

A Review Study on Capacitor Switching Transients of HV Transmission Line With VCB

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ABSTRACT: This paper represents the review on study of power quality problems such as switching transients, overvoltage, and harmonics on electrical power system. Among those problems, we can study details of switching transients phenomenon, its types, causes, and effects etc. on various Power system equipment. A transient occurs in the power system when the network changes from one steady state into another. The switching transient in a transmission system cannot be prevented as well as its total suppression is really difficult. Accordingly, over voltage control actions have to be implemented providing proper protection for the network. These revisions for switching transient solves the problems of proper selecting the model for demonstrating power system. Study also covers different operational cases to find suitable techniques to limit capacitor switching transients. The problems of the capacitive inrush currents and ways to reduce the magnitude of the inrush current, have been study from different papers and search a new intelligent system to reduce capacitor switching transients effortlessly in the transmission system.

KEYWORDS: Capacitor switching, Capacitor inrush current, switching transients, surge arresters, energization inrush, and pre- insertion of a resistor.

I. INTRODUCTION

In modern interconnected power systems exhibits a very complicated and nonlinear behaviour. When sudden changes in power system can cause the problems of transients due to peculiar nonlinear nature of the system. If the changes in the system during transients are in large enough, the system becomes unstable [1]. Stability can be maintained by using the switching parameter banks installed in the system with sufficient damping is provided by manipulating power flows between generating stations and load during transients. At ancient time, when the transmission voltages were about 220 kV and below, over voltages due to lightning were of very high and over voltages produced inside the system were not of much importance. In future years, with increase in transmission voltages from 400 kV and above, the over voltages generated inside the system reached the same order of magnitude as those of lightning over voltages as much higher [2]. Secondly, the over voltages thus generated last for extended times and therefore are severe and more dangerous to the system. The switching over voltages depends on the normal voltage of the system and hence increases with increased system voltage.

A transient arises in the power system when the network deviations from one steady state into another. This can be, for instance, the case when lightning strikes a substation directly. The majority of power system transients can cause switching action. Load break switches and disconnectors switch off and switch on parts of the network under load and no load conditions. In power system, transients have bad impact on its reliability and may cause damage or malfunctioning of major equipment. [3] When shunt capacitor switched on live networks with high frequency and magnitude, also can cause transients in the system. Power system consist of capacitor banks for voltage regulation or power factor improvement and also used for to filtered out higher harmonics [4]. Capacitor switching requires special attention because after current interruption, the capacitive load contain large electric charge which cause a dielectric ignition of the switching device. When this process occurs repeatedly the interruption of capacitive current emerges and which cause higher overvoltages in the system [5].

In general distribution power system, capacitors at the transformer stations are switched on in morning and as peak load increases to reduce online generation and regulate the voltage. And at night peak load get decreased and capacitor get switched off. These overvoltages are compounded by distorted harmonic waveforms generated by the customers

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 4, April 2017

nonlinear loads get amplified [6]. The magnitude of power frequency overvoltage is typically low as compared to switching of lightning overvoltage. The most common causes of overvoltages are, electric faults, sudden changes of load and Ferroresonance [7]. The medium voltage capacitor banks are designed for industrial utility and commercial power systems to improve power factor, increased the system capacity reduce harmonic distortion and improve voltage regulation. Capacitor switching is most demanding operations in medium voltage network. Due to associated transients. Any restrike can cause a stress for capacitor bank and circuit breaker which reduces their life time. Or in some cases if multiple restrikes occurs damages a capacitor and circuit breaker immediately [8].

