Line Committed HVDC based Offshore Wind Power Integration for Harmonic Compensation

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Abstract—Experimental validation in addition to detailed modeling and simulation of a new transformer-less series compensator for line-commutated HVDC rectifier terminal is presented. The compensator employs very small capacitors compared to those in conventional shunt compensators or fixed series capacitors for reactive power compensation of such links. The proposed device demonstrates fundamental-frequency reactive power and harmonic-current compensation.

Index Terms—AC–DC power converters, converters, energy conversion, flexible AC transmission systems (FACTS), high-voltage techniques, HVDC transmission, power conditioning, power harmonic filters, power quality (PQ), reactive power, reactive power control, static power converters.

1. INTRODUCTION
THE LARGE reactive power consumption and low-frequency current harmonics in line-commutated converter-based HVDC (LCC HVDC) transmission [1], [2] necessitate the use of large passive components, which make the terminal size large [3]. This is particularly problematic when it comes to deep-sea offshore wind farms with floating turbines and grid integration equipment being envisaged [4]. However, LCC HVDC continues to remain the preferred choice for large HVDC transmission projects due to its higher power transmission capability and marginally lower losses [5]. VSC HVDC based on modular multilevel converters (MMC) [6] is a promising technology and is tipped to quickly bridge the gap in power and voltage ratings between LCC and VSC technologies [7]. However, an interesting comparison of the converter-building areas of an existing LCC HVDC project commissioned in 2001 and a two-level VSC HVDC project commissioned in 2012 with the calculated converter-building area of a similar MMC-VSC HVDC project reveals that the two-level VSC converter building is almost twice and the MMC VSC HVDC converter building would be almost four times that of the LCC HVDC project [8]. This means that LCC HVDC can be more compact if the conventional compensation is replaced with a compact compensator. One of the compensation solutions employed in LCC HVDC is the capacitor-commutated converter-based HVDC (CCC HVDC) [9]–[11]. Series capacitors are connected in each phase between the converter transformer secondary and the thyristor converter. The location of these capacitors allows for smaller converter transformers as the megavolt-ampere (MVA) requirement for these transformers drops due to lower reactive power flow through them. The benefit is the variability in reactive power supplied by these capacitors with a change in active power reference. This is helpful in reducing the otherwise necessary switching operations in the shunt-connected capacitor banks. However, this variability is inadequate at lighter loads. The disadvantages also include slightly deteriorated harmonic performance and reduced stability [12]. Static compensator (STATCOM) [13], which can potentially replace the conventional shunt compensation arrangement for LCC HVDC, is a shunt-connected device which employs self
commutated switches for reactive/harmonic compensation. The static synchronous series compensator (SSSC) [14] is the series-connected counterpart of the STATCOM. Their drawbacks include higher switching losses due to high switching frequency, and the need for the switching-frequency filtering arrangement and an injection transformer.

A number of transformers less series compensators have been proposed in the literature in the low-, medium-, and high-power levels in ac transmission and distribution. These include the thyristor-controlled series compensator (TCSC), gate commutated series capacitor (GCSC), and magnetic energy recovery switch (MERS). Their benefits include the exclusion of the injection transformer and switching harmonic filter, and lower switching frequency leading to lower losses. This paper proposes a transformer-less series compensator for the rectifier terminal of LCC HVDC. The compensator is different from other transformer-less topologies in the way it injects series voltages. We propose the name series pulsed-voltage compensator (SPVC) since it injects two short-duration voltage pulses in every half cycle of operation. One of the characteristics of the SPVC is the reduction in the reactive power consumption of the main ac/dc converter. This results in lower rms ratings for the SPVC. Contrary to CCC HVDC, SPVC improves the harmonic behavior of the overall LCC HVDC terminal leading to lower (or no) filtering requirements. It is therefore expected that the SPVC, combined.

The schematic of the setup based on the CIGRÉ benchmark is shown in Fig. 1. The grid impedance comprised of $R_{s1}$, $R_{s2}$, and $L_{s1}$ is such that the short-circuit ratio (SCR) is 2.5, indicative of a very weak grid. The total capacitance in the shunt passive filter ($C_{f1} + C_{f2} + C_{f3} + C_{f4}$) is 273 µF. In addition, the total inductance ($L_{f2} + L_{f3}$) eliminate the reactive power, and to improve the harmonic content in currents. The subscript represents the concerned branch (for the branch with the -connected transformer and for the branch with the -connected transformer); whereas represents the concerned phase (a, b or c). Unless otherwise mentioned, small letters refer to the instantaneous quantity. The capital letters represent average values of active and reactive power on the ac side, and dc-link power, voltages, and currents. The rms values of currents and voltages on the ac side are also represented by capital letters.

