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APPLICATION OF SYNCHRONOUS SWITCH FOR FAULT ANALYSIS DURING SWITCHING OF CAPACITOR BANKS

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Abstract: During the switching of shunt capacitor banks, high magnitude and high frequency transients can occur. High-voltage capacitor banks have more stored energy, high system X/R ratio and less damping. The switching of these capacitor banks affects the power system and other utilities. User defined synchronous switch block has been used for fault analysis using Matlab/Simulink. This paper provides an analysis on capacitor bank switching transients, with and without asynchronous faults which is illustrated using a simple three-phase distribution system. A case study for capacitor bank switching and the method to eliminate these transients by a synchronous switch is studied, analyzed and verified based on THD values. By introducing various asynchronous faults in the line including capacitor bank, the effect of transients has been studied and analyzed with and without synchronous switch. The simulation results depict the promising effects of synchronous switch in suppressing the transients during switching of capacitor banks.

Keywords: Synchronous Switch

I. Introduction

A power quality problem can be defined as**:** Any power problem manifested in voltage, current, or frequency deviations that result in the failure or mis-operation of customer equipment. 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 increasing installations of power electronics based equipment, the power system disturbances depicted in Fig (1) has become a common phenomenon.

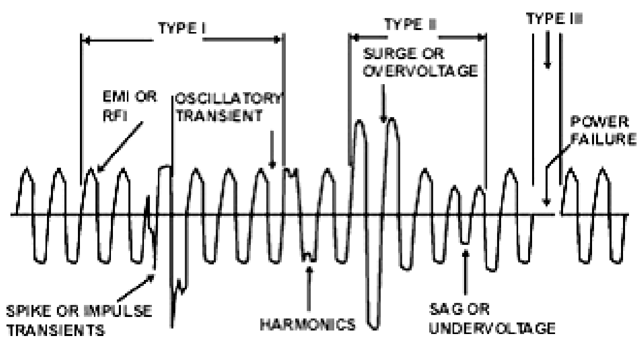

Fig 1: Types of Power Disturbances

Despite the significant benefits that can be realized using capacitors for power factor correction, there are a number of power quality related concerns that should be considered before capacitors are installed. A well designed capacitor bank application should not have an adverse effect on end-user equipment or on power quality. One of the more common power quality problems for consumers is transient voltages in the system 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 and is the phenomenon that this paper addresses. These switching transients have the ability to adversely affect industrial customer's power electronic and non-linear loads. The system becomes much vulnerable when the fault occurs on the line where the capacitor bank is connected and delivering the MVAR to the line. The momentary disruption due to the fault will introduce the transients in the system. The magnitude and distortion depends on the type of fault.

II. Fault Clearing In The Presence Of Capacitor Bank

If short circuit occurs near the capacitor bank, the energized bank discharges to the fault on nearby feeder. When the circuit breaker acts on the fault immediately after the arc extinction, the power network reacts with a TRV that stresses the gap. But transients shown in Figure 1, the presence of the large capacitor bank on the source side of the breaker influences the TRV across the breaker contacts. The rate of rise of the TRV (RRRV) is reduced because the source side capacitor bank provides the time delay prior to the initial rate of rise of the source side TRV. Hence the breaker attempts to interrupt the arc at the first current zero after contacts separation.

III. Transient Over-Voltages

A transient is defined in IEEE 1100-1999as:

A sub-cycle disturbance in the AC waveform that is evidenced by a sharp, brief discontinuity of the waveform. The transients may originate when a capacitor bank is switched in or out of the system. Capacitor switching is considered to be a normal event on a utility system and the transients associated with these operations are generally not a problem for utility equipment, since peak magnitudes are just below the level at which utility

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surge protection, such as arresters, begins to operate (1.8pu or above).

Prior to switching on a capacitor, the voltage across the terminals is zero. Because capacitor voltage cannot change instantaneously, energizing a capacitor bank results in an immediate drop in system voltage toward zero, followed by a fast voltage recovery(overshoot) and finally an oscillating transient voltage superimposed on the 60 Hz fundamental waveform as illustrated below in Fig. (2).

