Recommended Configuration for High Voltage Shunt Capacitor Banks

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***Abstract*— High voltage shunt capacitor banks (SCB) are widely used on power systems. The installation of shunt capacitor banks has beneficial effects such as the voltage regulation and the reduction of the losses of active power to be transmitted. At the same time, the presence of shunt capacitor banks impose constraints on apparatus present in a substation [1,2]. Currently, no specific configuration of shunt capacitor bank is recommended, grounded and ungrounded shunt capacitor banks can exist on the same transmission system. In this paper we will explore different configurations of shunt capacitor banks, the advantages and disadvantages of each configuration and we will recommend one which attenuates or completely eliminates some of the known constraints imposed by the presence of shunt capacitor banks in a substation.**

***Keywords*: Shunt capacitor bank (SCB), Outrush current, High frequency current, Circuit breaker (CB), Reignition, Damping reactor, Grounding, Transients, Transient recovery voltage (TRV), Rate of rise of recovery voltage (RRRV), Metal oxide varistor (MOV), Power System, EMTP-RV.**

I. Introduction

On the Hydro-Québec transmission system, high voltage shunt capacitor banks represent more than 12000 MVAR distributed mainly over four levels of transmission system voltages : 69kV, 120kV, 230kV and 315kV. The size of individual SCB varies between 8 MVAR on the 69kV level to 384 MVAR on the 315 kV level. Most of these shunt capacitor banks are ungrounded except for the 315kV level where all banks are grounded to reduce the insulation level of the shunt capacitor bank neutral and also to reduce the recovery voltage (RV) constraint on the circuit breaker of the shunt capacitor bank when opening. An internal study was conducted to recommend a common configuration for all high voltage shunt capacitor banks.

II. High Voltage Shunt Capacitor Bank Configurations Under Study

The main shunt capacitor bank configurations considered in the study as shown in Fig. 1 were :

- Ungrounded wye connected shunt capacitor bank;
- Grounded wye connected shunt capacitor bank;
- Grounded wye connected shunt capacitor bank with metal oxide varistor (MOV) in parallel with the damping reactor.

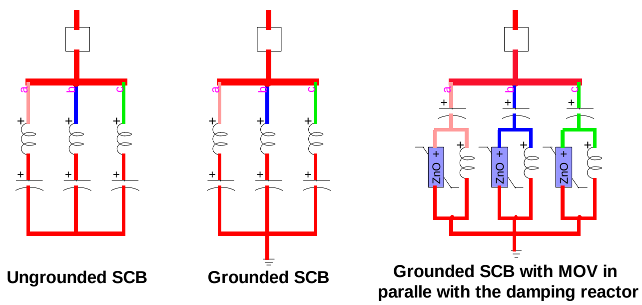

Fig. 1 Configurations of shunt capacitor banks under study

The third configuration is inspired from filter configuration used in HVDC substation and it was the subject of a publication were impact of high voltage shunt capacitor banks on general purpose circuit breaker was investigated in details and a preliminary solution was proposed [1].

III. Scenario Description

We have chosen a 230 kV substation as a scenario. Fig. 2 illustrates the EMTP-RV equivalent circuit of a 230 kV substation which is equipped with three shunt capacitor banks of 204 MVAR each.

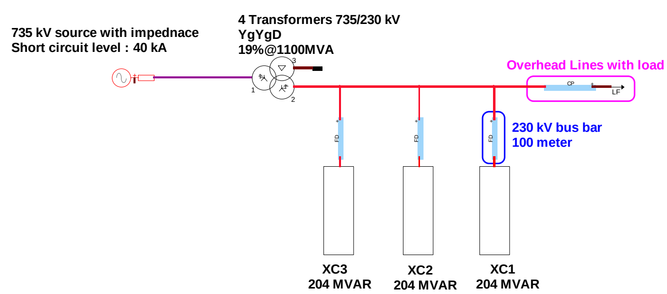

Fig. 2 EMTP-RV equivalent circuit of a 230 kV substation equipped with 3 shunt capacitor banks

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

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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.

IV. Constraints to be Considered to Choose the Appropriate Configuration of Shunt Capacitor Banks

For the previous mentioned configurations of shunt capacitor banks the following constraints will be explored to determine the impact and severity of each one and to help to chose the most appropriate configuration.

