Harmonic Measurements in a Capacitive Voltage Transformer: Improvement Considering the Transformer's Design Parameters

Manuel De La Hoz
Projects and Services Department
Arteche Group
Bizkaia, Spain
manuel.delahoz@arteche.com

Juan Chacón
Research and Development Department
Arteche Group
Bizkaia, Spain
juan.chacon@arteche.com

Dominique Alonso Sørensen
Projects and Services Department
Arteche Group
Bizkaia, Spain
dominique.alonso@arteche.com

Urko Zatika Larrinaga
Research and Development Department
Arteche Group
Bizkaia, Spain
urko.zatika@arteche.com

Cristina Rioja Barón
Projects and Services Department
Arteche Group
Bizkaia, Spain
cristina.rioja@arteche.com

***Abstract*—The power quality studies made for the deployment of renewable power farms consider the harmonic interaction between the existing grid and the corresponding farm. An accurate computational model describing the grid must consider the background harmonics at the point of common coupling before the commissioning of the renewable energy farm. Consequently, there is an increasing trend of measuring the harmonic distortion of electrical current and voltage across an instrument transformer to characterise the external grid. The use of the Capacitive Voltage Transformer (CVT) is a common practice in substations with voltage greater than 100 kV. It results to be a very cost-efficient solution in terms of accuracy, but its frequency response makes itself unsuitable for harmonic measurements due to its filter behaviour. The impact that this alteration has on the harmonic susceptibility, resonances, and emissions between the farm and the grid is studied and an alternative in the transformer industry sector is suggested to mitigate this problem. With that purpose in mind, the design parameters of the CVT are taken into consideration to obtain its transfer function and establish an enhancement on the harmonic voltage measurements.**

***Index Terms*—Distortion measurement, harmonic analysis, instrument transformers, power quality, power system harmonics**

Acronyms

BH	Background Harmonics
HD	Harmonic Distortion
CVT	Capacitive Voltage Transformer
REF	Renewable Energy Farm
PCC	Point of Common Coupling
THD	Total Harmonic Distortion
TF	Transfer Function Module

I. Introduction

As a consequence of the energy transition, the penetration of renewable energy sources is massively increasing, especially wind and solar farms [1]. One of the most common power quality issues dealing with renewable generation is related to harmonic distortion. The high-frequency switching of the power converters connected to the generators is the main culprit of the aforementioned harmonic distortion and has a cumulative effect on the electrical bulk system [2].

The grid operators are responsible for the proper operation of the whole network; therefore, is their duty to establish the maximum distortion limits of a range of harmonics and the Total Harmonic Distortion (THD) allowed at the Point of Common Coupling (PCC). Thus, a harmonic assessment must be done to determine these limits compliance [3].

To perform this harmonic study and determine whether the farm in stable operation meets these compliance limits, it is necessary to possess adequate knowledge of the Background Harmonics (BH) at the PCC before the Renewable Energy Farm (REF) connection. This BH is necessary to capture the future interaction between the grid and the renewable power farm [4]. As the harmonic assessment should try to grasp the future interaction between them, adequate field measurements are essential in its accuracy.

Typically, the harmonic distortion required for a grid diagnosis is measured in voltage and current transformers. When it comes to voltage transformers, it is usual to find CVTs, especially on high voltage transmission systems. Although this CVTs result to be a very cost-efficient solution in terms of accuracy (0.1, 0.2, and 0.5 class at nominal frequency) and signal transmission, the frequency response of a CVT makes itself unsuitable for harmonic measurements.

According to the technical report made by CIGRE [5], the external network should be modelled as a Thevenin's equivalent circuit dependent on the frequency as can be observed in Fig. 1. The voltage source modelled as follows represents and reflects the harmonic voltages measured through the CVTs. Consequently, if the measuring has been obtained through CVTs, as in the applicable case; the inaccuracy of the obtained BH due to the inner impedance characteristics of the CVT, would lead to unrealistic outcomes.

