A Development of Equivalent Grid Harmonic Model for Integration of Offshore WPPs: A case study for Northwest Turkey

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***Abstract*— The territorial water in northwest Turkey is rich in terms of high wind speed. There is a significant number of sites for the potential large-scale offshore wind power plants (OWPPs) in this region. The integration of large scale OWPPs may arise serious harmonic stability problems in transmission grids. To analyze grid harmonic stability and comply with the grid code requirements, it is crucial to construct harmonic models for the transmission grids. In large transmission systems, the development of an exact harmonic model needs much effort and it is not required in most cases. The harmonic characteristics of grids can be revealed by equivalent harmonic models which identify critical harmonic resonance points of the grid. In this paper, an equivalent harmonic model of the Turkish power grid has been developed for the harmonic resonance assessment studies of the potential OWPP located in the Kıyıköy of the Trakya region. For the equivalent model development studies, the transmission grid in Trakya region has been modelled in detail and harmonic impedance characteristics for the rest of the grid beyond İstanbul and Dardanel Bosphouruses has been determined using frequency sweep analyzes. In the last stage, the grid harmonic model has been downgraded into a three-bus system and the harmonic bus impedance matrix has been built up for harmonic resonance analyzes. The equivalent model development and analysis studies have been performed using Digsilent PowerFactory software.**

Keywords— Harmonic distortions, Offshore wind power plants, wind power plant grid connections, Harmonic impedance analysis, Harmonic propagation in grids

I. INTRODUCTION

Northwest Turkey is available for potential large-scale OWPPs thanks to the high wind speed potential in this region. The integration of large-scale offshore power plants could provide a high level of energy support to this region. However, the integration of large offshore power plants into the grids can lead to notable problems in terms of harmonic stability. Mitigating these distortion effects is greatly dependent on the capability of system operators on running the necessary simulations in a realistic manner to see the distortion effects interacting with the network. This can be achieved by developing harmonic models for the transmission grids. Developing an actual harmonic model requires significant effort and a lot of confidential information collected from different device manufacturers and system operators. Therefore, an exact harmonic model is not available for most cases as it needs a remarkable background preparation.

The harmonic characteristics of networks can be provided by developing equivalent harmonic models. Equivalent harmonic models show harmonic resonance points of a network in detail. These resonance points are critical for the harmonic currents and voltages introduced into the network. To generate an equivalent harmonic model, all equipment simulation models need to be re-created with additional frequency dependent parameters, especially for cables and transformers.

In common practice, transmission lines are implemented with lumped models for power flow analyses. This approach is not suitable for harmonic analyses since the lumped models can not present complete harmonic characteristics of the lines. For the harmonic analyses, the overhead transmission lines over 250km should be modelled with geometric models. The condition is more strict for the underground transmission systems since cables are assumed to have 20 to 40 times higher capacitance than overhead lines when comparing the same voltage and line length [1], [2]. Although it is advised to use cables in renewable power plants [3], the high capacitance of cables may lead multiple resonant points in lower frequencies. Because of these, a length of 3-4 km is considered as the limit for the implementation of geometric data for cables [1], [4]. For the Turkish transmission network, the lengths of the existing overhead lines reach over 230 km, while for cables this level is 17 km, which makes detailed modeling of cables crucial. Unlike overhead lines and cables, which are effective in both cases, transformers affect the grid impedance up to higher order harmonics in a resistive rather than inductive manner. By considering their frequency-dependent resistances, detailed models of transformers can lead to meaningful attenuations in parallel resonance quantities and thus filter investment costs [4].

In the literature, several works are carried out on the subject of offshore connections with regard to the effects of harmonics. Much of the work based on OWPP connections focuses on DC links established by (high-voltage DC) HVDC links [5], [6], [7]; in contrast to these, an OWPP connected via an AC connection is the focus of interest in this work. The model used for this study favors real network states and models, representing each line and other elements with their real properties and not with equivalents as used in [8], [9], [10]. In addition, for additional cases, an approach more readily available for harmonic studies, a frequency-dependent model, is used in the setup of lines and transformers.

