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Harmonic Effects of an OWPP Connection to Northwestern Part of Turkey-A Case Study

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Abstract**—** *Nowadays count of Offshore Wind Power Plant investments are increasing drastically. Although Turkey is not familiar with OWPPs there is a recent tendency towards OWPPs so as to supply the increasing energy demand and meet with the lower carbon emission targets. Higher interest on larger scale OWPPs resulted in a dramatic increase in count of relevant studies. Increased harmonic introduction is considered as one of the most remarkable effects of offshore wind power plants. In terms of Turkey, Northwest part is considered as suitable for a possible OWPP connection. In order to meet grid code limits in terms of harmonics, a detailed harmonic analysis is executed for two different scenarios in case of a large scale OWPP integration. Through the analysis a frequency dependent model is employed and real voltage harmonic measurements from selected connection points is added to the developed model. Whole simulations are executed by using Power Factory Software. With this study a detailed scheme for harmonic reaction of the Turkish Transmission Network to integration of a large scale OWPP is explicitly drawn.*

Keywords**—** *Harmonic distortions, Offshore wind power plants, large scale OWPPs, wind power plant grid integration, Harmonic impedance analysis, Harmonic propagation in grids, Wind turbine harmonics.*

I. INTRODUCTION

With its high wind speed potential and remarkable location, Northwest Turkey is selected for connection of an OWPP through this study. High need of energy is a direct result of the considerable amount of industries and a crowded population living at this region. In order to supply power to these, numerous power plants are constructed at the region. A significant amount of energy is produced by wind power plants (WPPs) (approximately one fifth of monthly production [1]) at Trakya region. Count of wind power plants (WPP) at the area is increasing day by day so the percentage of wind based production is continuously improving.

In terms of energy production, while some portion of energy production is made at the region, a remarkable amount of power is taken from the power plants stated at neighboring regions. This power transmission is mainly made via long high voltage overheadlines. Therefore all utilities and industries stated at the region is strongly bounded to the health and condition of these connectors.

OWPPs can be a remedy to energy need at the region with their high potential of power production capability. However, connection of a large scale OWPP can be a thread for the grid tranquility unless needed analysis and plant management is done properly. Although it may be a cure to meet the energy need of the region, integration of a large-scale offshore power plant needs a strictly conducted connection analysis. This connection analysis become more crucial in terms of harmonics as there are steel industry at the region which are prone to emit harmonics. The situation is the same when the high penetration of PE-based renewable systems at the region is considered.

Another important criteria for this kind of before connection analysis is the ability of simulation models to express real characteristics of the grid. In literature, in order to combat the uncertainty on reliability of simulation results, it is advised to employ frequency depended equipment models rather than lumped models [2], [3].

In terms of connection assessments must works concentrated on HVAC linked OWPPs [4], [5], [6], [7], [8], [9] rather than HVDC systems [10], [11], [12], [13] as HVAC is more matured than HVDC systems. Although it has many advantages like simpler design and lower complexity, long AC cables used in HVAC connected systems results in concerns on possible resonances and propagation of harmonic currents.

High Voltage Direct Current (HVDC) based connection systems have numerous advantages like no skin effect is present for DC lines with an addition of lower losses and lower costs in manufacturing process (for lines) over High Voltage Alternating Current (HVAC) systems [14]. Inspite of these numerous features that lowering the costs, HVDC systems need a particular investment on power electronic modules. The budget needed for these modules may be more remarkable than ever with nowaday's well-known chip crisis. Because of all given reasons above, an HVAC connection is designed instead of an HVDC system at Windflag project with the convention of keeping line lenghts low as possible (i.e by selecting a location for the OWPP close to the coasts). Therefore effects of AC cables are considered more elaborately through this study.

In this work, previously produced harmonic grid model in [15] is employed for a further harmonic penetration analysis. Since the designed model have a specially selected rate of power and design traits, possible wind turbine harmonics are extracted from the literature to be modelled to the WTGs. Once the possible harmonic contribution of WTGs are decided, a statistical voltage harmonic analysis is conducted at the connection busbars. As stated in std. IEC 61000-4-30 the measured data is filtered from the flagged data then the resulting data of 2 months time period is processed. Resulting analysis are done for the cases of (1) when only background harmonic voltages taken into account, (2) when both of the

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grid and OWPP side emits harmonics. The location and connection points of the OWPP is given in Fig.1.

This study is conducted in accordance with Windflag project. In the scope of the project a frequency dependent model of Trakya grid is developed [15] and this model is also adopted to this study. Outputs of executed harmonic analysis is again reported in the scope of the same project. Primary contribution of this study is the first before connection harmonic stability analysis is conducted for a large scale OWPP integration to Turkish grid. Executing these analysis in a novel approach using a frequency dependent grid model could also be considered as one of the main contributions of this work as no such a work was present for Turkish grid.

The rest of the paper is organised as *System Description* section as a second part at which general considerations regarding the focused location of study is summarized, *OWPP Side Harmonics* section at which definition of WTG harmonics is briefly explained, *Grid Side Harmonics* section at which definition of background harmonics is briefly explained, *Experiment* section at which scenarios of the simulation is stated and some background settings are given, *Results* section at which outputs of all scenarios are discussed and finally a *Conclusion* section at which main contribution and outcomes of the work is briefly explained.

II. SYSTEM DESCRIPTION

A. Trakya Region

Northwest Turkey also has some special traits that makes this area different from the rest of the Turkey. First of all the region constains two interconnection lines for connection to Bulgaria and Greece. The region also have a remarkable portion of onshore WPPs and one of the biggest thermal power plant. Including both industrial facilities which could be sources for distortive effects and also a remarkable count of end users who could be effected by these low signal quality effects; Trakya region is considered as representative for this study. At the Trakya part of Turkey: (1) two main interconnection lines one is connecting Turkey and Bulgaria and the other is connecting Turkey and Greece, (2) a remarkable portion of WPPs and other types of renewables and (3) many industrial facilities from textile to steel are present.

In terms of equipments; power transmission is strongly depended to health and tranquilty of long overhead lines. For a smaller portion of Trakya region power transmission is made via high voltage cables. Although usage of under ground tranmission elements is not so common for Turkey, count of Gas Insulated Station (GIS) transformator stations are increasing day by day. Since there is not enough space to construct conventional transformator stations especially for big cities like İstanbul, GISs constitute a high percentage among recently installed stations. This tendency to GISs will probably lead to a higher portion of cable installations in future. In terms of transformers generally two winding types are employed to step the voltage down or up to a specified level. In addition to this, three winding transformers are also being used to make the conversions between 400kV and 154kV levels.

