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Vree, D.; Beloqui Larumbe, L.; Qin, Z.; Bauer, P.; Ummels, B.C.

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Impact of WTG converter impedance model on harmonic amplification factor of the Dutch 110 kV transmission network using a 383 MW wind farm case study

D. VREE[1]
Energy Solutions B.V.

L. BELOQUI LARUMBE
Z. QIN
P. BAUER
TU Delft

B.C. UMMELS
Windpark Fryslân
and TU Delft

The Netherlands

SUMMARY

In this decade, a significant amount of additional wind and solar power will be integrated in the Dutch high voltage grid. The 383 MW nearshore Wind Park Fryslân is foreseen to be connected to the Dutch 110 kV grid in 2020 through two 55 km cable circuits. To quantify the risks of exceeding emission levels for both the TSO and the wind farm developer, harmonic voltage distortion studies for such a project must already be performed at an early phase of the project. Relevant data of wind farm components may not yet be available then and must therefore be estimated including data of the wind turbine generator (WTG). The objective of this paper is to assess the impact of a WTG converter impedance model on the harmonic impedance of the windfarm and subsequent harmonic voltage amplification. For this purpose, an analytical converter harmonic model with tuneable parameters has been developed. A sensitivity study was performed in a case study of Wind Park Fryslân to analyse the impact of these parameters on the harmonic amplification at the Point of Connection with the 110 kV grid. The length and amount of array cables were also included in the study. The paper follows a step-wise approach where subsequently wind farm impedance, grid impedance and amplification factor have been calculated.
It has been found that the WTG converter impedance model has a significant impact on the harmonic amplification of low harmonic orders (h=2 to h=10). Notably, not taking the converter impedance into account (infinite impedance) results in both over- as well as underestimation of the harmonic amplification over the mentioned frequency range. It is shown that, when no WTG manufacturer has been selected yet, the analytical converter model provides a valid alternative for performing early-stage harmonic studies.

KEYWORDS
Harmonic impedance - harmonic amplification - wind turbine generator - converter model

[1] D.Vree@Ensol.NL

I. INTRODUCTION

In this decade, a significant amount of additional wind and solar power will be integrated in the Dutch high voltage grid. The 383 MW nearshore Wind Park Fryslân (WPF), consisting of 89 WTGs of 4,3 MW each, is planned to be fully operational by mid-2021. The wind farm is located in the North West part of the Netherlands in the IJssel Lake, next to the Afsluitdijk, as shown in Figure 1a. The link between WTGs and Point of Connection to the transmission network of the Dutch TSO TenneT is shown in Figure 1b and will consist of around 90 km of 33 kV (three-core sub-lake) inter-array cabling, two 33/110 kV power transformers (onshore) and two 110 kV (single core onshore) cable systems of 55 km each.

