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Analysis and Mitigation Techniques of MV-Capacitor Bank Switching Transients on 132 kV Substation

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ABSTRACT:This paper presents the techniques to mitigate transients caused by capacitor switching in the distribution system. It includes the theory of capacitive switching transients with different methods of mitigation. The paper uses MATLAB/SIMULINK software package to simulate the specific mitigation devices. The mathematical calculations of different parameters such as transient voltages, current, and frequencies for each device are compared with obtained value from the simulations of each case study.

KEYWORDS: Capacitor Switching, Capacitor inrush current, switching transients, Surge arresters, Energization inrush,Pre- insertion of a resistor, MATLAB/SIMULINK.

I.INTRODUCTION

Historically, Capacitor Switching methods normally originated from the distribution circuit. They improve the performance of distribution system by dropping losses and reducing the voltage drop. The Capacitors are used to store reactive power and utilize it when the load required. Capacitor banks are well controlled, as they may energized or de-energized at the switching ON/OFF time of the bank. As the Capacitor switching transients have precious problems to produce the losses, overvoltages and also acquire the problems of transient inrush currents. In fact, Switching ON & OFF of the capacitor bank have cause the most severe switching transients in the distribution circuits when they linked with the utility system operations such as energizing a Cable or a large load on the system.

When discharge Capacitor is energized, then the system voltage immediately pulled down. Thus, the most severe problem of transients will arise when the uncharged capacitor is switched at a maximum voltage. Capacitor inrush current is also a common and more severe problem, when the capacitor is switched near to a capacitor that is already energized. This is sometimes called as Back-to-back capacitor switching. Capacitor switching transients in distribution circuits have a tendency tobe less severe due to low peak magnitudes and rapid decline in the system [3, 4]. But they affected composite equipmentsuch as adjustable speed drives and uninterruptible power supplies. In fact switched capacitors causes the most severe switching transients in the distribution circuits when they are compared with the typical operations such as energizing a large load on the system [9, 10].Most of the utilities are also comprise of surge arrester and fuses on the capacitor installations. The surge arrester protect the capacitor banks from the lightning overvoltages.Thefunction of the fuse is to separate the failed capacitor units from the system and clear the fault before the capacitor fails destructively. The switched capacitor units have vacuum switches with the automatic controller. Theoretically, it has been detected that these transients lead to the peak amplitude of 2p.u. But, due to the essential damping present in the circuit, these transients are partially below that peak value [4].

In this paper, Simulink analysis for mitigation of MV-capacitor switching transients on the distribution system thatare connected to the 40 MVA, two winding, three phase transformer at 132 kV/11 kV substation. The Capacitor banks have different mitigation systems, which are to be implemented before the feeder circuit and initially energized at the peak voltage of the circuit. From this mitigation system, the transient inrush current and voltages near the Capacitor bank are investigated. Now,to minimize these transients, three different MALAB models are proposed. From theseMATLAB simulations comparative results analysis have been included in this paper [1, 5].

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II.BASIC CONCEPT OF CAPACITOR SWITCHING TRANSIENT

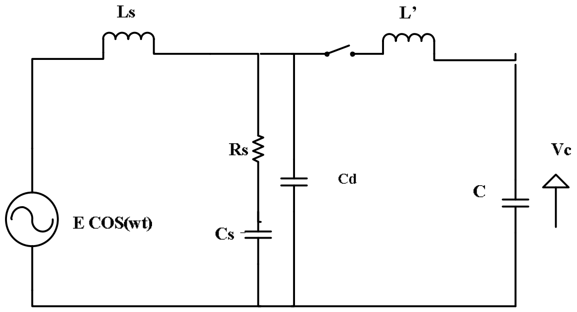

Fig 1. Single line diagram of Capacitive Switching Transients

Power System involves a large number of the capacitor bank for voltage regulation or power factor improvement and capacitor that are part of capacitor banks to filter out higher harmonics [6]. Fig 1 represents the leakage inductance of supplying generators. Ls, Cs generate together at the supply side that produces Transients Recovery Voltage and representsCapacitance of voltage transformer, current transformer, bus bars etc. The Capacitive load C is connected at the load side in series with the stray inductance L' with the load side of circuit breaker. When leakage inductance is much greater than stray inductance (Ls>>L') and (ωs>>$1/\omega C$) then the current flowing through the breaker rises by the supply voltage with the phase angle of90°.When energizing takes place by discharged capacitor bank at maximum voltage, voltage transients might reach at 2.5 to 3.0 p.u. but the losses get reduced as less value [1, 4]. Since the IEEE breaker standard permits up to a ¼ cycle difference between the instance of contacts touching during circuit breaker closing and grounded capacitors [8]. After the half cycle, the supply voltage has inverted polarity and the voltage across the breaker terminal is twice the peak value of the supply voltage. When the circuit breaker is in a closed position, the voltage behind the breaker is higher than the supply voltage, the voltage difference is [1, 4]