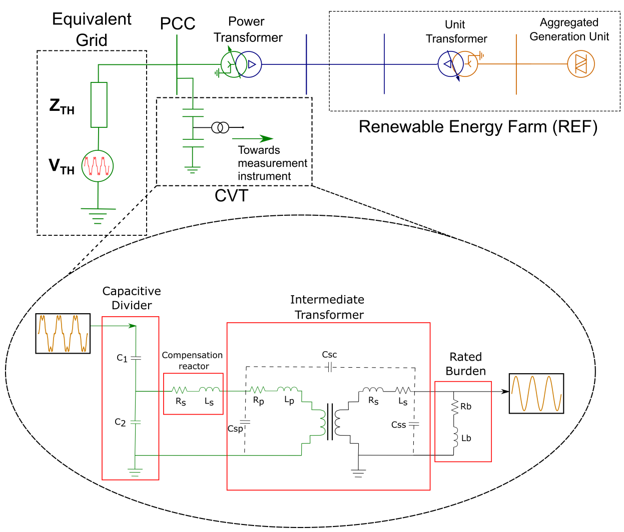

Fig. 1. CVT's elements and its location on the electric network.

Gale and Gassemi [6] suggested one possible solution. The proposed method corrects the harmonic measurements by adding current sensors on each capacitor under the divider branch of the CVT. However, it is only suitable if the current sensors are calibrated and connected to the CVTs during the manufacturing process. Otherwise, it is not usually feasible to de-energise and disassemble an already operating CVT to install these current sensors. This limitation revealed the compelling need of developing a methodology to address the challenge with fewer resource requirements.

II. Problem Statement

When a new REF is connected to the grid it is necessary to perform harmonic measurements to guarantee that the harmonic voltages do not exceed the standard limits, such as IEC 61000 3-6 [7]. The problem appears when such measurements are done in CVTs because harmonics measurements are severely affected by the transformer frequency response [8]. Additionally, it could be the only type of voltage transformer available in the substation where the REF will be connected.

This research develops a possible solution to the topic by dividing the issue into three phases. The first one is to quantify the error introduced in a harmonic study if the BH measurements are carried out through a CVT. The second one is to correct the measurement using the Transfer Function Module (TF) of the instrument transformer. The last step is to evaluate the consequences of this correction to the outcome of a harmonic load flow study for a REF assessment.

The paper is structured in the following order: in Section III, it is explained why the REF grid connection has an impact on the existent harmonic distortion (Harmonic Distortion (HD)). Section IV establishes the proposed method to improve the BH measurement accuracy across a CVT based on its simplified representation (TF). To demonstrate the benefits of this correction, a harmonic flow study is performed using a fictitious REF model. In section V the features of the grid, the REF and the CVT considered in the study case is described in more detail. In section VI the results obtained are presented, displaying the method´s improvement to the prediction capability of the HD assessment. Section VII and section VIII offer the discussion and conclusions respectively.

III. Harmonic Behaviour Due to a Renewable Energy Farm

REFs are fundamentally dispersed and intermittent energy sources, which exploitation is viable through power electronics embedded on high-power inverter. Regardless of its size, the use of electronic equipment due to its switching processes contributes to the Harmonic Distortion (HD) in current that is transmitted from the generator to the connection point. This harmonic distortion will propagate to other users of the grid through the distribution and transmission system [9].

Harmonic emissions contribution due to the switching equipment is not the only problem, but the non-linearity of the interaction between the grid impedance and REF's impedance produces parallel resonances that impact the voltage harmonics, increasing their value inside the REF and the PCC [10]. Some authors model the PCC impedance as a frequency-dependent RL circuit whose values are represented by a point on a geometrically represented sector or polygon [11]. The interaction between the grid and the REF at the PCC changes this impedance value for all the harmonic frequencies and consequently, the BH of the grid, the current harmonic emission of the REF, and the Thevenin's impedance on the connection point produce a specific HD on the PCC.

In conclusion, grid impedance is modified at the connection point of any new REF due to the interaction between the farm and the grid and as a consequence the HD observed at that point PCC is also modified.

Additionally, the increase in electrification of transportation and other new services and technologies can also make a notable contribution, such as rail systems and arc furnaces. The increasing of REFs connected to a node is not the only indicator that should be used to consider the possible harmonic pollution in a grid. Hence characterising and modelling the impacts of harmonics on the grid, and its measurement process gains even more importance.