A technique to present these overvoltages for new switchgears is, the installations of modern circuit breakers with low probability of restrike. Normally utility apply capacitor on three phase sections. And they are connected ground – wye on four wire multigrounded circuit. Capacitors save significant amount of money in reduced losses. Capacitor dielectrics must withstand with high voltage strength during normal operations. Capacitor must have an internal resistors that discharges capacitor to 50V or least within 5 min. When the capacitor charge with peak of its rating voltage, most utilities also used arresters and fuses on capacitor installations. Surge arresters protects capacitor bank from lightning overvoltages [9]. Vacuum switches are used in the controller. Fixed capacitor banks are typically used for switch on and off few time during their useful lifespan, lead in to transients, switched capacitor can cause the most severe switching transients [10]. So that to reduce that overvoltages in the power system, there will be different new techniques are created by different researchers with new softwares like MATLAB Simulink, EMTP, ATP, PSCAD etc. with the study of current voltage waveforms produced in the network. Several solution methods have been proposed and applied to reduce switching over voltages, namely, pre-insertion resistors, pre-insertion inductances, permanent inductances, surge arrestors and controlled switching. Among these, controlled switching of circuit breakers has become an increasingly used in the power system [10]. Utility companies install shunt capacitor banks for voltage support and reactive power compensation. During switching of capacitors, high magnitude and high frequency transient overvoltage can be observed at both the switched capacitor and remote locations, which may lead to severe problems such as customer equipment damage, nuisance tripping of adjustable-speed drives and transient voltage surge suppressor (TVSS) failure [21]. The power quality impact of a capacitor switching event is traditionally evaluated with electromagnetic transient (EMT) simulation programs, which are based on time-domain methods [23].

II. FACTORS AFFECTING DUE TO SWITCHING TRANSIENTS

A. Capacitor Bank

Capacitor banks are installed near to the load centre will reduce the magnitude of the reactive power drawn by the load from the utility distribution system. The most common method today for improving power factor is the installation of the capacitor bank. These bank are very economical and these installations reduces the magnitude of reactive power supplied to the load. Therefore supply of reactive power from utility power system is now reduced.

B. Capacitor size and location

Generally capacitors are rated in 'VAR' which indicates the quantity of reactive is supplied by the capacitor. If the system draws 310KVR for every hour of the day. A fixed capacitor of 310KVR can be installed to provide the required reactive energy by the system. Switched capacitors are not connected all the time, it gives flexibility in the control of power factor correction, losses and system voltage because they may get switched on and off all the time [11]. It depends on the control quantity, Voltage:-Control or improvement of voltage regulation. Current: - Current Magnitude Tie switch: - VAR has a high degree of regularity with respect to time. Reactive current control: - VAR demand. The KVAR delivered changes and given by,

$$KVAR \text{ delivered} = \text{Rated KVAR} \left(\frac{\text{Operating Voltage}}{\text{Rated Voltage}} \right)^2$$

Usually, the capacitor banks are placed at the location of minimum power factor by measuring the voltage, current, KW, KVAR, and kVA on the feeder to determine the maximum and minimum load conditions. Many utilities prefer a power factor of 0.95. The peaks and valleys in the KVAR demand curve make it difficult to use a single fixed capacitor bank to correct the power factor to the desired level.

C. Power Frequency Over voltages in Power Systems

The power frequency over voltages occurs in large power systems and they are of much concern in EHV systems, i.e. systems of 400 kV and above. The main causes for power frequency and its harmonic over voltages are,

- (a) Sudden damage to the loads, (b) Interruption of inductive loads or connection of capacitive loads,
- (c) Ferranti effect, unsymmetrical faults, and (d) Overload in transformers, etc [10].

D. Control of Overvoltages due to Switching

The over voltages due to switching and power frequency may be controlled by

- a) Energization of transmission lines in one or more steps by inserting resistances and withdrawing them after-wards,
- b) Phase controlled closing of circuit breakers, c) Drainage of trapped charges before reclosing,
- d) Use of shunt reactors, and e) Limiting switching surges by suitable surge arresters [11].

E. Control Switching on circuit breaker

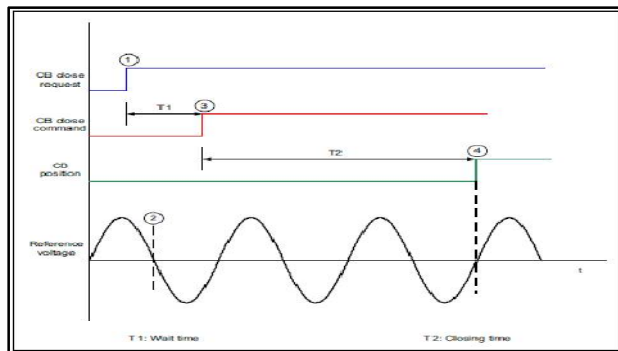


Fig.1 Controlled Switching on circuit breaker

Sequence of events for controlled switching in this example is as follows;

