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Performance Improvement of Line Commutated Converter based HVDC using STATCOM

Karthikeyan K, Lekshman K G, Malaya Sahoo
Grid system R&D,
ABB Global Industries and Services Limited,
Chennai, India

Suman Maiti
Department of Electrical Engineering,
IIT Kharagpur, India

***Abstract* — Line commutated converter (LCC) along with passive compensation system is widely used for high voltage direct current (HVDC) power transmission. The LCC with only passive compensation has many limitations such as commutation failure, fault ride-through and over-voltage during filter or capacitor bank switching when the ac grid is very weak. In this paper, a hybrid HVDC system is considered to overcome the inherent limitations of LCC based HVDC system. The hybrid HVDC system consists of a low rated VSC which is operating as static compensator (STATCOM) along with the existing LCC. The STATCOM is connected at the ac side of the inverter station. The performance improvement of LCC using the STATCOM is investigated.**

Keywords—LCC; HVDC; weak grid; fault recovery; STATCOM; VSC;

LIST OF SYMBOLS

LCC	Line commutated converter
VSC	Voltage source converter
HVDC	High voltage direct current
STATCOM	Static compensator
P_{LCC}	Active power associated to LCC
Q_{STAT}	Reactive power support from the STATCOM
Q_{filter}	Reactive power support from the passive system
Q_{ex}	Reactive power exchage with the grid and LCC
Q_{LCC}	Reactive power associated to LCC
V_{PCC}	Voltage at PCC

I. INTRODUCTION

Generally LCC based HVDC transmission is considered for transmitting the bulk power over a long distance. Thyristor technology which is used in LCC has inherent advantages such as rugged in construction, lower ON state loss, simple series connection, short time over-rating capability, higher power rating and lower cost. However, it has the following drawbacks

- Requirement of additional reactive power support and harmonic filtering
- Commutation failure at inverter station when the ac grid is weak
- Poor ac fault recovery
- No black start capability
- Need of larger foot-print, and
- Over-voltage at point of common coupling (PCC) during the switching of filter/capacitor banks.

The afore-said limitations can be overcome to some extent with the help of a hybrid configuration which consists of an LCC and a STATCOM. The STATCOM provides voltage support during transient conditions through faster reactive power compensation. Different configurations the hybrid HVDC system has been proposed in literatures. In [1], the hybrid configuration is used in the offshore wind power platform of the HVDC link. The LCC at the offshore station needs black start capability. Here, the STATCOM is used to support black start by providing necessary commutation voltage. In [2], HVDC link is formed using VSC at the offshore station and LCC at onshore station.

In this paper, the performance improvement of LCC using the STATCOM is presented. The emphasis is given on the reduction of over-voltage during switching of passive filters and capacitor banks. Also, the mitigation of dynamic voltage over-shoot during ac fault recovery with the help of STATCOM is addressed.

The paper is organized into seven sections. Introduction is given in section I. The section II describes the conventional LCC based HVDC transmission system. In section III, the configuration of hybrid-HVDC system is presented. Section IV and section V deal with the filter configuration without and with STATCOM respectively. Fault recovery using STATCOM is presented in section VI and conclusions are drawn in section VII.

II. THE CONVENTIONAL LCC BASED HVDC SYSTEM

A. ha

The conventional HVDC transmission system consists of two converter stations (one at sending end and the other at receiving end). Each converter station has a 12-pulse thyristor based LCC which is formed by two six pulse Graetz converter bridges. The 12-pulse converter requires 30^0 phase angle difference between line-voltages at the converter side and the same is obtained from through star-star and star-delta transformer connections. The 12-pulse converter at sending end is operating as a rectifier and the receiving end as inverter. Generally, these converters are operating at a minimum firing ($\alpha=15^0\pm2.5^0$) and extinction angle ($\gamma\approx17^0$) to achieve minimum reactive power consumption from the grid. The reactive power exchange (Q_{ex}) between LCC and ac grid should stay within the specified limit. Hence, the additional reactive power requirement of the converters will be supplied through tuned passive filters and capacitor banks.

The 12-pulse converter generates the current harmonics of order $12n\pm1$, where n = 1, 2, 3…. It is observed that 11th, 13th, 23rd and 25th harmonics are dominating in the converter current at ac grid side. In order to achieve better power quality, these harmonics have to be filtered out and prevented from entering into the grid. This demands the use of tuned passive filters at both the converter stations. Hence, in addition to the reactive power support, additional harmonic filtering also needs to be provided. Smoothing reactors are connected in series with the DC line to reduce current ripples the converter current.