III. OWPP SIDE HARMONICS

Before considering existing harmonic emissions from grid, WTG sourced harmonics are needed to be implemented. While doing this biggest constrait was decision of WTG sourced harmonics as no confidential 15MW full converter WTG data is present during the OWPP design process. In order to solve this problem, a literature review is conducted and the results are compared with an accessible 3MW WTG harmonic emission data and gathered values are manipulated to a level that make the data convenient to be shared.

During the decision process, many works are reviewed and it is observed that measurements are done at the PCC or collector bus of whole WPP for most of studies [16], [17], [18], [19] [20], [21], [22], [23], [24], [25], [4], [26], [27], [28], [29], [30], [31], [32], [33]. As individual WTG harmonic emission is the focus of interest PCC observations did not considered as sufficient for this analysis. Studies given in [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46] and [47] includes harmonic currents for individual wind turbines.

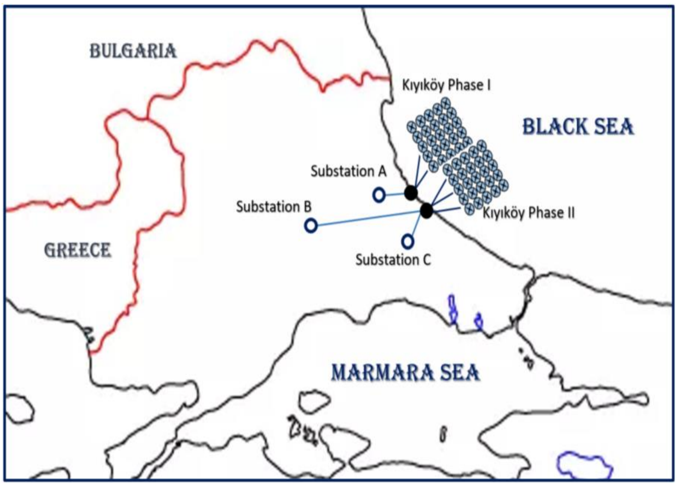

Fig. 1. Locations of designed OWPP and grid connection points (Substation A, B and C)

To decide on a reliable set of harmonic emission, all studies presenting individual WTG harmonic currents are re-evaluated and filtered according to parameters of;

- Examined WTG type in the study (as type 4 is selected for Windflag),
- Simulation type (real or manufactured data usage),
- Power rating of WTG (15MW power rating is selected for each WTG in Windflag)

As a result of above elimination process a set of harmonic current data presented in Table I is obtained by focusing into study given in [47] and the report presented in [37].

IV. GRID SIDE HARMONICS

Background harmonics are derived from the real time measurement data aggregated in accordance with std. IEC 61000-4-30 ed.2 via National Power Quality Monitoring System of Turkey. Gathered voltage harmonic data by use of power quality analyzers installed at the 400kV lines at each of the PCCs is filtered from the faults and flags and two months

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of recorded harmonic data is processed. At the end of this data aggregation and filtering process background harmonic voltage levels given in Table II is obtained.

TABLE I. Wind Turbine Harmonics

Harmonic Order	Ih/I (%)	Harmonic Order	Ih/I (%)
2	0,2	*17*	0,15
3	0,25	*18*	0,01
4	0,18	*19*	0,17
5	0,4	*20*	0,01
6	0,01	*21*	0,01
7	0,3	*22*	0,01
8	0,01	*23*	0,2
9	0,01	*24*	0,01
10	0,01	*25*	0,01
11	0,5	*26*	0,01
12	0,01	*27*	0,01
13	0,28	*28*	0,01
14	0,1	*29*	0,01
15	0,1	*30*	0,01
16	0,01		

V. Experiment

For the analysis three different states of the harmonic penetration scenarios are compared one is for only OWPP side harmonic contribution is assumed, one is for only penetration of background harmonics is taken into account and one is all harmonic sources are ON scenario. Whole study is grouped as 3 cases defined as:

- Case 1: When no OWPP side harmonic contribution is assumed and only the penetration of background harmonics are focus of interest, a harmonic analysis is done at PCCs
- Case 2: When both of the grid and OWPP side emits harmonics, harmonic analysis is done at PCCs

For above defined cases additional frequency sweeps are also done to see the different resonance conditions which can improve harmonic distortions as a following step.

VI. Results

This part of the study is summarizes general outputs of the study via a resonance point analysis and a voltage harmonic distortion distribution examination gathered from the introduced wind turbine harmonics. In terms of frequency sweeps the maximum point to be observed is limited to 30th harmonic (1500Hz) as it is not so relevant to come across with high level of distortions after this point. Harmonic distortions are also assessed up to 1500Hz.

A. Resonant Points Analysis

Since Turkish transmission grid is constructed as a mesh grid, in terms of resonance point analysis special attention is given to parallel resonance points. In order to examine all parallel resonance points in a closer to real scale, the model produced in [15] is employed at this study. A comparison of before and after connection of Kıyıköy OWPP is shown in Fig. 2 and Table III (recorded at Substation A busbar).

According to figure, 5 parallel resonance points have been detected for both of the cases (before and after connection OWPP). A critical resonance point which was not detected for after connection case is detected at onwards of 3rd harmonic for before connection case.

TABLE II. Background voltage harmonics recorded at the three PoC busbars.

Harmonic order	Subs.A (Vh in pu)	Subs.B (Vh in pu)	Subs.C (Vh in pu)
2	0,0028	0,003	0,0025
3	0,007	0,006	0,009
4	0,0012	0,001	0,0025
5	0,009	0,011	0,0159
6	0,0007	0,0012	0,0005
7	0,005	0,005	0,0095
8	0,0005	0,0007	0,0009
9	0,0007	0,0005	0,0006
10	0,00035	0,0006	0,0003
11	0,0012	0,0017	0,0003
12	0,0003	0,00035	0,0003
13	0,0007	0,0007	0,0007
14	0,00025	0,00028	0,0008
15	0,00025	0,00026	0,0017
16	0,0002	0,00025	0,0019
17	0,00025	0,00025	0,0009
18	0,0002	0,00025	0,0002
19	0,0002	0,00022	0,0000
20	0,00017	0,00022	0,0000
21	0,00017	0,00019	0,0000
22	0,00016	0,00018	0,0000
23	0,00017	0,00017	0,0002
24	0,00015	0,00017	0,0000
25	0,00015	0,00016	0,0000
26	0,00013	0,00016	0,0001
27	0,00013	0,00015	0,0003
28	0,00013	0,00014	0,0001
29	0,00013	0,00014	0,0000
30	0,00012	0,00014	0,0000

