Modelling and Dynamic Analysis of Offshore Wind Farms According to the French TSO Grid Code

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***Abstract*—Offshore wind farms are growing rapidly in the North Sea, being installed at more distant locations and becoming larger in size. The French government has the ambition to build 6 GW of offshore wind farms by 2020. Dynamic analysis for the integration of these farms to follow such ambitious plans has to be carefully performed to ensure system security. Through this article, a proposed reference offshore wind farm has been defined and modelled. An interconnection study has been realized based on ENTSO-E[1] offshore requirements and French Transmission System Operator (TSO) current requirements. The transmission system, which considers an AC submarine cable, has an important impact when fulfilling grid code requirements. Finally, using the IEEE 14-bus power system which integrates the reference offshore wind farm, stability studies have been also carried out.**

I. Introduction

Future offshore wind farm projects are expected to become more distant and comprise massive farms. Offshore wind farm development compels grid owners to have a better understanding of the impact of these units when integrated to the overall system. Currently, onshore wind power accounts for a total power capacity of 86 GW in Europe and the electrical power from offshore wind in Europe represented around 3 GW by the end of 2010 [1]. EWEA[2] expects 40 GW of electrical power from offshore wind by the end of 2020.

Currently, in France, there are no offshore wind farms, despite a huge offshore potential. Hence, the French government launched on July 11$^{\text{th}}$, 2011 the first call for tenders for the construction of 3 GW of generation using offshore wind farms and it targets to reach 6 GW by 2020 [2]. The 5 selected areas are shown in Fig. 1, and the main features of these farms are summarized in Table I. This has raised an urgent need of investigating the impact of the connection of offshore wind farms in the French electrical grid. In particular, there is an urgent need for a dynamic analysis of the impact of offshore wind farm integration in France, and its consequences for grid management, operation and control.

[1]ENTSO-E: The European Network of Transmission System Operators for Electricity.

[2]EWEA (European Wind Energy Association) an association based in Brussels that promotes the use of wind power in Europe.

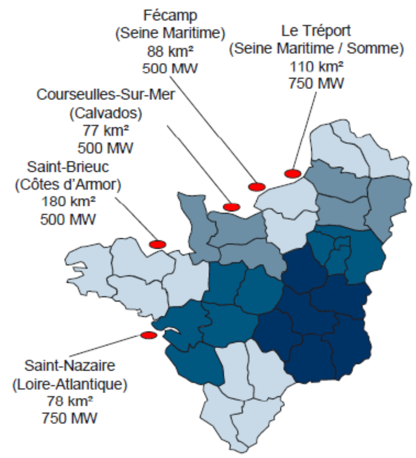

Fig. 1. The 5 selected offshore wind farm areas of the French tender

TABLE I
CONNECTION CHARACTERISTICS OF THE 5 OFFSHORE WIND FARMS

Le Tréport	Fécamp	Courseulles	Saint-Brieuc	Saint-Nazaire	
HVAC 225 kV	HVAC 225 kV	HVAC 225 kV	HVAC 225 kV	HVAC 225 kV (Power ≤ 480 MW)	HVDC 320 kV (Power > 480)
3 cables	2 cables	2 cables	2 cables	2 cables	1 bi-cable
			120 MVar	80 MVar	120 MVar
To be defined	Full converter PMSG, Alstom 6 MW	Full converter PMSG, Alstom 6 MW	Full converter PMSG, Areva M5000	Full converter PMSG, Alstom 6 MW	Full converter PMSG, Alstom 6 MW

Hence, the objectives of this article are to develop a reference offshore wind farm model, according to typical features of existing offshore wind farms in the North Sea, to characterize the dynamic behaviour of this wind farm regarding offshore grid requirements, and to characterize the impact of offshore wind farms on a typical study test network under different stability conditions. The test electric power system is the IEEE 14-bus power system which is shown in Fig. 2. Modelling and simulations of this system have been performed using the EMTP-RV software which is a software

