

Investigation and modeling of the inrush current generated by the capacitors switching in two modes the presence of current limiting inductor and its absence

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Abstract

Inrush current is a transient current that flows when capacitors are initially switched on. This high magnitude current can pose various issues, such as affecting circuit breakers, causing voltage dips, and damaging the capacitors themselves. Therefore, it is essential to investigate and understand its characteristics. When a current limiting inductor is present in the circuit, it restricts the flow of the inrush current by limiting its rate of rise. This helps in reducing the peak magnitude of the current and its potential harmful effects. The inductor adds impedance to the circuit, which slows down the rate of change of current. On the other hand, in the absence of a current limiting inductor, the inrush current can flow with full force, reaching high peak values. Switching in high-voltage capacitive banks used to control voltage and reactive power at high-pressure substations usually results in significant inrush currents and transient states. The ripples in the waveform cause damage to the power system and capacitive banks. In this way, it reduces the life of capacitive units or, if it continues, causes complete failure of capacitive banks. The use of current-limiting inductors in capacitive banks reduces the transient time in capacitive banks at the moment of switching and reduces the inrush current. In this paper, we use MATLAB Simulink to investigate the switching effect for a 20 kV capacitor bank with a capacity of 4.8Mvar, first without current-limiting inductor, and then with it and compare their results.

Keywords

Capacitor Bank, Inrush Current, Current-limiter Inductor.

1. Introduction

Investigation and modeling of the inrush current generated by capacitors switching is important to understand the behavior and impact of these currents on electrical systems. This analysis becomes crucial in cases where current limiting inductors are present or absent, as their presence can significantly influence the inrush current. Capacitor bank is one of the important equipments used in high voltage substations and the need to use capacitive banks in today's power grids is obvious. These banks are usually used in parallel in the above distribution and transfer substations for purposes such as power factor correction, voltage regulation, loss reduction, etc. Of course, this equipment also has weaknesses, the most important of which are Inrush current, switching problems, protection requirements and incidental costs [1-4].

Capacitors should be operated in a range less than the nominal voltage and frequency values. Capacitors are capable of withstanding switching passages with a peak voltage of up to $2\sqrt{2}$ times the rated value of the effective voltage without reducing their expected life. These overvoltages may cause a partial discharge in the

capacitive unit. Trapped loads and gases produced in the primary half cycle further intensify the discharge in the secondary half cycle. Accumulation of these damages causes more severe overvoltage damages with increasing time and finally failure of capacitor insulation. [5-8]

Short circuit caused by discharging capacitors during electrification in capacitor banks causes transient switching states in capacitor banks. This short circuit causes very high inrush current and consequently voltage perturbations. Inrush currents cause pressure on switching devices, fuses and capacitive units. [9-11] When there is more than one capacitor bank on a bus, electrification of the capacitor bank reduces the source impedance for the switching moment. As a result, it causes very high transient voltage in all capacitive banks connected to the bus. This voltage will eventually cause the capacitive unit to fail and reduce its useful life.[12]

To model the inrush current, various techniques can be employed, such as mathematical equations, simulation software, or circuit analysis tools. These models take into account factors like capacitor characteristics, circuit impedance, and the presence or absence of a current limiting inductor. By investigating and modeling the

inrush current, engineers can determine the necessary measures to mitigate its impact. This may include the addition of current limiting inductors, using soft-start circuits that gradually ramp up the voltage, or implementing control strategies to manage the switching of capacitors. Overall, the investigation and modeling of inrush current provide valuable insights for designing and operating electrical systems effectively and safely [13].

2. Inrush Current in Capacitor Switch

Capacitor switching applications are not limited to capacitive currents but are also used in the process of electrifying capacitor banks, overhead lines and cables. Capacitor bank switching is known for generating a large amount of transient voltage in power switch contacts.

There are many large capacitor banks for voltage regulation, to improve the PF (Power Factor), and capacitor banks are also widely used in filtering high harmonics in the overall system.

In the process of distributing the power system, there are cable networks that create a capacitive load. In case of any current interruption (power failure) of the load, the capacitive capacity of the system is charged and this charge in the capacitors causes damage to the dielectric due to high voltage.

When a large inrush current flows through the substations, the system must withstand the conditions created in the protection system as well as during switching. When there is voltage in the line, this voltage begins to fluctuate at an almost low frequency and magnitude. It doubles the voltage peak in the circuit, which can cause serious hazards. This article will discuss how to minimize high inrush current and what are the basic recommendations for it.

