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Spectral Analysis of a Transmission System based on AC Submarine Cables for an Offshore Wind Farm

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***Abstract*-In this paper, a detailed spectral analysis of an offshore wind farm, based on AC submarine cables is carried out. It is well known that due to the capacitive character of the AC submarine cables, it is very common to find resonance problems in the transmitted power, associated to this issue. For that reason, this paper first analyzes which is the proper "π" electric equivalent circuit to model the AC submarine cable in a given frequency range. Then, a detailed model and a spectral analysis of the entire transmission system is developed, deriving how factors such as submarine cable parameters, static reactive compensation, etc… affect to the amplitude and location of the resonances of the system. After that, a solution to mitigate the negative effect of these resonances is proposed, based on a passive filter design procedure. Finally, simulation results validate the performance of the offshore wind park under the proposed approach.**

I. INTRODUCTION

Harmonic amplification and harmonic interaction between offshore installations and onshore grid can be unacceptable for grid requirements and energy integration, thus, it becomes essential to know the frequency response of the transmission system. It is well known that the risk of harmonic resonance is bigger for AC transmission configurations than DC transmission configurations [1].

In the same way, for long AC submarine cables in conjunction with step-up transformer on the offshore substation a potential magnification of low order harmonics (inherently 3rd , 5th and 7th) may occur [2].

Therefore, in [3], a simplified method to calculate the resonance of the transmission system is proposed. This approach, only considers the capacitive part of the submarine cables, neglecting the inductive part. By means of this assumption, it is possible to simplify the transmission system of the offshore wind farm to a simple RLC equivalent circuit.

Hence, in this paper, in order to achieve an accurate model of the entire transmission system, a detailed spectral analysis is carried out.

For that purpose, to predict how the frequency response of the transmission system can be affected, this paper takes into account variations main characteristics, such as: submarine cable length, grids short circuit impedance and wind farms impedance.

II. WIND FARM TRANSMISSION SYSTEM

The general electrical layout of the offshore wind farm, depicted in Fig. 1, consist on: wind farm, offshore substation (step-up transformer), submarine cable, the interface between the wind farm and the point of common coupling (substation) and the grid.

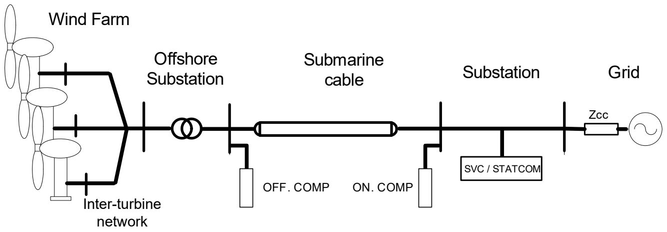


Fig. 1. General lay-out of the considered offshore wind farm.

The wind farm is 150 MVA rated power and is composed by full-converter wind turbines. For simplicity, all the wind turbines of the wind farm, are modeled with its single machine equivalent representation, as illustrated in Fig. 2. Consequently, the modeled transmission system is composed by only one equivalent machine-converter-filter rated to 150 MVA.

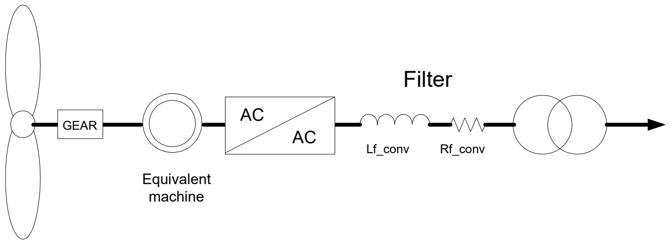


Fig. 2. General lay-out of the equivalent wind turbines.

The inter-turbine network is typically medium voltage, in this case 33kV. At the offshore substation, the voltage is step-up to the transmission system required level (150kV) and then the energy is transferred to the grid.

The transmission system consist in 3 phase submarine cables and in order to improve the transmission efficiency [4] and capacity, reactive power compensators and passive filters may be required.