B. *Commutation Failure and Fault Ride Through Capability of the LCC-HVDC System*

The inability to complete commutation of a thyristor valve before the commutation voltage reverses its polarity is known as commutation failure. Commutation failure occurs when there is not enough voltage-second area in the commutating voltage. Hence, the converter at the inverter station (operates at a firing angle close to 180^0) is more prone to commutation failure than the converter at rectifier station. Higher dc link current can also cause commutation failure [3]. Hence, the possibility to occur commutation failure is high in the case of transient conditions (such as AC faults), where the operating conditions are suddenly changed due to fault. Commutation failures can be detrimental to the HVDC system as it causes a virtual short circuit in the DC link. The commutation failure and multiple commutation failures can be prevented by providing sufficient reactive power support which improves the voltage profile of the PCC.

The recovery from an AC fault is also important for the LCC based HVDC systems. The reduction of recovery time and dynamic overvoltage during fault recovery can be possible by fast reactive power compensation system, e.g. STATCOM.

C. *Limitations of Passive Compensation for LCC based HVDC Systems*

The capacitor banks and passive filters are used to meet the steady state reactive power requirement and filtering of LCC generated current harmonics. The general disadvantages of passive filters are detuning due to ageing and resonance with source impedance under the presence of background harmonics. Apart from this, the passive filters/capacitor banks cause overvoltage during switching and do not provide sufficient reactive power during fault at PCC.

III. THE HYBRID HVDC SYSTEM MODEL

The system under study consists of a modified CIGRE bench mark HVDC model [4] with passive compensation system and IGBT based STATCOM. The STATCOM connected at the inverter end provides the reactive power support. The STATCOM can also perform active filtering for the LCC generated current harmonics. The LCC along with STATCOM is addressed in this paper as a “Hybrid HVDC System”. The block diagram representation of the model under study is shown in **Error! Reference source not found.**. The entire system is modelled in PSCAD/EMTDC simulation tool.

A. *The Grid*

The grid is modeled as an ideal voltage source connected through an impedance having an *X/R* ratio of 5 and short circuit ratio (SCR) of 50 at the rectifier side. Whereas, the inverter side is connected to a very weak AC system with a SCR of 2. The various harmonic frequencies (mainly 5th, 7th, 9th and 11th) are also taken into consideration [6] while modeling of AC system at inverter side. The rated ac side voltage is taken as 410kV at 50Hz.

B. *The LCC- HVDC Model*

In the study, an 800 MW LCC based mono-polar HVDC system has been considered. The nominal dc link voltage of the HVDC system is 520 kV [4]. It requires 420 MVAr reactive power support which is supplied through the passive components. In the passive compensation system, 220 MVAr is allotted to tuned passive filters and 200 MVAr to capacitor banks. Each unit of passive filter (110MVAr) comprises of one doubly tuned filter (55MVAr) and one high pass filter (55MVAr). The filter or capacitor bank is switched-in/out whenever either the reactive power exchange between the grid and the converter station is exceeded the limit (which is ±65 MVAr) or the grid voltage goes beyond the band (upper limit is 420 kV and the lower limit is 395 kV). The rectifier normally works in constant current control mode and the inverter operates in constant extinction angle control mode. The VDCOL control is enabled to transfer power even at very low voltages during faults.

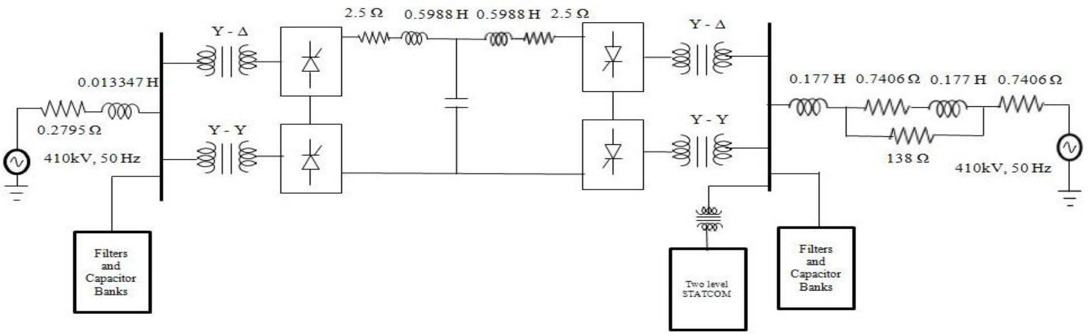

Fig. 1. LCC model with a STATCOM connected at the inverter end.

