Impact of High Voltage Shunt Capacitor Banks on General Purpose Circuit Breakers

M. Alawie *, Y. Filion, A. Coutu

***Abstract*—It is well known that during a fault on a bus bar with the presence of a shunt capacitor bank, a large part of the transient current meant to be interrupted by a bus bar or a line general purpose circuit breaker in the case of a reignition comes from the discharge of the capacitor bank. This high frequency current, a few kHz, is known as the Outrush current. This particular duty can exceed the applicable circuit breakers standards (IEC 62271-100 or IEEE C37.06) in terms of equivalent product of current frequency of $2x10^7$ A.Hz defined for general purpose CB and even the $8,5x10^7$ A.Hz defined for definite purpose CB. Also, an attempt of interruption at each zero crossing of this high frequency current for some technologies of circuit breaker can lead to a voltage escalation and in the worst case, the destruction of the circuit breaker. In this paper we will explore by simulation, using EMTP-RV, the impact of different configurations of shunt capacitor on general purpose circuit breakers using grounded and ungrounded shunt capacitor bank, also damping reactor on the neutral side of the shunt capacitor bank with varistors in parallel.**

***Keywords*: Shunt capacitor bank, Outrush current, Circuit breaker (CB), Reignition, damping reactor, Grounding, Transients, Transient Recovery Voltage (TRV), Rate of Raise of Recovery Voltage (RRRV), Power System, EMTP-RV.**

I. INTRODUCTION

SHUNT capacitor banks are widely used on power systems to provide reactive power close to the load centers. The installation of shunt capacitor banks on a power system has beneficial effects such as the voltage regulation and the reduction of the losses of active power to be transmitted. On the Hydro-Quebec transmission system the shunt capacitor banks represent more than 11300 MVAR distributed mainly on four levels of transmission voltages: 627 MVAR on the 69 kV level, 5400 MVAR on 120 kV level, 2730 MVAR on 230 kV level and 2580 MVAR on 315 kV level. The size of an individual shunt capacitor bank starts at 8 MVAR on the 69 kV level and goes up to 384 MVAR on the 315 kV level. Most of these shunt capacitor banks are ungrounded except for the 315 kV levels where all banks are grounded to reduce the insulation level of the neutral and also to reduce the RV constraint on the circuit breaker of the shunt capacitor bank.

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II. SCENARIO DESCRIPTION

We have chosen a 230 kV substation as subject of this study. Figure 1 illustrates the 230 kV substation which is equipped with ungrounded Wye connected shunt capacitor banks of 204 MVAR each. It should be noted that no filtered bank has been considered in the explored configurations.

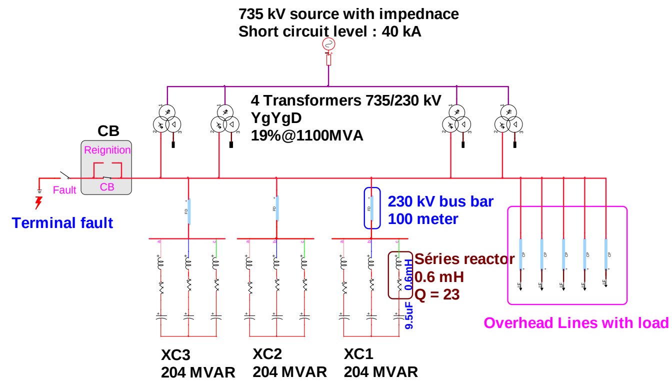

Fig. 1 EMTP-RV equivalent circuit of a 230 kV substation equipped with 3 ungrounded shunt capacitor banks

As shown in Fig. 1, each shunt capacitor bank is equipped with 0.6 mH damping reactor with a quality factor (Q) of 23 used to limit inrush current during energization. We have considered a bus bar distance of 100 meters between each shunt capacitor bank and the main bus bar. This substation feeds an 1100 MVA load through 5 overheads lines represented by a constant parameters line model (CP line). The power autotransformers, number of 4, are 735/230 kV and YgYgD connected with 19% of impedance based on 1100MVA. The power system is represented by a 735 kV source with impedance to reflect a short circuit level of 40 kA. In the next sections the influence of the configuration of the shunt capacitor banks will be studied during the interruption of a 3 phases and 1 phase fault to ground (terminal fault) by a general purpose circuit breaker. We will further simulate, for each configuration, a multi-phase reignition [1,2] at the peak TRVs and observe the impact on the outrush current seen by the circuit breaker.

III. UNGROUNDED WYE CONNECTED SHUNT CAPACITOR BANK

A. Case of 3 phases to ground fault

In this case we produce a 3 phase to ground fault (terminal fault) on the main bus bar that we clear some cycles later. We obtain a maximum TRV of 1.6 p.u. (i.e. 1 p.u. = 187,2 kV peak for a 230 kV system) on phase A of the CB as shown in Figure 2. RRRV in this case is less than 0.5 kV/µsec.

