

Voltage Source Converter (VSC) Operation at DC Lines close to AC Lines

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SUMMARY

For determination of the impact of AC to DC coupling on Voltage Source Converter (VSC) design and performance not only the coupling amplitude but also the resulting coupling mode (common mode or differential mode) is relevant. Symmetrical topology converters, with no or high impedance DC side grounding, have a very high impedance to common mode, so that only differential mode coupling can cause fundamental currents on the DC side. For all other topologies the specific current paths must be considered.

The AC to DC coupling amplitude and mode depend on many parameters. Elements such as line ground wires, which improve the tower symmetry in AC or DC applications, can increase the AC to DC coupling. Generally, it can be said, that configurations with separate AC and DC towers cause mainly a common mode coupling. The coupling mode for hybrid towers depends on the wire configuration on the tower, so that a general statement on the resulting mode cannot be made.

In case AC to DC coupling can cause a fundamental current flow on the DC line, counter measurements might be required to mitigate this current. Due to the cross modulation in a Line Commutated Converter (LCC), a fundamental current on the DC side causes a DC current flow on the AC side of the converter, which leads to the saturation of the converter transformer. In a VSC converter topology, the current paths and, therefore, the impact of the fundamental current on the DC side is different. Due to the installed energy storage available, the negative impact of the AC to DC coupling can be mitigated by the VSC converter control, without any additional hardware requirements.

KEYWORDS

HVDC, Hybrid Towers, AC – DC Coupling

1. Introduction

Obtaining right-of-way for new transmission projects is increasingly more difficult due to new regulatory, environmental or societal aspects. To overcome part of these challenges, some HVDC projects currently under development or in execution have the DC conductors laid on towers which are either in close proximity to AC lines or that even share the same tower. This close proximity to the AC lines has an impact on the insulation coordination of the new DC transmission system and on the converter design. The impact on the insulation coordination is discussed e.g. in [1]. The present paper shows the impact of nearby AC transmission lines on the operation and requirements of a voltage-sourced converter (VSC) by focusing on the induced fundamental-frequency AC voltages which appear on the DC line. The paper considers VSC units using controllable voltage-sourced type valves, e. g. MMC according to IEC 62747, since these valves represent the majority of new installed VSC. The first objective of the present paper is to analyse the AC to DC coupling depending on the tower configuration. The tower configuration determines not only the magnitude of the induced AC voltage but also the resulting mode (common or differential), both of which must be considered as they impact the design and control of a VSC.

For LCC-based HVDC systems, the impact of AC to DC coupling is known, as presented in [2]. Therefore, the second objective of the paper is to show how these fundamental harmonics adversely affect the operation of line-commutated converters.

The last objective is to analyse the adverse effects coming from the presence of a fundamental harmonic on the DC side of a VSC-HVDC. This paper shows that for the mitigation of these adverse effects, installation of additional hardware is not necessary. Instead, dedicated control functions or control structures may be used.

2. Coupling of AC to DC lines

In general, electromagnetic induction is a function of the loading of the energized line, the distance between the two lines and the length with which they run alongside each other.

The total coupling of AC to DC lines consists of two elements: (1) inductive coupling (i.e. magnetic-field induction) and (2) capacitive coupling (i.e. electric-field induction). The inductive coupling causes a *longitudinal* voltage on the DC line and depends on the ac current loading and the distance between the conductors. The capacitive coupling on the other hand creates a phase-to-earth voltage and depends on the ac line voltage.

If the AC-lines were configured to be geometrically symmetrical and the AC system were operated in perfect balance, then the influence of the three phases on the DC lines would compensate each other. However, due to different distances between the AC phases and the DC lines this compensation is not ideal, resulting in an induced AC voltage onto the DC line.