IV. Determination of Harmonics Distortion Considering CVT's Parameters

The method described in this paper is shown in Fig. 2. The aim is to observe the impact that a correction in the measurements obtained through a CVT has, both in the BH measurements itself, as well as in the HD obtained in the harmonic load flow.

Considering measuring through an ideal voltage transformer (TF_{ideal}), background harmonic voltages of the PCC without the presence of the farm (V_{BH}^{grid}) is directly obtained and used as a reference. On the contrary, when measurements are done through a CVT a modified harmonic distortion is recorded (V_{BH}^{ref}).

In order to compare accurately the methods' theoretical effectiveness, V_{BH}^{grid} is assumed to be a user-defined profile and hence, a percentage of the IEC 61000 3-6 standard planning limits have been considered. The transfer function (TF_2) of the CVT is used to calculate the altered onsite measurement (V_{BH}^{ref}) thus V_{BH}^{ref} can be compared to V_{BH}^{grid} in order to compute the error made by measuring through a real CVT.

To obtain the corrective transfer function ($1TF_1$), the CVT design parameter must be considered, and should be given by the manufacturer. If this parameters are confidential the TF could be shared instead. The corrective transfer function is applied to V_{BH}^{ref} to obtain the V_{BH}^{corr}, aiming to be as close as possible to the V_{BH}^{grid}.

Inaccurate measurement of the BH does have an impact when it comes to evaluating the input of the HD produced by the REF as the BH is input data for the simulation. For the purpose of quantifying the impact with the REF connected, the resulting HD and THD at the PCC will be evaluated using the different BH mentioned previously: V_{BH}^{grid}, V_{BH}^{ref} and V_{BH}^{corr}. The results have been obtained by using the PowerFactory 2020 SP3, carrying a balanced harmonic load flow.

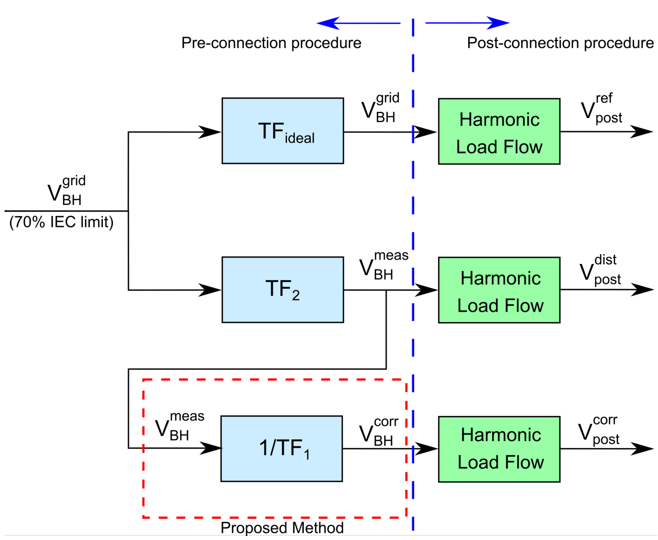

Fig. 2. Procedure to determine the harmonic distortion considering measurement on a CVT.

V. Modelling the Renewable Energy Farm and Capacitive Voltage Transformer

A. Global Description of the Model

To evaluate the impact on harmonic studies whether the BH measurements are carried out in a CVT, a wind farm is selected as the REF. The wind farm consist of 27 doubly-fed induction generator wind turbine system of 3.7 MVA each generator. The overall wind farm rated power is 100 MVA. In Fig. 3, the REF is presented. Every feeder is a lumped of different generators and power transformers connected in parallel.

B. Grid Model

The grid impedance will be initially modelled as a constant RL circuit in series and its value comes from the short-circuit power and nominal voltage shown in Table A1. Thus, the possible impedance resonances may arise exclusively when connecting the REF. The grid will present a characteristic BH (V_{BH}^{grid}) equivalent to a percentage of the IEC 61000 3-6 (70% IEC) [7] for indicative planning levels regarding the harmonic voltage limits. This is one of the most relevant input data that impact the post-connection HD on the PCC.