$$\Delta U = U_c - E \qquad (1)$$

This is called Ferranti rise and can be seen as the effect of capacitor acting as a source of reactive power [1, 6]. When the re-ignition occurs, the capacitance *C* discharges itself via the re-ignited arc channel and the inductances *L*s, *L*'. The result is an oscillating current with the following frequency and peak value. Frequency of the transients' oscillations and Rate of rising is calculated as:

$$f = \frac{1}{2\pi\sqrt{L_s\ C_s}} \quad (2)$$

$$\frac{du}{dt} = Z_s \frac{di_c}{dt} \qquad (3) \qquad \text{Where, } Z_s = \sqrt{\frac{L_s}{C_s}}$$

The smaller the value of *L*s, the higher the frequency and larger the amplitude of the transient current. At the instant of re-ignition the value of the voltage on the capacitor *C* is −*E*, the voltage is then+3*E* at the first zero crossing of the transient current [6].

III.CAPACITOR ENERGIZATION PROCESS

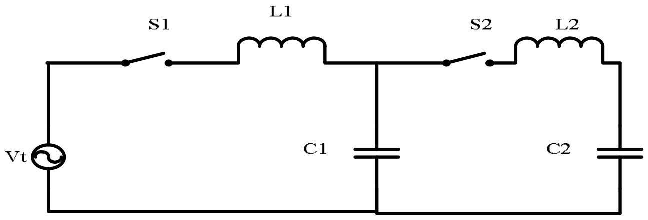

Fig 2. Basic capacitor energization process

At the time of the switching of shunt capacitor banks, with the high magnitude and high frequencies, the transients do occur. The transients are characterized by a surge of current having a high magnitude and a frequency as high as several 100 Hz [4, 10]. There is also transient overvoltage on the bus caused by the surge of inrush currents coming from the system source. The basic ideas of the capacitor energization are described in figure 2.Here resistances are neglected for simplification, as the capacitor C1 is energized by closing switch S1 [3].The voltage and current in the capacitor are given by following equations as,

$$V_{c1}\ (t) = V - [V - V_{c1}\,(0)]sin\omega t \qquad (4)$$

$$I(\,t) = \frac{V}{Z_1}\,sin\omega_1 t \qquad (5)$$

Where, V = Switching voltage when S_1closed
V_{C1}= Initial voltage at C_1

IV.DIFFERENT TECHNIQUES OF REDUCTION OF CAPACITIVE SWITCHING TRANSIENTS

There are many technologies and methods available to mitigate the switching transients such as a use of pre-insertion of the resistor, surge arrestor connected across the capacitor bank, and current limiting reactor. Each type of switching transients represents the different types of the transient output voltage and current with the help of MATLAB simulation models [1, 5].

A. Current Limiting Reactor

In this technique, the suitable rating of a current limiting reactor is used in series with the capacitor bank. Due to this current limiting reactor, surge impedance of the circuit gets improved and hence the peak inrush current get reduced. As the function of the inductor is opposing the change in current so that current cannot change instantly. Therefore increased frequency components of transients are restricted and the effect of these inrush transients current is compressed. The reactor output voltage and current are as shown in the simulation [5]. It is observed that as the current increases in the negative half cycle and this can be attributed to the exchange of energy between the two energy storing devices such as inductor and capacitor. The purpose of X/R ratio is the sharpness of tuning of output voltage and current. Also for damping purposes, when X/R ratio is at limiting lower value [6].

B. Resistor switching or pre-insertion of resistor

In a current interruption technique, the use of switching resistor in high voltage circuit breaker is well implemented to reduce the transient overvoltages and frequency of the transient recovery voltage (TRV) and current. For the medium voltage, two circuit breakers are used to pre-insert the resistor for limiting duration, such as

$$f_n = \frac{1}{2\pi}\sqrt{\left[\left(\frac{1}{LC}\right) - \left(\frac{1}{4}\left(\frac{R}{L} - \frac{1}{RC}\right)\right)\right]} \qquad (5)$$

$$R = \frac{1}{2}\sqrt{\frac{L}{C}} \qquad (6)$$

These methods use switching resistors connected in series with the capacitor bank. Due to the use of resistors, the losses in the circuit are increased some times and to decrease the peak value of transients in voltage and current. The time required is 1/4th of a supply frequency, i.e. 50/4 = 12.5 second. This helps to decrease the initial peak which is the most damaging of transients [2, 3].