There are methods for placing capacitors and inductors in the circuit that can significantly minimize the amount of inrush current generated at the moment of switching. Which are explained below:

2.1. Single Capacitor Bank Circuit

Consider the following single-phase circuit. This circuit has a switch of one capacitor and two inductors and it is assumed that the resistance of the circuit is almost zero and the value of inductor L1 is more than L2.

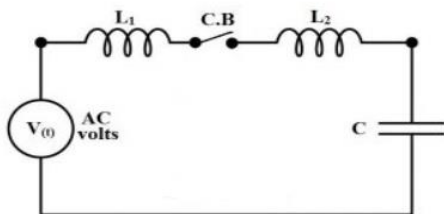


Fig. 1. A Single Capacitor Bank Circuit.

There is a power switch in the circuit to interrupt the circuit. This shape of the circuit is called a single capacitive bank.

In this case, the current depends on the parameters of the circuit and the initial state of the circuit.

Suppose a capacitor with voltage v0 is charged at time t0.

The current can be calculated from the following statement:

$$i = (V_t - V_0) \frac{1}{\sqrt{\frac{L_1}{C}}} \sin \omega_0 t \tag{1}$$

$$\omega_0 = \sqrt{\frac{1}{L_1 C}} \tag{2}$$

In this scenario, the damping current is reduced and the total current is established in the circuit.

2.2. Back-to-Back Capacitor Bank Circuit

This scenario is known as back-to-back capacitive bank switching.

Consider the following circuit for it:

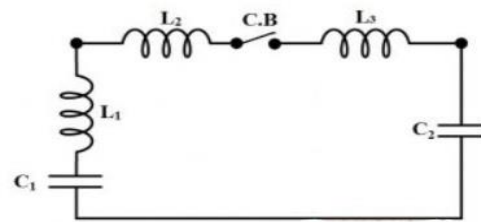


Fig. 2. A Back-to-Back Capacitor Bank Circuit

Consider the following single-phase circuit. This circuit has

In this case, when the switch is closed, there are two capacitors and two inductors.

The power switch is present at point b-b (ie the voltage difference between the two power switch contacts) when it is disconnected and in the event of any dielectric failure.

Therefore, the current formula can be obtained in the following way:

$$i(t) = V_{0b-b'} \frac{1}{\sqrt{(L_1 - L_2) \left(\frac{1}{C_1} + \frac{1}{C_2} \right)}} \sin \omega_2 t \tag{3}$$

$$\omega_2 = \sqrt{\left(\frac{1}{L_1 + L_2} \right) \left(\frac{1}{C_1} + \frac{1}{C_2} \right)} \tag{4}$$

$$V_{0b-b'} = V_m \frac{1}{\sqrt{1 - \omega^2 (L_1 + L_2)}} \tag{5}$$

$$\omega = \sqrt{\frac{1}{L_1 C}} \tag{6}$$

In this case, the current can be about ten times more than the maximum current in the circuit. But this current only affects one (local) capacitor and the rest of the system is safe.

2.3. Current-Limitor Inductor

To deal with the effects of inrush current, one of the most simple and practical ways is to use inductor in series

with the capacitor, and this is the main topic of this article, which we will simulate later.

The purpose of using a reactor is to limit the rate of increase of transient current and its value is calculated from the following equations:

$$L_p = \frac{V_p}{2\pi \times f \times I_p}$$

$$L = \frac{L_p}{n}$$

Where V_p is the peak voltage of the network (in KV), I_p is the peak current transient (in amperes), n is the number of parallel capacitive banks, and L_p is the limiting reactor inductance for n parallel capacitive banks.

According to KCL, we know that inductor current does not jump; so it can be a good tool to limit the increasing current of the capacitor at the moment of connection to the network. Based on this, the contactor for switching capacitors have been developed that are equipped with a small limiting inductor with an air core.

3. Simulation of Inrush Current

In this section, we simulate the offensive current created by capacitive switching in MATLAB. The simulation performed for 20KV capacitors with 4.8Mvar reactive power capacity.

First, we do this simulation for a situation where there is no current limiting inductor in the circuit.

