Switching Transients due to a Power Factor Correction Capacitor Bank in LV Power System and Their Comparison with Lightning Impulses

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***Abstract*— Switching transients generated by a five-step 50 KVAR shunt capacitor bank in a low voltage power system have been generated and characterized with the view of providing a database to investigate their effects on electrical network components. Three balanced single-phase RL loads were connected to the three-phase separately. The results show that the current impulses generated during the switching operations may be high enough to either damage or degrade the equipment connected to the power system. The experimental set up was simulated for a 415 V/ 240 V power system by means of Power System Computer-Aided Design (PSCAD) software. Data analysis were conducted on the amplitude, the rise time and the pulse duration of the transient current waveform. Consequently, the simulation and experimental results were compared to have reasonable agreement. Thus, the PSCAD simulation model could be used to generate capacitor bank switching impulses for various configurations in a low voltage system, to develop a data bank. The measured and simulated transient waveforms are compared with extreme case (higher 5%) of positive lightning waveforms. The outcome of this study can serve as a guide for manufacturing technologists as well as electrical engineers in addressing a main issue of capacitor banks, the generation of switching transients in LV systems and their effects on downstream equipment.**

Keywords— Capacitor banks; switching transient; power systems; power factor; PSCAD

I. INTRODUCTION

Transients are sub-cycle events observed in electrical systems of which the duration may vary from pico-seconds to few milliseconds, based on the type of transient source. Transients are generated naturally during lightning activities. Man-intervened events such as nuclear explosions, high power microwave emission and switching operations of electrical power systems also generate transients. Characteristics of voltage and current transients are quite different from that of other power anomalies such as harmonics, blackouts, brownouts, swells and sags.

The literature review on the switching transients reveal that a majority of such studies are confined to transients generated in the switching operations of inductive loads in both medium voltage (MV) and low voltage (LV) systems [1-4]; circuit breakers in MV and HV systems [5-7] and capacitive loads in MV and HV systems [8-12]. The circuit breaker switching could energize or de-energize both capacitive and inductive loads, however, a majority of the studies focuses on the transients generated by the circuit breaker itself.

Capacitor banks (CBs) serve an essential purpose in the electrical systems (correcting the power factor), however, they pose a risk of damage to the downstream equipment due to the transients they generate under various conditions [13]. The conditions that leads to the generation of such transients may be regular switching operations for energizing and de-energizing processes, interruption of short circuits, lightning strikes, or system failure [14]. Phasor analysis or other simplified analysis methods are usually inadequate to understand such impulses, due to system frequency dependencies and nonlinearities [15]. Therefore, time-domain computer models are typically developed as a mean of characterizing the severity of transient events. The computations are typically done using simulation software such as the Power System Computer Aided Design (PSCAD).

The studies done on the transients generated by shunt capacitor banks connected to HV transmission lines and MV distribution lines [10, 12, 16, 17], depict that they can seriously affect the durability and reliability of power system components and equipment in the same power system. On the other hand, due to the increasing number of applications of CBs in lower MV and LV systems, especially in the form of power factor correction CBs, the effects of transients generated by them in utility and consumer equipment have been significantly increased in the recent past [18, 19]. One major drawback in developing solutions to mitigate CB switching transients is the lack of information on the characteristics of transient waveforms, specifically on LV systems. This study has been undertaken to fill-up that vacuum.

II. METHODOLOGY

This study investigates the transient behavior of current and voltage, immediately after a power factor correction CB in a LV system is energized. A shunt CB with five steps connected on a line-to-line configuration have been used for the experimental work. Three single phase loads are connected between the lines and neutral. Such configuration was selected as it is the common practice that could be observed in many of the industrial LV installations. The same set up and operational procedures have been simulated using PSCAD software. The simulated waveforms were compared with measured waveforms to justify the simulation. Characterization parameters of the transient features have been selected by following similar studies in the literature on other systems [20-22].

The analysis was simplified by selecting an RL load circuit. Such simplifications have commonly been adopted in the literature [23-25]. The simulation is conducted to determine the highest degree of over-voltage transients and inrush currents generated when a 440V CB is energized. The model executes several runs in PSCAD /EMTDC with different closing times of the circuit breaker of the CB within a time period of 5 ms (quarter-cycle of a sine-wave at 50Hz). In the first step of the CB is energized, closing a pre-selected breaker. Expressions for the current and the frequency of the subsequent oscillations in the capacitor have been derived in the literature [26].