A. High frequency (HF) current and impact on general purpose circuit breakers (Line and bus bar CB)

A constraint that is currently not seriously considered in the presence of shunt capacitor banks in a substation is the capability of a general purpose circuit breaker to support without any damage a high frequency (HF) current with multiple zeros crossing in case of reignition during the interruption of a fault [1]. The HF current in this case is the sum of the short circuit current of the source and the current discharge of the shunt capacitor bank (outrush). These high current and frequency values creates a hydrodynamic choc wave, which represent a mechanical constraint especially for oil circuit breakers. Also not to neglect the amount of energy available in this HF current and the impact that could have on the switching device. Furthermore, any attempt of interruption at each zero crossing of the HF current for some technologies of circuit breaker can lead to a voltage escalation following each unsuccessful interruption attempt [2,3]; a situation that in the worst case can result in the destruction of the circuit breaker. This particular duty, HF current, can exceed largely the applicable circuit breakers standards [4,5]. Test current and frequency recommended values according to standards, equivalent product $\hat{I}\times f$, are for a total limit of 2×10^7 A.Hz. for general purpose circuit breakers.

B. Recovery Voltage (RV) duty of the shunt capacitor bank circuit breaker

The recovery voltage (RV) duty of the shunt capacitor bank circuit breaker when switching under normal or faulted conditions depends on the configuration, grounded or ungrounded SCB; choosing an appropriate configuration will reduce significantly the RV stress on the circuit breaker.

C. Location of the damping reactor in the configuration

In the case of back to back switching, a damping reactor is normally used to reduce the inrush current during the energization of a shunt capacitor bank. This damping reactor is generally located between the circuit breaker and the shunt capacitor bank. A circuit breaker failure was documented when trying to clear a fault between the series reactor and the capacitor because of a high rate of rise of recovery voltage (RRRV) exceeding largely the duty test of the shunt capacitor bank circuit breaker [6]. This high RRRV is due to the natural frequency of the damping reactor. The location of the damping reactor in the recommended configuration of the shunt capacitor bank should be considered to avoid the installation of an attenuation component.

D. Injection of high frequency current to the grounding grid of the substation

Whether in the case of a phase to ground fault, three phase to ground fault, back to back switching or a circuit breaker reignition and depending on the configuration of the shunt capacitor banks, a high frequency current can be injected to the grounding grid of the substation. This high frequency current could be an issue because of the electromagnetic coupling between the grounding grid of the substation and the protection/control circuits which may create interference and potential failure of these circuits.

E. Evolution of a phase to neutral fault on the shunt capacitor bank to a three phase fault

Depending on the configuration of the shunt capacitor bank, a phase to neutral fault (phase flashover of the shunt capacitor due to insufficient insulation of units, pollution, ice,…) on the shunt capacitor can evolve or not to a three phase fault.

F. Insulation level of the shunt capacitor bank neutral

As mentioned in the introduction, one of the reason why the 315kV level shunt capacitor banks are grounded was to reduce the cost associated to the insulation level of the neutral of the SCB. To note that the cost related to the insulation level of the SCB neutral is more significant for higher voltage SCB i.e. 315kV and 230 kV and less significant for lower voltage levels as the 161kV, 120kV and 69 kV.

V. Case of Ungrounded Wye Connected SCB

A. Constraint of HF current and impact on general purpose circuit breakers (Line and bus bar CB)

In the case of three phase to ground fault with a multi-phase reignition on the peak transient recovery voltage (TRV) of each phase, a severe HF currents with multiple zeros crossing were found to be far beyond the values given in applicable standards [1]. The results of simulation show clearly, see Fig.3, a peak value of 90 kA for phase A and 110 kA for phase C with a frequency of almost 2 kHz for a total constraint of 18×10^7 A.Hz. and 22×10^7 A.Hz. respectively. These values are far beyond the standards limit of 2×10^7 A.Hz.