- a) Circuit breaker close request is received at point 1
- b) In order to determine the target point, next voltage zero is detected at point 2
- c) Knowing the circuit breaker closing time and power system frequency, target voltage zero is identified
- d) Time to give close command to the circuit breaker is estimated, and the close command is applied at point 3
- e) Contacts of the circuit breaker touches at target voltage zero at point 4

F. Power Quality Problem

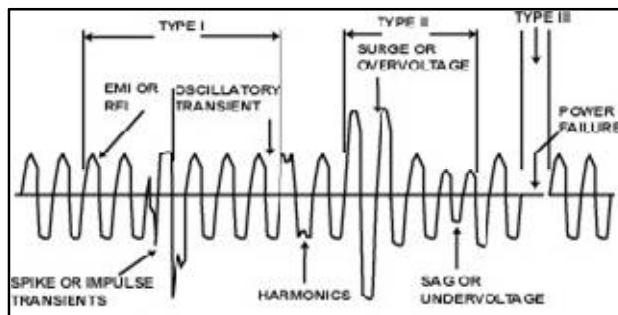


Fig.2 Types of Power Disturbances

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Vol. 6, Issue 4, April 2017

The quality of electric power has been a constant topic of study, mainly because poor power quality can lead to economic losses, especially in industrial processes, due to loss production. Due to growing connections of power electronics based equipment. One of the more common power quality problems for consumers are transient voltages in the system [12, 13]. That result from capacitor bank switching and, to a lesser extent, harmonic distortion once the capacitor is energized. The energizing transient, a power quality issue, is important because it is one of the most frequent system switching operations. The various Types of Power Disturbances are as shown in above fig 2.

G. Transient Recovery Voltage

Circuit breakers provide the mechanism to interrupt the short-circuit current during a system fault. When the breaker contacts open, the fault current is not interrupted instantaneously. Instead, an electric arc forms between the breaker contacts, which is maintained as long as there is enough current flowing. Since the fault current varies sinusoidally at the power frequency, the arc will extinguish at the first current zero. However, at the location of the arc, there are still hot, ionized gases and, if voltages exceeding the dielectric capability of the contact gap develop across the open contacts of the circuit breaker, it is possible that the arc will reignite.

Circuit interruption is a race between the increase of dielectric strength of the contact gap of the circuit breaker or switch and the recovery voltage. The latter is essentially a characteristic of the circuit itself. For inductive circuits, we know that the current lags the voltage by an angle less than ninety electrical degrees. Thus, when the current is zero, the voltage is at its maximum. This means that, immediately after interruption of the arc, a rapid build-up of voltage across the breaker contacts may cause the arc to reignite and re-establish the circuit. The rate by which the voltage across the breaker rises depends on the inductance and capacitance of the circuit.