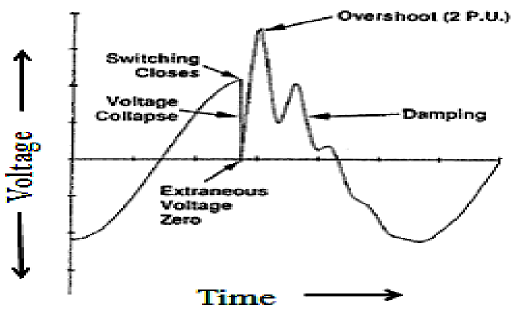

Fig 2: Switching Transient

The peak voltage magnitude of the transient depends on the instantaneous system voltage at the moment of energizing, and under worst-case conditions this can be 2.0 times greater than the normal system peak voltage. In addition, to the transient over-voltage phenomenon's, application of shunt capacitors can lead to the following side effects: Increased transient inrush current of power transformers, and prolonged decay rate of the transient. Severe harmonic distortion and resonance with load-generated harmonics and capacitors can be stressed due to switching transient speed drives are extensively used in industrial applications for improved motor speed control, energy due to the transient overvoltage due to capacitor-switching transient causing the DC bus to exceed the overvoltage trip point.

III. Synchronous Closing/Zero-Voltage Crossing/ Controlled Closing

Zero-crossing switching is also called synchronous switch that switch the capacitor bank of each phase corresponding to zero crossing of the phase voltage, thereby preventing the generation of switching transients .

For implementing the zero voltage switching a single feeder system with a capacitor bank is used. An integrated S-function (level 2) block is used to incorporate MATLAB program for zero voltage switching viz. synchronous switch. Based on specified switching time the making of three-phase circuit breaker near zero voltage will be done in coordination with instructions given to synchronous switch.

A Simulink model of a feeder of the distribution system with integrated S-function block is shown in Figure 9.The input for the S-function block is the voltage waveform from the three-phase V-I measurement block.

The user specified switching time is given as instruction through the parameter field of the S-function block. Synchronous switch block continuously monitors the voltage of the system.

The Synchronous switch reads the user specified switching time and outputs actuating signal by calculating the difference in time between instant of zero switching and actual one. By this the vacuum switch closes and connects the capacitor bank to the distribution system.

IV. Step By Step Procedure To Achieve Synchronous Switching

- Receive a trip command from the utility dispatch center.
- Start monitoring the feeder voltage obtained from the potential transformer.
- Check for voltage-zero condition.
- If the condition is matched, send a trip signal to vacuum switch to open/close the capacitor bank
- Record the magnitude of the transient voltage after the switch is closed
- Cross-check if the voltage transient is within the acceptable range, and if necessary adjust close time accordingly.

V. Result Analysis

FFT is done for the test system and results are observed for five cycles. Phase A voltage wave form is shown in the Fig 3. Total harmonic distortion is calculated for each phase at different times of switching. Results from both synchronous switching circuit and uncontrolled switching circuit are compared with each other and results are presented in the table 1 .

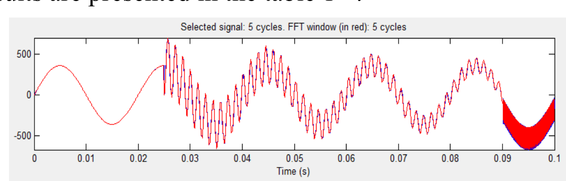

Fig: 3Uncontrolled Phase A Voltage.