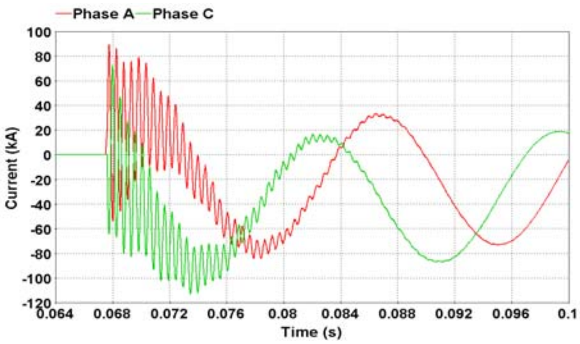

Fig.3 Current observed on phase A and C after a multi-phase reignition

As we know, the size of the damping reactor has an important impact on the frequency and the amplitude of the discharge current (outrush). We have made the same simulation with higher values for damping reactor: 1mH, 2mH, 3,5mH and 5mH; even with a 5 mH damping reactor we obtain a product of frequency current in the order of $6{,}2\times10^{7}$A.Hz. which is a lot more higher than the limit of 2×10^{7}A.Hz. Also the current zeros crossing were not completely eliminated. Furthermore, increasing the size of the damping reactor without completely eliminating the zero crossing is not beneficial considering that the di/dt will be much lower and consequently it will increase the probability that some technology of circuit breaker will attempt more easily to interrupt a zero crossing current [1].

In the case of single phase to ground fault and as shown in Fig. 4, the peak value of the current is 70 kA with a frequency of 700 Hz for a reignition on the peak TRV of the faulted phase.

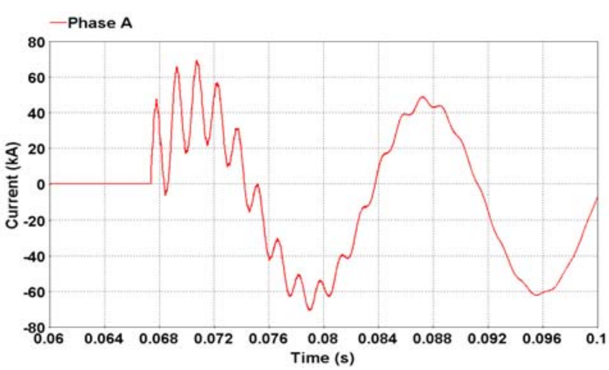

Fig.4 Current observed on the faulted phase after a reignition

Also in this case the product of current and frequency still exceeding the standards limit with two zero crossing.

B. Recovery Voltage (RV) duty of the shunt capacitor bank circuit breaker

The recovery voltage (RV) duty of the shunt capacitor bank circuit breaker when switching an ungrounded shunt capacitor bank in normal condition depends mainly on the non-simultaneity of contact separation in the different poles. The maximum value of RV is a 3 p.u. of the system voltage. In case of switching a SCB under faulted condition the RV depends on the sequence in which the three phase interrupt and on the non-simultaneity of contact separation. A maximum RV of 3,45 p.u. of the system voltage can be obtained in case of phase to neutral fault [2,7,8].

C. Location of the damping reactor in the configuration

In this case we have considered a damping reactor of 0.6mH located between the SCB and the circuit breaker as shown in Fig.1. Field measurement [9] have revealed that the natural frequency of the damping reactor is around 450kHz. When the circuit breaker clear a fault between the SCB and the damping reactor, we observe a front wave created by the damping reactor with a rate of rise of recovery voltage (RRRV) in the order of 21kV/µsec as shown in Fig. 5.

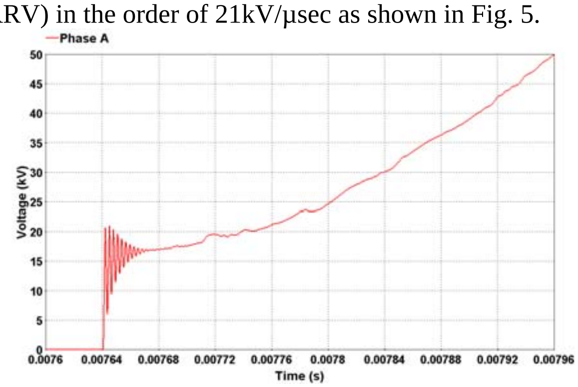

Fig.5 Front wave created by the damping reactor

This value of RRRV in reference to a short line fault (CLF) requirement in IEC standard [2] exceed largely the test duty value of 8.6kV/µsec for a 230kV circuit breaker with a short circuit capacity of 40kA. Therefore, a 3 nF choc capacitor is required between the damping reactor and the circuit breaker to reduce the RRRV to an acceptable value of 5,4 kV/µsec for a CB tested for CLF.