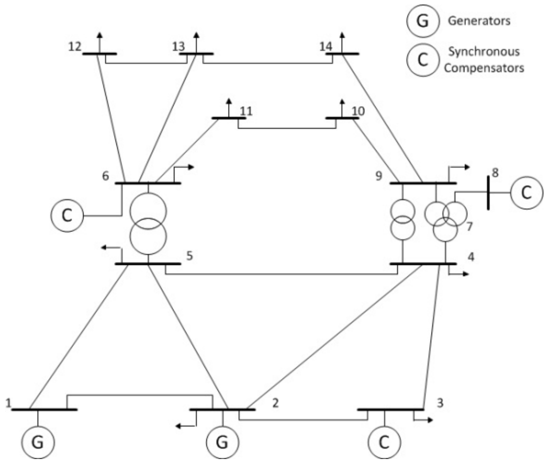

Fig. 2. The IEEE 14-bus power system single line diagram. Adapted from [4].

specialized for the simulation and analysis of electromagnetic transients in power systems [3]. To this aim, the typical IEEE 14-Bus system has been modelled in detail, including the development of data for its compatibility with EMTP studies.

Before performing dynamic simulations and analysis, a literature review of the state of the art of offshore wind farm technologies was performed [5]. First, a reference offshore wind farm has been proposed and modelled. Secondly, offshore grid code requirements have been identified and tested on the reference offshore wind farm. Finally, simulations have been carried out in order to characterize the dynamic behaviour in an interconnected electric power system.

II. A PROPOSED REFERENCE OFFSHORE WIND FARM

A. *Offshore technologies*

From a technical scope, offshore wind facilities have been originally developed using onshore technologies, despite their differences and the fact that offshore wind turbines have to resist to more stringent environmental conditions. However, large technological improvements have been achieved recently and wind turbine manufacturers are today developing new wind turbines which are specifically built to resist offshore conditions. An electrical network of an offshore wind farm can be seen in Fig. 3. It consists of: wind turbines with their own internal transformer; internal submarine cable; offshore substations (if needed); transmission submarine cables and onshore substation with onshore cables [6]. This whole system is connected to a Point of Common Coupling (PCC). Other types of electrical network exist but are rarely used for offshore wind farms.

From the state of the art on electrical offshore wind farms, already connected in the North Sea, the main features of built and in project offshore wind farms are:

- Wind turbine generators are either DFIG or full converter induction machines. However currently many permanent magnet synchronous generators with a full-scale converter with or without gearbox are developed by wind turbine manufacturers for a specific offshore use. Until now, this technology was still too expensive but the efficiency of this turbine is superior to other kinds of turbines and this technology seems to become the standard for offshore wind farms currently installed.
- The internal voltage of offshore wind farms is around 33 kV. This means that each wind turbine has its own transformer which raises the voltage from 690 V which is the output voltage of wind turbines to 33 kV AC.
- The layout of offshore wind farms is AC/AC or in the near future (2012) AC/DC in Germany. Moreover, offshore wind farm turbines are connected radially.
- The presence of a transformer on an offshore or onshore substation depends on the transmission distance: Between 0 and 10 km, the offshore wind farms do not need an additional substation. Therefore several HVAC lines are needed (33 kV) for the transport of electrical power to the grid. Between 10 and 60 km, a preferred solution is now to use one transformer (or many) in an offshore substation. Offshore wind farms will be connected to the onshore electrical grid by one or several HVAC lines (130 kV - 150 kV). Currently 245 kV HVAC lines are available and 400 kV HVAC lines will also be available in the near future [6]. One of the problems is the limitation of the allowed transmitted power by these lines. If the active power of offshore wind farms is large, a great number of lines are needed in order to transfer the electrical power to the grid, which increases connection costs. Further than 60 km, the most economical and performing solution would be the use of HVDC transmission systems by using the VSC-HVDC technology [7,8]. This is becoming the standard choice for larger and more distant offshore wind farms.

