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Development and Analysis of Radial Feeder Protection for Capacitor Switching Transients

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Abstract— **Transient current in power system is very common factor, due to many switching operations. This paper focusing on recovery capacitor switching transient has been proposed for system protection. It will protect from mal-operation of relay to improve the reliability of the system. During Group of generator switching, transformer switching, Series capacitor switching, Shunt capacitor switching, Tap-changing operations will cause high inrush current in radial distribution system. This work comprises of a radial feeder three phase system protection improvement deals with overcurrent relay. This approach significantly improves the performance of radial feeder protection under transient condition for the period of starting. The high inrush currents can do mal function of protective relays and it will cause a severe damage to the system and end user equipment. The series reactor load adopted to compensate current and voltage waveform problems of sensitive relays doing mal operation under transient conditions. The series reactor consists of a series inductor having a common for three phase load side. The extensive simulation results have been carried out in MATLAB/Simulink environment power system blockset toolboxes.**

Keywords— **Radial feeder protection, Capacitor switching, Series reactor, Transient current.**

I. Introduction

The function of protective relaying is to cause the quick removal from service of any element of a power system when it suffers a short circuit, or when it starts to operate in any abnormal manner that might cause damage or otherwise hold up with the effective operation of the rest of the system. A secondary function of protective relaying is to provide indication of the type of failure. Human observation and automatic oscillograph records are provided for analyzing the effectiveness of the fault-prevention and features including the protective relaying itself. This paper will focus on the mal function of protective relay. Power system network consists of generators, transformers, circuit breakers, relay and transmission line and distribution circuits. Fault occurs on any part of the system, it must be quickly detect and disconnect from the system. There are two principle reasons for it.

Firstly, if the fault is not cleared quickly, it may cause unnecessary interruption of service to the customers. Secondly, rapid disconnection of faulted apparatus limits the amount of damage to it and prevents the effects of fault from spreading in to the other part of the system. This paper will focus on the mal function of protective relay. Back-up relaying is employed only for protection against short circuits. It causes short circuits are the major type of power failure, there are more opportunities for failure in short primary relaying. Consequently fail-to-trip may not lead to loss of more components, based on the fault is finally cleared by remote back up protection or just by local back up protection. But a mal operation of protective relay will always lead to loss of at least one component in the system.

In the presence of harmonic-producing loads, capacitors used for power factor correction can cause parallel or series resonance problems which tend to increase the total harmonic distortion (THD) of the voltage and current waveforms. This work considers the addition of a power factor correction capacitor, in the presence of harmonic loads and at the harmonic load site. In both the resonance created by the addition of the capacitor caused the harmonic distortion of the voltage and current waveforms to increase. Another problem is transient over voltages created by switching capacitor. Radial distribution has much potential to improve radial distribution system performance and it should be encouraged.

However, radial system designs and operating practices are normally based on radial power flows and this creates a special challenge to the successful introduction of insure that distribution generation will not degrade distribution system power quality, safety or reliability. The relay operating principle, design and application are presented as well as results from computer simulation studies and laboratory tests. A spectral analysis of voltage and current waves is made to extract the acceptable capacitor switching times by observing the transient over-voltages

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and current. The solution to mal-trips is dependents on many factor, but mainly the immunity of protective relays against the impact of any non-fault transient.

II. CONFIGURATION OF RADIAL FEEDER PROTECTION

Transmission line protection presents many fundamental relaying considerations that apply to the protection of other types of system protection. Each electrical element will have problems unique to itself, but the concepts of reliability, selectivity, local and remote backup, zones of protection, coordination and speed which may be present in the protection of one or more other electrical apparatus are all present in the considerations surrounding transmission line protection. Transmission lines are also the links to adjacent lines or connected equipment; transmission line protection must be compatible with the protection of all of these other elements. This requires coordination of settings, operating times and characteristics.

