Parameter analysis on the Harmonic Amplification for Offshore Wind Power Plants: a Case Study in the Netherlands

F. Barakou, G. Ye, K. Koreman, M. Westbomke, A. Menze

***Abstract*—In the design phase of connecting wind power plants (WPPs) to the transmission network, harmonics amplification due to different system parameters (e.g. the long HVAC cable connection) need to be determined. Not all parameters to calculate the harmonic voltage distortion gain are known in detail. The aim of this paper is to analyze the impact of some uncertainties on the harmonic voltage distortion gain by the use of a real case study. Impacts of several aspects, such as network condition (e.g. transmission network contingencies and WPP contingencies), modeling approach (cable modeling) and parameter uncertainties (e.g. cable capacitance), are investigated via simulations. It can be concluded that the transmission network contingencies as well as the Windfarm contingencies have the most significant effect on harmonic amplification. The effect of the export cable modeling is also noticeable while the cable capacitance uncertainties have a less critical effect on harmonic amplification.**

***Keywords*—Harmonic impedance, harmonic amplification, transmission network, wind power plants, network modelling**

I. Introduction

During the design phase of connecting large offshore wind power plants (WPPs) to the transmission network, the connection requirements need to be considered, including power quality in terms of harmonic amplification. The application of long cables (and sometimes power factor correction, filters etc.) can cause resonances between the offshore WPP and the transmission network. Next to the emissions of the WPP the harmonic amplification factor needs to be assessed at the Point of Connection (PoC) when a new WPP is to be connected to the grid. This is because both phenomena can lead to the amplification of existing background distortion levels [1]. The aim of this research is to identify the important parameters, together with the associated uncertainties, which are crucial for a Transmission System Operator (TSO) to know when estimating the harmonic amplification before the connection of a new wind farm. The results will support the decision process for investing their limited resources into the analysis of more critical parameters compared to the ones having less impact. A case study in the Netherlands is used to analyse the impact of various parameters on the resulting harmonic amplification.

The transmission network, the cable system and the WPPs, all have impact on the resulting harmonic amplification at the PoC. In [2], [3], the harmonic issue due to the offshore WPPs was discussed, in terms of the resonance with the connected grid and the collection system. The impact due to the long HVAC cable in the transmission grid was investigated in [4], [5]. The impact of uncertainties in HVAC cable modeling to harmonic behaviour is analyzed in [6]. In [7] transfer admittance and current transfer functions are used to study primary and secondary emissions in wind power plants between the turbines and the public grid. In this way it possible to assess harmonic propagation and the risk of high distortion levels without detailed knowledge of the emission from individual turbines.

In [8], an impact study was performed including the transmission system, cable system and WPP, however excluding the various High Voltage (HV) system states (e.g. N-1 or N-2 contingencies). This could be insufficient since it is important to cover all operational states in the design phase for connecting new WPPs to obtain all possible amplification factors and to identify critical conditions. The cable modeling has a significant impact on the calculation of harmonic amplification factor. Therefore, it is necessary to know how these effects will alter the harmonic amplification factor for the entire system. Furthermore, during the design phase of a WPP there are several uncertainties mainly due to the fact that the components and their parameters have not been chosen yet, and due to manufacturing tolerances. Therefore, the impact of these uncertain parameters to the harmonic amplification needs to be quantified. The harmonic impedance of WPPs is also very important on the harmonic amplification [9]. In this paper, a real case of two offshore WPP connections in the Netherlands is simulated. Based on a base case the impact of transmission network operational states, offshore WPP operational states, cable modelling and uncertainty of cable capacitance are analyzed and their impact is quantified. Frequency sweeps are used to calculate the harmonic amplification factor and the results are given covering all transmission system operational states (N, N-1, N-2).

Section II describes the method for calculating harmonic amplification factor and the modeling approach for both the transmission network and the offshore WPP is presented. In section III the harmonic impedance and harmonic amplification factor results of the case study are presented. In Section IV conclusions are drawn.

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II. Methodology

In order to evaluate the increment of the harmonic voltage amplification before and after connection of the offshore WPPs, the index harmonic amplification factor need to be calculated as given in (1).

$$HG = \left|\frac{Z_W}{Z_W + Z_g}\right| \tag{1}$$

where:

- Z_g indicates the harmonic impedance of the grid at the Point of Evaluation (PoE)
- Z_W indicates the harmonic impedance of the WPP that is connected including the export cable to the WPP.

Fig. 1 shows the schematic overview of the connection of a new WPP to the grid. The background harmonic voltage distortion is represented as V_g and I_W represents the emission of the WPPs. To quantify the impact due to the variation of individual parameters, a base case is defined as a reference for comparisons with results based on model parameter changes.