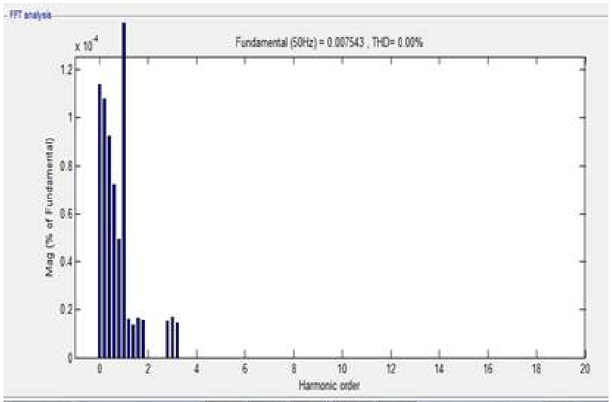

Fig4: Harmonic of voltage wave form when controlled synchronous switch is not used

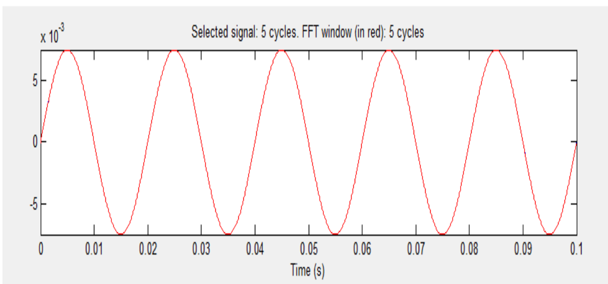

Fig. 5: voltage wave form of Phase A when controlled synchronous switch is used.

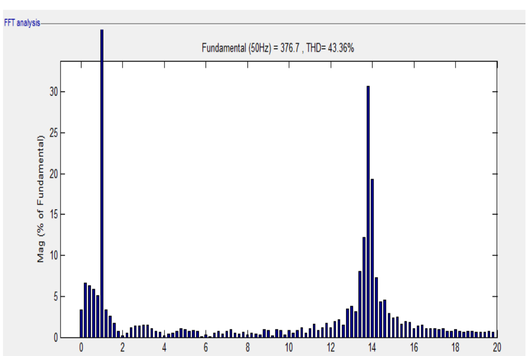

Fig. 6: Harmonic of voltage wave form when controlled synchronous switch is used.

Table 1 : comparison table of phase a voltage with and without switching control

SWITCHING TIME (SEC)	CIRCUIT VOLTAGE PHASE A		CIRCUIT WITH ZERO VOLTAGE SWITCHING VOLTAGE PHASE A	
	FUNDAMENTAL	% THD	FUNDAMENTAL	% THD
0.02	360.7	3.32	359.2	0.00

				7
0.025	376.7	43.36	359.2	0.005
0.0333	383.9	38.89	359.2	0.004
0.05	362.8	4.01	359.2	0.011
0.06	360	2.86	359.2	0.001

From the waveforms given in the **Fig-3 to Fig-6**it is clear that employing of synchronous switch reduces the harmonic distortion up to zero percentage. Current inrush **(Fig-7)** is experienced by the system when capacitor bank is closed instantaneously. The total harmonic distortion is calculated for each phase current.

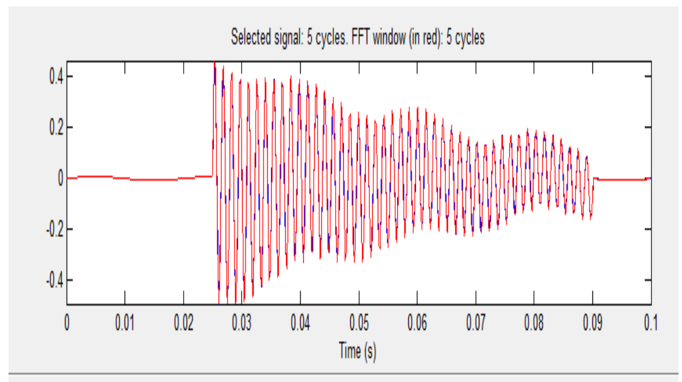

Fig. 7: Inrush current wave form of Phase A when controlled synchronous switch is used.