Fig. 1. Schematic arrangement of the LCC HVDC test setup based on the CIGRÉ benchmark values.
The structure of the SPVC in each phase is shown in Fig. 2. The value of $C$ is 10 F. The reference polarity of $\psi$ is chosen such that the reactive power of the compensator is positive when it is supplying reactive power and vice-versa.

### III. SWITCHING STRATEGIES FOR SPVC

Three modes of operation are discussed as follows.

#### A. Discharge Mode

In this mode, should have a polarity in order to assist commutation. With reference to Fig. 2, if the current flow direction is from the grid to the converter, switching and on would connect the positive dc bus to the converter and the negative dc bus to the grid side and would be positive. This would discharge the SPVC dc link and would go down according to

\[
v_{\text{comp}jk} = v_{\text{comp}dcjk} = v_{\text{comp}dcjk}(kt) - \frac{C}{\beta} \int i_{ljk} dt
\]  

(1)

Where is the residual voltage on the SPVC dc link before the start of discharge activity, is the instantaneous current flowing from the grid to the converter, refers to the instant at which the concerned switches are turned on, and when they are turned off. The situation is depicted in Fig. 3(a). Assuming to be large, and, thus, would fall to zero. If reaches zero and the switch

#### B. Charge Mode

If all of the switches are turned off during the positive half cycle of $i_{ljk}$ [Fig. 3(c)], $D_{ljk}$ and $D_{4jk}$ form the conduction path and the SPVC dc-link capacitor would charge according to

\[
v_{\text{comp}jk} = -v_{\text{comp}dcjk} = -\left( v_{\text{comp}dcjk}(kt) + \frac{1}{\beta} \int i_{ljk} dt \right)
\]  

(2)

Likewise, the complementary set of diodes (i.e., and would conduct the current during the negative half cycle [shown in Fig. 3(d)] and charge the dc link according to

\[
v_{\text{comp}jk} = v_{\text{comp}dcjk} = v_{\text{comp}dcjk}(kt) + \frac{1}{\beta} \int i_{ljk} dt
\]  

(3)

#### C. Bypass Mode

$S_{2jk}$, turned on alone, would select the negative dc bus or $S_{3jk}$, switched on alone, would select the positive dc bus of the SPVC as the bypass path during the positive half cycle. Similarly, $S_{4jk}$, turned on alone, would select the negative dc bus
and $S_{jk}$, switched on alone, would select the positive dc bus as the bypass path during the negative half cycle of $i_{jk}$. Fig. 3(e) and (f) depicts the situation with the negative dc bus selected as the bypass path.

IV. CONTROL OF SPVC

Simulink / Sim Power Systems was used to simulate two cases. Case I demonstrates reactive power control with a changing active power reference and case II shows the capability of SPVC to follow a changing reactive power reference with fixed. In addition to the control loop in Fig. 4, two more control loops have been added. The first depicted in Fig. 5) is for active power control which compares the reference dc-link current on the HVDC line with to generate the required firing delay angle. The second loop (shown in Fig. 6) is for keeping at a fixed value around 15 , a compromise between minimum reactive power consumption and fast power control above rated power for limited duration. is kept constant through the use of relatively slow on load tap changers (OLTCs) on the converter transformers, which change the voltage magnitude upon sensing the change in to bring it back to the reference value. Sim Power Systems does not contain OLTC transformer blocks for time-domain simulations. We have, therefore, created an alternative solution by creating the grid voltages behind its impedance using controlled-voltage source blocks. The loop in Fig. 6 controls these voltages based on the comparison of with .The simulations start with the SPVC bypassed in both cases. The SPVC is connected at 3 s and demonstrates its capability of following. At 6 s, the reference (or) is changed, and the performance of the SPVC is demonstrated for the next 3 s. The base values are 1000 MVA, 500 kV, and 2 kA for plotting purposes.