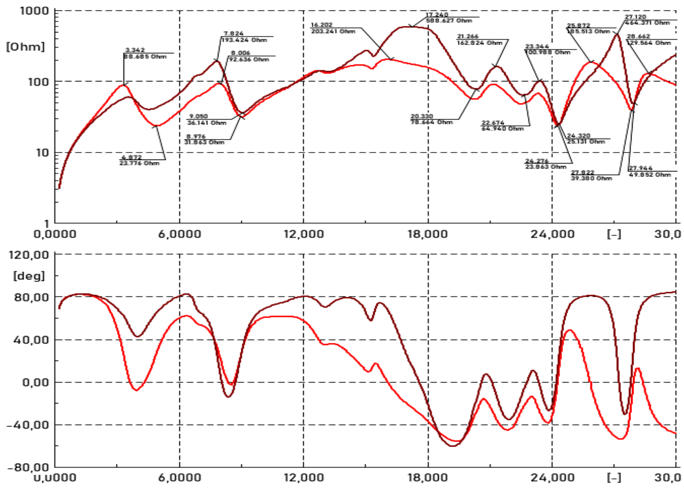

Fig. 2. Comparison of harmonic impedances for before-after connection of OWPP- results for Substation A (after connection is shown with bold color and before connection is shown with light color-red)

For before connection case 4 more parallel resonance zones are detected at approximately 8th,16th, 26th and 29th harmonics. For higher order harmonics instead of existing 3 parallel resonances at 21st, 23rd and 27th harmonics in after connection case; for before connection case two resonance points occured at approximately 26th and 29th harmonics. In table all series and parallel resonances detected at frequency sweep analysis done at Substation A busbar for before and after

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connection of OWPP to the Turkish grid is summarized. Since a previously detected resonance point at approximately 3rd harmonic is disappeared for after connection case, it can be concluded that grid strenght is increased with additional large scale OWPP integration. In addition to this a possible mitigation investment (i.e. harmonic filter) is prohibited with this integration.

B. Harmonic Spectrum

Once all series and parallel resonance points are revealed, a harmonic load flow is executed for each of the PoCs. All harmonic analysis is done for Case 1 (when only background harmonics are defined) and Case 2 (when both WTG and background harmonics are defined). Although main point of interest was on the case at which both WTG and background sourced harmonics are defined, an additional case is also examined to evaluate the harmonic penetration of grid for when only background harmonics are present. A summary for penetration of background harmonics for each of the PoCs is given in Fig.3. All simulations for Case 1 and Case 2 are executed for when the OWPP is connected to the grid.

According to Figure, no visible excess of limit is observed when only backgrounds are defined. For lower order harmonics (2nd,3rd, 5th and 7th) despite being higher then the higher order harmonics, the level of emission is again stayed in grid code limits taken from Turkish Grid Code for voltage level of 400kV.

TABLE III. Comparison of harmonic impedances for before-after connection of OWPP (Substation A)

After connection-SubA			Before connection-SubA		
Harmonic order no.	**Harmonic type**	**Impedance (ohm)**	**Harmonic order no.**	**Harmonic type**	**Impedance (ohm)**
7.824	parallel	193.424 Ohm	***3.342***	parallel	88.685 Ohm
9.050	series	36.141 Ohm	***4.872***	series	23.776 Ohm
17.240	parallel	588.627 Ohm	***8.006***	parallel	92.636 Ohm
20.330	series	78.664 Ohm	***8.976***	series	31.863 Ohm
21.266	parallel	162.824 Ohm	***16.202***	parallel	203.241 Ohm
22.674	series	64.940 Ohm	***24.276***	series	23.863 Ohm
23.344	parallel	100.988 Ohm	***25.872***	parallel	185.513 Ohm
24.320	series	25.131 Ohm	***27.822***	series	39.380 Ohm
27.120	parallel	464.371 Ohm	***28.662***	parallel	129.564 Ohm
27.944	series	49.852 Ohm			

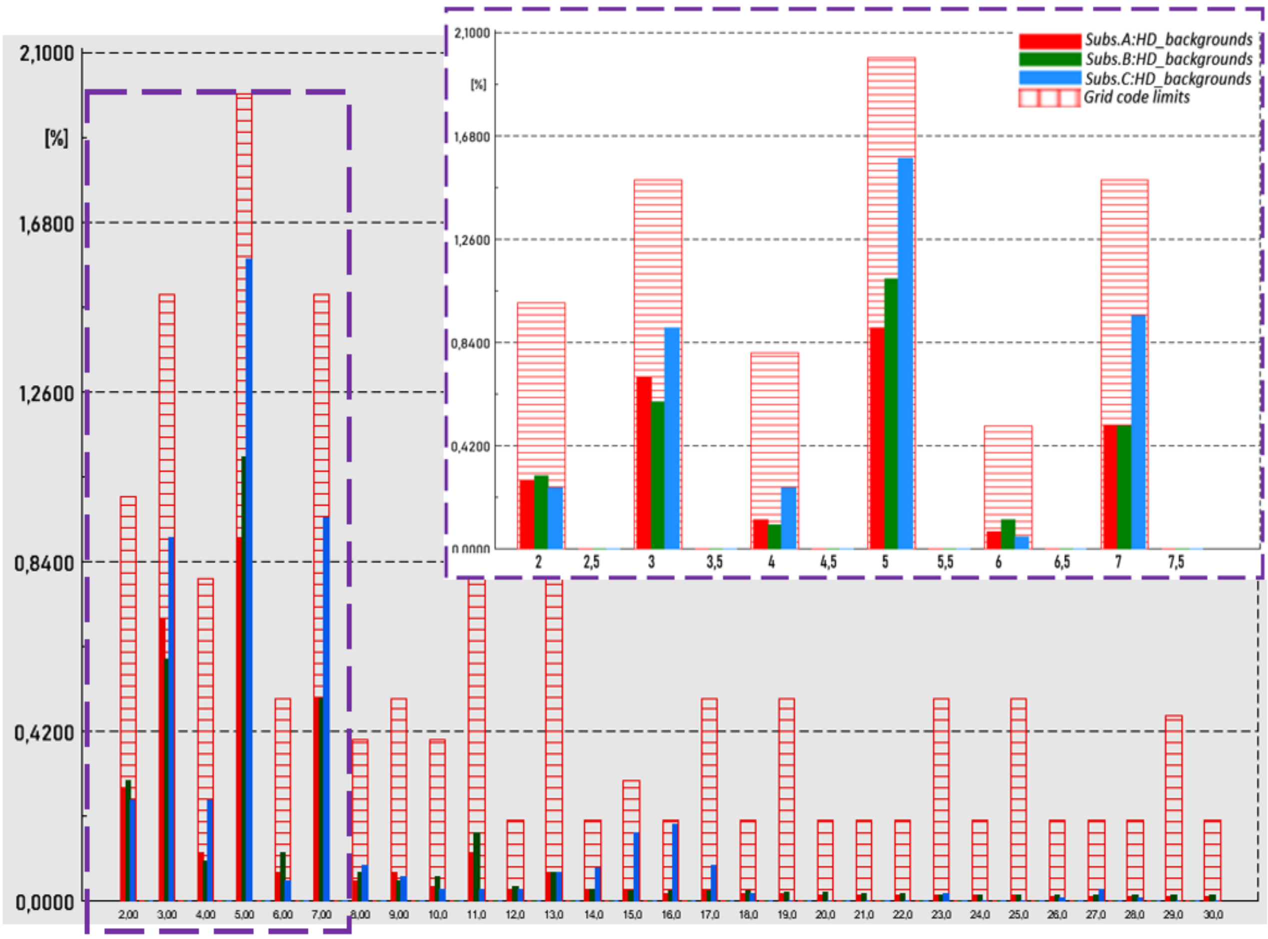

Fig. 3. Harmonic distortion results for each of the PoC busbar when only the background harmonics are defined (Case 1).