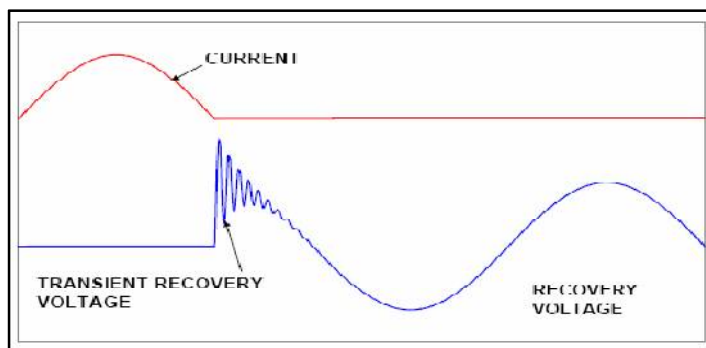


Fig.3 Transient Recovery Voltage

H. Switching Transients

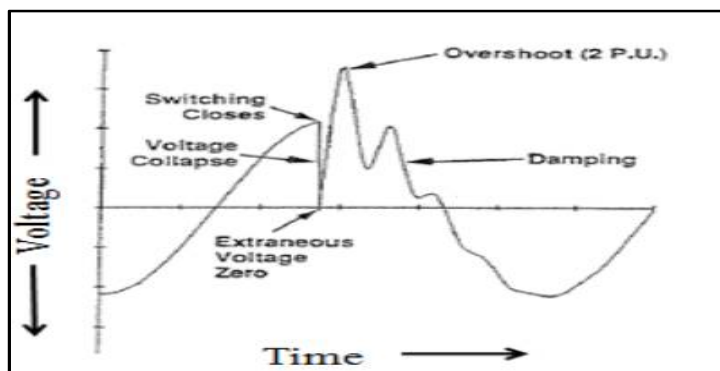


Fig.4 Switching transients

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Vol. 6, Issue 4, April 2017

The basic objectives of switching transient investigations are to identify and quantify transient duties that may arise in a system as a result of intentional or unintentional switching events, and to prescribe economical corrective measures whenever deemed necessary. The results of a switching transient study can affect the operating procedures as well as the equipment in the system. The following include some specific broad objectives, one or more of which are included in a given study:

- Identify the nature of transient duties that can occur for any realistic switching operation. This includes determining the magnitude, duration, and frequency of the oscillations.

- Determine if abnormal transient duties are likely to be imposed on the equipment by the inception and/or removal of faults. - Recommend corrective measures to mitigate transient over-voltages and/or over-currents. This may include solutions such as resistor pre-insertion, tuning reactors, appropriate system grounding, and application of surge arresters and surge-protective capacitors [7]. Devices currently available for transient over-voltage control either attempt to minimize the transient over-voltage (or overcurrent) at the point of application or limit the overvoltage at remote locations. Various methods for restraining capacitor switching transients are,

- The use of a series current limiting reactor and a switch pre-insertion resistor/inductor.
- Zero-voltage closing control and A three-dc reactor-type transient limiter
- Fixed inductors and MOV arresters and also Dividing the capacitor bank into smaller size banks,
- Avoiding the application of capacitors at multi-voltage levels to eliminate the possibilities of secondary resonance.
- Time the switching device to close at the best possible time (when voltage across the switch is zero) rather than altering the circuit parameters.

These approaches may cause problems with:-Series resonance, Voltage rises at the capacitor's terminals during the steady state, Need for an additional control circuit, Complexity of the setup and control strategy [21].

J Harmonics

The benefits realized by installing capacitor banks comprise the drop of reactive power flow on the power system. Thus, the capacitor bank should be placed as close to load as possible for peak results. However, this may not be the best engineering solution or the most economical solution due to interaction of harmonics and capacitors [12]. Harmonic distortion can be moved to the utility power system where its trouble of the sinusoidal waveform is commonly referred to as noise. Power electronics is the major source of harmonic distortion. However, apart from power electronic devices there are other sources of harmonic distortion such as arcing devices and equipment with saturable ferromagnetic cores [14]. Application of capacitor banks can create series or parallel resonance, which magnifies the problem of harmonic distortion. If the resonant frequency is near one of the harmonic currents produced by the non-linear loads, a high-voltage distortion can take place. The total harmonic distortion (THD) of the current varies from some 200% at some load terminals to a few percent at transmission level [15].

K Inrush Current

Inrush current input surge current or switch-on surge refers to the maximum, instantaneous input current drawn by an electrical device when first turned on (Fig 5). The selection of over current protection. Devices such as fuses and circuit breakers is made more complicated when high inrush currents must be tolerated. The over current protection must react quickly to overload or short circuit but must not interrupt the circuit when the (usually harmless) inrush current flows. The inrush current into the newly connected bank is determined by the size of the capacitor bank and the inductance between the two banks. The larger the banks, and the smaller the inductance between banks, the higher will be the inrush current. The frequency of the inrush current is determined by the ratio of capacitor bank reactance and the impedance between the banks. The smaller the impedance, the higher will be the frequency [21].