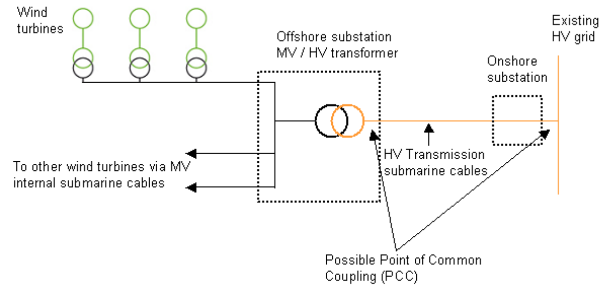

Fig. 3. A typical offshore wind farm single line diagram . Adapted from [9].

B. *A reference offshore wind farm*

In order to have a consistent and systematic approach in the study of offshore wind farms and their dynamic behaviour, a standard offshore wind farm model has to be defined. Therefore a state of the art of existing technologies and already installed offshore wind farms in Europe (together with wind farms in planning), was made in order to find a reference offshore wind farm model which has the most common characteristics [5,6]. The chosen specifications of the reference offshore wind farm which will be used in the next 2 case studies are:

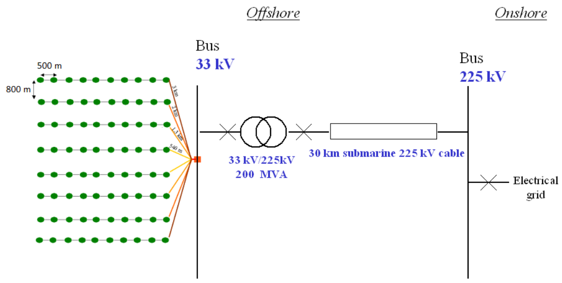

Fig. 4. The reference offshore wind farm single line diagram.

- Power: **200 MW**;
- Wind turbine: **Full Converter Permanent Magnet Synchronous Generator, 3 MW**;
- **Radial** connection; Internal voltage **33 kV**; One offshore transformer **33/ 225 kV**;
- AC/AC Wind farm: **HVAC 225 kV** (30 km).

The general characteristics of the reference offshore wind farm have been defined as shown above and the single line electrical diagram of this offshore wind farm is presented in Fig. 4.

C. Modelling of the reference offshore wind farm with an AC 225 kV transmission system

In this section, the offshore wind farm model with an AC transmission system will be developed. First, the wind turbines are modelled using a full converter permanent magnet synchronous generator represented in Fig. 5. This permanent magnet synchronous generator with power converters has been modeled in EMTP-RV using average models for the power converters model. It can be underlined that the produced reactive power can be controlled through 3 different ways: constant reactive power order; constant power factor order or voltage control.

The reference offshore wind farm consists of 80 wind turbines. In order to reduce computation time, it is possible to aggregate each radial line of the reference offshore wind farm which has 8 lines and 10 turbines per line. The principle of N wind turbine aggregation is to calculate different outputs for one wind turbine and then to multiply outputs by N. However, it is necessary to evaluate the impact of such an aggregation on dynamic studies. To this end, a voltage dip has been applied at the PCC, and the voltage level of a totally aggregated line has been monitored. Then the same simulation has been performed with the same line which is now non-aggregated (i.e. fully modelled with 10 turbines per line). The voltage levels of the first, middle and last wind turbines are shown in Fig. 6 and compared with the aggregated model. The difference between the aggregated line voltage level and the non-aggregated line voltage level is around 0.3 % during pre and post-fault and around 3 % during the fault. The impact of such an aggregation is negligible and will not bear a significant influence in further simulation results.