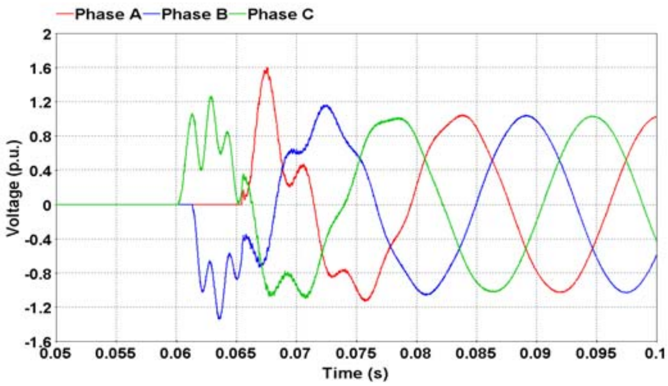

Fig. 2 TRV observed on each phase of the circuit breaker during 3 phases fault interruption

Thereafter a reignition has been simulated on the peak TRV of phase A; which resulted in a TRV on phase B and C of the CB in the order of 2,0 and 2,5 p.u. respectively as shown in Figure 3.

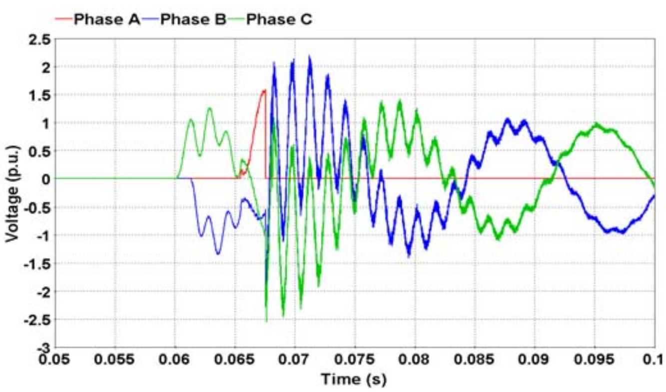

Fig.3 Transient voltage observed on phase B and C of the CB after a reignition on phase A – 3 phases fault

The current observed on phase A is close to 70 kA peak with a frequency of 700 Hz as shown in Figure 4.

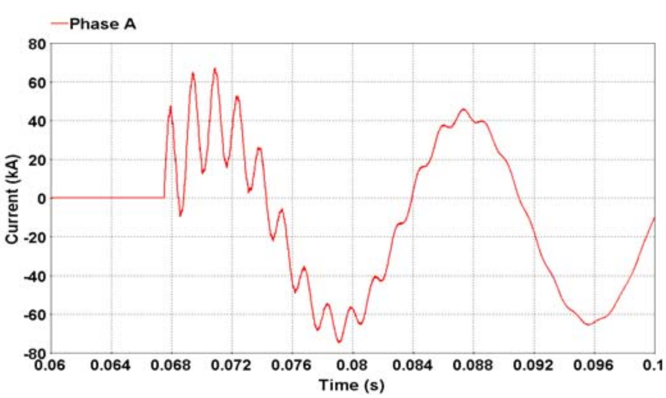

Fig.4 Current observed on phase A after a first reignition

In fact this current is a combination of two components; a 60 Hz component coming from phase A of the source and a 700 Hz component representing the discharge of phases A, B and C of the shunt capacitor bank in the fault.

The TRV of 2,5 p.u. observed on phase C exceeds largely the standard value of 1.82 p.u. in applicable standards [5] so we further simulated a multi-phase reignition on phase A and C. Severe currents and additional high frequency current zeros were found to be far beyond the values given in applicable standards. Figure 5 shows clearly a peak value of 90 kA for phase A and 110 kA for phase C with a frequency of almost 2 KHz.

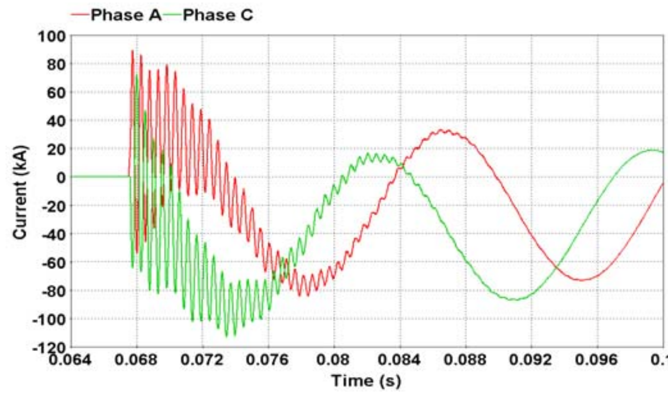

Fig.5 Current observed on phase A and C after a multi-phase reignition

The high frequency of the current can be simply explained by the resonance frequency between the shunt capacitor bank and the damping reactor where they follow the natural frequency of an LC circuit given by:

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

The multiple zero crossing in the breaker reignition current can be explained by the fact that this current is the sum of a high frequency current which is the discharge of the shunt capacitor banks (outrush) and the short circuit current of the source. A zero crossing current result when the current discharge is higher then the short circuit current of the source which is the case.

These high current and frequency values create a hydrodynamic choc wave, which represent a mechanical constraint especially for oil circuit breakers. Furthermore, test current and frequency recommended values according to the standards, equivalent product, are for a total limit of $2x10^7$ A.Hz. for general purpose CB. In this case the value obtained by simulation as shown in Figure 5 is $18\ x10^7$ A.Hz, largely exceeded the value according to the standards even for a definite purpose CB ($8\ x10^7$ A.Hz). It is also of note that some technologies of CB such MOCB (Minimum Oil Circuit Breaker) can attempt to interrupt this high frequency current leading to a voltage escalation following each unsuccessful interruption attempt[3,8]; a situation that in the worst case can result in the destruction of the circuit breaker.