C. *The STATCOM*

The STATCOM is modeled as a two level voltage source converter (VSC) connected to the grid using a coupling transformer. Maximum rating of the STATCOM is 100 MVA, with a peak line current of 2.1 kA. The STATCOM is connected to the grid through a 100 MVA transformer (Y-Y connection) with voltage ratings of 410/39 kV. Sine-triangle PWM method with a switching frequency of 10 kHz is used for generating switching pulses. The dc link capacitor of the STATCOM is rated at 90 kV with energy rating of 891kJ. The decoupled vector control is implemented for the independent control of active and reactive power output of the STATCOM [5]. The *d*-axis voltage under steady state is chosen to be in phase with the grid voltage vector such that by controlling i_d, the active power flow can be varied and by controlling i_q, the reactive power output can be regulated. The DC-link voltage is maintained by the control of i_d , where the d-axis current reference (i_d^*) is generated from the error of DC link voltages using a PI controller. The reactive power generation/absorption is controlled by an AC voltage regulation loop, which generates the reference *q*-axis current (i_q^*). The *d*-axis and *q*-axis voltage equations which governs the dynamics of STATCOM are given in (1) and (2) respectively.

$$e_d = Ri_d + L\frac{di_d}{dt} - L\omega i_q + v_d \tag{1}$$

$$e_q = Ri_q + L\frac{di_q}{dt} + L\omega i_d + v_q \tag{2}$$

where, v_d , v_q are the *d*-axis and *q*-axis components of the grid voltage (v_{grid}) scaled by the turns ratio of the transformer. e_d , e_q are the *d*-axis and *q*-axis components of the STATCOM generated voltages behind the leakage impedance of the transformer. *R*, *L* are the resistance and leakage inductance of the coupling transformer which comes in between converter terminals and PCC.

The term $Ri_d + L\,di_d/dt$ of (1) is generated by the d-axis PI controller and the rest of the term, i.e. $-L\omega i_q + v_d$ is supplied as feed-forward signal. Similarly, $Ri_q + L\,di_q/dt$ is generated by the q-axis PI controller and $L\omega i_d + v_q$ is provided as feed-forward signal. The block diagram representation for the implementation of the decoupled vector controller is shown in Fig. 2. The i_q^* of Fig. 2 is either generated by the AC voltage regulator or computed from the reactive power reference following (3).

$$Q_{ref} = \frac{3}{2} v_d i_q \tag{3}$$

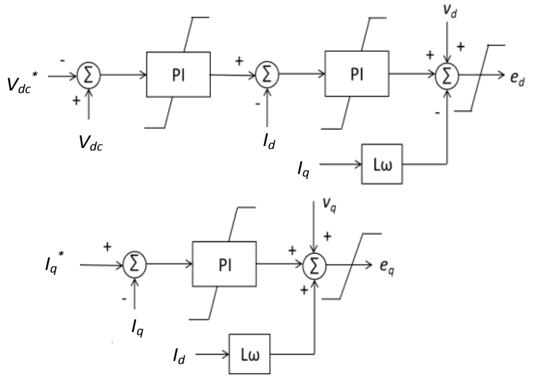

Fig. 2. Decoupled Control of STATCOM.

IV. FILTER CONFIGURATION WITHOUT STATCOM

The size of the filter/capacitor bank is presented in this section for a weak grid with an SCR of 2 without STATCOM. The change in PCC voltage (ΔV) during switching of filter/capacitor bank can be calculated using the following formula (4).

$$\Delta V = \frac{Q_{filter\,new}}{(S_{sc} - Q_{total})} \tag{4}$$

Where $Q_{filter\ new}$ is the reactive power of the newly added filter/capacitor bank, S_{sc} is the short circuit capacity of the grid where the filter/capacitor bank is connected and Q_{total} is the total amount of the reactive power after the addition of a new filter/capacitor bank. Two configurations of filter/capacitor banks are proposed in the subsequent sections considering the maximum allowable fluctuation of PCC voltage during filter/capacitor bank switching is 5%.

A. *Filter/Capacitor Bank Configuration - I*

If the step change in the voltage is limited to 5% for the system with SCR of 2, the maximum size of the filter/capacitor bank is computed as 54 MVAR. As discussed in III.B, the number of filter banks are four (220/54 which is approximately equal to 4) of 54 MVAr and the number of capacitor banks are also four of 50 MVAr. The 54 MVAr filter bank is realized with high pass filter of 27 MVAr and the double tuned filter of 27 MVAr in order to meet the harmonic requirements of the LCC. The total amount of reactive power output from the 8 units of filter and capacitor banks is 416 MVAr (i.e. 54x4+50x4=416 MVAr) which is close to 420 MVAr. The absolute minimum filter has now become 54 MVAr and the total number of switching points are 7. The RMS line to line voltage at the PCC point, the reactive power absorbed by the LCC, the reactive power supplied by the passive compensation system and the reactive power exchanged with the grid for the aforementioned filter/capacitor configuration are shown in Fig. 3.

It is observed from the Fig. 4 that with 54 MVAr filter banks and 50 MVAr capacitor banks, the maximum over voltage due to switching is only 2 %. However, the no load voltage is 421.5 kV which is still above allowable limit of 420 kV. Hence, if the reactors are not used to absorb the additional reactive power at no load, the absolute minimum filter has to be resized.

