Methodology for Modelling and Assessing Harmonic Impact of HVDC Connections in the Vicinity of Renewables

Kah Leong Koo and Zia Emin

***Abstract*–This paper presents a methodology to assess the harmonic impact of multiple HVDC connections and renewable generation in the vicinity of each other. It will study the impact of HVDC connections by using voltage source converter (VSC) and current source converter (CSC) technologies with an offshore wind farm connected in close proximity. The interaction of these connections is investigated using a generic multiple-node transmission network model that is constructed using typical parameters for the electrical models based on publicly available data or calculated by employing established theoretical models. The model and harmonic impact of the passive assets and harmonic emissions on the power system harmonic distortions are both studied and discussed. Sensitivities due to the HVDC interactions and offshore wind farm cable lengths are studied and presented using different study cases and adverse impact on harmonic levels is discussed.**

***Keywords*: harmonics, harmonic distortion, VSC, CSC, HVDC, offshore wind farm, cables, filters, PWM.**

I. Introduction

HVDC technologies are being used widely to facilitate the export and interchange of high power transfers from renewable generation to the main transmission system. While this offers a solution to export power to the main transmission system, there are challenges for HVDC connections connecting into a similar geographical location. This is the case where there are designated areas for offshore wind farm connections, all landing at specific areas of onshore transmission systems. More often than not, HVDC connections are technical solutions proposed in the vicinity to allow interchange of the power from renewable generation. This inevitably leads to a congested corridor in the main transmission system not only for the power transfer but also through the addition of extra harmonic levels in the area.

Based on a generic typical transmission system developed from an IET and IEEE paper, a practical example with two HVDCs connecting at a single onshore transmission system substation with several offshore wind farms in the vicinity can be constructed. Two different HVDC technologies will be used for these interconnections: one using voltage source converter (VSC) technology and the other current source converter (CSC) technology, representing the main competing technologies. Both of these HVDC connections cause voltage and current distortions at different frequencies with known characteristic and non-characteristic harmonics: lower order harmonics from CSC, and higher order harmonics dependent on the modulation techniques from VSC. Manufacturers can in effect deal with these known harmonic emissions from the converter plant, as they are based on design to a degree. However, where there are multiple HVDC connections potentially causing interaction between them, this could lead to problematic harmonic resonances previously not considered. The presence of renewable offshore wind farm generation connecting at onshore transmission substations in close proximity will exacerbate the problem. These offshore wind farm connections equally distort voltage and current via their power electronics and passive assets. These all result in the need to accurately identify where harmonic planning levels could be exceeded resulting in non-compliance and hence the need for mitigation.

This paper discusses a methodology to determine and evaluate harmonic levels using a simple generic multiple-node transmission network model with the two different HVDC connections and an offshore wind farm connection for illustration using a power system analysis tool. The HVDC models use typical publicly available data from known installations and theoretically determined harmonic emissions to explain the effects of these connections. The offshore wind farm connection is also modelled using typical publicly available parameters and its impact is investigated. Any adverse impact on the harmonics levels as a result of these connections is also discussed.

II. Impact of Harmonic Levels Due to Passive Equipment and Different Harmonic Generation

An example power system model is constructed and used in this paper to investigate the impact of harmonic levels due to HVDCs and an offshore wind farm. The harmonic levels in the power system are as a result of additional harmonic current injections from these connections and modification of existing harmonics on the system by the passive electrical assets of the connections. These can be summarized as follows:

- CSC HVDC harmonic generation – the converter bridge consists of thyristors which generates harmonic currents during its operation. The characteristic current harmonic order depends on the pulse number of the converter and causes additional harmonic distortion in the network.
- VSC HVDC harmonic generation – the converter bridge consists of IGBTs, GTOs and are self-commutated where different switching strategies can be applied. This

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produces harmonic emissions of a higher frequency and causes additional harmonic distortion in the network.

- Wind turbine harmonic generation – the nature of the harmonics generated depends on the wind turbine type (fixed-speed induction generator, doubly-fed induction generator, fully back-to-back AC/DC/AC converter) and causes additional harmonic distortion in the network.
- HVDC passive assets – cable assets, AC harmonic filters and transformers are passive equipment of HVDCs and do not generate harmonic currents. However, these assets affect the impedance of the network at different nodes at fundamental and at harmonic frequencies. As a result, harmonic levels in the power system are also affected and modelling of these assets is necessary to determine the modification in existing harmonic level in the network.
- Onshore wind farm passive assets – medium voltage (MV) onshore cable, offshore cable (MV and LV), reactors, transformers and AC harmonic filters are typical passive assets which do not generate harmonic currents. This has the same effect as in HVDC passive assets but in the case of offshore wind farms, the MV cables (typically at 132kV) are of substantial length and can significantly affect the harmonic impedance which could adversely affect the harmonic voltage distortion levels.