In this work, an equivalent harmonic model was developed for the harmonic resonance assessment studies of the potential OWPP in Kıyıköy of Trakya region. For the development of equivalent harmonic studies, the transmission grid in the Trakya region was modeled in detail, with additional frequency dependencies defined, and harmonic impedance characteristics for the rest of the grid beyond İstanbul and Dardanel Bosphouruses were determined using frequency sweep analyses. In the final phase of the study, the network harmonic model was downgraded to a three-bus system and the harmonic bus impedance matrix was constructed for harmonic resonance analysis. At the impedance analysis both direct and transfer impedances are evaluated for each of three (point of connection) PoC as in [11]. Since parallel resonances are critical for mesh grids, parallel resonances are main focus of interest for this study [12]. Both phase and sequence domains are assessed for resonances and similar patterns are investigated as in [13]. The development and analysis studies of the equivalent harmonic model were performed using the Digsilent PowerFactory software. The main contribution of this study is the development of the first equivalent harmonic model of the Turkish grid for a potential large-scale OWPP connection to the north-western side of Turkey.

The rest of the paper is organized as System Description section as the second part summarizing general working condition considerations, Harmonic Domain Modeling section briefly explaining the definition of frequency dependence of elements, Building Z-Busbar Matrix section at which results of the analysis and some background settings are given, and finally a Conclusions section where the main contribution and results of the work are briefly explained.

II. SYSTEM DESCRIPTION

A. *Transmission Grid on Northwest Turkey*

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; Northwest Turkey is considered as representative for this study. At the Northwest 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 at the area is mainly dependent on overhead lines, smaller portion of power flow is made via underground cables. Two-winding HV transformers are used to step the voltage down from 400kV or 154kV levels to a variety of MV levels depending on the needed level of end user occupations and autotransformers are used for conversions between 400kV and 154kV levels.

B. *Kıyıköy Offshore Power Plant*

The connection point for the proposed OWPP is selected according to previously conducted studies by considering a wide range of parameters from bathymetry to bird migration routes [14]. In addition to many appropriate facilities a wind speed of greater than 8.75 m/s [14] has become a deciding factor for selection of Kıyıkoy for OWPP connection. Kıyıköy OWPP has a total power generation capacity of 1.8 GW, designed as two phases (900 MW each). Phase I of Kıyıköy OWPP is connected to busbar of Sustation A and phase II is connected to busbars of Substation B and C as also indicated in the Fig.1.

III. HARMONIC DOMAIN MODELING

A. *Modelling Approach*

For harmonic model development studies, proximity to the connection point is considered a critical factor in terms of the level of detail in device model design. According to [1] a distance of 3 busbars is considered as the limit for detailed modelling. In this work, this boundary is extended to one region and the rest of the network is used as only equivalent.

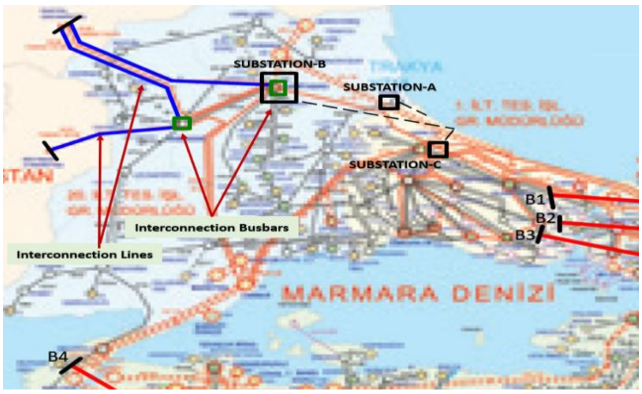

Fig. 1 Detailed modeled Trakya Region and its connections with the rest of the grid, B1, B2, B3 and B4 are boundary busbars representing Trakya side ending points of the connection lines over the Bosphorus and Dardanelles. Substation A, B and C are denoting three connection busbars of OWPP.

To reduce the grid into the Trakya region, first the region is separated from the rest of the network by the two connection points from the strait with corresponding grid equivalents as shown in Fig. 1.

To achieve a reduced network equivalent that is completely isolated from the rest of the network, DigSilent Power Factory's Network Reduction Tool is used.