B. *Filter/Capacitor Bank Configuration - II*

In order to address the issue discussed in IV-A, the number of filter steps could be increased. The allotted filter reactive power of 220 VAr could be split into five filter banks where each unit is rated for 44 MVAr. The reactive power compensation of capacitor banks is kept unchanged. Therefore, the total amount of reactive power supplied by the 9 units of filter and capacitor banks is 420 MVAr (i.e. 44x5+50x4=416 MVAr). The RMS line to line voltage at the PCC point, the reactive power absorbed by the LCC, the reactive power supplied by the passive compensation system and the reactive power exchanged with the grid for the nine filter and capacitor banks configuration are shown in Fig. 5. It is observed from the Fig. 6 that with 44 MVAr filter banks and 50 MVAr capacitor banks, the maximum over voltage due to switching is only 1 % of the rated voltage.The steady state voltage at no load is also maintained below the allowable limit which is 418.6 kV (1.021 pu).

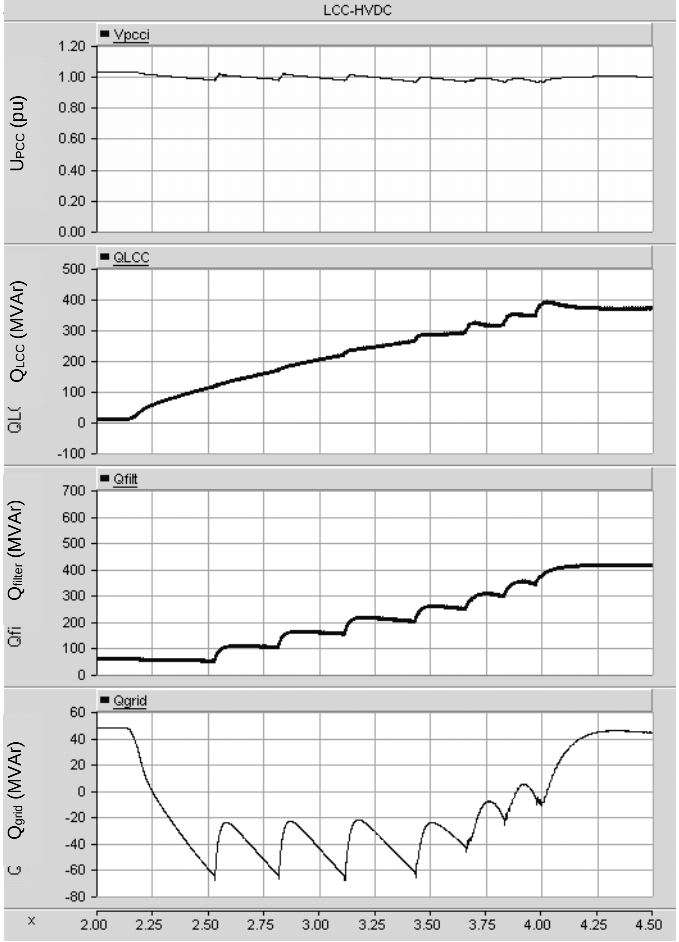

Fig. 3. System response for the switching of filter/capacitor bank configuration-I.

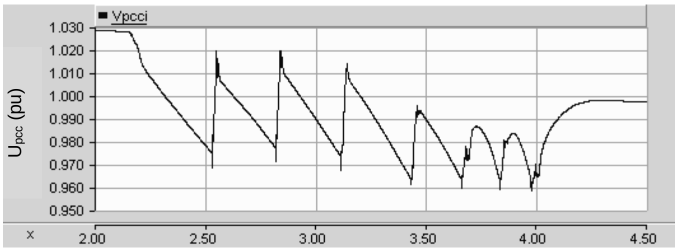

Fig. 4. Transients due to the switching of filter/capacitor bank in configuration-I.

