Background harmonic amplifications within offshore wind farm connection projects

Y. Fillion, S. Deschanvres

***Abstract*—Aiming 20% of renewable in its energy mix, France has announced since 2012 the construction of 6 offshore wind power plants on the North-western coast for a total of 3 GW. The wind farms are going to be connected to the 225 kV network, with AC XLPE insulated cables from 38 km to 60 km long. RTE observed in its recent studies [4] as others [5] [6] that the association of long extra High Voltage AC (HVAC) cables with the grid is responsible for background harmonic amplifications. For wind farm connections, amplifications up to 20 times were estimated for harmonics #3 to #7 taken into account various grid scenarios including grid contingencies, load variations, and wind farm projects uncertainties. With the use of more and more of long HVAC cables to develop the grid, RTE had the opportunity to be involved in the commissioning of a 90 kV- 59 km long-HVAC cable named Normandy 3 (N3) between Jersey island and France. During this phase, the cable was placed in a configuration very similar to offshore wind farm connections that makes possible to study background harmonic amplifications and compare with offshore wind farm projects. The results are presented in this paper and confirm that N3 is not subject to dangerous harmonic levels but that some low frequency harmonics can be amplified. As this experimentation confirms the theory explained at the beginning of this paper, offshore wind farm connections projects are now studied to evaluate future harmonic constraints. A frequency-domain steady-state based method is presented with an example of results. Finally passive filters are intended to be installed which are discussed here with further time-domain simulations.**

***Keywords*: HVAC cables, resonances, harmonics, steady-state, frequency-domain, time-domain, filtering, EMT studies.**

I. Introduction

The French government launched in 2012 a call for tender for the building of 6 offshore wind farms in the north west of France, around 500 MW each. RTE, as the French transmission system operator (TSO), is responsible for the connections of the wind farms, including offshore submarine cables. For this kind of projects, it is important to perform transient and insulation coordination studies as well as to address harmonic issues. This paper is going to explain the phenomenon of background harmonic amplification. It presents the experience gained from a recent cable energization and eventually gives the results of the study of harmonic constraints for the connections of offshore wind farms.

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A. *Offshore wind farm connection principle*

The 6 offshore wind farms are going to be connected to the 225 kV network with insulated XLPE cables. These cables are between 38 and 60 km long so they inject a high amount of reactive power. In order to limit this reactive power injected on the grid, shunt reactors are installed onshore (and not offshore as it would have been much more space consuming and expensive). As a consequence, steady state voltages are higher at the offshore delivery point than at the onshore connection point which requires designing booster transformer to control the voltage on the connections independently from the grid voltage. A single line diagram of a connection is shown on Fig. 1.

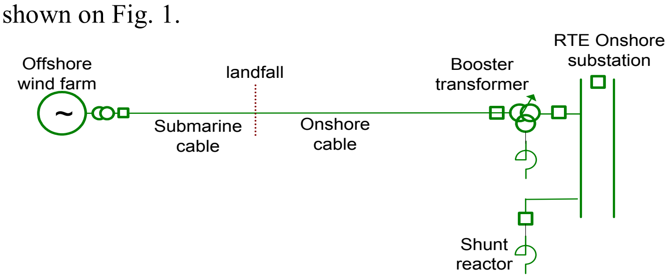

Fig. 1. Single line diagram of a wind farm connection.

A connection cable is designed for 250 MW so 500 MW wind farms are actually divided in two half wind parks, each with a connection. Booster transformers are made of an excitation unit equipped with a tap changer and a unity ratio series unit. The interest of the booster transformer is to give the possibility to control the voltage on the connection without changing the voltage on the grid. The excitation unit gives an image of the primary side voltage and reinjects it in phase or in phase opposition on the secondary side through the series transformer to respectively boost or buck the secondary side voltage. Boosters are very similar to the phase shifting transformers except that one controls the amplitude of the voltage instead of the phase. In most of the grid situation for offshore wind farm projects, the transformers will be used to buck the offshore voltage but they are commonly called "booster" transformers.

B. *Investigation of background harmonic amplification*

It has already been shown that harmonic amplifications need to be studied for wind farm connection projects ([5] [6]). Here it is proposed a simplified analysis of the phenomenon. The diagram of the Fig. 1 can be modelled with a very simple RLC circuit, as follows on Fig. 2:

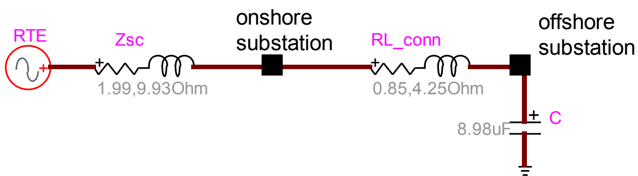

Fig. 2. Simplified model of an offshore wind farm connection.