D. Injection of high frequency current to the grounding grid of the substation

This constraint is not applicable in the case of ungrounded shunt capacitor bank.

E. Evolution of a phase to neutral fault on the shunt capacitor bank to a three phase fault

In case of a flashover on a phase to the neutral of the SCB (insufficient insulation level of units, pollution, ice,…) the other phases will see respectively a voltage of 1,73 p.u. leading to biphase and three phase fault.

F. Insulation level of the shunt capacitor bank neutral

Since the shunt capacitor bank is ungrounded the neutral should be fully insulated. In this case and for a 230kV system the basic impulse insulation level (BIL) of the neutral should be of 950 kV.

VI. CASE OF GROUNDED WYE CONNECTED SCB

A. Constraint of HF current and impact on general purpose circuit breakers (Line and bus bar CB)

For a multi-phase reignition following a three phase to ground fault clearing and with a grounded SCB the HF currents are more severe. The simulation results show a peak values of 140kA on phase A and 135kA on phase B with a frequency of 2kHZ with multiple zeros crossing (see Fig. 6). The total constraint $\hat{I}\times f$ is around 28×10^7 A.Hz. which is far beyond the standards limit of 2×10^7 A.Hz.

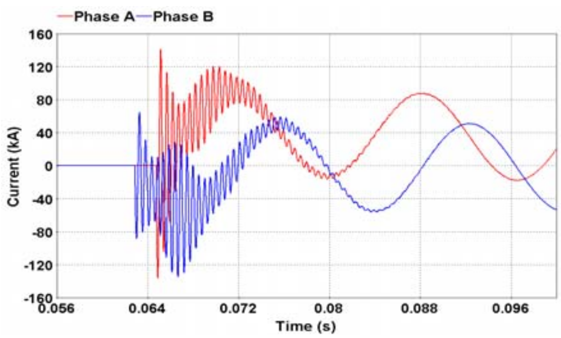

Fig.6 Current observed on phase A and C after a multi-phase reignition

In the case of one phase to ground fault and as shown in Fig.7, the total $\hat{I}\times f$ constraint is around 19×10^7A.Hz. for a reignition on the peak TRV of the faulted phase.

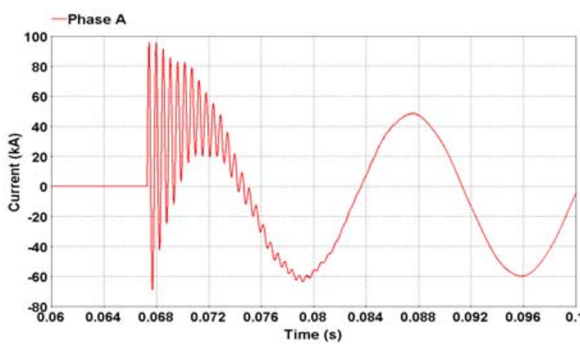

Fig.7 Current observed on the faulted phase after a reignition

Also in this case the product of current and frequency still largely exceeding the standards limit with multiple zeros crossing.

B. Recovery Voltage (RV) duty of the shunt capacitor bank circuit breaker

When the current is interrupted following a switching of a grounded shunt capacitor bank in normal condition, a peak voltage is trapped in the capacitor; a half cycle later the voltage between the contact will rise to 2 p.u. of the system voltage. In the case of switching SCB under faulted condition the RV is 2,8 p.u. of the system voltage [2,7,8].

C. Location of the damping reactor in the configuration

This constraint as mentioned before is independent from the grounding or not of the SCB; it depends mainly on the location of the damping reactor in the configuration. Since the damping reactor is located at the same position for both ungrounded and grounded SCB, the results obtained for an ungrounded SCB (see section V- C) still valid for a grounded SCB.

D. Injection of high frequency current to the grounding grid of the substation

With a grounded SCB it was observed that the most severe total HF current injected to the grounding grid of a substation is in the case of three phase to ground fault. This high frequency current is the sum of the contribution of each shunt capacitor bank. As shown in Fig. 8 we observe in case of three phase to ground fault a total injection to the grounding grid of 105kA. It is of note that a statistical study in EMTP-RV was used to determine the worst case (by varying the time application of the fault).

