EMTP-based Analysis of Pre-insertion Resistor and Point on wave switching Methodology

S. Zondi
Dept. of Electrical and Electronic Engineering Technology
University of Johannesburg
E-mail: Simphiwe.zondi@conco.co.za

P. Bokoro; B. Paul
Dept. of Electrical and Electronic Engineering Technology
University of Johannesburg
E-mails: pitshoub@uj.ac.za
bspaul@uj.ac.za

***Abstract*— The switching of high-voltage capacitor banks for reactive power and voltage control usually produces significant transients. These high amplitude disturbances have a tendency to damage or reduce the lifespan of capacitor units, thus leading to complete failure of capacitor banks. Pre-insertion resistors or inductors as well as synchronous switching (Point on Wave) methods can be used to mitigate transient phenomenon. In this work, EMTP simulations of transient voltage for single and back to back capacitor banks indicate that pre-insertion resistors methodology can significantly reduce transients, and could therefore be combined with synchronous switching to effect transient mitigation.**

Keywords: Capacitor banks; Transient overvoltage and inrush current; single and Back to back switching.

I. INTRODUCTION

Capacitor switching transients are created by the effective short circuit provided by a discharged capacitor during energization. This short circuit creates high inrush currents and subsequent voltage dips on the source [1]. The high inrush currents also stress switching equipment, fuses, and the capacitor units. When more than one capacitor bank exists on a common bus, the energized capacitor bank provides an extremely low source-impedance for the second switching capacitor bank leading to extremely high transient voltage in both banks. The voltage transient will eventually damage the capacitor units or shorten the unit's lifespan due to continuous exposure to voltages that exceed their design durability [2].

The point on wave (POW) switching method is mostly used to mitigate switching transients. There is however shortcomings related to this method due to mechanical linkage drift over time. This causes problems as transients of up to 1.2 p.u could be observed for switching at half voltage of the peak voltage waveform.

In this paper the on-line switching of a high voltage capacitor bank installed at Durban North Substation of EThekwini Municipality in South Africa is analyzed using the EMTP software. In this paper, the pre-insertion resistors and the POW methods are used in combination in a bid to provide effective and reliable switching transient mitigation, despite mechanical linkage drift in POW.

II. CAPACITOR BANK SWITCHING TECHNIQUES

To improve transient phenomena during capacitor bank energization, the pre-insertion and synchronous switching methods are examined:

A. Pre-Insertion Resistors

Resistors are typically inserted into the capacitor-energizing circuit for 10 to 15 milliseconds prior to the closing of the main contacts, through the closing of an additional set of contacts [4]. Synchronization between the resistor and main contacts is required and is usually achieved by connecting the resistor contact rod directly to the main contact control rod. Once the switching has been achieved, the resistor is then switched off the circuit.

B. Synchronous Switching (POW)

These devices are typically high-speed vacuum switches or SF_6 circuit breakers with sophisticated electronic controls [4]. The individual poles of the switch or breaker are usually controlled to close near zero crossings of the voltage waveform to minimize transients. Two types of POW switching in practice, namely:

1. Independent Pole Operation (IPO)

This is achieved by having a circuit breaker, with three independent poles, and a synchronizing relay which serves to monitor the voltage waveform. This relay does issue a closing command to each individual pole. This form of synchronous switching appears to be quite reliable and accurate. However, the drawback related to this switching mechanism seems to be the cost involved in the implementation. This therefore paves the way for the three-pole switching approach.

2. Three-pole switching (Mechanical Linkage)

This is achieved by having a circuit breaker with three dependent poles, a synchronizing relay monitoring the voltage waveform, and set to issue a closing command to a master pole. The other poles are mechanically linked to the master pole and staggered 120 electrical degrees apart [5], such that all poles close at the zero crossing of the voltage waveform. In terms of the time setting, these degrees can be represented as 3.3ms time difference between the pole operations for 50Hz systems.

