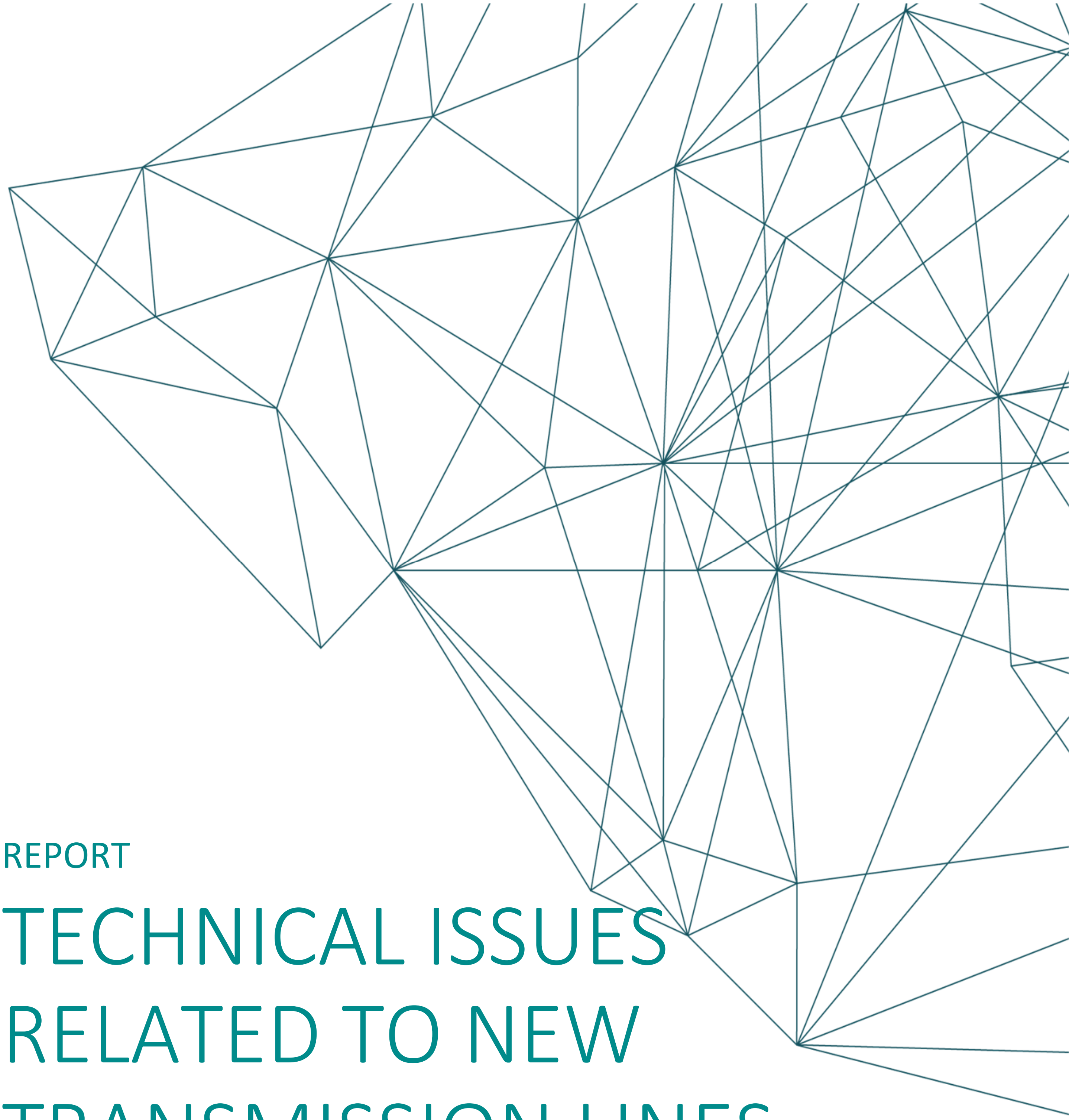

REPORT

TECHNICAL ISSUES RELATED TO NEW TRANSMISSION LINES IN DENMARK

West Coast Line from German border to Endrup and Endrup-Idomlund

ENERGINET

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Glossary – words and abbreviations