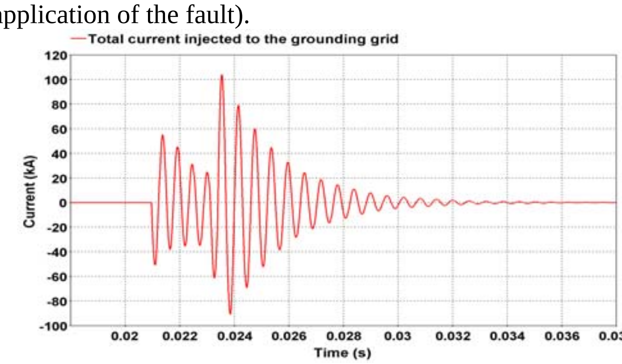

Fig.8 Total HF current injected to the grounding grid in case of three phase to ground fault

E. Evolution of a phase to neutral fault on the shunt capacitor bank to three phase fault

The possibility of evolution of a phase to neutral fault on the shunt capacitor to three phase fault is decreased in the case of a grounded shunt capacitor bank because the maximum voltage that will be seen by the other phases is around 1,40 p.u. compared to 1,73 p.u. in the case of ungrounded shunt capacitor bank.

F. Insulation level of the shunt capacitor bank neutral

Since the shunt capacitor bank is grounded the neutral will be at minimum insulation; a BIL of 95kV is sufficient.

VII. CASE OF GROUNDED WYE CONNECTED SCB WITH MOV IN PARALLEL WITH THE DAMPING REACTOR

It was demonstrated through simulations in the previous sections that, both configurations, ungrounded and grounded SCB represent particularly an issue for general purpose CB present in a substation because of the severe high frequency current with multiple zeros crossing in case of a reignition during fault interruption. Inspired by the configuration of filters used in HVDC substation and to overcome the constraints mentioned previously, a metal oxide varistor (MOV) as shown in Fig.1 in parallel with the damping reactor was studied. Also, the location of the damping reactor/MOV in the configuration was carefully chosen to attenuate or eliminate some of the already mentioned constraint.

A. Constraint of HF current and impact on general purpose circuit breakers (Line and bus bar CB)

In the proposed configuration the varistor will bypass the damping reactor and will partially discharge the capacitor bank through the bus bar impedance. When the varistor stops conducting, the damping reactor returns in the circuit to discharge the remaining stored energy in the shunt capacitor bank. 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 zeros crossing, and also lower peak current for that period of time.

The best result in term of eliminating peak high frequency current with multiple zeros crossing was obtained with a maximum continuous operation voltage (MCOV) of 24 kV. Fig. 9 show the results for a multi-phase reignition on phases A and B after clearing a three phase to ground fault. We notice that the first current peaks (155kA on phase A and 110kA on phase B), which represent the conduction period of the varistor, have zeros crossing with very high di/dt, almost 1000A/µsec. We presume that no circuit breaker will attempt to interrupt such a very fast current variation.

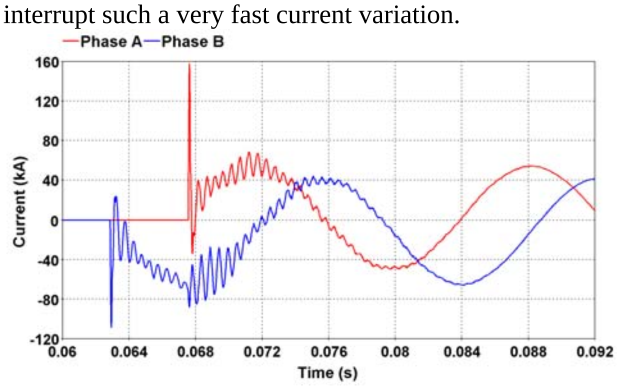

Fig.9 Current observed on phase A and B after a multi-phase reignition

In order to reduce the first high peak current and to completely eliminates the current zero crossing we have pushed the simulation to find the best combination of damping reactor/MOV. Fig.10 shows the results obtained for a damping reactor of 3,5 mH where the first peak current was considerably reduced on phase A (105kA) and zero crossing were completely eliminated on both phases.