After seperation, network representations are constructed by frequency sweep analysis performed on the connecting busbars located near the two Bosporus and using the resistance and inductance values collected, remaining parts of the network are mapped with a realistic representation usable for power quality analysis.

In order to draw a more realistic picture in terms of the network response to the harmonic currents, it is important to model elements that determine the resonance point, such as lines and transformers, with frequency-dependent properties. Modeling at this level of detail is generally tied to the reliable data that could be obtained, and for the same reason these types of modeling studies are generally limited to general assumptions. In this study, overhead lines, cables and transformers are modeled with collected geometric and frequency dependent data and harmonic impedances are extracted from the PCC busbars selected for the OWPP connection.

Once the Turkish region is reduced to the Trakya region and the interior of this region is redesigned as a harmonic equivalent, further frequency sweeps are performed on three connecting busbars to reduce the grid to a three-busbar system. The result of the carried out frequency-based analysis is a Z busbar matrix calculated for each Point of Connection (PoC) as given in equations (1) and (2). Z matrix is established by impedances constructed as a ratio of harmonic voltages to harmonic currents. For each driving point impedance harmonic voltage occurred at one busbar by the flow of harmonic current at the same busbar is divided to flowed harmonic current, and for each transfer impedance harmonic voltage occurred from a flow of harmonic current at the neighboring busbar is divided to source harmonic current measured at the neighboring busbar (i.e. Z_{AB} is calculated as the harmonic voltage measured at Substation A divided by flowing harmonic current at Substation B).

$$Z_{BUS}(f) = \begin{bmatrix} Z_{AA}(f) & Z_{AB}(f) & Z_{AC}(f) \\ Z_{BA}(f) & Z_{BB}(f) & Z_{BC}(f) \\ Z_{CA}(f) & Z_{CB}(f) & Z_{CC}(f) \end{bmatrix}$$

$$Z_{AA}(f) = \left.\frac{V_A}{I_A}\right|_{I_B=I_C=0}$$

$$Z_{BB}(f) = \left.\frac{V_B}{I_B}\right|_{I_A=I_C=0} \quad (1)$$

$$Z_{CC}(f) = \left.\frac{V_C}{I_C}\right|_{I_A=I_C=0}$$

Where; $Z_{AA}(f)$, $Z_{BB}(f)$, $Z_{CC}(f)$ are demonstrating driving point impedance,

$$Z_{AB}(f) = Z_{BA}(f) = \left.\frac{V_A}{I_B}\right|_{I_A=I_C=0}$$

$$Z_{BC}(f) = Z_{CB}(f) = \left.\frac{V_B}{I_C}\right|_{I_A=I_B=0} \quad (2)$$

$$Z_{AC}(f) = Z_{CA}(f) = \left.\frac{V_C}{I_A}\right|_{I_B=I_C=0}$$

And, $Z_{AB}(f)$, $Z_{BC}(f)$, $Z_{AC}(f)$ are demonstrating transfer impedances between PoC busbars.

B. Harmonic Modelling of Overhead Lines and Cables

In order to define a more suitable network model for power quality studies, transmission lines, in particular because of their higher capacitance - i.e. a higher probability of larger resonance magnitudes - the cables are remodeled, and overhead lines are also modeled by defining their geometric and phase-wise properties in a distributed parameter-based approach instead of lumped π models. For this study, overhead lines and cables are modeled with distributed parameters without exception as depending on lengths, as shown in Fig. 3.

At which;

$$\frac{Y'}{2} = \frac{Y}{2}\frac{tanh\frac{\gamma l}{2}}{\frac{\gamma l}{2}} \quad (3)$$

$$Z' = Z\frac{sinh\gamma l}{\gamma l}$$

Where;

$$\gamma = \sqrt{zy} \quad (4)$$

$$Z_c = \sqrt{z/y}$$

At which eventually results in the relations of;

$$Z' = Z_c sinh\gamma l \quad (5)$$

$$Y' = \frac{1}{Z_c} tanh\frac{\gamma l}{2}$$

This circuit model is valid for both overhead lines and cables which both of them defined in Power Factory by taking into account geometric information of each element. This model of line has the same properties with the equivalent π models since they are modelled as totally distributed, rather than π sections as used in [15].