C. Renewable Energy Farm Model

The modelled REF will be a set of wind generators whose overall do not exceed the short-circuit ratio of 10% in such a way that the impact on grid voltages or operation can be negligible. All generator units operate at their nominal value and a unit power factor. The technical specifications of both the wind farm and the PCC are described in Appendix A. The model graphical representation is shown in Fig. 3.

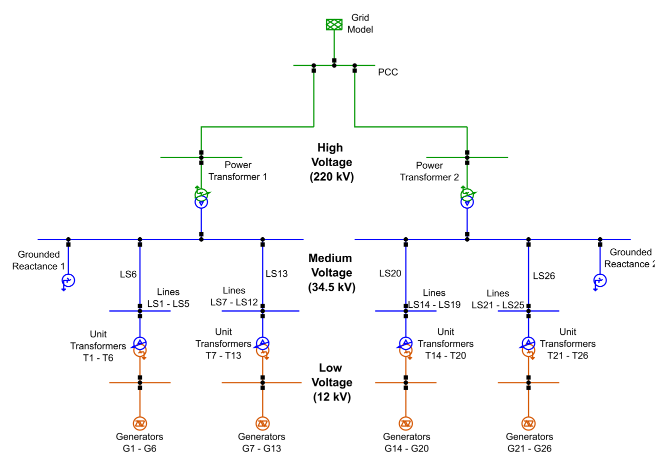

Fig. 3. Renewable energy farm model.

All the generators were considered as ideal in terms of harmonic electric current (this is, its Norton's impedance is assumed as infinite), the percentage of electric current to each harmonic is shown in Appendix B

D. Capacitive Voltage Transformer Model

The model of the CVT considered is presented in Fig. 4 where the stray capacitance are shown in dotted lines. (TF_1) of the CVT is calculated without considering stray capacitance (the orange elements in Fig. 4), whereas, (TF_2), stray capacitance are included . In both transfer function calculations, the magnetisation inductance value will be at the unsaturated part of the B-H curve. The two types are considered to demonstrate whether the stray capacitance is significant or not in the harmonic range of study, up to the 50^{th} harmonic, considering the difficulty to measure these items by manufacturers.

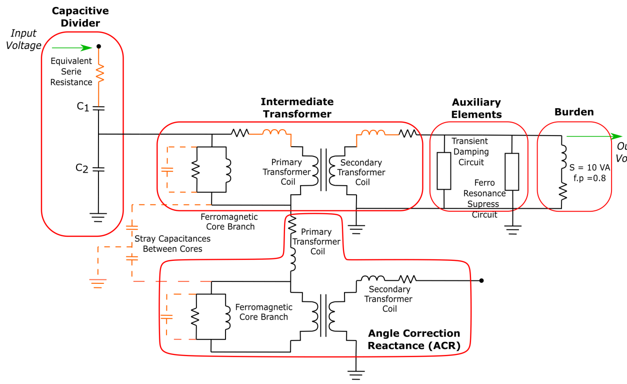

Fig. 4. Scheme of the CVT models.

The frequency response of the two CVT types is shown in Fig. 5. The dotted-blue line curve represent TF_2, which is the most accurate TF as it takes more parameters of the CVT into consideration. The discontinuous red curve pictures the approximate TF_1 frequency response, considering the information supplied by the manufacturer and the proposed method implemented in yellow.

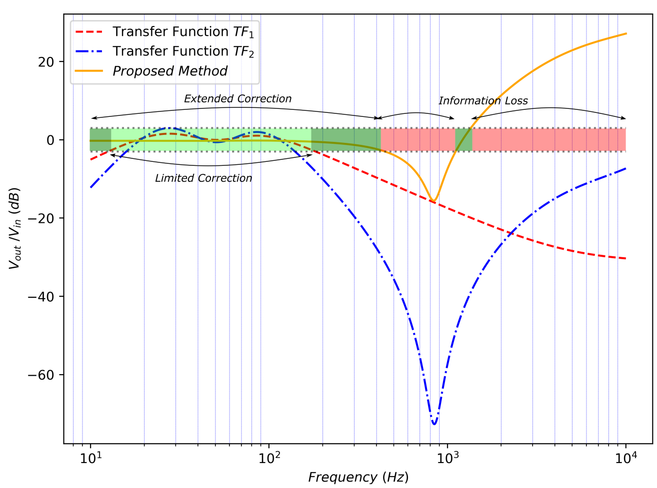

Fig. 5. Frequency response and method propose of the CVT.