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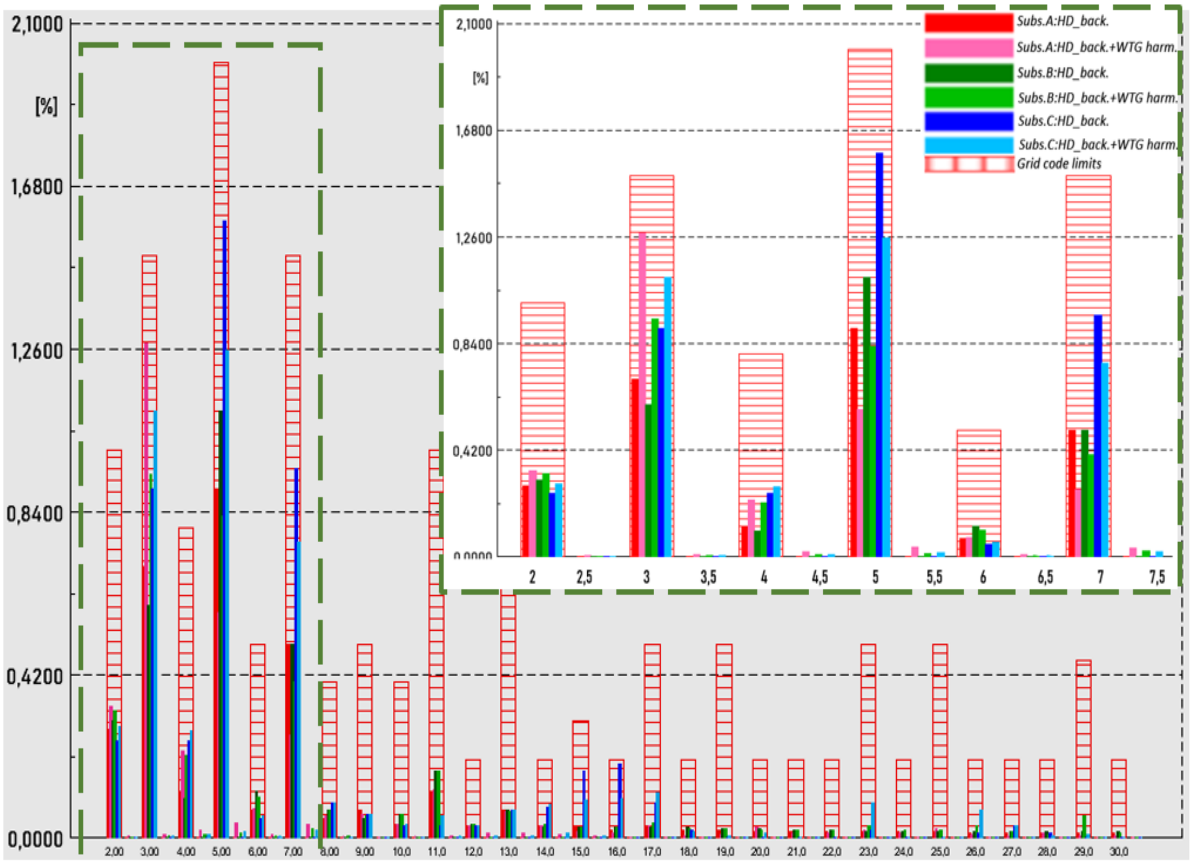

Fig. 4. Harmonic distortion results for each of the PoC busbar when both WTG and background harmonics are defined (Case 2).

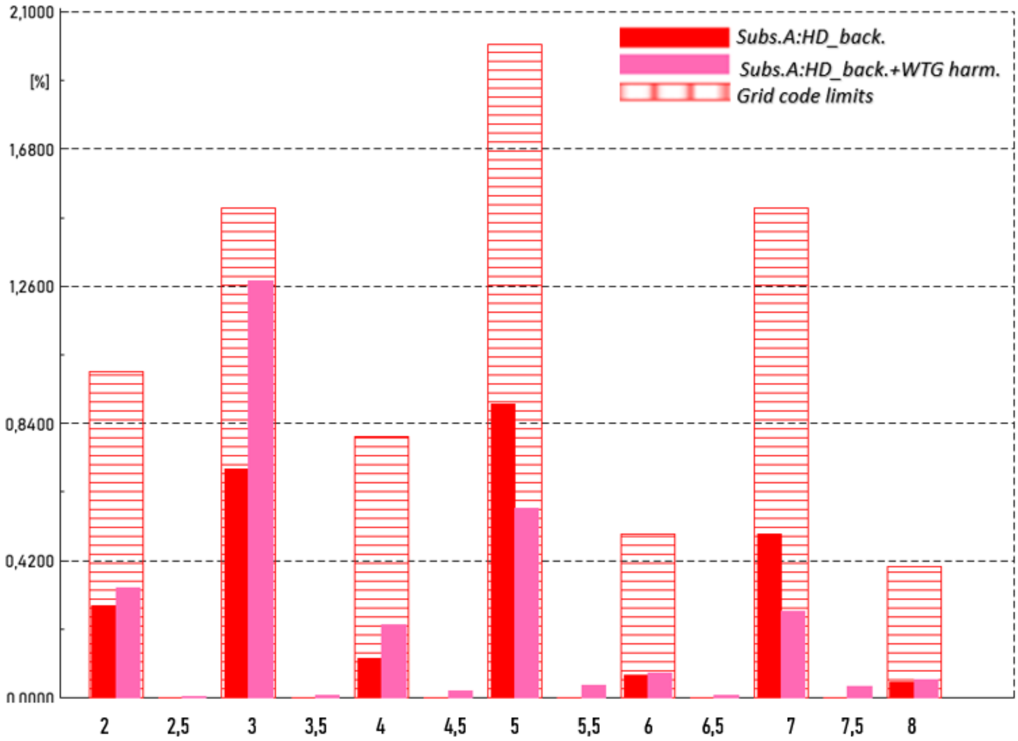

Fig. 5. Comparison of Case 1 and Case 2 results for Substation A

Among three PoC busbars, highest levels of harmonics are seen at Substation C. Since Substation C has the weakest connections to the grid, so the lowest grid impedance seen from this point, this situation is resonable. Since at 5th

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harmonic, voltage harmonic level is close to the limit, special attention is given to this point at Case 2 simulations.