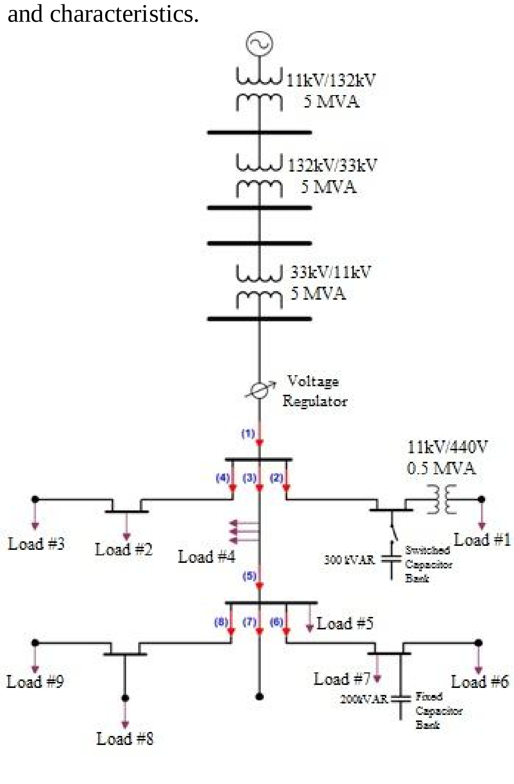

Fig. 1. Radial Feeder System-13 bus system

The purpose of power system protection is to detect faults or abnormal operating conditions and to initiate corrective action. Relays must be able to evaluate a wide variety of parameters to establish that corrective action is required. Obviously, a relay cannot prevent the fault. Its primary purpose is to detect the fault and take the necessary action to minimize the damage to the equipment or to the system. The most common parameters which reflect the presence of a fault are the voltages and currents at the terminals of the protected apparatus or at the appropriate zone boundaries. The fundamental problem in power system protection is to define the quantities that can differentiate between normal and abnormal conditions. This problem is compounded by the fact that ‘‘normal’’ in the present sense means outside the zone of protection.

Electric power distribution is the portion of the power delivery infra structure that takes the electricity from the highly meshed, high-voltage transmission circuits and delivers it to customers. Primary distribution lines are “medium-voltage” circuits, normally thought of as 600 V to 33 kV. At a distribution substation, a substation transformer takes the incoming transmission level voltage (132 to 33 kV) and steps it down to several distribution primary circuits, which fan out from the substation. Close to each end user, a distribution transformer takes the primary-distribution voltage and steps it down to a low-voltage secondary circuit (commonly 33 kV/11 V other utilization voltages are used as well). From the distribution transformer, the secondary distribution circuits connect to the end user where the connection is made at the service entrance.

A. Structure of power system

Overview of the power generation and delivery infra structure and where distribution fits in. Functionally, distribution circuits are those that feed customers. Some also think of distribution as anything that is radial or anything that is below 33 kV. The distribution infra structure is extensive after all, electricity has to be delivered to customers concentrated in cities, customers in the suburbs, and customers in very remote regions few places in the industrialized world do not have electricity from a distribution system readily available. Distribution circuits are found along most secondary roads and streets. Construction is mainly overhead. A mainly utility may have less than 50 ft of distribution circuit for each customer. A rural utility can have over 300 ft of primary circuit per customer.

Extensive infra structure, distribution systems are capital intensive businesses. An Electric Power Research Institute (EPRI) survey found that the distribution plant asset carrying cost averages 49.5% of the total distribution resource (EPRI TR-109178, 1998). The next

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largest component is labour at 21.8%, followed by materials at 12.9%. Utility annual distribution budgets average about 10% of the capital investment in the distribution system. The growth of underground distribution system has been extremely rapid and as much as 70% of new residential construction is via underground systems.

III. CONTROL OF CAPACITOR SWITCHING TRANSIENT

The capacitor-switching transients can be controlled by many methods in nature. It can prevent the protective relay and end user equipment from non-fault condition.

1. Series inrush-current-limiting reactors
2. Resistance switching
3. Point-of-wave switching (synchronous breakers)
4. Application of surge arresters
5. Dividing the capacitor bank into smaller size banks (the smaller the size of the capacitor bank being switched, the lesser is the transient)
6. Avoiding the application of capacitors at multi-voltage levels to eliminate the possibilities of secondary resonance
7. Coordination with utility, if the utility capacitors are located close to the distribution system
8. Considering steady-state voltage rise due to application of capacitors. The transformer taps may have to be adjusted.