III. MODEL OF THE SUBMARINE CABLE

The submarine cables have at each differential length a resistive, inductive and capacitive component. The submarine cables have lumped parameters. The manufactures in general provide the parameters as a function of the length.

To carry out a detail analysis of the submarine cable with lumped parameters, a good option is a model based on the Bergeron's travelling wave method [5]. Bergeron's travelling wave method can be used for any fundamental frequency and this model is characterized by two values: the surge impedance (Zc) and phase velocity (v).

$$Zc = \sqrt{\frac{L}{C}} \qquad (1)$$

$$v = \frac{1}{\sqrt{LC}} \qquad (2)$$

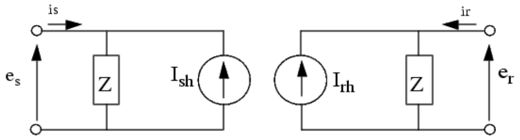


Fig. 3 Two port model, for lumped parameters submarine cable.

The equivalent model of this method is shown in Fig. 3 and its equations are.

$$I_{sh}(t) = \left(\frac{1+h}{2}\right)\left[\frac{1}{Z}e_r(t-\tau) + hi_r(t-\tau)\right] + \left(\frac{1-h}{2}\right)\left[\frac{1}{Z}e_s(t-\tau) + hi_s(t-\tau)\right] \qquad (3)$$

$$I_{rh}(t) = \left(\frac{1+h}{2}\right)\left[\frac{1}{Z}e_s(t-\tau) + hi_s(t-\tau)\right] + \left(\frac{1-h}{2}\right)\left[\frac{1}{Z}e_r(t-\tau) + hi_r(t-\tau)\right] \qquad (4)$$

$$Z = Zc + \frac{R}{4} \qquad \tau = l\sqrt{LC} \qquad h = \frac{Zc - \frac{R}{4}}{Zc + \frac{R}{4}} \qquad (5)$$

Where: R is the total line resistance [ohm], l is length, τ is the travel time of the line [s], L inductance [H/unit length] and C is capacitance [F/unit length.]

Bergeron`s travelling wave method is very complex for a detailed analysis of all the transmission system, hence to carry out a model simplification, the parameters are concentrated in an equivalent simplified model.

For submarine cables which have big capacitive component, are usually used models that take to account this factor. For example, models based on "π" circuits or RLC circuits [6].

In this paper, submarine cables are modeled by "π" equivalent circuits. Some authors [7],[8] have adopted also simplified "π" models for this analysis.

This paper pays special attention in the transmission system frequency response analysis. Therefore, the submarine cable model should be valid for frequencies further away than the fundamental (50-60Hz).

To obtain a valid model based on "π" circuits for transients and different frequency harmonics, it is necessary to model the submarine cable with more than one "π" circuit Fig. 4. So, the number of "π" circuits to use as a valid submarine cable model is determined by following factors:

- Traveling time.
- The frequency response required from the model.
- The length of the submarine cable.

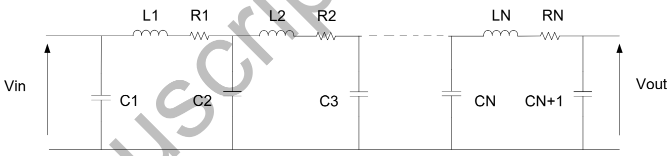


Fig. 4 Submarine cable model with N "π" circuits.

A good approximation of the maximum frequency range represented by the "π" circuits line model is given by the following equation [5]:

$$f_{\max} = \frac{Nv}{8l} \qquad (6)$$

Where: N is the number of "π" sections

IV. SYSTEM PARAMETERS

In this section, the objective is to define and parameterize the main components of the system. In this sense, the submarine cable is 50Km long with the characteristics shown in TABLE I.

TABLE I
SUBMARINE CABLE CHARACTERISTICS

	Vn (kV)	In(A)	R (Ω/Km)	L (mH/Km)	C (μF/Km)
Cable	87/150	1088	0.0151	0.352	0.233

With regards to the submarine cable model, it is modeled to have a 2,5kHz valid frequency range. This frequency range is because 2,5kHz is a typical switching frequency for power converters.