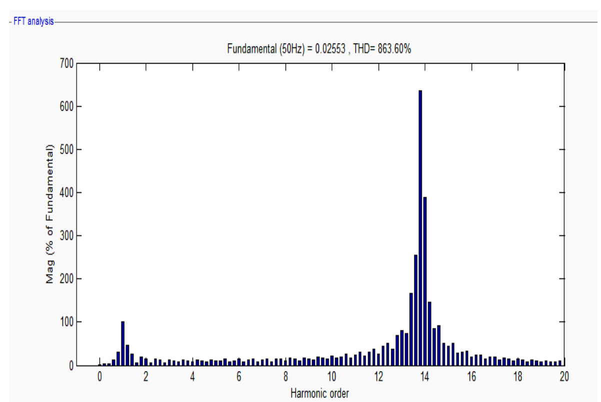

Fig 8: Harmonic of Current wave form when controlled synchronous switch is used.

Table 2: comparison table of phase a voltage with and without switching control .

SWITCHING TIME (SEC)	CIRCUIT CURRENT PHASE C	CIRCUIT WITH ZERO VOLTAGE SWITCHING CURRENT PHASE C

	% OF FUNDAMENTAL(50 HZ)	TOTAL HARMONIC DISTORTION %	% OF FUNDAMENTAL(50 HZ)	TOTAL HARMONIC DISTORTION %
0.02	0.026	736.02	0.007542	0.04
0.025	0.025	453.36	0.007542	0.04
0.0333	0.02495	80.24	0.007543	0.04
0.05	0.01635	1089.74	0.007543	0.04
0.06	0.01359	1230.92	0.007543	0.04

THD Analysis:

The total harmonic analysis block is placed in both controlled and uncontrolled circuits. Comparison of results when circuit is switched at instantaneous and uncontrolled timings is presented.

Table3: Comparison Table of THD of Voltage and Current of 3-Phase system with and Without Synchronous Switch.

PARAMETER	ZERO VOLTAGE SWITCHING	SWITCHING AT VOLTAGE
VOLTAGE	0.00049983	1.649
CURRENT	0.00049983	1.866

Total harmonic distortion is calculated at different switching times in the circuit and compared with zero voltage switching. The following table presents the comparison.

Table4: Comparison of THD of Voltage of 3-Phase system with and Without Synchronous Switch with Different Switching times.

Switching time (sec)	Zero voltage switching (THD %)	Instantaneous Switching (THD %)
0.02	0.00049983	1.876
0.025	0.00049983	1.866
0.0333	0.00049983	1.864
0.05	0.00049983	1.878
0.06	0.00049983	1.875

VI. Analysis Of Fault Transients With Switching Capacitor Banks

An LG fault is created at the load side using fault block in the test system.

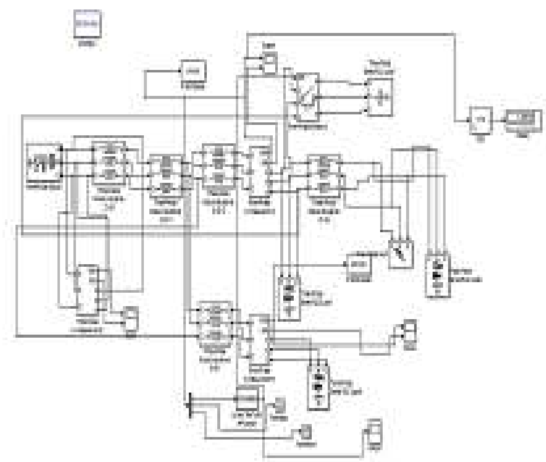

Fig. 9: Simulink diagram of test system.

Capacitor bank is switched at an instant of 0.03secand after 0.01 sec LG fault is created at load side which is cleared after one and half cycle of time duration . During fault conditions, the capacitor bank introduced transients in the system during fault duration. (Fig. 10)

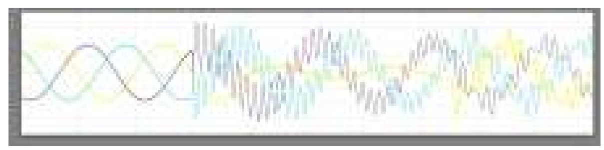

Fig. 10: LG fault response in the system's voltage and (load side).