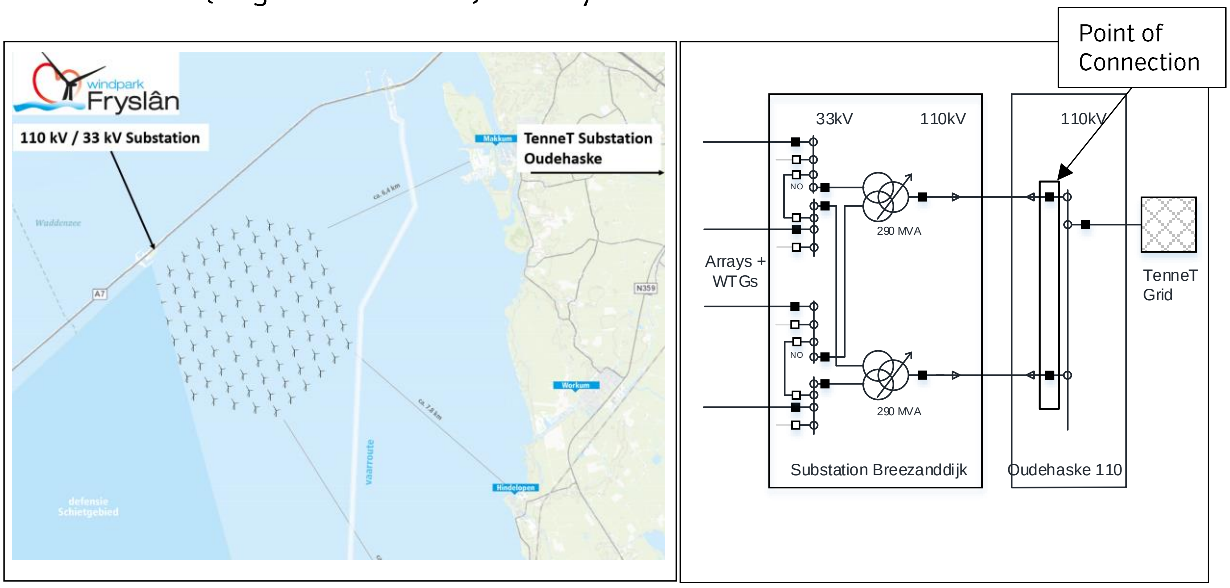

Figure 1 Wind Park Fryslân a) Location in the Dutch coast b) Simplified circuit diagram

Based on the long cable lengths and the low short-circuit power of the 110 kV transmission network, it was foreseen that the impact of WPF on the harmonic voltage distortion within the network could be significant. WPF and TenneT therefore decided to jointly perform harmonic voltage distortion studies already at an early phase of the project, to quantify the risks for both parties (i.e. possible need for harmonic filters) and prevent project delays later on (e.g. due to the need to resolve power quality issues or grid code non-compliance).

When performing such an early assessment, it must be noted that the final design of the electrical infrastructure is not available yet and relevant data of wind farm components must be estimated. Here not only the cable data play a role as addressed in for example [1] but also the WTG converter model which usually is provided by the manufacturer (see for example [2]). As in the early stage of any wind farm no WTG manufacturer has been selected yet, this also means that no WTG harmonic model is available. The question arises, to what extent harmonic voltage distortion studies can therefore still deliver meaningful results at a stage when such data and models are missing.

The objective of this paper is to assess the impact of a WTG converter impedance model on:

a) the harmonic impedance of the windfarm at Point of Connection and
b) the harmonic voltage amplification factor at Point of Connection.

For this purpose, a sensitivity study is performed in which the converter parameters are varied. As previous work mainly focussed on export cabling [1] but the sensitivity of the results to changes in the array cable system data is unknown, also this aspect is taken into account.

This paper is organized as follows. In section II, the methodology is presented where specific attention is given to the modelling of the WTG impedance, the key parameters to be considered and the step-wise study approach. In section III the results of the WPF case study are presented and discussed following the step-wise approach. Finally in section IV conclusions are drawn and recommendations are made for further work.

II. METHODOLOGY

Steady-state harmonic assessment

This paper follows the assessment method used by TenneT to evaluate the impact of a power park module (in this case a wind farm) on harmonic voltage distortion in the Dutch grid which is documented in both [2] and [3]. In this method the grid impedance is modelled by a Thevenin equivalent whose impedance consists of a frequency-dependent resistance and reactance. These are defined by a range where all possible grid conditions are taken into account, resulting in impedance envelopes (grid impedance loci).

The assessment then consists of the following three steps:

1) Calculation of the maximum background harmonic distortion amplification factor (k), where

$$k = \left|Z_{windfarm} / \left(Z_{grid} + Z_{windfarm}\right)\right|; \quad (1)$$

2) calculation of the new harmonic contribution at the Point of Connection caused by the WTG converters (V_{INC}); and
3) calculation of aggregate effect of background amplification and new harmonic contributions from

$$((k-1)*V_{BCK} + V_{INC}). \quad (2)$$

As the study is focussed on impedances only (and not on the new harmonic contribution by the WTGs), only the first step (harmonic voltage amplification) has been considered. For this purpose, both the grid impedance and the wind farm impedance were modelled as further explained in following sub-sections. At the end of this section (see sub-section Study approach), the details of the method for performing the first step are described.

In this paper only the low order frequencies are assessed, e.g. harmonic order 2 up to including 25 (100 Hz – 1250 Hz).

Grid Impedance Modelling (Z_{grid})

As introduced above, the grid impedance will be modelled by selecting R_{grid} and X_{grid} for each harmonic order from the corresponding impedance locus. For this selection an algorithm is used which determines the Z_{grid} which leads to the highest value of the amplification factor k using formula (1). As, in the case of this paper, a sensitivity study is done that leads to different wind-farm impedances, the procedure of selecting Z_{grid} and calculation of the highest amplification factor is repeated for each $Z_{windfarm}$. The resulting amplification factors for each scenario will be compared.