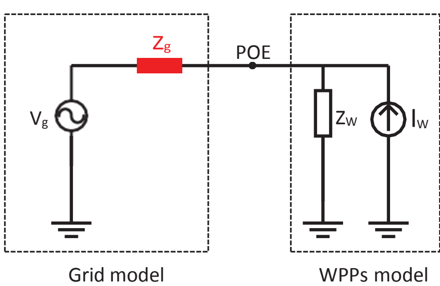


Fig. 1: Schematic overview of the connection of a new WPP to the grid.

The single line diagram of one of the two WPPs connected to a 380 kV TenneT substation is presented in Fig. 2. Two 400 MVA 380/225/33 kV auto transformers connect the station to the external/offshore TenneT network. The TenneT export system consists of two parallel export cable circuits with aluminium conductor subsea cables installed in the offshore part (around 47 km) and copper subsea cables installed in the onshore part (around 16 km). All cables are in trefoil formation. Variable reactors are connected to 220 kV onshore and offshore to compensate for the cables and a Temporary OverVoltage (TOV) filter is installed at the one 220 kV export circuit (it is a C-type filter tuned for the second harmonic). The offshore substation has two 400 MVA and 230/66/66 kV transformers connected to the four 66 kV platforms. The Wind Turbine Generators (WTGs) are connected to the platforms through 12 array cables and each array cable string connects 7-8 WTGs. Officially the PoCs of the windfarm are located at the four 66 kV platforms but for this analysis the point of evaluation (PoE) is located at the 380 kV substation. In the next subsections, the modeling details of the transmission network, the interconnected land and offshore cables as well as the wind turbines are elaborated.

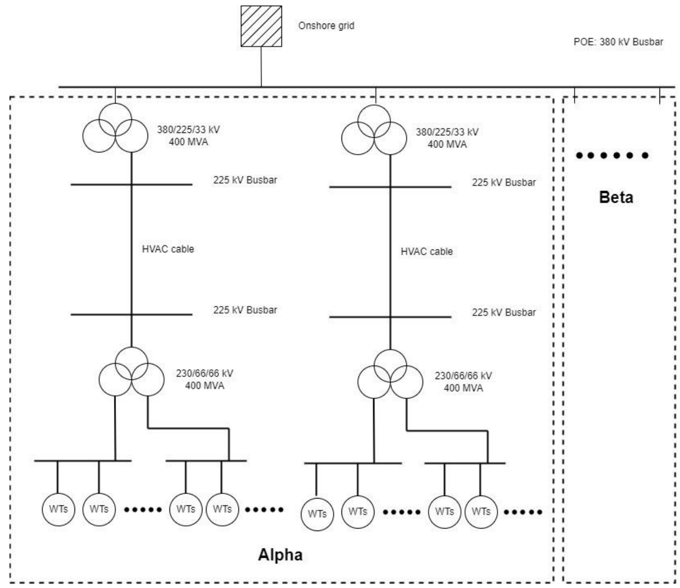


Fig. 2: The layout of the WPPs connecting to the TenneT grid.

A. Transmission Network modeling

The complete Dutch transmission network is included in the model covering the voltage levels of 380 kV, 220 kV, 150 kV and 110 kV. The 380 kV overhead lines (OHLs) are modelled using tower geometry and conductor/earthwire electrical data. In [10], [11] is mentioned that skin effect should always be modelled when calculating the series impedance for both OHLs and cables. If the transmission lines are not modelled using geometrical data skin effect correction factors can be used to account for the skin effect. In the model used for this study the lower voltage OHLs as well as for the underground power cables a distributed parameter pi model is used with a frequency dependent resistance to account for skin effect. The input parameters of the transformer model are the leakage inductance the magnetizing current as well as the copper and iron losses. The power transformers are also modeled with frequency dependent resistance in order to include the skin effect. The resistance was adjusted using (2) which is embedded in DigSILENT PowerFactory frequency polynomial characteristic [12].

$$R(f) = R_{AC}\left(1 - a + a \cdot \left(\frac{f}{f_{nom}}\right)^{b}\right) \tag{2}$$

The values of a and b used in the model are shown in Table I.

TABLE I: Parameters for skin effect formula

	a	b
OHL type 1	1	0.5
OHL type 2	0.2	0.75
Transformers	0.1	1.5

The impact of the distribution network load model to the harmonic studies in transmission network is discussed in [13], [14]. For this study the distribution network is modelled as an RLC lumped model according to the powerflow and it is connected to a distribution transformer (modelled only with its short circuit impedance). Since for this study the substation of evaluation is at 380 kV, the contingency analysis has been executed traversing a number of elements (circuits, transformers and shunts) in the vicinity. In total 51 N-1 and 1275 N-2 cases were considered.