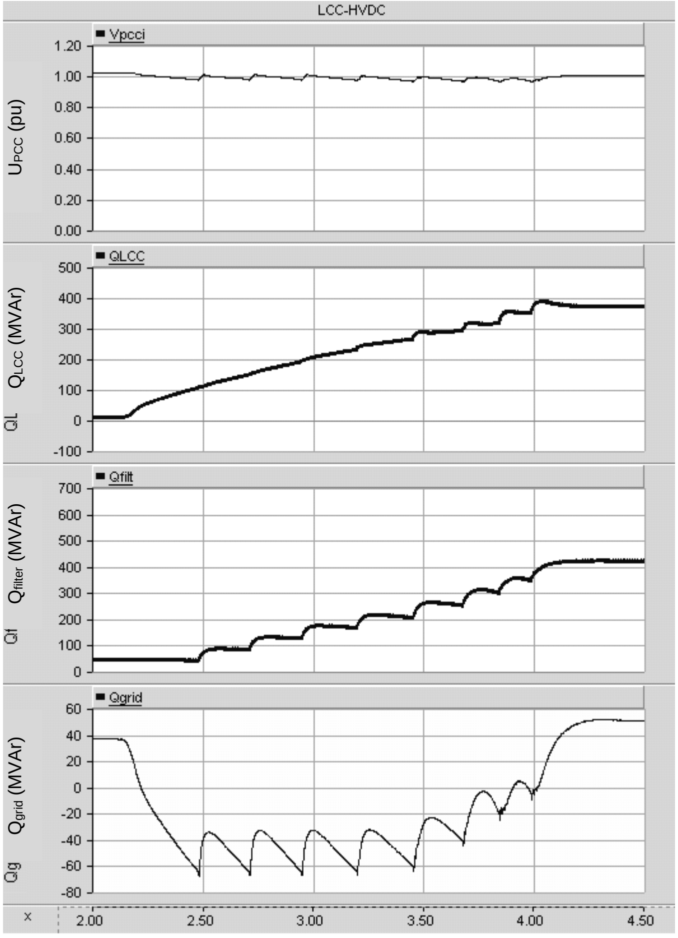

Fig. 5. System response for the switching of filter/capacitor bank configuration-II.

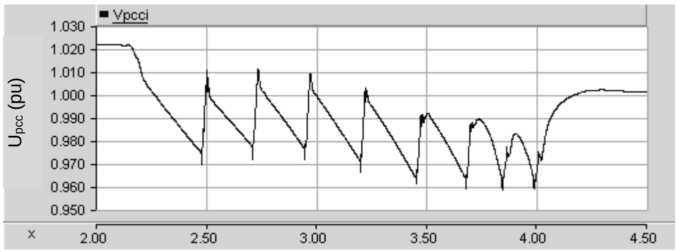

Fig. 6. Transients due to the switching of filter/capacitor bank in configuration-II.

V. Resizing of Filter/Capacitor Banks with STATCOM

From section IV, it is observed that the weak ac grid requires more number of filter/capacitor banks to keep PCC voltage fluctuation within the specified limit during the switching. The resizing of the filter/capacitor banks is possible with the help of a STATCOM. The number of filter/capacitor banks could be reduced by increasing their rating, as it is possible to switch a larger filter/capacitor bank without violating the limit of PCC voltage. This will reduce the overall cost and footprint of the switch-yard.

Based on the above discussion, the required reactive power of 420 MVAr can be split up into two filter banks of 110 MVAr each and one capacitor bank of 200 MVAr. One of the 110 MVAr filters is permanently connected at the PCC. A STATCOM of 100 MVA is connected at the inverter station which can be operated either in AC voltage regulation mode or reactive power control mode. After resizing the filter/capacitor banks, the switching studies have been carried out and the performance of the system has been discussed as follows.

A. *Filter/Capacitor Bank Switching Studies with STATCOM in AC Voltage Regulation Mode*

The STATCOM control is coordinated with LCC in such a way that the voltage limit and the reactive power exchange limit are not exceeded during switching. The Fig. 7 shows the system response with the use of STATCOM in AC voltage regulation mode. The STATCOM is brought into operation at t=1.5s. The STATCOM brings the AC voltage to 1pu within 10ms, as it is operated in the voltage regulation mode. Initially the STATCOM is operated in the inductive mode and it enters in capacitive mode as the active power of LCC ramps up and no further filter switching is performed. The STATCOM maintains the PCC voltage at 1pu until reactive power limit of ±100 MVAr is reached. Further, the voltage regulation is not possible by the STATCOM and hence the PCC voltage starts falling. The next filter bank will then be switched-in when the reactive power exchange or the minimum voltage limit is exceeded. It can be observed that STATCOM as an AC voltage regulator maintains the PCC voltage within the limit for the first filter switching. However, for the second switching of 200 MVAr capacitor bank, the peak voltage is reached to 1.0646 pu which is above the allowable limit of 1.05 pu. The main reason for such an over voltage during the switching is due to the slow nature of the AC voltage controller which is a conventional PI controller.