The impedance loci used in this study are the actual loci as WPF received from TenneT. An example is shown in Figure 2.

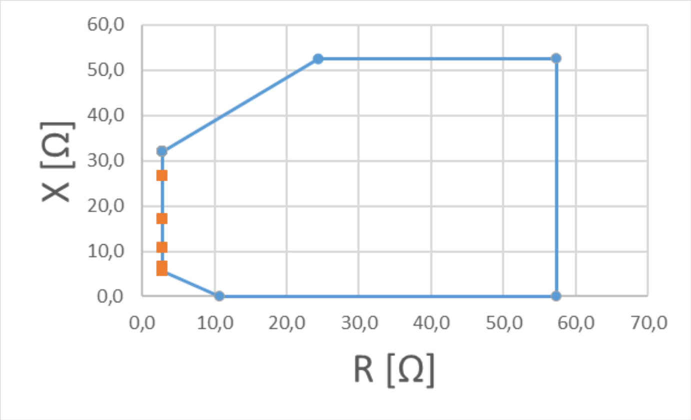

Figure 2. Impedance locus of WPF for harmonic orders h=5 to h=9. The orange markers are the impedance points for case S1 (see below for explanation of cases) leading to the highest k for each h.

It is noted that the number of possible grid configurations is very large and that many grid conditions do not occur frequently (e.g. N-1 and N-2 situations). After the complete assessment, a separate assessment of the risk of occurrence of the highest k can be made. This falls outside the scope of this paper.

Wind Farm Modelling

The wind farm impedance $Z_{windfarm}$ at Point of Connection has been determined by the frequency impedance scan function of the simulation tool Power Factory using a full scale wind farm model including 89 converter WTG impedances, WTG transformers and respective array cable sections. Also the two 33 kV to 110 kV main transformers and two 55 km export cable circuits have been included in the windfarm model.

In order to study the impact that different elements have on *k*, a sensitivity study was performed. In this study, some WTG converter and array cable parameters were varied, while the transformers, export cable and grid impedance models remained unchanged.

Even if for certain studies it can be interesting to calculate and compare different levels of aggregation of the wind farm, for the purpose of this paper (sensitivity study of the effect of WTG converter on k) it was just necessary to aggregate the whole wind farm in one single impedance. That is why the frequency impedance scan will be performed at the point of connection. This aggregated impedance could then also be used by TenneT to assess the impacts of other network additions within the TenneT Grid on steady-state harmonics.

WTG converter modelling

Generic full-converter model

For the WTG converter impedance a generic full-converter WTG impedance model is used which was developed by TU Delft as part of the LowHarm project [4]. A representation of the WTG harmonic impedance model is shown in Figure 3. The impedance Z_{conv} includes the first stage of the converter passive filter (an inductor per phase) and the most significant control loops; whereas $Z_{PWM\ filter}$ represents the other filter stages (e.g. a capacitor and an inductor to form an LCL filter or several trap-filters in parallel).

It is noted that the model is analytical, so it is possible to obtain different WTG impedances depending on the converter parameters. The model includes a double Synchronous Reference Frame Current control, which is typical in the latest onshore and offshore wind turbine converters [5-8]. The model was developed using the theory of transfer matrices and complex transfer functions [9] and has been published in [10].

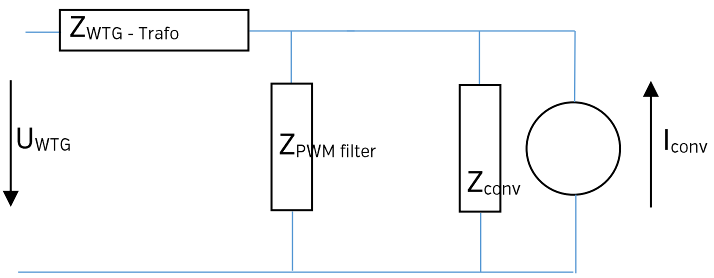

Figure 3 WTG impedance model

Model evaluation and parameter ranges
In order to evaluate the analytical model and in order to properly tune its parameters, various models developed by WTG manufacturers have been reviewed. For confidentiality reasons, the main characteristics and the authors' observations are presented in a generic way and bear no relation to one specific model. Not all manufacturers provide a separate model for Z_{conv}. Instead they provide an aggregate impedance, either 1) including all three impedances shown in Figure 3 or 2) only the impedances of the external passive components (neglecting Z_{conv}). Generally, WTG impedance models of the same type of WTG (full converter, type 4) and power level should provide similar results. It is noted that specific manufacturers are capable of adding control changes tuned at a limited number of frequencies, which could lead to significant differences of the impedance at those frequencies. This aspect is specifically investigated in case S2 (see below).