The isolated CB (50.0 kVar and five steps), a type that is commonly used in industrial sites, is connected to the three-phase, 415 V (phase-to-phase) LV system, to measure the transient switching voltage and inrush current at the output of different loads with different power factor conditions (Figure 1). The capacitor steps are five steps 5, 5, 10, 15, 15 kVar respectively (Figure 1a). The steps could be implemented (switch) one at a time or two steps simultaneously. Figure 1b shows the circuit diagram that explains the five step CB connected to the applied load. Figure 1b elaborates the almost similar loads to which each phase is connected. Each load includes two inductive components and one resistive component. The two inductive load components could separately be connected with the resistive load component (by switches) to get a large variation in load condition. Let's label the two inductive loads as Load-A and Load-B. Load-A has the specifications: the rated voltage of 415/240, 50Hz, 2.0kVAR in 21 steps with each step is 0.41A. Load-B: voltage rated is 240/415V, 50Hz 5.76 KVAR in 24 steps each step is 1.0A. The resistive load is 240/415VAC, 3PH. 50HZ, 6.0 kW. The exact load resistance of the three phases were; 30.50 Ω, 31.21 Ω and 31.11Ω respectively in the phases labeled as A, B and C. These load are connected with the five steps CBs. The locations of voltage and current measuring points in the circuit are depicted in Figure 1c. Note that both line-to-line voltages and line-to-neutral voltages have been measured. A photograph of the real experimental set up is shown in Figure 2.

Although we recorded the line currents and phase voltage (with respect to the neutral) in all phases, we present only the parameters pertinent to phase-A in this study (and line A-to-line B voltage). The purpose of the similar loads in all three phases is to implement a balanced 3-phase load. It is emphasized that the circuit has three single-phase loads but not a single three-phase load. This is of high importance that in the former case the observations could be quite different to the outcomes reported in this study. Thus, it should be investigated separately.

Following the experimental work, the over-voltage and inrush current phenomenon were simulated using PSCAD (Power System Computer Aided Design) software. For the distribution circuit in LV power systems, the study investigated the transients generated by the switching operations for five step CB, which is very similar to the experimental set up. Figure 3 illustrate the PSCAD model of 3 single-phase loads connected to the CB. The simulations were realized at the maximum load conditions. Figure 4 depicts the realization of the five step CB by developed and readily available components in PSCAD software. Figure 5 depicts the PSCAD model developed for representing the real and reactive power in the load. Figure 6 details the switching controller circuit of the CB.

The purpose of the simulation part of this work is to extend the investigation into many other capacitor steps and load combinations as we have the opportunity to validate the simulation outcomes with the experimental work done in this study. Thus, this study is somewhat different from the typical trends where the main focus is on system simulation, which is then validated by the experimental work. Hence, the CB and loads were pre-determined with the available resources, and consequently the simulations were carried out according to the experimental set up.

III. RESULTS AND DISCUSSION

A. *Experimental Outcomes*

Transient voltage and current waveform during the energizing of the CB with initial power factor (cos φ) of the system (without the connection of the CB) 0.51 were obtained. This initial power factor was based on the available settings of the RL load used. Consequently, back-to-back switching was also applied. The characterization was done under the peak values, rise time and time duration of the transient overvoltage and transient currents at different switching steps. Additionally, the excess energy per unit resistance (action integral) was also calculated for the transient current waveforms. Figure 7 depicts the criteria used for the analysis of various parameters pertinent to the current waveform. Note that the amplitude of the transient is measured from the starting point of the transient itself, thus the amplitude is independent of its position of occurrence in the 50 Hz signal. The rise time (RT) is indicated as the time between the points having magnitude 10% and 90% of the peak value. Duration of the transient (DT) is measured from the initial point to the point at which the transient value is less than 10% of the transient peak value. The criteria of measuring the amplitude of voltage transient embedded on the sinusoidal waveform at 50 Hz is depicted in Figure 8. Note that the measured transient amplitude is independent of the instant of occurrence.

Table-1 depicts the variation of the power factor with respect to the capacitor steps. Note that at each step the power factor was changed from 0.51 to the end value (eg. In step 2 cos φ changed from 0.51 to 0.85). In the last three capacitor steps the circuit changed to a capacitive orientation.

Table-2 depicts the average values of the current and voltage parameters, both amplitude and temporal. The switching operation did not make any transient variation in the line-to-neutral waveform (VAN). This is expected as the capacitors and the switches are connected in a line-to-line shunt configuration. However, the line-to-neutral voltage was also recorded to evaluate the simulated circuit.