The size of the limiting reactor has an important impact on two aspects of the discharge current of a shunt capacitor bank. The first aspect is the frequency of the discharge current where increasing the size of the limiting reactor means decreasing the frequency of the current. Also, increasing the size of the limiting reactor means decreasing the peak value of the discharge current since this current follow the given formula:

$$I_{Peak} = \sqrt{\frac{2}{3}} \times E \times \sqrt{\frac{C}{L}} \qquad (2)$$

We have simulated the previous configurations with 4 different values for limiting reactors: 1mH, 2mH, 3,5mH and 5mH.

In case of clearing a 3 phases to ground fault the maximum TRV obtained is reduced from 1,6 p.u. on phase A in the original case (with 0,6mH for damping reactor) to: 1,5 p.u. in case of 1mH, 1,4 p.u. in case of 2mH and 1,35 p.u. in case of 3,5mH and 1.48 p.u. in case of 5mH.

A first reignition on phase A give rise to TRV on phase B and C of : respectively 2,16 and 2,38 p.u. in case of 1mH damping reactor, 1,89 and 2,13 p.u. in case of 2 mH and 1,80 and 1,88 p.u. in case of 3,5mH, 1,88 and 1,98 p.u. in case of 5mH. The reignition currents are similar in shape to Figure 4 with a peak value between 70 and 80 kA depending on the size of the damping reactor.

A multiphase reignition has been simulated on phases A and C. As we see in Figure 6 and 7 the peak value of the current and the frequency decreased with the increasing of the damping reactor. We notice that with the use of 5 mH the product frequency current is around $5{,}4 \times 10^{7}$ A.Hz which is still a lot higher than the constraint for a general purpose CB, i.e. 2×10^{7} A.Hz. Also, the zero crossing was not completely eliminated and we notice two zero crossing before the first natural zero. We've noticed also that in case of 5mH the di/dt (100 A/µsec) is mush lower than the original case of 0.6mH (di/dt of 500 A/µsec) increasing the probability that a MOCB will attempt to interrupt a zero crossing current.

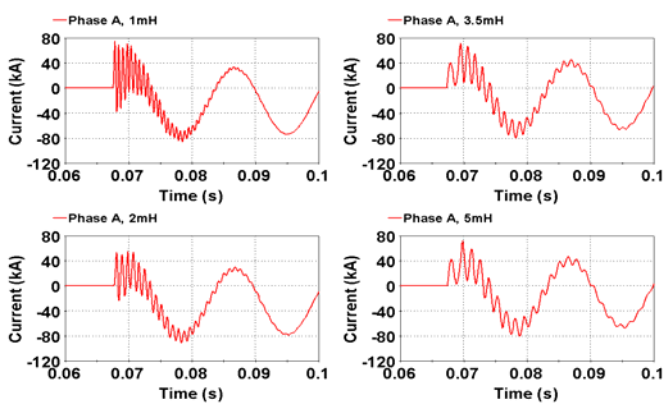

Fig.6 Current observed on phase A for different values of damping reactor after a multi-phase reignition

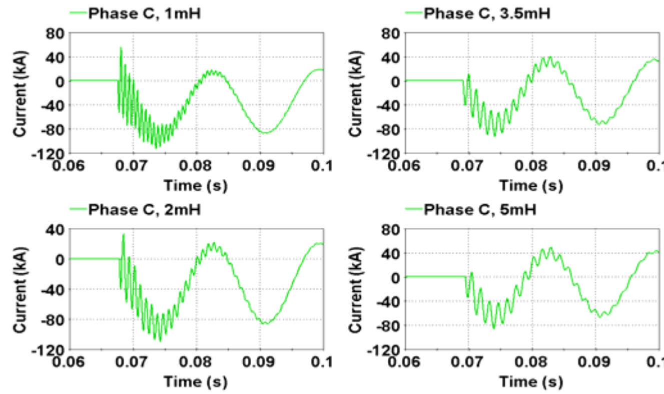

Fig.7 Current observed on phase C for different values of damping reactor after a multi-phase reignition

B. Case of 1 phase to ground fault

In this case as shown in Figure 8, the TRV observed on the faulted phase is 1,46 p.u. and the RRRV still less than 0,5 kV/µsec.

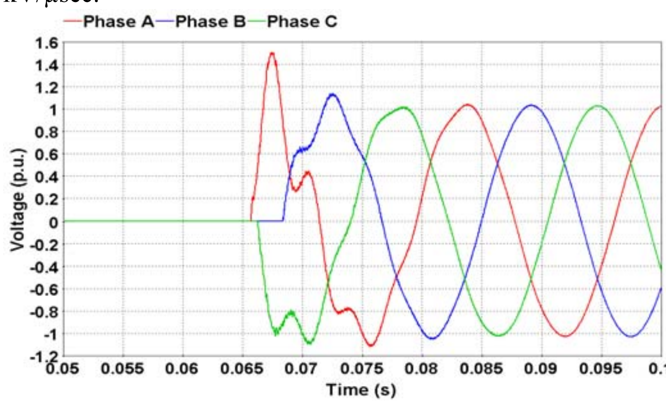

Fig. 8 TRV observed on each phase of the circuit breaker after clearing 1phase to ground fault

The same simulations have been performed also in this case with a reignition on the faulted phase. We observed a transient voltage in the magnitude of 2,4 p.u on phase C and 2,0 p.u. on phase B (see Figure 9).

