Impact of a new Interconnector between France and Great Britain on the continental European transmission grid

Final report

commissioned by

Aquind Limited

20th April 2020

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Content

Abbreviations

AC	Alternating current
CRE	Commission de Régulation de l'Énergie
DC	Direct current
ENTSO-E	European network of transmission system operators for electricity
IFA	Interconnecteur France-Angleterre
RES	Renewable energy sources
TSO	Transmission system operator
TYNDP	Ten-year network development plan
VSC	Voltage source converter

1 Background

Aquind Limited (Aquind) plans to build a direct current (DC) interconnector between France and Great Britain. The new interconnector shall have a net transmission capacity of 2,000 MW. The connection to the French transmission grid shall be established in the substation Barnabos located South-West to the connection point of the already existing Interconnecteur France-Angleterre (IFA) having also a capacity of 2,000 MW.

As part of the 2017 Aquind exemption request, the Commission de Régulation de l'Énergie (CRE) asked Aquind to provide a study concerning the impact of the planned interconnector on the continental European transmission system (in particular the French system including its interconnectors to Great Britain and Belgium). In an e-mail CRE has described the scope of the requested study.

Within that outline CRE asked for investigations regarding the technical repercussions determined by the Aquind interconnector in terms of system stability after an outage in the transmission grid (especially in the transient time period), compliance with network security requirements such as the (n-1)-criterion and the voltage situation in the transmission grid influenced by increasing import/export capability between France and Great Britain. The analyses shall focus on the French 400/225-kV-grid including interconnections with neighbouring systems

In 2017 we supported Aquind by performing qualitative and quantitative assessments regarding the different aspects mentioned before. Due to different developments during the Aquind application process in the last few years, the envisaged commissioning is delayed. Hence, Aquind has requested us to update our study for adjusted target years taking into account relevant changes with respect to network expansion for the target years as well as assumptions regarding conventional generation system (installed capacity and merit order) and renewable energy sources (RES) compared to the assumptions of the 2017 study.

In this report we introduce our approach and the given input data (chapter 3) and discuss the gathered results (chapter 4). In chapter 5 we summarise the main conclusions of our investigation.

2 Company profile

Consentec GmbH is a boutique consultancy based in Aachen, Germany, focusing on economic, regulatory and engineering issues related to energy supply, with a special focus on network planning and operation, security of supply, network and system integration of RES as well as market design and regulation of natural monopolies in the electricity and gas supply sectors. Consentec was founded in 1999 as spin-off of RWTH Aachen University and has a present staff of 18. Dr.-Ing. Wolfgang Fritz and Dr.-Ing. Dipl.-Wirt.-Ing. Christoph Maurer are the Managing Directors.

Consentec supports its clients by consultancy work, technical and economic studies, specialised software solutions, training, and expert reports. Consentec's staff members and founders can draw upon profound knowledge and long-standing professional experience in the field of system engineering and economics of power and gas supply, as well as a comprehensive international contact network to the companies and institutions involved in operation and regulation of the energy supply sector. Our main clients are ministries, regulatory authorities, transmission and distribution network operators, energy suppliers, industry associations, IT providers and equipment manufacturers based in European countries.

On a case-by-case basis we cooperate with reputable academic institutes, consulting and software companies.

3 Approach and database

3.1 Stability constraints

To our understanding this aspect of the required investigations refers to an analysis of the dynamic system behaviour after faults in the vicinity of the converter station.

The assessment of impacts of any fault in the transmission system requires a substantial quantitative analysis in order to derive requirements for the design and set-up of the protection of the DC link and, potentially, network and/or generation facilities in its vicinity. Such an investigation has to be based on a real model of the transmission and generation system (e.g. including actual technical parameters of lines and transformers as well as generator data) and appropriate calculation software.

Typically, such calculations are in the sole responsibility of the TSOs themselves because only they have access to a detailed and a real load flow model of the continental European transmission grid (which is confidential data in possession of the TSOs) and the required calculation software.

Thus, we set the focus on the assessment of faults on the new interconnector and discuss the repercussion on the rest of the transmission system on a qualitative basis.

3.2 Thermal constraints

We possess a load flow model of the continental European transmission system that has been derived from public information sources and hence is free from third parties' intellectual property rights. While the model by principle cannot yield the same level of accuracy as a TSO's model, we are convinced that it is sufficient for the given task, for two reasons. Firstly, the impact assessment is performed by a comparison of the situation with and without the new interconnector, i.e. emphasis is on the incremental effect rather than absolute measures of network loading etc. Secondly, it is reasonable to assume that any relevant impact on the load flow situation (and hence on thermal constraints) can only occur in a geographically limited region around the converter station. The proof of the latter aspect by means of numerical examples is part of our assessment. As regards an analysis of the impact on the regional transmission grid around the converter station, we analysed realistic (also including extreme) cases of network utilisation. In the 2017 scope of work CRE requested an assessment of the first five years after commissioning of the new interconnector. This is covered by numerically analysing the target years 2025 and 2030, assuming a linear progression in this timeframe.

Figure 3.1 illustrates how input data and calculation steps intertwine.