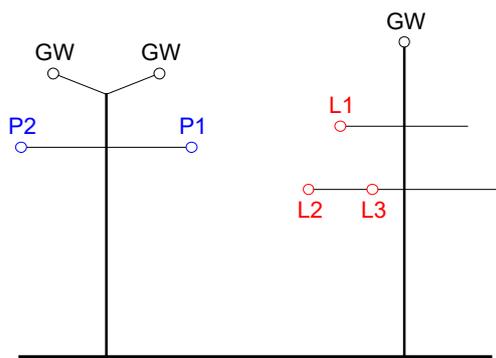


Figure 1: Separate tower configuration

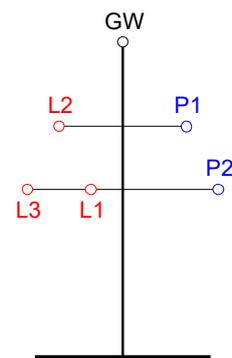


Figure 2: Hybrid tower configuration

The following investigations will be performed for two scenarios: the first one is done with separate towers for the AC and DC lines (Figure 1), whereas the second one done with a hybrid system, where the AC and DC lines are on the same tower (Figure 2). In the case of individual towers, a spacing of 75 m between the towers (centre to centre) is assumed. For the mean conductor height, the mid-span conductor sag is considered with a 0.7 factor. The tower and the conductor bundle geometries are given in Table 1. A bundle of four conductors is assumed in both the AC and DC lines, with a bundle spacing of 40 cm are assumed.

	horizontal distance / m with respect to DC-tower centre		height above ground / m mean incl. conductor sag	
	Separate Towers	Hybrid Towers	Separate Towers	Hybrid Towers
DC pole conductor bundle P1	10	11	30 – 0.7·17	31.2 – 0.7·8.4
DC pole conductor bundle P2	–10	14.2	30 – 0.7·17	22.2 – 0.7·8.4
Two DC line ground wires	–7 and +7	-	40 – 0.7·15	-
AC conductor bundle L1	–11 + 75	–7.8	31.2 – 0.7·8.4	22.2 – 0.7·8.4
AC conductor bundle L2	–14.2 + 75	–11	22.2 – 0.7·8.4	31.2 – 0.7·8.4
AC conductor bundle L3	–7.8 + 75	–14.2	22.2 – 0.7·8.4	22.2 – 0.7·8.4
One AC line ground wire	75	0	46.6 – 0.7·8.4	46.6 – 0.7·8.4

Table 1: Conductor coordinates in the transmission system.

With the data given in Table 1, the inductive coupling matrices can be formulated. Thereby, the equations stated below in detail are valid for the case of separate AC and DC towers, which have in total eight conductor bundles and ground wires forming, hence, a system of eight order. For the case of a hybrid tower, only one ground wire exists, therefore the system is of sixth order and can structurally be derived from the eight-order system by omitting the last two lines and columns. The self-inductances are given as L'_{n-n} while g_n is the mean geometric distance of a conductor or a conductor bundle. In the mutual inductances L'_{n-m} , the value d_{n-m} is the distance between the considered conductors or conductor bundles. Both depend on the AC frequency and the earth resistivity ρ_{earth} , which is here assumed to be 100 Ωm .

$$\underline{U} = j\omega l \underline{L}' \underline{I} \quad \text{where } l \text{ is the length of the parallel-running line sections} \quad (1)$$

$$\underline{U} = \left[\underline{U}_{DC,P1} \underline{U}_{DC,P2} \underline{U}_{AC,L1} \underline{U}_{AC,L2} \underline{U}_{AC,L3} \underline{U}_{DC,gw1} \underline{U}_{DC,gw2} \underline{U}_{AC,gw} \right]^T, \underline{I} = \left[I_{DC,P1} \dots I_{AC,gw} \right]^T \quad (2)$$

$$\underline{L}' = \begin{bmatrix} L'_{DC,P1-DC,P1} & \dots & L'_{DC,P1-AC,gw} \\ \vdots & \ddots & \vdots \\ L'_{AC,gw-DC,P1} & \dots & L'_{AC,gw-AC,gw} \end{bmatrix} = \begin{bmatrix} \underline{L}'_{(5 \times 5)} & \underline{L}'_{(5 \times 3)} \\ \underline{L}'_{(3 \times 5)} & \underline{L}'_{(3 \times 3)} \end{bmatrix} \quad (3)$$

$$L'_{n-n} = \frac{\mu_0}{2\pi} \ln \left(\frac{D_\infty}{g_n} \right), L'_{n-m} = \frac{\mu_0}{2\pi} \ln \left(\frac{D_\infty}{d_{n-m}} \right) \quad \text{with } D_\infty = 658 \cdot \sqrt{\frac{\rho_{earth}}{f_{AC}}} \quad (4)$$