Word	Abbreviation	Description
Circuit		An element of the transmission grid that carries electrical power
Combined grid solution	CGS	HVDC link part of the Krieger Flak grid connection concept
Contingency		The unexpected failure or outage of a grid element, such as a transmission line or an HVDC link
Distribution system operator	DSO	
Extra high voltage	EHV	Transmission voltage levels above 300 kV
Environmental impact assessment	EIA	The assessment of the environmental consequences of a project
Energinet		Transmission system operator in Denmark
Gas-insulated transmission line	GIL	
Gas-insulated switchgear	GIS	
High voltage alternating current	HVAC	
High voltage direct current	HVDC	
Interconnector		A transmission line that connect the Danish market to Europe and facilitate trade of electricity between markets
Line commutated converters	LCC	
Million Danish krone	mDKK	Official currency of Denmark, Greenland and the Faroe Islands
Modular multi-level converter	MMC	
N-1 principle	N-1	The rule according to which the grid elements remaining in operation within a TSO's control area after occurrence of a contingency are capable of accommodating the new operational situation without violating operational security limits
Overhead line	OHL	
Photovoltaic	PV	Energy generation involving converting solar energy into direct current electricity using semiconducting materials
Polyethylene	PE	
Phase-shifting transformers	PST	A grid component employed to control the flow of active power
Reinforcement		The required upgrade or expansion of the transmission grid in order to accommodate consumption or generation. Reinforcement includes transmission lines, transformers and substations

Sulphur hexa fluoride	SF_6	An inorganic, greenhouse gas used as an electrical insulator in various electrical components
Sheath voltage limiters	SVL	
TenneT TSO GmbH		System operator in Germany
Transmission grid		A meshed grid of transmission lines (400 kV, 220 kV, 150 kV and 132 kV)
Transmission line		A transmission circuit in the form of an overhead line (OHL) or an underground cable (UGC)
Transmission system operator	TSO	
Underground cable	UGC	
Voltage source converter	VSC	
Cross-linked polyethylene	XLPE	A form of polyethylene with cross-links used for cable insulation

Substations:
EDR – Substation Endrup
IDU – Substation Idomlund
REV – Substation Revsing
STS – Substation Stovstrup
KLIX – Substation Klixbüll (Northern Germany)

Summary with background and conclusion

Background

In December 2015, Energinet sought the permission of the Minister of Energy, Utilities and Climate to establish 400 kV overhead lines between Endrup and Idomlund, and between Endrup and the Danish-German border.

In October 2017, the Minister approved the two projects, and Energinet notified the Danish Environmental Protection Agency of the projects in March 2018. The first public hearing phase of the EIA process ran from 9 April to 9 May 2018, and a series of public meetings were held at which the projects were presented as was the political agreement from November 2016 which states that, in general, 400 kV transmission lines are to be established as overhead lines.

Based on feedback from local residents in the affected areas along the route of the proposed transmission line, the Minister requested Energinet in June 2018, to prepare a technical report detailing, for example the share of underground cabling that can be utilized for the new transmission line. The aim is to find a solution that limits the environmental impact and alleviate any public concerns as much as possible. The Minister requested that Energinet discuss the following options with reference to the approved 400 kV overhead line solution as a reference (Alternative A):

- The approved 400 kV overhead line solution – with an increased cable share without the need for establishing additional compensation stations (Alternative B)
- The approved 400 kV overhead line solution – with an increased cable share and resulting need for establishing additional compensation stations (Alternative C)
- Full underground cabling of the 400 kV connection (Alternative D)
- Perspectives for using 150 kV or 220 kV cable installations with full underground cabling (Alternative E)
- Perspectives for using high-voltage direct current (HVDC) connections with the laying of necessary cable installations underground or offshore (Alternative F)

Overall conclusion

For the Idomlund-Endrup and Endrup-German border connections, 400 kV underground cables can be used to a limited extent, but long sections of underground cabling will entail considerable risks and may potentially compromise Denmark's security of supply.