Fig. 3 shows the harmonic impedances up to 1250 Hz for N-0, N-1 and N-2 operational states at the PoE without the connection of the cable system and WPPs. These grid impedances are used to represent the external grid in the following simulations.

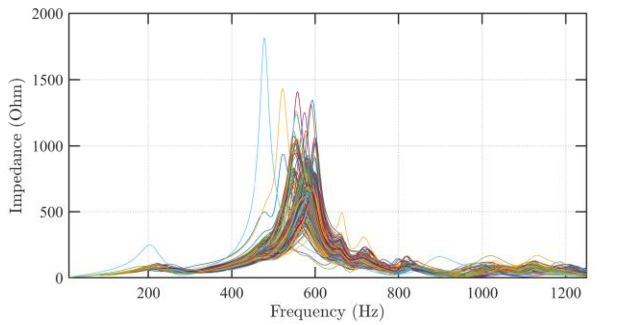


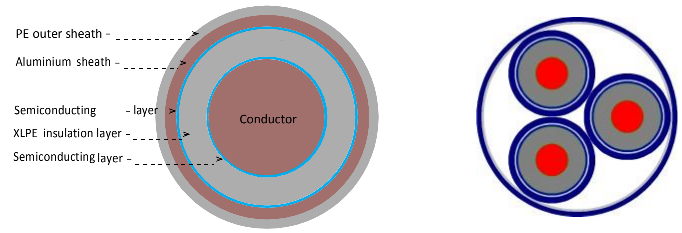
Fig. 3: The grid impedances at the PoE for N, N-1, and N-2 operational states before the connection of the WPP

B. *Cable modeling*

The common practice for modeling export cable systems is to model the cable as a distributed parameter pi-model with positive, negative and zero sequence impedances where the positive sequence resistance is frequency dependent to account for the skin effect. Harmonic studies take place before the actual connection of a WPP and real-life data are not available. Thus, information from cable data sheets are used and a laying configuration is assumed, in this case trefoil formation.

For this analysis the 220 kV export cable system was modeled in two ways. In the first case the distributed parameter pi-model was used while for the second case the cables were modeled in more detail using geometrical data and the electrical characteristics of the cable layers and the pipe where the submarine cable system is enclosed. The distributed parameter pi-model does not include the most accurate frequency dependency of the resistance and inductance of the line which is the case for the detailed geometrical data model. For the geometrical data model the series impedance and shunt admittance matrices were calculated using the complicated equations of [15] . Fig. 4 shows the geometrical structure of the cable layers that were modeled and the laying formation used.

In Fig. 5 the harmonic impedances of the two cable models are compared when only the cable is considered (sending side is open-ended and receiving side is short-circuited). It is apparent that there is a significant difference between the two impedances where for the detailed cable model case the harmonic resonance amplitude is greatly decreased and shifted to higher frequencies.



(a) (b)

Fig. 4: (a) The geometrical structure of the cable and (b) the laying formation used for the detailed cable model construction.

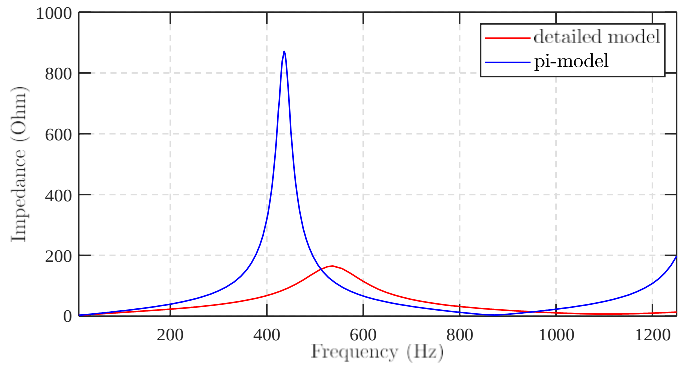


Fig. 5: Harmonic impedance comparison between the detailed cable model and the distributed parameter pi model for the 220 kV export cable.

C. *Wind power plants modeling*

The power electronic converters that are used to interface the wind turbines with the rest of the system have been shown to have a high impact in the results when harmonic compliance assessments are performed. Apart from being one of the main harmonic sources in WPPs and, possibly, one of the solutions that can be applied in case of grid-code power-quality violations, power electronic converters are very important to be modeled in harmonic studies because they may affect the appearance and the location of resonant frequencies, and alter the amplification factors of harmonics [16].