III. Description of Generic Case Model

A generic network model has been developed as shown in Fig. 1. The network model was constructed such that it represents a power system which consists of:

- a transmission network equivalent,
- two different technology HVDC connections,
- a typical offshore wind farm connection, and
- typical demands at grid supply points.

The data for the network components used are sourced from publicly available manufacturer data, publications and/or calculated based on established performance characteristics. Hence, for discussion purposes, the harmonic studies described in Section (IV) of this paper can emulate and simulate results closer to actual performance.

A. *Power system model description*

The power system model shown in Fig. 1 is constructed such that the power system comprises an adequate representation of the transmission network, grid supply points and the distribution network elements. The transmission network is modelled at 400kV by six interconnected nodes with a combination of overhead lines and cables. The six interconnected nodes include two nodes with demands from distribution networks, two reduced equivalents at transmission level and three connections (two HVDC converters and an offshore wind farm). A possible layout for the connection of the HVDCs and offshore wind farms has been presented previously [1]. The reduction of the transmission system to the two nodes at BUS2 and BUS5 where equivalent grid infeed GRID_EQUIV1 and GRID_EQUIV2 are connected could be extended further upstream into the transmission network depending on the strength of the network and its influence on the sensitivity of the connections studied. Table I lists the circuit data for overhead lines, cables and transformers used in the power system model chosen from either manufacturers or published information. Further explanation on the assumed data is summarized below.

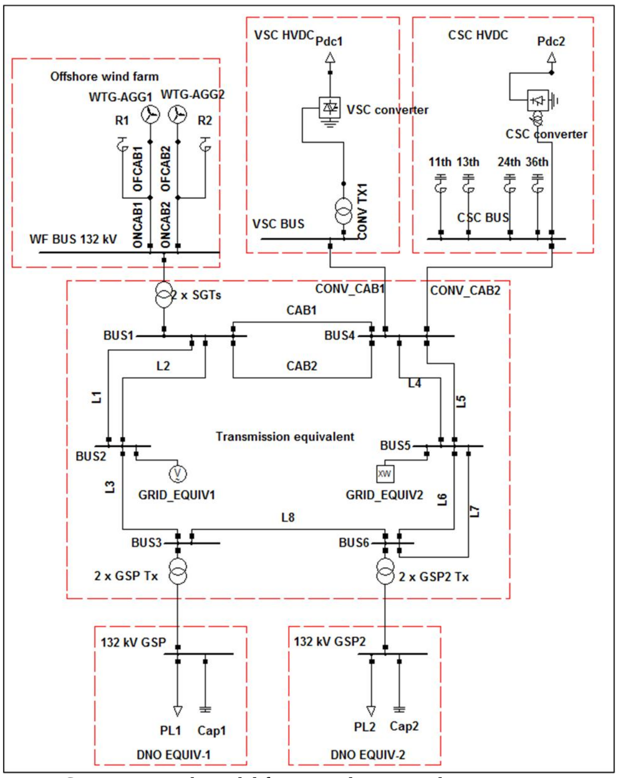

Fig. 1. Generic network model for example case study

- Overhead line – a 400kV, 4x400mm^2 ACSR phase conductors, 1x400mm^2 ACSR earth wire double-circuit overhead line was assumed [2]. Various lengths connecting the transmission nodes are as listed in Table II.
- Cables – a three-core 132kV XLPE with 800mm^2 Cu conductor [3] is used for the wind farm offshore cable (OFCAB1, OFCAB2). A single-core 132kV 2000mm^2 Alu conductor in trefoil formation [4] is used for the onshore wind farm cable sections (ONCAB1, ONCAB2) and a single-core 400kV 1600mm^2 Alu conductor in flat formation [4] is used for the transmission network and converter cables (CAB1, CAB2, CONV_CAB1, CONV_CAB2). The lengths assumed for the various cables are listed in Table II. However, where a range of lengths is given then these indicate that sensitivity studies have been performed to demonstrate the effects of the cable length on the harmonic distortion behaviour.
- Transformers – a 400/132kV 300MVA transformer with an assumed typical impedance and X/R ratio based on IEEE C37 standard was used for the power system model.
- Fault infeed – the equivalent transmission fault infeed at BUS2 and BUS5 each of 10GVA was assumed and

selected on the basis of a realistic fault level which will allow harmonic resonances and sensitivities of connections to be illustrated.

- Shunt reactors – shunt reactors were assumed to be 100Mvar each (R1 and R2) utilized to compensate the wind farm cables and were chosen based on design sizes of offshore wind farms [5].
- Demands – distribution demands at 132kV supply points were modelled to represent realistic damping offered by loads. A lumped capacitance was added to supplement their model such that it represents distribution system cable and power factor correction capacitors. This also illustrates resonance behaviour at the supply points. The demands were assumed to be at 80MW and 50MW at 0.97 and 0.93 power factors for PL1 and PL2 respectively. The lumped capacitance Cap1 and Cap2 are assumed to be 12Mvar and 5.6Mvar respectively, exhibiting resonance at the 5th harmonic at the supply nodes.