When both WTG and background harmonics are defined (Case 2), resulting harmonic distortion distribution is occurred as given in Fig.4. Highest levels of voltage harmonics again occured for 5th harmonic for Case 2. Although introduction of WTG harmonics increased the harmonic levels generally, there also occured some damps in harmonic levels implementing that WTG and background harmonics mitigate each other in some cases.

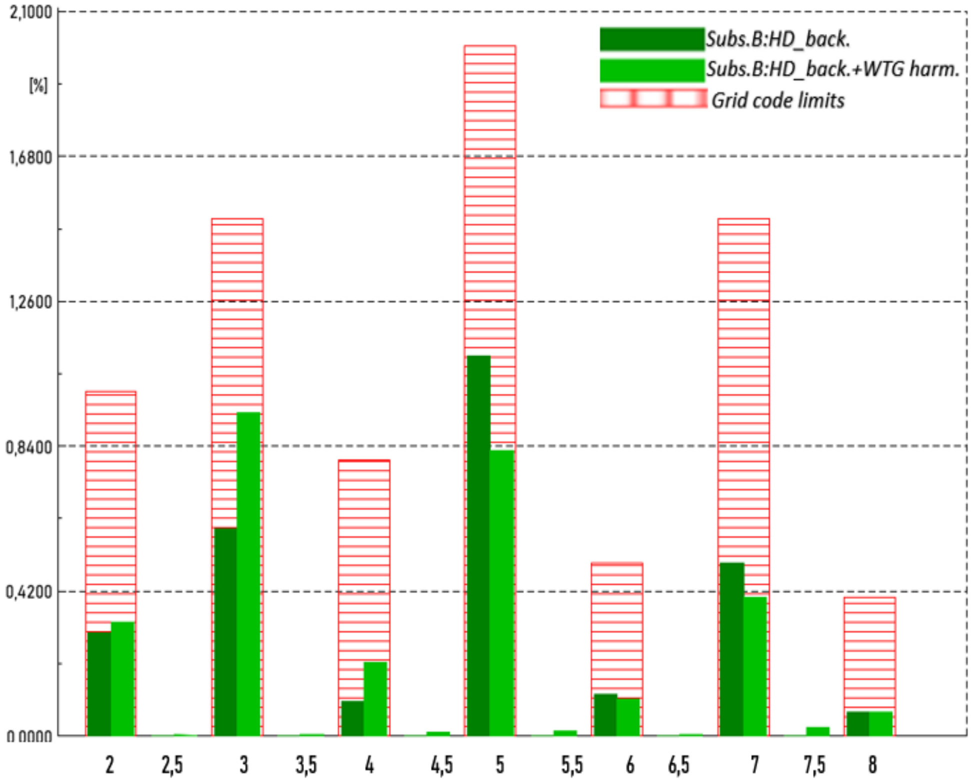

Fig. 6. Comparison of Case 1 and Case 2 results for Substation B

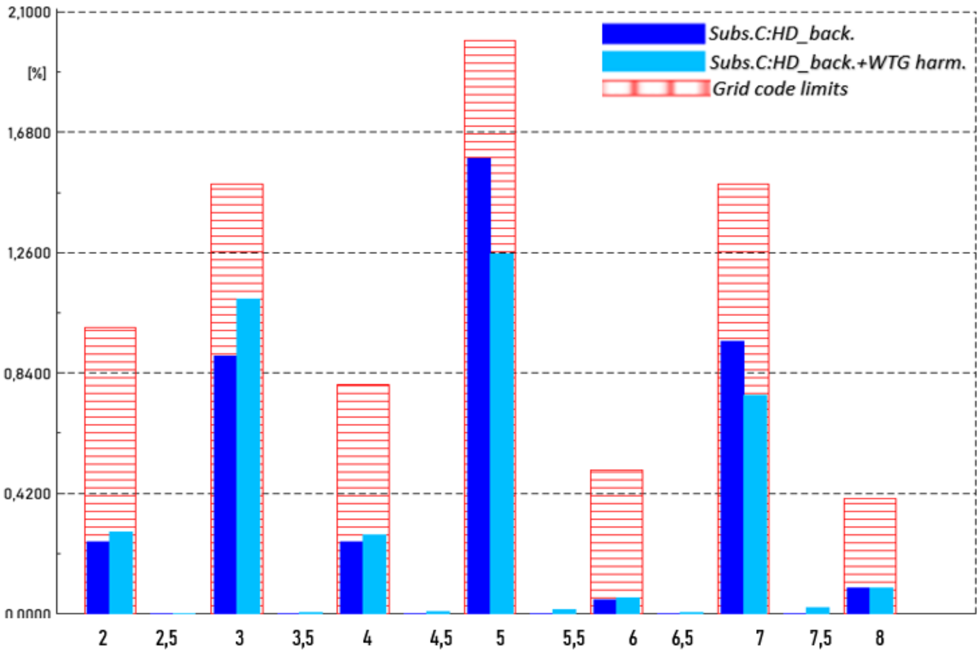

Fig. 7. Comparison of Case 1 and Case 2 results for Substation C

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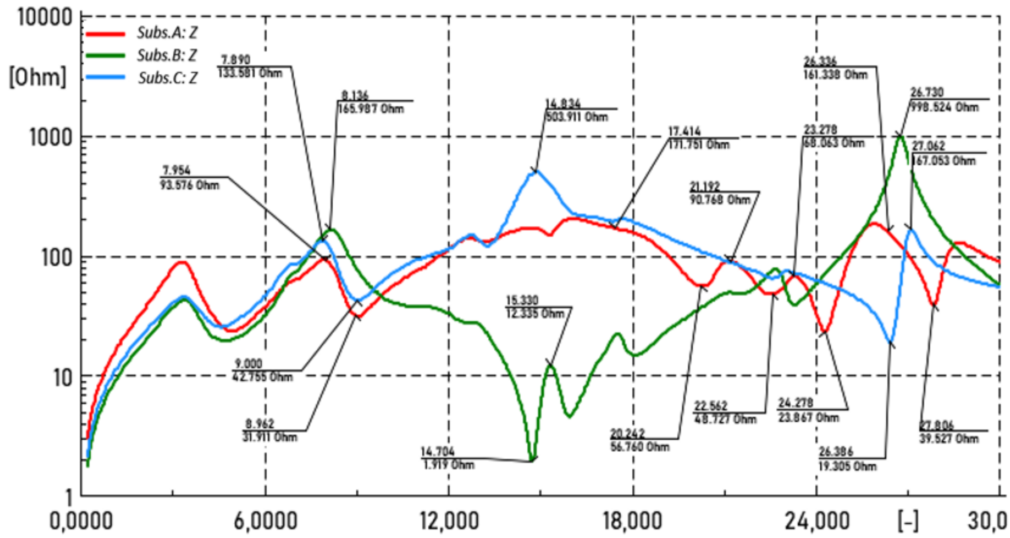
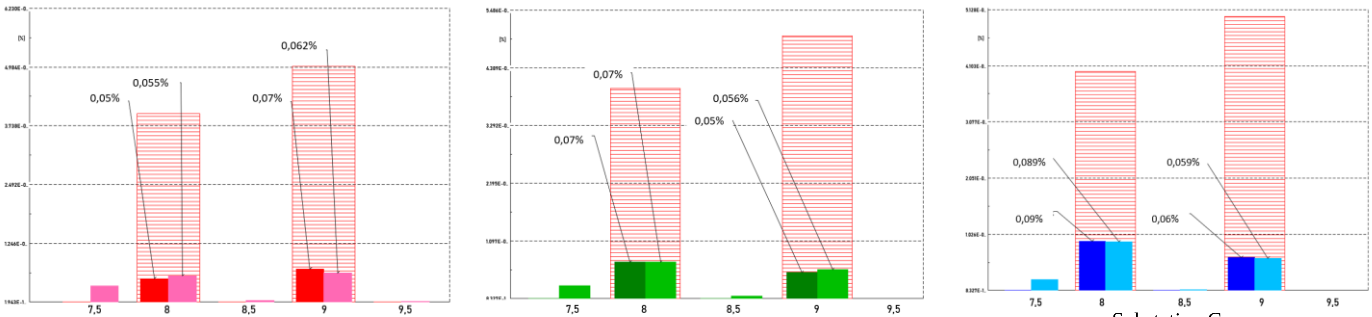


Fig. 8. All resonance points for three PoC busbars

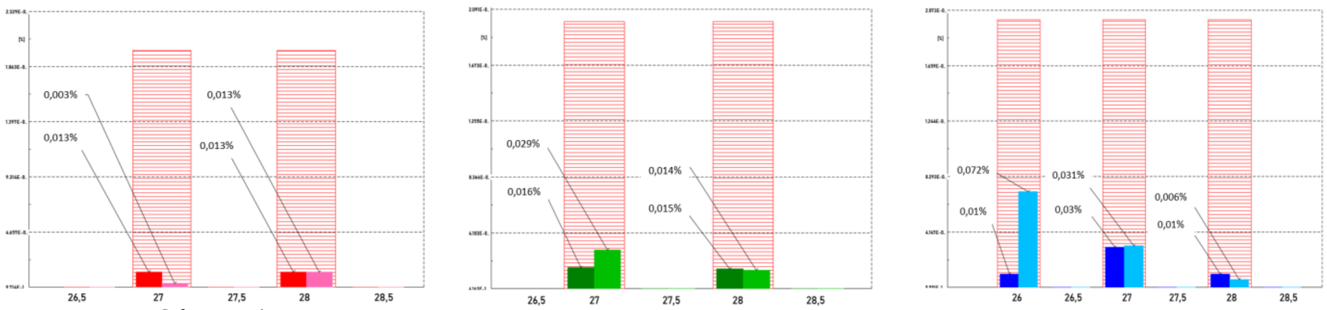
TABLE IV. All resonance points for three PoC busbars

Substation A			Substation B			Substation C		
Harmonic order no.	**Resonance type**	**Impedance (ohm)**	**Harmonic order no.**	**Resonance type**	**Impedance (ohm)**	**Harmonic order no.**	**Resonance type**	**Impedance (ohm)**
7.954	parallel	93.576 Ohm	***8.136***	parallel	165.99 Ohm	***7.890***	parallel	133.58 Ohm
8.962	series	31.911 Ohm	***14.704***	series	1.919 Ohm	***9.000***	series	42.755 Ohm
17.414	parallel	171.75 Ohm	***15.330***	parallel	12.335 Ohm	***14.834***	parallel	503.911Ohm
20.242	series	56.760 Ohm						
21.192	parallel	90.768 Ohm						
22.562	series	48.727 Ohm						
23.278	parallel	68.063 Ohm						
24.278	series	23.867 Ohm						
26.336	parallel	161.34 Ohm	***26.730***	parallel	998.52 Ohm	***26.386***	series	19.305 Ohm
27.806	series	39.527 Ohm				***27.062***	parallel	167.05 Ohm



Substation A Substation B Substation C

Fig. 9. Harmonic voltage results for all PoC busbars focused on 8th and 9th harmonics (for all graphs bold colour represents Case 1 results and light colours represent Case 2 results).



Substation A Substation B Substation C

Fig. 10. Harmonic voltage results for all PoC busbars focused on impedance zone from 26th harmonic to 28th harmonic (for all graphs bold colour represents Case 1 results and light colours represent Case 2 results.