It is observed that after energizing capacitor bank, transients are obtained and mitigated slowly with time. But due to LG fault a drop in phase a voltage is observed. When LG fault is cleared , due to re-energizing of the capacitor bank transients raised again.

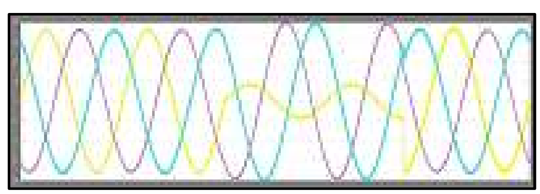

Figure 11:LG fault response in the system's voltage and current with synchronous switch (load side).

It is observed from above waveforms that transients due to switching of capacitor banks are greatly reduced and there is no effect of zero voltage switching on LG fault characteristics.

Same procedure is followed to study the fault condition on source side in the system. **Fig. 12** and **Fig. 13** shows the voltage and current waveforms on source side.

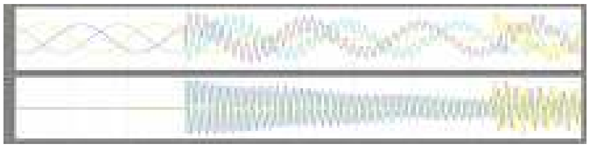

Fig. 12:voltage and current waveforms during LG fault at source side without synchronous switch.

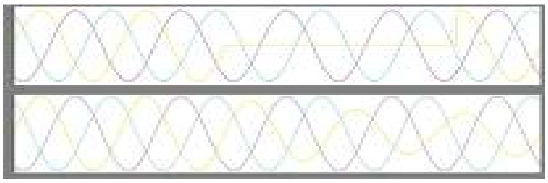

Fig. 13:Voltage and current waveforms during LGfault at source side with synchronous switch.

Table : 5 comparison of THD % of phase a voltage with and without switching control(LG fault on load side).

Switching time (sec)	THD% in phase A voltage without synchronous switch	THD% in Phase a voltage with Synchronous switching
0.02	44.30	36.49
0.025	69.34	36.48
0.033	60.83	36.34

LL Fault Response Of The System Without Capacitor Bank:

A LL fault is created between phase A and phase B at 0.04 seconds and the fault is cleared at 0.075 seconds in the line which has a capacitor bank energized at 0.02 seconds.

Fig 14: voltage and current waveforms of the test system with capacitor bank and LL fault on load side .

From the results it is observed that after clearing of fault transients are reappeared due to re-energizing of capacitor bank.

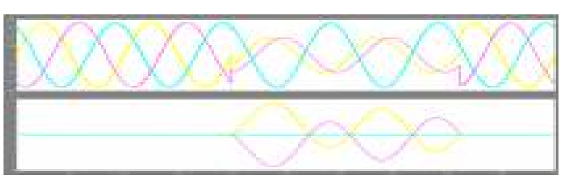

Fig 15: voltage and current waveforms of the test system with capacitor bank and LL fault on load side simulated with ZVS scheme.

Table 6: comparison of THD % of 3-phase voltage of test system (LL fault on load side)

Switching time (sec)	THD in voltage with synchronous switching	THD %voltage without Synchronous switching
0.02	0.00049983	1.737
0.025	0.00049983	1.617
0.033	0.00049983	1.632

From above table it is observed that ZVS switching reduces harmonic distortion due to re-energizing of capacitor bank.

LLG Fault Response Of The System Capacitor Bank

To analyze the system's voltages and currents during LLG fault along with capacitor bank, LL fault is created in the line where the capacitor bank is already energized . capacitor bank is energized at 0.02 seconds and LLG fault is created at 0.04 seconds and cleared at 0.075 seconds.