Developing an accurate frequency-dependent model of these elements, then, is crucial for steady-state harmonic calculations. Usually, the typical procedure in industry is to represent the converter as a Norton or Thevenin equivalent in parallel or series with an impedance which represents the converter harmonic impedance, including passive filters [11]. This procedure is, however, a very difficult task due to the fact that the harmonic response of a power electronic converter depends on very specific details of its control loops and modulation techniques, which fall under the proprietary information of the wind turbine manufacturers.

For this analysis each WTG is modeled as a voltage source in series with the converter impedance which should include the impact of closed-loop controls and the converter line reactor. Three Pulse Width Modulation (PWM) filters are connected after that and then we have the WTG transformer (see Fig. 6).

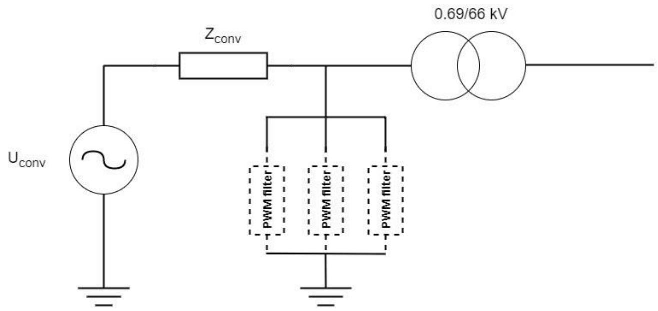


Fig. 6: WTG harmonic model.

Fig. 7 gives the harmonic resistance and reactance of one of the four 66 kV platforms where 3 strings of 8 WTGs are connected (including the respective array cables and transformers).

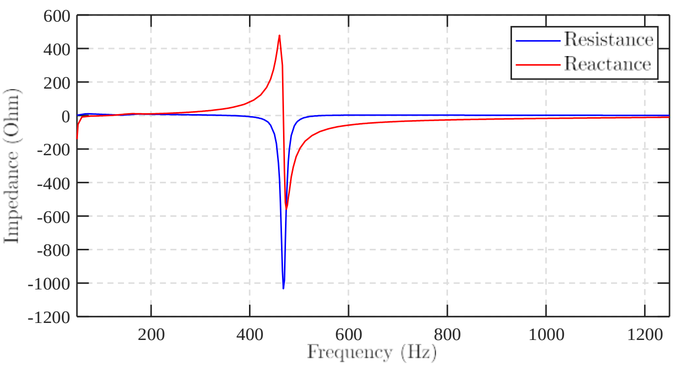


Fig. 7: Harmonic impedance of one 66 kV platform including 24 WTGs, WTG transformers and array cables.

III. Simulation results

In this section, the results of executed simulations are presented. The results were obtained using frequency domain balanced impedance calculations. Fig. 8 shows the calculated harmonic impedance and harmonic amplification factor for the N-0 grid operational state at the PoE when the two WPPs are connected. The highest amplification effect can be found between 600 to 700 Hz. There is also a small amplification close to the fundamental frequency and around 150 Hz. A number of parameters which can affect Z_g and Z_W are identified and the impact of each is quantified, including the network operational states, the WPP operational states, the cable model and cable capacitance uncertainties.

A. Impact of the operational states (outages) in the grid

As shown in Fig. 9a, different operational states in the grid give diverse impedances and it is important to know the boundaries for a safe design. The effect of a component outage is different dependent on the type of component as well as the location of the component (usually the closer to the point of evaluation the larger the effect). Since there would be a maximum and minimum values at each frequency, a range can be obtained between them which shows all possible