Transformers are key elements of an offshore wind farm electrical layout. In the reference offshore wind farm model,

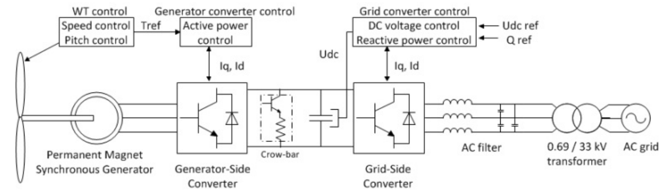

Fig. 5. A full converter permanent magnet synchronous generator model. Adapted from [10].

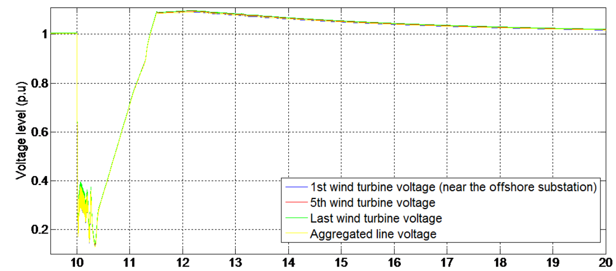

Fig. 6. Aggregation impact on terminal wind farm voltage during a voltage dip.

each 3 MW wind turbine must be associated with a 0.69 / 33 kV transformer. Moreover, an offshore substation is built in order to host a 33 / 225 kV transformer. The equivalent model of these transformers in EMTP-RV is a simplified model which is represented by a three-phase impedance.

The XLPE[3] 3-phase submarine technology is used for 33 kV and 225 kV cables. With EMTP-RV, it is possible to use 33 kV[4] and 225 kV[5] submarine cables with their geometrical characteristics. The 225 kV submarine cable of the reference offshore wind farm has large capacitive properties. The 225 kV cable produces in general reactive power and will raise the overall voltage of the offshore wind farm compared to the PCC voltage.

III. Test on Grid Code Requirements

In order to be allowed to connect offshore wind farms to the French transmission electrical power system, it is necessary that French wind producers choose adequate dimensioning characteristics of wind farm components in accordance with transmission system operator's (TSO) requirements. Nowadays, the French TSO Réseau de transport d'électricité (RTE), does not give information about future grid requirements which will be specific to French offshore wind farms. The only available information is that the PCC will be offshore, which means that the transmission submarine cable will not be part of the responsibility of the power producer [2]. The study case of the 200 MW reference offshore wind farm connected with a 30 km AC transmission line is therefore realized based on two connection studies: the ENTSO-E offshore requirements applied at the onshore PCC [11] and RTE classical power plant requirements applied at the offshore PCC [12]. From a

[3]XLPE, Cross-linked polyethylene

[4]XLPE copper cable, ABB, cross section of 250mm^2 and a capacitance of 0.23 uF/km.

[5]XLPE copper cable, cross section of 500mm^2 and a capacitance of 0.14 uF/km.

TABLE II
SIMULATION CASES FOR CONNECTION STUDY

Grid requirements	Offshore producer - ENTSO-E	Classical producer - French TSO
PCC	Onshore	Offshore
Constructive capabilities	P/Q and U/Q diagrams	U/Q diagrams
Low voltage fault ride-through	ENTSO-E fault ride-through curve for an offshore producer	RTE fault ride-through curve for a producer connecting to the 225 kV network

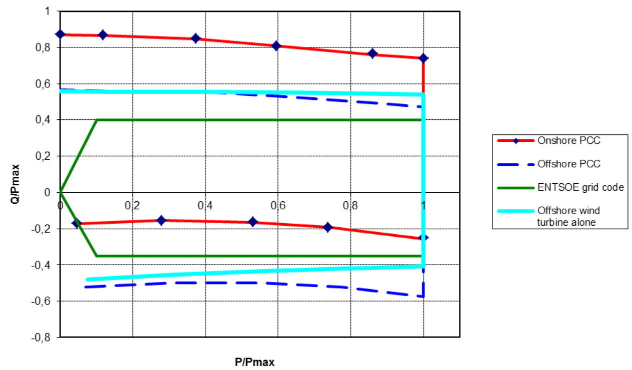

Fig. 7. (P,Q) diagram of the reference wind farm at U_n = 1 p.u and in green the ENTSO-E (P,Q) diagram requirement.

literature review on offshore grid codes in Europe, this study has focused on two main grid requirements: (i) constructive capability regarding to reactive power supply, and (ii) low-voltage fault ride through capability. The performed tests are summarized in Table II.