A. Case

The active and reactive powers are plotted in Fig. 7. As the SPVC is connected $Q_k$, drops from a value of 0.55 to 0 p.u., as

![Fig. 7. Active and reactive powers (a) into the two converter transformers, (b) in the Y branch, and (c) in the D branch.](image)

Instructed by the control loop in Fig. 4, starts from 0 p.u. and settles at approximately 0.3 p.u. At the next transition of to 0.5 p.u. at 6 s, the SPVC adjusts itself so that settles to 0 p.u. again. Remarkably, the drop in is not equal to the rise in . This can be explained using Fig. 7(b) and (c). The injection of forces early commutation reducing and . The net reactive power on the converter transformer primary in each branch is zero. The behaviors of the control loops in Figs. 4–6 are plotted in Fig. 8(a)–(c), respectively. With reference to panel (a), settles to around 0.2
radians. As drops, increases. This is because the current charging the compensator dc-link goes down and has to be increased to achieve a voltage high enough for forcing commutation so that remains 0 p.u., plotted in Fig. 8(b), increases from 15, but is brought down by the loop in Fig. 6, which brings down as seen in panel (c).

The current commutation from phase to during the positive half cycle is shown in Fig. 9. With the SPVC connected [Fig. 9(b) and (c)], the commutating voltage reversal is forced at earlier instants and, therefore, the current commutates earlier. The voltage injected by the series compensator starts to drop (ultimately to zero) as the current starts to commutate. This voltage is again restored [Fig. 9(d)] as described earlier. The change in the commutation duration in Fig. 9(a) and (b) is worth noting. When this current is transformed to the primary

![Fig. 8. Operation of the control loops in case I. (a) Y_charge, (b) α, and (c) V_{sa}.](image)

![Fig. 9. Half-cycle plots in the Y branch: (a) without SPVC, (b) with SPVC and P_a = 1 p.u., (c) with SPVC, and P_a = 0.5 p.u., and (d) the SPVC dc-link voltage with the SPVC and P_a = 0.5 p.u. and added to the phase current from the branch, the effect becomes more pronounced. One cycle of the current is plotted in Fig. 10(a) and (b), without and with series compensation, respectively. The total harmonic distortion (THD) drops from 4.4% to 2%, the magnitude of the 11th harmonic drops from 4.8% to 2%, whereas that of the 13th drops from 3% to 0.3%.

The voltages appearing across one of the thyristors in the main ac/dc conversion bridge and across one switch in the
SPVC are plotted in Fig. 11(a) and (b), respectively. The variation in the peak voltage across the thyristor is insignificant; however, the harmonic content is changed.

**B. Case II**

The capability of the compensator to follow changing $Q_8$R is demonstrated here. As before, the simulations start with the SPVC disconnected. $P_{8R}$ is fixed at 1 p.u. for this case. The SPVC is connected at 3 s. At 6 s, $Q_8$R is changed to 0.3 p.u. Simulation results are plotted in Fig. 12. The plots are similar to case I up to 6 s. After that, as $Q_8$R is increased from 0 to 0.3 p.u., the SPVC reduces the injected voltage and $Q_{ij}$ and $Q_{1D}$ are allowed to increase in such a manner so that the sum of $Q_{1Y}$ and $Q_{1D}$ and the reactive power consumed by the leakage reactance of the converter transformers minus the sum of $Q_{compY}$ and $Q_{compD}$ becomes 0.3 p.u. (equal to $Q_8$R).

The behavior of the control loops is presented in Fig. 13. In contrast to case I, is reduced when there is a smaller requirement of reactive power compensation from the series compensator [panel (a)]. $\alpha$ is kept constant [panel (b)] by changing $U_{sk}$, reflected in panel (c).

One cycle of $i_{sa}$, in the period with partial compensation is presented in Fig. 14. The waveform for full compensation has been discussed in case I. The current THD has been reduced to 1.3% from 2.2% with full series compensation and from 4.4% in the case with no series compensation. Similarly, the magnitude of the 11th harmonic drops to 1.2% from 2% (with full compensation) and 4.8% (with no series compensation). The 13th harmonic drops to 0.4%.

**Fig. 12. Active and reactive power in case II.**
This results shows that the SPVC not only compensates for reactive power with very small capacitors, but also drastically improves harmonic content in LCC HVDC. The implication of harmonic behavior improvement is a drastic reduction in (or complete elimination of) shunt passive compensation.

REFERENCES