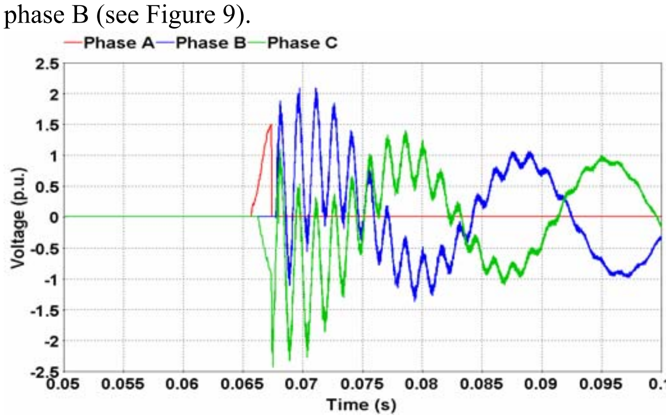

Fig.9 Transient voltage observed on phase C and B of the CB after a reignition on phase A

The current is quite similar to the one obtained when we simulate a first reignition after clearing a 3 phases to ground fault. The peak value is 70 kA with a frequency of 700 Hz.

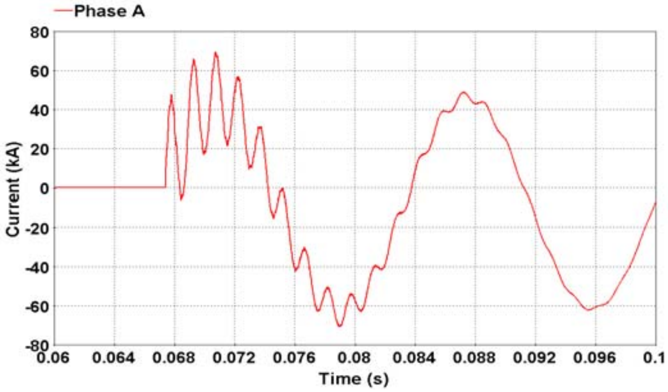

Fig.10 Current observed on phase A after a first reignition

The simulations of multi-phase reignition proves as shown in Figure 11 that no current will be observed on the second phase (phase C in this case).

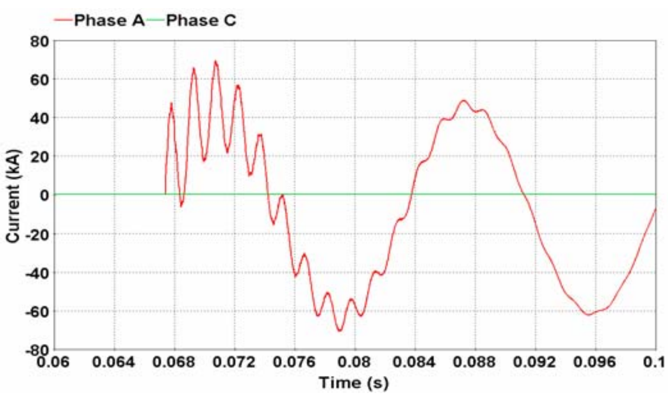

Fig.11 Current observed on phase A and C after a multi-phase reignition

IV. Grounded wye connected shunt capacitor bank

In this case the neutral of the shunt capacitor bank will be simply connected to earth.

A. *Case of 3 phases to ground fault*

As shown in Figure 12, in this case with 3 phases to ground fault a maximum TRV of 1,37 p.u. is observed on phase B. RRRV in this case is less than 0,3 kV/µsec.

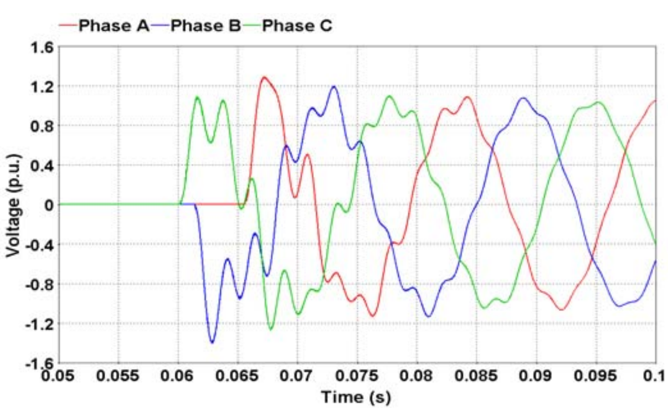

Fig. 12 TRV observed on each phase of the circuit breaker

With a reignition on the peak TRV of phase B; we obtained a transient voltage on phase A and C of the CB in the order of 2,5 and 2,4 p.u. respectively as shown in Figure 13.