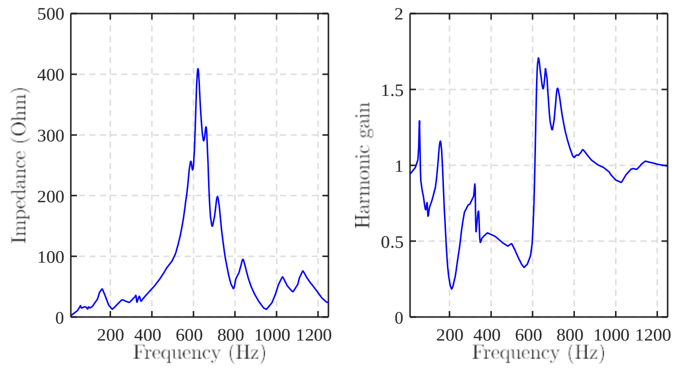
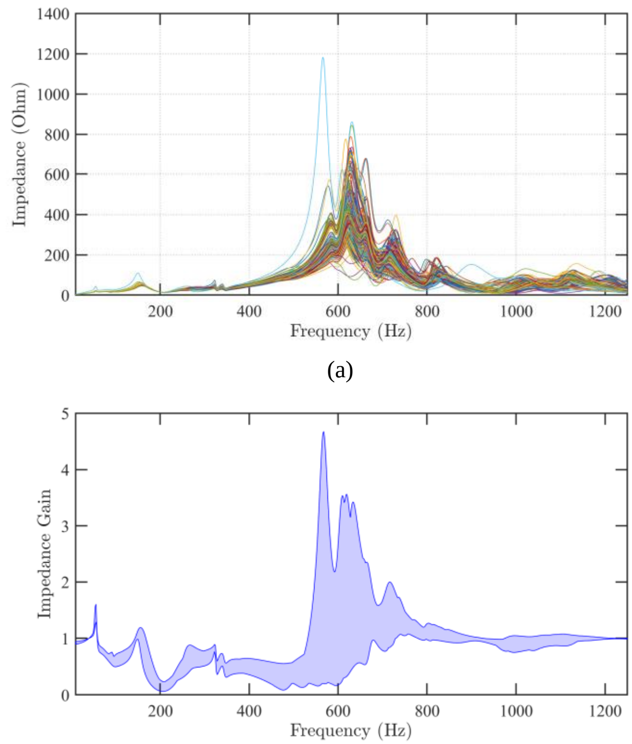


Fig. 8: Harmonic impedance and harmonic amplification factor for N-0 grid operational state with the two connected WPPs.



(a)

(b)

Fig. 9: (a) Harmonic impedance and (b) harmonic amplification factor range covering all N-0, N-1, and N-2 operational states

results. Fig. 9b shows the harmonic amplification factor for all N-0, N-1, and N-2 operational states. It has been found that the first frequency range where significant amplification is observed is between 550 to 750 Hz. The maximum harmonic amplification factor at this frequency range for the N-0 state is around 1.7 while considering N-1 and N-2 operational states, the same metric reach values of approximately 5. With a harmonic amplification factor of 5, the steady state harmonic emissions from the source could be amplified 5 times which can have an impact on power quality. Therefore, the contingency conditions are important to be considered during the design phase.

B. Impact of the operational states (outages) of the wind farm

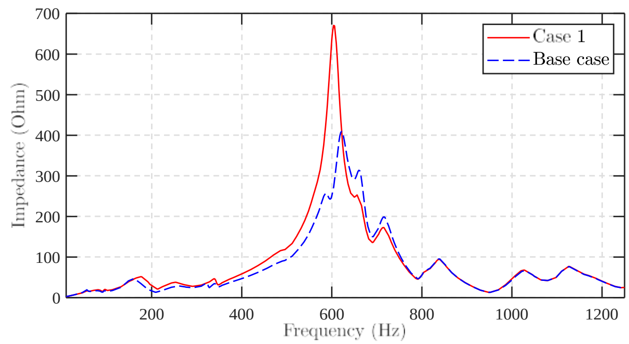
Contingencies in the WPPs can also have an impact on the harmonic impedance and harmonic amplification factor. In this subsection four different operation states of the windfarms are evaluated for all N-0, N-1, and N-2 grid operational states.

- **Case1:** Alpha WPP is connected while Beta WPP and both export systems are out of service.
- **Case 2:** Alpha WPP and export system is out of service while Beta WPP is connected.
- **Case 3:** One of the two export systems of Alpha and Beta WPPs are out of service and the 66 kV platforms connected to these export systems are connected to the other platforms.
- **Case 4:** Alpha WPP is connected while Beta WPP and both export systems are out of service and its 66 kV platforms are connected through a 66 kV interconnection cable link to Alpha platforms.

Fig. 10a illustrates the comparison of the harmonic impedances for N-0 between case 1 and the base case. Fig. 10b shows the harmonic amplification factor for all N-0, N-1, and N-2 operational states of case 1 compared to base case. It is evident that when only the first WPP is connected the harmonic impedance and amplification factor shift to lower frequencies and the magnitude is higher. Exactly the same behaviour as for case 1 is spotted for case 4 (see Fig. 13) meaning that the impedance of the interconnected platforms with the WTGs of the second WPP do not make a significant difference in the results. That is to be expected since the array cables and WTGs are behind the 220/66/66 kV transformers and the capacitance of the HVAC cable together with the transformer inductance and the grid impedance are the most determining factors for the resonances at the frequency range used for this study. Thus, we can conclude that the export system is more important for the harmonic amplification factor compared to the number of WTGs and array cables connected to it. For case 2 and 3 (Fig. 11 and Fig. 12)the harmonic impedance and amplification factor shift to lower frequencies and the amplitude of the amplification factor is slightly lower than the base case. Thus, it can be seen that contingencies in the WPPs can have a significant impact on the impedance and harmonic amplification factor and need to be considered.