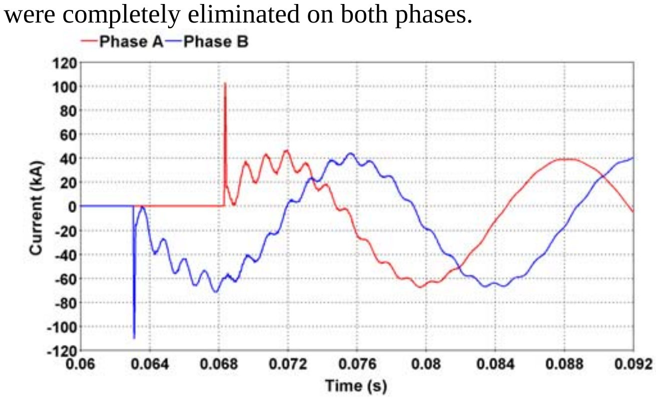

Fig.10 Current observed on phase A and B after a multi-phase reignition with a damping reactor of 3,5 mH

As we know the scenario as described in section III used in the simulations is very pessimistic and do not represent the real impedance between shunt capacitor banks in a substation. So, we have represented in EMTP-RV the substation with the real distance of bus bar between the shunt capacitor banks as shown in Fig.11.

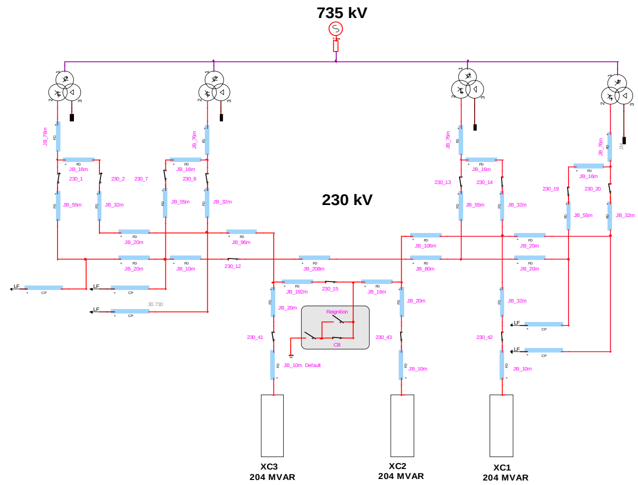

Fig.11a) A realistic representation of bus bar impedance between SCB

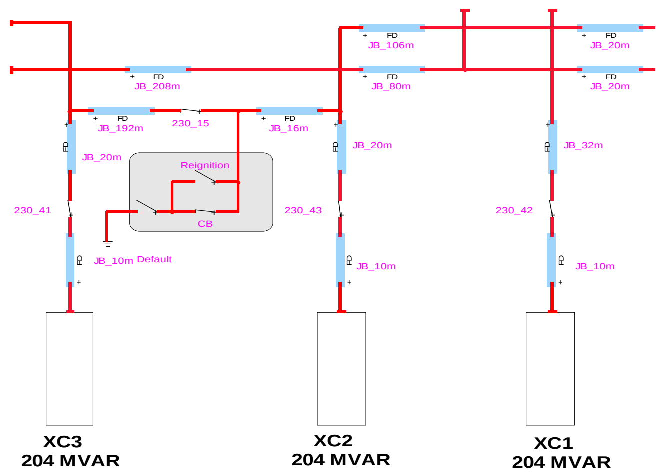

Fig.11b) A realistic representation of bus bar impedance between SCB

Fig.12 shows the result of simulation with more realistic representation of bus bar impedance between the shunt capacitor banks. We observe more reduction of the amplitude of the first peak, a maximum peak value of 85kA on phase B during the conduction of the MOV with the absence of zeros crossing.

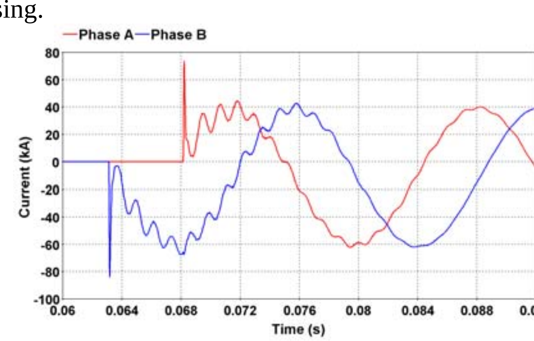

Fig.12 Current observed on phase A and B after a multi-phase reignition with a realistic representation of bus bar impedance between shunt capacitor banks

B. Recovery Voltage (RV) duty of the shunt capacitor bank circuit breaker

The recovery voltage (RV) duty of the shunt capacitor bank circuit breaker are the same of those of grounded SCB as explained in section VI-B.