A. Reactive power supply

In order to be allowed to connect power plants to the electric power system, each producer has to provide (U,Q) capability diagram of the power plant. This diagram should especially be drawn for different values of the active power output of the plant. Each TSO requires a (U,Q) diagram which has to be respected. Offshore wind farms have to be able to change their reactive power inside the diagram. However, if the constructive capabilities of these power plants do not allow to reach these operating points, producers have to add, for example, local compensation sources (passive reactive compensation, FACTS, etc.) which may be built after the connection of these power plants. Different operating points have been simulated at constant voltage (1 p.u) in order to establish the (P,Q) diagram of the offshore wind farm, and have been simulated at constant power (1 p.u) in order to establish (U,Q) diagrams. The (P,Q) and (U,Q) diagrams of the reference offshore wind farm are plotted with ENTSO-E initial requirements, in Figs. 7 and 8, respectively.

The resulting (P,Q) diagram when the PCC is onshore, is shifted compared with the diagram required by ENTSO-E and does not allow to reach operating points when the whole system "wind farm + submarine cable" is lagging reactive power. This gap is due to the submarine cable which generates reactive power. The same behaviour can be observed in Fig.

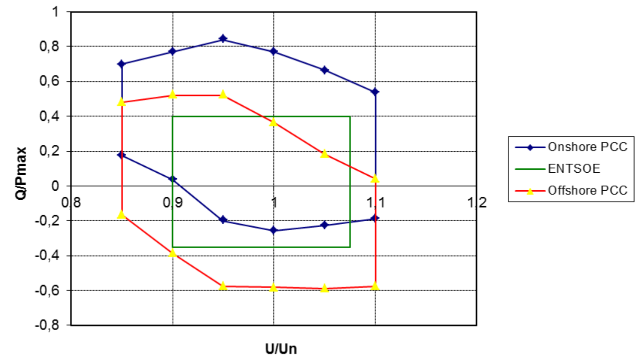

Fig. 8. (U,Q) diagram of the reference wind farm at $P_{farm} = P_{max}$ and in green the ENTSO-E (U,Q) diagram requirement.

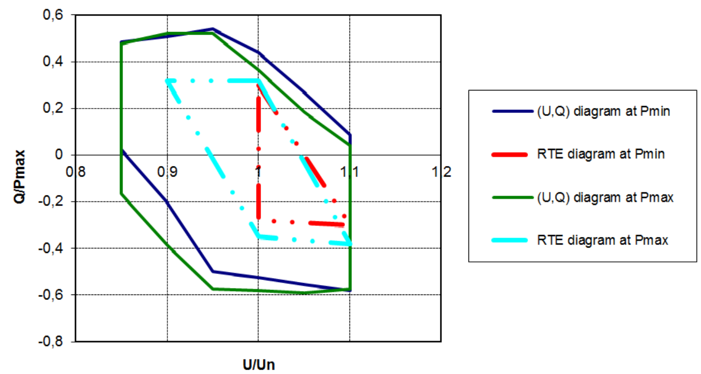

Fig. 9. (U,Q) diagram of the reference wind farm at P_{max} and P_{min} and in dash the RTE (U,Q) diagrams requirement.

8. In conclusion, the offshore wind farm could comply with ENTSO-E constructive capability requirements for reactive power if the PCC is offshore. However, if the PCC is onshore, the presence of the 225 kV sub-marine cable should be compensated by an additional element in order to satisfy requirements on reactive power absorption. In Fig. 9, (U,Q) diagrams of the reference offshore wind farm at P_{min} and P_{max} have been plotted. The P_{min} value is not specified by RTE and has been set here to be equal to $0.1P_{max}$. The offshore wind farm respects the RTE constructive capability requirements at the offshore PCC.