C. *By using surge arrester*

One more technique is to reduce the capacitive inrush current switching transient. In this method, the gap type surge arresters are coupled in the series with the nonlinear resistors can be used laterally with capacitor bank to reduce the higher degree of transient pressure. It is set in such a way that to remain non-conducting at energizing the gap, the capacitor gets discharged and energy get dissipated through the resistor. However, if the gapless metal oxide is used when capacitor will not be discharge with the lower voltage [7, 8]. The installed location and ratings of surge arresters are provided in the MATLAB model. The maximum rating and the particular energy absorption capability will be determined with the study and V-I characteristic of surge arresters [6, 7].

V. SYSTEM REPRESENTATION

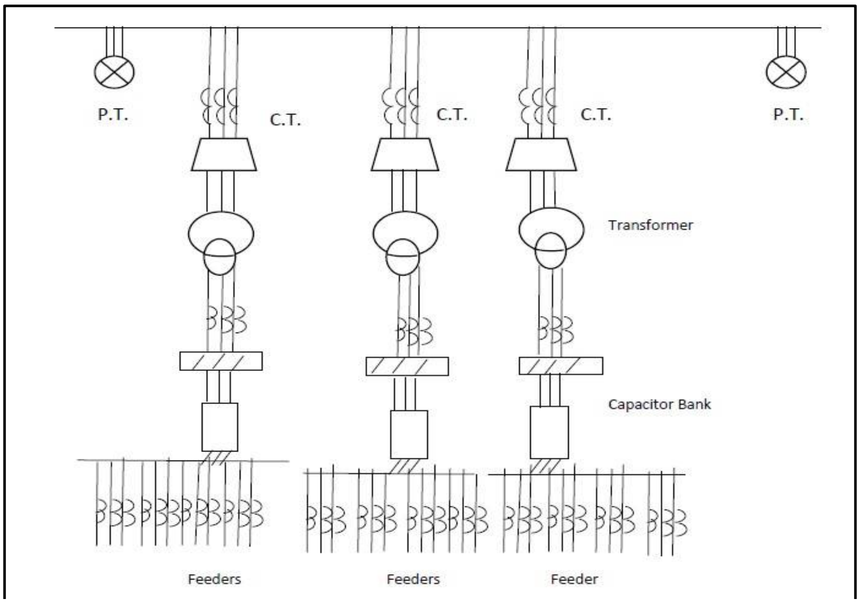

Fig 3. Basic representation of 132 kV Substation

VI.SIMULATION MODEL

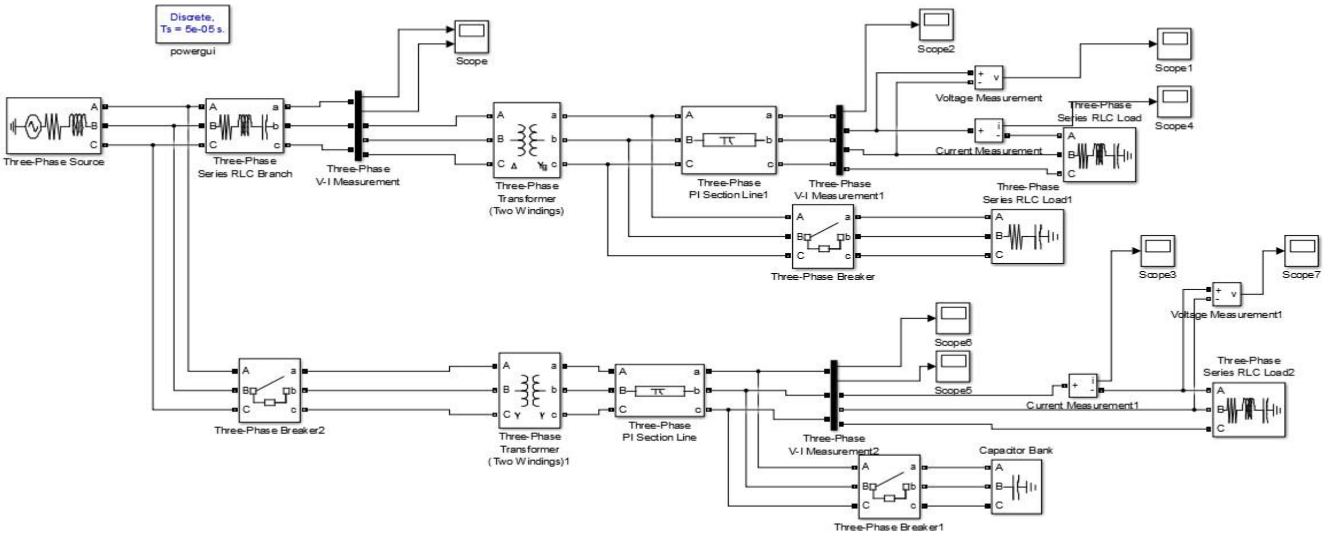

Fig 4. MATLAB/Simulink model of the capacitor bank with CB on 132 kV substation.

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A. System data

The system under the study includes a 132 kV/33kV/11kV substation source, transformer, feeder, circuit breaker with the capacitor bank and the loads. Single line diagram shows that the source of 132 kV are connected with the three phase short circuit level 24.4 MVA. The 132/11kV distribution three phase two winding transformers are included in the requirement of the substation excluding super feeder under study. Simulations are carried out with the load of 40 MVA at 0.87 lagging p.f. These values are included in MATLAB/Simulink device in the model of capacitor bank of 5 MVAr.The switching operation of capacitor bank produces overvoltage and increases frequencies with inrush current that analyzed on CB, I_{max} = 3.3mA. Here, when the capacitor bank switched on, it produces the inrush current as, I_{peak}= 3.0 mA [1, 3].