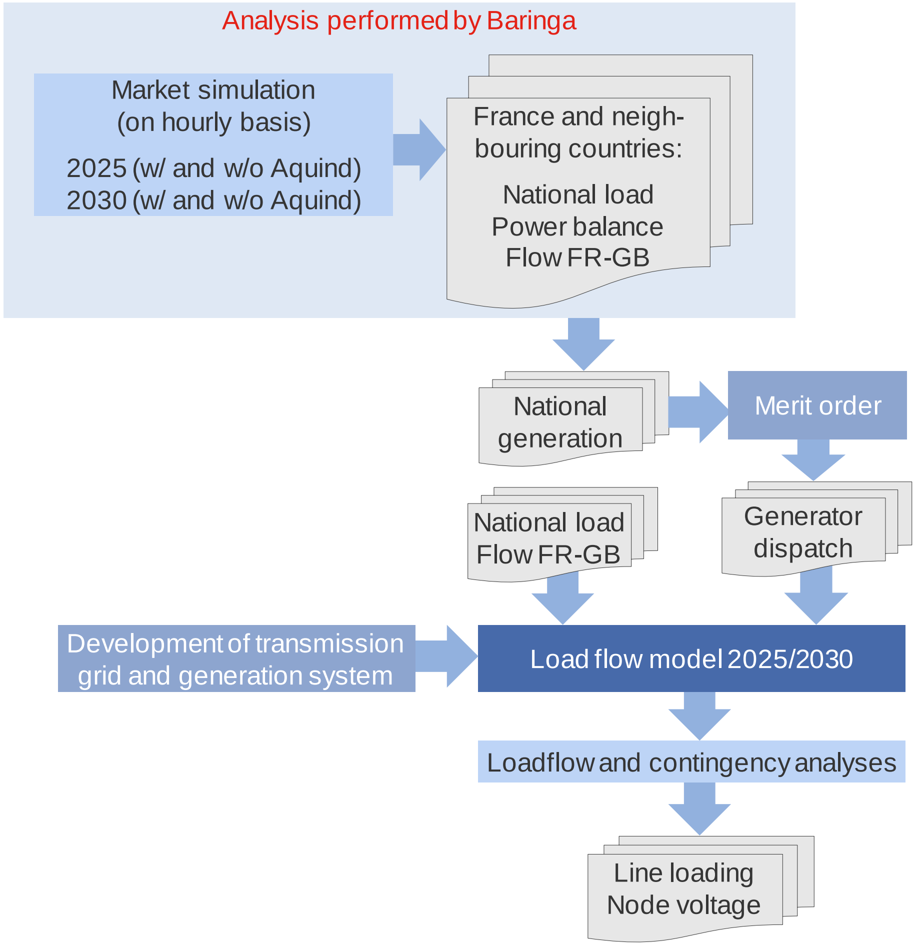

Figure 3.1: Workflow for quantitative assessment

For both target years we set up our grid model according to official network development plans (in particular, the Ten-Year Network Development Plan (TYNDP) 2018 published by ENTSO-E) in order to reflect the respective situations. Based on the given progress of planning and commissioning, we considered the following projects when modelling the respective network topology for 2025 and 2030:

Network expansion until 2025:

- Uprating the existing 225 kV double circuit overhead line Genissiat (FR) - Verbois (CH)
- Reconductoring the existing double-circuit 400 kV cross-border line between Lille (Avelin/Mastaing, FR) - Avelgem (BE) - Zomergem (Horta, BE) with High Temperature Low Sag conductors
- Replacing the conductors of the double circuit 400 kV overhead line between the substations of Horta (BE) and Mercator (BE) with high performance conductors
- Operation of a second circuit at 400 kV OHL Muhlbach (FR) – Eichstetten (DE), instead of the currently operated circuit Eichstetten (DE) – Vogelgrun (FR) at 225 kV and reinforcement of the existing circuit at 400 kV OHL Muhlbach - Eichstetten
- IFA2 (DC interconnector FR-GB)
- FabLink (DC interconnector FR-GB)
- ElecLink (DC interconnector FR-GB)

- DC interconnector FR-IT
- ALEGrO (DC interconnector BE-DE)

Network expansion between 2025 and 2030:

- New double-circuit 400 kV overhead line substituting to the existing 400 kV single circuit line between Rueyres (FR) and La Gaudière (FR)
- Upgrade of the existing overhead line between the substations Ensdorf, Uchtelfangen and Vigy (implementation of High Temperature Low Sag (HTLS) conductors or a reconstruction of the tie-line in the existing route)
- Celtic Interconnector (DC interconnector FR-IE)

As the number of extension projects for the AC transmission grid, in particular within the relevant area around the converter station in France is rather small, the main development until 2025 and between 2025 and 2030 relates to national demand and the generation system.

The generation system assumed for the respective target year has been derived from the TYNDP scenarios “2025 BEST” (BEST = best estimate) and “2030 ST” (ST = sustainable transition), respectively.

With respect to the development of the French generation system, being the most relevant system for the investigations, in both target years there is no coal fired generation anymore and the nuclear power plant in Fessenheim is assumed to be shut down before 2025.

For 2025 this results in an installed capacity of nuclear power plants of around 52 GW. As regards RES capacity in France, we assumed almost 30 GW of wind energy (of which 3.5 GW are offshore, where the connection points to the grid have been derived from public information regarding the first two tendering rounds issued by the French government in 2011 and 2013[1]) and about 21.5 GW of photovoltaic units to be installed until 2025.

Especially for the French generation system, the TYNDP scenario expects significant changes between 2025 and 2030. Changes that have impact on the load flows in the transmission grid are the decommissioning of about 15 GW of nuclear power plants and the simultaneous increase of installed RES of 23.5 GW in total (+10 GW wind onshore, +3.5 GW wind offshore and +10 GW solar PV). While the additional RES generation capacity is connected to the grid according to the regional distribution applied for 2025, the nuclear generation decrease is modelled on unit level taking into account the commissioning date of the respective power plant. This means, that the oldest units with an installed capacity of 15 GW in total are taken out of the model for the analyses of target year 2030.

The network situations to be considered are described by national load and power balance, in particular for France and neighbouring countries, and the flows on the DC connections with Great Britain that are already existing or assumed to be in operation for the respective target years (i.e. IFA, IFA2, ElecLink, FabLink and Aquind). All required data has been provided by Baringa, an advisor to Aquind Limited.