TABLE I
CIRCUIT DATA FOR NETWORK MODEL

POWER SYSTEM MODEL OVERHEAD LINE DATA			
LINES	R (Ω/km)	X (Ω/km)	C μF/km
L1, L2, L3, L4, L5, L6, L7, L8	0.017	0.004	0.014
POWER SYSTEM MODEL CABLE DATA			
ONCAB1, ONCAB2,	0.034	0.10	0.35
OFCAB1, OFCAB2	0.034	0.101	0.275
CAB1, CAB2, CONV_CAB1, CONV_CAB2	0.084	0.179	0.19
POWER SYSTEM MODEL TRANSFORMER DATA			
MVA Rating	% R on rating	% X on rating	X/R
300	0.3	12	40

TABLE II
CIRCUIT DATA FOR NETWORK MODEL

OVERHEAD LINE & CABLE LENGTH	
LINES	Length (km)
L1, L2, L3, L8	30
L4, L5	40
L6, L7	50
CONV_CAB1	5
CONV_CAB2	6
CAB1, CAB2	10
ONCAB1, ONCAB2	10 - 30
OFCAB1, OFCAB2	30 - 40

B. CSC and VSC HVDC model description

For the CSC HVDC, a 500MW, 450kV DC 6-pulse converter was assumed. The AC harmonic spectrum was calculated based on well-established theoretical equations with no dc-ripple and overlap is used for illustrating the full range of characteristic harmonics and its interaction with the other connections. The 6-pulse as opposed to the more common 12-pulse configuration is purposely chosen to allow the whole range of low order characteristic harmonics to be investigated. The calculated ideal harmonic current spectrum that was utilized in the power system model is shown in Fig. 2 [6]. The CSC converter also includes a 6km cable connection at 400kV from the converter station to the transmission network node. It is common for CSC HVDC to include harmonic filters mainly tuned to the characteristic lower order harmonics. Based on published data [7], harmonic filters of orders 11th, 13th, 24th and 36th are included in the model to illustrate their effect on harmonic resonances.

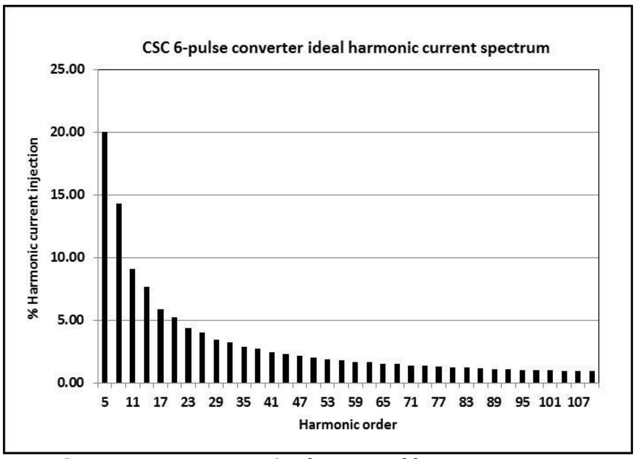

Fig. 2. Current source converter 6-pulse assumed harmonic spectrum

The AC harmonic generation characteristics of VSC HVDC depend on the modulation strategies and switching frequencies. In the power system model in this paper, a sinusoidal base PWM (SPWM) modulation strategy with a carrier frequency of 1350Hz and carrier ratio of 27 is assumed. This is selected to produce a harmonic spectrum at the higher order harmonics from 23rd upwards to allow the upper end of harmonics generated by this category of HVDC technology to be illustrated. The sideband harmonics generated from the selected modulation strategy are calculated using equation (1).

$$K_h = n \times p \pm m \tag{1}$$

where K_h is the harmonic orders generated, n is an integer number from 1 upwards, p is the carrier ratio and m is the modulation index. Based on equation (1) and an assumed modulation index of 0.8, an assumed theoretical maximum harmonic voltage spectrum across the harmonic range was produced as shown in Fig. 3 [8]. In the case of the VSC HVDC, no filters were assumed, but the impact of harmonic injections on filter requirements is discussed later in the paper. The VSC converter is modelled with an assumed 5km 400kV cable connection between the converter station and transmission network node.

C. Wind farm model description

An offshore wind farm that is representative of most layouts has been included in the power system model. This is categorized by MV cables at 132kV from the onshore to the offshore substations and connecting to the 400kV transmission system via 400/132kV transformers [9]. The offshore wind farm modelled consists of offshore subsea cables and a section of onshore cable. Based on offshore wind farm installations in the United Kingdom (UK), the cable lengths will vary depending on size and suitable sites within territorial waters. Considering the installed and planned offshore wind farms in the UK, it is important to look at the sensitivities to study the impact of the cable lengths on the harmonic resonances [10, 11].