IV. CAPACITOR SPECIFICATIONS

The specifications for capacitors are identified by the industry standards. They include tolerances and acceptable operating ranges. The capacitors shell be capable of continuous operating without exceeding the following limits.

i. 110% of peak voltage
ii. 120% of rms voltage
iii. 135% of name plate Kvar
iv. 180% of nominal rms current based on rated kVAR and rated voltage.

A. Voltage

Nominal system voltages are specified line to line. The capacitor units are single phase and appropriate phase voltage is to be used. Capacitors are capable of operation at 110% of rated rms voltage and the crest should not exceed $1.2\sqrt{2}$ rated rms voltage. The max operating voltages for shunt capacitors are listed in table I.

TABLE I
VOLTAGE AND KVAR RATING OF THE CAPACITOR UNITS

Terminal to Terminal Voltage	Kvar
216V	5,7.5,13.3,20 and 25
240V	2.5,5,7.5,10,15,20,25 and 50
480V and 600V	5,10,15,20,25,50,60 & 100
2.4kV,4.16kV & 4.8Kv	50,100,150 and 200
6.64kV,7.2kV,8.32kV,9.96kV,11.4kV,12.47kV,13.8kV, 14.4kV,15.12Kv	50,100,150,200,300 and 400
19.9kV,20.8kV and 23.8Kv	100,150,200,300 and 400

B. kVAR Rating

Capacitor unit ratings are specified in kVAR. Normally available capacitor ratings are 50, 100, 150, 200, 300 and 400kVAR per unit. The capacitor units are capable of continuous operation but exceeding 135% of name plate kVAR. The typical kVAR ratings are listed in table. If the operating voltage increases or decreases from the nominal operating voltage, then the kVAR delivered changes accordingly.

$$\text{kVAR delivered} = \text{Rated kVAR}(\text{Operating Voltage}/\text{Rated Voltage})^2$$

C. Frequency

Power factor Capacitors are designed for operation at 50 or 60Hz. The capacitor kVAR output is directly proportional to the system operating frequency. If the capacitor operates at a different frequency then the rated frequency, then the kVAR delivered is:

$$\text{kVAR delivered} = \text{Rated kVAR}(\text{Operating Frequency}/\text{Rated Frequency})$$

By adding series current-limiting reactors can be reduced amplitude of the inrush current. But hardware implementation is very high cost. The dynamic modification of pickup current as a function of the load current. It increases the sensitivity in the most probable operating state. But it takes time and manual operation. The algorithm can be used online, since immediately after the switching instant, it can be applied. During transient cannot do any prediction. Capacitor switching is one of the common causes of an overvoltage transient encountered in power systems. Transient can be measured in this method. The phenomena adversely affect the voltage in radial system, resulting in the nuisance tripping at the customer terminals or even damage to sensitive equipments (Electromagnetic Transients Program). Although the proposed method is tested on a distribution system, its application is not limited only to radial power

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systems and can be used in all distribution systems. The drawback of using this method in over-current protections is the need to measure voltage in addition to current that increases the cost of hardware implementation.

V. SIMULATION

The controlled capacitor bank is switched into the feeder to evaluate its effect on the feeder. The peak transient voltages, harmonics, and the high frequency inrush currents that originated as a result of this switching operation near the capacitor bank and near the load are concentrated. The controlled capacitor bank switch was closed at 5.4ms where the voltage of phase A reaches its peak value. Fig. 2. shows the transient response of the three-phase voltages near the capacitor bank before and after the switching operation.