At the following step, a point base analysis is executed for each of the busbars. Results for after connection of OWPP regarding the comparison of Case 1 and Case 2 situations are given in Fig.5 and Fig.6 and Fig.7. For convenience all figures are zoomed to show harmonic voltages up to a certain level of harmonic frequency.

C. Detailed Harmonic Anaysis for Resonance Points

In order to present all harmonic reactions at resonance points, a further detailed analysis is executed. In the scope of this analysis, results of executed frequency sweeps and harmonic load flows are re-evaluated in a resonance point focused manner. For this part of simulations after connection case is considered. To assess all PoCs in terms of resonance points, a frequency sweep is executed for after connection case. For convenience only most common resonence point zones are evaluated in terms of harmonic current penetration. Fig.8 implements all resonance points detected at all PoC busbars, results also summarized in the table given below (Table IV).

According to given figure (Fig. 8) and table (TABLE IV), two resonance zones at 8^{th} to 9^{th} harmonic and 26^{th} to 28^{th} harmonics are inspected elaborately. Magnified results for harmonic distortion for these zones are given in Fig.9 and Fig.10. According to figures; a sudden increase in the magnitude of the harmonic voltages is appeared for all resonance points. The situation is the same for both parallel and series resonances. In terms of parallel resonances, highest resonance impedance is detected for approximately at 27^{th} harmonic looking from the Substation B busbar. This resonance is demonstrated with a peak at harmonic distortion results in Fig.10 at this point both for Case 1 and Case 2 scenarios. Although in this type of studies parallel resonances evaluated elaborately as they are more critical for mesh grids, there also detected series resonance based jumps in harmonic distortion level as an output of this study. For example for series resonance points at approximately 9^{th} harmonic looking from Substation A and C and at approximately 26^{th} harmonic looking from Substation B, there inspected visible increases in harmonic distortion levels.