Z_{sc} is the short circuit impedance of the grid at the onshore connection substation. Z_{sc} is mainly an inductance as the grid is rather inductive. RL_{conn} and C represent the impedance of the connection. The impedance RL_{conn} represents mainly the booster transformer and the capacitor C the submarine and underground cables which are very capacitive elements. This circuit is a well known RLC circuit, which is resonant at the frequency f_0 defined by (1). As a consequence, voltages and currents can be highly amplified near the resonance frequency as described by equation (3):

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Where

$$L = L_{sc} + L_{conn} \tag{2}$$

$$\left|\frac{V_{offshore}(f_0)}{V_{RTE}(f_0)}\right| = \frac{1}{\omega_0 RC} = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{\omega L}{R}\frac{1}{\omega\sqrt{LC}} = \frac{X}{R}\frac{\omega_0}{\omega} \tag{3}$$

As an example with S_{sc}=3500 MVA, X/R=5 and ω_0/ω=5, then R=2.8 Ω, L=45 mH and C = 9.0 μF which gives $\left|\frac{V_{offshore}(f_0)}{V_{RTE}(f_0)}\right| = 25$. Therefore the 5th harmonic offshore voltage can be 25 times higher than the 5th harmonic onshore voltage in this simple example. With a more appropriate modelling of the network and the connection, RTE expects that amplifications are not going to be so high but this example shows how important it is to investigate background harmonic amplifications. This paper is focused on the amplification of background harmonics, which means harmonics coming from the grid. It is surely important to study harmonics generated by wind turbines but this is not the purpose of this paper.

II. Normandy 3 Application Case

The first French offshore wind farms will be commissioned in 2019. In order to address correctly the harmonic background amplification issue and be ready for 2019, RTE performed on-site measurements and analyzed background harmonic amplification phenomena. The first energization of the new Normandy 3 (N3) cable between France and Jersey island was an excellent opportunity.

A. Presentation of Normandy 3 project

N3 is the new 90 kV interconnector cable between the RTE Periers substation in France and the JEC South Hill substation in Jersey. It is partly composed of a pipe type submarine cable of 38 km for a total of 59 km between the two stations, the rest being underground cables. A variable shunt inductance installed in Periers substation allows compensating the reactive energy of the cable from 61% to 95%. A series inductance is installed in South-Hill to balance the power flow between N3 and the two other cables connecting Jersey to the mainland.

During the commissioning of the cable, N3 was energized from RTE Taute 90 kV substation and has been kept connected and unloaded during 24 hours as shown on Fig. 3 to test the cable. This temporary situation is similar to a wind park connected to the grid with no generation.

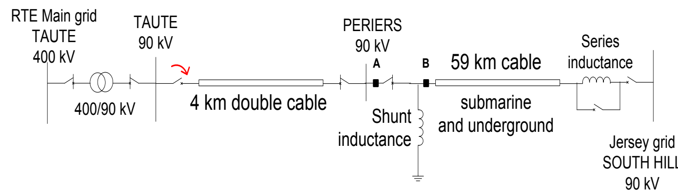

Fig. 3. Commissioning of Periers-South Hill cable.

On the N3 cable project, low harmonic amplifications were expected from studies. Nevertheless a severe resonance was measured on the 4th harmonic but as even harmonics are very low on the grid, this resonance is not an issue.

Cable N3 commissioning was instrumented with power quality measurement devices over two weeks straddling the date of first switching. The goal was to compare harmonic amplitudes in the Periers 90 kV substation before and after cable energization. Switching transients are also recorded in Periers to validate the study model.

Due to some measurement unit failures, the only measurements available were:

- Current and voltage harmonics in the Periers substation in point B (see Fig. 3) and only after cable energization due to the position of the measurement devices regarding the N3 cable circuit breaker.
- Current and voltage transients in point B (see Fig. 3). They correspond to currents and voltages of the N3 cable.

These issues are partly handled as explained in the next sections.

B. Modelling for Normandy 3

A model of the N3 cable commissioning is built to run simulations and to analyze how harmonics behave on this part of the grid.

The EMT model is composed of a Frequency Dependent Network Equivalent (FDNE) which represents the entire 400 kV grid seen from the Taute 400 kV substation. This equivalent presents the advantage to seriously shorten time-domain simulations [7].

The Taute 400/90 kV 5-legged transformer is modelled with a hybrid model taking into account the geometry of the magnetic core as developed in [3]. Its tertiary load is set with a parallel RLC circuit.

Both underground and submarine cables are represented with wideband models [1] which are frequency dependant.

Circuit breakers are modelled with ideal switches.

The shunt inductance is assumed to behave as a non linear inductance. The V-I characteristic coming from manufacturer tests is supplied by JEC. The shunt inductance is placed on its lowest tap during energization for zero-miss effect issues.

Finally the series inductance is modelled as an ideal inductance since it doesn't have a significant role during the cable energization.

The resulting model is shown on Fig. 4.

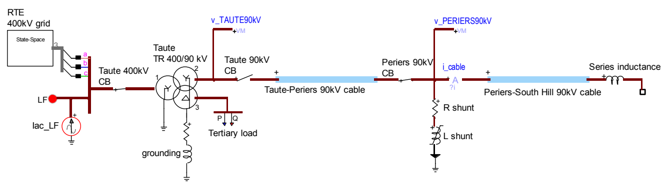

Fig. 4. EMT model for the commissioning of Periers-South Hill cable.