Detailed manufacturer wind turbine generator (WTG) emission data at the turbine level are not modelled in the study. Instead the IEC 61000-3-6 aggregation method based on equation (2) was used [12] to derive injection currents for the purpose of illustrating the effect of the wind farm harmonic emissions as also referred to by IEC 61400-21 [13].

$$I_h = \sqrt[\propto]{\sum_j I_{hj}^{\propto}} \qquad (2)$$

where $\boldsymbol{I_h}$ is the magnitude of the resulting harmonic current (order $\boldsymbol{h}$), for all WTGs connected to one export circuit;
$\boldsymbol{I_{hj}}$ is the magnitude of each individual WTG at wind farm collector bus (order $\boldsymbol{h}$);
$\boldsymbol{\alpha}$ is the summation exponent dependent on the harmonic order as shown in Table III.

TABLE III
SUMMATION EXPONENT

Harmonic Order	Exponent α
$h < 5$	1
$5 \le h \le 10$	1.4
$h > 10$	2

For the power system model in this paper, it is sufficient to illustrate the contribution of harmonic injections from the wind farm by aggregating the WTGs injection at the remote end of the offshore collector bus for each of the two export circuits. The individual WTG harmonic current injection is based on measurements in an actual wind farm according to IEC 61400-21 measurement procedure [14]. This is aggregated for 70 WTGs for each export circuit and Fig. 4 shows the aggregated harmonic current spectrum of this offshore wind farm. It is assumed that filters for harmonic mitigation at the wind farm are not needed. This allows the effect of the wind farm cables and WTGs harmonic injections only to be distinctly studied on the HVDC harmonic performance.

IV. HARMONIC STUDIES AND DISCUSSION

A. Study cases considered

There are two areas of harmonic impact that were examined when studying the effects of the connections in the example power system model. They are:

- the harmonic voltage distortion due to the active harmonic current injections from the connections described, and
- the effects of the passive assets of the connections on the system resonances and hence background harmonics.

The study cases investigated the connections by firstly looking at the interactions of the HVDCs followed by the impact of the offshore wind farm on the HVDC connections. The various study cases are summarized in Table IV.

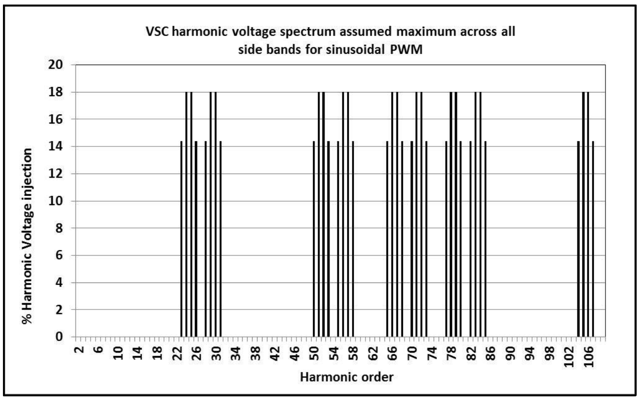

Fig. 3. Voltage source converter SPWM assumed harmonic spectrum

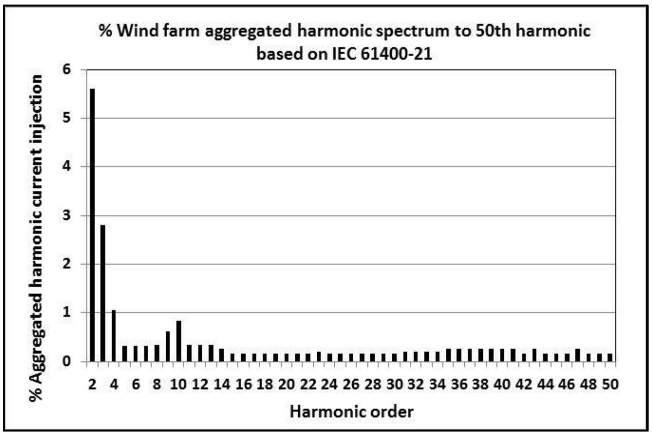

Fig. 4. Aggregated wind farm harmonic currents for one export circuit

TABLE IV
STUDY CASES

Study Cases	Description
P1	Intact with no HVDCs and offshore wind farm connections
P2	Only VSC HVDC connected
P3	Only CSC HVDC connected
P4	Both CSC and VSC HVDCs connected
P5	Both HVDCs and offshore wind farm (designated as C1 with onshore cable length = 10km, offshore cable length = 30km)
P6	Both HVDCs and offshore wind farm (designated as C2 with onshore cable length = 20km, offshore cable length = 35km)
P7	Both HVDCs and offshore wind farm (designated as C3 with onshore cable length = 30km, offshore cable length = 40km)

B. Impact of connections on power system harmonic resonances

The study results in this section show the frequency impedance plots calculated using DigSilent PowerFactory analysis software. The frequency scan plots are shown for BUS4 specifically to illustrate the effect of the passive assets of the HVDCs and offshore wind farm on the harmonic resonance characteristics.