For each considered situation selected out of the hourly based market results (5 market situations per target year taking into account the two cases with and without Aquind, i.e. 20 situations in total) we derived the respective national power balances from the load and generation

[1] As the planned offshore wind parks are widely spread over the North-Western coast, the impact of line loadings in the vicinity of the converter station Barnabos is highly limited.

figures. In order to calculate precise line loadings, we broke down the national generation into a generator dispatch on the basis of a power plant data base (i.e. a merit order approach taking into account parameters such as fuel type, year of construction and efficiency factor resulting in unit-specific marginal costs) and entered these generation data into the grid model.

By means of load flow and contingency analysis we determined the impact of the new interconnector on pre and post contingency line loadings and identified potential cases (situations and locations) of overloading and assessed different ways of remedies (e.g. topology changes, redispatch or network reinforcement).

In addition to that, we analysed the export/import capabilities in case of a double circuit outage of one of the 400-kV-connections to Barnabos.

3.3 Voltage constraints

While thermal constraints could be restricting the intended use of the new interconnector for exchanging power between France and Great Britain, voltage issues would rather be a side effect. Moreover, the impact of the interconnector on the voltage situation could be controlled by the choice of technology of the converter stations – which as of now will be designed based on the voltage source converter (VSC) technology. Consequently, we treated this aspect by conceptual argumentation rather than substantial numerical simulation.

4 Results

4.1 Stability constraints

Faults on a DC interconnection are comparable to the loss of load or generation in the connected systems leading to an increase or decrease of frequency in the transient time period. Such cases are already covered on system level by provision of reserve power and emergency plans. As the possible impact of a fault of the DC line under consideration is far below other critical incidents (like faults in major power plants) we do not expect any critical consequences regarding impacts on system balance.

Another important question is whether disturbances like a loss of the DC link itself or faults of lines or transformers in its vicinity may result in oscillations within the system which might seriously endanger system security. As regards the generators connected to the AC grid, automatic protection systems are installed in order to prevent the equipment from damage. The same accounts for converter stations of DC links which have to consider critical faults for the design of their protection systems.

Further potential repercussions caused by technical failures in the converters of a DC link such as upper harmonics or overvoltage in the AC system after a short circuit can be resolved with automatic control technology or using earthing equipment at both ends of the DC line.

Hence, negative influences on the AC power system due to faults on the DC connection can be mostly avoided assuming a proper use of existing technology and protection settings.

There are no (severe) incidents regarding the continental European transmission system in the past to be traced back to faults on DC interconnections, such that it is very likely that any repercussions of faults on new interconnections (such as Aquind) on the rest of the power system can be effectively avoided. This is also confirmed by the network situation in the area of the Barnabos substation. The highly meshed 400-kV-network with low interior impedances as well as the existence of large generators (nuclear plants in Penly, Paluel and Flamanville) in the vicinity of this substation lead to a comparatively high short-circuit power in Barnabos compared to typical 400 kV substations. As short-circuit power is a good indicator for a system's resistance against disturbances in the transient time frame, we would not expect stability concerns to be a major issue here.

4.2 Thermal constraints

4.2.1 Overview of grid parameters and generation system in relevant area

In order to determine drivers for the network utilisation in the relevant network region, we analysed the grid topology as well as the location and technology power plants.

The 400-kV-network in the area close to the converter station for the DC link is dense and provides a high amount of transport capacity. This is mainly driven by the necessity to transmit the power infeed of the nuclear power plants located in Penly and Paluel with an installed generation capacity of about 2,800 MW or 5,600 MW, respectively, i.e. 8,400 MW in total. Paluel is connected to the substation Barnabos by four 400-kV-circuits with about 8,000 MW of transmission capacity. Penly is connected to the substations Barnabos and Argoeuvres each with two 400-kV-circuits having about 3,600 MW of transmission capacity. There is no direct connection to the 225-kV-grid in the Barnabos substation.

Thus, the grids are mostly decoupled such that the surrounding 225-kV-grid is mainly of distribution nature while the 400-kV-grid has mainly transmission function. The power infeed of the thermal power plants in Le Havre (600 MW) is used to supply the demand of the large industrial area located at the Le Havre harbour while power plants in Amfard and Chapelle d'Arblay (both with installed capacities less than 100 MW) are connected to the 225-kV-grid located in South-West direction to Barnabos. Hence, the impact of generation infeed in these units on the 400-kV-line loading in the relevant region is highly limited.

At the substation in Barnabos the power is transmitted via a 400 kV double-circuit via Penly to Argoeuves in North-East direction. Further four 400 kV double-circuits connect Barnabos with the substations Remise and Terrier in South-East direction. It is also supplied with a 400 kV double circuit from the South-West (substation Rougemontier) while another 400 kV double circuit to the South connects 400-kV- and 225-kV-grids at La Vaupaliere. Each circuit can transmit about 1,800 MW, i.e. Barnabos is connected to approximately 18,000 MW of transmission capacity (Figure 4.1).

Figure 4.1: Transmission grid and generation facilities in vicinity of French converter station Barnabos (source: ENTSO-E)

As the nuclear power plants in Penly and Paluel as well as the one in Flamanville (in the west of the displayed network region) can be assumed to be in operation in every demand situation, it can be concluded that the network utilisation is more or less determined how load flows originated by the amount and the regional distribution of load and generation together with the operation of the DC links (i.e. flows from or to Great Britain) add up or cancel each other out, respectively.[2]

Thus, in a situation without the new interconnection between France and Great Britain power infeed up to 16,600 MW (11,200 MW generated in the nuclear power plants plus 5,400 MW via

[2] The mentioned nuclear power plants are assumed to be still operative in 2030.

IFA, IFA2, ElecLink and FabLink) has to be transported in the network region of the Northern French coast. With Aquind the transmission requirements reach about 18,600 MW.