The area represented with a coloured ribbon is an estimated value of the measuring deformation, between ± 3 dB, (40 % of the actual value). If we only consider as valid the section of TF_1 where the amplification/attenuation of the BH input is not greater than 3 dB, as an indicator of accuracy for the approach, it results to be a fairly conservative consideration. One contribution of the proposed method is that the range of harmonics feasible to correct can be extended compared to TF_1's range.

VI. Results

A. Pre-Connection Procedure

The results of applying the proposed method in the measured BH are observed in Fig. 6. Considering the BH measured in the CVT (TF_2) concerning the reference (TF_{ideal}), it is observed that for almost all the harmonics evaluated the CVT produced an attenuation (except for the 2^{nd} harmonic, which is amplified).

In the case of the proposed method ($1/TF_1$), the harmonics up to the 10^{th} order do not exceed the threshold of 3 db, the same as from the 22^{nd} to the 26^{th} harmonic, corresponding to the areas shaded in green in Fig. 5. In the case of the correction, there is an overestimation that becomes exacerbate for the harmonics greater than 27^{th}, corresponding to the previously indicated in red as the Information loss area. (for example, the 29^{th} harmonic depicted in Fig. 6)

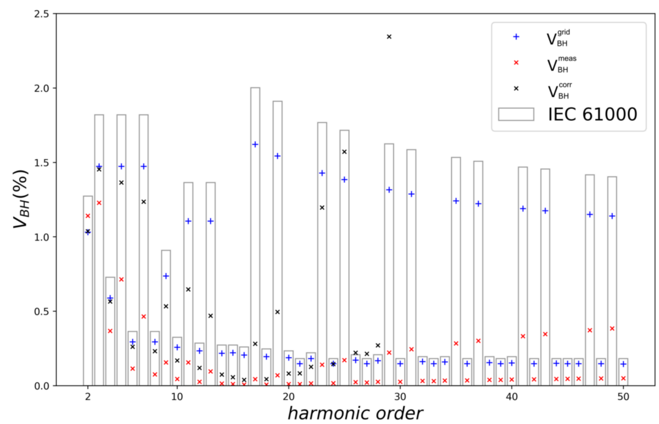

Fig. 6. Distortion of the background harmonic in the on the pre-connection procedure.

The calculated THD values on the pre-connection procedure, where just the background harmonics of the grid are considered and are shown in Table I. The relative error is related to the original (V_{BH}^{grid}). It is observed that for any measured THD limit set by the grid operator, measurements made on CVTs will always underestimate the harmonic contamination on the grid.

TABLE I
Total Harmonic Distortion under Pre-Connection Procedure

	Grid (TF_{ideal})	CVT (TF_2)	Corr. ($1/TF_1$)
THD (%)	5.72	2.15	3.64
ϵ_{rel} **(%)**		62.4	36.4

The calculation of the THD using the method implemented (Corr.($1/TF_1$)) is compared to the THD obtained considering the BH measured across the CVT without any correction, whereas an improvement of 41.6 % is obtained with the reference (V_{BH}^{grid}) as a base.

B. Post-Connection Procedure

The HD obtained when the REF is connected to the PCC is shown in Fig. 7. In this case, the resonances produced in the interaction between the farm and the grid affect the results of the HD post-connection. It is observed that for the harmonics from the 12^{th} to the 15^{th} harmonics there is a standard limits non-compliance. However, due to the attenuation caused by the CVT utilisation on the measurement in the CVT it is not detected as problematic on the installation. For this harmonic order interval, the proposed model still underestimates the existing problem, but it offers a better approximation considering the direct measurements through the CVT.