In conclusion, the location of the PCC can have an impact on the fulfilment of (U,Q) and (P,Q) diagrams for the same offshore wind farm.

B. Fault Ride Through (FRT) Capability

Offshore wind farms should be able to stay connected to electrical networks during a voltage dip. The "no-logout" of the reference offshore wind farm will be tested when a FRT curve defined by ENTSO-E occurred at the onshore PCC, and a second FRT defined by RTE occurs at the offshore PCC. Fig. 10 shows a single line diagram of the test system.

Only results for the classical producer — RTE case — are shown here while ENTSOE results are given in [5]. In Fig. 11, the FRT thresholds and wind turbines voltages are shown in black and blue traces, respectively. In steady state, the reactive power of the offshore wind farm is kept at 0 MVar at the PCC.

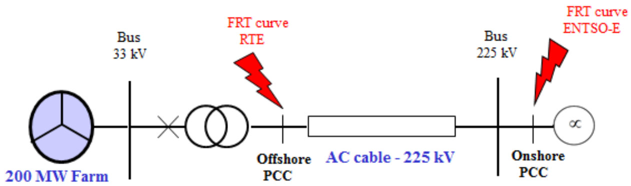

Fig. 10. Single line diagram of the test system.

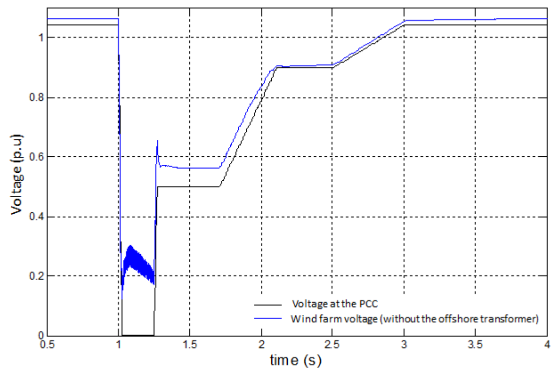

Fig. 11. Wind farm voltage during a voltage dip RTE case.

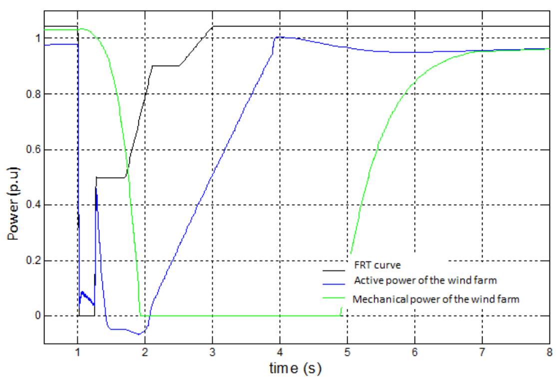

Fig. 12. Active and mechanical power during a voltage dip RTE Case.

In these test conditions, if wind turbine manufacturers certify that each wind turbine can fulfil RTEs fault ride through requirement, then the offshore wind farm can be connected on RTEs electrical power system. Fig. 12 shows the dynamic behaviour of the offshore wind farm. The active power (in blue) goes from 1 p.u to 0 p.u and the mechanical power is null only 1 second later. During this time, crow-bars absorb the surplus of energy. After the end of voltage dip, active power stored in capacitors is provided to the grid and the mechanical power comes back a few seconds later.

The reference offshore wind farm fulfils RTE requirements concerning constructive capability and Fault Ride Through (FRT) capabilities. However, the design of the studied farm is not enough to satisfy all the tests required by ENTSO-E. The transmission cable imposes a limit for the fulfilment of the requirements set by the (U,Q) and (P,Q) diagrams. It is possible to conclude that the choice of the PCC location is important for the design of the offshore wind farms because the “wind farm + cable” system will not have the same limits and characteristics than the wind farm alone would have.