C. Results

1) Model validation

At first, EMT simulations were run and compared with switching transient records in order to validate the model of Fig. 4. Fig. 6 and Fig. 7 compare respectively with the simulation results the N3 cable voltages and currents that were measured in the Periers substation at point B. Measured and simulated line-to-neutral voltages and line currents can almost be superimposed. Transients are well reproduced by simulations and a 193 Hz resonance can be observed. The association of the N3 cable and the existing grid creates a parallel resonance at this frequency, see on Fig. 5, at the Taute 90 kV substation and at the Periers 90 kV substation.

These signals allow being confident with the model built in the previous section. Unfortunately, currents in the shunt inductance are not part of these recorded signals which does not allow validating the behaviour of the inductance. However, it presents a high shunt impedance, so this impedance has a limited impact on background harmonics amplification.

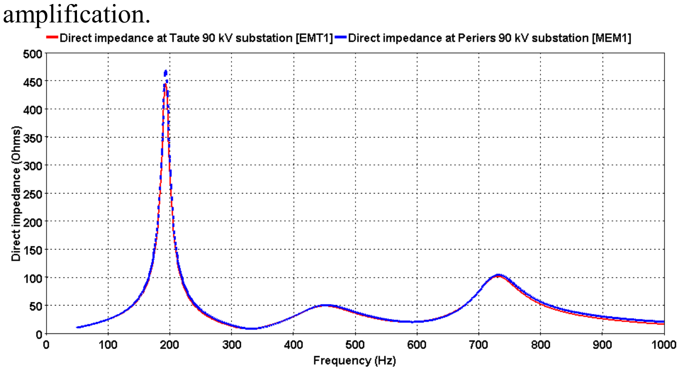

Fig. 5. Direct impedance at the Taute 90 kV (red) and the Periers 90 kV substations (dashed blue).

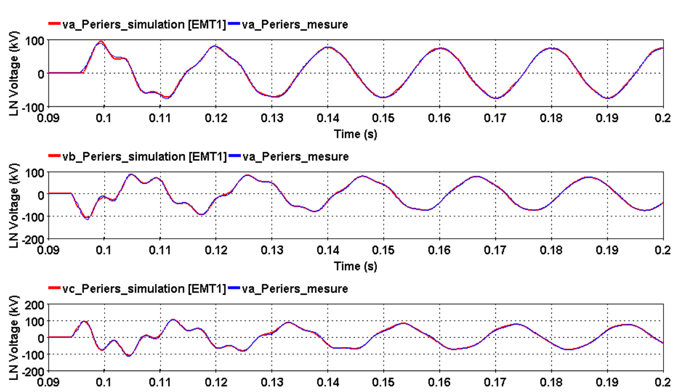

Fig. 6. Comparison of simulated (in red) and measured (in dashed blue) voltages when energizing N3 cable.

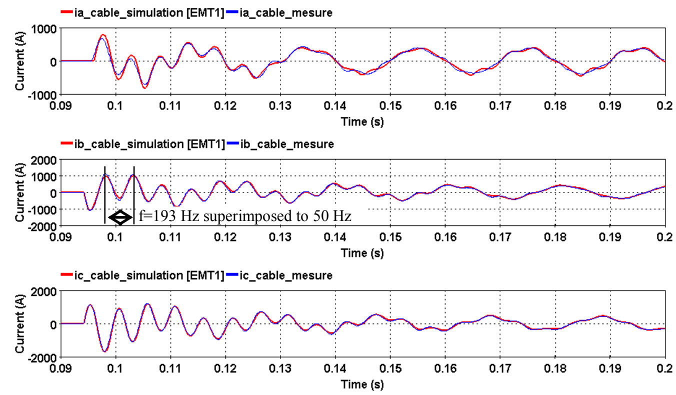

Fig. 7. Comparison of simulated (in red) and measured (in dashed blue) currents when energizing N3 cable.

2) Background harmonic amplification

Due to hardware failures, voltage and current harmonics were measured in the Periers 90 kV substation only after the cable energization at point B, see Fig. 3. The recordings are given on Fig. 8. The 95th percentile of the harmonic amplitudes and the Total Harmonic Distortion are expressed based on the amplitude of the fundamental.

Mostly low order odd harmonics disturb the 50 Hz signal as it could be expected. The harmonics on the 3rd, the 5th and the 7th rank are the highest ones whatever it is in voltage or in current. Harmonic voltages are less than 1.5% which ensures a good power quality for RTE's clients. However it can be observed almost 10% of the 5th harmonic in the cable current. 1% of the 4th harmonic is also measured although even harmonics should be almost inexistent.