4.2.2 Considered scenarios

We analysed several different market situations in order to cover a realistic bandwidth of network utilisation scenarios. These scenarios also contain rather extreme (but still realistic) cases leading to potentially high line loadings. Scenarios 1 and 2 reflect situations with peak/high load in France combined with a high demand of energy imports but different flow directions between France and Great Britain. Scenario 3 is a situation with high demand but more or less neutral power balance without significant flows between France and Great Britain. Scenarios 4 and 5 represent medium load situations with high French export capacities reflected by a clear positive power balance resulting, amongst others, to export flows from France to Great Britain.

Figure 4.2 (target year 2025) and Figure 4.3 (target year 2030) introduce the significant parameters of the considered scenarios.

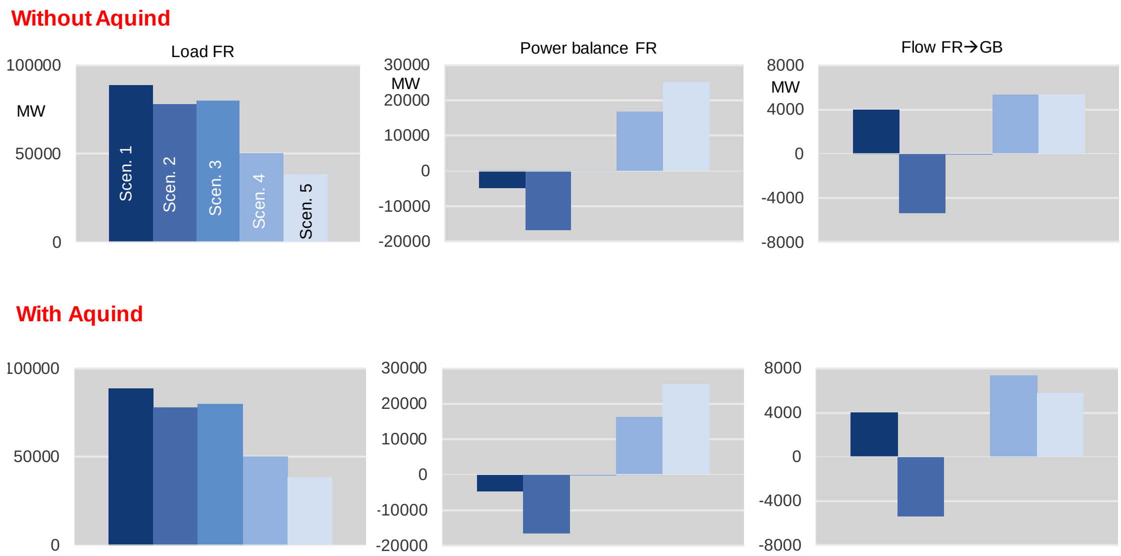

*Figure 4.2: Main parameters of considered scenario for **target year 2025***

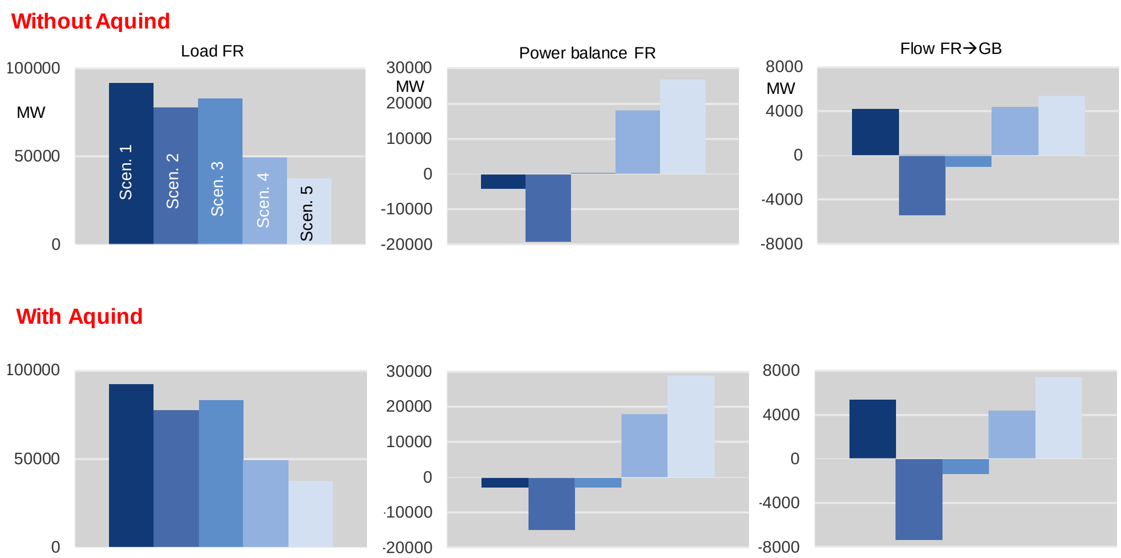

*Figure 4.3: Main parameters of considered scenario for **target year 2030***

4.2.3 Contingency analysis

Generally, our analyses show that the impact of the new interconnector on the flows in (n-1)-case decreases rapidly with the distance between the observed line and the converter station. Accordingly, high loading in the French grid outside the closer vicinity of the converter station (including for instance the French-Belgian border) is not notably originated by the new DC link. Thus, the focus in the following presentation of results is set on the 400-kV- and 225-kV-lines connected to the substations Barnabos, Rougemontier, Penly, Tilleul and Terrier.

Furthermore, we found out that the outage of any interconnection between France and Great Britain does not cause problems in terms of network loading or available generation capacity.[3]

In the following, we discuss the impact of the market situation, the target year and the existence of Aquind on the network loading, separately.

Impact of market situation

In order to assess the impact of the market situation on the network loading, we calculated the line-specific maximum (n-1)-loading of selected 400- and 225-kV-lines in the relevant network region. The results given in Figure 4.4 refer to the target year 2025 without Aquind.