C. Impact of cable modelling methods

As mentioned in Section II-B two methods are used to model the export cables. In the base case they are modeled as a distributed parameter pi-model with positive, negative and zero sequence impedances where resistance is frequency dependent to account for the skin effect. For the detailed cable model case the export cable system is modeled using geometrical data and the electrical characteristics of the cable layers. In Fig. 14a the comparison of the harmonic impedances for N-0 between the detailed cable model case and the base case is depicted. Fig. 14b shows the comparison of the harmonic amplification factor for all N-0, N-1, and N-2 operational states and it is evident that the modelling detail of the cable has a considerable impact on the harmonic magnitude and



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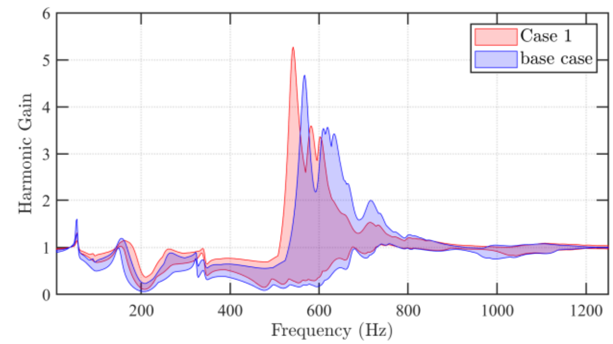

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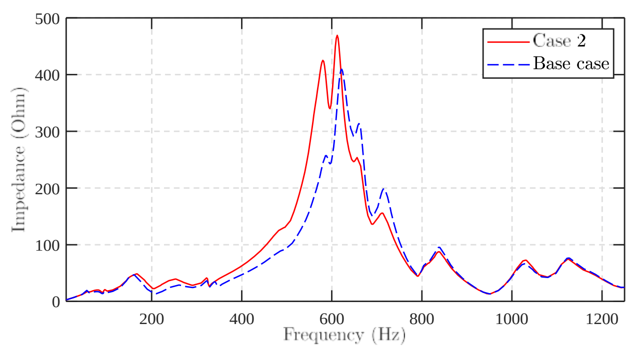
Fig. 10: (a) Harmonic impedance comparison for N-0 and (b) harmonic amplification factor range comparison for all N-0, N-1, and N-2 operational states between case 1 and base case



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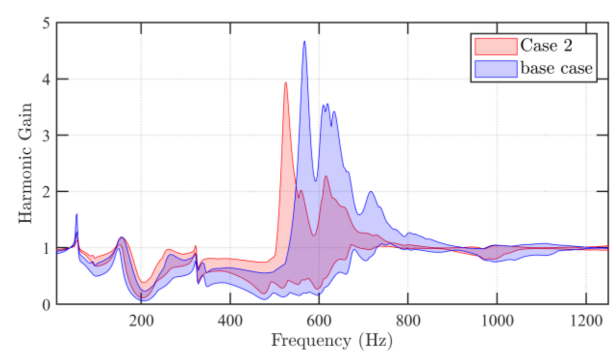

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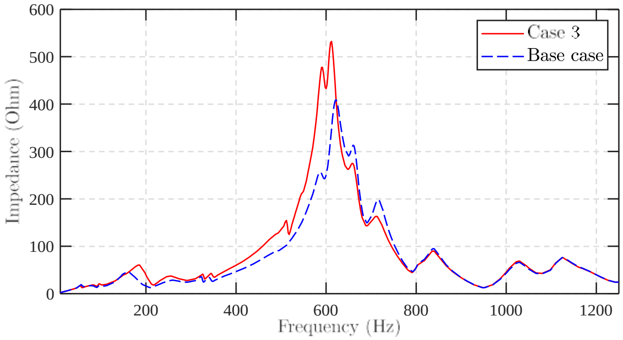
Fig. 11: (a) Harmonic impedance comparison for N-0 and (b) harmonic amplification factor range comparison for all N-0, N-1, and N-2 operational states between case 2 and base case



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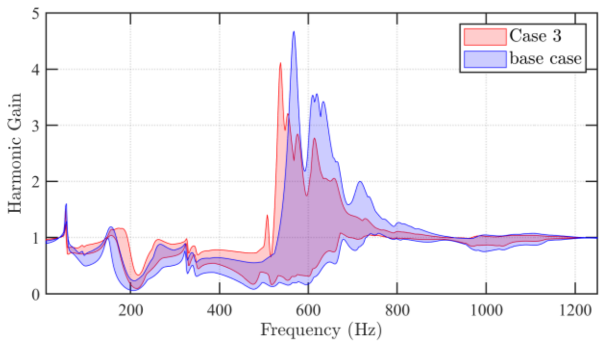