In the (8×8) inductance matrix of eq. (3) the first five lines and columns ($\underline{L}'_{(5 \times 5)}$) represent the inductive coupling between all AC and DC conductor bundles and the last lines and columns ($\underline{L}'_{(3 \times 3)}$) the coupling between all ground wires. The matrices $\underline{L}'_{(3 \times 5)}$ and $\underline{L}'_{(5 \times 3)}$ are transposed with respect to each other and represent the coupling between conductor bundles and ground wires. Without any ground wires only $\underline{L}'_{(5 \times 5)}$ was necessary to describe the coupling mechanism. Nevertheless, even if ground wires are present it is convenient to eliminate them mathematically so to reduce the system's order to five as outlined in eq. (5) and (6).

$$\left[\underline{U}_{DC,gw1} \underline{U}_{DC,gw2} \underline{U}_{AC,gw} \right]^T = \vec{0} \Rightarrow \left[I_{DC,gw1} I_{DC,gw2} I_{AC,gw} \right]^T = f \left(\left[I_{DC,P1} \dots I_{AC,L3} \right]^T \right) \quad (5)$$

$$\Rightarrow \underline{L}'_{ground \text{ wires eliminated}} = \underline{L}'_{(5 \times 5)} - \underline{L}'_{(5 \times 3)} \cdot \left(\underline{L}'_{(3 \times 3)} \right)^{-1} \cdot \underline{L}'_{(3 \times 5)} \quad (6)$$

$$\text{with } \underline{U} = \left[\underline{U}_{DC,P1} \underline{U}_{DC,P2} \underline{U}_{AC,L1} \underline{U}_{AC,L2} \underline{U}_{AC,L3} \right]^T, \underline{I} = \left[I_{DC,P1} I_{DC,P2} I_{AC,L1} I_{AC,L2} I_{AC,L3} \right]^T$$

Now the voltages induced into the DC pole conductor bundles P1 and P2 caused by the load currents in the AC conductor bundles L1 to L3 can be calculated using eq. (1) and (6). In this example a purely positive sequence load current of 2.5 kA is assumed in the AC system. For the hybrid system this results in an induced voltage of 30.5 V/km in the DC pole 1 conductor and 40.9 V/km in pole 2. In the case of separate AC and DC towers, these voltages are 14.7 V/km and 10.1 V/km, respectively. Moreover, the ground wires can have a rather unexpected effect with respect to the induced voltages. In the case of separate AC and DC towers, but without the AC system's ground wire, the induced voltages are 9.7 V/km and 5.6 V/km only. This is about 35 to 45% less than the values stated above, where all ground wires have been considered in the calculations. To explain this effect, let us take a closer look at the inductance matrix with mathematically eliminated ground wires. On eq. (6) only the

elements which represent the inductive coupling from the AC conductors into the DC pole conductors are of interest, as drafted in eq. (7). Therein the elements stated as $L'_{(2 \times 2)}$ and $L'_{(3 \times 3)}$ represent the inductive coupling within the DC pole conductor bundles and within the AC conductor bundles. The term $L'_{(3 \times 2)}$ stands for the inductive coupling from the DC pole conductors into the AC conductors. These three partial matrices are not of interest for the further explanations.

$$L'_{\text{ground wires eliminated}} = \begin{bmatrix} L'_{(2 \times 2)} & L'_{P1-L1,g.w.elim.} & L'_{P1-L2,g.w.elim.} & L'_{P1-L3,g.w.elim.} \\ L'_{(3 \times 2)} & L'_{P2-L1,g.w.elim.} & L'_{P2-L2,g.w.elim.} & L'_{P2-L3,g.w.elim.} \\ & & L'_{(3 \times 3)} & \end{bmatrix} \quad (7)$$