C. Location of the damping reactor in the configuration

This configuration with the damping reactor located at the low voltage of the SCB, as shown in figure 1, eliminate completely the problem associated to this constraint as explained in section IV-C.

D. Injection of high frequency current to the grounding grid of the substation

With this configuration, the total HF current injected to the grounding grid in case of three phase to ground fault is less severe then the one in the previous case i.e grounded SCB. With a statistical studies in EMTP-RV (to obtain the worst case) we observe as shown in Fig.13 two peaks; the first one of 54 kA and the second one of 70 kA for a very short period (less then 150µsec) and they decrease to less then 20 kA rapidly.

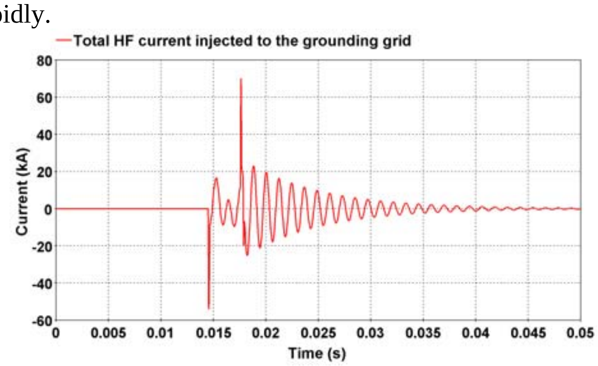

Fig.13 Total HF current injected to the grounding grid in case of three phase to ground fault

The sections of the grounding grid of the substation where SCB are installed are densely meshed with a multipoint connection to the rest of the grounding grid of the substation. This is mean that if there is electromagnetic coupling between the grounding grid of the substation and protection/control circuit, it will happen in presence of mush lower HF current. Each SCB, in this case, inject one third of the total HF current observed in figure 13 and it will split into the mashed grid to smaller values of current.

E. Evolution of a phase to neutral fault on the shunt capacitor bank to three phase fault

Again, the possibility of evolution of a phase to neutral fault on the shunt capacitor bank to three phase fault as explained previously for a grounded shunt capacitor banks is decreased also for this configuration.

F. Insulation level of the shunt capacitor bank neutral

Since the shunt capacitor bank is grounded, the neutral will be at minimum insulation and a BIL of 95kV is sufficient. The insulation of the damping reactor will be much lower then the two previous configurations. Because the damping reactor is located in parallel with the MOV for this configuration, both will have the same insulation level.

VIII. Results obtained for SCB connected to 315kV, 120kV and 69 kV voltage level system

With the investigation done for several configurations of SCB for the 230 kV voltage level in the previous sections, it was clearly demonstrated that the third configuration i.e. wye connected SCB with MOV in parallel with the damping reactor is an appropriate choice. Furthermore, the combination of a damping reactor of 3,5mH and a MOV of 24kV of MCOV found to be a solution for the HF current constraint not only for 230kV voltage level but also a common solution for all other voltage level. It is clear that a particular attention should be given to the energy absorbed by the MOV depending on the worst event, the size of the SCB and the voltage level.

IX. Conclusions

A study based on transient simulation was conducted to determine and recommend a common configuration for high voltage shunt capacitor banks. It was demonstrated that both configurations grounded and ungrounded SCB represent an issue for CB because of HF current. We have proposed a configuration consisting of a higher value for the damping reactor (3,5mH) with a MOV in parallel (MCOV of 24 kV). The proposed configuration resolve the problem associated to HF current and at the same time eliminates/attenuates other constraints:

- Considerably attenuate the high frequency current injection to the grounding grid of the substation in case of three phase to ground fault;
- Reduce the RV constraint on the SCB circuit breaker;
- Eliminate the RRRV constraint on the SCB circuit breaker related to the location of the damping reactor in the configuration;
- Reduce the insulation level of the SCB neutral;
- Eliminate the possibility that a phase fault on the SCB evolve to a three phase fault.

X. References

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