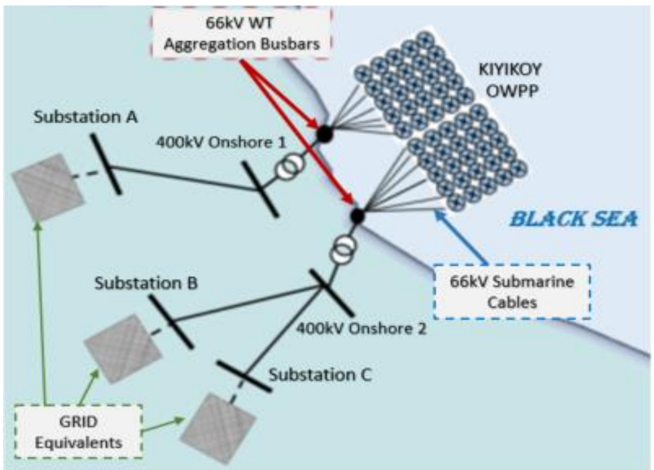

Fig. 2 Grid connections of the constructed system.

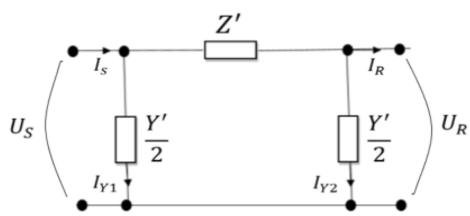

Fig. 3 Equivalent Pi model for transmission lines [2]

C. *Harmonic Modelling of Transformers*

Since inductance in transformers changes so slowly with respect to frequency, it is recommended to ignore the frequency dependence of inductance up to a certain frequency level [4]. Also in [16], since it is proved that the first resonance occurs from 10 kHz, this approach could be considered applicable. For frequency dependencies of transformers, resistances are therefore the focus of interest in this study.

Frequency dependencies are defined to each High Voltage (HV) transformer by using just the information of short circuit impedance (%Z) and X/R ratio and by defining a frequency polynomial characteristic via Power Factory related tool. Different from the mostly used approximation of transformer resistance [10], [16], [17] and [18]; the proposed model in [4] is manipulated to a version that could be usable in Power Factory yielding the equation given below. Firstly %R(pu) values of transformers are calculated by the following equation;

$$R_{pu} = \frac{\%Z}{100}.\cos(\tan^{-1}[X/R]) \qquad (6)$$

And defined polynomial characteristic equation taken from Power Factory;

$$y(f_h) = (1-a) + a(f_h/f_1)^b \qquad (7)$$

With coefficients of a=0,1 and b=1,99 taken from[19].

By using the above given equation and multiplying it with transformer short circuit resistance value, yielding to the defined frequency dependent transformer resistance of;

$$R_s = R_{pu}[(1-a) + a(f_h/f_1)^b] \qquad (8)$$

Fig. 4 Equivalent transformer model (Model 3, taken from[4])

IV. BUILDING Z-BUSBAR MATRIX

A. *Detailed vs Lumped Model*

A detailed model for the Trakya region of Turkey is built as defined in the sections above by remodeling transformers and lines. A harmonic impedance assessment is performed at Substation A to see the impact of the detailed modelling. Fig.5 summarizes the results of the impedance analysis carried out. According to this figure, locations and sizes of resonance points are apparently changed between two network models. For parallel resonances; the number of visible resonance points is reduced to one for the detailed model, while it was eight for the lumped model. Regarding the magnitude of the parallel resonance impedances, the highest impedance value is recorded as 2185,743 ohms for the 26th harmonic at lumped model. In the detailed model, this value is reduced to a magnitude of 880,064 ohms for the 16th harmonic. First frequency point of resonances is important in deciding whether it is possible for the system to overcome effects caused by harmonic distortion, so location of this resonance is also noteworthy for this phase of the analysis. In the detailed model, the first point of parallel resonances is shifted from around 13th harmonic to the 16th harmonic, showing that additional work to mitigate lower order harmonics are not required in the real case.