Parameter selection and delineation
The following set of parameters were selected as the base case for this study and the resulting impedance is shown in Figure 4. Compared to the other WTG impedances this impedance shows typical behaviour with a general inductive behaviour and smooth curves over both resistance and reactance.

- Switching frequency: 2,5 kHz.
- Nominal AC voltage: 690 V.
- Rated power: 4,3 MW.
- Current control bandwidth: 530 Hz.
- Phase-Locked Loop (PLL) bandwidth: 30 Hz.
- Line reactor: 19µH (0,054 p.u.).
- Line reactor resistance: 5 mΩ (0,045 p.u.).

Figure 4 WTG converter impedance Z_{conv} of base case S1

In order to limit the complexity of the model, the external PWM filter was not considered in this study as this is usually tuned to higher frequencies than considered in this study.

The assumption is that, if a realistic control structure and line reactor design have been chosen, then varying certain parameters in the analytical model will provide realistic results. In the sensitivity study, the following parameters have been varied: switching frequency, bandwidth of current control, active power output, and size of the output inductor, amongst others. The following WTG converter impedance scenarios will be presented in this paper where parameters were selected on their impact on the harmonic gain (k):

- S0: no converter connection (infinite impedance)
- S1: base case (described above and shown in Figure 3)
- S2: Addition of a virtual impedance in the control structure
- S3: Current control bandwidth +10%
- S4: Current control bandwidth – 10%
- S5: Switching frequency +20% (which decreases the overall control and modulation delay by 17% approximately)
- S6: Switching frequency -20% (which increases the overall control and modulation delay by 25% approximately)
- S7: reference case (impedance of existing WTG[1])

Further cases for the sensitivity study were selected as follows to study the impact of array cables and amount of WTGs on the amplification factor k (with converter impedance of S1):

- S11: Array cable length minus 10%
- S12: Array cable length minus 50%
- S13: One array cable string + WTGs switched off (93% WTGs)
- S14: Six array cable strings + WTGs switched off (49% WTGs)

For array cables and export cables, a frequency dependent impedance model was used based on the results as presented in [11].

Study approach

The study will be performed through the following steps:

1. Determination of wind farm impedance at Point of Connection without taking into account the impedance of the transmission network for all cases.
2. Assess and discuss resonances within the wind farm.
3. For each harmonic order h: determine Z_{grid} within the impedance loci resulting in the highest harmonic gain (k) using the wind farm impedance, with infinite WTG impedance S0, and the base case WTG impedance S1
    a. Result: Z_{grid} (R_{grid}, X_{grid}) and resulting k of each harmonic order for S0 and S1
4. Determination of the amplification factor k using the fixed grid impedance (Z_{grid}) of S1 for other wind farm impedances as found in step 1 (scenarios S2-S7, S11-S14)
    a. Result: k of each harmonic order and each case
5. Assess and discuss changes in harmonic amplification at Point of Connection and how the WTG converter model influences the corresponding amplification factors.
6. For scenario's with significant change of k on certain harmonic orders, determine new Z_{grid} within impedance loci resulting in the highest (worst case) k for the wind farm impedance of that scenario.
    a. If in 6 k is still significantly lower, the specific scenario Sx has a positive effect on k for that harmonic order

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[1] Due to confidentiality, only a general comparison to the base case S1 has been included.

III. RESULTS AND DISCUSSION

Windfarm impedance at Point of Connection (step 1)

The frequency dependent impedances at Point of Connection of cases S0, S1, S2, S3, S4, S12 and S14 in the sensitivity analysis are shown in below figures. The results of other cases have been omitted for readability of the figures and limited difference to the S1 case.