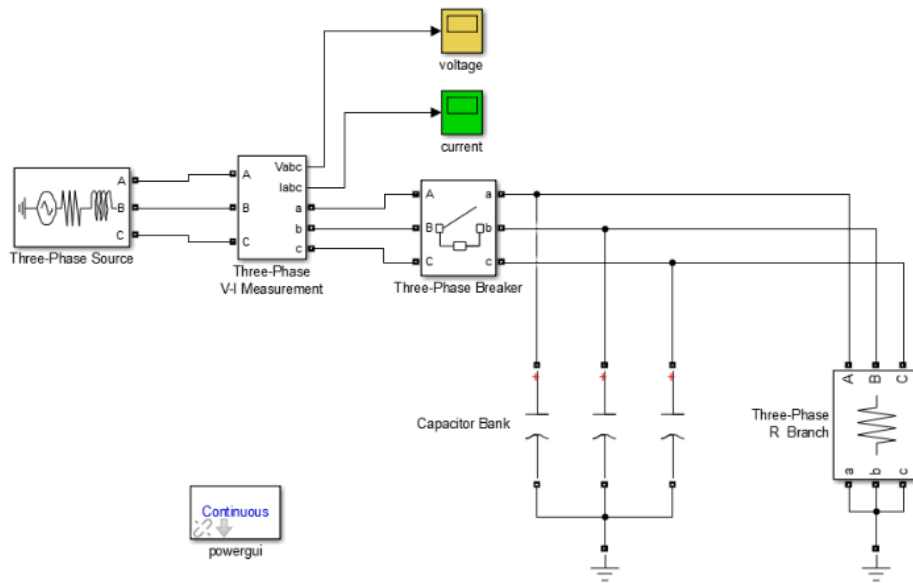
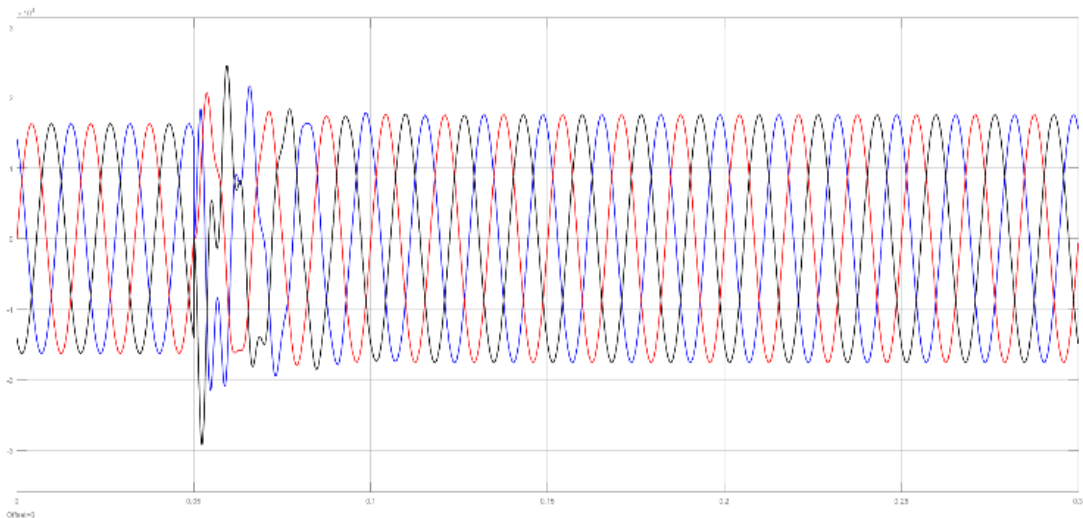
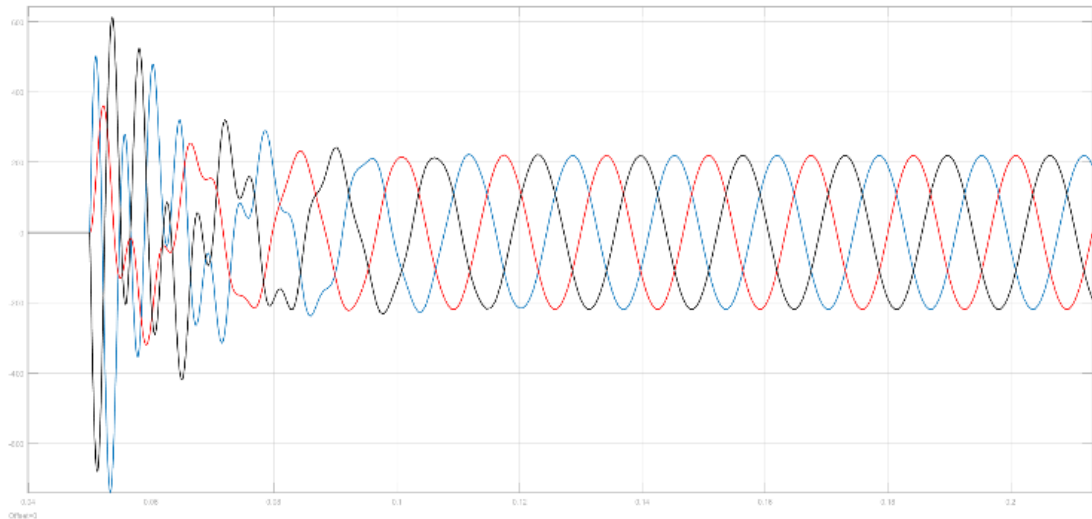