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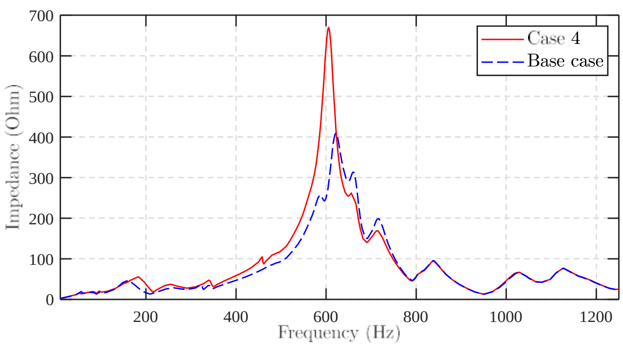
Fig. 12: (a) Harmonic impedance comparison for N-0 and (b) harmonic amplification factor range comparison for all N-0, N-1, and N-2 operational states between case 3 and base case



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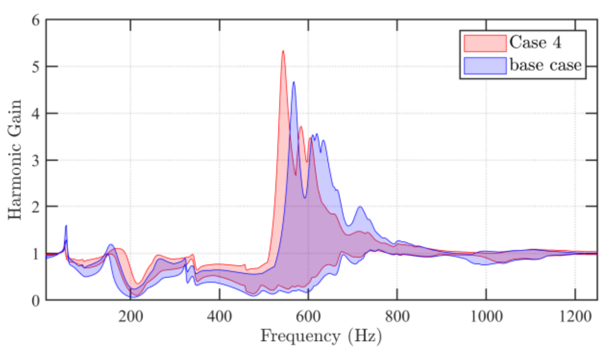

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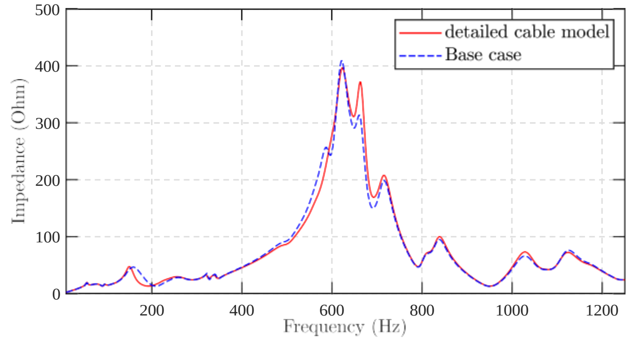
Fig. 13: (a) Harmonic impedance comparison for N-0 and (b) harmonic amplification factor range comparison for all N-0, N-1, and N-2 operational states between case 4 and base case



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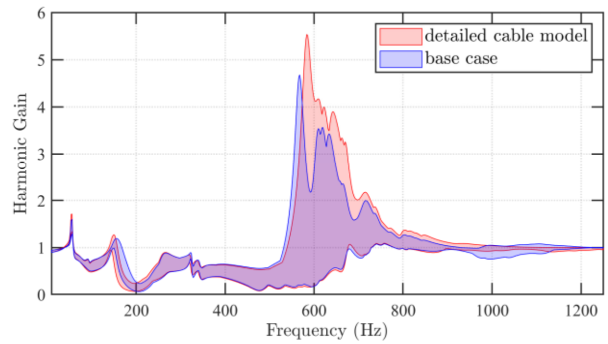

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Fig. 14: (a) Harmonic impedance for N-0 and (b) harmonic amplification factor range comparison for all N-0, N-1, and N-2 operational states between the detailed cable model case and base case

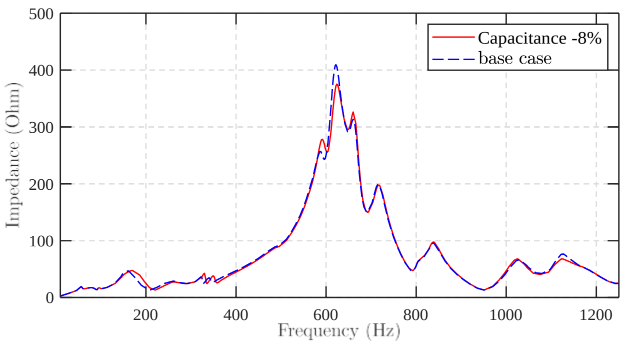
frequencies since the maximum harmonic amplification factor value for the detailed cable model is 5.5 at around 580 Hz while for the base case the value is 4.5 at around 550 Hz.