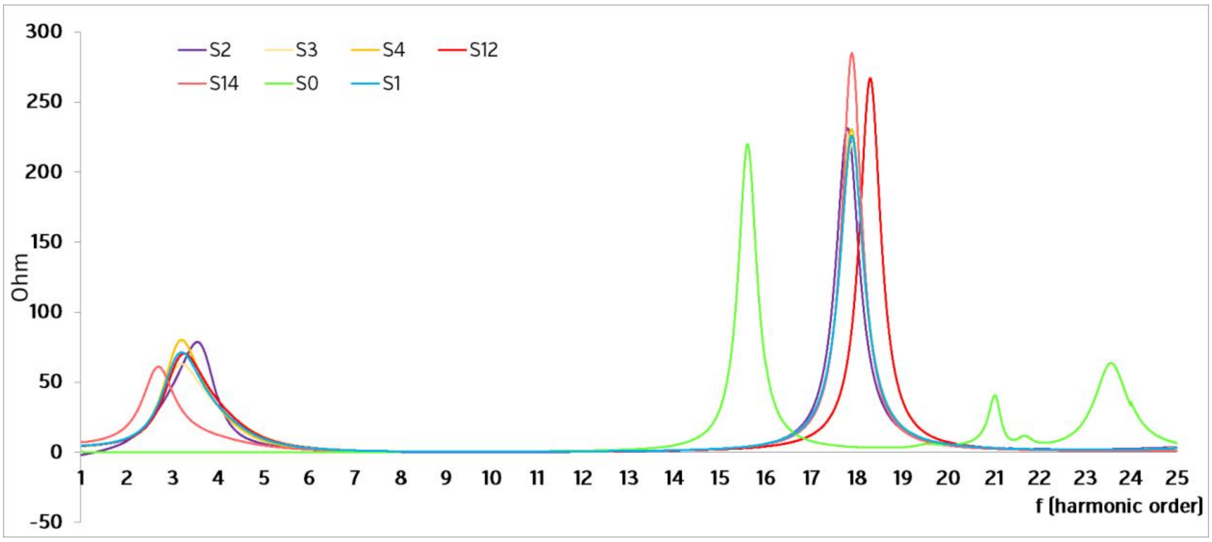

Figure 5. Resistance at Point of Connection for 7 cases investigated

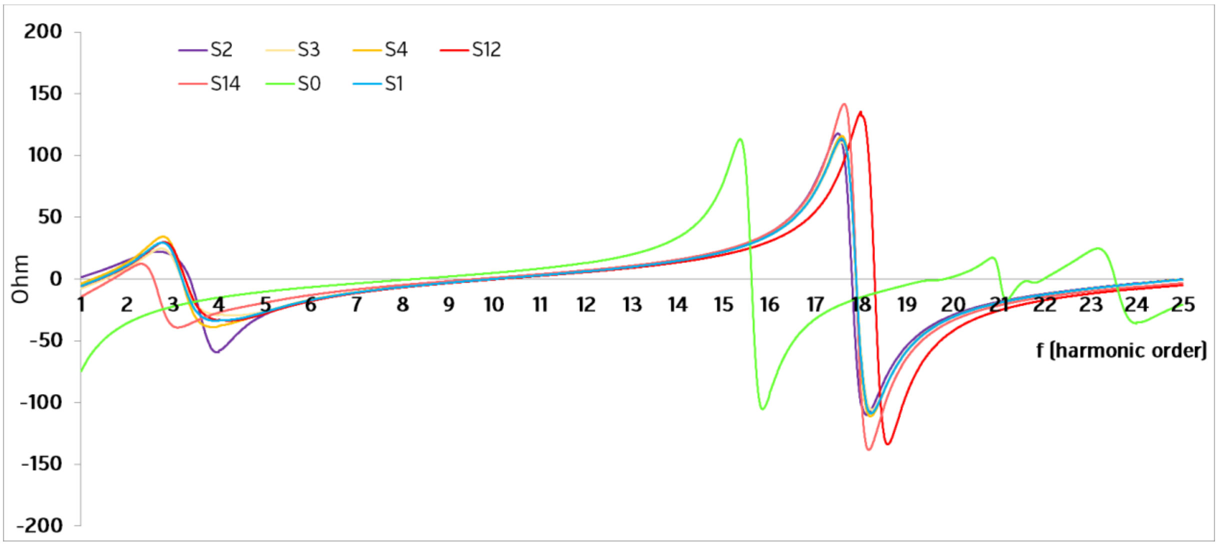

Figure 6. Reactance at Point of Connection for 7 cases investigated

Assessment of resonances (step 2)

When analysing formula (1) on page 3, it is noticeable that the amplification factor becomes very high when $Z_{windfarm}$ cancels out Z_{grid}. This situation occurs whenever the $X_{windfarm}=-X_{grid}$ and the resistances $R_{windfarm}$ and R_{grid} are low. In the low frequency range, a HV grid is typically inductive and an (offshore) windfarm capacitive due to the long export cable leading to a high risk of large amplification factors and subsequently high harmonic distortion.