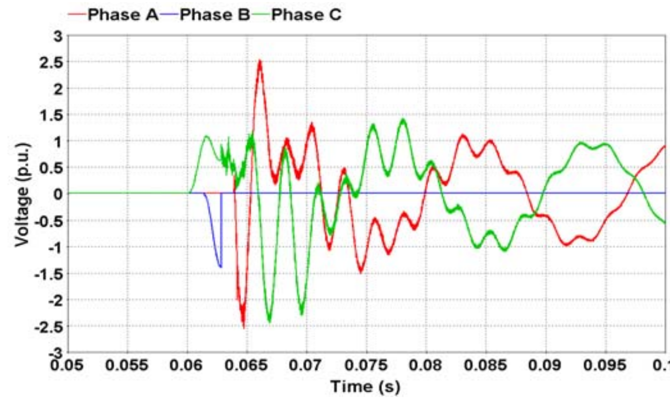

Fig.13 Transient voltage observed on phase A and C of the CB after a reignition on phase B

We notice in this case that the current observed on the phase B is around 90 kA peak value with a frequency of 1.8 kHz combined to a multiple zero crossing as shown in Figure 14.

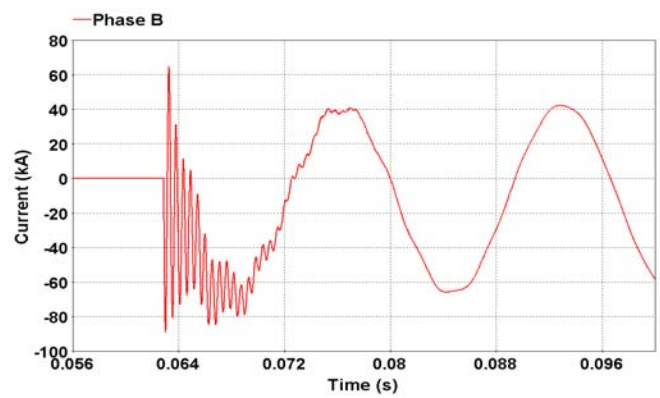

Fig.14 Current observed on phase B after a first reignition

A simulation of a multi-phase reignition on phase B and A show again a severe currents and additional high frequency current zeros; Figure 15 shows clearly a peak values of 90 kA on phase B and 141 kA for phase A with a frequency of almost 2 KHz. These values are again far beyond the limit values given in standards.

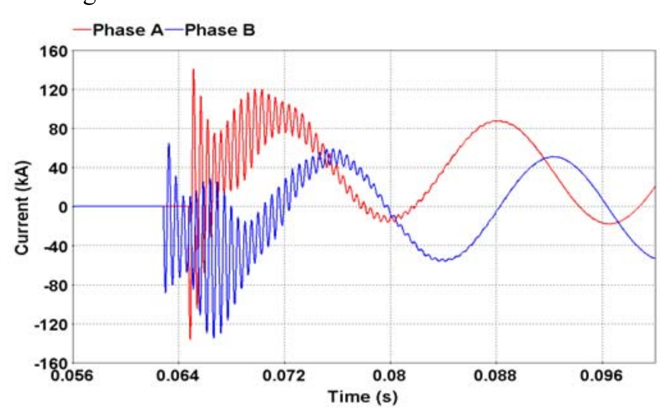

Fig.15 Current observed on phase B and A after a multi-phase reignition

Again, the grounded Wye configuration has been simulated with different values for the damping reactor (1mH, 2mH, 3,5mH and 5mH).

In case of clearing a 3 phases to ground fault, a maximum TRV has been observed also on phase B around 1,38 p.u. independently of the damping reactor size.

A first reignition on phase B give rise to TRV on phases A and C of : respectively 2,17 and 2,24 p.u. in case of 1mH damping reactor, 1,45 and 1,29 p.u. in case of 2 mH and 1,40 and 1,37 p.u. in case of 3,5mH, 1,47 and 1,49 p.u. in case of 5mH. As we see in Figure 16, with 5mH damping reactor the product frequency current still around $6,2\times10^7$ A.Hz the same value obtained for a multiphase reignition in case of ungrounded Wye shunt capacitor bank and the constraint still exceeding the limit value of 2×10^7 A.Hz. for a general purpose CB. Also, the zero crossing was not completely eliminated and two zero crossing were found before the first natural zero crossing.

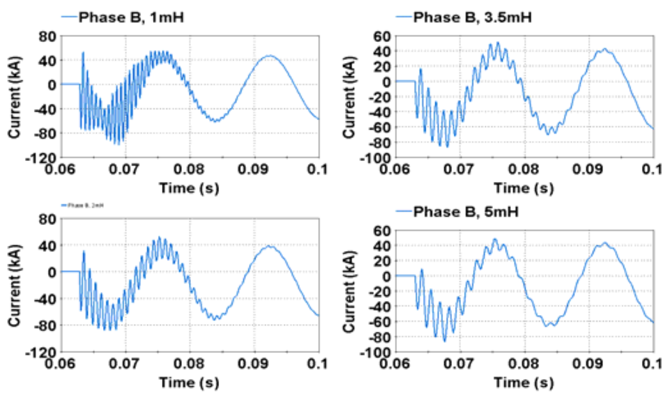

Fig.16 Current observed for different values of damping reactor after a reignition on phase B

With a multi-phase reignition, the simulations show the presence again of the constraints in term of current frequency product and the zero crossing.

B. *Case of 1 phase to ground fault*

In this case we observed as shown in Figure 17 the same TRV obtained in case of ungrounded shunt capacitor bank: a maximum value of 1,47 p.u. on phase A with RRRV less than 0,3 kV/µs.