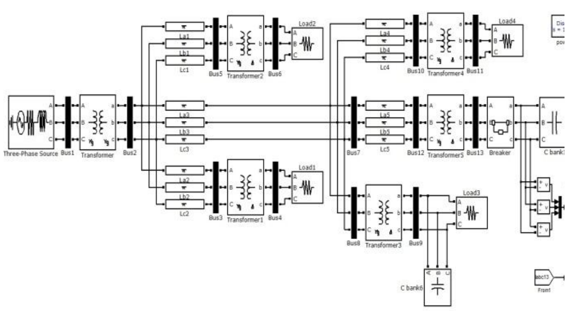

Fig. 2. Normal Radial System

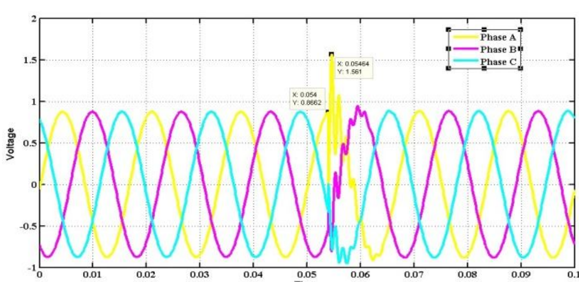

Fig. 3.Transient Observed Near the Capacitor Bank

The peak of phase A voltage reached almost 160% of its steady state. Theoretically, the transient should reach 200% of its steady value. In this case it reached only 160% due to the damping caused by impedance present in the system. The current is zero until the switch is closed, and then an inrush transient current from the fixed capacitor bank charged the controlled bank at the frequency established by the inductances of the conductors between the banks and the capacitances of the capacitor banks. The inrush currents observed during the time of capacitor energization can be seen in Fig. 4.

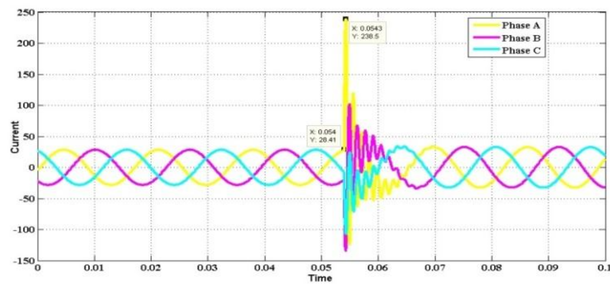

Fig. 4. Inrush Current Observed Near the Capacitor Bank

Neglecting the system resistance, the inrush current into the capacitor can be given as Eq.

$$i(t) = \frac{V(0)}{Z_0} sin\omega_0 t \qquad (1)$$

$$Z_0 = \sqrt{\frac{L}{C}} \; and \; \omega_0 = \frac{1}{\sqrt{LC}} \qquad (2)$$

and0 , is the difference between the source voltage and the initial voltage of the capacitor at the instant of energization. Fig. 6 shows the magnitude of inrush currents near the load.

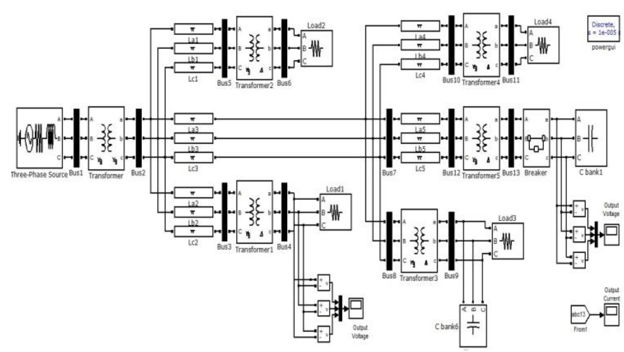

Fig. 5. Normal Load Radial Feeder with Load Analysis

In order to completely eliminate the over-voltages and the inrush current produced by energizing a capacitor bank, it is required that there is a zero voltage difference across the contacts of the capacitor bank switch when the contacts meet. Fig. 8 give the voltage and current

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waveforms when closing the switch at voltage zero (t=0.05s).

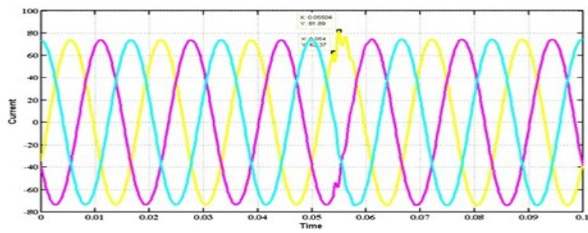

Fig. 6. Inrush Current near the Load

The magnitudes and the period of oscillation of the transient voltages and currents in the circuit are reduced considerably and their peak values are closed to steady state values.