VII. SIMULATION RESULTS

A. Initial Case

The Simulink diagram shown in fig 4. The capacitor bank was introduced into the network at 0.06 sec and taken out at 0.08 sec. When the capacitor bank is injected into the system at the peak voltage of phase A then it produces inrush current with magnitude Imax= 1.5 mA.This inrush current has transient nature and frequency of magnitude as determined by the system inductances and capacitances. The main objective is to mitigate the transients in the capacitor bank of the current, voltage level to the normal base value. So that it reduces the peak overvoltage and inrush current between the banks to half of the base value of current [5].

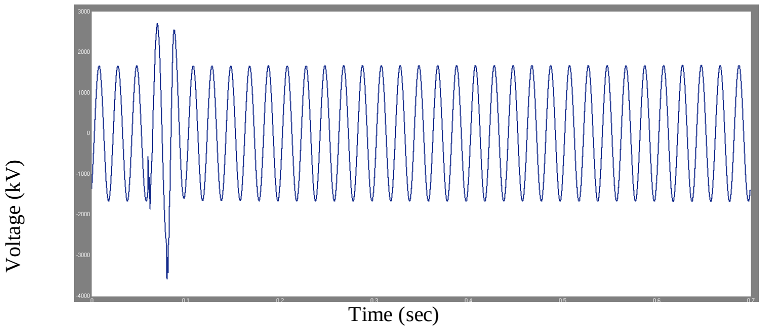

Fig 5. The voltage near capacitor bank when energized at peak voltage of phase A (Initial case)

B. Simulation Using Current Limiting Reactors

With reference to the above initial base value, the reactors are used with the control of the capacitor bank, which has an inductance of 2.5 mH per phase. When energizing, at the peak phase A, the system voltage is 2.35 p.u. The charging of the capacitor after the switching operation can be appreciated in fig 6. By increasing the value of current limiting reactor the magnitude of inrush current is limited to desired value approximately to half of the base value [4].

Referring above simulation result:

V_{max} = 15 kV, V_{normal} = 11 kV, V_{shoot} = 15-11 Kv, $Z_{total,\ new}$= V_{max}/ I_{max}= 10.71 ohm

$L_{total,\ new} = (C_{eqvt})*(Z_{0\ total,\ new})^2$= 1.3 mH' $L_{reactor}$ =L_{total} - $L_{cap\ ban}$= 1.3 mH- 0.1mH = 1.2 mH
$P.F._{load}$ = 0.87 $P.F._{corrected}$= 0.9, $P.F._{difference\ =}$ 0.02, $P_{reactor}$= V_{shoot}* I_{shoot}*$PF_{uncorrected}$= 704 kVAr