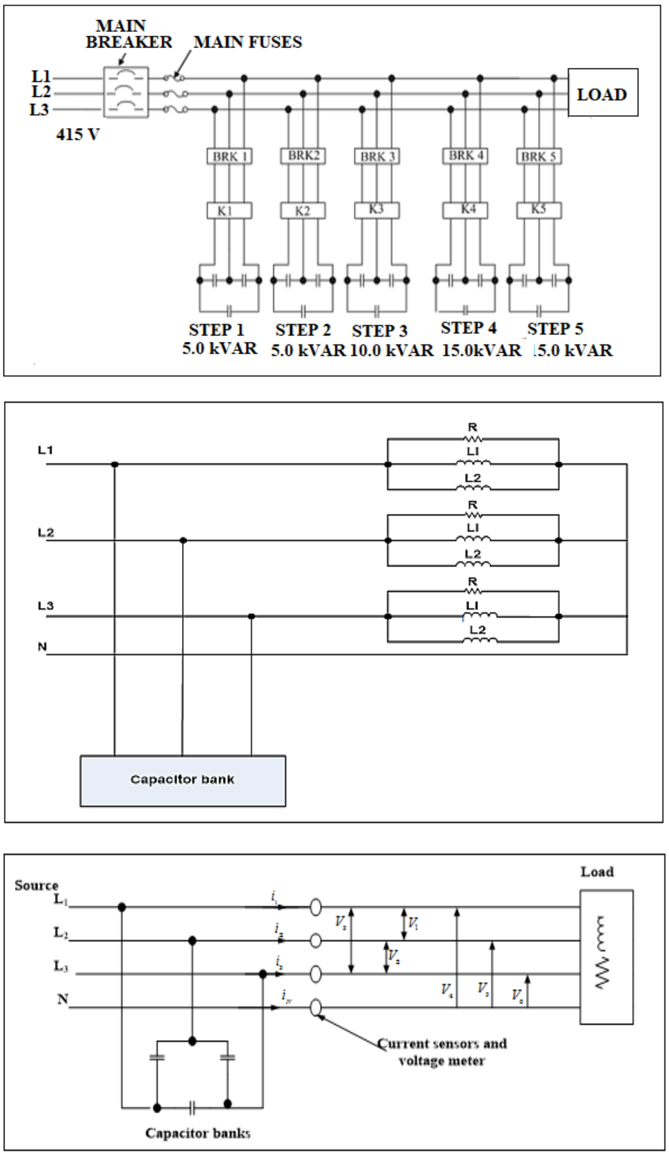

Figure 1. a. Five step CB with the indication of the maximum load conditions. b. The single phase loads in the three phases. c. Current and voltage measurement with RL loads.

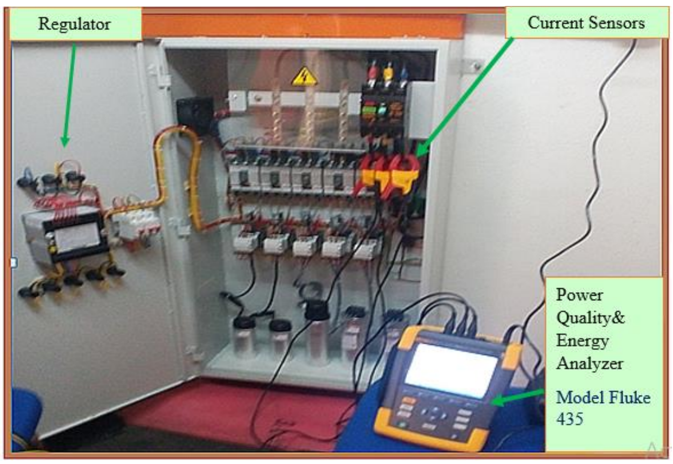

Figure 2. Shunt CB unit connection for experimental setup.

As it is evident, the measured line-to-line transient voltage (between line A and line B) is even smaller than the peak nominal voltage. Additionally, the transient amplitudes are quite random. Even the standard deviation of the three values for the same switching step was extremely large. Such small voltage fluctuations that occur for rather short time durations may not harm the downstream equipment connected in phase-to-phase supply. And also as we have connected single phase loads the line-to-line transients do not play a significant role. Due to these reasons we do not pay much attention to the voltage transients recorded in this study other than providing the statistics for future references.

Compared to the line-to-line voltage transients, the line current transients show a significant amplitude compared to the amplitude at nominal frequency. Note that the temporal characteristics of the current waveforms resemble those of typical switching impulses [27, 28], however, at higher switching steps the impulse duration reaches extreme values. Compared with pulse duration, the variation of the rise time for different steps is not very significant. It can also be noted that the peak transient current increases with the capacitor steps and reaches the maximum at step 5. The worst scenario could occur if the transient appears at the peak of the nominal voltage with its polarity as same as that of the instantaneous nominal voltage.

B. *Simulation Outcomes*

The simulation results pertinent to the balanced single-phase load of the same circuit are presented herewith. Each transient is represented by a voltage and current impulse at the points of measurement. The results pertinent to Phase A are depicted in Table 3. For Phase A, VANS represents the phase voltage of the phase A with respect to the neutral, IAS is the peak line current under nominal voltage and ITS is the peak transient current. Note that both VANS and ITS are measured from the initial value to the peak value of the transient (similar to the analysis of the experimental data), thus, the numerical figures given in Table 1 are independent of the position of occurrence of the transient in the 50 Hz waveform. Figure 9 shows a simulated transient current waveform for CB step 5 switching with initial power factor 0.51.

To compare the simulated and measured parameters, we calculated the percentage difference of each parameter, ΔParameter (%) by the following equation.

$$\Delta Parameter\ (\%) = \frac{Measured\ parameter - Simulated\ Parameter}{Measured\ Parameter} \times 100$$

The calculated values of the ΔParameter (%) are given in Table 4.