TABLE III
IMPEDANCE AND CAPACITANCE OF THE IEEE 14-BUS SYSTEM FOR EMTP SIMULATIONS

Positive sequence	Negative sequence	Zero sequence
Z_{Line}	Z_{Line}	$3{*}Z_{Line}$
C_{Line}	C_{Line}	$0.5{*}C_{Line}$

IV. Reference Wind Farm Dynamic Analysis Simulations

In this section, the dynamic behaviour of the reference offshore wind farm and the interaction in a typical interconnected electric power test system is analysed. The 14-bus IEEE power system will be used and has been substantially modified for this study.

A. IEEE 14-bus power system modeling

In Fig. 2, the single line diagram of the IEEE 14-bus power system is shown. The proposed reference offshore wind farm has been modelled complying to EMTP simulation requirements. Hence it was necessary to modify the IEEE 14-bus system in order to have a full modelling details as required for electromagnetic transient simulations using this network.

In EMTP-RV, the modelling of the generators is the same for a single-phase (positive-sequence) or for a detailed EMTP power system model. In order to take into account transient and sub-transient phenomena, a two-axis generator model is used. The machines include Automatic Voltage Regulators (AVRs).

The transmission lines of the IEEE 14-bus power system have to be transformed from single-phase positive-sequence elements to three-phase elements. This can be easily done by using the positive sequence, negative and zero sequences of these elements. If Z_{Line} and C_{Line} are the impedance and the capacitance of the line, respectively, the value of the sequence components can be obtained as shown in Table III. The same method is used for transformers for which a tap ratio is added.

Loads are represented by a static constant power load model. The power absorbed by each phase is divided by 3.

A power flow study of the IEEE 14-bus power system has been carried out. From this study, Buses 1 and 2 are production buses whereas buses 9 to 14 are consumption buses. Buses 10 to 14 have low voltage levels. It is characteristic of a radial production power system. This kind of power system has rotor angle and voltage instability issues. In the French case, offshore wind farms will be built and connected at the end of the electrical grid and near consumption sources. Therefore it has been chosen to connect the offshore wind farm to Bus 13 which has the lowest voltage level, to develop some conceptual analogies with the French grid, specially considering the case of Brittany (Western part of France) which is voltage stability constraint.

B. Simulation of a network fault

A simulation of a network fault has been carried out in order to understand the dynamic impact of the reference offshore wind farm on the IEEE 14-bus power system. A three phase fault on Line 24 between buses 2 and 4 occurs at 10 s, and cleared after 100 ms by opening Line 24. Rotor angle

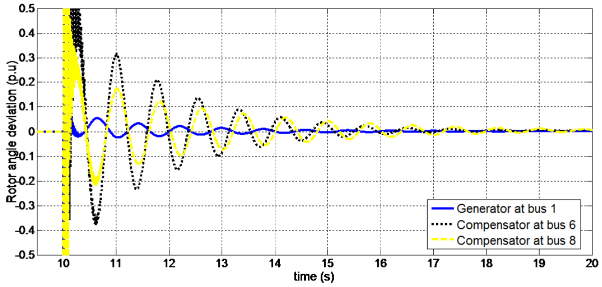

Fig. 13. Rotor angle deviation during the fault no offshore wind farm installed.

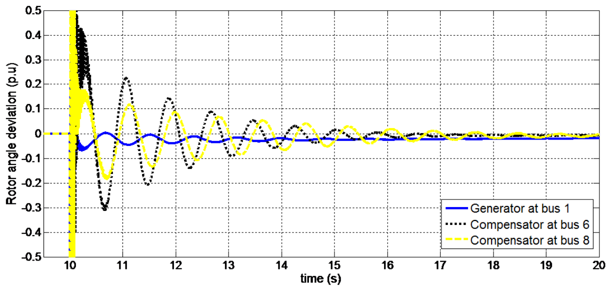

Fig. 14. Rotor angle deviation during the fault with the offshore wind farm.

deviations of Generator 1 and compensators at buses 6 and 8, and active power through the Line 34 between buses 3 and 4 have been recorded.