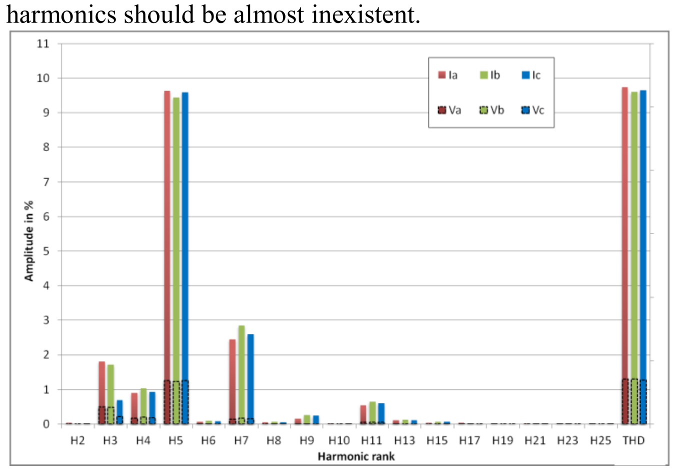

Fig. 8. Current and voltage harmonic amplitudes measured in Periers 90 kV substation when cable N3 is at no load.

Since the harmonic measurements before the cable energization failed, the model validated in previous section is used to understand this harmonic content.

The measured harmonics could either be due to transformer saturation or the shunt inductance saturation, or could be generated by an impedance unbalance of the N3 cable project, or could come from the 400 kV grid.

However, harmonic measurements are performed under normal conditions close to nominal voltages which ensure the saturation of non linear inductances is not reached.

Impedance unbalance among the 3 phases of the network is not important enough to participate significantly in the previous harmonic content as well as the tertiary load on the Taute transformer.

Therefore, it is clear that during the commissioning, harmonics come exclusively from RTE's 400 kV grid.

As a consequence, several harmonic voltage sources are tuned in Taute 400kV substation to obtain the same harmonic content in current and voltage in the Periers 90 kV substation (tuned with a 10% average relative error). This work is done in time-domain by choice but could have also been done in frequency-domain. For simplicity reasons harmonics are tuned only on phase A and from the 3rd to the 7th rank. Harmonic voltage sources are placed in series with the FDNE for this purpose.

The tuned harmonic voltages illustrate directly what the harmonic voltages are supposed to be in real life in the Taute 400 kV substation before the cable energization. As can be seen in Table I, odd voltage harmonics are estimated in the Taute 400 kV substation at reasonable and common levels with amplitudes lower than 1,5% of the fundamental.

TABLE I
TUNED VOLTAGE HARMONIC AMPLITUDES IN THE TAUTE 400 KV SUBSTATION TO GET THE PERIERS HARMONIC CURRENTS AND VOLTAGES.

Harmonic n°	3	4	5	6	7
Amplitudes (in % of fundamental)	0.27	0.11	1.53	X	0.96

Nevertheless 10% of harmonic 5 and 1% of harmonic 4 were measured in the cable currents. The explanation comes with Fig. 9. On this figure is plotted a red solid curve corresponding to the direct impedance seen from the Taute 400 kV substation of the link Taute-Periers-South Hill, the equivalent network being excluded. On this curve, this impedance of the link Taute-Periers-South Hill close to the resonance appears relatively low compared with the one at other frequencies. The frequency domain relation $I_h=U_h/Z_h$, enforces the current for a given voltage U_h and an impedance Z_h. Therefore, 1.5% of harmonic voltage at the 5th rank is responsible for almost 10% of harmonic current at the same rank in the Periers substation since the impedance is low at 250 Hz.

For certain harmonic, a low impedance does not lead to a high harmonic current if the initial harmonic voltage is insignificant. It is the case for the 3rd harmonic which stays weak on Fig. 8. The same phenomenon happens on the 4th harmonic even if a low impedance is noticed at 200 Hz according to Fig. 9. The resonance centred on 193 Hz amplifies the 4th harmonic but as its initial voltage value is very low on the 400 kV grid (0.11% from Table I), the resulting harmonic current stays weak at 1%. Still 1% is not common for the 4th harmonic which should be insignificant.

Fig. 9 gives also a dashed blue curve illustrating the impedance seen from Taute 400 kV if the N3 cable interconnector was fictively replaced by an overhead line of the same length with common parameters (X=0.4 Ω/km, R=0.08 Ω/km, and C=9 nF/km). The impedance at low harmonics is much higher which explains why harmonic currents are usually not as high through overheadlines. On this curve, the resonance at 550 Hz is created by the cable between the Taute and the Periers 90 kV substations which has been modelled.

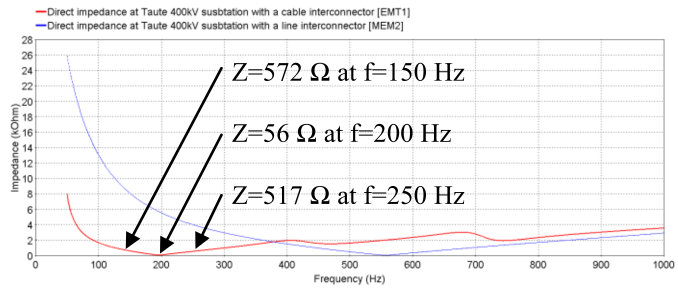

Fig. 9. Direct impedance of the link Taute-Periers-South Hill seen from the Taute 400 kV substation. In red, interconnector N3 with cable. In dashed blue, interconnector N3 with fictitious overheadline of same length (59 km).