For this purpose, a model with 10 "π" circuits is used, in agreement with the equation (6) has a valid frequency range as follows:

$$f_{\max} = \frac{Nv}{8l} = \frac{N}{8 \cdot l \cdot \sqrt{LC}} = \frac{10}{8 \cdot 50 \cdot \sqrt{0.352 \cdot 0.233 \cdot 10^{-9}}} = 2760Hz \Rightarrow 17340 rad/s \qquad (7)$$

In the same way, it is considered a inductor as a grid side converter filter. This filter is as big as possible to filter the signal and enough to be able the transmission at rated power without voltage rise problems. Finally, the step-up transformers are simplified as inductances.

TABLE II

PARAMETRS USED IN THE THEORETICAL AND SIMULATION MODEL

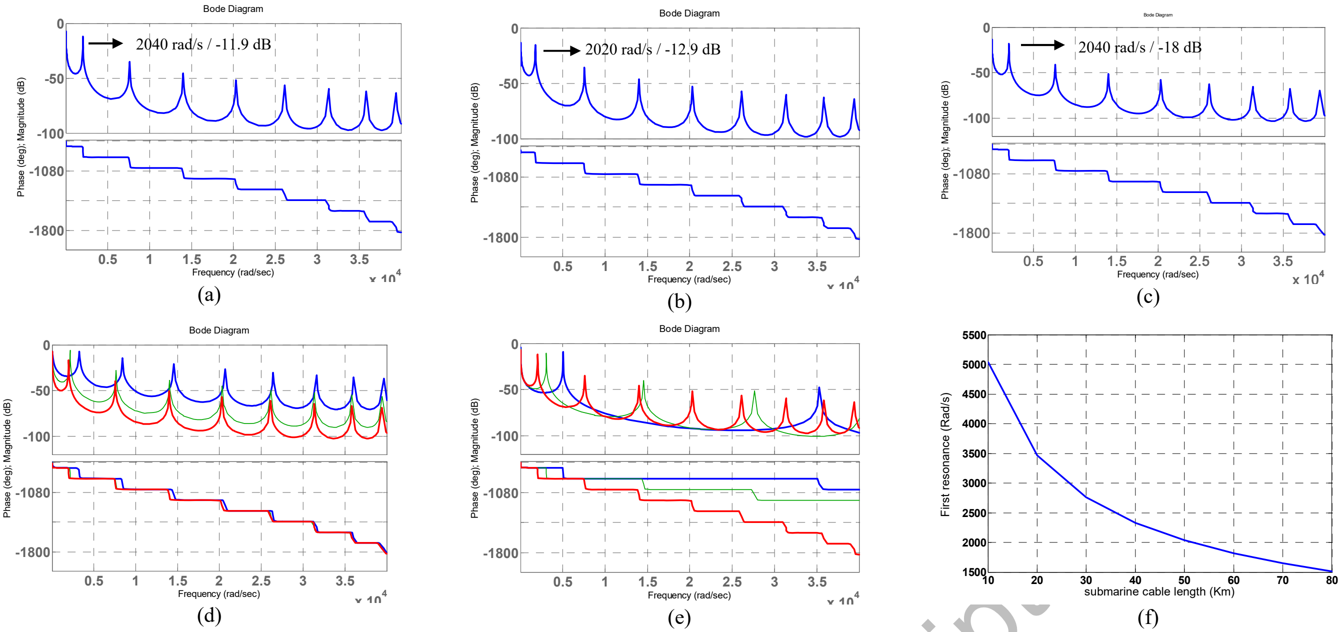
Parameter	Value
Lcc	17.2 mH
Rcc	0.18 ohm
Ccable	11.65 µF
Rcable	0.755 ohm
Lcable	17.65 mH
Lcomp	1.74 H
Lf	0.5835 H
Cf	1.929 µF
Rf	50 ohm
Ltra	17.16 mH
Rtra	0.8 ohm
Lf_conv	212.6 mH (4.5 µF * a^2)
Rf_conv	0. 141 ohm (3µ ohm * a^2)

a= transformer relation.