Figure 13 shows that the generator at Bus 1 oscillates against compensators at buses 6 and 8. It can be inferred that generators (Bus 1 and Bus 2) oscillate against consumption sources (Bus 6 to Bus 14). In Fig. 14, the offshore wind farm has been added, which has improved rotor angle oscillations damping and has created a shift of the rotor angle between the compensator at Bus 6 and compensator at Bus 7. This can be explained by the fact that a production source was added on the consumption side and it creates a shift in the angle of the eigenvectors which is an effect of the addition of damping, see [13]. In Fig. 15, it is confirmed that oscillation damping has been improved and a shift has appeared.

When considering single installations of offshore wind farms, as shown in this study, their inclusion into the network strengthens the electric power system by increasing (small-signal) rotor angle stability and by providing an increase of supplementary reactive power. While wind farms can strengthen the stiffness of power networks, in the case of rotor angle stability, much attention has to be paid to the interaction between the installation of adjacent wind farms which may enter in resonance at high frequencies and excite oscillatory modes which are related to converter control [14].

Moreover, reactive power management will be challenging due to the fact that the offshore wind farms cannot produce constant reactive power. As an offshore wind farm produces renewable wind energy which is by definition an intermittent energy source, the offshore wind farm will be not able to produce either active power or reactive power in sufficient amounts when the wind is null. Therefore reactive and active power management solutions should be used in order to overcome this problem. These power management solutions

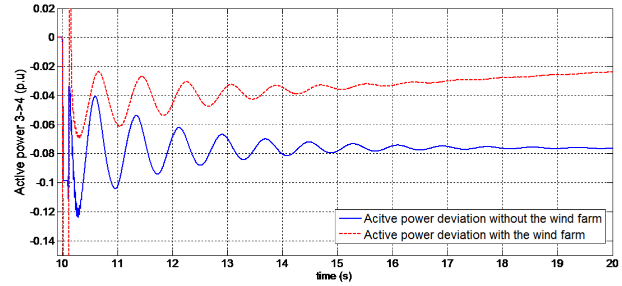

Fig. 15. Active power deviation through Line 34 during the fault.

can be used by integrating storage capacity, consumption management, and other technologies. This challenging issue poses an interesting application and research challenge for the power industry and academia alike.

V. Conclusions and Discussion

This article has presented modelling and a dynamic analysis of a proposed reference offshore wind farm for use in offshore interconnection studies in France. A state of the art review has been carried out and exploited in order to define a reference offshore wind farm. The modelling of this offshore wind farm has been presented and aggregation for interconnection studies has been justified.

Connection studies based on ENTSO-E offshore grid requirements and French TSO classical grid requirements have been carried out. It has been shown that the AC transmission system (submarine cable) can influence the fulfilment of requirements, and therefore the choice of PCC location will be a matter of concern. French TSO grid requirements for offshore producers do not exist yet, however, this study and the reference farm developed can serve as an initial benchmark for important studies that must be carried out to achieve the ambitious plans set forth by the French government.

Simulations on the IEEE 14-bus power system have been realized in order to characterize the dynamic impact of the reference offshore wind farm on this system. The IEEE 14-bus power system has been modified to comply with EMTP modelling requirements. A case study of a three phase fault on a line and its clearing has been presented in this paper. The simulation results show that oscillation damping and power flow has been improved thanks to the installation of the offshore farm. The offshore wind farm provides a relief to the power system by increasing reactive power compensation capabilities. However, due to the fact that offshore wind farms are intermittent energy sources, the challenge is to develop an appropriate solution for reactive and active power management. FACTS, HVDC, storage components and consumption management can be solution to overcome uncertainty issues.

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