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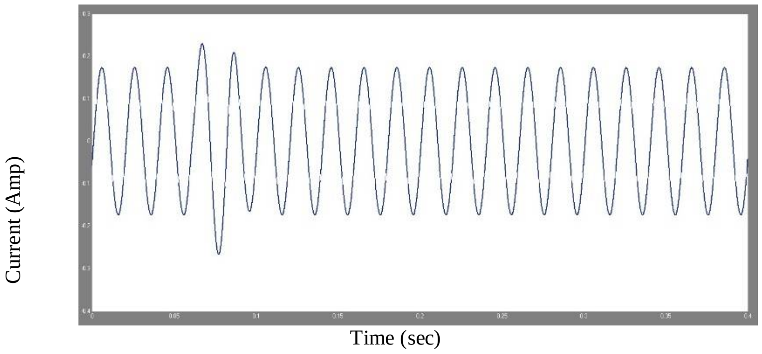

Fig 6. Current at capacitor banks when energizing at the peak system (on-axis time (sec) = 0.05 sec and on y-axis current in Amp = 0.1mA)

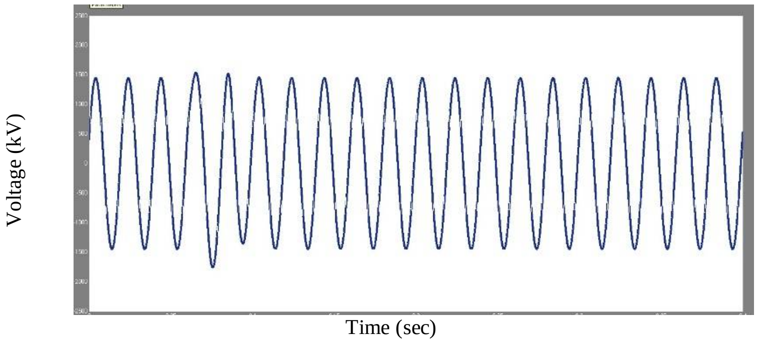

Fig 7. Voltage at nearbyCB (on x-axis time in sec = 0.05 sec and on y-axis voltage in volts = 1 p.u)

C. *Simulation using the pre-insertion resistors*

The resistors are connected in series with the controlled capacitor bank to damped the transient inrush currents. This technology required the use of an additional switch to disconnect the resistors one-quarter of a cycle after the energization of the controlled Capacitor bank. That is the additional switch is closed at 0.68 second after the simulation started. The resistors were disconnected from the circuit to reduce steady state losses.The resistance per phase reduced the peak currents and voltage [4].By knowing the value of capacitance and current to be mitigated, the value of resistor can be calculated as,

$$R = \frac{1}{2}\sqrt{\frac{V_{SYS}}{I\omega C}} = 0.3\ Ohm/phase$$

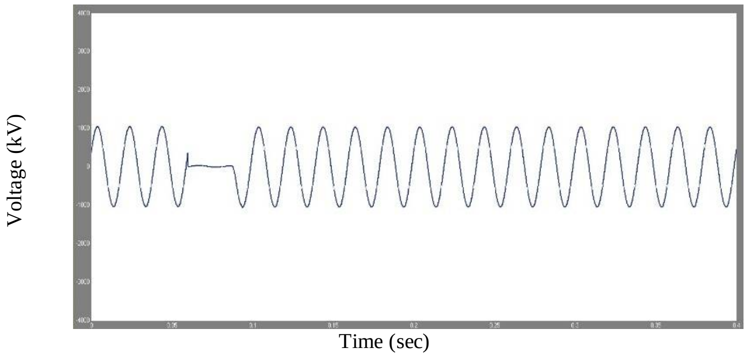

Fig 8. Voltage at breaker when pre-insertion of resistor (on x-axis time (sec) = 0.05sec, on Y-axis voltage in volt = 1 p.u.)