V. SPECTRAL ANALYSIS OF THE TRANSMISSION SYSTEM BASED ON STATE EQUATIONS

To obtain the frequency response of the transmission system, the state equations method is used. This analytical method is based on modeling the system with state variables, and the state variables are in generic case internal variables of the system.

Once the system and their parameters are defined (TABLE II), to obtain the poles of the system and all the dynamics._So, writing equations in matrix notation, it is possible obtain the state matrix equation (8).



(a) (b) (c)

(d) (e) (f)

Fig. 5. Bode diagram of basic transmissions system (a), bode diagram of basic transmission system with static compensators (b), bode diagram of transmission system modeled as two turbines (c), bode diagram of the transmission system with inductive filter variation (d) and bode diagram of the transmission system with submarine cable length variation (e). First resonance in function of the cable length (f).

Then, to analyze the system dynamics, it is necessary to obtain the Eigen values of the system.

A. Basic AC Transmission System

The next step of the analysis, is to apply the state equations method, in the equivalent circuit of the transmission system.

The basis of the transmission system is the step-up transformers, grid side converter filters and the submarine cable. Nevertheless, the transmission system can be composed by other important components depending of different configurations, such as static reactive power compensators, passive filters or power electronic devices.

So, the equivalent circuit of the basic transmission system, with N "π" circuits for submarine cable model is shown in Fig. 6.

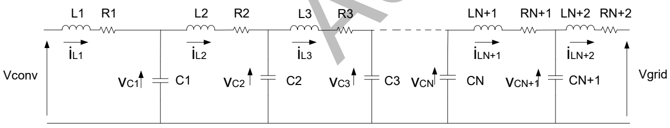


Fig. 6 Equivalent circuit of the transmission system.

Where, L1 and R1 represents step-up transformers and grid side converters filter's impedance, L2 to LN+1=Lcable/N, R2 to RN+1=Rcable/N, C1 and CN+1=Ccable/2N, C2 to CN Ccable/N and LN+2 with RN+2 represents the grid is short circuit impedance.

Hence, to obtain the frequency response of the equivalent circuit, it is necessary to calculate the differential equations of the independent variables (currents in inductors and voltages in capacitors) and then obtain the matrix notation. The generic expression of the state matrix, of the basic transmission system is shown in equation (8).

Finally, the frequency response of the equivalent circuit (relation between converter voltage and PCC current, i/v) is shown in Fig. 5(a). In this frequency response, we can observe equal resonance peaks as number of "π" circuits used for the cable model. However, the valid frequency range is determined by equation (7). The first resonance is the most important, since as mentioned before it is the most problematic.

B. Effect of the Static Reactive Power Compensation

The submarine cables present a high shunt capacitance, this effect causes the capacitive charging and discharging currents in the cable and this current generates reactive power. The rated current of the cable is thermally limited. Thus, as the length of the cable increase, their shunt capacitance and the charging currents increase as well. As a consequence, the load carrying capability of the cable is reduced.

In order to use the submarine cable without length limit and reduce conduction losses, the ideal solution is a distributed compensation of the reactive power along the length of the submarine cable. Unfortunately, this option is not possible in submarine cables. Hence, the second option is to compensate the reactive power at both ends [4].

There are many options to compensate the energy at both ends, for instance with power electronic devices, static inductances or with a combination of both. In this paper only static inductances have been adopted. This inductances, slightly modify the equivalent transmission system modeled in subsection A.