B. *Z- Busbar Matrix*

In this phase of the study, a Z-busbar matrix for the reduced three-busbar model of Turkey for the large-scale connection assessment of OWPPs is prepared. For each PoC, direct impedances and transfer impedances between the other two busbars are calculated up to 1500 Hz, giving the diagrams shown in Fig. 6. These plots are then summarized in Table I and Table II as lower resolution version of the results presented in Fig. 6. Impedance phase angles for each case are also given in Figure 6. Vertical lines shown in angle diagrams of transmission impedance appear due to the change in angle from (-180) to (+180).

Table I is devoted to the positive and negative sequence driving point impedances and busbar transfer impedances and Table II is summarizing zero sequence results. Tables give an assessment of the coherence of three busbar resonance points.

The focus for this study is mainly on the parallel resonances. According to Table I, the 8th, 14th and 27th harmonics are the most frequently observed resonance points. Although not recognized for the A, B and C phase impedances shown in Fig. 5, the 27th harmonic resonance is detected for sequence-based analysis. This situation is a direct result of unbalanced network conditions.

V. CONCLUSIONS

As a result of this study a comprehensive analysis is conducted regarding a possible OWPP connection to the Turkish Grid. To make the analysis in a more close-to-real scale, neighborhood of the PCCs (Trakya Region) is remodeled with additions of corresponding frequency dependent parameters and geometric data of lines and transformers gathered from manufacturers. In the following step, lumped and detailed models of grid is compared in terms of locations of resonance points and resonance magnitudes. According to this it is concluded that both locations and magnitudes of resonances are strongly dependent to network design level of detail. Then for the detailed model a Z busbar is built using both driving point and transfer impedance information gathered from three PoC busbars. As a result of this analysis critical resonances are revealed both for individual busbars and couplings between each pairs of busbars.

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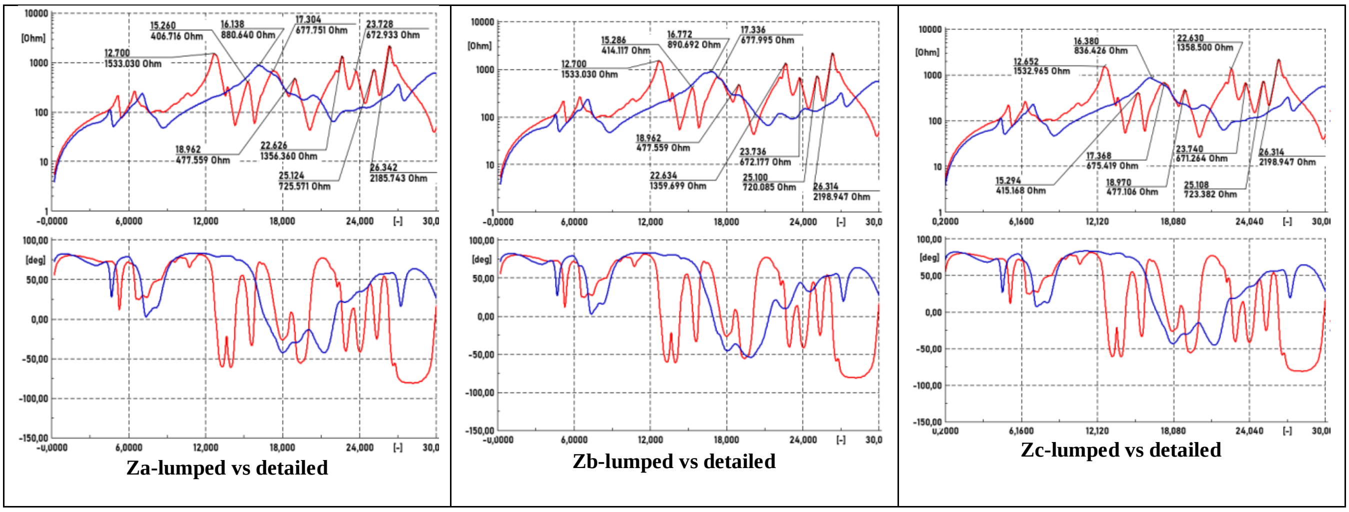