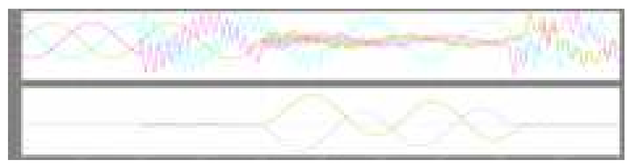

Fig.16: voltage and current waveforms of the test system with capacitor bank and LLG fault on load side .

By above obtained results it is observed that transients are obtained with capacitor bank presence and on fault clearing obtained transients have a low frequency but huge magnitude compared with system's normal voltage.

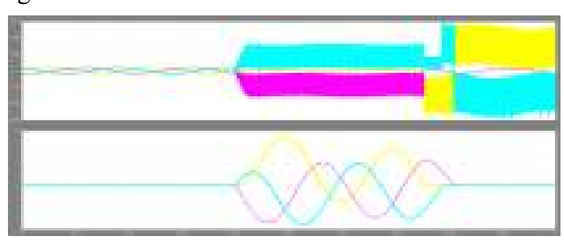

Fig 17: voltage and current waveforms of the test system with capacitor bank and LLG fault on load side simulated with ZVS scheme.

From above results it is observed that no transients are observed due to capacitor switching through zero voltage switching scheme. Similarly on source side also LLG fault is observed.

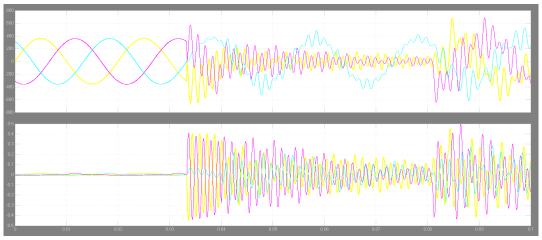

Fig.18: voltage and current waveforms of the test system with capacitor bank and LLG fault on source side.

From results obtained it is observed that transients are emerged violently with fault clearing .

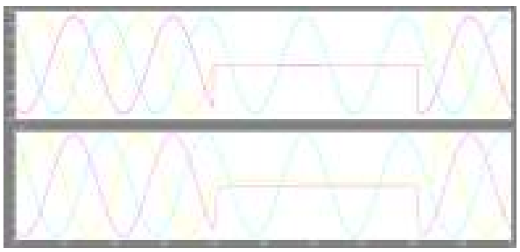

Fig 19: voltage and current waveforms of the test system with capacitor bank and LLG fault on source side simulated with ZVS scheme.

From above results it is observed that transients are very much reduced.

Table 6.7: comparison of THD % of 3-phase voltage of test system (LLG fault on load side)

Switching time (sec)	THD % in Three phase voltage with Uncontrolled switching	THD% in Three Phase voltage with Synchronous switching
0.02	1.773	0.7193
0.025	1.721	0.00049983
0.033	1.774	8.162

From above table it is observed that ZVS switching reduces harmonic distortion due to re-energizing of capacitor bank when switched at 0.02 and 0.025 . But harmonic distortion is increased with ZVS switching when capacitor is switched at 0.033 seconds. This is because of presence of ground in the fault.**Three Phase Short Circuit Response Of The System Without Capacitor Bank:**

Three phase short-circuit fault is the most severe fault occurring on the system. This fault makes power flowing to the load as zero% unacceptable power loss until fault is cleared.

Here in the test system a three phase short circuit fault is created in the line at 0.04 seconds and cleared at 0.075 seconds. The response of the system is observed.

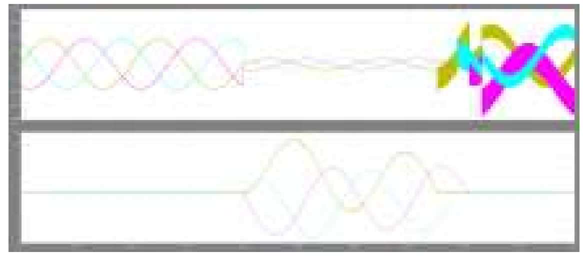

Figure 20: Voltage and current waveforms of the test system without capacitor bank and three phase short circuit fault on load side.