$$d/dt\cdot\begin{bmatrix} i_{L1}\\ v_{C1}\\ i_{L2}\\ ....\\ i_{LN+1}\\ v_{CN+1}\\ i_{LN+2}\end{bmatrix}=\begin{bmatrix} i_{L1}\\ v_{C1}\\ i_{L2}\\ ....\\ i_{LN+1}\\ v_{CN+1}\\ i_{LN+2}\end{bmatrix}\cdot\begin{bmatrix} {}^{-R1}/_{L1} & {}^{-1}/_{L1} & 0 & .... & 0 & 0 & 0\\ {}^{1}/_{C1} & 0 & {}^{-1}/_{C1} & .... & 0 & 0 & 0\\ 0 & {}^{1}/_{L2} & {}^{-R2}/_{L2} & .... & 0 & 0 & 0\\ .... & .... & .... & .... & .... & .... & ....\\ 0 & 0 & 0 & .... & {}^{-RN+1}/_{LN+1} & {}^{-1}/_{LN+1} & 0\\ 0 & 0 & 0 & .... & {}^{1}/_{CN+1} & 0 & {}^{-1}/_{CN+1}\\ 0 & 0 & 0 & .... & 0 & {}^{1}/_{LN+2} & {}^{-RN+2}/_{LN+2}\end{bmatrix}+\begin{bmatrix} {}^{1}/_{L1} & 0\\ 0 & 0\\ 0 & 0\\ .... & ....\\ 0 & 0\\ 0 & 0\\ 0 & {}^{-1}/_{LN+2}\end{bmatrix}\cdot\begin{bmatrix} Vconv & Vred\end{bmatrix} \tag{8}$$

$$d/dt\cdot\begin{bmatrix} i_{L1}\\ i_{L2}\\ v_{C1}\\ i_{L3}\\ v_{C2}\\ \cdots\\ i_{LN+2}\\ v_{CN+1}\\ i_{LN+3}\\ i_{LN+4}\end{bmatrix}=\begin{bmatrix} i_{L1}\\ i_{L2}\\ v_{C1}\\ i_{L3}\\ v_{C2}\\ \cdots\\ i_{LN+2}\\ v_{CN+1}\\ i_{LN+3}\\ i_{LN+4}\end{bmatrix}\cdot\begin{bmatrix} {}^{-R1}/_{L1} & 0 & {}^{1}/_{L1} & & & \cdots & 0 & 0 & 0 & 0\\ 0 & {}^{-R2}/_{L2} & {}^{1}/_{L2} & & & \cdots & 0 & 0 & 0 & 0\\ {}^{1}/_{C1} & {}^{1}/_{C1} & 0 & {}^{1}/_{C1} & & \cdots & 0 & 0 & 0 & 0\\ 0 & 0 & {}^{1}/_{L3} & {}^{-R3}/_{L3} & {}^{1}/_{L3} & \cdots & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & {}^{1}/_{C2} & 0 & \cdots & 0 & 0 & 0 & 0\\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\\ 0 & 0 & 0 & 0 & 0 & \cdots & {}^{-RN+2}/_{LN+2} & {}^{-1}/_{LN+2} & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & \cdots & {}^{1}/_{CN+1} & 0 & {}^{1}/_{CN+1} & {}^{1}/_{CN+1}\\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & {}^{1}/_{LN+3} & {}^{-RN+3}/_{LN+3} & 0\\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & {}^{1}/_{LN+4} & 0 & {}^{-RN+4}/_{LN+4}\end{bmatrix}+\begin{bmatrix} {}^{1}/_{L1} & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & {}^{-1}/_{LN+4}\end{bmatrix}\cdot\begin{bmatrix} Vconv & Vred\end{bmatrix} \tag{9}$$

Therefore, it is necessary to derive the frequency response analysis of the transmission system with this compensation. The new equivalent circuit is shown in Fig. 7 where L2 and LN+3 are Lcomp from TABLE II.

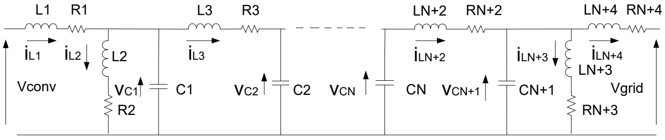


Fig. 7. Equivalent circuit of the transmission system with static compensation.