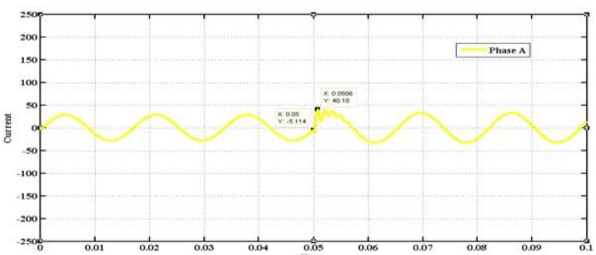

Fig. 8. Voltage-Zero Response of Current Waveform

Closing the switch at voltage-zero is possible only when there is a control which can sense that particular condition. Sensitivity analysis has been conducted to provide the tolerable limits of switching times where a minimum transient can be observed. Varying the switching time of the capacitor bank, several simulations have been carried out and the results obtained are determined to calculate the tolerance limits. Any transient under 130% of the steady state voltage magnitude will not show much impact on the power quality. Fig. 9 shows a voltage transient that reaches 115% and Fig. 10 shows a transient which is 130% of the normal steady state value.

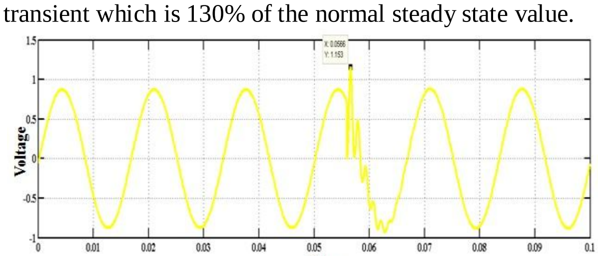

Fig. 9. 15% Transient Observed Near the Capacitor Bank

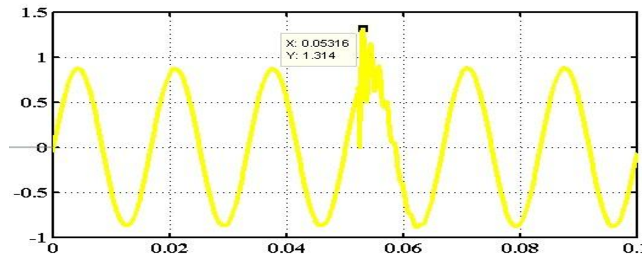

Fig. 10. Voltage Transient which is 130% of its Normal Steady State Value

Simulating the model at different time intervals and analyzing the results, showed that closing the capacitor bank at zero-crossing of voltage wave would mitigate the transients completely from the system. As closing the switch precisely at voltage zero cannot be obtained, the study recommends closing the switch approximately 2.5 before or after the zero-crossing is acceptable for a minimum transient. Being highly dependent upon equipment, system impedances and weather conditions closing times will vary for each capacitor bank installation.

Detailed analysis of the switching transient behavior has been done taking into account sizing of capacitor bank and timing of the switch on the feeder. The magnitude of the peak transient voltages and inrush currents has been observed for different time intervals as shown in Table II and III.

Table II
Transient Magnitudes Observed for Different Capacitor Bank Sizes when Switched at Different Time intervals

Closing timings	200kVAr capacitor bank	300kVAr capacitor bank
Zero-crossing	No transient observed	No transient observed
2	1.1p.u	1.13p.u
2.5	1.323p.u	1.279p.u
Peak	1.612p.u	1.561p.u

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Table III
Current Magnitudes Observed During Switching at Different Intervals and for Different Capacitor Bank Sizes

Closing timings	200kVAr	300kVAr
Zero-crossing	No transient observed	40.18A
2	120.7A	163.9A
2.5	143.7A	193.5A
Peak	178.9A	238.5A

The acceptable levels to close the capacitor bank switch have been determined on a 300kVAr bank. When these timings are applied to study the transient behavior of a different size capacitor banks, it can be noticed that the peak voltages are slightly higher or lower than the 300kVAr capacitor bank. Acceptable transient behavior can be achieved by decreasing the proposed time interval slightly.The magnitude of inrush current increases with the increase in capacitor bank size as can be observed in Table III.

