INTEGRATION OF OFFSHORE WIND POWER IN TRANSFORMER-LESS SERIES COMPENSATION OF LINE-COMMUTATED CONVERTERS

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Abstract: Wind energy is gradually becoming a major contributor to the overall energy production, especially in the developed world. This is because of the ever-increasing concerns about long-term availability of conventional fuels, global warming, and energy security. Wind power production is gradually moving offshore because of scarcity of onshore sites (particularly in Europe), environmentalists’ concerns over noise and visual pollution, and better wind conditions out in the open sea. Offshore wind farms are generally located close to the shore currently in shallow waters. However, more power demand from wind will eventually put more and more wind farms farther out in the deep sea. This would require floating turbine and grid-integration platforms.

This is where High Voltage Direct Current (HVDC) interconnection between the offshore power plant and the onshore grid would become more attractive than the AC option. The power to be transmitted, if in excess of a certain amount, would necessitate either multiple Voltage Sourced Converter based HVDC (VSC HVDC) links or a single Line Commutated Converter based HVDC (LCC HVDC) link. The latter could be a cheaper option. LCC HVDC is and will remain the preferred choice for point-to-point transmission of bulk power in the foreseeable future due to it being a proven technology in use for more than half a century, its lower losses, and high power and voltage capability. There remain inherent issues of black-start, high content of lower-order harmonics, and high fundamental-frequency reactive-power consumption. The reactive power and harmonics are traditionally compensated-for by shunt-connected passive filters, which take up a lot of area and make the LCC HVDC terminal size large and expensive.

In a deep-sea offshore perspective, this would increase the cost of the floating platform. This work has explored the possibilities of improvement in transformer-less series compensation of LCC HVDC so as to reduce the size of the converter terminal. The behaviour of the capacitor commutated converter based HVDC (CCC HVDC) was first compared to the conventional system. Later on, the Gate Commutated Series Capacitor (GCSC) was analysed for its potential in the reduction of the converter terminal size.

I. INTRODUCTION

Wind power [18-20] has seen enormous growth in the past couple of decades [21, 22]. The scarcity of land in Europe and opposition to visual and noise pollution [23, 24] are forcing the planners and developers offshore [25]; the additional advantage being better wind conditions. The researchers and planners envisage a European super-grid that would integrate the renewable resources much more efficiently and increase their penetration into the energy mix [26]. The technology of all the components required in such a system is growing rapidly.

Currently, the offshore wind plants are located in shallow waters close to the coast [31, 32]. The implications are solid foundations for turbine & grid-integration platforms and AC connection to the onshore grid. The distance to shore is going to increase in the future [33]. This will result into the following: The water depths will be too much to economically build structures with solid foundations extending from water level to the ocean floor, forcing the construction of floating structures for turbines and grid-integration equipment [33]. The distances to shore will make High Voltage Direct Current (HVDC) transmission [34-38] attractive, technically and economically [39]. Subseacable based AC transmission requires intermediate reactive power compensation and also suffers from stability issues. The stability problem limits the maximum transmission distance.

In addition, for a given voltage insulation level, HVDC technology can transmit more power than its AC counterpart. The increased distance will also mean exposure of the equipment to tougher weather conditions. The reliability of equipment will be of utmost importance as the climatic conditions might not permit servicing and repair for major part of a year. The reliability constraints and the cost of the floating platform demand the grid-integration equipment be optimally compact.
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 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 selfcommutated 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 transformer-less series compensators have been proposed in the literature [15]–[21] in the low-, medium-, and high-power levels in ac transmission and distribution. These include the thyristor-controlled series compensator (TCSC), gatecommutated 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.

Fig1: Schematic arrangement of the LCC HVDC test setup based on the CIGRE benchmark values.

II. ARRANGEMENT OF THE PROPOSED COMPENSATOR:

The grid impedance comprised of \( R_1 \) and \( L_1 \) 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 \( C_{T1}+C_{T2}+C_{T3}\) is 273 MVar. In addition, the total inductance \( L_{T1}+L_{T3} \) is 450 mH. The goal of reactive compensation is to reduce or eliminate the reactive power \( Q \), and to improve the harmonic content in currents \( i_k \). The subscript \( j \) represents the concerned branch (\( j-D \) for the branch with the \( YD \)-connected transformer and \( j-Y \) for the branch with the \( YY \)-connected transformer); whereas \( k \) 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. 2 SPVC in one phase

The structure of the SPVC in each phase is shown in Fig. 2. The value of $C$ is 10 $\mu$F. The reference polarity of $v_{compjk}$ 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 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 then 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

$$v_{compjk} = v_{compdcjk} = v_{compdcjk} - \frac{1}{C} \int i_{tjk} dt$$  \hspace{1cm} (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. 2 (a). Assuming to be large, and, thus, would fall to zero. If reaches zero and the switch

$$v_{compjk} = v_{compdcjk} = v_{compdcjk} - \frac{1}{C} \int i_{tjk} dt$$  \hspace{1cm} (2)