In the same way, the generic matrix of the transmission system with static compensation is shown in equation (9). It is very similar to equation (8), but with other two variables, L2 and LN+3.

the frequency response of the system is shown in Fig. 5(b). It is very similar frequency response in comparison with the basic transmission system. The main difference appears in low frequencies, the compensation filter this frequencies.

C. *Validation of the Consideration of Multiple or Aggregated Model Wind Turbine.*

As mentioned before, the wind farm is modeled with its single-machine equivalent representation, thus, in this section this simplification is analyzed. This is due to the fact that the wind farm is composed by multiple power converters, with their filters in parallel.

So, in this section the wind farm is modeled with two equivalent machines. Hence, with two equivalent full-converter wind turbines and two equivalent filters. The equivalent circuit of the system is depicted in Fig. 8.

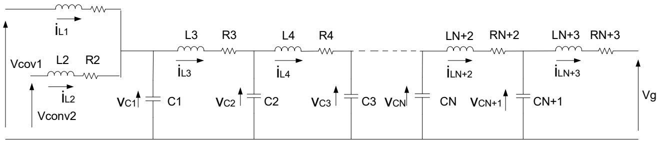


Fig. 8 Equivalent circuit of the transmission system with wind farm modeled as two equivalent wind turbines.

In the same way, the method of the state equations is applied in the equivalent circuit with two inputs, to obtain the state matrix and the frequency response. This frequency response is shown in Fig. 5(c).

Fig. 5(c) shows the same resonance frequencies as the basic transmission system Fig. 5(a). But for the considered case, i.e. two inputs case the overall frequency response is splitted into two equal frequency response diagrams. Hence applying the superposition principle it is possible to reach the same frequency response.

VI. EFFECT OF THE VARIATION IN TRANSMISSION SYSTEM'S MAIN COMPONENTS IN THE FREQUENCY RESPONSE.

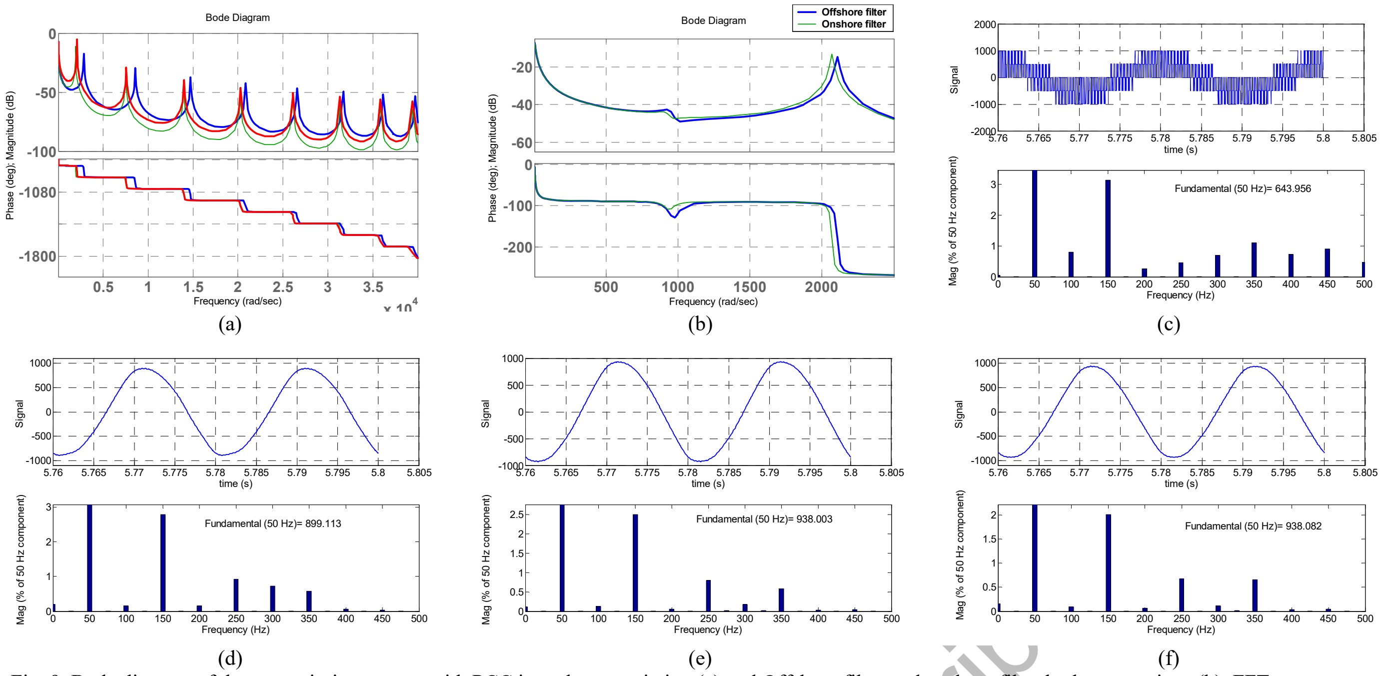
Knowing the influence of different elements in the transmission system's frequency response can help to optimize the design of the transmission system. Insomuch as can help to avoid unwanted resonances. Hence, in this section different frequency responses in function of different characteristics are obtained.