D. *Conclusion*

The project Normandy 3 of interconnection between Jersey and France presented a configuration very similar to offshore wind farm connection projects during its commissioning where a 59 km long cable was let at no load during 24 hours.

Despite hardware failures, some measurements were done in order to study background harmonic amplifications on this project and make a parallel with offshore wind farms connection ones.

Current and voltage switching transients allowed validating the model that was decided to be built for this analysis. Very good correlation between measurements and simulation on current and voltage were achieved both in amplitude and frequency.

From this validated model, harmonic measurements were reproduced and analyzed in time-domain. The measured strong 5th harmonic cable currents are explained by a reasonable initial level of the 5th harmonic on the 400 kV grid and the influence of long cables lowering the grid impedance at certain frequency compared with common overheadlines.

Being still acceptable, the 4th harmonic becomes significant on the measured cable current because of the presence of a resonance created by the association of the N3 cable and the inductive grid.

For offshore wind farm projects, as it will be explained in the next chapter, resonances can be accorded to low order odd harmonics which will require filtering.

III. OFFSHORE WIND FARM PROJECTS

As explained in section I. , for offshore wind farms the association of long connection cables with the main grid will create resonances that could amplify harmonics.

However, unlike the Normandy 3 project, EMT studies [4] had shown these resonances can be accorded to significant low order harmonics like the 3rd, the 5th and the 7th. This section explains how calculations are run and how the results are handled.

A. *Study method*

RTE's assessment of harmonic issues for wind farm connections consists both in on-site measurements and simulations with EMTP. Measurements are made to assess the level of harmonic voltages currently existing on the grid. They are performed for several weeks on substations where wind farms are going to be connected. Then, simulations allow knowing the amplification of these harmonics due to the connections of the wind farms.

Background harmonic amplification is a steady state phenomenon so it is satisfactory to perform simulations in steady state. Time domain simulations are necessary if we need to take into account non linearity and control systems, as explained later in section E. For this study, frequency scan simulations are performed, which is basically a calculation of a steady state at each frequency. As explained previously, the study focuses on amplification of harmonics that currently exists on the grid. To model harmonics, a current source is connected to the onshore substation. Then, in the EMTP-RV simulation tool, the "input impedance" component is used. It consists in a 1 A current source which deactivates every other 50 Hz sources. It is clear that this harmonic source modelling is arbitrary and does not intend to represent a specific harmonic source on the network. Harmonics are mostly generated by domestic loads and some consumers at transmission level so the 1A current source is just an equivalent of all harmonic sources of the grid. Two different situations are studied: one corresponding to the present network (2014) without wind farm connections (called the reference situation) and one with the connections and a few grid developments expected within the coming years (the future situation). Simulating the reference situation gives the harmonic voltages on the onshore connection substation $v_{h\_onshore\_calculated\_reference}(f)$. These values can be compared to the harmonic voltages measured on the field at the same substation $v_{\_onshore\_measured}(f)$. Then, when the future situation is simulated, the resulting signals have to be multiplied by the ratio $\frac{\text{v\_onshore\_measured (f)}}{\text{v\_onshore\_calculated\_reference (f)}}$ to be interpreted in absolute value.

The results can also be presented in relative value, by defining the amplifications for onshore signals with (4) and offshore signals with (5):

$$Gain_{onshore}(f) = \frac{v_{onshore-calculated-future}(f)}{v_{onshore-calculated-reference}(f)} \quad (4)$$

$$Gain_{offshore}(f) = \frac{v_{offshore-calculated-future}(f)}{v_{onshore-calculated-reference}(f)} \quad (5)$$

The denominator is always the harmonic voltage onshore since it is the one measured on site. Attention must be paid to voltage and current bases.

It can be noted that this method is based on the assumptions that background harmonic sources will not change in the coming years. It is indeed very difficult to guess how harmonics can grow or decrease since they are spread all over the grid.

B. Modelling and scenarios

1) A large model of RTE's grid

To study background harmonic amplification, two models are implemented in EMTP. As explained in previous section, a model of the French grid in 2014 is at first built. This model will be referred to the reference one. Then a second model including every new grid development and offshore wind farms is developed.

The entire 400 kV grid is considered in both cases. Reference [2] showed how the local grid can influence a frequency scan. Moreover modelling local grids allows pushing back the influence of loads consisting in simple parallel RLC representations. As offshore wind farms will be built on the North-western cost, the 225kV grid is modelled and a particular attention is paid to the modelling of the local 90 kV and 63 kV grids. In these grids, lines are considered with the Bergeron model and on-site measured data. Transformers and autotransformers are based on three non-ideal one-phase units. Saturation is not implemented since this study is looking at harmonics in steady-state. Finally, generators are modelled with Thevenin equivalents.

2) Offshore wind farm connections

Offshore wind farm connections to the main grid are composed with submarine and underground cables, booster transformers and shunt inductances for voltage control.

Submarine cables are represented as pipe type cables with a wideband model [1]. Sheaths are not cross bonded for submarine cables. Underground cables are represented as single core cables with the same model but the sheaths are cross bonded.

The booster transformers models are made of three non ideal single-phase units. Short-circuit impedances and losses are shared for simplicity reasons among the high voltage winding, the medium voltage winding and the low voltage one. This model is encapsulated in a device with the short-circuit impedances and losses being automatically calculated from the transformer tap. Saturation is not taken into account for this study but can be added if transformer energizations have to be simulated.

Beside the boosters and the cables, offshore wind farms are connected thanks to shunt reactors to regulate the voltage. Some are connected to the bus bar onshore substation and rated at 80 MVAr at 225 kV. Some others are connected to the low voltage side of the booster transformer and rated at 64 MVAr at 20kV. They are all modelled with a linear inductance and a resistance to take into account losses.

3) Offshore wind farms

As shown in [8] and [9], modelling the wind farms in details is of importance to carry out correct studies. The data for future French offshore wind farms are not fully available yet. Wind turbines are represented with equivalent circuits but a detailed collector grid model is already available.

Each wind farm is considered to be two wind parks of half the power, roughly 250 MW each. Wind turbines are represented by a Thevenin equivalent with an impedance assumed to be the choke inductance of inverter. Filters are also considered. These pieces of equipment are connected on the secondary side (LV side) of the wind turbine transformer. It is modelled with three non ideal single-phase units and parameterized with short-circuit test data. The collector grid of the wind farm is represented between the wind turbine transformers and the wind park transformer. Fig. 10 gives a partial view of wind park models for this study.

A PV bus is related to each Thevenin equivalent. A load flow is run before frequency- or time-domain simulation ro initialize the sources.

These models will be improved when additional data will be available. Then harmonic studies will be updated along the projects planning phase.

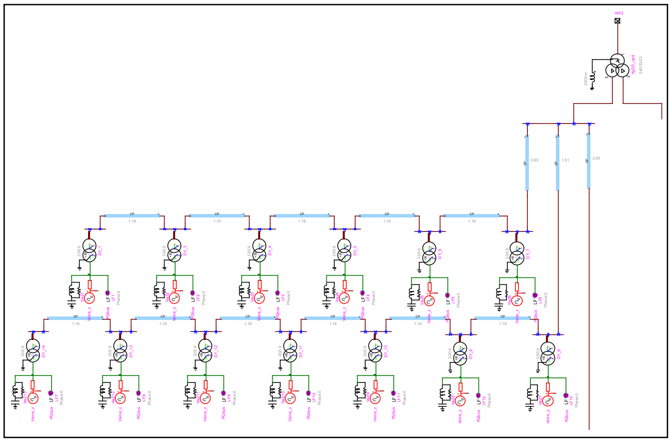

Fig. 10. Partial view of a wind park model. A wind farm is composed of 2 wind parks.

4) Variables and scenarios

In planning stage, sensitivity analysis is required. 5 years before the wind farm commissioning, it is impossible to know all the characteristics of the components.

The sensitivity analysis is concentrated on the booster transformer, the cables and the wind generators.

For the booster transformer its design is already known. It counts 25 taps as impedance which varies from 4 Ω to 8.5 Ω depending of the voltage control.

For other components still in the bid process, RTE only knows the variation range of key parameters. For cables for instance, length are known but the sections have not been decided yet when this first harmonic study was ordered. In this case, three scenarios are considered:

- minimum section,
- median section,
- maximum section.

For wind turbines, the choke inductance is taken variable from 0.11 pu to 100 pu. The value 100 pu refers to the wind turbine converter being disconnected.

Beside these variables, it was observed that the AC main grid topology was relatively of second importance for harmonic studies.

C. Results

Simulations are performed in the frequency-domain as explained in section IIIA. from 50 Hz to 2500 Hz with a frequency step of 1 Hz. A load flow is run before each frequency simulations to initialize voltage sources and loads.

As example, Fig. 11 and Fig. 12 show voltage harmonic amplifications calculated for a given wind farm at the offshore delivery point and at the onshore connection point. These amplifications illustrate how 2014 measured harmonics could be amplified with future offshore wind farm connections. The legends are not given since the number of scenarios is too important to distinguish them. The results are given over the interval where resonances are concentrated, i.e. roughly [50 ; 500] Hz.

On these figures, it can be noted that harmonic voltage amplifications are more important at the offshore delivery point than at the onshore connection point.

Table II shows the resulting harmonic voltage amplitudes at the same location. Estimations are made thanks to harmonic voltage measurements performed on-site in 2014 and the calculated amplification factors. When amplification factors are read on Fig. 11 and Fig. 12, an uncertainty of +-10 Hz is taken into account. It can be clearly noted that even if the most severe resonances are not centred on the common grid harmonics (the 3rd, the 5th or the 7th), some smaller can be strong enough to lead to 9% of the nominal voltage on the 5th harmonic in 2019 in this given example. For other wind farm as was presented in [4], the harmonic amplifications can reach 20 times.

Unlike at the offshore delivery point, voltage harmonics are expected much smaller at the onshore substation on Fig. 12, reaching 2% of the nominal voltage for the 5th harmonics for instance.

The resonances are also responsible for high harmonic currents in cables. Currents have been observed to be the strongest on the regulated high voltage side of the booster transformer (on the wind farm side). On the 5th rank, currents reached 21% of the maximum current in steady state, i.e. 891A for this given wind farm. It is to be compared to the 3rd harmonic which reaches 2% only.

Because it is uncertain if such harmonic are dangerous or not for high voltage components and because RTE shall limit voltage distortion for its clients, i.e. with a level of each voltage harmonics of maximum 4% of the nominal voltage, different solutions for reducing these harmonics are now investigated. Among them, passive filtering seems to be the most convenient.

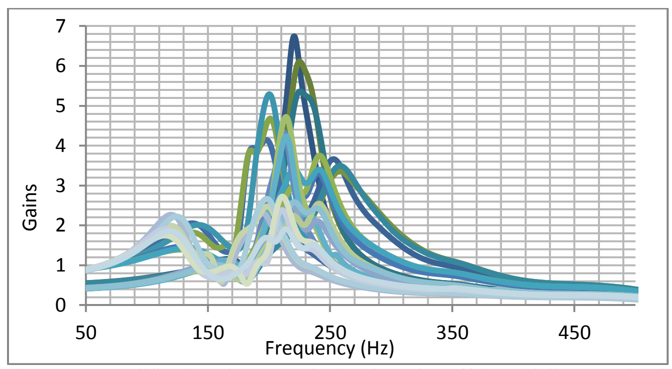

Fig. 11. Amplification factors calculated at the offshore delivery point in various scenarios.

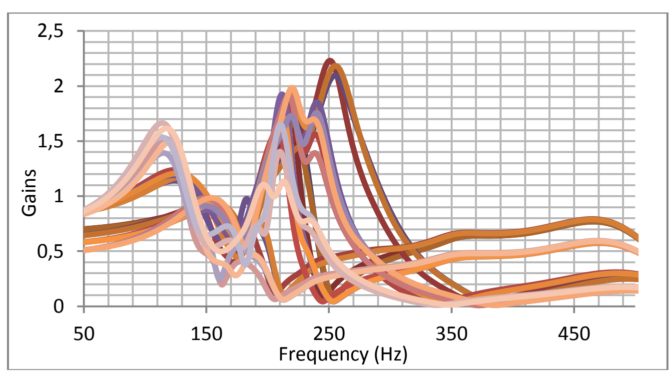

Fig. 12. Amplification factors calculated at the onshore connection point in various scenarios.

TABLE II

EXAMPLE OF RESULTS OF BACKGROUND HARMONIC AMPLIFICATION CALCULATIONS FOR A GIVEN WIND FARM.

Location	Harmonics	Maximum gains	Harmonic amplitude measured in 2014 (%Vn)	Harmonic amplitude calculated in 2020 (%Vn)
Offshore	H3	2,0	ref. onshore	1,0
	H5	5,0	ref. onshore	9,0
Onshore	H3	2,3	0,5	1,2
	H5	1,1	1,8	2,0

D. Solutions

In a general manner on RTE's grid, harmonics should remain under 4% of the nominal voltage with a total harmonic distortion under 6% but the limits can be more severe depending of the harmonic ranks. Even harmonics are not expected on the grid what justifies lower limits at 3% for the 2^{nd} rank, 2% for the 4^{th} and 1% for the remaining even ranks.

Several solutions have been investigated to solve background harmonic issues. The first one is based on active filtering that could be implemented in an onshore STATCOM or directly in the wind turbines. Based on a power electronic technology, the principle is to generate harmonics in phase opposition to the amplified grid harmonics. Active filtering appears to be a flexible solution since the control strategy of power electronic devices can be adjusted regarding harmonic amplitudes and frequencies to be filtered. However, this solution has not been chosen because: wind turbine manufacturers are not willing to guaranty such functionalities; STATCOMs are expensive solutions to filter harmonics. Moreover active filtering has never been used at high voltage levels in industrial applications even if some developments are in progress.

So, conventional passive filters installed in the onshore substations were finally chosen. Installation of filters on the offshore wind farm platforms was proposed but this solution was quickly shown not cost effective since it would have required to oversize the platform.

Passive filtering is a mature solution consisting on the association of inductances, capacitances and resistances. Much less flexible than active filtering, filters are tuned once for all for specified harmonic ranks. For most of offshore wind farms connections the 5^{th} harmonic rank need to be filtered. For each single tuned filter, a space of 30m x 38m is reserved in 225 kV substations for a maximum height of 8m. An example of damped LC filer is given on Fig. 13 a). The values of the components are currently studied. In order to limit the impact of filters on grid voltage the filters are specified to inject less than 35 MVAr at 225 kV.