The vector of the first line [$L'_{P1-L1,g.w.elim.}$ $L'_{P1-L2,g.w.elim.}$ $L'_{P1-L3,g.w.elim.}$] of eq. (7) represents the coupling from the AC conductor bundles into the DC pole 1 conductor bundle (cf. eq. (8)) and the second line ($L'_{P2...}$) the coupling into the DC pole 2 conductor bundle. These vectors can be transformed into symmetrical components as stated for DC pole 1 in eq. (8). The equation for DC pole 2 can be derived analogously. Therein the inductances $L'_{DC,P1-AC(0)}$, $L'_{DC,P1-AC(1)}$ and $L'_{DC,P1-AC(2)}$ represent the coupling from zero, positive and negative sequence current of the AC system into the DC pole 1 conductor bundle.

$$\underline{U}_{DC,P1} = j\omega l \cdot \underbrace{\begin{bmatrix} L'_{P1-L1,g.w.elim.} & L'_{P1-L2,g.w.elim.} & L'_{P1-L3,g.w.elim.} \end{bmatrix}}_{L'_{P1-L123,g.w.elim.}} \cdot \begin{bmatrix} I_{AC,L1} \\ I_{AC,L2} \\ I_{AC,L3} \end{bmatrix}$$

$$\stackrel{!}{=} j\omega l \cdot \begin{bmatrix} L'_{DC,P1-AC(0)} & L'_{DC,P1-AC(1)} & L'_{DC,P1-AC(2)} \end{bmatrix} \cdot \begin{bmatrix} I_{AC,(0)} \\ I_{AC,(1)} \\ I_{AC,(2)} \end{bmatrix} \quad (8)$$

$$\Rightarrow \begin{bmatrix} L'_{DC,P1-AC(0)} & L'_{DC,P1-AC(1)} & L'_{DC,P1-AC(2)} \end{bmatrix} = L'_{P1-L123,g.w.elim.} \cdot \underline{\mathbf{S}}^{-1}$$

$$\text{with } \begin{bmatrix} I_{AC,L1} \\ I_{AC,L2} \\ I_{AC,L3} \end{bmatrix} = \underline{\mathbf{S}}^{-1} \cdot \begin{bmatrix} I_{AC,(0)} \\ I_{AC,(1)} \\ I_{AC,(2)} \end{bmatrix}, \quad \underline{\mathbf{S}} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \end{bmatrix} \quad \text{and } \underline{a} = e^{i2\pi/3}$$

For the system with separate AC and DC towers, the coupling inductances into DC pole 1 are given in Table 2, which compares the original configuration with two DC and one AC ground wire and a configuration without the AC system's ground wire (but still with both DC system ground wires). From the values $L'_{DC,P1-AC(1)}$ it can easily be understood, that the inductive coupling of a purely positive sequence AC current would be smaller if the AC system did not have ground wires. In contrast to this, the effect of a zero sequence AC current is reduced by additional ground wires (cf. $L'_{DC,P1-AC(0)}$). For positive sequence AC currents, the most relevant part is not the absolute value of the coupling inductances $L'_{P1-L1,g.w.elim.}$, $L'_{P1-L2,g.w.elim.}$ and $L'_{P1-L3,g.w.elim.}$ but the difference between them. For the zero sequence, simply calculating the sum is effective. It should be understood, the idea here is not to suggest certain ground wire configurations, but to raise awareness that in inductive coupling calculations all ground wires have to be considered. Omitting those may lead to incorrect results, which are not on the safe side.