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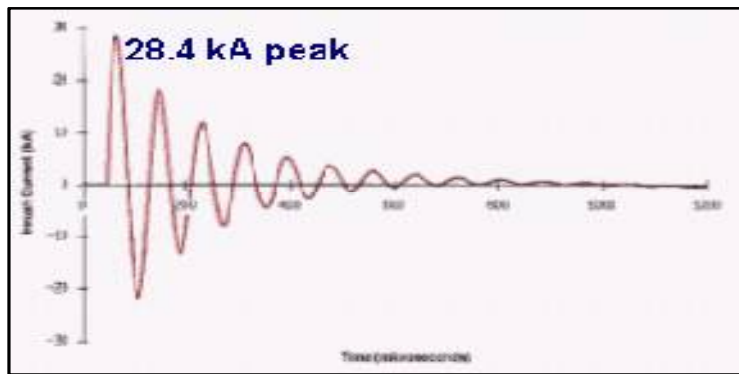


Fig.5 an Example of Inrush Current Transients

III. BASIC CONCEPT OF CAPACITOR SWITCHING TRANSIENT

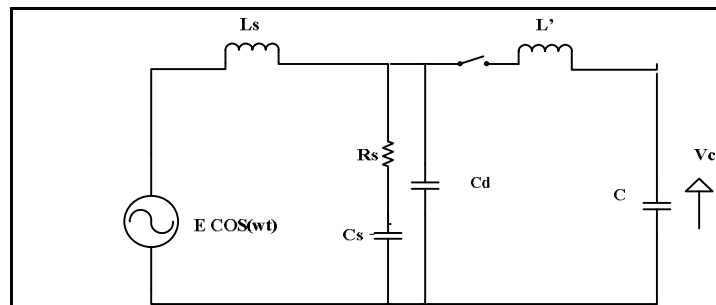


Fig. 6 Single Line Diagram of Capacitive Switching Transients
Capacitor Bank Energization.

Power System consists of a large number of the capacitor bank for voltage regulation or power factor improvement and capacitor that are part of filter banks to filter out higher harmonics. In addition, cable network or distribution system form a mainly capacitive load for the switching device. Capacitive load contains an Electrical charge and can cause a dielectric re-ignition of the switching device. When the process repeats, the interruption of capacitive currents causes high over voltages [10]. Fig.6 represent the single line diagram of Capacitive switching transients represents the L_s is the inductance of the supply and represents the system inductances of the supplying generators and the leakage inductance of the power transformers, R_s and C_s generate together the supply side TRV and represents the damping and the capacitance of the transformer and so the capacitor load is represented by a lumped capacitor C_s , Connected via a stray inductance L' , with the load side of the circuit breaker[16].

When Leakage inductance L_s much greater than L' ($L_s \gg L'$) and ($\omega L_s \gg 1/\omega C$) then the current flowing through the breaker get increases by the supply voltage with the phase angle 90° . When energizing takes place by uncharged capacitor bank at maximum voltage, voltage transients might reach approximately 2.5 to 3.0 p.u. but the losses get reduced as less value. After half cycle the supply voltage has reversed polarity and the voltage across the breaker terminal is twice the peak value of the supply voltage. When Circuit breaker is in a closed position, the voltage behind the breaker is higher than the supply voltage, The voltage difference is [10,16]

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

This is called Ferranti rise and can be seen as effect of capacitor acting as a source of reactive power.

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Frequency of the transient's oscillations and Rate of rise calculated as,

$$f = \frac{1}{2\pi\sqrt{L_s C_s}} \quad (2) \quad \frac{du}{dt} = Z_s \frac{di_c}{dt} \quad (3) \quad \text{Where, } Z_s = \sqrt{\frac{L_s}{C_s}}$$

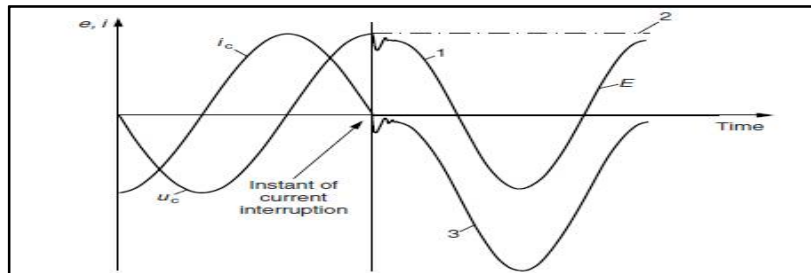


Fig. 7 Current and voltage traces during the interruption of a capacitive current 1: supply voltage, 2: voltage on the capacitor, and 3: voltage across the circuit breaker