This synchronous switching approach is used in this paper, as it has proven to be more cost effective. However, it has also proven to be less reliable due to mechanical links drifting over time.

III. EMTP SIMULATION

A simulation has been conducted on EMTP software in order to evaluate the magnitude and durations of capacitor bank switching transients. The simulation was done on Isolated and back to back capacitor bank. Figure 1 below also shows the single line arrangement of the Durban North Substation which will be used for this simulation. Figure 2 shows the same single line drawing including a 40Ω pre-inserted resistor.

A. Simulation Parameters

The simulation is based on the on-line switching of an isolated capacitor bank followed a few seconds later, by the on-switching of the second bank while the first is on line. This is referred to as back to back capacitor bank switching. The data that will be used is from Durban North Substation and is listed in table 1 below.

Description	Value	Unit
Voltage $_{L-L}$	132	kV
Voltage $_{L-N}$	76.3	kV
Series Inductance	0.6	mH
Internal Resistance	10	Ω
Capacitance	26	µf
Series Groups	12	No.
Parallel Groups	3+3	No.
Capacitance	0.465	µf
Capacitor Voltage	6985	V
Voltage across the series group	83.82	kV
Pre-insertion Resister	40	Ω

Table 1 System Parameters

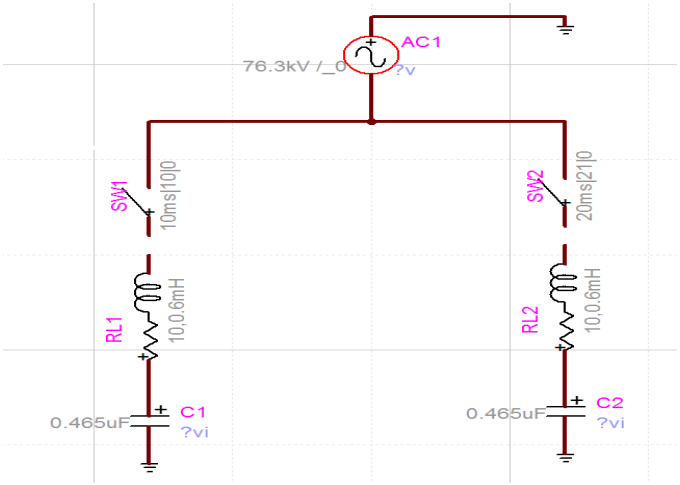

Figure 1: Durban North Single Line Arrangement without pre-insertion resistor

B. Methodology

The following steps are used in order to complete the simulation:

a. Compare on site SF6 Circuit breaker speed test results before and after commissioning of the Durban North Substation Capacitor Bank.
b. Simulate switching on-line of capacitor bank at peak voltage, without pre-insertion resistor.
c. Simulate switching on-line of capacitor bank at peak voltage, with pre-insertion resistor.
d. Simulate switching on-line of capacitor bank at half peak voltage, without pre-insertion resistor
e. Simulate switching on-line of capacitor bank at half peak voltage, with pre-insertion resistor.
f. Simulate switching on-line of capacitor bank at zero voltage crossing (POW), without pre-insertion resistor.
g. Simulate switching on-line of capacitor bank at zero voltage crossing (POW), with pre-insertion resistor.