Analysis has been done to determine the harmonic content present in the system. Tables IV and V show the total harmonic distortion (THD) in the voltage and current waveform, obtained for different size capacitor banks. From Table 3.4, it can be stated that the THD increases with the increase in the size of capacitor bank. Results obtained from this study indicate that the distribution system is not affected with harmonics.

Table IV
Total Harmonic Distortion Present in the Voltage Waveform.

Closing time	200kVAr	300kVAr
Zero-crossing	0.37%	0.47%
2	2.64%	2.75%
2.5	3.19%	3.32%
Peak	4.12%	4.29%

TableV
Total Harmonic Distortion Present in the Current Waveform during Energization

Closing time	200kVAr	300kVAr
Zero-crossing	2.41%	4.12%
2	16.25%	32.96%
2.5	19.64%	26.73%
Peak	25.29%	34.46%

VI. RESULTS AND DISCUSSION

Several switching time intervals of capacitor bank have been simulated using MATLAB/SIMULINK software to study the response of the transient over-voltages and currents and, the harmonic content present. The study has been performed on 150kVAr, 300kVAr,

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600kVAr, 1200kVAr capacitor banks. This chapter presents the results obtained on a 300kVAr bank. After the model was built, simulation results were recorded. Simulation of the model has been done to analyze the response of the transients by switching the capacitor bank 'on' at different time intervals, taking phase A in control. FFT analysis has been carried out by using the SIMULINK software to find the total harmonic distortion in the system.

A. Transient observed when the capacitor bank is switched at the voltage peak (Worst case scenario)

1) Response of transient at the capacitor bank.

Fig. 11 and Fig. 12 show the transient disturbance of the 3-phase voltage and current waveforms of all 3 phases. As the transient is characterized by a surge of current having a high magnitude and a frequency as high as several hundred Hertz, it can be noticed from the results that the voltage reaches 60% of its normal per-unit value and the current value reaches 200% its normal value when the switch is closed.

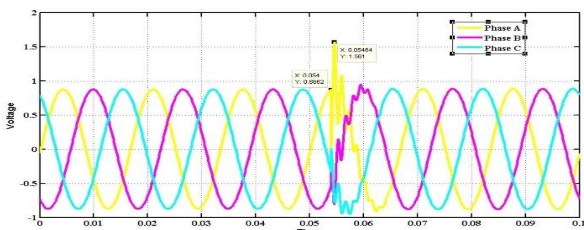

Fig. 11. Transient Response of the Voltage Waveform

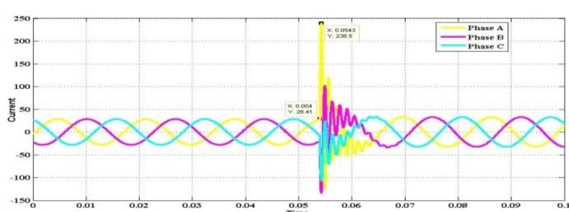

Fig. 12. Transient Response of the Current Waveform

Fig. 11, 12 displays the disturbance created in phase A of the voltage and current waveforms. Table 2 lists the magnitude of peak values obtained by the voltage and current waveforms near the capacitor bank during the time of closing the switch.

2) Response of the transient near the load

Fig. 9 and Fig. 10 depict the transient disturbance observed during the simulation of all phases A voltage and current waveforms. It can be noticed that the transient over-voltage remains almost the same. Table II gives the magnitude of peak values obtained by the voltage and current waveforms near the load centre during the time of closing the switch.

B. Transient observed when the capacitor bank is switched at the voltage zero (Best case scenario)

1) Response of transient at the capacitor bank

When the capacitor bank is switched at the zero-crossing of the voltage waveform the following transient disturbances are observed near the capacitor bank.

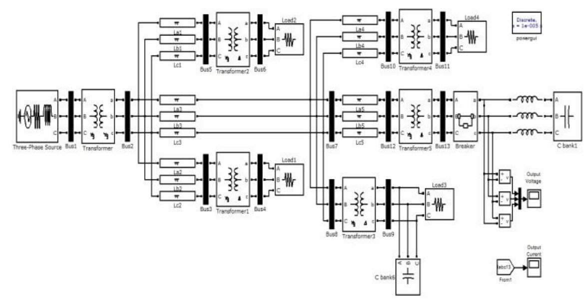

Fig. 13. Series Reactor Connected in Line

It can be noticed that switching at the zero-crossing of the voltage waveform would result in transient free operation of the system. Fig. 11, 12 displays disturbance on phase A voltage and current waveforms. Table 6 lists the magnitude of transient observed.