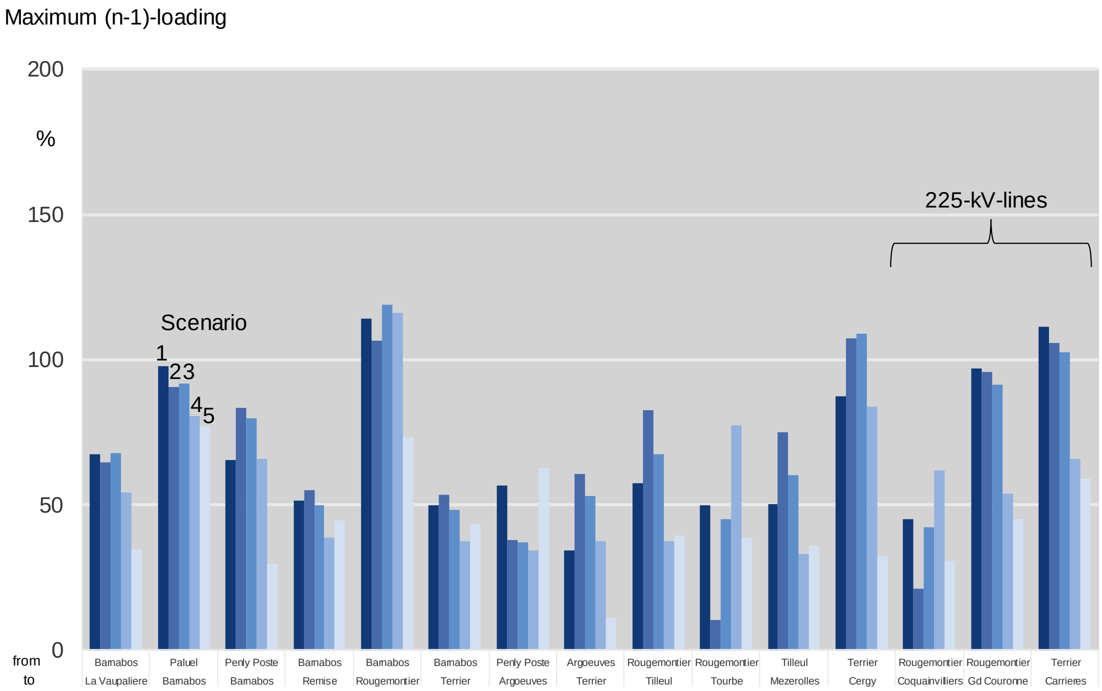

Figure 4.4: (n-1)-loading of selected lines for considered market situations (target year 2025 without Aquind)

In scenarios 4 and 5 (where flows on the interconnection between France and Great Britain are in direction Great Britain) the (n-1)-loading on the considered lines is always below 100 % except for the line Barnabos→Rougemontier (116 %). In these situations, the load in France is rather

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[3] An outage of the DC link(s) would cause a generation deficit or surplus in the connected system depending on the flow direction on the interconnection. This analysis focused on the French system and investigated whether the required generation increase/decrease can be performed with the generation capacities in the respective situation and verified the load flow situation after modifying the generation dispatch in France according to the assumed merit order.

medium or low, while the total export of France increases from scenario 4 to 5. The consequences of these conditions are that load flows to the South originated to a notable extent by the infeed of the nuclear power plants are partly displaced by load flows due to exports towards Belgium, The Netherlands, Germany and Great Britain. This is also underlined by the fact that line loadings decrease on almost all of the observed lines with higher French exports. Thus, export situations turn out to be rather uncritical with respect to the risk of network overloading in the relevant area.

In scenarios 1 to 3 France has a high load combined either with an import situation as in scenarios 1 and 2 (in scenario 2 energy is also imported from Great Britain) or a neutral power balance as in scenario 3. In these scenarios, the loading of the following lines exceeds the 100%-limit:

- Scenario 1:
  - 400-kV-line Barnabos→Rougemontier (114 %)
  - 225-kV-line Terrier→Carrieres (111 %)
- Scenario 2:
  - 400-kV-line Barnabos→Rougemontier (107 %)
  - 400-kV-line Terrier→Cergy (107 %)
  - 225-kV-line Terrier→Carrieres (106 %)
- Scenario 3:
  - 400-kV-line Barnabos→Rougemontier (119 %)
  - 400-kV-line Terrier→Cergy (109 %)
  - 225-kV-line Terrier→Carrieres (103 %)

For scenarios 1 and 2 the line loadings are the consequence of the total import situation of France when load flows from Belgium and Germany add up with the infeed of the nuclear power plants located at the Northern French border. This is even emphasized in case of France is importing from Great Britain (cf. scenario 2). Although some lines in the closer vicinity of the Barnabos substation are slightly relieved by the flows out of the converter stations (which have partly flow contributions in opposite direction compared to those flow shares originated by the nuclear power plants infeed), a number of lines have higher loading with import from Great Britain because load flow contributions with identical direction unify a few substations towards the South (in particular lines Argoeuves→Terrier, Terrier→Cergy, Rougemontier→Tilleul and Tilleul→Mezerolles).

With respect to scenario 3 the load flow pattern results from a high French generation infeed to cover the also high demand as imports from and exports to surrounding level out each other almost completely. Furthermore, there are no flows between France and Great Britain, such that the relieving effect on some of the lines in case of importing flows from Great Britain over the DC links mentioned above do not arise and causing the loadings above 100 % on the 3 indicated lines. Compared to the situation in scenario 2 where flows increase towards the South due to imports from Great Britain the respective line loadings are lower in scenario 3 because regional effects resulting from high demand in combination with high domestic generation infeed are more substantial than directional load flows that are typical for import situations.

These considerations lead to the conclusion that especially in case of French import from Great Britain critical (n-1)-loadings in the transmission grid may occur.

For all lines being overloaded the loss of the parallel circuit constitutes the critical outage. Thus, we further analysed the line loadings in case that after the outage of one circuit the second system is switched off (be it automatically by a line protection setting or manually as counter-measure). In this case the network loading in the relevant region is below 100% (for the considered scenarios and the given input database)[4]. This seems to be reasonable as even in todays' framework, situations are likely where Penly, Paluel and Framanville have maximum output and at the same time the existing DC links are fully used in direction France. Hence, the present transmission grid has to be capable to cover such network situations[5].