From results obtained it is observed that no transients are experienced by the system

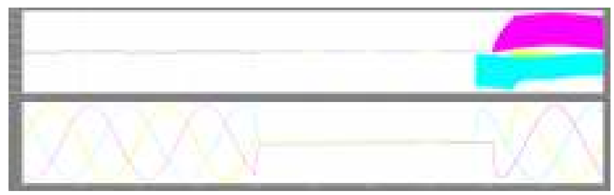

Figure 21: voltage and current waveforms of the test system without capacitor bank and three phase short circuit fault on source side.

By results obtained it is observed that when three phase fault is cleared a huge transients are appeared which can damage the system extremely.

VI. Conclusion

This paper has discussed the importance of zero voltage switching technique to reduce the transients associated with the switching of capacitor banks during fault. FFT analysis is carried out to check the harmonic distortion in the test system and the results obtained indicate that the test system considered is free from harmonics through ZVS switching. MATLAB code is developed such that the synchronous switching block interactively closes the switch at voltage zero irrespective of the time given by the user.

It is observed that transients are reduced during the fault. Different types of fault responses of the test system are studied. It is observed that ZVS switching also decreases the transients due to reconnection of capacitor bank (after fault clearing) irrespective of time of fault occurrence and clearance.

Zero voltage switching decreases the harmonic distortion in the test system voltage obtained due to capacitor switching transients. It is observed that in LLG and three phase short circuit fault conditions , harmonic distortion in system's voltage is increased due to the presence of ground in the fault with synchronous switching block employed in the system. Zero Voltage Switching do not change the short circuit current and voltage drop in the system during fault conditions. A smooth transition from one state to other state is observed.

It is also observed that among all the faults, LG fault gives larger harmonic distortion in the system's voltage followed by LL, LLG and three phase short circuit fault when a fault occurs on load side. When fault occurs on source side ,irrespective of the type of fault, harmonic distortion caused in the system's voltage is nearly same. So ZVS technique can be employed to decrease the transients due to capacitor bank switching.

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Appendix

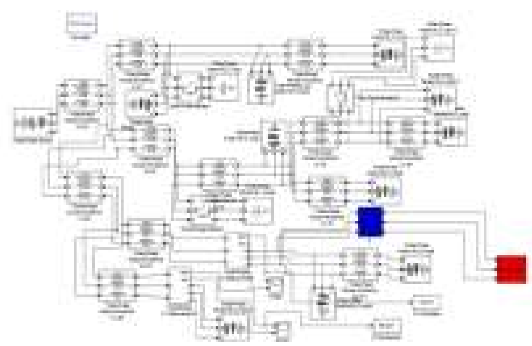

Fig. 1: Test system considered for analyzing switching transients

For implementing the zero voltage switching a single feeder system with a capacitor bank is used. An integrated s function (level 2) block is used to incorporate MATLAB program for zero voltage switching. A MATLAB program is developed to control the switching time of the vacuum switch. The program is integrated with the SIMULINK based distribution system using Level-2 M file S-function. The program takes a user specified switching time and closes the three-phase circuit breaker near zero voltage irrespective of the time specified by the user. The block is indicated as "zerocrossdet" block in Simulink diagram shown below. A Simulink model of a feeder of the distribution system with integrated S-function block is shown in Figure

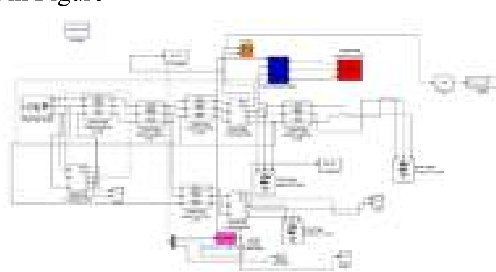

Fig. 2: Test system considered for analyzing switching transients