The voltage transient is a source-side phenomenon. At the load side, where the capacitor bank or the cables are connected, there is no change in voltage. The trapped charge causes a constant voltage, but when the supply voltage has the opposite polarity, nearly two times the peak value of the supply voltage is present across the breaker contacts. When we realise that the small capacitive current could already be interrupted at a short arcing time and that the arcing contacts therefore have not travelled very far, the gap between the arcing contacts is still narrow and a dielectric breakdown of the extinguishing medium can occur. When the re-ignition occurs (see Figure 5.3), the capacitance C discharges itself via the re-ignited arc channel and the inductances L_s and L' . The result is an oscillating current with the following frequency and peak value

$$f = \frac{1}{2\pi\sqrt{L_s * C}} \quad (4) \quad \text{And Peak value } I = \frac{2E}{\sqrt{\frac{L_s}{C}}} \quad (5)$$

From below fig 8, The smaller the value of L_s , the higher the frequency and larger the amplitude of the transient current. When at the instant of re-ignition the value of the voltage on the capacitor C was $-E$, the voltage is then $+3E$ at the first zero crossing of the transient current. When the arc Channel extinguishes, the circuit breaker interrupts the oscillating current. The recovery voltage across the contact gap has now increased to $4E$ (the contribution of the supply-side voltage is $-E$ and of the trapped charge on the capacitor C is $+3E$) [10].

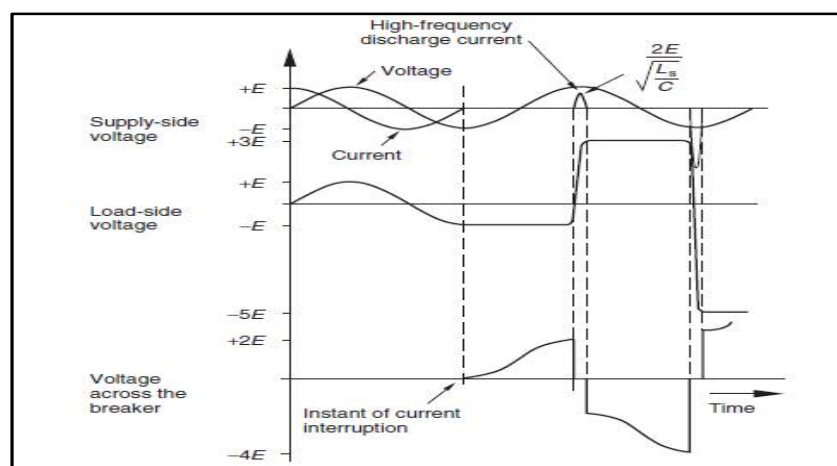


Fig.8 Re-ignition of the circuit breaker when interrupting aCapacitive Current

IV. CAPACITOR ENERGIZATION PROCESS

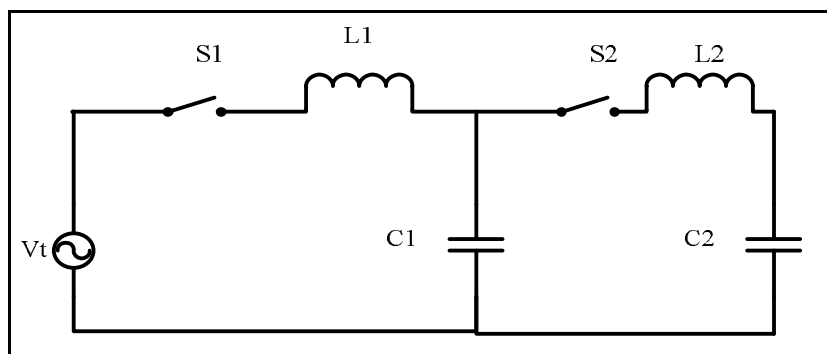


Fig. 9 Basic Capacitor energization process

The basic circuit diagram for Capacitor switching process is given as shown in fig.9 .At the time of the switching of shunt capacitor banks, with high magnitude and high frequencies, transients can occur [18]. The transients are characterized by a surge of current having a high magnitude and a frequency as high as several 100 Hz. There is also transient's overvoltage on the bus caused by the surge of inrush currents coming from the system source. Basic concepts of capacitor energization are explained in fig 2. Where resistances are neglected for simplification, as capacitor C1 is energized by closing switch S1 [17]. The voltage and current in the capacitor are given by following equations as,

$$V_{c1}(t) = V - [V - V_{c1}(0)]\sin\omega t \quad (6) \quad I(t) = \frac{V}{Z_1} \sin\omega_1 t \quad (7)$$