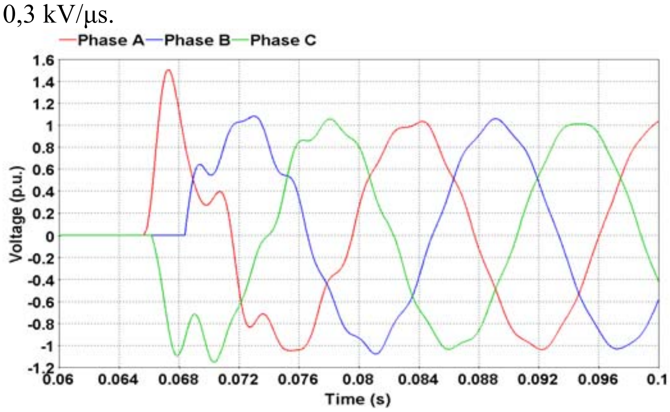

Fig. 17 TRV observed on each phase of the circuit breaker

As shown in the next figure, the transient voltage obtained after a reignition on phase A lead to significantly lower values then those obtained in case of ungrounded shunt capacitor bank. In this case we observed 1,5 p.u. on phase C and 1,3 p.u. on phase B.

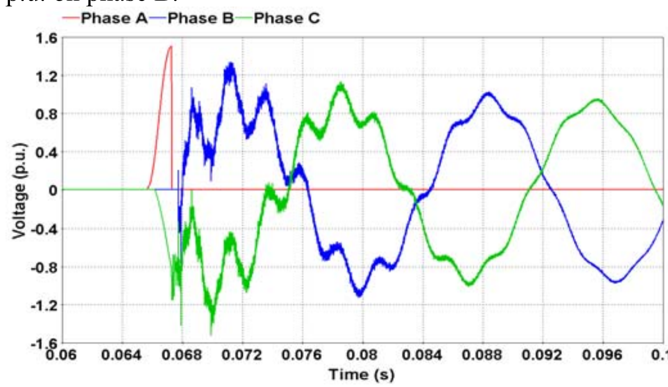

Fig.18 Transient voltage observed on phase C and B of the CB after a reignition on phase A

The next figures 19 and 20 show clearly that in case of a 1 phase to ground fault in presence of grounded capacitor bank, the total current when a reignition occur on a phase is the sum of the source short circuit current and the high frequency current which is the discharge of the shunt capacitor bank. The current in this case has a peak value of 96 kA with a frequency of almost 2 kHz. Also, in case of multi-phase reignition no current is observed on the second phase.

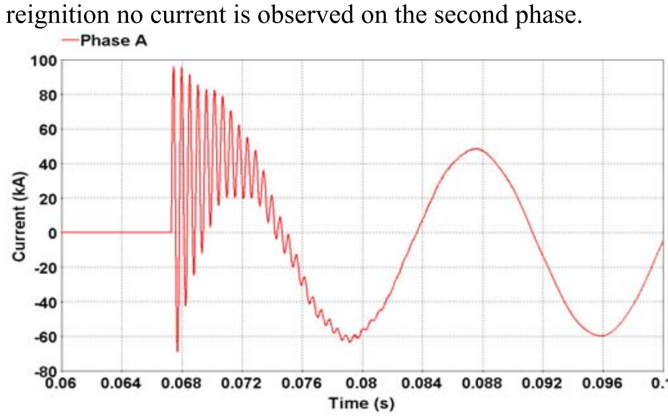

Fig.19 Current observed on phase A after a first reignition

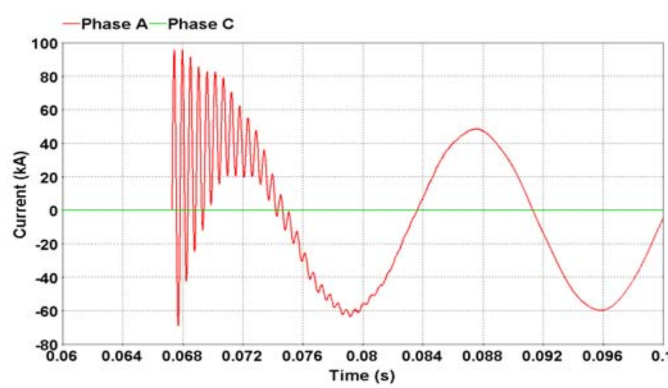

Fig.20 Current observed on phase A and C after a multi-phase reignition

V. GROUNDED WYE CONNECTED SHUNT CAPACITOR BANK WITH VARISTOR IN PARALLEL WITH THE DAMPING REACTOR

It was demonstrated through the simulation in previous sections that, both cases, the ungrounded and the grounded shunt capacitor banks represent an issue for general purpose CB present in a substation and in particular oil circuit breaker because of the severe high frequency current with multiple zero crossing. Also explained is that the high frequency of the current depends mainly on the resonance between the shunt capacitor bank and the damping reactor following formula (1). The zero crossing depend on two parameters, the high frequency of the current and the fact that the current discharge from shunt capacitor bank is higher than the source short circuit current. Inspired by the configuration of filters used in HVDC substation and to overcome the constraint mentioned previously we have decided to put in parallel with the damping reactor a Metal Oxide Varistors (MOV) as shown in Figure 21. When conducting, the varistors will bypass the damping reactor and will partially discharge the capacitor bank through the bus bar impedance. During the conduction period of the varistors, it is expected that the circuit breaker see a very high peak current resulting from the discharge of the shunt capacitor bank and from the source. When the varistors stops conducting, the damping reactor returns in the circuit to discharge the remaining stored energy in the shunt capacitor bank. As explained in the previous paragraphs, since the discharge current (outrush) of the shunt capacitor is much lower than the short circuit current of the source we can predict the elimination of the current zero crossing, and also lower peak current for that period of time.