Fig. 5 compares the frequency resonances for harmonic order $h \le 15$. This shows that case P2 does not shift the harmonic resonance significantly compared to P3 where shifting of resonance from 6.6 to near the 5^{th} harmonic order can be observed. Additional resonance near 11^{th} and 13^{th} are introduced from the AC filters of the CSC HVDC. When both HVDCs are connected, it is important to note that the resonance shifts higher up from 5.3 to 5.5 and will reduce existing 5th harmonic level in the power system.

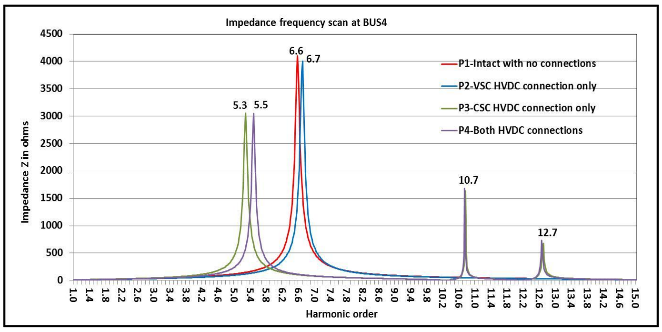

Fig. 5. BUS4 impedance frequency scan HVDC connections ($h\leq15$)

For $15<h\leq50$, the resonance at 19th has shifted to the 18th when the CSC alone and both HVDCs are connected as shown in Fig. 6. Resonance above the 22.5 has shifted higher to 23.5 and 23.7 for P3 and P4 cases respectively. Therefore, if there is existing 23rd background harmonic level measured on the system this could result in its amplification leading to higher levels of harmonic distortion and hence possible planning level breaches.

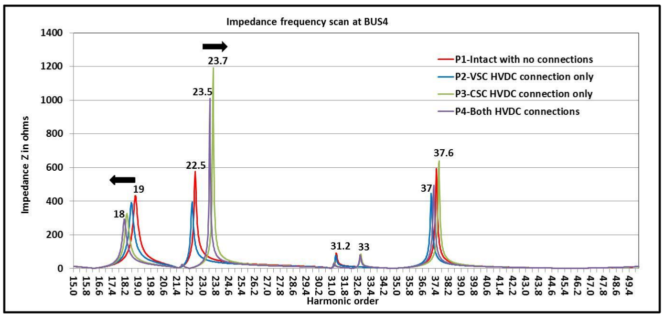

Fig. 6. BUS4 impedance frequency scan HVDC connections ($15<h\leq50$)

For $50<h\leq100$, all P2, P3 and P4 study cases of HVDC connections have lowered the resonant frequencies compared to an intact system as shown in Fig. 7. It is noted that the shift of the system frequencies is more significant in this range of harmonic frequencies. It is also noted that this shift in harmonic resonant frequencies is due to the cable connections between the converter stations (CSC BUS, VSC BUS) and the transmission node (BUS4). Hence, this could have an impact on the harmonic emissions from the VSC type HVDC where the harmonic spectrum is rich in this frequency range.

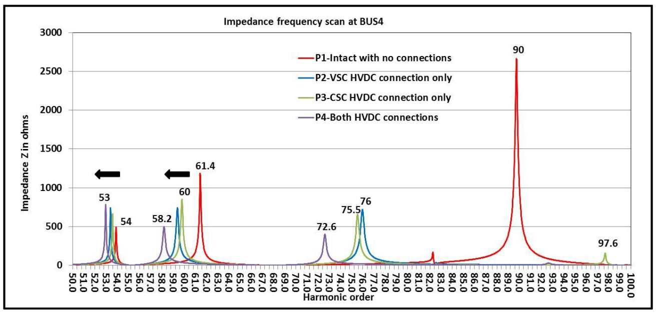

Fig. 7. BUS4 impedance frequency scan HVDC connections ($50<h\leq100$)

Considering the effect of the offshore wind farm, for $h\leq15$, all three wind farm cable lengths have a significant impact on the resonant frequencies. As shown in Fig. 8, the resonant frequency for P4 at h=5.5 has resulted in two resonant frequencies being generated to the left and to the right. The resonant frequency range to the left can vary from 3.6 to 4.6 while to the right can vary from 6 to 7 for the cable lengths studied. This can adversely affect the harmonic distortions especially from the HVDC when the resonant frequencies coincide with harmonic current emissions especially for the CSC HVDC or existing background harmonics can be amplified in this range. There is no effect on the resonant frequencies at h=10.8 and h=12.7 in this particular example due to the 11th and 13th AC harmonic filters of CSC HVDC.