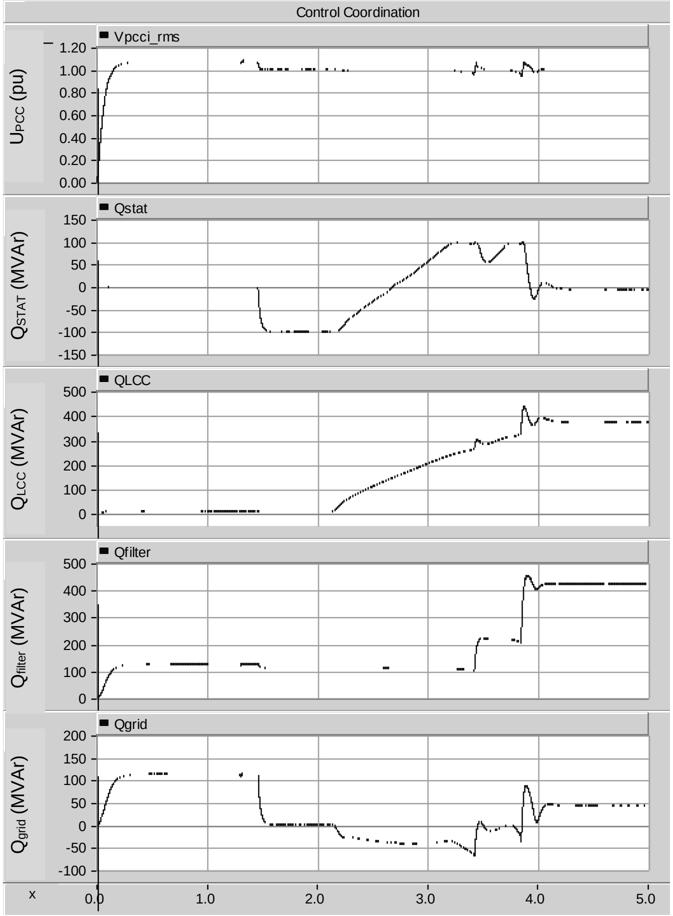

Fig. 7. PCC Voltage profile during capacitor switching with STATCOM as an AC voltage regulator.

B. *Filter/Capacitor Bank Switching Studies with STATCOM in Reactive Power Control Mode*

In this case, the STATCOM supplies the reactive power difference between LCC and passive compensation system i.e. Q_{LCC} - Q_{filter} and maintains Q_{ex} to zero. At, any instant, the difference power (Q_{LCC} - Q_{filter}) is supplied as a reference Q to the STATCOM. Thus, the voltage regulation loop which contains PI controller is eliminated. Consequently, the delay associated to the voltage regulation loop is avoided. With this control method, a faster and effective minimization of the switching transients can be achieved. Fig. 8 shows the system response with the proposed reactive power compensator.

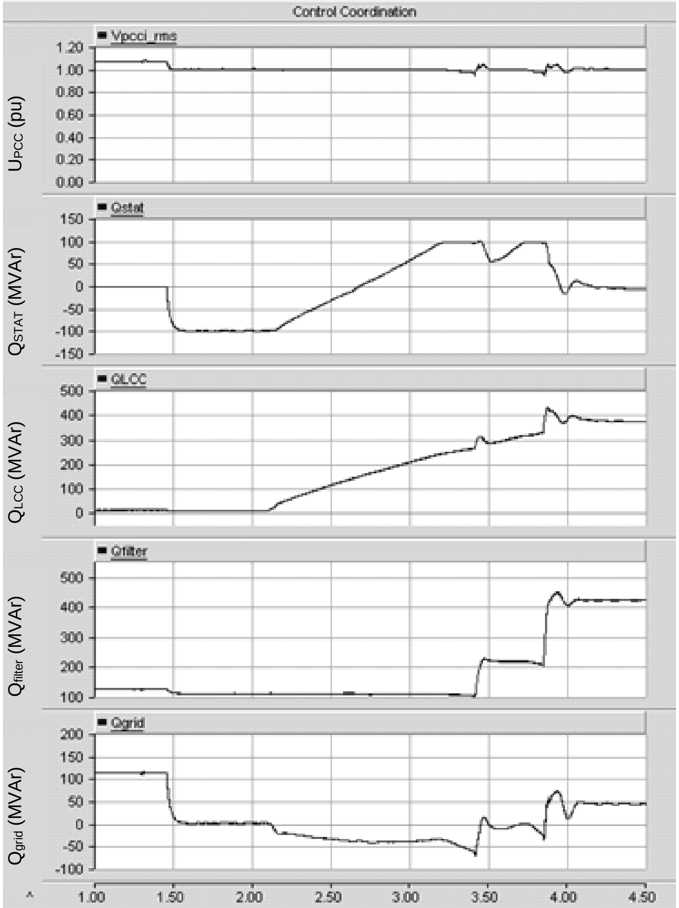

Fig. 8. PCC Voltage profile during capacitor switching with STATCOM as grid reactive power compensator.

The STATCOM works in the AC voltage regulation mode under normal operation and enters into the reactive power control mode whenever filter/capacitor bank switching is taken place. It is important to mention that the peak voltage after switching-in of the filter bank has been reduced to 1.0445 pu from 1.0646pu. The results show that there is a sufficient improvement in the PCC voltage variations during switching with the use of active compensation by the STATCOM. The results for the switching of 200 MVAr capacitor bank have been summarized in TABLE I.