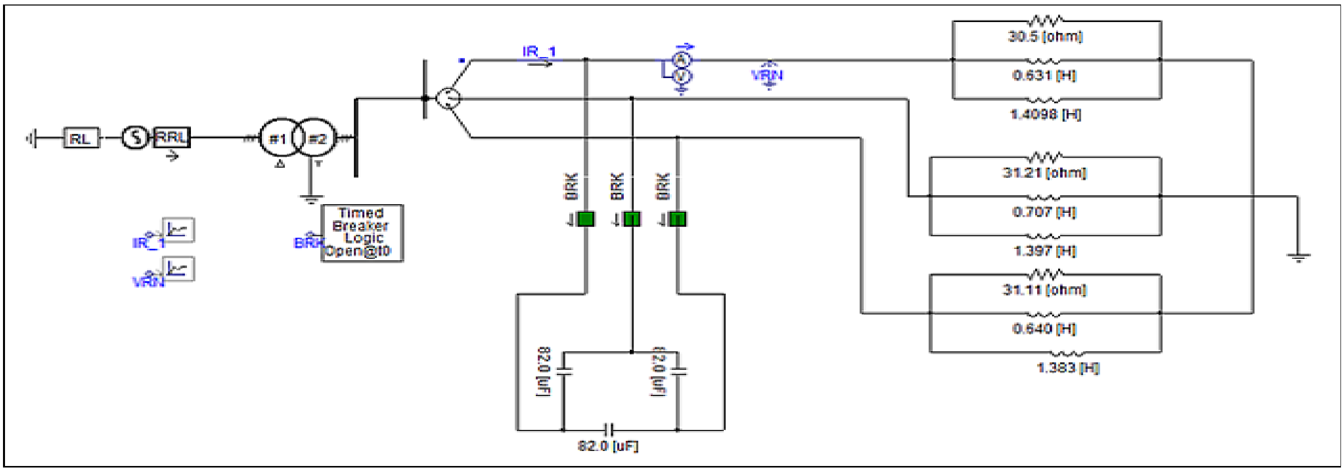

Figure 3. PSCAD model of a single phase load connected to CBs.