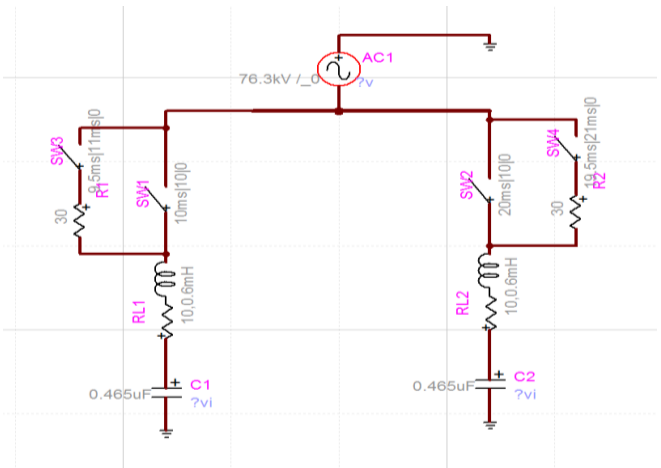

Figure 2: Durban North Single Line Arrangement with pre-insertion resistor

C. SF6 Circuit Breaker Speed Test Results

A circuit breaker speed test was conducted before the commissioning of the capacitor bank at Durban North Substation. In order to achieve zero crossing or POW, the circuit breaker poles must lag each other by 3.3ms, thus 120 electrical degrees is achieved. Therefore the expected results are dA-B = 6.6ms and dA-C = 3.3ms. The speed test results before commissioning are shown in figure 3.

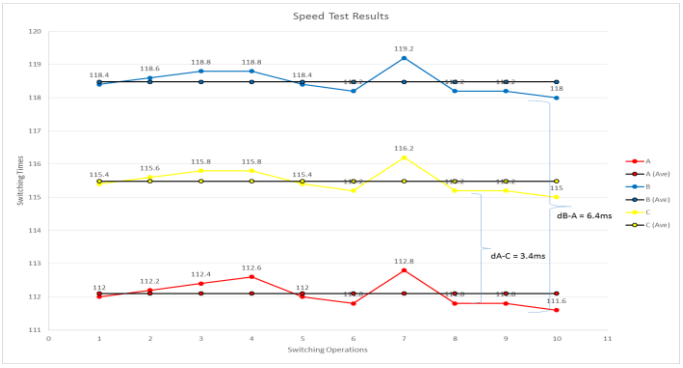

Figure 3: Speed test results before commissioning

The ideal switching points which correspond to the speed test results are indicated in figure 4.

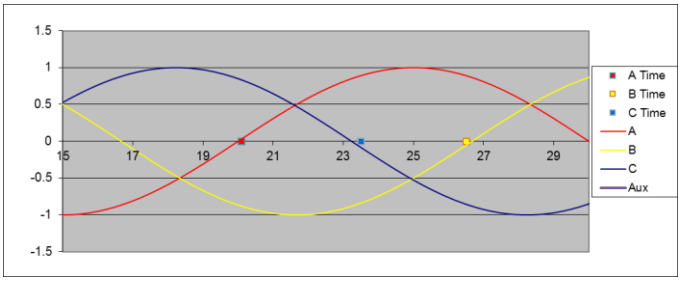

Figure 4: Ideal point on wave switching

The results of the speed test obtained six months post commissioning of the Durban North Substation capacitor banks is shown in figure 5. It is evident from the speed test result that there has been a drift in the mechanical linkages of the circuit breakers.

Figure 5: Post commissioning speed test results

The waveforms obtained as a result of drift of the mechanical linkages are shown in figure 6. It could be seen that the circuit breaker phases are not switching at the zero crossing as expected.

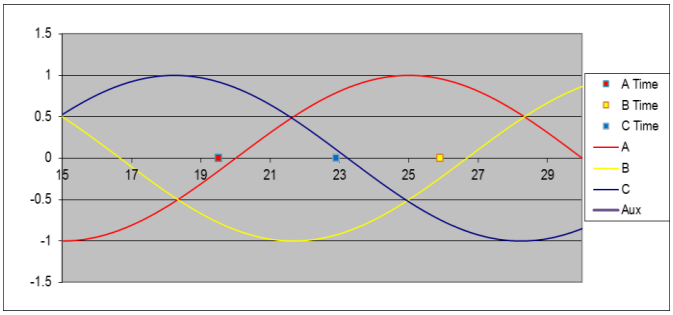

Figure 6: Incorrect switching point due to mechanical linkage drift

IV. Combination of Pre-Insertion Resistors and Synchronous Switching

A. Case 1: Switching takes place at peak voltage without Pre-insertion Resistor

a. SW 1 closes 10ms at red phase peak (Isolated Bank).
b. SW 2 close 20ms at red phase peak with C1 in service. (Back to Back Bank).