Dependency on target year

Due to the development of the transmission grid as well as the generation system in Europe, the load flow situations could change in the time period between 2025 and 2030. In order to highlight the effect of the considered target year, we analysed the maximum (n-1)-loadings for scenario 2 (maximum French import) for the case without Aquind.

The results for this scenario show a rather weak dependency of the network loading on the target year (Figure 4.5), as in the relevant network region there are no changes in network topology. The resulting (n-1)-loadings on the monitored lines for 2030 are either slightly smaller or higher due to a reduction of conventional generation which is mainly replaced by an increased share of RES compared to 2025 leading to a regional shift of actual generation infeed.

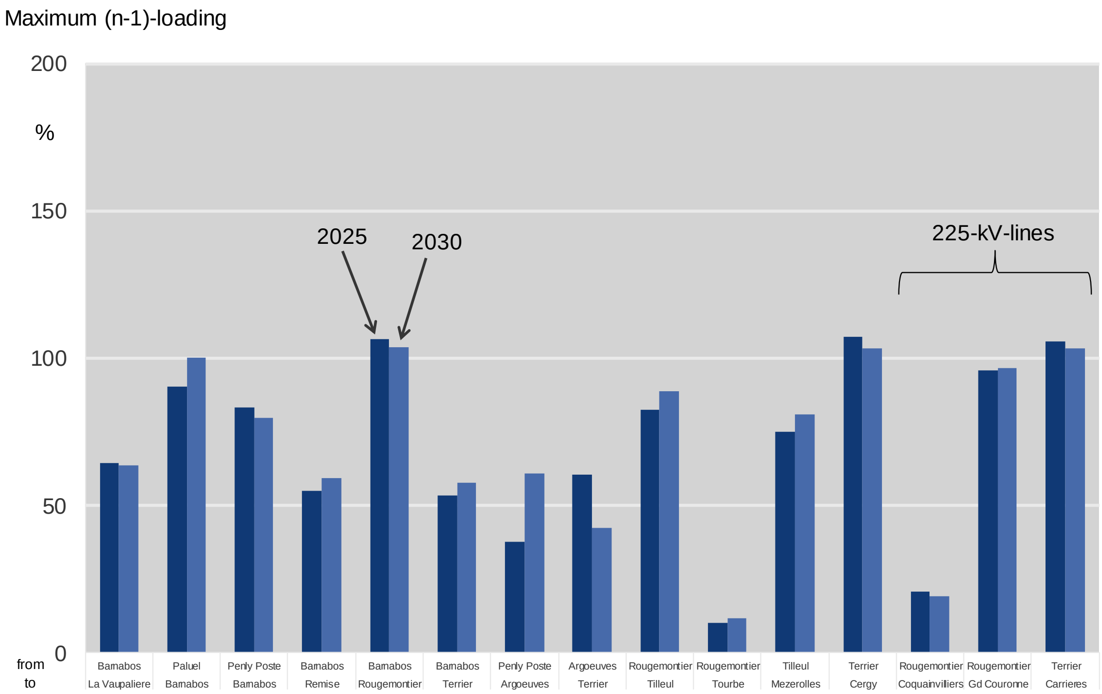

Figure 4.5: (n-1)-loading of selected lines for considered target years (scenario 2 without Aquind)

[4] This behaviour could be observed also for the situation with the new interconnector.

[5] Note that a similar solution as described above could also be reached by switching measures which will limit the influence of the infeed of the nuclear power plants especially on the lines Barnabos→Rougemontier and Terrier→Cergy

Impact of Aquind interconnector

The planned new interconnector Aquind shall have a capacity of 2,000 MW. As discussed in the sections above, in a situation without Aquind power infeed of already 16,600 MW has to be transported. With Aquind the transmission requirements indeed increase to about 18,600 MW but stay in the same dimension.

For scenario 2 (maximum French import) in target year 2030, the (n-1)-loadings on the lines connected to substations south to Barnabos further increases as expected due to an increase of imports from Great Britain by 2,000 MW for the case with Aquind (Figure 4.6).