- Step-up transformers and grid side converter filters impedance.
- Impedance of the submarine cable (length variation)
- Grid's short circuit impedance.

A. *Effect of the Wind Turbine Inductive Filter Variation.*

In first, the influence of the grid side converter's inductive filter and the step-up transformers impedance is evaluated. The impedance of this two elements is represented by L1. This inductance have a variation of 4000% (10mH to 400mH) and the frequency response is shown in Fig. 5(d).

This impedance have effect mainly in the static gain. Increasing the impedance, the static gain decrease, but does not significantly modify the resonance frequencies.



(a) (b) (c)

(d) (e) (f)

Fig. 9. Bode diagram of the transmission system with PCC impedance variation (a) and Offshore filter and onshore filter bode comparison (b). FFT comparison, voltage (c) and currents (d), (e) and (f).).

B. Effect of the Submarine Cables Length Variation

In the same way, the influence of the submarine cable length is evaluated. The length of the submarine cable is changed from10 to 50 Km. The frequency response as a function of this variation is shown in Fig. 5(e). Submarine cables length variation affect to the resonance frequency. Submarine cable length is the main factor in resonance frequency changes. Therefore, the first resonance frequency location as a function of the cable length is shown in Fig. 5(f).

C. Effect of the Point of Common Coupling (PCC) Impedance

Finally, are considered different grids short circuit impedances. The variation of the short circuit inductance is in the range of 1% to 23% (5mH to 100mH). The frequency response as a function of this variation is shown in Fig. 9(a).

The grid's short circuit impedance do not change the frequency response significantly. It only provokes, a little change in static gain and a little change in resonance frequencies.

VII. HARMONIC RESONANCE MITIGATION BY MEANS OF PASSIVE FILTERS

The resonances in transmission system's frequency response can cause problems or incompatibilities with the grid code requirements. Hence, it is necessary measure the harmonic emission of the wind farm. If the harmonic level in PCC is higher than grid code requirements, there are different options to mitigate the harmonics. Passive filters, active filters or a combination of both.

First order passive filters are RLC branches. Thus, this elements change the frequency response of the system. In this section how this filters change the frequency response is analyzed.

A. Passive Filter Design

Passive filters are based on a variable impedance in function of the frequency. So, to filter one harmonic the filter is tuned to present minimum impedance at this frequency. Therefore the biggest part of the harmonic power goes to the filter. But, in the fundamental frequency (50-60Hz), the filter also presents an impedance. Consequently, the filter increases the active power losses of the system. The study of this paper does not pay attention to the system efficiency and these losses are not calculated.