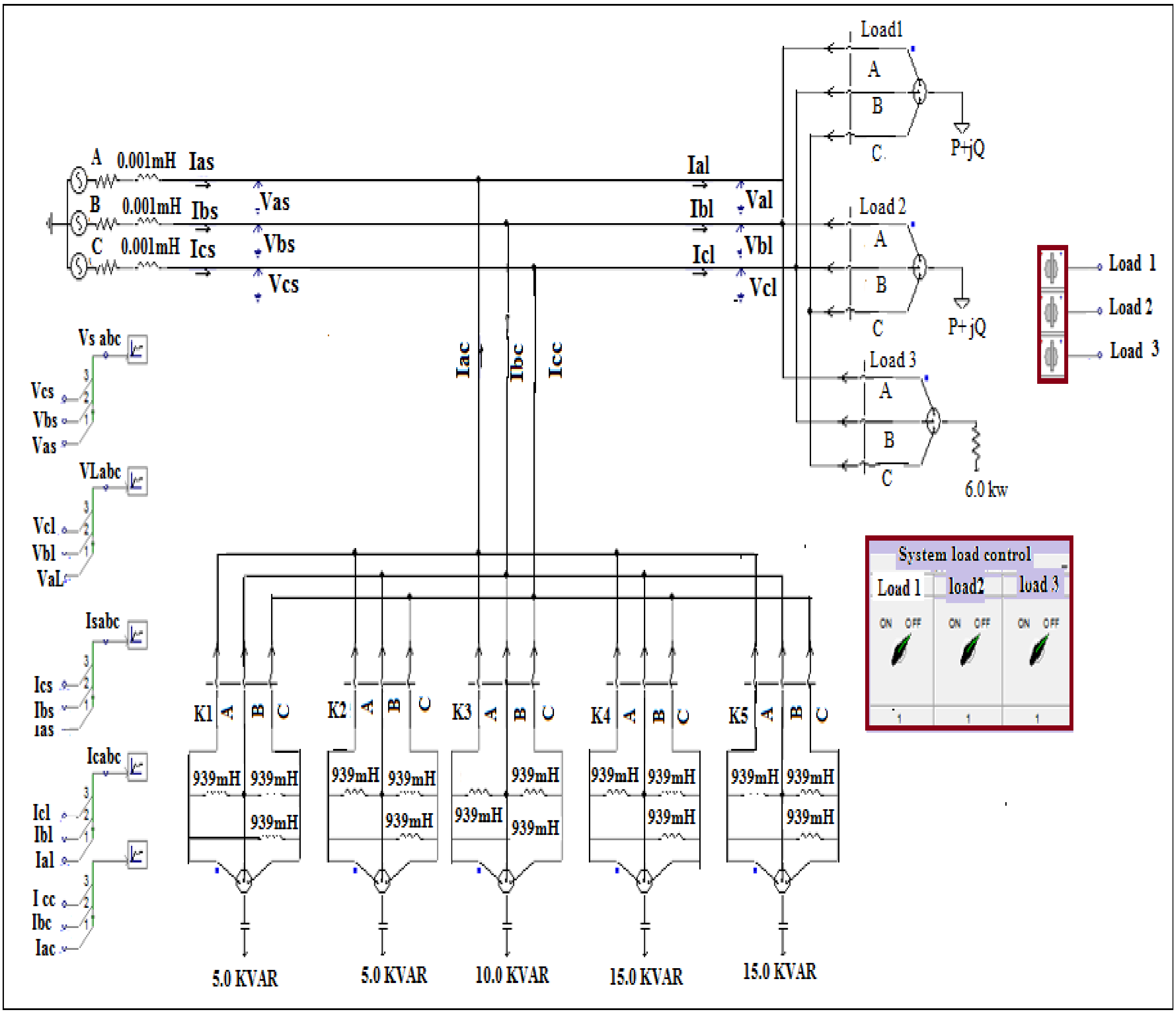

Figure 4. PSCAD simulation model of five step CB together with loads.

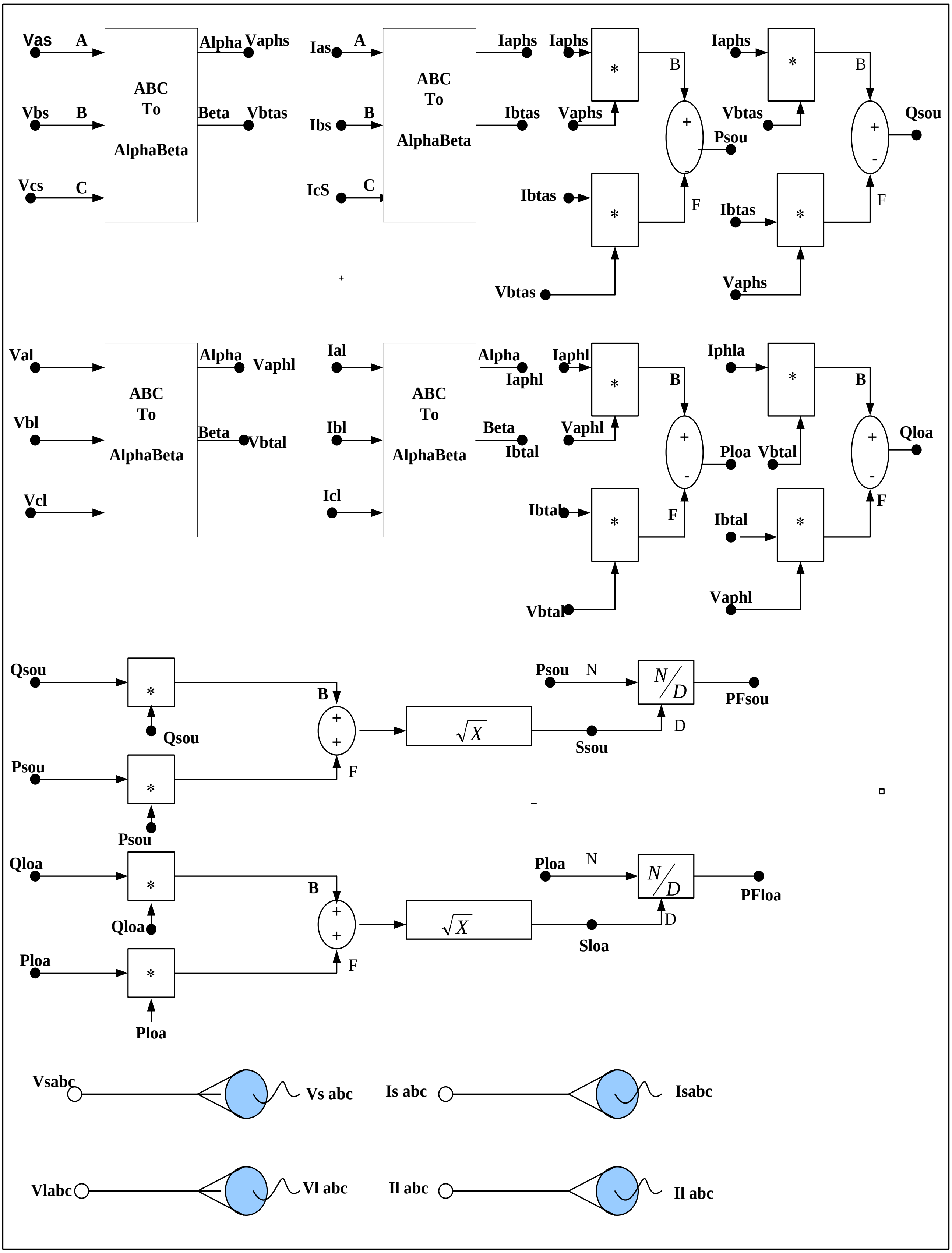

Figure 5. PSCAD simulation model of real and reactive power in the load.

