigate such transient. Based on simulation using the current limiting reactor this method is able to reduce the magnitude of the transient in voltage and current waveforms. This method still, its effect was still noticeable and lasted for a few milliseconds. Further study must be made by the power provider company on this topic to provide better power quality to customers in near future.

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