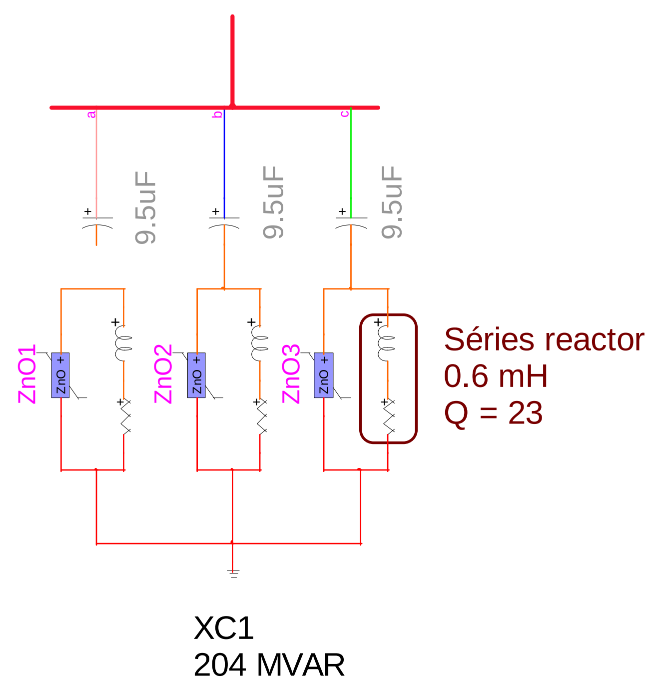

Fig.21 Grounded Wye shunt capacitor bank with MOV in parallel with the damping reactor

A. *Choice of varistors*

The varistors was modeled in EMTP-RV by using data from the buyer guide [7] for high voltage surge arrester. We have started with MCOV of 68 kV and decreased until obtaining satisfactory results in term of eliminating peak high frequency current with multiple zeros crossing. These results will be presented in the next sections.

B. *Case of 3 phases to ground fault*

As we see in Figure 22 and explained in the introduction of this section, the presence of the varistors in parallel with the damping reactor have a great benefit in term of reducing considerably the number of zero crossing and decreasing the number of high peak currents to be seen by the circuit breaker.

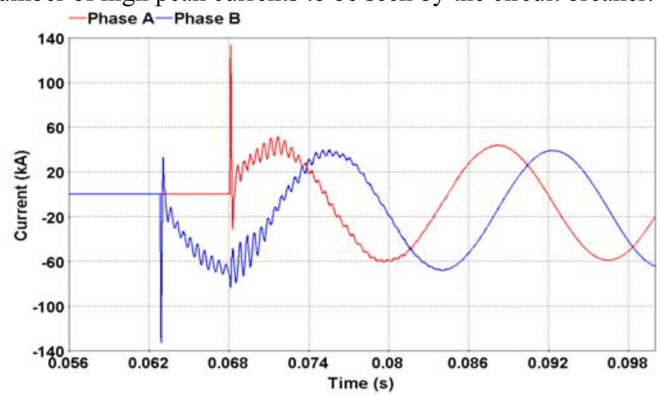

Fig.22 Current observed on phase B and A after a multi-phase reignition

We notice that the first current peaks, which represent the conduction period of the varistors, have zeros crossing with very high di/dt observed, almost 1500 A/µs. we presume that no circuit breaker will attempt to interrupt such a very fast current variation.

The next figures show a comparison between reignition currents for different values of damping reactor. We can clearly see that there is no significant effect on the shape of the current, in terms of peak values and zero crossing, when raising the size of the damping reactor above the value of 0.6mH used in the basic scenario.

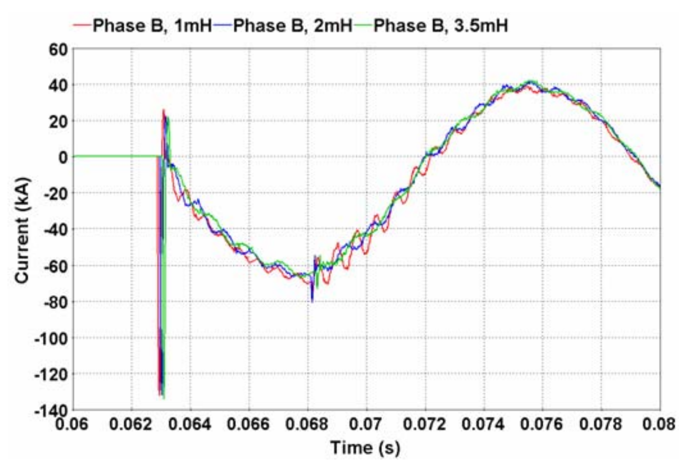

Fig.23 Current observed on phase B after a multi-phase reignition for different values of damping reactor