Fig. 3. Capacitor bank switching model without current limiter inductor.



(a)



(b)

Fig. 4. Capacitor switching curves without inductor current limiter (a)voltage curve (b)current curve.

As can be seen and expected, after capacitive switching, a very large current (inrush current) is generated in the circuit, and as previously discussed, this

current causes severe damage to the power system, so it is necessary to reduce this current.

In this part of the simulation, current limiting inductors are placed in series with capacitors.

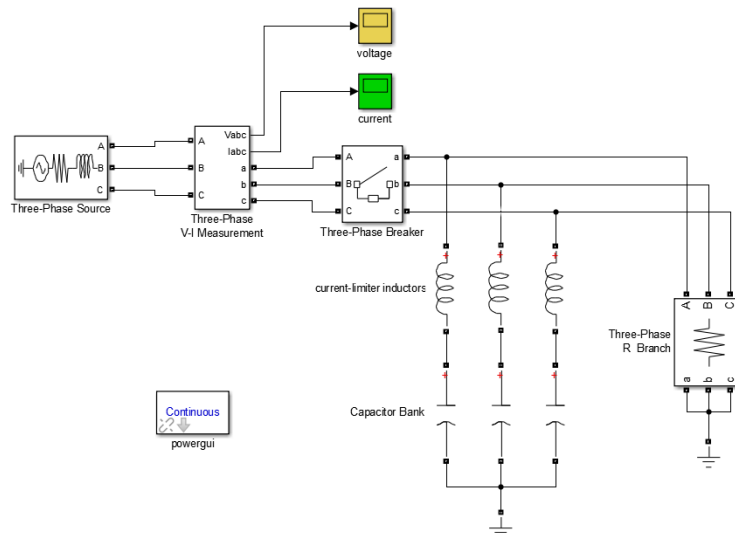
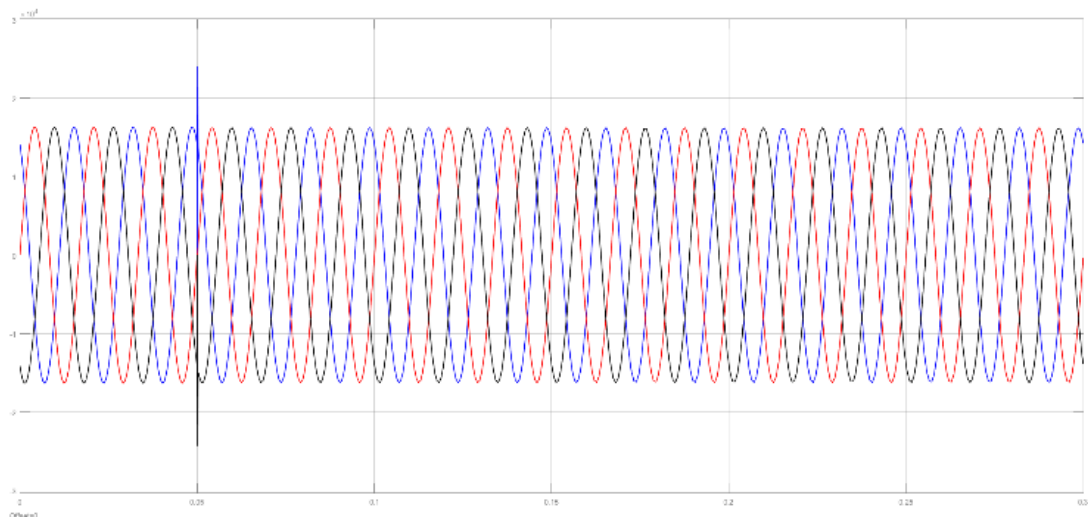
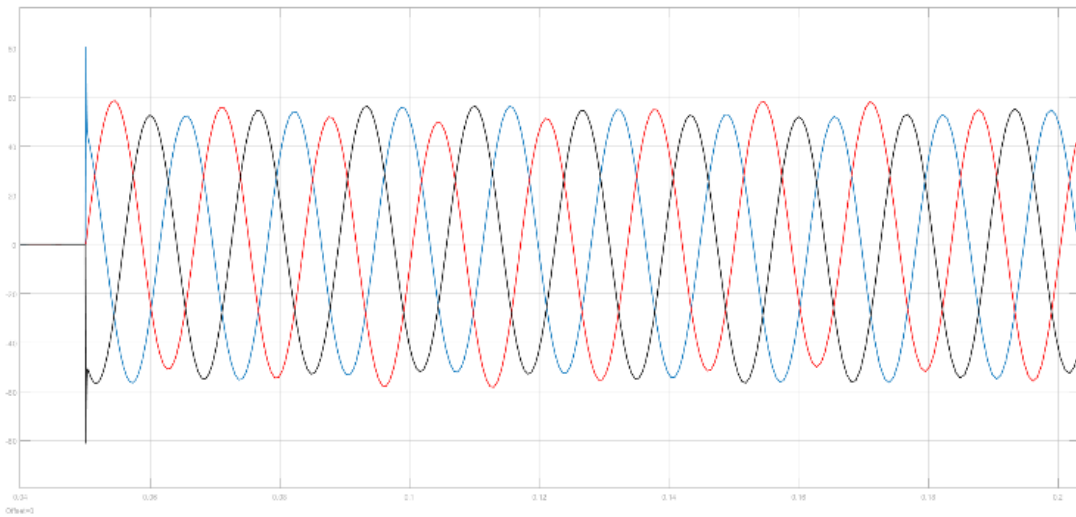