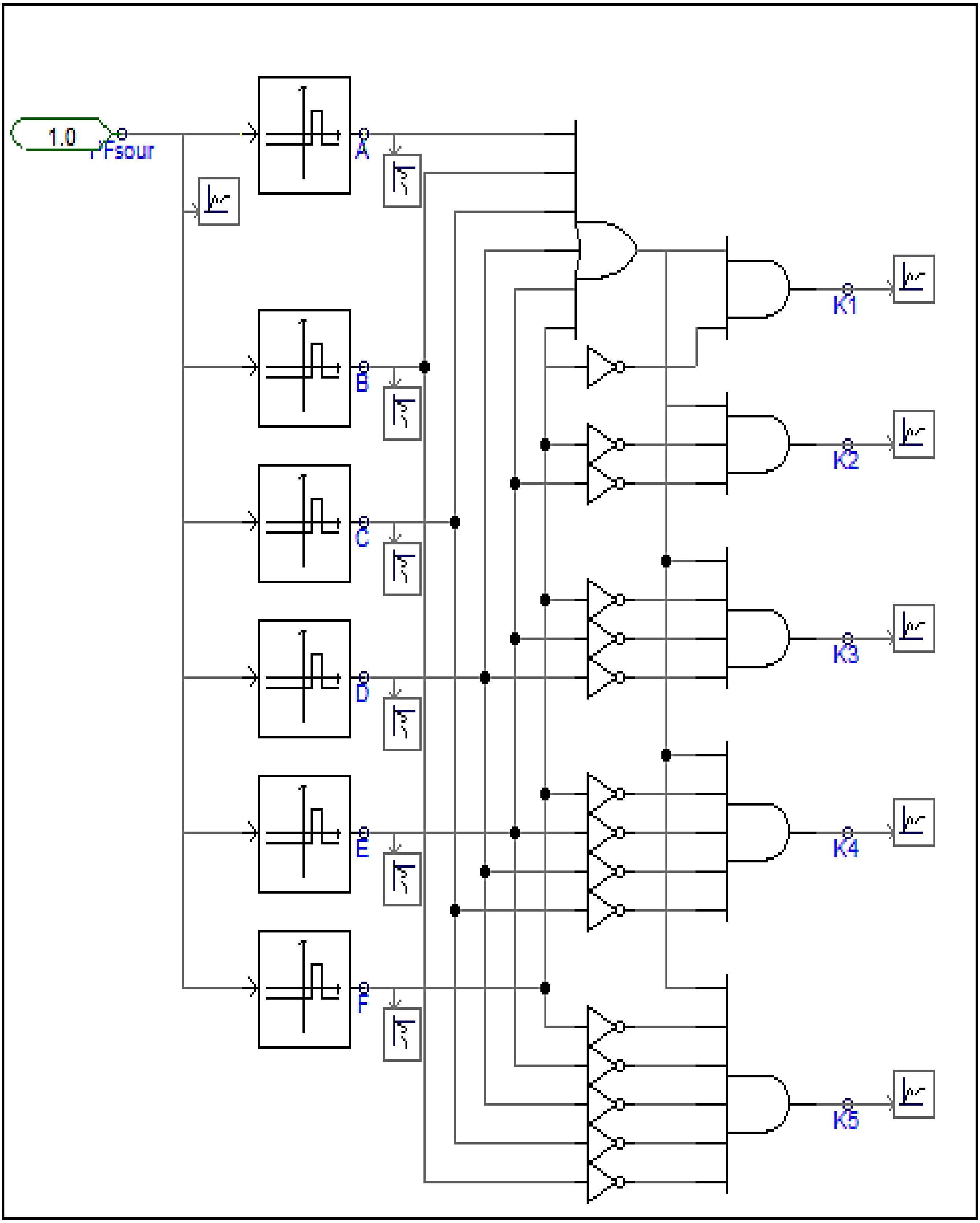

Figure 6. Controller Circuit of the CB

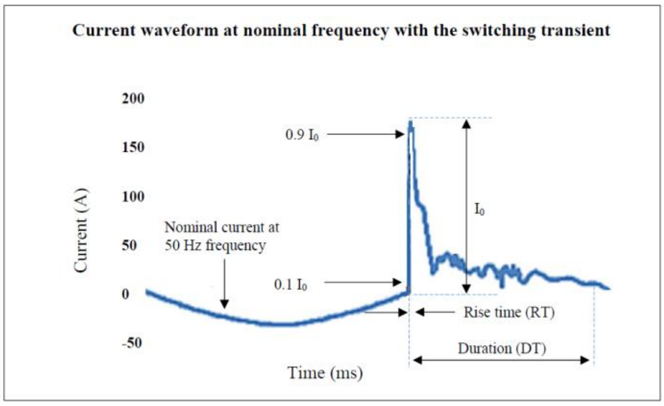

Figure 7. Transient embedded on the nominal current waveform at 50 Hz frequency at the step 5 switching (initial cos φ = 0.51) of the CB