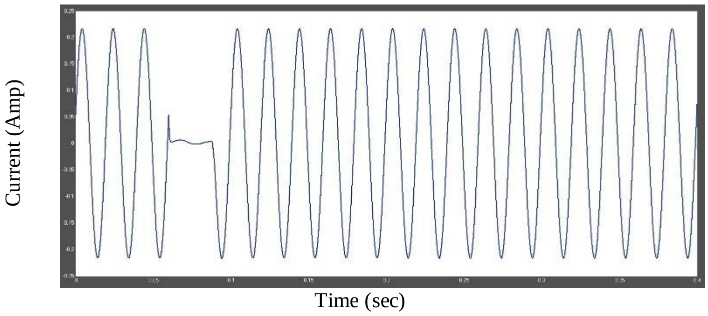

Fig. 9. Peak inrush current nearby VCB using pre-insert resistors. (On x-axis time in sec = 0.05 sec and on y-axis current in ampere = 5 mA)

Fig 9. Shows that peak inrush current was reduced to 0.5mA.It is interesting to note that the transients were damped faster with this resistor than reactors. It can be seen that the frequency of the high inrush current was almost same as that of obtained in the base case, because the value of inductanceand capacitance of the circuit was not changed. The peak voltage reached up to 1.3178 p.u. and then reached to the constant value after restoring frequency transient. This magnitude is less than the current limiting reactor [1].

D. Simulation using the surge arrester

In this technique, the gapless type of surge arrester is connected across the capacitor bank. Here surge arresters are connected phase to phase and phase to neutral of the capacitor bank. In this different positions of surge arrester across the capacitor bank, the phase to ground connection is chosen for the simulation as shown in figure [7, 1]. The overcurrent across the CB is limited to 2.3 kA.Here, V peak = 1.5 p.u. the peak voltages and currents at the capacitor bank using CB are as shown in Fig 11. This value of overvoltage and current withstanding able limit.

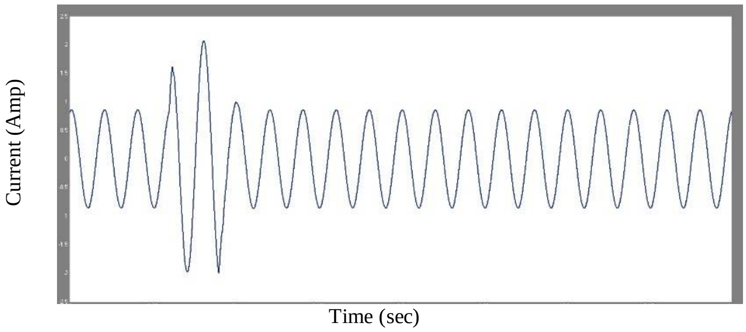

Fig 10. Current between banks using Circuit breaker for controlled capacitor bank (on x-axis time in sec= 0.05 sec and on y-axis current Ampere = 0.5 A)

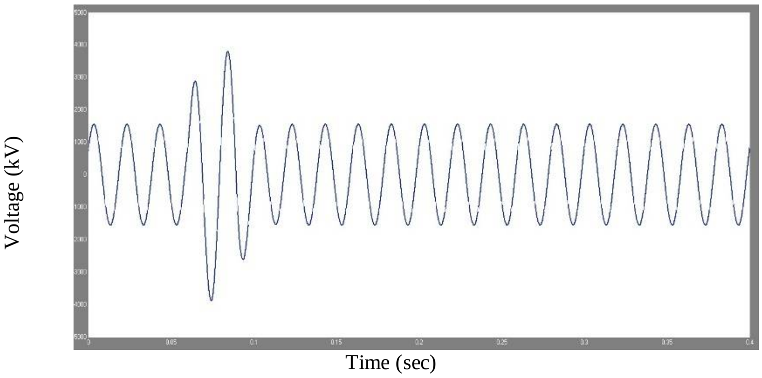

Fig 11. Voltages at the controlled bank using the surge arrester. (On x-axis time in sec = 0.05 sec and on y-axis Voltage in Volt = 1000 V)

VIII. CONCLUSION

In this paper, the characteristics of the switching transientcoming from the utility system of the capacitor bank are analyzed. For customers having the power quality problems, these can be controlled by the different mitigation techniques as we have seen in the MATLAB simulation results. Devices used for this power system are more vulnerable to power quality variations than equipment's as applied in past decays. We have analyzed three techniques to mitigate the switching transients. It has been observed that practically current limiting reactor is expensive than the other technique, for high voltage switchgear, surge arresters technique is used which is less expensive. But, ideally, pre-insertion resistor method can have ideal component values to mitigate the capacitor switchingtransient. Therefore the other two techniques to be considered to reduce the transients in voltages and current. But, also in lesser degree values. Still, its effect was noticeable and lasted for a few milliseconds. Hence, this is to conclude that practically current limiting reactor has the higher cost, here in MV switchgear surge arrester is the best choice to reduce transients with less complexity and cost of the equipment are concerned.

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