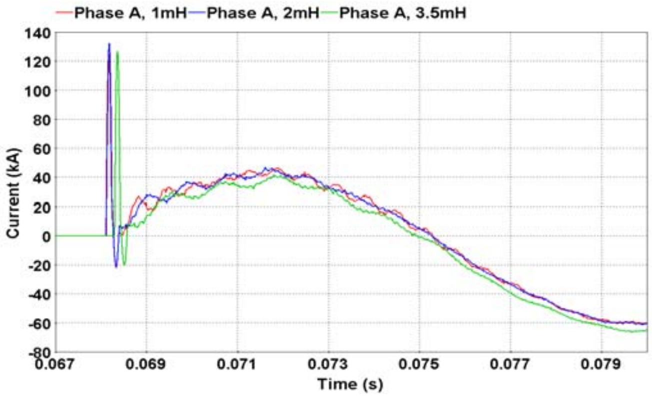

Fig.24 Current observed on phase A after a multi-phase reignition for different values of damping reactor

C. Case of 1 phase to ground fault

In this case the simulation was done with 0.6 mH as a damping reactor. It is easy to predict that the high frequency current will be attenuated and the number of zero crossings will be reduced due to the presence of the varistors in parallel with the damping reactor. Figures 25 and 26 show the shape of the current after a first reignition on the faulted phase.

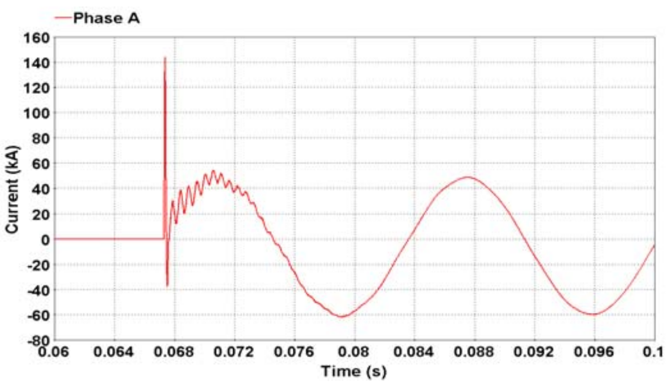

Fig.25 Current observed on phase A after a first reignition

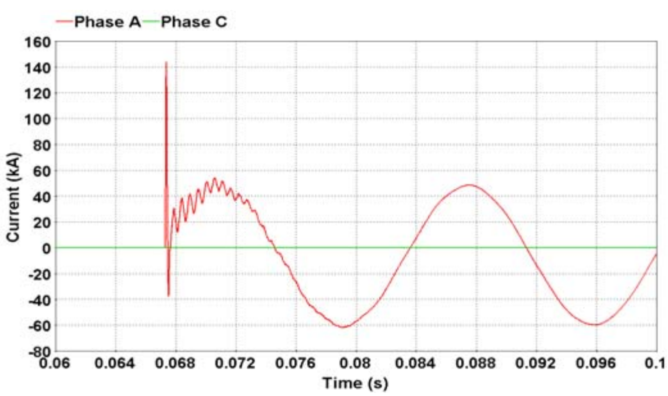

Fig.26 Current observed on phase A and C after a multi-phase reignition

VI. CONCLUSIONS

Transient simulation study was conducted for the purpose of evaluating the impact of the configuration of high voltage shunt capacitor banks on general purpose circuit breakers. In the case of a 3 phases to ground fault, both configurations, grounded and ungrounded shunt capacitor bank represent an issue for some technology of circuit breakers in case of a multi-phase reignition because of the multiple zero crossing and the current frequency product limits expressed in the standards. We have also noticed that even with the increase of the damping reactor size the same issues persist. In case of a reignition for a phase to ground fault we have noticed an advantage for the ungrounded shunt capacitor bank where the high frequency and the multiple crossing zeros quite less.

The configuration with varistors seems to resolve the issue mentioned above where the zero crossing and the high frequency current are considerably reduced. We have noticed also that the use of a bigger damping reactor does not represent an advantage in this configuration. It is important to keep in mind that the constraints explored in this paper could represent a problem for some circuit breaker technology such as the MOCB.

VII. REFERENCES

[1] L. Van der Sluis, A.L.J. Jansen "Clearing faults near shunt capacitor banks" IEEE PES 1990, Atlanta

[2] L. Van der Sluis, A.L.J. Jansen "Controlling the transient currents and overvoltage after the interruption of a fault near shunt capacitor banks" International Conference on Large High Voltage Electric Systems 1988, Paris

[3] A. Sabot, C. Morin, C. Guillaume, A. Pons, J.P. Taisne, G.Lo. Pizzo, H.U. Morf "A unique multipurpose damping circuit for shunt capacitor bank switching" IEEE Transaction on Power Delivery, Vol. 8, No. 3, July 1993

[4] Report by working group 3.4.17 of the IEEE Surge Protective Devices Committee "Impact of shunt capacitor banks on substation surge environment and surge arrester applications"

[5] IEC 62271-100 "High-voltage switchgear and controlgear- Part 100: Alternating-current circuit-breakers"

[6] IEEE C37.06 "AC high-voltage circuit breakers rated on a symmetrical currents basis"

[7] Parafoudres Haute tension, guide de l'acheteur, ABB.

[8] F. Martin, E. Joncquel "Circuit breaker tripping near capacitor banks" CIGRÉ 2006, Paris