L' in $\mu\text{H}/\text{m}$	$L'_{P1-L1,g.w.elim.}$	$L'_{P1-L2,g.w.elim.}$	$L'_{P1-L3,g.w.elim.}$	$L'_{DC,P1-AC(0)}$	$L'_{DC,P1-AC(1)} = (L'_{DC,P1-AC(2)})^*$
One AC g.w.	0.218	0.239	0.222	$0.679 + j0$	$-0.012 - j0.014$
w/o AC g.w.	0.290	0.301	0.287	$0.877 + j0$	$-0.004 - j0.012$

Table 2 : Coupling inductances into DC pole 1 for separate AC and DC towers.

Depending on the network configuration, the DC line can run near different AC line segments. The total inductive coupling is, therefore, the sum of the individual segments. In that case, not only the current amplitude but also the phase difference between the AC line segments determine the induced voltage. Furthermore, the transposition scheme of the parallel running AC lines as well as the length of the coupled lines affect the voltage induction. For an initial design to evaluate the impact on the converter design, a worst-case assumption can be used where the AC lines are operated at their maximum current ratings, and the induced voltages in all segments are considered to be in phase. For the impact determination on the converter design not only the coupling amplitude but also the coupling modes (common or differential mode) must be considered (Figure 3). Assuming a

comparatively long distance between the AC and DC conductors (e.g. parallel running, but separate towers for AC and DC system), the distance from the AC conductors to each individual DC conductor is about the same. Hence, the voltages induced to the positive and negative pole conductor of the DC system (V_{ind_p} and V_{ind_n}) can be then assumed to be roughly equal in magnitude and angle, and, therefore, the resulting effect is mainly of common mode. With AC and DC conductors located on the same tower, the distances from the AC conductors to the positive and negative pole conductor of the DC system are different, so that additionally to the common mode, differential mode voltages will also be induced. For systems with a dedicated metallic return conductor (third DC conductor) the analysis with common and differential mode is not immediately applicable, but the principle statements about distances between AC and DC systems are still valid.

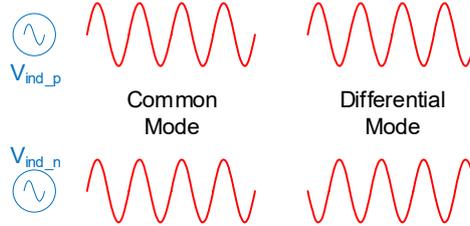


Figure 3: Waveform representation of the coupling modes.

Fundamental frequency current caused by the induced voltage highly depends on the coupling mode and the converter topology. Concentrated voltage induction representing the induced voltages is exemplary shown in (Figure 4).

For the symmetrical monopole topology, with no or very high impedance DC-side grounding, fundamental current can only be created by induced voltages in differential mode. In common mode the induced voltages appear as a zero-sequence voltage on the converter side of the transformer (V_0). In configurations with a low impedance DC side grounding (e.g. bipolar configuration), the resulting current paths must be considered to determine the coupling effect.

An energized conductor creates an electrical field which induces a voltage in any other conductor located in this field. A phenomenon known as electric field induction. Compared to inductive coupling, the electric field induction is a phase-to-ground voltage as shown in Figure 5. The resulting capacitive coupling voltage is significantly smaller compared to inductive coupling voltage and only applies to hybrid towers, therefore it was neglected in the previously presented calculations.

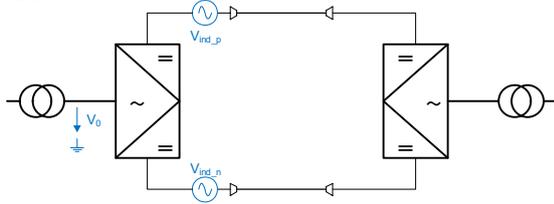


Figure 4: Symmetrical monopole configuration with induced voltages

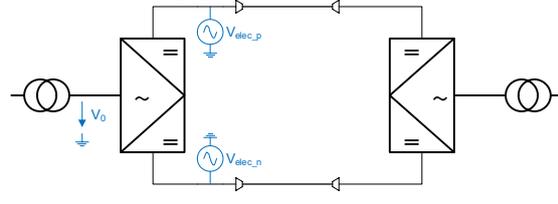


Figure 5: Symmetrical monopole configuration with electric field induced voltages