When looking at Figure 6 to case S0 (the case without the converter model), a clear capacitive behaviour of the system from h =2 tot h = 10 can be noticed.

With the converter, an inter-farm parallel resonance is introduced at 170 Hz, approximately. This is a resonance between the capacitive export cable, the main 33kV/110kV transformers and the WTG inductance. This resonance is very important because it significantly changes the $Z_{windfarm}$ in this frequency range and therefore the amplification factor. It makes the windfarm inductive for h=2 and h = 3 but more capacitive for h = 4 to h = 9. This shows the importance of the WTG converter impedance in this frequency range. One step further and one of the key points of this sensitivity study, then, is to see how the different scenarios affect this resonance.

Reduction of array cables (S12) has no influence on this first resonance (small shift on the main resonance at h = 18). Only S14 has a clear impact which is the result of the significant reduction of WTGs (only 44 instead of 89). Varying current control bandwidth (S3/S4) has a small but significant impact on the damping of both resonances, although not so much on the frequency at which they appear. Changing of the switching frequency (S5/S6) has almost no impact.

The significant impact of S14 shows that the converters could influence the frequencies of these resonances, however a very radical change should be done to the converter impedance in order to match the effect of having half of the number of WTGs disconnected. With this idea in mind, scenario 2 was proposed. In this scenario, a virtual impedance was added to the converter control following guidelines in [12] which has an impact on the wind farm impedance in the frequency range 100 – 250 Hz (h = 2 to h = 5).

Determination of amplification factor of cases S0 and S1 (step 3)

In the below table the amplification factors are shown as derived from the impedances of cases S0 and S1. For S0 high amplification factors were found for h = 2 to h = 6 whereas this range was shifted for S1 to h=4 to h=8. This change is caused by the inter-farm resonance as discussed in step 2.

Table 1. $Z_{windfarm\ (wf)}$, Z_{grid} and amplification factor k for cases S0 and S1

	Case S0					Case S1				
h	R_{wf} [Ω]	X_{wf} [Ω]	R_{grid} [Ω]	X_{grid} [Ω]	k	R_{wf} [Ω]	X_{wf} [Ω]	R_{grid} [Ω]	X_{grid} [Ω]	k
2	0,21	-35,81	6,90	24,10	2,61	10,07	11,01	0,20	0,70	0,96
3	0,19	-22,29	5,08	19,97	3,87	62,27	20,90	0,20	0,70	0,99
4	0,21	-15,05	2,40	13,89	5,27	33,80	-33,35	3,70	16,83	1,16
5	0,22	-10,22	2,80	10,24	3,38	9,83	-26,69	2,80	26,71	2,25
6	0,26	-6,60	2,80	6,60	2,16	3,25	-17,09	2,80	17,10	2,88
7	0,29	-3,53	2,80	5,70	0,94	1,35	-10,83	2,80	10,82	2,63
8	0,36	-0,76	3,04	5,53	0,14	0,74	-6,48	2,80	6,49	1,84
9	0,43	2,02	4,30	4,63	0,25	0,53	-3,01	2,80	5,70	0,72
10	0,57	5,00	8,21	2,23	0,44	0,50	0,04	5,80	5,15	0,06

Determination of amplification factor of other cases with fixed Z_{grid} and assessment (step 4 and 5)

With the fixed R_{grid} and X_{grid} of S1, the amplification factors of the other cases have been determined and are shown in Table 2. The red and green colors highlight the highest and respectively lowest amplification factors.