One circuit is in resonance when the applied voltage and the current through the filter are in phase. It follows that in resonance the filter impedance is equal to ohmic impedance. In other words, the reactance of the circuit is zero. So, the inductive reactance and capacitive reactance are the same. This phenomena only occurs in one determined frequency, the resonance frequency. Thus, the impedance and the resonance of the filter is calculated with:

$$Z = Rf + j\left(X_{Lf} + X_{Cf}\right) \tag{10}$$

$$\omega \cdot Lf - \left({}^{1}\!\big/_{\omega \cdot Cf} \right) = 0 \Rightarrow \omega \cdot Lf = {}^{1}\!\big/_{\omega \cdot Cf} \tag{11}$$

In equations (10) and (11), there are two independent variables L and C, so there are multiple combinations to obtain a determined resonance frequency. Therefore, to design passive filters this factors are also taken into account: Harmonic power and the quality factor.

In the resonant frequency, the imaginary component disapears from the impedance. So the harmonic power in this frequency and the maximun resistance for the filter is calculated with the equations:

$$P_{harmonic} = Rf \cdot I^2 \quad (12)$$

$$P_{harmonic} = Rf \cdot \left(\frac{V^2}{Rf^2}\right) = \frac{V^2}{Rf} \Rightarrow Rf = \frac{V^2}{P_{harmonic}} \quad (13)$$

On the other hand, the quality factor (Q) of the filter is determnined by the equation:

$$Q = \frac{fo}{\Delta f} = \frac{1}{Rf} \cdot \sqrt{\frac{Lf}{Cf}} \quad (14)$$

Where: fo is resonance frequency and Δf the band width. Q is define as a relationship betwen voltage rise in the inductance (or capacitor) and the resistor. It is usully bigger than 10.

The cut frequencies or limit frequencuies define (Δf). They are frequencies where the current magnitude is 0,707 times the resonance current.

So, the filter resistance determine the power of the filter and the quality factor, the band width.

B. *Analysis for best filter location in the wind park*

The location of the passive filters is very important, because determine passive filters shunt impedance (impedance in parallel with the filter in the equivalent circuit) and the route of the harmonics.

In short, the best location for passive filters is offshore. In offshore location, the shunt impedance of the filter is bigger than onshore and components have less harmonic stress.

For low shunt impedance the filter need less ohmic impedance to conduct the harmonic power to the filter. To mitigate harmonics in the system. The frequency responses of the two options (offshore filter and onshore filter) are compared in Fig. 9(b).

VIII. SIMULATION VALIDATION

The conclusions derived into the previous section, are based on state equations method, there are theoretical results. Thus, in this section the results are validated in PSB/Simulink. The simulation is based on the above described wind farm model. With regards to the simulation parameters they are defined on TABLE II.

The harmonic sources in offshore wind farm are mainly power converters. It is very common that not perfectly tuned control strategies, can inject harmonics to the transmission system.

In the same way, a simulation of the transmission system is carried out. Then the frequency components of the converter voltage (Fig. 9(c)) and PCC current are analyzed. For this purpose the FFT (Fast Fourier Transform) method is used. After this, there are compared to verify the above frequency response of the basic transmission system.

The THD of the PCC current without filter is 3.09 %, higher than IEEE 519 norm (case: $69kV<Vn\leq161$) requirement (2.5 %).

In next step, the same simulation scenario with offshore passive filter and onshore passive filter are simulated, in order to compare the different harmonic components of the system without passive filter (Fig. 9(d)), with offshore passive filter (Fig. 9(e)) and with onshore passive filter (Fig. 9(f)).

The FFT of the converter voltage does not present significant changes, because the system impedance out of the filters band width not have significant changes.

The filters improve the THD of the PCC current in both cases (offshore and onshore), but with offshore filter the THD is 2.23% and with onshore filter 2.7%.

IX. CONCLUSIONS

The first resonance of the transmission system have a big potential of harmonic magnification. This resonant frequency is mainly in function of the submarine cable characteristics and length. Other factors as static reactive compensation, short circuit impedance or transformers impedance not affect significantly.

Passive filters can mitigate harmonics and change the frequency response of the transmission system. Passive filters have minimum impedance in harmonic frequency to absorb the harmonic. Therefore, the best location have the biggest impedance in parallel with the filter, offshore location. Obviously, this results should be validated with experimental results.

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