3. Coupling impact on LCC converter

For line-commutated converters a strong harmonic interaction between the AC and the DC side of the converter exists. This cross-modulation mechanism is well-known and detailed in [3], wherein the investigations are separated into positive and negative sequence harmonics. Here, an alternative approach with a two-sided frequency spectrum is presented. This approach offers the opportunity of a more compact representation without the need for distinguishing between positive and negative sequence harmonics, but finally leads to the same results. For simplicity the following outline is based on 12-pulse converters in AC grids with a fundamental frequency of $f_0 = 50$ Hz.

According to [3] the characteristic harmonics on the AC side of a 12-pulse converter are given with eq. (9) and in the case of an induced DC harmonic $f_{dc} = k \cdot f_0$ additional non-characteristic harmonics are generated as stated in eq. (10).

$$f_{ac,char.} = \left. \begin{array}{l} (12n + 1)f_0 \text{ for positive sequence} \\ (12n - 1)f_0 \text{ for negative sequence} \end{array} \right\} \text{ with } n \in \mathbb{N}_0 \quad (9)$$

$$f_{ac,non-char.} = \left. \begin{array}{l} (12n + 1 \pm k)f_0 \text{ for positive sequence} \\ (12n - 1 \pm k)f_0 \text{ for negative sequence} \end{array} \right\} \text{ with } n \in \mathbb{N}_0 \quad (10)$$

In a two-sided frequency spectrum, positive sequence harmonics have a positive harmonic order and negative sequence harmonics correspond to a negative ordinal number. As a consequence, the characteristic and non-characteristic harmonics as stated above can be rearranged in form of eq. (11) and (12). It is easy to proof that eq. (9) and (11), or respectively eq. (10) and (12), result in the same absolute values of ordinal numbers and negative harmonic orders correspond to negative sequence harmonics.

$$f_{ac,char.} = (\pm 12n + 1)f_0 \text{ with } n \in \mathbb{N}_0 \quad (11)$$

$$f_{ac,non-char.} = (\pm 12n + 1 \pm k)f_0 \text{ with } n \in \mathbb{N}_0 \quad (12)$$

In the statements above k does not necessarily have to be an integer. Therefore, the equations are generally applicable for induced DC harmonics of arbitrary frequency and are not limited to multiples of the fundamental frequency. Though, in the following only a fundamental frequency voltage ($k = 1$) induced on the DC side of the line commutated converter will be considered. According to the statements above, the lowest order non-characteristic harmonics, caused by a fundamental frequency component on the DC side, are obtained with $n = 0$ and are 0 Hz and +100 Hz. These are the commonly known transformer direct current and positive sequence second harmonic component. This direct current magnetization of HVDC transformers can be problematic, as even comparatively small currents increase the transformer's heating and audible noise emissions and cause the generation of additional AC and DC harmonics. Therefore, it is important to be able to calculate the resulting transformer direct current and evaluate, whether its magnitude is within the transformer's specification or special measures have to be adopted.

In a first step the induced fundamental frequency voltages in the conductors of the DC system are calculated according to eq. (1) and (6). As already aforementioned, the induce voltages depend on the transposition scheme and the load current of the AC lines, as well as the spacing from AC to DC conductors and the conductor bundle geometries. For the case that several independent 3-phase AC systems run in parallel to the DC system, the phase angles of the individual AC systems also have an impact.

The fundamental frequency current, resulting from these voltages and flowing through the DC circuit, depends on the total effective impedance of the current path in the DC circuit. The current path itself (e.g. only through the pole conductors or also via ground), and hence the impedances of this path, depend on the magnitudes and phase angles of the induced voltages (are the induced voltages mainly common or differential mode), the HVDC converter's DC side impedance, the impedances of passive components (e.g. DC filters, smoothing reactors and neutral bus surge capacitors) and the DC line impedance. Thereby, the converter DC side impedance can be calculated according to [4] or [5] and, furthermore, the impedance of the DC line may also include the impedance of a current path via ground.