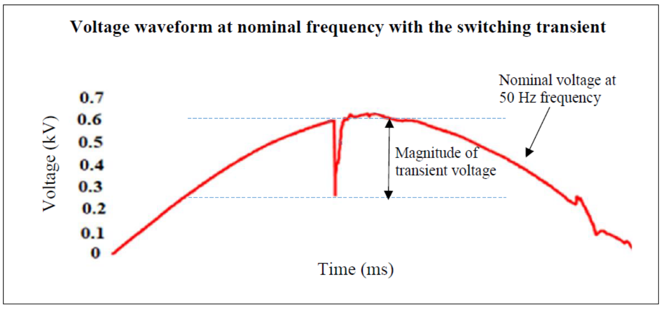

Figure 8 Transient embedded on the nominal voltage waveform at 50 Hz frequency at the step 5 switching (initial cos φ = 0.51) of the CB

Table-1. Variation of power factor when Switching Capacitor Steps with initial power factor 0.51

Capacitor step		Power factor (cos φ)	Orientation
1	5 kVar	0.66	Inductive
2	5 kVar	0.85	Inductive
3	10 kVar	0.93	Capacitive
4	15 kVar	0.91	Capacitive
5	15 kVar	0.95	Capacitive

Table-2 Average parameters measured. I_A: Peak value of the operational (50 Hz) line current, I_T: Peak value of the transient current, V_{AB}: Peak value of the line A-to-line B voltage, V_T; Peak transient voltage, RT: Rise time of the transient current waveform, DT: Duration of the transient current waveform.

Capacitor step	IA (A)	IT (A)	VAN (V)	VAB (V)	VT (V)	RT (µs)	DT (µs)
1	34	116	339	611	458	220	510
2	27	129	340	609	52	180	910
3	35	155	339	611	130	180	4900
4	36	165	340	634	146	300	1500
5	36	167	340	612	343	130	2300

Table-3 Simulated parameters. I_{AS}: Peak value of the operational (50 Hz) line current, I_{TS}: Peak value of the transient current, V_{ABS}: Peak value of the line A-to-line B voltage, RT: Rise time of the transient current waveform, DT: Duration of the transient current waveform.

Capacitor step	IAS (A)	ITS (A)	VANS (V)	VABS (V)	RT (µs)	DT (µs)
1	21	116	315	597	220	1630
2	21	127	315	597	240	1620
3	37	158	316	585	170	1940
4	49	170	318	693	210	1950
5	49	165	318	681	160	2510

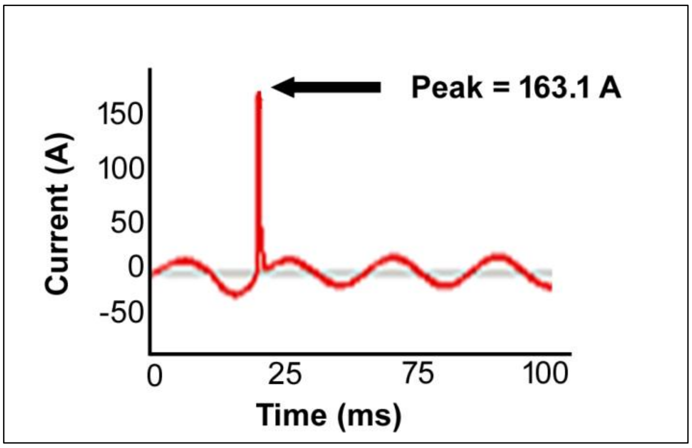

Figure 9. Simulated transient current observed in phase A as the capacitor step 5 is energized. The initial power factor was 0.51.

Table-4 Comparison between the measured and simulated parameters

Capacitor step	ΔIA (%)	ΔIT (%)	ΔVAN (%)	ΔVAB (%)	ΔRT (%)	ΔDT (%)
1	38	0.0	7.1	2.3	0.0	-220
2	22	1.6	7.4	2.0	-33	-78
3	-5.7	-1.9	6.8	4.2	5.6	60
4	-36	-3.0	6.5	-9.3	30	-30
5	-36	1.2	6.5	-11.3	-23	-9.1

Considered the possible random variation in the measured parameters, apart from the time duration of the transient other parameters have acceptable level of agreement between their measured and simulated values. The most vital parameter of the study, the measured transient amplitude has remarkable agreement with the simulated counterpart. Therefore, we can conclude that the simulation model could be used for a much wider range of CBs and loads in predicting the switching transients at the energizing of the CBs in LV systems. It should be noted that the in most cases of DT the simulated value has a higher value than the measured value. It is also of interest that for CB step 1 switching, the transients generated in experimental and simulated cases have remarkably similar amplitude rise time whereas it records the largest difference of all parameters when it comes to the pulse duration. The simulated pulse duration is more than twice that of the measured value. Further studies are required to compare these measured and simulated parameters, before making firm conclusions or introducing correction factors. However, the present study could confidently confirm that the simulation model could be used to compute the amplitudes and rise times of transient currents pertinent to CB switching, for a wide range of systems with shunt connected line-to-line CB and series connected three single phase RL loads.

C. Comparison with Lightning Waveforms

To explore the possibilities of filtering capacitor bank switching transients by the lightning surge protectors (SPDs), we made a comparison between the switching transients analyzed in this study and the recorded lightning transients. After analyzing the various parameters of the switching transient waveforms with Negative first stroke, negative subsequent stroke and positive stroke waveforms we have made the following observations.