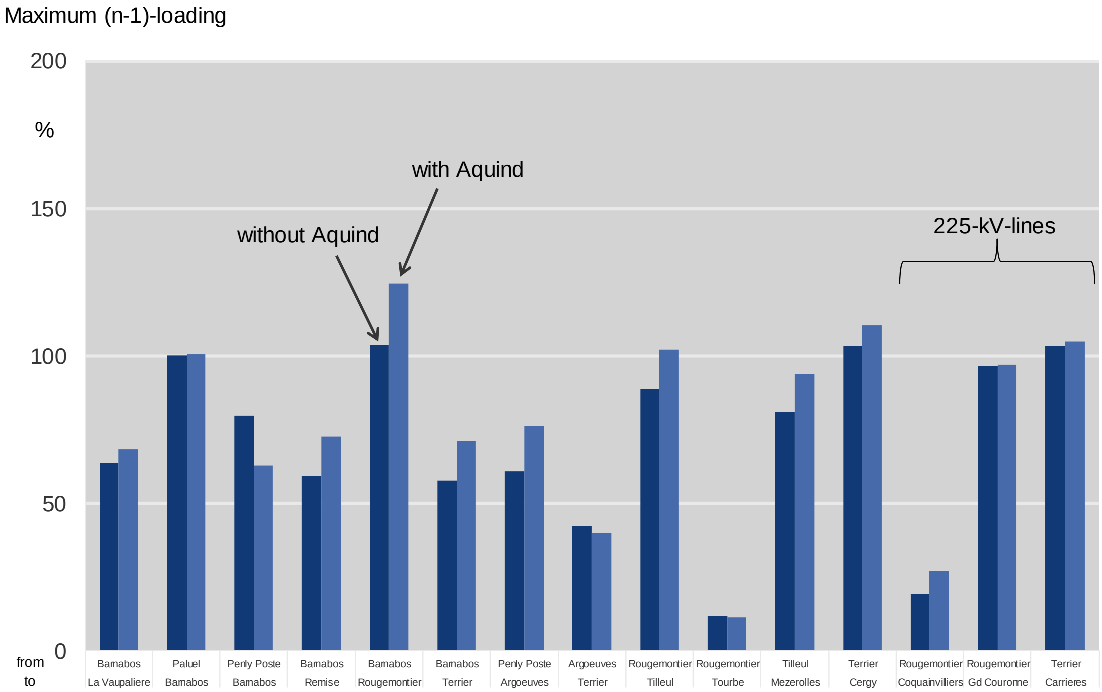

Figure 4.6: (n-1)-loading of selected lines for case with and without Aquind (target year 2030, scenario 2)

In the case without Aquind there are 3 lines with a (n-1)-loading above 100 %, namely Barnabos→Rougemontier (104 %), Terrier→Cergy (103 %) and Terrier→Carrieres (104 %). For the case with Aquind the (n-1)-loading increases on the monitored lines between 1 and 20 % such that the maximum (n-1)-loading of these lines is around 125 % (Barnabos→Rougemontier). Some of the lines are even relieved in the case of additional import from Great Britain over the Aquind interconnector.

Only for the line Rougemontier →Tilleul the additional loading of about 14 % in the case with Aquind causes an additional overload compared to the situation without the new interconnector (but with limited criticality as the resulting (n-1)-loading reaches only about 102 %).

However, the amount of remaining overload as well as the additional loading on the different lines caused by Aquind (partly) used in import direction turn out to be rather moderate. Thus, for the four lines having (n-1)-loadings above 100% the network loading in the relevant region stays below 100% in case that after the outage of one circuit the second system is switched off (be it automatically by a line protection setting or manually as countermeasure), as already discussed in the previous sections. Furthermore, the probability of such situations to occur is not notably influenced in case that Aquind is realised. Thus, in case of high (n-1)-loadings with

Aquind countermeasures as in the case without Aquind or even today (mainly network topology modifications by switching measures) are likely taken, such that the necessity to modify the generation dispatch (so-called “redispatch”) is not originated by building the new DC interconnection.

Although the flows may increase on some lines in some of the considered scenarios, the realisation of the new interconnection does not cause additional critical network situations and overload compared to the situation without Aquind.

Note, that the nuclear power plants in Paluel and Penly are assumed to be operative in 2030 for the performed analyses. As the infeed of these generation units highly affect the line loading in the relevant area of the transmission grid, potential overload would significantly reduce in case that one or both of the mentioned power plants would be included in the expected decommissioning of 15 GW nuclear generation capacities until 2030.

In situations with France exporting to Great Britain, such as in scenario 4 for target year 2025, the realisation of Aquind and its usage to further increase export to Great Britain results in an overall reduction of (n-1)-loadings on the monitored lines as expected (Figure 4.7).

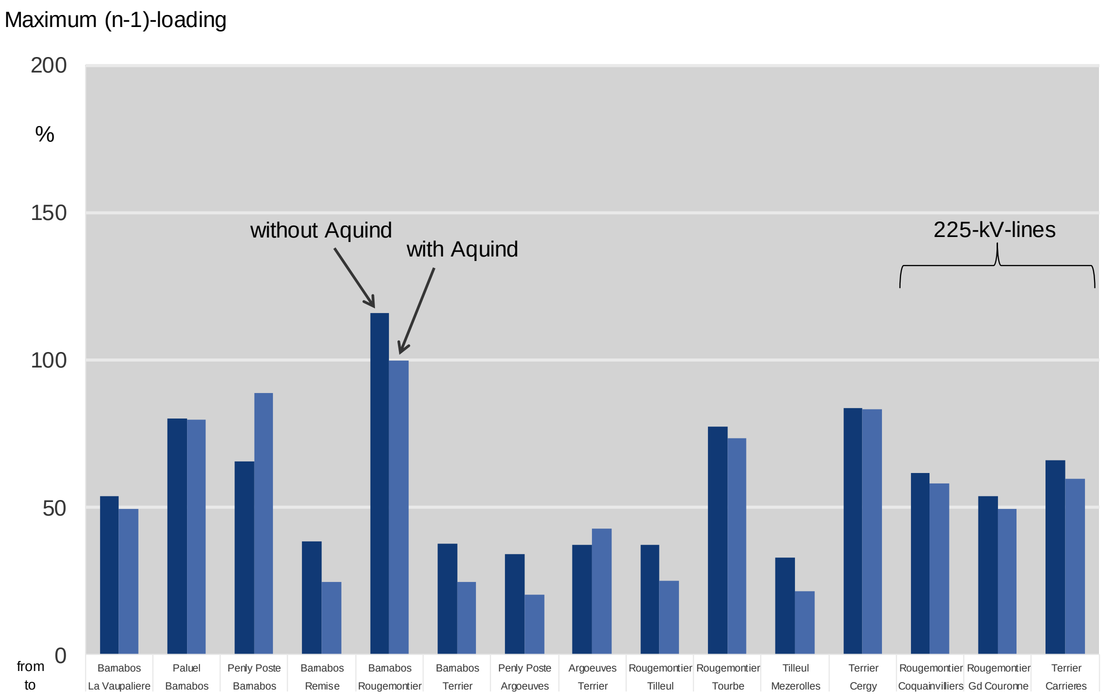

Figure 4.7: *(n-1)-loading of selected lines for case with and without Aquind (target year 2025, scenario 4)*

4.2.4 Import/export usability between France and Great Britain

In addition to analysing the impact of different drivers for potentially high network loading, we investigated a specific situation with a weakened 400-kV-grid connected to the converter station Barnabos against the background of the usability of import/export capacity between France and Great Britain.