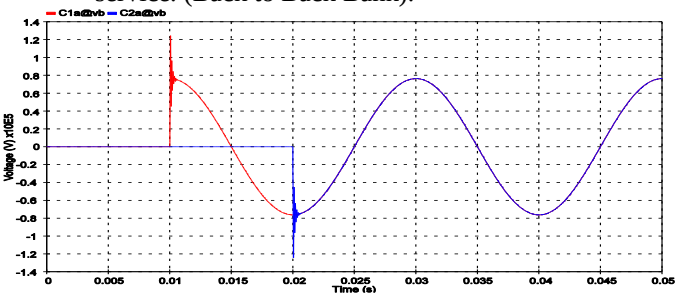

Figure 7: Voltage waveform switching at peak

B. Case 2: Switching done at peak voltage with Pre- insertion Resistor

a. SW 1 closes 10ms at red phase peak.
b. SW 3 closes 9.5ms pre-insert 40 ohm resistor and 11ms open.
c. SW 2 close 20ms at red phase peak with C1 in service.
d. SW 4 close 19.5ms pre-insert 40 ohm resistor.

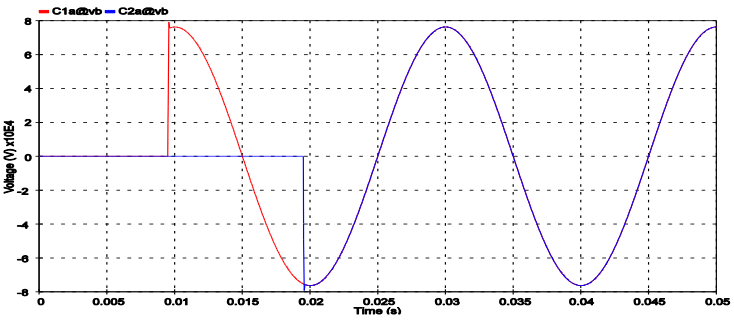

Figure 8: Voltage waveform switching at peak

C. Case 3: Switching done at half peak voltage without Pre-insertion Resistor

a. SW 1 closes 7.5ms at red phase peak (Isolated Bank Bank).
b. SW 2 close 17.5ms at red phase peak with C1 in service. (Back to Back Bank).

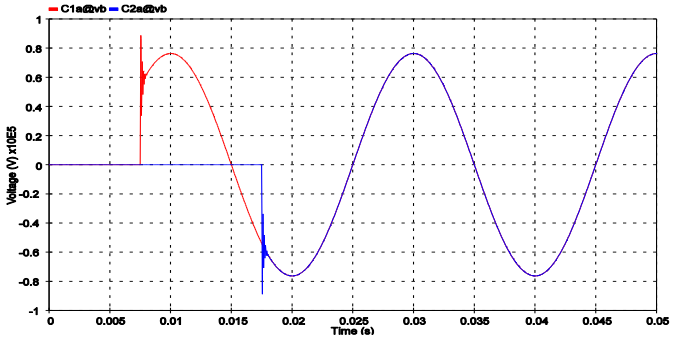

Figure 9: Voltage waveform switching at half peak

D. Case 4: Switching done at half peak voltage with Pre-insertion Resistor

a. SW 1 closes 7.5ms at red phase peak.
b. SW 3 close 7ms pre-insert 40 ohm resistor and 11ms open.
c. SW 2 close 17.5ms at red phase peak with C1 in service.
d. SW 4 close 17ms pre-insert 40 ohm resistor.