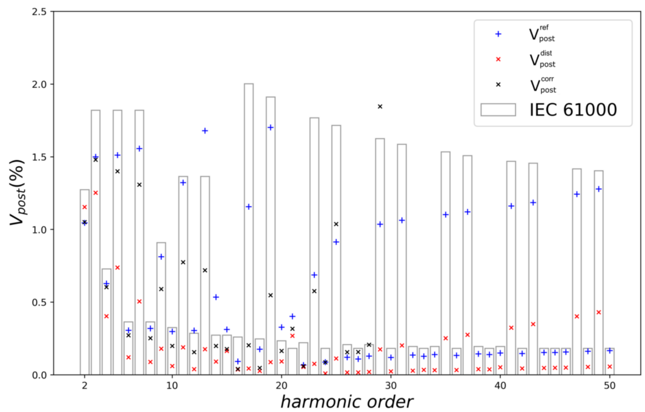

Fig. 7. Different harmonic distortion measurement on the post-connection procedure.

Fig. 8 indicates the percentage of deviation between the proposed method and the post-connection measurements in the CVT. 40 % has been chosen to represent the 3 dB attenuation analysed in Fig. 5. It is seen that from the 10^{th} harmonic, as well as between the 21^{th} to the 26^{th} harmonic is possible to obtain an improvement in the measurement within the established parameters, such as in the pre-connection procedure.

The calculated THD values on post connection-procedure are shown in Table II. The relative error is related to the THD calculated with the ideal BH (70 % IEC).

TABLE II
TOTAL HARMONIC DISTORTION UNDER POST-CONNECTION PROCEDURE

	Grid (TF_{ideal})	CVT (TF_2)	Corr. ($1/TF_1$)
THD (%)	5.59	2.22	3.44
ϵ_{rel} **(%)**		60.3	38.5

However, the prevailing condition in the measured values remains the same, presenting the lowest THD (CVT measured BH, considering the TF_2), with a relative error of 60.3 %.

VII. Discussion

Our results suggest that a frequency response knowledge, although incomplete, of the CVT, could improve the voltage harmonic measurements obtained through it. This improvement is crucial when the only instrument transformer available at the PCC is one of this kind. The method implemented in this paper could apply not only for CVT but

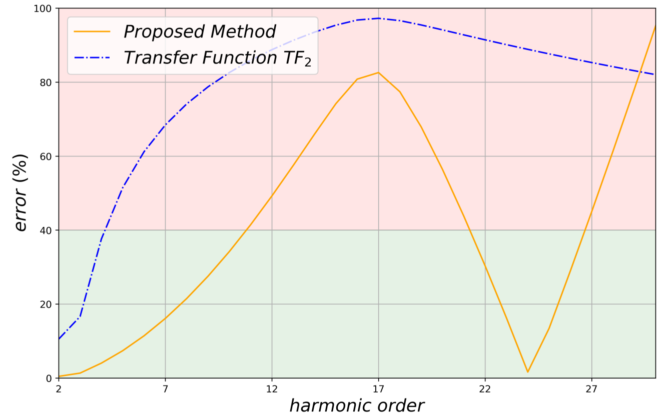

Fig. 8. Estimate error in the post-connection procedure.

for other types of instrument transformers such as the inductive ones.

It is important to emphasise that measuring the transformer's TF once it is installed is virtually impossible. Furthermore, for modelling the CVT in complete detail as in this research, it is crucial to have the inner elements values and tolerances of the specific transformer under study; which requires information of the confidential design of each manufacturer.

The method proposed in this paper opens the way for transformer manufacturers to share information with the customer without losing competitiveness. Besides, it allows measuring with accuracy a certain range of frequencies. However, this does not solve the problem for all measured frequency ranges requested by the system operators nowadays.

A problem with CVTs is that it attenuates the measures at certain frequencies, and amplifies the measures at other frequencies. After a certain frequency value, the CVT attenuates so much the measures that are not possible to revert it.

Nowadays, there does not exist any test in the industry that compels the determination of the CVT's TF experimentally. One research line under interest is what requirements need it to attain this objective with the manufacturer that not implies an exorbitant increment in the net cost of the CVT. As future works, we consider it necessary to evaluate the precision class behaviour in measurement transformers under a wide frequency range and how to improve the experimental determination of the stray capacitance of the instrument transformer.