Relevant in this context is a case where the double-circuit Barnabos-Rougemontier is out of operation (e.g. for maintenance reasons).

Assuming the conditions in scenario 2 of target year 2030 the transmission grid would be substantially overloaded in case of an outage on the 400 kV double circuit Terrier-Cergy. In this exemplary calculation we identified an overload of about 1,100 MW on the remaining system on the aforementioned line.

Consequently, the transmission capacity between France and Great Britain or the energy infeed of the nuclear power plant in Paluel and/or Penly might be reduced in order to fulfil network security requirements in situations where both circuits of Barnabos-Rougemontier are affected by planned or unplanned outages[6]. In the aforementioned example a reduction of import capacity from Great Britain of more than 7,000 MW would be necessary. Similar reliving effects would be created by redispatch measures inter alia reducing the energy infeed of Paluel and Penly by about 8,500 MW in total. (Note that relieving effects of network topology measures such as opening of busbar couplings have not been taken into account.)

As such cases are rather rare[7] and large maintenance work is normally coordinated in order to avoid potentially critical network situations, the aforementioned countermeasures would be more or less taken only in exceptional cases. It is important to mention, however, that with Aquind the situation changes only gradually. Hence, (n-1)-overloading in the described situation will also occur without Aquind and similar measures might be necessary even today.

4.3 Voltage constraints

The voltage level at the substations mainly depends on the overall loading of the transmission grid, i.e. the higher the line loading, the higher the voltage drop between beginning and end of the line. In order to ensure an appropriate voltage level in each situation, the output of reactive power in the generation units is controlled according to the respective conditions. In addition to that, the network topology influences the voltage level because the network elements in operation consume reactive power and the electrical distance between a substation and reactive power source (i.e. mostly power plants) is affected.

In the context of a DC interconnection, an appropriate voltage level at the converter station is required due to the demand of reactive power for commutation, especially as regards the usual use of line-commutated converters with thyristors as switching elements, such as the IFA.

With respect to the substation Barnabos being the planned location for the Aquind converter station, the voltage level can be effectively controlled by the nuclear power plants in Penly and Paluel. In addition to that, Aquind will be designed using the VSC technology, i.e. that an appropriate voltage level in order to provide the required amount of reactive power for the converters is ensured by the envisaged converter design even in cases of a weakened 400 kV grid in the vicinity of the converter station as potentially increasing voltage drops are automatically covered by the converter equipment.

Furthermore, with the VSC design the new interconnector can contribute positively to improve the voltage profile in this network region due to the controllable infeed/consumption of reactive power, especially in the case of a planned or unplanned outage of the surrounding nuclear power plants.

[6] Note that a potential overload would significantly reduce in case that the power plants in Paluel and/or Penly would be included in the excepted decommissioning of 15 GW nuclear generation capacities until 2030.

[7] As maintenance usually affects only one circuit of a double-circuit line, we assume that the discussed network situation could occur once in a time period of several years at the utmost

5 Conclusions

In our study regarding the impact of a new DC link between France and Great Britain on the continental European transmission system we analysed different aspects of technical constraints. The main findings derived from the results are:

- Repercussions of faults on the new interconnector including the converter stations can be effectively avoided by a proper use of protection technology. An assessment of the impact of faults beyond the interconnector is subject to more detailed studies.
- The network loading is driven by the load situation and the overall power balance in France as well as the flow direction between France and Great Britain. The highest line loadings occur for the case of French import from Great Britain. The impact of the considered target year is moderate to low.
- Line loadings above 100% in the (n-1)-case can occur – depending on switching state – on the 400-kV-lines Barnabos→Rougemontier and Terrier→Cergy and the 225-kV-line Terrier→Carrieres. For all lines the outage of the parallel circuit constitutes the critical topology. With the new interconnection the maximum (n-1)-loading can increase by about 20 % without causing additional overload of notable extent in the transmission grid. However, assuming that after the outage of one circuit the second circuit is switched off (be it automatically by a line protection setting or manually as countermeasure) a situation occurs where the network loading in the relevant region is below 100% regardless of the considered case with or without Aquind.
- In the case of a planned or unplanned outage of both circuits on the 400-kV-line Barnabos-Rougemontier the transmission capacity between France and Great Britain or the infeed of the nuclear power plants in Paluel and/or Penly has possibly to be reduced (in both cases with and without Aquind) in order ensure network security requirements. Based on results of exemplary calculations, such countermeasures might be substantial (more than 7,000 MW reduction of import capacity to France from Great Britain, or about 8,500 MW of redispatched power, respectively). In case that the envisaged decommissioning of nuclear power plants in France (about 15 GW until 2030) would comprise the generation units in Paluel and/or Penly (which are assumed to be in operation for both target years), the magnitude of necessary countermeasures would be significantly reduced.
- The voltage at the substation Barnabos can be effectively controlled by the nuclear power-plant in the vicinity of the substation such that the provision of reactive power required for commutation in the converters of the DC interconnection is ensured, regardless of the converter technology. As Aquind will be designed using the VSC technology, an appropriate voltage level at Barnabos is automatically adjusted by the envisaged converter design even in cases of a weakened 400 kV grid in the vicinity of the converter station. In particular, the new interconnector would be beneficial with respect to the voltage profile in this network region due to the controllable infeed/consumption of reactive power, especially in the case of a planned or unplanned outage of the surrounding nuclear power plants.

We conclude that the realisation of the planned new DC interconnection between France and Great Britain has no severe negative impact on the continental European transmission system concerning the aspects considered in this study. Any problems that might arise could be managed by the design of Aquind and the respective converter stations itself. In particular, the realisation of Aquind would not cause additional investments in the transmission grid (for instance in order to restore the fulfilment of network security requirements).