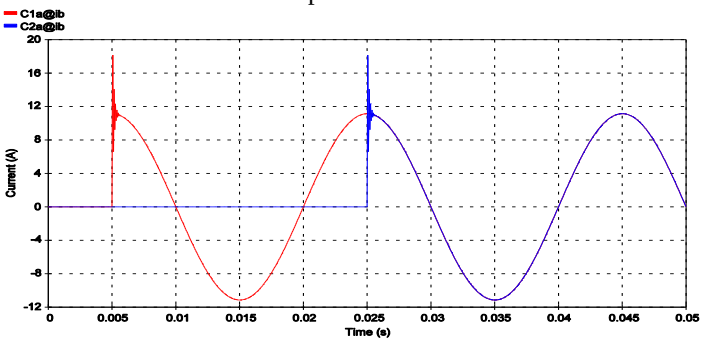

Figure 10: Voltage waveform switching at half

E. Case 5: Switching done at zero voltage crossing – without Pre-insertion Resistor

a. SW 1 close 5ms at red phase peak (Isolated Bank)
b. SW 2 close 25ms at red phase peak with C1 in service. (Back to Back)

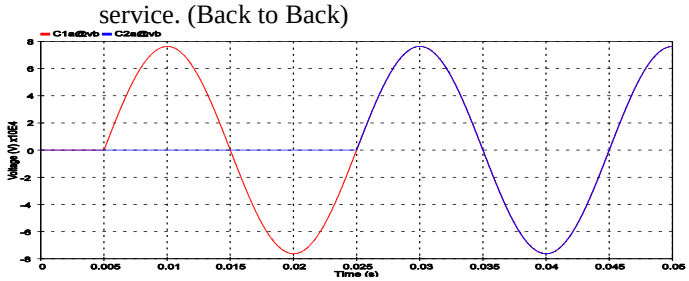

Figure 11: Voltage waveform switching at zero crossing

F. Case 6: Switching done at zero voltage crossing with Pre-insertion Resistor

a. SW 1 closes 5ms @ red phase peak.
b. SW 3 close 4.5ms pre-insert 40 ohm resistor.
c. SW 2 close 25ms @ red phase peak with C1 in service.
d. SW 4 close 24.5ms pre-insert 40 ohm resistor.