TABLE I. PEAK VOLTAGES WITH CAPACITOR SWITCHING

Parameter	Without STATCOM	STATCOM in AC Voltage Regulation mode	STATCOM in Reactive Power control mode
Temporary Over Voltage	1.106 pu[1]	1.0646 pu	1.0445 pu

VI. STUDY ON FAULT RECOVERY WITH STATCOM

The voltage and power recovery are mainly determined by the amount of reactive power support available after the removal of fault. During the recovery process, the active power reference of LCC (I_{order}) is increased gradually. Therefore, the reactive power drawn by the LCC (Q_{LCC}) also increases as a function of active power. Note that the passive filters and capacitor banks remain connected at the PCC during the fault and recovery process. During recovery, the PCC voltage builds up, and as a result, the reactive power injected by the passive components (Q_{filter}) also increases according to the square of the PCC voltage. However, the reactive power absorption by the LCC is not enough. The surplus of reactive power (Q_{filter}-Q_{LCC}) is flown towards the grid, which leads to dynamic overvoltage at PCC. This excess reactive power can be absorbed by a STATCOM in a controllable manner which helps in the reduction of dynamic overvoltage and recovery time.

In order to study the effect of fault on the system, a solid three-phase line to ground fault is applied for 5 cycles at the inverter terminals of the HVDC converter. The STATCOM operates in AC voltage regulation mode which maintains the PCC voltage at 1 pu during steady state conditions. The Fig. 9 shows the fault recovery using STATCOM operating in ac voltage regulation mode. It is observed from the figure that the fault recovery time is reduced. However, the dynamic overvoltage is increased, as reported in TABLE II. For fast recovery, reactive power injection is needed and for minimizing the voltage overshoot reactive power absorption is required. So, the STATCOM should shift its operating modes from capacitive to inductive during the recovery period. The AC voltage regulator does not permit fast mode shift due to the inherent delay of the PI controller. Because of this reason, the dynamic overvoltage is increased when the STATCOM is operated in voltage regulation mode.

To reduce the recovery time, as well as dynamic overvoltage, a ramp-type-compensator is developed which does not use any PI controller. In this control method, STATCOM will inject full capacitive reactive power when the fault is detected. The reactive power will be ramped down to inductive as soon as the fault is cleared and PCC voltage starts build up. The profile of the PCC voltage and the reactive current reference (i_q^*) generated by the ramp-type-compensator are shown in Fig. 10. The capacitive reactive power injected from t_a to t_b as shown in Fig. 10 will improve the recovery process. The inductive reactive power drawn between t_b and t_c will reduce the voltage overshoot. When the i_q^* of STATCOM reaches the limit (inductive mode), the same is held at this value until the voltage starts to fall below 1 pu. As soon as the PCC voltage starts falling below 1pu, the reactive current reference is then ramped up from the full inductive mode current limit. The mode shift from ramp-type-compensation (RTC) to voltage-regulation (VR) is taken place when the reactive current reference of both the compensators become equal. This ensures a smooth transition between the two control modes. The Fig. 11 shows the recovery by using the STATCOM working as ramp-type-compensation mode. The recovery time and voltage overshoot with this control method are given in TABLE II.

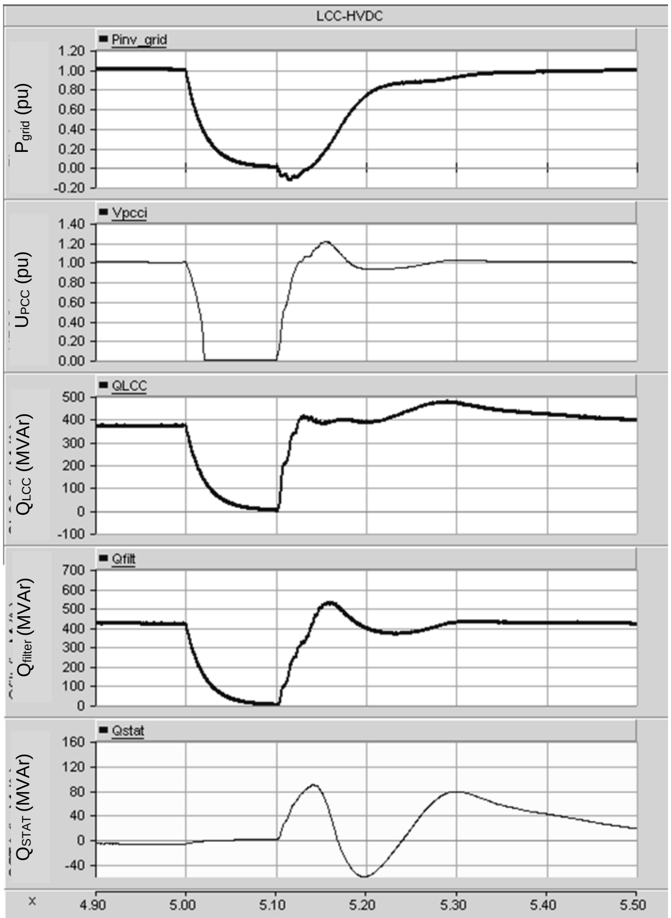

Fig. 9. Fault recovery using STATCOM in ac voltage regulator mode.