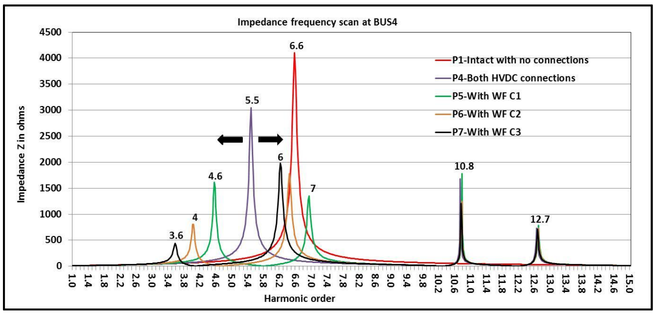

Fig. 8. BUS4 impedance frequency scan with wind farm effect ($h\leq15$)

For $15<h\leq50$ and for $50<h\leq100$ there is no noticeable effect on resonant frequencies due to the inclusion of offshore wind farm connection on the HVDC connections as shown in Fig. 9 and Fig. 10 for all the cable length combinations.

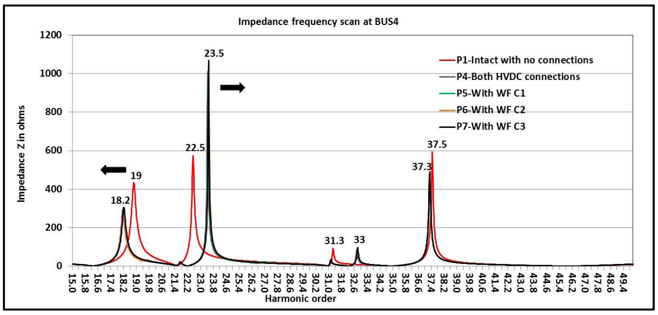

Fig. 9. BUS4 impedance frequency scan with wind farm effect ($15<h\leq50$)

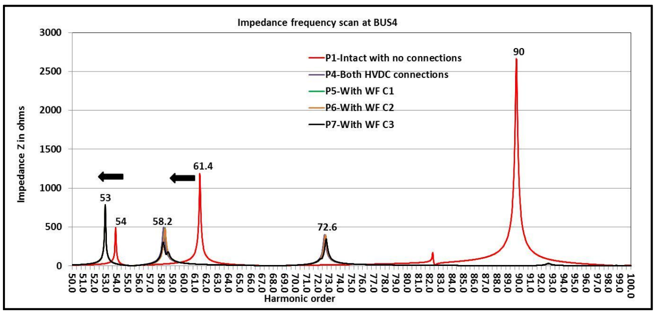

Fig. 10. BUS4 impedance frequency scan with wind farm effect ($50<h\leq100$)

C. Impact of power system harmonic distortions from active harmonic injections

The study results in this section show the harmonic voltage distortion plots calculated using DigSilent PowerFactory analysis software. The harmonic voltage distortion plots are shown for BUS4 to illustrate the effect of the different HVDC technology and offshore wind farm harmonic emissions on the harmonic distortion.

With reference to Fig. 11, it can be observed that when both HVDCs are connected (P4), the overall harmonic distortion has reduced compared to when the CSC HVDC is only connected (P3) for $h<20$, with noticeable reduction for $h=17$. This is due to the effect of the cable connection from VSC BUS to BUS4. The impact of the VSC HVDC harmonic spectrum can be observed from $h=23$ to $h=31$ and clearly shows the combined harmonic distortions; the CSC HVDC overlap is as expected, i.e. not a linear summation as given in Table V for the overlapping harmonic range.

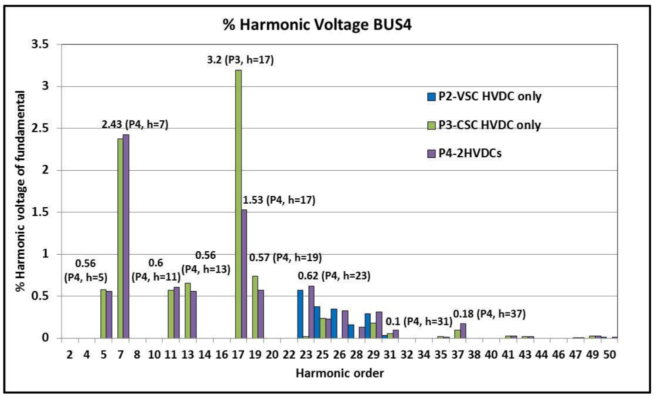

Fig. 11. BUS4 harmonic voltage distortion HVDC connections for $h \leq 50$

TABLE V

SUMMARY OVERLAPPING HARMONIC VSC AND CSC DISTORTIONS COMPARED

h	% Harm voltage distortion (as simulated in PowerFactory)			Linear summation (VSC only + CSC only)	Ratio of both HVDCs to linear summation
	VSC only	CSC only	Both HVDCs		
25	0.375	0.239	0.229	0.613	0.373
26	0.351	0.000	0.327	0.351	0.933
28	0.158	0.000	0.134	0.158	0.850
29	0.296	0.184	0.316	0.480	0.659
31	0.032	0.054	0.097	0.087	1.114