Fig. 5 Harmonic phase impedances seen at Substation A connection busbar for original and renewed states of Trakya grid (red line representing frequency sweep results for a all lumped grid scenario and blue line representing results for when the Trakya grid is modelled in detail

TABLE I. POSITIVE & NEGATIVE SEQUENCE HARMONIC RESONANCE POINTS FOR EACH BUSBAR

Busbars&Couplings	**Harmonic Order Of Resonance Point**					
	7_{th}	8_{th}	14_{th}	17_{th}	20_{th}	27_{th}
SubsA-Direct Imp. (Ohm)				✓		✓
SubsB-Direct Imp. (Ohm)		✓	✓			✓
SubsC-Direct Imp. (Ohm)		✓	✓			✓
Transfer Imp. A<->B (Ohm)		✓	✓	✓	✓	✓
Transfer Imp. A<->C (Ohm)	✓			✓		✓
Transfer Imp. B<->C (Ohm)		✓	✓			✓

TABLE II. ZERO SEQUENCE HARMONIC RESONANCE POINTS FOR EACH BUSBAR

Busbars&Couplings	**Harmonic Order Of Resonance Point**				
	4_{th}	7_{th}	12_{th}	16_{th}	24_{th}
SubsA-Direct Imp. (Ohm)		✓		✓	
SubsB-Direct Imp. (Ohm)	✓	✓			✓
SubsC-Direct Imp. (Ohm)		✓	✓		
Transfer Imp. A<->B (Ohm)	✓	✓		✓	✓
Transfer Imp. A<->C (Ohm)	✓	✓		✓	✓
Transfer Imp. B<->C (Ohm)	✓	✓			✓

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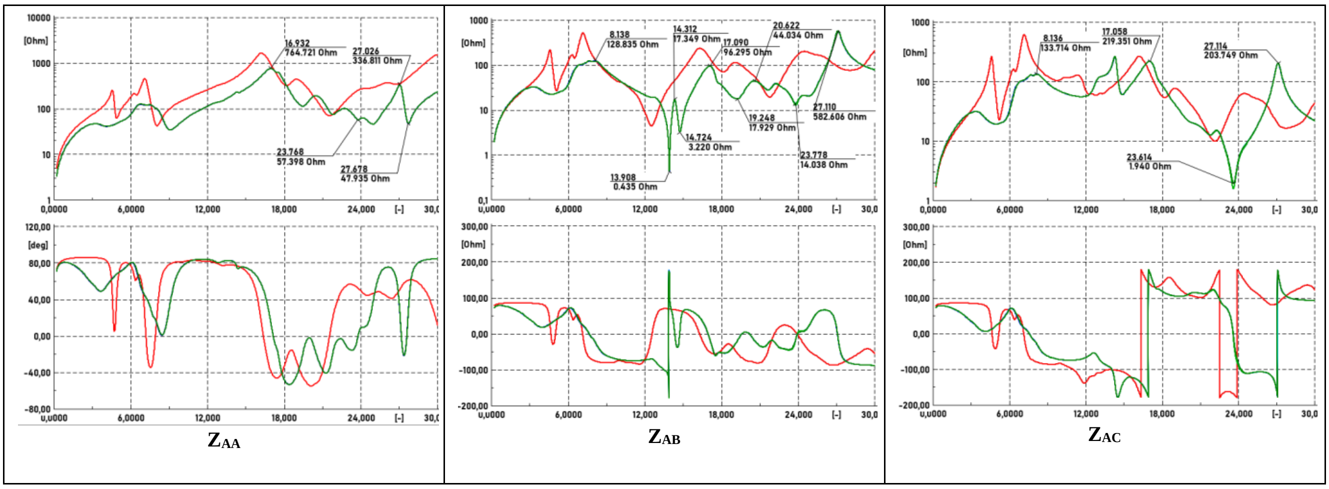