Similar reasoning can be used to switch on the complementary set of switches in the negative half cycle of $i_{tjk}$ to discharge the SPVC. The situation is presented in Fig. 5.2 (b) and is governed by

$$v_{compjk} = -v_{compdcjk} = - \left( v_{compdcjk} - \frac{1}{C} \int i_{tjk} dt \right)$$  \hspace{1cm} (3)

B. Charge Mode

If all of the switches are turned off during the positive half cycle of $i_{tjk}$ [Fig. 3(c)], $D_{1jk}$ and $D_{4jk}$ form the conduction path and the SPVC dc-link capacitor would charge according to

$$v_{compjk} = -v_{compdcjk} = - \left( v_{compdcjk} + \frac{1}{C} \int i_{tjk} dt \right)$$  \hspace{1cm} (4)

Likewise, the complementary set of diodes (i.e., $D_{2jk}$ and $D_{3jk}$) would conduct the current during the negative half cycle [shown in Fig. 3(d)] and charge the dc link according to

C. Bypass Mode

$S_{2jk}$, turned on alone, would select the negative dc bus or, switched on alone, would select the positive dc bus of the SPVC as the bypass path during the positive half cycle. Similarly, $S_{1jk}$, turned on alone, would select the negative dc bus and $S_{3jk}$, switched on alone, would select the positive dc bus as the bypass path during the negative half cycle of Fig. 3(e).

IV. CONTROL OF SPVC

The SPVC can only inject as much voltage in a phase as is available on its dc-link capacitor. Second, the larger the series injected voltage, the earlier the commutating-voltage crossover will be. The strategy adopted is to charge the SPVC dc link when the concerned phase is carrying the peak current. The discharge would occur during commutation of current into the concerned phase. Current commutates into a phase during the positive and negative half cycles. Therefore, the sequence should be to charge during the positive half cycle, discharge during the commutation in the negative half cycle, charge again during the negative half cycle, discharge during
the commutation in the Positive half cycle, and, finally, charge again during the positive half cycle. The starting point of control is depicted in Fig. 5.3. And are compared to half of the reference reactive power. This is done because the two branches are identical in their reactive power consumption and, thus, the SPVCs in the two branches take an equal burden. Since the current into the LCC rectifier terminal is trapezoidal, we can assume that the current is constant (equal to ) during the interval in which the SPVC dc link has to be charged. The peak of this voltage can be calculated using (3) or (4) assuming the initial voltage on the SPVC dc link is to be zero and 

\[ \theta_{thy} = \theta_{discharge} - \alpha. \quad (12) \]

V. SIMULATION SETUP AND RESULTS

Simulink/SimPowerSystems 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 a limited power for limited duration. is kept constant through the use of relatively slow onload 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. SimPowerSystems 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 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.

Case I:

The active and reactive powers are plotted in Fig. 6. As the SPVC is connected, drops from a value of 0.55 to 0 p.u., as

\[ v_{iYab} = V_{iYabM} \sin(\omega t). \]

\[ v_{iYab}(\omega T_{discharge}) = V_{compdcjkM} \Rightarrow V_{iYabM} \sin(\omega T_{discharge}) = I_d \gamma_{charge}/\omega C. \]

\[ \omega T_{discharge} = \sin^{-1}(I_d \gamma_{charge}/V_{iYabM}.\omega C) \]

\[ \theta_{discharge} = \theta_{ab} + \omega T_{discharge} \]

If \( \theta_{discharge} > 2\pi \) then \( \theta_{discharge} = \theta_{discharge} - 2\pi \)

If \( \theta_{discharge} < 0 \) then \( \theta_{discharge} = \theta_{discharge} + 2\pi \).

\[ \gamma_{discharge} = \alpha + \gamma_{charge} + \pi/12. \]
Fig 6.1 Active and reactive powers (a) into the two converter transformers, (b) in the Y branch, and (c) in the D branch.

Fig 6.2 Operation of the control loops (a) Y charge, (b) alpha, (c) Vsa, and (d) Isa.
VI. CONCLUSION

A transformerless series compensator for a 500-kV dc, 2-kAdc, 1000-MW, single-pole LCC HVDC rectifier terminal has been proposed in this paper. The simulation and experimental results reveal that the compensator can manage the reactive power of such a system with varying active and reactive power references and require very small capacitors when compared to existing solutions. The compensator injected voltages are of the order of 150 kV (0.3 p.u. of the dclink voltage) when compensating for full reactive power at full load. It has also been shown that the harmonic pollution is reduced by the compensator, reducing the overall requirement for shunt passive filters. Modern LCC HVDC voltage ratings have gone up to 800 kVdc. The proposed compensator should then have the capability to inject 240 kV (800 0.3) to achieve full reactive compensation at full load. Power transmission capacities of HVDC cables are a bottleneck; also, it is better to carry power to the shore in several smaller-capacity cables instead of a single connection from acability point of view. The proposed solution can be equally applicable to this configuration as the platform size would be smaller than competing topologies.

A useful study would be the assessment of losses in the proposed compensator. The switching frequency is much lower than the STATCOM or SSSC solutions bringing down the losses. Also, switching is performed at zero current during the discharge mode, at zero voltage during the bypass mode after discharge, and at zero voltage during charging mode. The bypass mode after charging involves switching at non-zero voltage and current.

REFERENCES: