Transient Studies performed by RTE for the connection of offshore wind farms

S. Deschanvres, Y. Vernay

***Abstract*-- At the beginning of 2012, the French government announced that four offshore wind farms were going to be built in the northwest of France. These first four French wind farms are going to produce around 500 MW each. The French TSO, RTE, is responsible for the connection of the farms to the grid, including the submarine part of the connection.**

The wind farms are going to be connected to the 225 kV network, with AC insulated cables, whose length will be between 40 and 60 km. The insertion of long EHVAC insulated cables in the grid requires transient studies.

An important topic is the energization of offshore transformers, which may lead to unexpected harmonic overvoltages. This paper describes harmonic impedance simulations performed for these offshore wind farm projects. It shows a criterion used for frequency scan analyses as well as the main conclusions from the application of this criterion to studies of wind farm connections.

I. INTRODUCTION

The European Union has set itself the goal of raising the share of renewable energy sources in the final overall energy consumption of the Union from 8.5% in 2005 to 20% in 2020. In the field of electricity production, wind power is going to be a way to achieve this objective.

At the beginning of 2012, the French government announced that four offshore wind farms were going to be built in the northwest of France. Like many other countries, France is expanding renewable sources of electricity, aiming at reducing greenhouse gas emissions and enhancing the security of energy supply. These first four French wind farms are going to produce around 500 MW each and other power plants are to be implemented in the near future. In the beginning of 2013, another call for tenders was published for the construction of 1000 MW.

The French TSO, RTE, is responsible for the connection of the farms to the grid, including the submarine part of the connection. It means that RTE performs technical studies to design the wind farm connections. Of course, transient studies are part of these.

A. The four wind farm projects

The four areas where the wind farms are going to be built are located in the north-west of France.

Fig 1 Wind farm locations

Considering the power of wind farms and the distance between the plants and the existing network, the farms will be connected to the 225 kV network, with AC insulated cables.

The lengths of submarine and onshore insulated cables depend on the area. The total length should be between 40 and 60 km.

Long HVAC cables produce a lot of reactive power. Thus, there is a need for reactive power compensation equipment, such as shunt reactors close to cable terminals. Usually, when dealing with insertion of EHVAC insulated cables into the grid, we prefer to install shunt reactors at both ends of the cable so that reactive power compensation is optimized and network voltage is not degraded.

For offshore wind farm connections, RTE decided not to install any compensation equipment at the offshore end of the cable, because the offshore platform belongs to the producer (and not to RTE). Moreover, shunt reactors are heavy equipment and need some maintenance so it is more cost-effective to install them onshore.

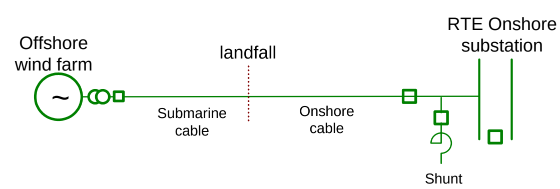

Fig 2 Wind farm connections diagram

According to steady state studies, this is a constraint. Because all the cable reactive current would flow all the way

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through the cable, the current capacity of the cable couldn't be optimized.

Furthermore, voltage at the offshore end of the cable will be a few kV above the voltage at the onshore end of the cable.

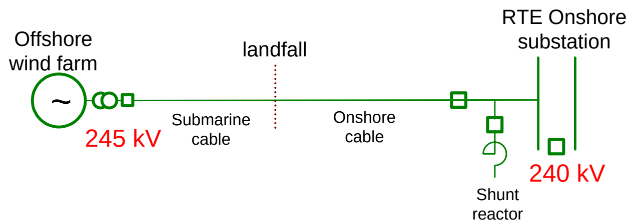

Fig 3 Wind farm connections diagram

This last point can lead to problematic situations. RTE has an obligation to keep voltage below 245 kV on its 225 kV grid. This means that RTE would have to keep the voltage of its substation below 240 kV, considering that there is a difference of 5 kV between onshore and offshore voltages. That would be an unacceptable constraint because the actual situation is that voltage on RTE substation is quite often above 240 kV for grid operation purposes.

The solution chosen by RTE is to control the connection voltage on the cable without changing voltage on the RTE grid. This can be done thanks to a booster transformer inserted between HVAC cable and RTE grid with an on-load tap changer on the shunt transformer.

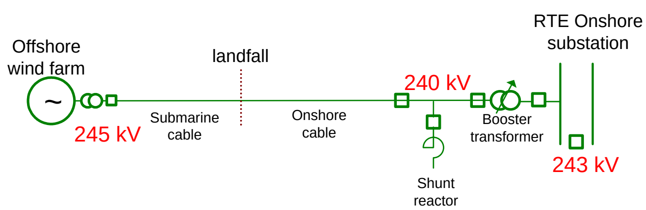

Fig 4 Wind farm connections diagram

B. Transformer energization studies

Currently, the grid is rather inductive since it is made of coiled hardware (such as transformers or shunt reactors), power generation units and overhead lines. On the contrary, insulated cables are highly capacitive elements. So, connecting a power plant with an underground cable is like installing highly capacitive elements on the grid. From a very simple point of view, we can consider that this is equivalent to a LC oscillating circuit, which has possibly high impedance at a certain resonance frequency. Thus, there is concern that the network impedance seen from the connection point of the producer has a harmonic resonance.

This feature can be problematic for energizing the producer's transformers. Due to the magnetic properties of its iron core, a transformer generates harmonic currents during its energization. If the grid impedance is high enough at a harmonic frequency, these currents generated by the transformer could result in transient overvoltages that can be dangerous for the dielectric strength of the network component and especially for the transformer itself.

C. Harmonic impedance assessment

This study allows us to detect potential adverse resonance created by the insertion of long HVAC cable. In order to do so, we investigate the direct sequence impedance of the grid seen from the connection point of the power plant (or the connection point of the producer transformer). Obviously, there are other transformers or autotransformers near the connection point. Their energization could also be problematic. But the worst resonance impedance is measured at the end of the cable. In a first part we can thus limit our scope of study to that point of observation. EMTP- RV is used for frequency scan analyses.

II. THE NETWORK MODELING IN EMTP

Transformer energization is a low-frequency phenomenon (from 50 to 2000 Hz) so it has to be studied with an extensive network modeling. Most of the lines are modeled with distributed constant parameter line model in EMTP. Insulated cables are modeled with frequency dependant parameters. Some long overhead lines, close enough to the connection point, are modeled with frequency dependant parameters.

When considering computation time, it is indeed more effective to model few lines in the study area, with frequency dependent parameters and other lines with constant parameters without loss of accuracy on the frequency response at the point of interest.

The size of the network modeling has a great influence on the precision of the frequency scan calculations. The advice for the modeling of the network of the joint CIGRE/CIRED WG CC02 [4] is to model accurately at least all the primary transmission network for a proper evaluation of the harmonic impedances. A work done by the authors in the Cigre Brochure [5] shows that for one French 400kV substation, the complete modeling of the 400 kV network and of the 225 kV up to one node is necessary to represent accurately the harmonic impedance of the network between 50 Hz and 1000 Hz.

For the studies of the four wind farm connections, one network model was done with the all 400 kV French network and the North West part of the 225 kV network modeled in EMTP-RV. Loads and power generation parameters are based on a real situation of the electric French system. To do so RTE has developed a link between system tools and EMTP, which allows us to set power generation units and loads parameters with data from the SCADA [1]. This method prevents some human mistakes during the modeling and makes the EMTP file consistent with a real situation.

III. FREQUENCY SCAN ANALYSIS

From the frequency scan, we get the harmonic impedance (usually between 50 and 1000 Hz). However, it is not obvious to say if the resonance impedance observed is too high or if the resonance harmonic is too low.

That is why we need an objective criterion to exploit the results of the frequency scan simulations. In order to do so, a methodology for calculating a harmonic criterion has been developed at RTE for frequency scan analyses. This methodology has been used for present offshore connection studies. It is explained below. We obtain this criterion from time-domain simulations of a simplified transformer energization, in which maximal network resonance is found by variation of simple components (R, L and C). The simplified circuit used is shown in the figure below:

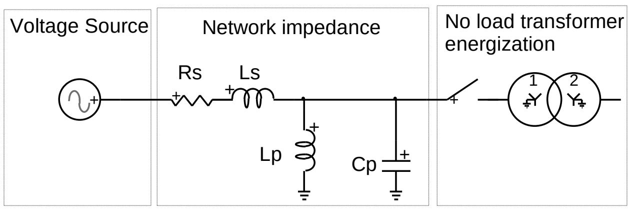

Fig 5 Simplified circuit for harmonic criterion

The value of Ls represents the short-circuit impedance of the network. This value is fixed at the beginning of the criterion. The capacitor Cp represents a cable which generates a resonance. This value is calculated for the first part of the calculation to have a *i*th harmonic resonance.

$$C_p = \frac{1}{(2\pi i f)^2}\left(\frac{1}{Lp} + \frac{1}{Ls}\right) \qquad (1)$$

where i is the harmonic number.

An inductance Lp can be added to represent an eventual cable compensation. The voltage source has also to be adjusted to get the desired energization voltage of the transformer.

After this setting, a complete transformer energization is run with variation of circuit breaker switching times and residual fluxes in the transformer. Usually 400 circuit breakers switching times per period and 10 values of transformer residual fluxes are considered. The maximal voltage recorded (V_{max}) at transformer terminals is compared to the maximal admissible voltage (V_{limit}). Usually at RTE, V_{limit} is set at 1.3 pu for 400kV and 225kV transformers. After this comparison, the value of Rs is modified by dichotomy depending if we want to have lower or higher resonance impedance. A complete transformer energization is run again until we have a good match between V_{max} and V_{limit}. The final value of Rs is saved and a new value of Cp is calculated to have the (i+1) harmonic resonance. The final value of Rs corresponds to a maximal value of resonance amplitude (Z_{max}) admissible at the studied harmonic to not reach harmonic overvoltage higher than 1.3 pu. The same procedure is done for all studied harmonics and a graph of Z_{max} per harmonic can be drawn. Examples of this graph are given on figure 7 for different energization voltages.

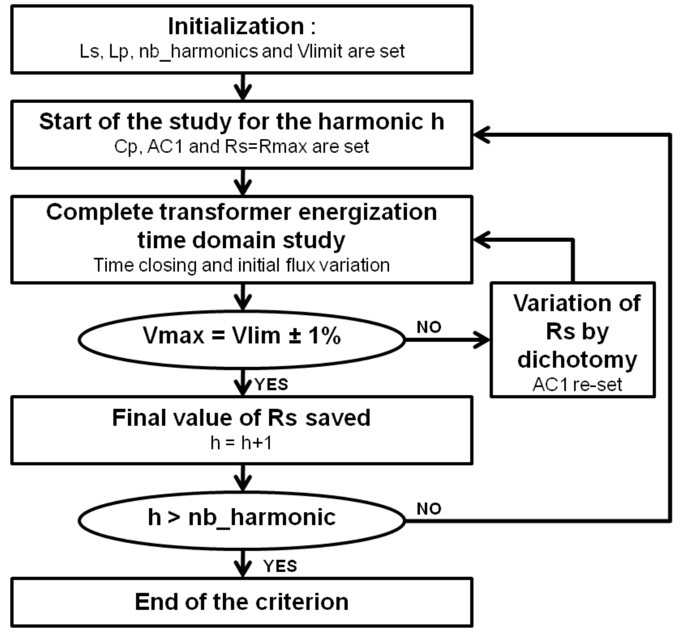

Fig 6 Harmonic criterion algorithm

The convergence of the harmonic criterion algorithm can be long and may depend on initial parameters, such as the first value of Rs (R_{max}). At RTE, it has been chosen to calculate the value of Z_{max} only for the first ten harmonics and to use the Z_{max} value of the tenth harmonic, which is in generally very high, for higher harmonics.

As the criterion redoes transformer energization studies, which themselves included lot of time domain studies, it took almost 50 hours of calculus to establish it with an Intel i5/640 processor. As we have mentioned before, this large calculation time can be optimized with simple adjustments such as the first value Rs for the beginning of the dichotomy. Plus, this calculation is just performed once per transformer and can be used after for several studies. Also, the harmonic criterion has been completely scripted in EMTP-RV, all the parameter calculations, simulation launching and results analysis are done automatically by just one click. Therefore, this time of calculation is not time consuming for the user.

At RTE, several criteria have been run for typical transformers of the network and have alloweda faster analysis of harmonic studies for transformer energization issues. A criterion has been specially defined for the studies of offshore connections, taking into account expected characteristics of producer transformers.

We keep in mind that our criterion validity is limited. The main reasons are:

- The transformer used for the criterion calculation has got certain characteristics, especially a given saturation curve.
- The harmonic criterion takes only one resonance into consideration whereas multiple resonances can be seen on frequency scans.
- The simplified network does not take into account multiple resonance phenomena due to other saturable elements of the network which can amplify harmonic

overvoltages.

Those points are not really an issue because a scan frequency study is mostly a method to identify the most dangerous grid schemes. These schemes can then be studied through temporal simulations with specific modeling for more accurate results. Temporal simulations are very time consuming for modeling and for simulation time, so frequency scan studies allow us to save time by selecting critical grid schemes.

Transformer saturation highly depends on the voltage at the node where the transformer is energized. For the connection of offshore wind farms, we have seen that we will use booster transformers to drive the voltage of the connection. So we have the possibility to lower the voltage if we want to make transformer energization easier.

That is the reason why we have defined the criterion at different voltages.

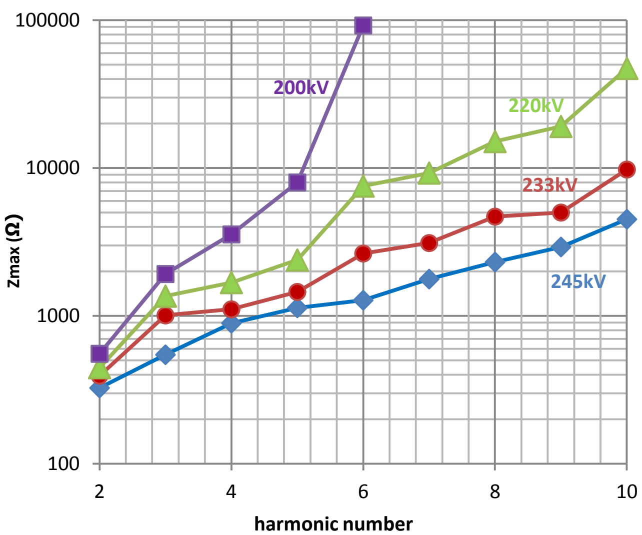

Fig 7 Harmonic criterion for frequency scans analyses

It is clear from the graph above that the lower is the substation voltage, the lower is the saturation and, as a consequence, the higher is the maximal harmonic impedance we can reach. Actually only the points at each harmonic are calculated and are relevant for the criterion. A resonance between two harmonics, for example let's say at 275 Hz would be less dangerous than a resonance on the 5th or 6th harmonic. However it has been chosen to link points to have a more readable graph.

IV. HARMONIC IMPEDANCES SEEN FROM THE PRODUCER TRANSFORMER

Usually, harmonic impedance results depend highly on the grid topology. That is why we have performed frequency scan studies in various grid schemes (lines or transformers out of service, load levels).

However, for all the four connections, it was found that harmonic resonance impedances are rather constant versus the topology studied. This is due to the particular configuration of the connections, where insulated cables (submarine and onshore) are in series with a booster transformer. The observation was that the impedance of booster transformers is a critical parameter of the calculation, much more important than the equivalent impedance of the grid.

As a consequence, conclusions of frequency scan simulations are really similar for the four connections. Indeed, the same booster should be installed on the four connections.

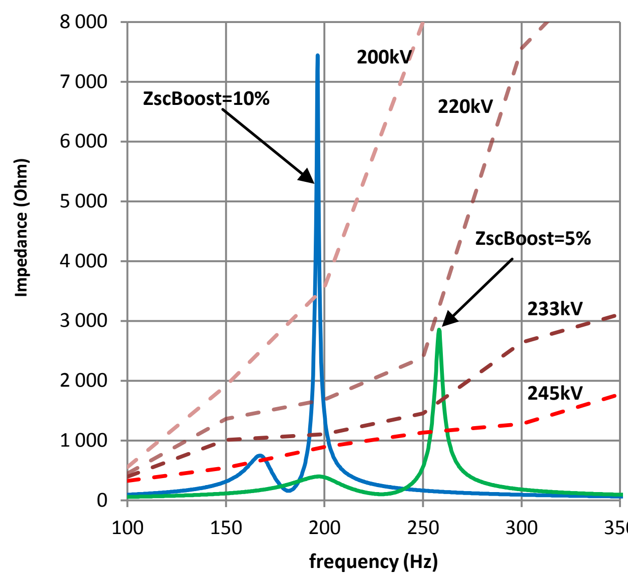

Fig 8: typical impedance at producer's end of the connection cables

From the Fig 8, we can conclude that:

- Harmonic impedance directly depends on booster impedance
- Some severe resonances are found: low harmonic resonance impedance is above the harmonic criterion. So there is a risk of harmonic overvoltages during transformer energization

More precisely, with a booster impedance of 5%, impedances are below criteria at 220 and 200 kV but above criteria at 233 and 245 kV. But it is not feasible to have both a booster impedance of 5% and a connection voltage below 220 kV because the booster impedance is maximal when the connection voltage is minimal.

V. DISCUSSION

Studies have shown that severe resonances are expected. These resonances can lead to dangerous harmonic overvoltages during energization of the producers' transformers. A solution to damp these overvoltages has to be defined for the connection of the four wind farms. One interesting point is that results are quite robust to the grid topology and to the substation where the connection is realized. This point suggests a possible common solution for the four offshore wind parks.

When the frequency scan studies were done, there were still big uncertainties about some data used for the modeling of the connections: onshore length and submarine cables, the substation where cables will be connected… Thus it is another advantage that conclusions are quite robust. Even if the cable route and the length of the cables might change, conclusions should remain the same: it is necessary to define a procedure or to design equipment to prevent harmonic overvoltages.

VI. CONCLUSION

As the owner of the future offshore wind farm connections, RTE has performed harmonic impedance analyses regarding possible resonances leading to harmonic overvoltages during the transformer energization.

A harmonic criterion has been developed to have a fast analysis of the frequency scan studies. This criterion takes into account the phenomena of resonance during transformer energization by EMTP time domain simulations.

For the four wind farms, severe resonances were found compared to the harmonic criterion.

Solutions will be further discussed and designed in collaboration with the producers. Time domain simulation will be necessary and possible once basic parameters of the connections (such as length of the cables, characteristics of the transformers) will be known in detail.

VII. REFERENCES

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