Fig. 5. Capacitor bank switching model without current limiter inductor.



(a)



(b)

Fig. 6. Capacitor switching curves with current limiting inductor (a) voltage curve (b) current curve

As can be seen, the series of current-limiting inductors and capacitors has caused the inrush current to be reduced to a desirable level. Reduction of the inrush current has occurred in a very short time. Voltage curve perturbations are also reduced and all these makes the power system less damaged.

4. Comparison Criteria

A Power system use capacitive banks according to their structure and applications and use different methods to deal with inrush current caused by switching.

In this paper, methods are proposed that each has its own characteristics. It should be noted that each method of dealing with inrush current has its own criteria and the comparison of these methods is appropriate to the power system used.

In this paper, the method of using current limiting inductor was further investigated and simulated for switching a 20 kv capacitive bank with a reactive power capacity of 4.8 Mvar.

comparison of Figures 5 and 6 shows well that the presence of current-limiting inductor reduces the voltage perturbations in the power system And when the current limiter inductor is not used, a large inrush current is created in the network at the moment of switching capacitor bank, which can cause serious damage.

5. Conclusion

Switching on capacitive banks causes an unwanted transient state that may damage the capacitive units and over time cause the capacitive bank to fail completely. The use of resistors and current-limiting inductors reduces the transient effects of switching in capacitive banks and reduces the inrush current. One way to show this clearly is to use MATLAB Simulink and simulate with it.

In this paper, this was done for a 20 KV capacitive bank with a reactive power capacity of 4.8 Mvar, and in two cases, the presence of a limiting inductor and its absence, we were able to observe the inrush current and voltage perturbations at the switching moment. In the first stage of switching in the capacitive bank without current limiting inductor was simulated, which resulted in severe distortion in the voltage and current waveform,

and also the current level was extremely high. But in the second stage, current limiter inductor was used, which resulted in an extraordinary reduction of distortion in the voltage waveform, which was close to zero. Also, the distortion of the current waveform was minimized and the amount of current was reduced compared to the previous stage. With this method, the voltage transient mode is greatly reduced and even close to zero, and also the level of short circuit current is significantly reduced so that it does not pose a problem for capacitor bank units and other devices of power systems.

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