For some other wind farms, the 3^{rd} or the 7^{th} harmonic rank in addition to the 5^{th} will be an issue according to the simulations. In these cases, a doubly tuned filter will be considered. It consists in the association of passive components such as inductances, capacitances and resistances but their values will be set to create a parallel resonance at two harmonic ranks. The layout of such filter is given on Fig. 13 b). The footprint would be a bit larger with 40m x 40m and 8m as maximum height.

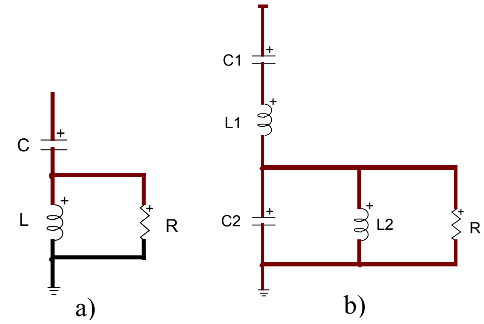

Fig. 13. a) Single tuned damped LC filter. b) Doubly tuned damped LC filter.

E. Time-domain simulations

Before the wind farms commissioning, estimated in 2019, several issues need to be studied in addition to an updating of the results with more accurate input data. As example, when more details on wind generators will be available, additional harmonic studies will be performed taking into account the control of wind turbines.

Then, time domain simulation will be required since many operating points will be necessary to be studied. However, such simulations need much more computation time compared to frequency-domain simulations. The use of a harmonic network reduction algorithm is essential to speed up the time domain simulations. An example is given here.

The 400 kV grid including parts of the North-western 225 kV and local 90kV and 63 kV is reduced to a Frequency Dependant Network Equivalent [7]. This grid was made of 4699 electrical nodes. As shown on Fig. 14, the rest of the model is unchanged for a given wind farm.

Harmonics are assumed to be in phase in this example with the Norton 50 Hz source. An aggregated harmonic source is placed in parallel of the Norton impedance and previously set without the wind farm connections to give 0.5% of the nominal voltage at the 3^{rd} harmonic rank and 1.8% at the 5^{th} harmonic rank. Then, harmonic sources being kept constant, the wind farm connections are added and a time-domain simulation is launched to observe the new voltage signals at the onshore connection point and the offshore delivery point.

As expected since our model is linear, for any given scenario the simulation leads to the same voltage amplitudes and relative amplifications than those calculated with the frequency-domain method in section C. Calculations last 16.4s with a regular computer with a simulation time of 100 ms and a time step of 10 µs. With a state space based on a sparse matrix algorithm as developed in [10], calculation time is even more reduced with 1.73s.

The same simulation is done with the full grid model instead of the frequency dependent equivalent. It takes 71.7s to get the same results.

As preparation to future works, these results show the great benefit of frequency dependent network equivalents described in [7] using state space based on sparse matrix algorithm [10].

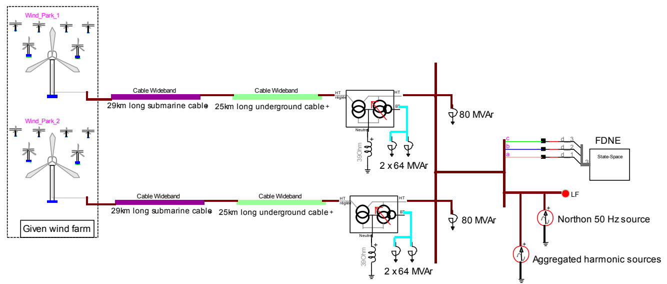

Fig. 14. Reduced model to study background harmonic amplification in time-domain for a given wind farm.

IV. Conclusions

The six first French offshore wind farms are currently under design with the objective to increase from 2020 France energy mix by a total of 3 GW. RTE is in charge of their connection to the main grid. It is based on the association of long AC submarine and underground cables which are going to be connected to the 225 kV grid through booster transformers.

This paper showed such association of capacitive and inductive components creates LC resonances which can amplify background harmonics if they match in terms of frequency. In theory, amplifications can easily reach 25 times with common cables, booster transformers and grid characteristics what encourages RTE to perform harmonic studies and measurements for the connection of the offshore wind farms.

Frequency-domain simulations can be used to estimate background harmonic amplifications like on the Normandy 3 cable project. Comparisons between frequency-domain simulations and on-site harmonic measurements showed close results. Time-domain simulation can also be useful to consider control systems at many operating points. Reducing grid models to Frequency Dependent Network Equivalent would be necessary to speed up simulations.

When harmonic limits are exceeded as it could be with future offshore wind farm connections on the 3rd, the 5th or the 7th harmonic ranks, passive filters need to be installed.

Harmonic amplifications are not a new issue ([5], [6]). It is something one needs to look at in the design phase of projects to anticipate any troubles. As a consequence, many complex EMT simulations are expected in the years to come.

V. References

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