The rightmost column shows there is a slight amplification with a factor of 1.114 for $h=31$ and can be explained by the resonance observed at around 31st harmonic.

For $h>50$, the harmonic distortions from the VSC HVDC are more dominant as shown in Fig. 12. As can be seen for $h=58$ and $h=73$ case P4 with both HVDCs, resulted in significant harmonic distortion due to the resonant condition for these frequencies.

Fig. 13 illustrates the significant impact the offshore wind farm connection could have on harmonic distortions for the 4th and 7th harmonic. The graph compares the effect of cable length (study cases P5, P6 and P7) against the study case P4 with two HVDC connections. This is due to the shift in resonant frequency as well as being coincidental with the harmonic emissions. For P5, this effect can be seen on the significant harmonic distortion of 23.5% for $h=7$ and for P6, in high harmonic distortion of 5.2% for $h=4$. These are due to resonant frequencies as described for the different offshore wind farm cable lengths in the previous section. With the longest cable length combination (P7) studied, the harmonic distortion is less problematic than the shorter length combinations for this particular example power system. However, from Fig. 8, the shift of resonant frequency towards the 3rd harmonic for P7 could amplify existing background 3rd harmonic distortion level or result in high 3rd harmonic distortion attributed to any uncharacteristic 3rd harmonic injection from a CSC HVDC.

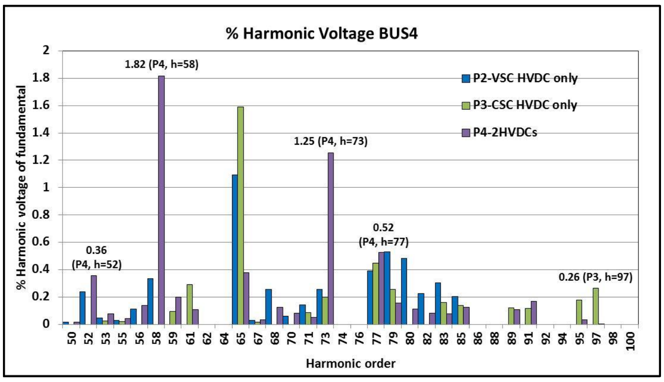

Fig. 12. BUS4 harmonic voltage distortion HVDC connections for $50<h \leq 100$

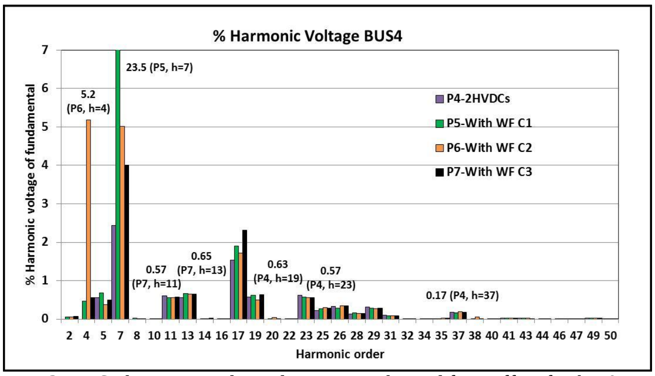

Fig. 13. BUS4 harmonic voltage distortion with wind farm effect for $h \leq 50$

For $h>50$, it is noted from Fig. 14 that some attenuation of harmonic voltage distortion at BUS4 is observed for the 58th and 73rd when the offshore wind farm is connected (P5, P6 and P7). This coincides with resonant frequencies of $h=53$ and $h=73$ also seen at BUS1 (for P4) which provides additional paths for the harmonic currents.