Table 2. Amplification factors k of all cases with a fixed Zgrid as determined for case S1

	S1			S2	S3	S4	S5	S6	S7	S11	S12	S13	S14
h	R_{grid} [Ω]	X_{grid} [Ω]	**k**	**k**	**k**	**k**	**k**	**k**	**k**	**k**	**k**	**k**	**k**
2	0,20	0,70	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,98
3	0,20	0,70	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	1,00	1,01
4	3,70	16,83	1,16	1,17	1,13	1,18	1,17	1,14	1,08	1,15	1,13	1,21	1,55
5	2,80	26,71	2,25	3,21	1,99	2,51	2,23	2,30	2,75	2,24	2,20	2,28	1,84
6	2,80	17,10	2,88	3,60	2,67	3,05	2,78	3,05	4,07	2,89	2,92	2,82	2,07
7	2,80	10,82	2,63	3,10	2,58	2,67	2,54	2,79	3,17	2,65	2,73	2,54	1,87
8	2,80	6,49	1,84	2,11	1,86	1,82	1,79	1,92	1,89	1,86	1,95	1,75	1,27
9	2,80	5,70	0,72	0,74	0,75	0,69	0,71	0,72	0,54	0,74	0,85	0,63	0,35
10	5,80	5,15	0,06	0,03	0,06	0,06	0,07	0,05	0,08	0,06	0,07	0,07	0,14

Table 2 shows that, even if not exactly equal, the analytical model (S1) provides a realistic approximation of the harmonic amplification factors in comparison to the impedance used in the reference case (S7). On the one hand, the magnitudes do not seem to be exactly equal; however, the frequency ranges in which high amplification factors appear are properly estimated. Thus, when in an early stage of wind farm development no WTG manufacturer has been selected yet, the analytical converter model provides a valid alternative. Note also on Table 1 that not including any converter model (S0) provides unrealistic results.

The results show that even with significant changes to the converter model (S2, S7), array cable system (S12) or both (S14) the range of high amplification does not shift (h = 4 to h = 8) as it is the case when comparing S0 to S1. The reason for this is that the inter-farm resonance of step 2 has not been shifted sufficiently to cause any effect. Further study is needed to see if, with a different design of the virtual impedance S2, the first inter-farm resonance could be shifted to higher frequencies, so that $Z_{windfarm}$ becomes either inductive or very capacitive around the 5^{th}-7^{th} harmonic (frequencies in which having a high amplification factor is undesirable).

However, the results do show that the magnitude of the amplification can be significantly influenced if modifications are done to the converter model (S2-S7). This is mainly caused by changes in magnitude of $R_{windfarm}$ and $X_{windfarm}$ which directly impact the amplification factor k as can be derived from formula (1). For example, a higher $R_{windfarm}$ [h] will lead to a lower k [h].

Finally it is noted that even a significant change to the array cable system (50% length reduction, S12), leads to almost no effect on the amplification factors. This is due to the long export cable length used in this case study which is dominating the results in the lower frequency range. For a wind farm with short export cable length, changes to the array cable system may have more impact on the harmonic gain.

Determination of amplification factor with new selection of Z_{grid} (step 6)
To further analyse the effect on changes to the windfarm impedance on harmonic gain, for cases with a large variation of k compared to S1, the factor k has been recalculated with a new Z_{grid} selected from the impedance loci. These new amplification factors are shown in Table 3 and are higher than the corresponding factors in Table 2. Only in the frequency range with high amplification factors (h= 5 to 7), a significant change was found for case S14 where the positive reductions compared to S1 in Table 2 are much lower or even changed to an increase of amplification compared to S1 (for h = 5). This example shows that a change in

windfarm impedance leading to lower amplification may be completely cancelled by the wide range of grid impedances resulting from the impedance loci.

Table 3. Amplification factors k with new Z_{grid} for each case

	S0	S1	S2	S3	S7	S14
h	**k**	**k**	**k**	**k**	**k**	**k**
2	2,61	0,96	0,96	0,96	0,96	0,98
3	3,87	0,99	0,99	0,99	0,99	1,12
4	5,27	1,16	1,22	1,14	1,09	1,57
5	3,38	2,25	3,29	2,00	2,88	2,56
6	2,16	2,88	3,60	2,67	4,07	2,71
7	0,94	2,63	3,10	2,58	3,23	2,23
8	0,14	1,84	2,11	1,86	1,94	1,37
9	0,25	0,72	0,74	0,75	0,54	0,35
10	0,44	0,06	0,03	0,06	0,08	0,14

IV. CONCLUSION

This paper describes a case study on harmonic amplification at the Point of Connection caused by a large wind farm connected to the Dutch 110 kV grid with a specific focus on the WTG converter impedance model.

The study shows that the WTG converter impedance model has a significant impact on the harmonic amplification of low harmonic orders (h=2 to h=10) and that this model shall therefore be carefully selected. Not taking the converter impedance into account will result in both over as well as underestimation of the harmonic amplification over the whole frequency range (case S0 compared to S1 and S7).