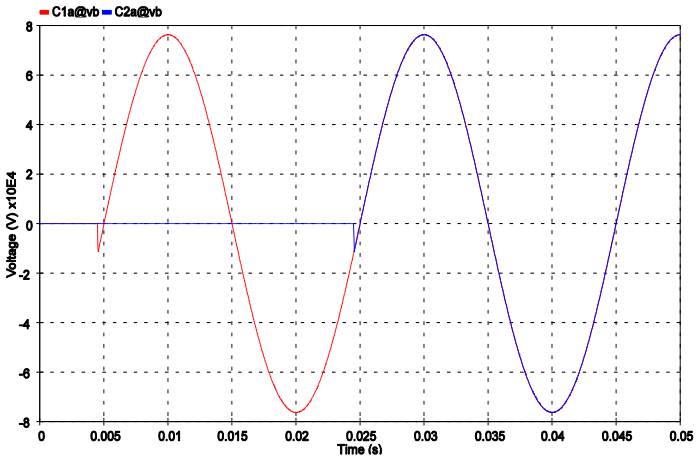

Figure 12: Voltage waveform switching at zero crossing

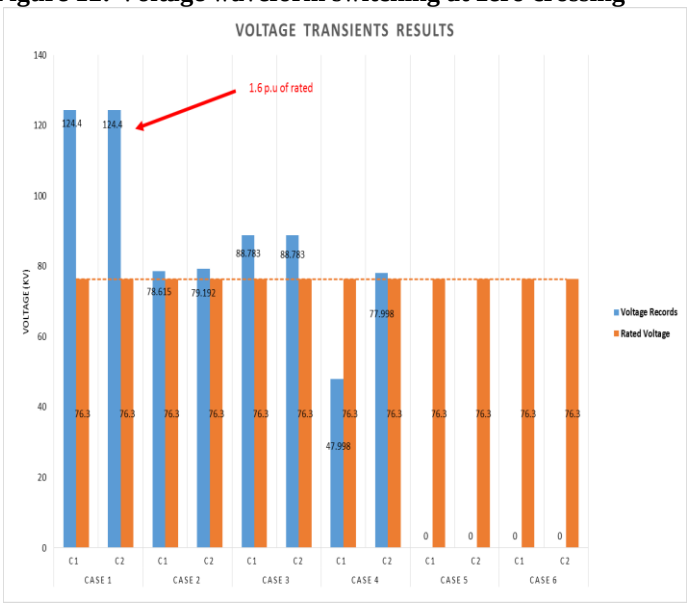

Figure 13: Simulation Results

V. Results and Discussion

As demonstrated in Figure 3 and 5 above, the circuit breaker speed tests results recorded before and after commissioning of the capacitor bank at Durban North substation are not the same. This is an indication of a mechanical drift in the circuit breaker linkages. The drift will cause a shift in the timing of the circuit breaker switching as seen in figure 4 and 6, this shift causes a deviation in the circuit breaker switching sequence and voltage zero-crossing switching is not achieved, causing transients which in turn cause damage to the capacitor units. Figure 13 show a graph plotting the results obtained from the EMTP simulation, C1 and 2 represents that energization of capacitor ban 1 and 2 respectively.

Case 1: switching demonstrates the worst case scenario, switching on-line of capacitor banks at peak voltage without pre-insertion resistor, voltage rise up to 1.6 p.u. This is to demonstrate the effect of mechanical linkage drift to maximum or worse case.

Case 2: illustrates the introduction of a 40 ohm pre-insertion resistor, switched in 0.5ms prior to closing of the circuit breaker and disconnected 1ms after switching on-line of the circuit breaker. This scenario reduces the voltage transients to 1.03 p.u. as well as significantly reduces the current transients by up to 45%.

Case 3: demonstrates switching of the capacitor bank at half peak of the voltage waveform. This also show the effect of transients in the event of a mechanical linkage drift. In this scenario, high voltage transients are still evident, these transients exceed the capacitor bank rating and can damage or shorten the life span of the capacitor units.

Case 4: illustrates the insertion of a 40 ohm resistor in order to mitigate the apparent transients when switching at half peak of the voltage wave form. The insertion of a resistor also proves to reduce the transient that are generated when switching at half peak of the voltage wave form.

Cases 5 and 6: illustrate the ideal switching scenario: this is the zero-crossing of the voltage waveform or the ideal point on wave to switch in capacitor banks. Case 6 also demonstrates that the inclusion of a 40 ohm pre-insertion resistor will not affect the circuit operation.

As case 6 represents the ideal point on wave switching, which is on the zero-crossing of the voltage waveform, it is however difficult to sustain switching at this point on the voltage waveform due to circuit breaker mechanical linkages drifting from the commissioned position.

VI. CONCLUSION

The effectiveness of POW switching using mechanically linked 3-phase, 3-pole circuit breakers, for the purpose of transient voltage mitigation, when capacitor banks are switched on-line, is analysed in this paper. The EMTP simulation results on the different case scenarios, point to the following:

a. The transient voltage and current induced result from the circuit breaker mechanical linkage drift. This causes switching to take place beyond zero crossing.

b. The magnitude of the resulting transient current is dependent on the initial conditions of the contacts of the breakers. These observations indicate that POW switching of capacitor banks using mechanically linked 3-phase, 3-pole SF6 circuit breakers, is prone to induce transient current and voltage which in turn aggravate current unbalance resulting from capacitance failure in the bank. The fundamental source of these problems remains the shift of the linkage between the breakers which tends to occur in a very short period of time, and thus making this technique non effective.

c. The introduction of pre-insertion resistors tends to reduce the effect of transients at the switching on line of capacitor banks.

d. Consideration must be made to combine POW using mechanical linked circuit breakers and pre-insertion resistors. The resistor will compensate for the POW in the event of a mechanical linkage drift.

VII. REFERENCES

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