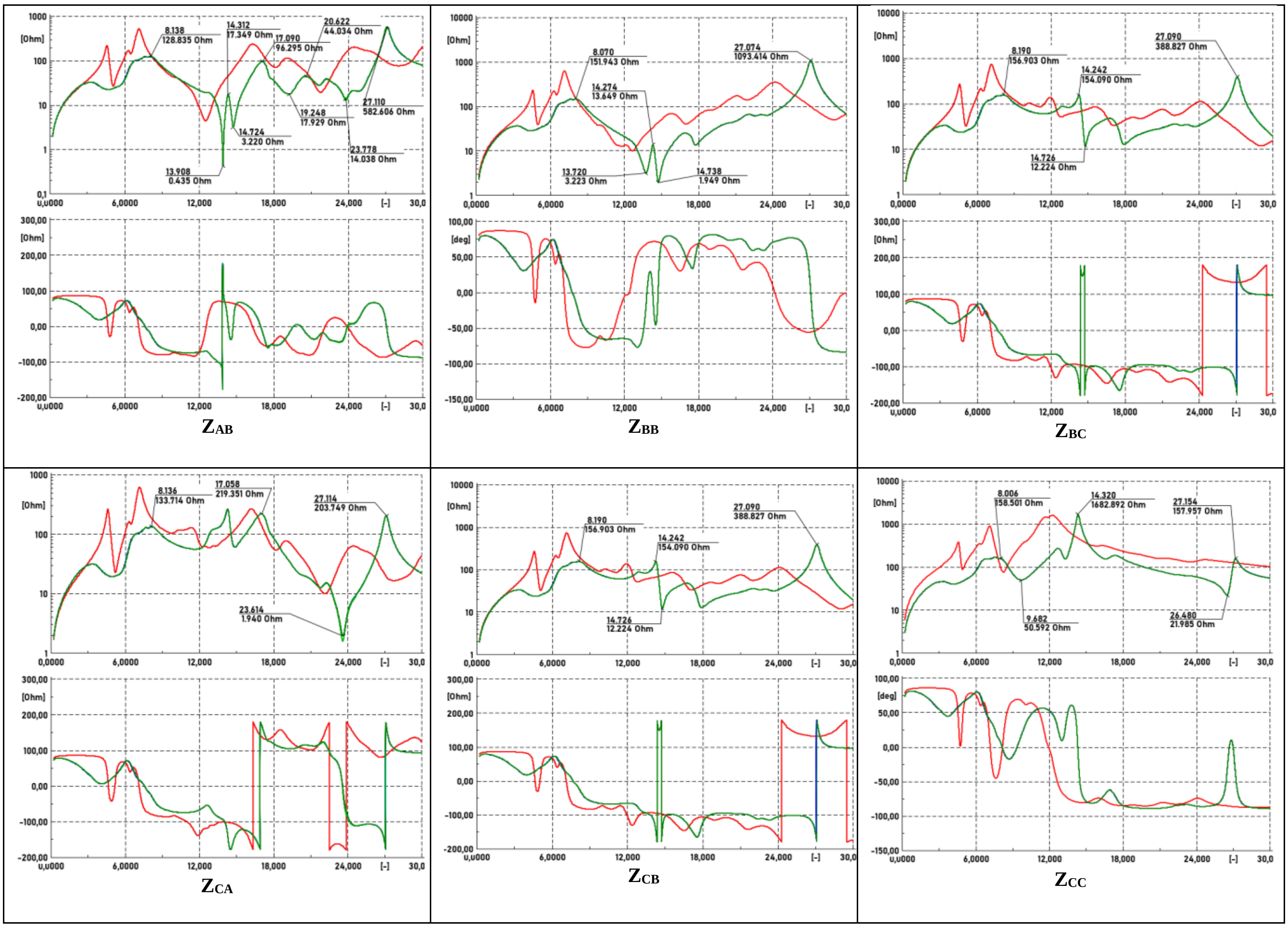

Fig. 6 Direct and transfer impedances for three PoC i.e. Z_{AA} is direct impedance for Substation A and Z_{AB} and Z_{AC} are transfer impedances between Substation A - Substation B and Substation A - Substation C respectively. Each graph is given with an additional impedance angle graph at the bottom and

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