When in an early stage of wind farm development no WTG manufacturer has been selected yet, the analytical model as proposed in this paper provides a valid alternative leading to similar results as the reference case with a manufacturer model (S7).
Importantly, such results allow for early identification of the critical harmonics, the likelihood of harmonic level exceedances and thereby the need for harmonic filters.

Also, this paper shows that converter modifications can alter harmonic voltage amplification across a certain frequency range. Thus, it is expected that these control modifications could help to mitigate harmonic voltage amplification issues which could be of help in the current and future wind farm designs. However, this concept must be studied further in order to verify the concept and to develop a general methodology for designing a virtual impedance as proposed in case S2. Not only it is challenging to modify the wind farm impedance as desired, but even if a specific wind farm impedance is designed in order to reduce the amplification factor k for a specific grid impedance, when re-assessing the whole grid impedance loci the changes that seemed beneficial at first might turn out to be detrimental.

A last conclusion is that array cables have a minor impact on the harmonic impedance of the wind farm compared to the long 55 km export cable.

V. ACKNOWLEDGEMENT

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BIBLIOGRAPHY

[1] F. Barakou, C. F. Jensen, G. Lietz, M. VAL ESCUDERO, "Impact of uncertainties in HVAC cable modelling on transmission system harmonic behaviour", Cigré session 2018, C4-304

[2] R. de Groot, F. van Erp, K. Jansen, J. van Waes, M. Hap, L. Thielman, "Method for Harmonic and TOV Connection Impact Assessment of Offshore Wind Power Plants - Part I: Harmonic Distortion", in Proc. The 17th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants (17th Wind Integration Workshop), Stockholm, Sweden, 2018.

[3] Eirgrid, "Power Quality Requirements for Connection to the Transmission System", revision 1.0 of September 2015.
http://www.eirgridgroup.com/site-files/library/EirGrid/Note-on-Harmonics-Power-Quality-Requirements-for-Connection-to-Transmission-System.pdf

[4] LowHarm: NL focussed research project "Large Offshore Wind farm Harmonics Mitigation". https://projecten.topsectorenergie.nl/projecten/large-offshore-wind-harmonics-mitigation-00029042

[5] L. Shuai, R. Sharma, K. H. Jensen, J. N. Nielsen, D. Murcia, S. Pirzada, P. Brogan, and P. Godridge, "Eigenvalue-based stability analysis of sub-synchronous oscillation in an offshore wind power plant," in 17th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Power Plants (17th Wind Integration Workshop), Stockholm, Sweden, Oct 2018.

[6] Ł. H. Kocewiak, J. Hjerrild and C. L. Bak, "Wind turbine converter control interaction with complex wind farm systems," IET Renewable Power Generation, vol. 7, pp. 380–389, July 2013.

[7] M. Bollen, J. Meyer, H. Amaris, A. M. Blanco, A. Gil de Castro, J. Desmet, M. Klatt, . Kocewiak, S. Rönnberg, and K. Yang, "Future work on harmonics - some expert opinions part i - wind and solar power," in 2014 16th International Conference on Harmonics and Quality of Power (ICHQP), pp. 904–908, May 2014.

[8] P. Brogan, "The stability of multiple, high power, active front end voltage sourced converters when connected to wind farm collector systems," in 2010 Electrical Power and Energy Conference (EPEC), 2010.

[9] X. Wang, L. Harnefors, and F. Blaabjerg, "Unified impedance model of grid-connected voltage-source converters," IEEE Transactions on Power Electronics, vol. 33, pp. 1775–1787, Feb 2018.

[10] L. Beloqui Larumbe, Z. Qin, P. Bauer, “Output Impedance Modelling and Sensitivity Study of Grid-Feeding Inverters with Dual Current Control,” IEEE 45th Annual Conference of the Industrial Electronics Society (IECON 2019), October 2019.

[11] Cigre report C4.309, “Impact of Cable Impedance Modelling Assumptions on Harmonic Losses in Offshore Wind Power Plants ”, Cigré sessions 2018.

[12] X. Wang, Y. W. Li, F. Blaabjerg and P. C. Loh, "Virtual-Impedance-Based Control for Voltage-Source and Current-Source Converters," in IEEE Transactions on Power Electronics, vol. 30, no. 12, pp. 7019-7037, Dec. 2015.