Generally a system would damp the resonances occur in higher order harmonics (as 26th or 27th harmonics at this example) and it is not common to have these order of harmonic contents in a real transmission system. Therefore a resonance at these level of harmonics is not critical unless a harmonic source injects these harmonics apparently. However as real state of a grid is not easy to be drawn and even for this study only one scenario is taken into account in grid modelling, it could be useful to examine all resonances as possible.

VII. Conclusions

As a result of this study a comprehensive analysis is conducted regarding a possible OWPP connection to the Turkish Grid. In the scope of Windflag project for the selected busbars, a before and after connection analysis is made in terms of resulting harmonic impedances and an additional harmonic analysis is also executed for after connection case regarding voltage harmonics. To make the analysis in a more close-to-real manner a previously developed frequency dependent model is preferred. In the end, it is observed that especially with the addition of OWPP to the grid, seen harmonic impedances from the PoC busbars changes dramatically. Moreover, at this analysis it is inspected that a critical resonance point detected at before connection case has disappeared when OWPP is connected. This effect of resonances is also examined with the implementation of voltage harmonics recorded at these three PoC busbars yielding the result that characteristics of harmonics is mainly drawn by existing series or parallel resonances.

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References

[1] Turkish Electricity Transmission Corporation, «TEİAŞ,» [Online]. Available: https://www.teias.gov.tr/. [Erişildi: 30 September 2022].

[2] J. J. Grainger and W. D. Stevenson, Power System Analysis, McGraw-Hill, 1994.

[3] C. J. C4/B4.38, «Network Modelling for Harmonic Studies,» Cigre, 2019.

[4] Ł. H. Kocewiak, J. Hjerrild and C. L. Bak, «Wind Farm Structures' Impact on Harmonic Emission and Grid Interaction,» *Environmental Science,* 2010.

[5] Ł. H. Kocewiak, B. Gustavsen and A. Hołdyk, «Wind Power Plant Transmission System Modelling for Harmonic Propagation and Small-signal Stability Analysis,» *Renewable Power Generation,* 2019.

[6] J. Li, J. Yang, Z. Shi, K. Wang, H. Li, X. Xie and F. Li, «The harmonic characteristics analysis of offshore wind farms transmitted by the submarine cable based on time domain simulation,» *Journal of Physics: Conference Series,* 2021.

[7] W. Wiechowski and P. B. Eriksen, «Selected Studies on Offshore Wind Farm Cable Connections - Challenges and Experience of the Danish TSO,» *IEEE,* 2008.

[8] Q. Lai, C. Liu and L. Yao, «Remote Harmonic Mitigation within Offshore Wind Power Plants by Embedded Active Filters in Grid-Side Converters,» *IEEE 4th Conference on Energy Internet and Energy System Integration*, Wuhan, 2020.

[9] Ł. H. Kocewiak, I. A. Aristi, B. Gustavsen and A. Hołdyk, «Modelling of wind power plant transmission system for harmonic propagation and small-signal stability studies,» 2017.

[10] L. Yang, Z. Xu, L. Feng, Z. Zhang, Z. Xu and F. Xing, «Analysis on Harmonic Resonance of Offshore Wind Farm Transmitted by MMC-HVDC System,» *2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, 2019.

[11] M. Cheah-Manea, L. Sainz, E. Prieto-Araujoa and O. Gomis-Bellmunta, «Impedance-based analysis of harmonic instabilities in HVDC-connected Offshore Wind Power Plants,» *Electrical Power and Energy Systems,* no. 106, pp. 420-431, 2019.

[12] I. Sowa, J. L. Dominguez-Garcia and O. Gomis-Bellmunt, «Impedance-based analysis of harmonic resonances in HVDC connected Offshore Wind Power Plants,» *Electric Power Systems Research,* 2018.

[13] A. H. Manchola, T. Priebe, M. Hölzer and M. Dommaschk, «VSC

HVDC active damping for the Sylwin 1 offshore wind power plants,» *The Journal of Engineering*, 2018.

[14] R. Ryndzionek and Ł. Sienkiewicz, «Evolution of the HVDC Link Connecting Offshore Wind Farms to Onshore Power Systems,» *energies*, vol.13, no. 1914, 2020.

[15] Ş. N. Güler, K. Ç. Bayındır, A. Tan, M. Yeşil, M. Akdeniz, Ü. Çetinkaya and J. Guerrero, «A Development of Equivalent Grid Harmonic Model for Integration of Offshore WPPs: A case study for Northwest Turkey,» *ICSMARTGRID 2022*, İstanbul, 2022.

[16] Ł. H. Kocewiak, J. Hjerrild and C. L. Bak, «Harmonic Analysis of Offshore Wind Farms with Full Converter Wind Turbines,» *8th International Conference on Large-Scale Integration of Wind Power into Power Systems*, 2009.

[17] J. C. L. d. Silva, T. Ramos and M. F. M. Júnior, «Modeling and Harmonic Impact Mitigation of Grid-Connected SCIG Driven by an Electromagnetic Frequency Regulator,» *Energies*, vol. 14, no. 4524, 2021.

[18] K. V. Bhadane, M. S. Ballal, A. Nayyar, D. P. Patil, T. H. Jaware and H. P. Shukla, «A Comprehensive Study of Harmonic Pollution in Large Penetrated Grid-Connected Wind Farm,» *MAPAN- Journal of Metrology Society of India*, 2020.

[19] S. H. Memon, M. Kumar, A. H. Memon, Z. A. Memon and S. A. Soomro, «Total Harmonic Distortion (THD) Analysis of Grid Integrated Permanent Magnet Synchronous Generator (PMSG) With Full Scale Converter (FSC) Based Wind Farm,» *IJCSNS International Journal of Computer Science and Network Security*, vol. 18, no. 12, 2018.

[20] Z. Liu, J. Rong, G. Zhao and Y. Luo, «Harmonic Assessment for Wind Parks Based on Sensitivity Analysis,» *IEEE Transactions on Sustainable Energy*, vol. 8, no. 4, 2017.

[21] L. Sainz, J. J. Mesas, R. Teodorescu and P. Rodriguez, «Deterministic and Stochastic Study of Wind Farm Harmonic Currents,» *IEEE TRANSACTIONS ON ENERGY CONVERSION*, vol.25, no. 4, 2010.

[22] L. Sainz, J. J. Mesas, R. Teodorescu and P. Rodriguez, «Deterministic and Stochastic Study of Wind Farm Harmonic Currents,» *IEEE Transactions on Energy Conversion*, vol. 25, no. 4, 2010.

[23] C.-Y. Chang, S.-Y. Chan, J.-H. Teng and R.-C. Leou, «Harmonic current characteristic analysis for wind turbines,» *IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS)*, 2013.