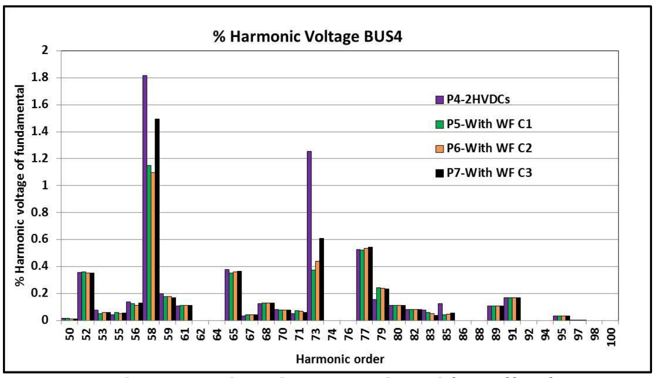

Fig. 14. BUS4 harmonic voltage distortion with wind farm effect for $50<h \leq 100$

V. CONCLUSIONS

A generic power system model has been developed and utilized to demonstrate a methodology for assessing the harmonic impact of HVDC connections in the vicinity of other HVDC and/or renewable energy sources. It is illustrated that multiple HVDCs affect each other and influence the harmonic distortion characteristic of the power system and hence it is necessary to model them discretely to study their interaction(s). It is shown that the cable connections of the HVDCs, although relatively shorter compared to the offshore wind farm cables, influence the harmonic resonances between the HVDC connection cases (P2, P3 and P4) that were studied and that the VSC type HVDC could be impacted more adversely at the higher end of the harmonic frequency spectrum.

It is also illustrated that an offshore wind farm connected in the vicinity of HVDC converter stations, further affects the harmonic resonance of the power system and could introduce additional resonances. The power system is shown to be particularly sensitive to the offshore wind farm cable lengths demonstrated by the typical ranges studied. For the example utilized in the paper, it was shown that the harmonic frequencies exhibit more sensitivity at the lower end of the harmonic spectrum (e.g. for $h \leq 15$).

Where both HVDCs are injecting harmonics in the same frequency range (demonstrated by overlapping harmonic spectrum between the two different technologies), then the overall combined harmonic distortion could be amplified or attenuated.

It was shown that at the higher harmonic frequencies ($h>50$) the resultant harmonic distortions from the VSC HVDC can be higher due to the emissions at this part of the frequency spectrum. This was demonstrated for the 58th and 73rd harmonic orders for the particular power system model. This condition is no better in the lower harmonic orders, where it was demonstrated that for the 4th and 7th harmonic orders, high levels of harmonic distortion could occur, influenced by the length of the offshore wind farm cables.

In summary, the paper demonstrates the need to consider various connection types together in order that their interactions can be analyzed. This approach will avoid development of incorrect mitigation solutions, which could occur when connections are assessed in isolation from each other. Furthermore, harmonic frequencies investigated in this paper for $h>50$ are shown to be necessary considering the VSC harmonic spectrum and more specifically their coincidence with power system resonances. However, it is not possible to determine the upper threshold of the harmonic range based on the studies performed in this paper.

VI. REFERENCES

[1] K. L. Koo, "Harmonic modelling for assessment of HVDC and Wind Farm for setting harmonic limits to a transmission system", The IET Power Quality Seminar: A holistic view of supply network protection, 6 November 2012, Birmingham, UK.

[2] N. Tleis "Power System Modelling and Fault Analysis – Theory and Practice" Elsevier, 2008.

[3] NKT cables GmbH, "High Voltage Cable Systems – Cables and Accessories up to 550 kV", www.nktcables.com

[4] PRYSMIAN Cables & Systems, "High Voltage Cables", www.prysmian.fi

[5] K. L. Koo, Z. Emin, S. Wijesinghe, D. Griffiths, "Triton Knoll Offshore Wind Farm Connection and Design Studies", PS1: Interaction between Transformer and the Power System, Cigre SC A2 & C4 Joint Colloquium 2013, 8th – 12th September 2013, Zurich, Switzerland.

[6] K. R. Padiyar, "HVDC Power Transmission Systems – Technology and System Interactions", John Wiley & Sons, 1990.

[7] B. Bergdahl – ABB Power Systems Sweden, Rebati Dass – ABB Limited India, "AC-DC Harmonic Filters for Three Gorges-Changzhou ± 500 kV HVDC Project", www.abb.co.uk

[8] J. M. D. Murphy & F. G. Turnbull, "Power Electronic Control of AC Motors", Pergamon Press, 1988.

[9] F. Ghassemi, K. L. Koo, "Equivalent Network for Wind Farm Harmonic Assessments", IEEE Transactions on Power Delivery, VOL 25, NO.3, JULY 2010.

[10] A. J. Hernandez M, S. Wijesinghe, A. Shafiu, "Harmonic Amplification of the 576 MW Gwynt-Y-Mor Offshore Wind Power Plant", 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, 13-15 November 2012, Lisbon, Portugal.

[11] http://www.4coffshore.com/windfarms/

[12] IEC TR 61000-3-6 Electromagnetic Compatibility, Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems, Ed. 2, 2008.

[13] IEC 61400-21 Wind Turbines – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines, Ed. 2, 2008-08.

[14] S. Tentzerakis, N. Paraskevopoulou et al., "Measurement of Wind Farm Harmonic Emissions", IEEE Power Electronics Specialists Conference, 15-19 June 2008, Rhodes.