After calculating the fundamental frequency current in the DC circuit, the part which flows into the DC terminals of the current-source converter must be calculated. This fundamental frequency current flowing into the converter DC terminals inter alia depends on DC filters, smoothing reactors and the converter's DC side impedance.

In the last step, the calculation of the direct current component in the transformer windings can be calculated with the approach stated in eq. (13) [6]. The equation is valid for the Yy-transformers' converter side winding. Therein, the rms value of the fundamental frequency current flowing into the DC terminals of the converter must be used.

$$I_{dc, Yy-transf. conv. side} = \frac{\sqrt{6}}{\pi} I_{rms \ 50 \ Hz, conv. dc \ terminals} \quad (13)$$

From Figure 6 it can be recognized that this transformer direct current is not a direct current in the proper sense, but a direct current *component*. This can be seen in the waveform of the AC current, represented by the bold curve in black, which has a higher magnitude in positive than in negative direction. Hence, the mean value of this current is positive, which equals to a positive direct current

component. The reason for this effect is the fundamental frequency component in the DC side current (dashed curve in Figure 6) and the fact that in LCC converters this DC side current builds the envelope of the AC side currents. The latter is true because in LCC converters the current on the DC side is directly switched through to the AC side by the converter valves (cf. Figure 7). In contrast to VSC converters, an energy storage inside the LCC converter arms, which could decouple AC and DC side and thus would prevent this switch through, does not exist. Hence, the fundamental frequency component in the DC side current affects the amplitude of the AC side currents in a way so that a direct current component is generated on the AC side currents.

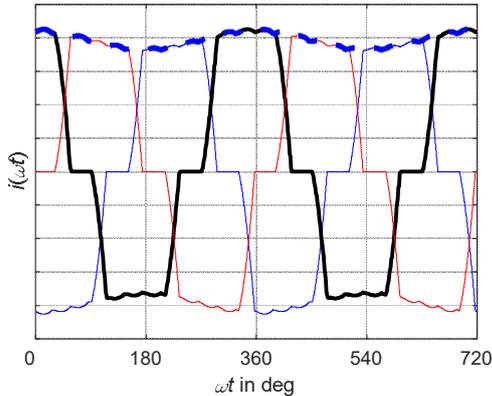


Figure 6: AC and DC currents of LCC with fundamental frequency component on DC side

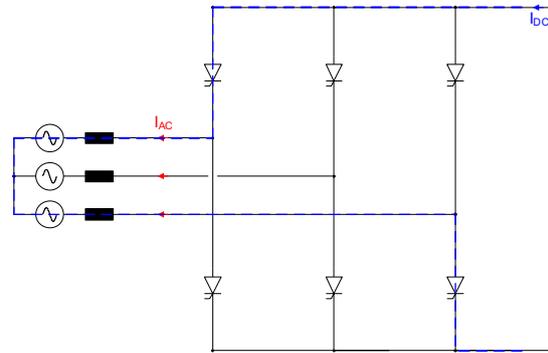


Figure 7: DC current path through the LCC

Typical limits for the admissible steady-state direct current component of HVDC transformers are in the range of below 10 A to few tens of amperes. Should the calculated transformer direct current component exceed the specified limit, a fundamental frequency blocking filter can be provided on the converter's DC side. Such filters are single-tuned parallel resonance circuits which have high impedance at the tuning frequency of 50 Hz. Installed in the DC circuit as a series element, it significantly reduces the fundamental frequency current flow in the DC circuit and, hence, the transformer direct current component. It can be installed on the HV terminal in series connection with the smoothing reactor or in the DC neutral. In the latter case, it must be connected between the converter terminal and the neutral bus surge capacitor; otherwise it will effectively be bypassed by the surge capacitor, which reduces the blocking effect drastically. In bipolar arrangements, individual blocking filters must be provided for every pole. As the blocking filter is installed in the DC circuit of the HVDC system its reactor must be rated for the full HVDC direct current. Therefore, the blocking filter's reactor can be an additional smoothing reactor coil, which is advantageous with respect to spare parts.