VIII. Conclusions

In this research, a particular CVT has been considered to evaluate the impact of harmonic voltage measurements obtained through it on the harmonic assessment of the REF integration to the transmission grid. When the power quality measures are made at a CVT, the state of the HD on the grid is underestimated, especially if there are other REF and other harmonics sources on the surroundings. Due to the difficulty of characterising the frequency response of a CVT, since this information is sensitive and is only available for the manufacturer, a method of measurements correction with partial information from the CVT is proposed and validated.

Considering the THD calculations, the proposed method improves the harmonic load study compared to using the measurements acquired by the CVT without any correction considering the REF modelled. This improvement is much valuable when considering individual low-order harmonics, such as the 5^{th}, 7^{th} and 11^{th}, typical highly emitted by REF's power electronic devices.

Our results suggest that even in the most extreme cases without the possibility of measurement in an instrument transformer it is possible to seize the impact of the REF on the grid's HD. This would be a viable step to improve the prediction of harmonic studies as long as exist a commitment on the part of the manufacturers to provide this information.

Acknowledgement

This research has been technically and financially supported by Arteche Group. In the meantime, this research would not have been possible without the unconditional support of our managers Mrs. Sonia Gonzalez, C.O. of Project and Services, and Mr. Oscar Fernandez de Retana C.O. of Research and Development; on behalf of our company Arteche Smart Grid; facilitating the collaboration between our different departments.

References

[1] C. Jägemann, M. Fürsch, S. Hagspiel, and S. Nagl, "Decarbonizing europe's power sector by 2050—analyzing the economic implications of alternative decarbonization pathways," *Energy Economics*, vol. 40, pp. 622–636, 2013, doi: 10.1016/j.eneco.2013.08.019.

[2] X. Liang, "Emerging power quality challenges due to integration of renewable energy sources," *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 855–866, 2016, doi: 10.1109/TIA.2016.2626253.

[3] T. Vu, D. A. Robinson, V. Gosbell, S. Perera, and R. Memisevic, "Evaluation of practical application of different harmonic allocation methodologies," in *2020 19th International Conference on Harmonics and Quality of Power (ICHQP)*. IEEE, 2020, pp. 1–6, doi: 10.1109/ICHQP46026.2020.9177875.

[4] R. Vazquez, M. Muñoz, M. Alonso, H. Amaris, and C. Alvarez, "Background harmonic distortion measurement at power networks with wind farms," in *International Conference on Renewable Energies and Power Quality (ICREPQ'16), Madrid (Spain)*, 2016, pp. 4–6, doi: 10.24084/repqj14.500.

[5] International Council on Large Electric Systems, "Network Modelling for Harmonic Studies," International Council on Large Electric Systems, Geneva, CH, Standard CIGRE JWG C4/B4.38, 2019.

[6] F. Ghassemi, P. Gale, T. Cumming, and C. Coutts, "Harmonic voltage measurements using cvts," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 443–449, 2005, doi: 10.1109/TPWRD.2004.837675.

[7] IEC, "Electromagnetic compatibility – (EMC) – Part 3: Limits –Section 6: Assessment of emission limits for distorting loads in MV and HV power systems – Basic EMC publication," International Electrotechnical Commission, Geneva, CH, Standard IEC/TR 61000-3-6:1996, 1996.

[8] J. Le, H. Zhang, C. Gao, and Q. Zhou, "Harmonic voltage measurement error of the capacitor voltage transformer," *PloS one*, vol. 13, no. 11, p. e0205231, 2018, doi: 10.1371/journal.pone.0205231.

[9] K. Malekian, F. Safargholi, W. Schufft, T. Dreyer, J. Cassoli, S. Adloff, F. Ackermann, H. Moghadam, S. Rogalla, G. Kaatz *et al.*, "Harmonic model validation of power generation units," *IET Renewable Power Generation*, vol. 14, no. 13, pp. 2456–2467, 2020, doi: 10.1049/iet-rpg.2018.6268.