Where, V = Switching voltage when S1 closed, Vc1 = Initial voltage at C1

V. DIFFERENT TECHNIQUES OF REDUCTION OF CAPACITIVE SWITCHING TRANSIENTS

There are many technologies and methods are available to mitigate transients such as a use of pre-insertion of the resistor, surge arrester connected across the capacitor bank, and current limiting resistor. Each type of switching transients represents different transients output with the help of MATLAB simulation [10, 16].

A. Current Limiting Reactor

In this technique, the suitable rating of a current limiting resistor is used in series with the capacitor bank. Due to this reactor surge impedance of the circuit get increased and hence peak inrush current get decreased. 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 this inrush transients current is compressed. [16]. It is clear that as the current increases in the negative half cycle and this can be attributed exchange of energy between two energy storing devices such as inductor and capacitor. The purpose of X/R ratio is for the sharpness of tuning, also for damping purposes, X/R ratio is lower [10]. Here reactor of particular rating is used in series with the capacitor bank. Due to use of this reactor the surge impedance of the circuit increases and hence the peak of inrush current cannot change instantly. Therefore higher frequency components of transients are constrained and the effect of these inrush current is compressed.

B. Resistance switching or pre-insertion of resistor

In a current interruption technique, the use of switching resistor in high voltage breaker is well implemented to reduce overvoltage and frequency of TRV. And current for medium voltage, two breakers are used to pre- insert the resistor for duration, such as,

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$$f_n = \frac{1}{2\pi} \sqrt{\left[\left(\frac{1}{LC}\right) - \left(\frac{1}{4}\left(\frac{R}{L} - \frac{1}{RC}\right)\right)\right]} \quad (8) \quad R = \frac{1}{2} \sqrt{\frac{L}{C}} \quad (9)$$

This methods used switching resistors are connected in series with the capacitor bank. Due to the use of resistors losses in the circuit are increased and to decreased 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 initial peak which is most damaging of transients. In power systems, the resistance is generally, much less than the reactance. [19].

C. By using Surge arrester

Another technique to reduce the current transients, the gap type of surge arrester are connected in the series nonlinear resistor can be used along with capacitor bank to reduce higher extent transient stress. It is set in such a way to remain non-conducting at energizes the gap, the capacitor gets discharged and energy dissipated through the resistor. However, if gapless metal oxide is used when capacitor will not discharge below voltage. The Metal Oxide surge arrester exhibits dynamic characteristics such that the voltage across the surge arrester increases as the time-to-crest of the arrester current decreases and the voltage of arrester reaches a peak before the arrester current peaks [13, 16]. The installed location and rating of surge arresters are provided. The maximum ratings, and in particular the energy absorption capability will be determined with study and characteristic V-I of surge arresters [20].

VI. CONCLUSION

This paper concludes that controlled switching of circuit breaker is the best technique to reduce switching overvoltage than any other method. Without using surge arrester or controlled switching peak over voltages can reached to maximum limiting p.u. values. This voltage are dangerous to whole power system if the surge arresters, Current limiting reactors are used at both ends of the lines these over voltage are reduced to a limiting value. Today this controlled switching are applies by using external control device which take place voltage and current signals to an inputs, such applications decrease the reliability of the system, since the cabling and environmental conditions affect the operation of the controller. The magnitude and frequency of the inrush current Resulting from energizing capacitor bank is a function of the point on the wave of the applied voltage where the contacts were closed. The capacitance and inductance of the circuit, the charge on the capacitor at closing time any damping resistance contained in the circuit. Due to this there are various easy methods to reduced switching transients developed by different researchers by using software simulations of like MATLAB Simulink, EMT, and ATP etc.

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