Capacitor switching transients have no resemblance to the waveforms of negative lightning. The rise time and pulse duration of the measured current transients are similar to the extreme cases (higher 5%) of the same parameters of positive lightning [29]. However, pulse amplitude of the capacitor switching transients is approximately three magnitudes lesser than that of extreme positive lightning. There are few important points to be considered in the comparison of CB switching transients and extreme values of positive lightning currents, with respect to their effects on downstream equipment.

1. Positive lightning is less than 5% of the total ground flashes in most parts of the world [30]. The positive lightning that resembles the temporal characteristics of CB switching transients are less than 5% of the total positive lightning. Thus the chances of a high amplitude positive lightning current entering a power line that feeds LV equipment is very rare.

2. In the event of a positive lightning with high current amplitude striking a power line, most probably an arcing will take place from the line to earth or to a nearby grounded object due to the large voltage developed.

3. Lightning is an external source, thus even when coupled with LV network the transient current is distributed in many paths. In the case of TT wiring system, the transient current may flow into either transformer star-neutral ground or any subscriber ground by line-to-neutral arcing (or through a load at a subscriber. In other cases of wiring systems, the current may flow into the star-neutral ground of the substation via subscriber loads. In either case, the current that flows in a given path will be significantly less than that enters into the power line at an external location.

4. CB switching transients are generated internally each time the CB is energized. In most of the industrial sites where the power system consists of CBs with step switching facility, the transients are generated much more frequently than that happen in the case of lightning.

The above points depict that, the frequency of CB switching transients penetrating the defense lines of internal equipment is larger than positive lightning currents that resemble same temporal characteristics. Due to the splitting and deviating of lightning currents, the final exposure of equipment to CB switching transient currents and lightning transient currents may not have very high difference in amplitude. Such argument infers that the probability of equipment degradation (if it is not for catastrophic damage) due to CB switching transients may not be insignificant at all.

It is quite evident that the existing surge protective devices (SPDs) that are designed for protection of equipment against lightning transients could suppress CB switching impulses due to their low voltage amplitudes. The voltage protection level (for lightning voltage impulses of 1.2/50 μs and lightning current impulse of 8/20 μs) of even Type III SPDs has a minimum value of 600 V and 3 kA in most cases [29]. Therefore, a new technology should be developed for suppressing CB switching impulses unless the CB is modified to prevent generating such [31]. It is also interesting to investigate the modifications that are required for the placement configurations of SPDs recommended for lightning protection, at present [32, 33].

The outcomes of this study also emphasizes that it will be of high importance to automate the capacitor controlling system to optimize the switching step so that the maximum power factor for a given load is obtained by implementing the best possible capacitive load. It is advisable to integrate AI system into the control panel to implement capacitor addition by back-to-back switching rather than single step large leaps (such as the step 5 which generates the highest transient amplitude). Such automation is essentially needed in power systems with distributed generators as the CB switching occurs frequently due to the source fluctuations. None of the CB control algorithms [34, 35) or switching control [36] and optimal transmission switching methods/algorithms developed so far have taken the suppression of switching impulses into account.

IV. CONCLUSSIONS

CBs installed in LV systems for power factor correction are known to generate switching transients during the energizing and de-energizing operations. This study investigated the switching transient phenomena by energizing five-step 50 KVAR shunt CB in a LV power system with an electronic energizing technique. Although the 3-phase system consists of three balanced single phase RL loads the data has been presented pertinent to only one load. The results show that significantly high load-dependent transient currents could be generated during the switching operations. The transients could be one magnitude greater than the peak of nominal current and exist for few milliseconds in the extreme cases. By temporal characteristics they resemble the higher 5% of positive lightning, however the amplitudes are about three magnitudes less. Due to the very high frequency of occurrence and internal location of the source, compared with lightning, the CB switching transient currents may be high enough to either damage or degrade the equipment connected to the power system. The severity of transients depends on the switching step; thus it is advisable to replace large abrupt steps by smooth variation (gradual addition) of capacitive load into the power system.

The same CB in an electrical network model in an LV power system (0.415 kV) with same loads was simulated using PSCAD software. The generated current transients were in well agreement in terms of amplitude and rise time with the experimental results. The pulse duration shows a large deviation in some switching steps, however, compared with the random nature of the impulses, the variation may be acceptable. This outcome shows that the PSCAD simulation model could be employed to generate CB switching impulses for any configuration in an LV system, to develop a data base of switching impulses pertinent to CBs.

The rise time and pulse duration of the measured current transients due to capacitor bank switching are similar to the higher 5% of the same parameters of positive lightning. On the other hand, pulse amplitude of the capacitor switching transients is about three magnitudes lesser than that of extreme positive lightning.

The outcome of this study provides vital information for CB manufacturers to improve their devices by integrating suitable surge suppressors to their systems and also the end-user electrical engineers to automate the capacitor switching operation to minimize the generation of transient currents with large amplitudes.

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