[10] M. Bradt, B. Badrzadeh, E. Camm, D. Mueller, J. Schoene, T. Siebert, T. Smith, M. Starke, and R. Walling, "Harmonics and resonance issues in wind power plants," in *PES T&D 2012*. IEEE, 2012, pp. 1–8, doi: 10.1109/TDC.2012.6281633.

[11] N. Hingorani and M. Burbery, "Simulation of AC System Impedance in HVDC System Studies," *IEEE Transactions on Power Apparatus and Systems*, vol. PA89, no. 5, pp. 820–&, 1970, doi: 10.1109/TPAS.1970.292644.

Appendix A
Wind Farm Technical Information

The Table A1 contains the technical information related to the network used for the study

TABLE A1
PARAMETER VALUES FOR THE STUDY WIND FARM OF FIG. 3

	Grid
PCC	$S_k^{"}$ = 6323 MVA, X/R = 13.97 Z_2/Z_1=1, X_0/X_1 = 2.462, R_0/X_0 = 0.226
	Transformer
Power Transformer 2 units	S_T = 50 MVA,VG_T = Yd11, V_{HV}/V_{LV} = 220/34,5 kV u_k = 12.56%, P_{cu} = 68.33kW, u_{kou} = 3%, X_0/R_0 = 2.93, I_0 = 0.2%, P_0 = 75 W, Asymmetric Phase Shifter with 27 taps, 1.25% per tap.
Unit Transformer 27 units	S_{TU}= 3,7 MVA,VG_{TU} = Dyn11, V_{HV}/V_{LV} = 34.5/12 kV u_k = 6 %, P_{cu_u} = 26 kW, u_{ko_u} = 3.5 %, X_0/R_0 = 2.51, I_{0_u} = 1.5 %, P_{0_u} = 5.5 W, Asymmetric Phase Shifter with 5 taps, 2.5 % per tap.
	Generators
Generator (27 units)	DFIG WT System, Ideal Harmonic Current Source, P_{ng} = 3.3 MW, U_{ng} = 12 kV Q_{ng} = 1.2 kVAr
	Evacuation Lines
Underground Line (LB01-LB26)	U_{nLS} = 34.5 kV, $I_{nLS(ground)}$ = 0.596 kA, R_{LS} = 0.0563 Ω/km, X_{LS} = 0.1364 Ω/km, B_{LS} = 93.5 ηS/km, $d_{LS1} - d_{LS26}$ = [0.28, 0.39, 0.45, 0.28, 0.28, 2.74, 0.31, 0.28, 0.28, 0.33, 0.27, 0.38, 0.64, 0.28, 0.28, 1.69, 0.28, 0.33, 0.28, 2.49, 0.86, 0.29, 0.28, 0.30, 0.94, 5.7] km.
Overhead Line (OL-1, OL-2)	U_{nL} = 220 kV, I_{nL} = 1.5 kA, R_L = 0.0857 Ω/km X_L = 2.193 Ω/km, B_L = 2.803 ηS/km d_{L1} = 3 km, d_{L2} = 1 km

Appendix B
Harmonic Emission Spectrum

The Table B1 contains the harmonic current contribution in percentage of each generator.

TABLE B1
HARMONIC EMISSION CURRENT OF THE GENERATION UNITS

h	%	h	%	h	%	h	%	h	%
2	0.21	**12**	0.12	**22**	0.10	**32**	0.10	**42**	0.22
3	0.19	**13**	0.38	**23**	0.11	**33**	0.25	**43**	0.12
4	0.28	**14**	0.12	**24**	0.00	**34**	0.11	**44**	0.11
5	0.61	**15**	0.15	**25**	0.00	**35**	0.24	**45**	0.12
6	0.14	**16**	0.11	**26**	0.00	**36**	0.11	**46**	0.00
7	0.65	**17**	0.13	**27**	0.00	**37**	0.10	**47**	0.00
8	0.17	**18**	0.11	**28**	0.00	**38**	0.21	**48**	0.10
9	0.18	**19**	0.12	**29**	0.00	**39**	0.11	**49**	0.00
10	0.12	**20**	0.11	**30**	0.10	**40**	0.51	**50**	0.00
11	0.31	**21**	0.11	**31**	0.00	**41**	0.11		