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[1] This study is carried out using PSCAD simulation tool, but the results are not included here due to page restriction.

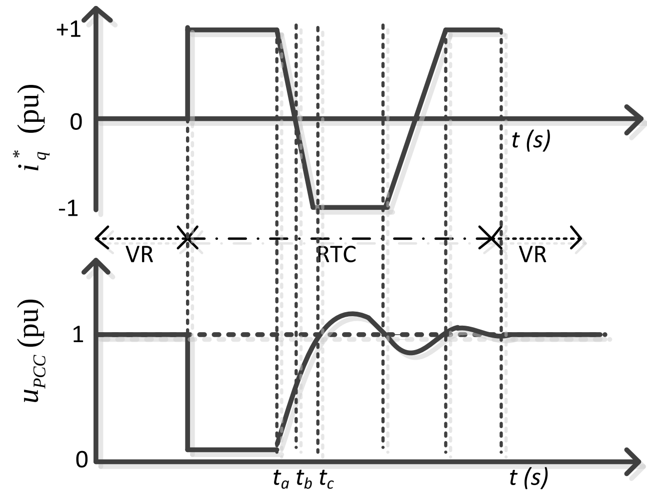

Fig. 10. Reference current (i_q^*) generated by the proposed method

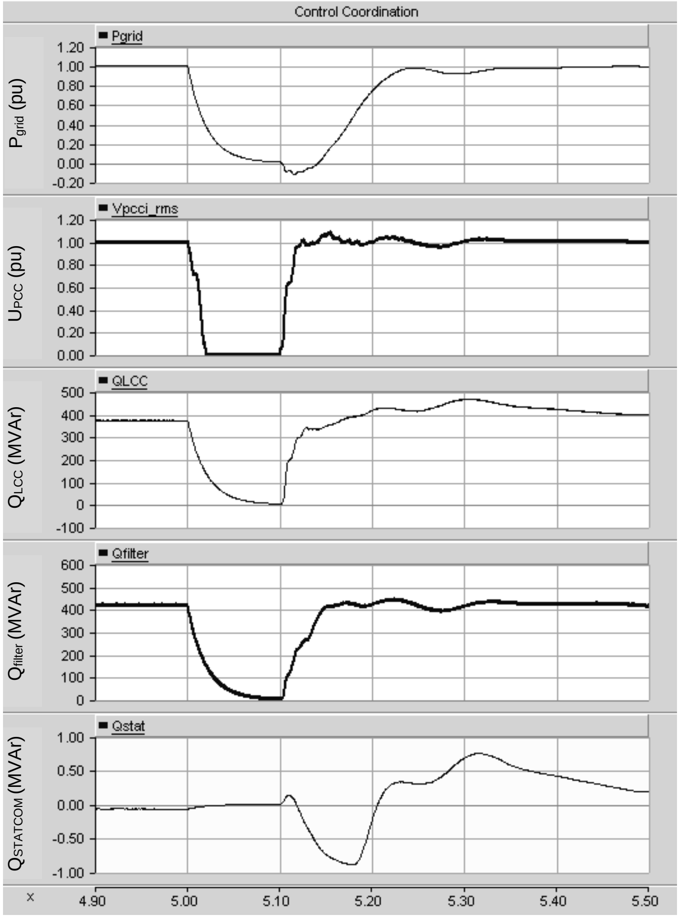

Fig. 11. Fault recovery using STATCOM in ramp control mode.

TABLE II. FAULT RECOVERY WITH DIFFERENT STATCOM COMPENSATION TECHNIQUES

Parameter	*Without STATCOM*[2]	*AC Voltage Regulator*	*Ramp Type Compensator*
Recovery Time	450 ms	220 ms	200 ms
Temporary Over Voltage	1.183 pu	1.215 pu	1.087 pu

VII. CONCLUSIONS

The performance of the LCC during filter switching and fault recovery have been improved using a 100 MVA STATCOM. To reduce the overvoltage during filter switching, a method is developed which ensures that the reactive power exchange during filter switching is zero. With the proposed algorithm, it is now possible to switch a larger filter/capacitor bank without violating the PCC voltage limit. As a result, the number of filter/capacitor bank can be reduced which in-turn reduces the foot-print of AC switch-yard. A fast ramp-type-compensator is also proposed to achieve fast fault recovery with less dynamic overvoltage. The proposed algorithms are verified through PSCAD simulation and the results are discussed.

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[2] This study is carried out using PSCAD simulation tool, but the results are not included here due to page restriction.