D. Impact of cable capacitance uncertainties

The value of cable capacitance is an essential factor to determine the resonant point. One of its uncertainty source is due to the manufacturer tolerances of cable parameters (insulation thickness etc.), which can account for capacitance value difference of up to 8%. Therefore, these uncertainties need to be involved when the possible harmonic amplification factor is calculated. Fig. 15b shows the range of harmonic amplification factor with ±8% uncertainty of the export cables capacitance. The impact of capacitance uncertainty for both the harmonic amplification factor magnitude and frequency is less significant compared to the previously examined cases.

IV. Conclusions

During the design of an offshore WPP, it is crucial for a Transmission System Operator (TSO) to know the level of harmonic amplification due to a new connection in order to be able to determine whether mitigation measures for possible harmonic emission exceedances are necessary. The paper aims to quantify the impact of several parameters to the harmonic amplification for offshore wind power plants, based on a real case in the Netherlands.



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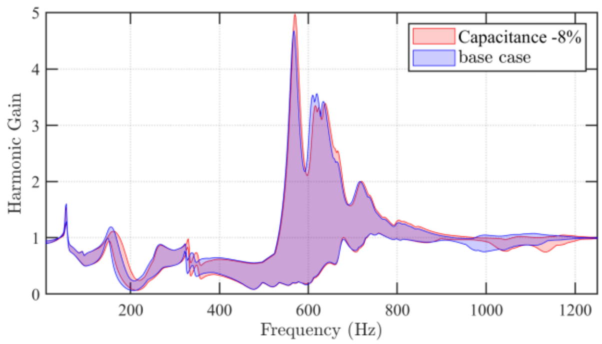

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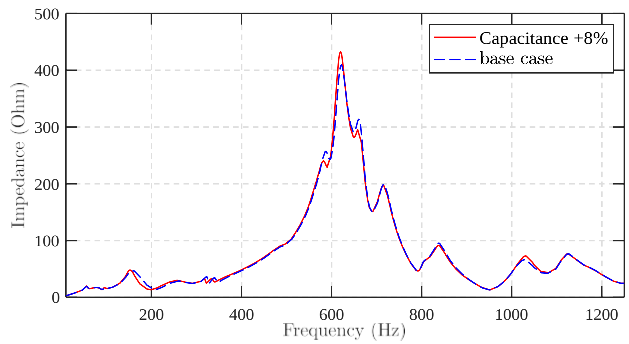
Fig. 15: (a) Harmonic impedance for N-0 and (b) harmonic amplification factor range comparison for all N-0, N-1, and N-2 operational states between 8% decreased cable capacitance and base case



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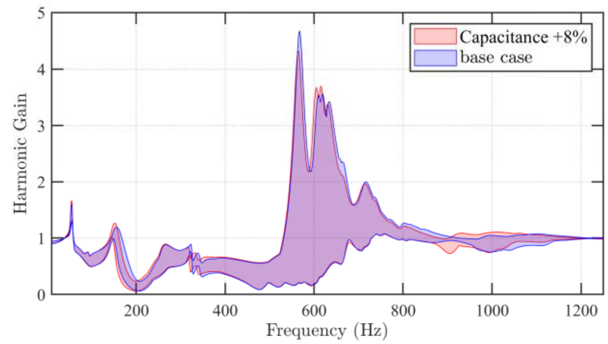

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Fig. 16: (a) Harmonic impedance for N-0 and (b) harmonic amplification factor range comparison for all N-0, N-1, and N-2 operational states between 8% increased cable capacitance and base case

It can be concluded that transmission network contingencies is one of the most influential factors to determine the grid impedance and associated harmonic amplification factor. However, some system states causing high amplifications can be very unlikely to occur and for these a risk analysis may be necessary. It is also observed that contingencies in the WPPs have a significant impact on the impedance and harmonic amplification factor. The modelling detail of the cables connecting the WPP to the transmission network has a considerable effect on the harmonic amplification factor. More specifically, the distributed pi-model for the cable is highly likely to be insufficient so the detailed cable model is strongly recommended considering the geometrical data and the cable design parameters. The tolerance of cable capacitances only slightly affect the harmonic impedance amplification. Thus, if a similar tolerance level can be given by the cable manufacturer, these uncertainties could be ignored during the evaluation. In this paper, important parameters which affect the harmonic impedance amplification factor are identified and it is recommended that special care for these is paid for future WPP connections.

V. Credit authorship contribution statement

Fani Barakou: Conceptualization, Investigation, Data curation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Gu Ye :** Conceptualization, Investigation, Data curation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Kees Koreman:** Conceptualization, Writing - review & editing. **Martin Westbomke:** Writing - review & editing. **Andreas Menze:** Writing - review & editing.

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