Finally, it can be stated that for most LCC-HVDC systems, where a fundamental frequency voltage induction is to be investigated, AC and DC systems are built on separate towers and with a certain spacing between the individual systems' line routes, so that fundamental frequency blocking filters usually are not necessary even for the case of parallel lines running for portions with significant length.

4. Coupling impact on VSC converter

The coupling impact on VSC is different in comparison with the one in LCC due to the different paths of the DC side currents through the converter and due to the converter controls. The converter modules can be represented by six controllable voltage sources, which can separately change the voltage depending on control requirements (Figure 8). That means in VSC topologies a physical path through the converter is available for the DC current and any harmonic current coming from the DC side and the DC currents have not to be closed through the AC side as for the LCC.

Extending the methodology presented in [7], the DC side behaviour of the converter can be modelled by an ideal DC voltage source and a converter impedance (Figure 9). The DC converter impedance of a Modular Multilevel Converter (MMC) is defined by a passive impedance ($Z_{dc_passive}$), which is defined by the converter hardware such as DC reactors, converter reactors, DC filters and by an active impedance (Z_{dc_active}), which is defined by the converter control. Given the energy storage capability of

a VSC, the impact of the control on the converter behaviour is therefore significantly more effective compared with a LCC.

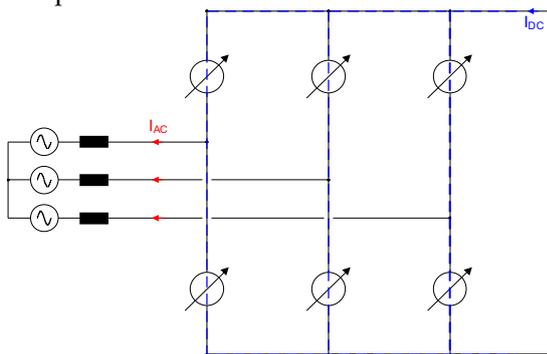


Figure 8: DC current path through a VSC.

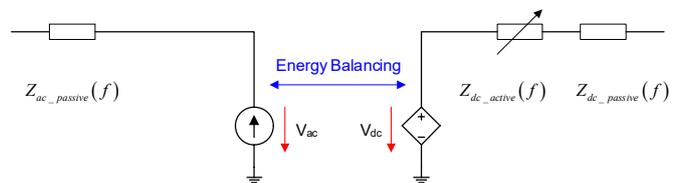


Figure 9: Modeling of the ac and dc converter behaviour.

The voltage sources and impedances of AC and DC side can be controlled independently. Due to the limitation of the converter energy, the AC and DC sides are coupled by the converter energy balancing requirements. With the given control capabilities, the negative effects of the fundamental frequency harmonics can be avoided by two control functions. The first control function increases the active impedance Z_{active} for the fundamental frequency, reducing therefore the fundamental harmonic current on the DC side. However, the increase of the active impedance Z_{dc_active} for the fundamental frequency might have negative effects on the dynamic performance. The second control function is the AC current control. On the AC side, the converter control emulates a current source behaviour by actively controlling the AC currents (I_{AC}). The emulation of the current source behaviour causes a high impedance for any other harmonics from the AC or DC side. This control function does not reduce the DC fundamental current but avoids the coupling of the DC current to the AC side of the converter, by injecting positive phase sequence currents.

The described system behaviour assumes an ideal converter control and identical parameters of the converter equipment in all phases. In case of any imperfection a cross modulation from the DC to the AC side might be possible, creating, in the worst case, a DC current on the AC side of the converter. Due to the accurate control capability of the VSC, this DC currents can be eliminated by implementation of an appropriate control function. The biggest challenge in DC currents elimination is not the control but the determination of these currents. Compared to nominal currents, the DC currents are significantly smaller, and are usually below the measuring tolerance of the current transducers required for the converter AC current control in a VSC. If an elimination function for the DC currents is required, an additional measuring channel with a reduced resolution amplitude and frequency can be installed.

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