Table VI
Results Obtained Near the Capacitor Bank

	Maximum peak observed near the load when switched at t=zero-crossing
Voltage (phase A)	No transient observed
Current (phase A)	40.16A

Table VII gives the harmonic content and total harmonic distortion present in the phase A voltage waveform.

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2) Response of transient near the load

The following data is obtained near the load when the capacitor bank is switched at zero crossing of the voltage. Fig. 13 and Fig. 14 are the voltage and current waveforms obtained near the load.

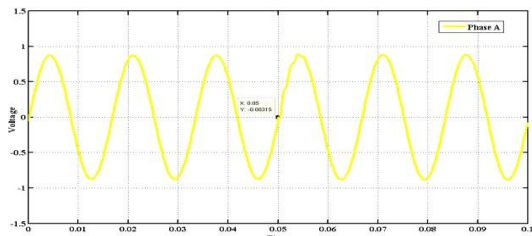

Figure 13: Transient Response of Voltage Waveform

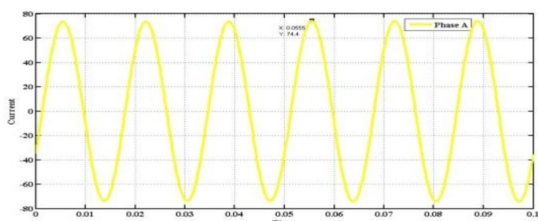

Figure 14: Transient Response of Current Waveform

C. Sensitivity Analysis (130% of steady state value)

1) Response of the transient near the capacitor bank

The transient disturbance in phase A voltage and current waveforms. It can be observed from the simulation that the transient observed is in the acceptable level. Table 6 gives the maximum peaks of voltage and current observed during the impact of switching.

Fig. 15 and 16 show the response of phase A voltage and current waveforms near the capacitor bank.

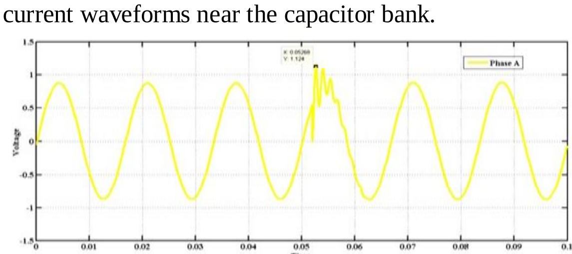

Fig.15. Transient Response of Voltage Waveform near Load

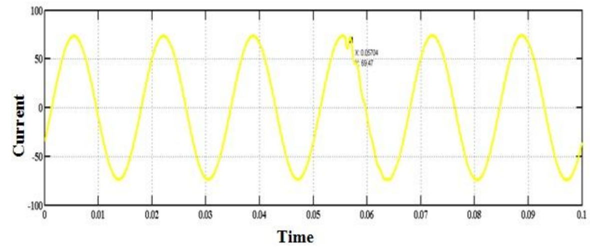

Fig. 16. Transient Response of Voltage Waveform near Load

Under transient condition made by testing them with the same group of relays. The one whose final tested waveform is above the others has better mal-trip immunity. During the development of a relay, the longest practical line length may be taken. For the setting of a specific relay, the actual line length can be taken. The waveform have to be determined for different operational states and for switching instants.

VI. CONCLUSIONS

The fault discrimination has achieved in the overcurrent relays at the time of capacitor bank starting. In existing system capacitor bank were used to compensate the power factor improvement. The new technique is implemented using to improve the immunity against switching transients due to switching capacitor bank in the IEEE 13-bus radial distribution systems. The simulation result of the proposed method is improved the reliable operation of radial system. High sensitivity sometimes causes undesirable operation of the relays and it considered reduced by this proposed method. Causal Productions has used its best efforts to ensure that the templates have the same appearance.

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