[24] Ł. H. Kocewiak, B. L. Ø. Kramer, O. Holmstrøm, K. H. Jensen and L. Shuai, «Resonance damping in array cable systems by wind turbine active filtering in large offshore wind power plants,» *IET Renewable Power Generation*, vol. 11, no. 7, pp. 1069-1077, 2017.

[25] Ł. H. Kocewiak, J. Hjerrild and C. L. Bak, «Harmonic models of a back-to-back converter in large offshore wind farms compared with measurement data,» *Environmental Science*, 2009.

[26] V. Myagkov, L. Peterseny, S. B. Lazaz, F. Iovx and L. H. Kocewiak, «Parametric Variation for Detailed Model of External Grid in Offshore Wind Farms,» *Environmental Science*, 2014.

[27] S. K. Chaudhary, F. D. Freijedo, J. M. Guerrero, R. Teodorescu, C. L. Bak, L. H. Kocewiak and C. F. Jensen, «Harmonic Analysis and Active Filtering in Offshore Wind Power Plants,» *14th Wind Integration Workshop: International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, 2015.

[28] C. F. Jensen, Ł. H. KOCEWIAK and Z. EMIN, «Amplification of Harmonic Background Distortion in Wind Power Plants with Long High Voltage Connections,» *CIGRE 46th Session*, Paris, 2016.

[29] L. Shuai, K. H. Jensen and Ł. H. Kocewiak, «Application of Type 4 Wind Turbine Harmonic Model for Wind Power Plant Harmonic Study,» *15th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, 2016.

[30] M. Lehmann, M. Pieschel, M. Juamparez, K. Kabel, L. H. Kocewiak and S. Sahukari, «Active Filtering in a Large Scale STATCOM for the Integration of Offshore Wind Power,» *17th International Wind Integration Workshop*, Stockholm, 2018.

[31] M. ELtouki, T. W. Rasmussen, E. Guest, L. Shuai and L. Kocewiak, «Analysis of Summation in Wind Power Plants Based on Harmonic Phase Modelling and Measurements,» *17th International Wind Integration Workshop*, Stockholm, 2018.

[32] E. Guest, K. H. Jensen and T. W. Rasmussen « Mitigation of Harmonic Voltage Amplification in Offshore Wind Power Plants by Wind Turbines with Embedded Active Filters,» *IEEE Transactions On Energy Conversion*, 2019.

[33] Ł. H. Kocewiak, C. Álvarez, J. Cassoli, P. Muszynski and L. Shuai, «Wind Turbine Harmonic Model and Its Application, Overview, Status and Outline of the new IEC Technical Report,» *14th Wind Integration Workshop: International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, 2015.

[34] R. Melício, V. Mendes and J. Catalão, «Comparative study of power converter topologies and control strategies for the harmonic performance of variable-speed wind turbine generator systems,» *Energy*, cilt 36, pp. 520-529, 2011.

[35] A. Morales, X. Robe and J. C. Maun, «Assessment of Wind Power Quality: Implementation of IEC61400-21 Procedures,» *Renewable Energy and Power Quality Journal*, vol. 1, no. 3, 2005.

[36] B. Sabir, V. K. Rawat, M. Faizan and M. Tahir, «Analysis of Generated Harmonics in DFIG Driven by Wind Turbine during Linear & Non-Linear Load,» *International Conference on Computer Communication and Informatics*, Coimbatore, 2021.

[37] DNV GL, *Measurement of power quality characteristics of the wind turbine of the type ENERCON E-82 E4 according to IEC 614000-21 Ed. 2.0*, 2013.

[38] G. A. Mendonça, H. A. Pereira and S. R. Silva, «Wind Farm and System Modelling Evaluation in Harmonic Propagation Studies,» *Renewable Energies and Power Quality*, 2012.

[39] B. Badrzadeh and M. Gupta, «Practical Experiences and Mitigation Methods of Harmonics in Wind Power Plants,» *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, vol. 49, no. 5, 2013.

[40] S. T. Tentzerakis and S. A. Papathanassiou, «An Investigation of the Harmonic Emissions of Wind Turbines,» *IEEE Transactions on Energy Conversion*, vol. 22, no. 1, pp. 150 - 158, 2007.

[41] C. F. Jensen, C. L. Bak, L. Kocewiak, J. Hjerild and K. Berthelsen, «Probabilistic Aspects of Harmonic Emissions of Large Offshore Wind Farms,» *10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, 2011.

[42] D. Schwanz, M. Bollen, A. Larsson and Ł. H. Kocewiak, «Harmonic mitigation in wind power plants: Active filter solutions,» *17th International Conference on Harmonics and Quality of Power (ICHQP)*, Belo Horizonte, Brazil, 2016.

[43] E. Ebrahimzadeh, F. Blaabjerg, M. Xiongfei Wang and C. L. Bak, «Harmonic Stability and Resonance Analysis in Large PMSG-Based Wind Power Plants,» *IEEE Transactions on Sustainable Energy*, 2016.

[44] Ł. H. Kocewiak, J. Hjerrild and C. L. Bak, «Statistical Analysis and Comparison of Harmonics Measured in Offshore Wind Farms,» *OFFSHORE 2011*, Amsterdam, Netherlands, 2011.

[45] H. Emanuel, M. Schellschmidt, S. Wachtel and S. Adloff, «Power quality measurements of wind energy converters with full-scale converter according to IEC 61400-21,» *10th International Conference on Electrical Power Quality and Utilisation*, Lodz, Poland, 2009 .

[46] K. YANG, Wind-Turbine Harmonic Emissions and Propagation through A Wind Farm, Thesis for the degree of Licentiate of Engineering, Skelleftea, Sweden: Lule˚a University of Technology, 2012.

[47] M. Bollen and K. Yang, «Harmonics - Another Aspect of The Interaction Between Wind power Installations and the Grid,» *22nd International Conference on Electricity Distribution*, 2013.

[48] I. A. Aristi, Switching Overvoltages in Offshore Wind Power Grids, Measurements, Modelling and validation in Time and Frequency Domain. PhD Thesis, Technical University of Denmark, November 2011.

[49] C. F. FLYTKJÆR, «Power System Component Harmonic Modelling,»

International Journal of Scientific Engineering and Science
Volume 6, Issue 10, pp. 36-45, 2022. ISSN (Online): 2456-7361

Harmonics in Power Electronics and Power Systems, 29-31 October.

[50] S. A. Papathanassiou and M. P. Papadopoulos, «Harmonic analysis in a power system with wind generation,» *IEEE TRANSACTIONS ON POWER DELIVERY,* vol. 21, no. 4, 2006.

[51] C. F. Jensen, «Harmonic background amplification in long asymmetrical high voltage cable systems,» *International Conference on Power Systems Transients*, Seoul, Republic of Korea, 2017.