The report shows a risk of voltage distortion, also known as noise, which exceeds permissible limits in large parts of the transmission grid. The implication of this is shortened lifetime and miss-operation in electricity grid components and consumers’ electrical appliances.

In connection with the two original 400 kV projects between Idomlund-Endrup and Endrup-German border, a maximum of 10 % underground cabling was assumed for the full route, equalling to approximately 17 km. The report concludes that this share can be increased to up to 15 %, equalling approximately 26 km of the route. Although not desirable for technical reasons, it is envisaged that this could be achieved with the use of:

- Using cables with extra high transmission capacity – for example aluminium cables with very large conductor cross sections. However, very little experience of use of this cable type exists worldwide. Using large cables and switching from two parallel cable installations to one cable installation reduces the amount (length) of cables and thereby the issues regarding voltage distortion.
- Installing filters in the 400 kV grid to mitigate the negative impact of underground cabling.

Underground cabling of the 400 kV route to above 15 % would, regardless of cable type or application of filters, increase system complexity and up risk levels considerably. This is because of the requirement for the installation of many new filters, compensation devices and other components in the electricity grid to mitigate the negative impact of long underground cable sections. Solutions would involve untested controls and technology when taking into account the scope required, increasing the risk of faults and outages.

Alternative solutions such as the use 150 kV or 220 kV cables, HVDC-connections, offshore connections and gas-insulated transmission lines all involve significant risks and fail to meet Denmark's requirements for energy transport. Thus, these solutions do not constitute alternatives to the implementation of the current projects in Western and Southern Jutland as 400 kV overhead lines.

Conclusions on alternative solutions B, C, D, E and F

Up to 15 per cent of underground cabling for sections:

Underground cabling at 400 kV is possible for up to 15 % of the total route, as described in Alternative B. A larger cable share as in alternatives C and D - introduces voltage distortion in large parts of the transmission grid and consequently, a significant risk of voltage distortion becoming uncontrollable and related limits being exceeded. Voltage distortion beyond permissible limits will result in mis-operation in electricity grid components and consumers' electrical appliances or reduced lifetime. In addition, amplified voltage distortion may lead be pushed to our neighbouring countries' electrical systems, giving rise to the same risks elsewhere.

Increasing the share of 400 kV cables beyond the established 15 %, will also result in a more complex and less robust electricity grid as, various other mitigation measures need to be employed to counteract the effects introduced by the use of underground cables. One specific example is the need for an unknown number of filters that must be fitted, and furthermore the need for these to be compensated by reactors. In addition, cable charging currents must be compensated to allow the transmission of energy through the cables. All in all, the sheer number of additional components required calls for automated control of these. This type of control has currently not been developed for large electricity systems. Besides this, an increase in the number of components in the electricity grid increases the risk of faults and supply failures.

150 kV and 220 kV cables are at risk of overloading and require reconstruction of the grid

Installation of 150 kV or 220 kV cable in the Idomlund-Endrup and Endrup-German border sections will require massive restructuring of the transmission grid in Jutland.

The 150 kV grid makes up the electricity grid’s "local roads" and is used for local collection and distribution of energy. The 400 kV grid makes up the "motorways" and is used to transmit large quantities of energy over long distances. Shifting the transmission of large quantities of energy to a lower voltage level (Alternative E) will affect not only the individual cables, but the overall 150 kV grid. This will require very extensive grid reinforcements to prevent overload in other 150 kV grid branches, among other things. Electricity generation changes as the wind blows and reaches very high volumes in certain hours. Large generation fluctuations combined with changes to consumption and cross-border exchange increase the risk of overloads and unacceptable voltage control. Consequently, operation of the electricity system becomes very complex and requires the introduction of automatic control of the overall transmission grid. Such control systems are not currently available. At the same time, great complexity increases the risk of faults and outages. The same control-related challenges apply to a 220 kV solution.

Moreover, 150 kV and 220 kV cable solutions will have significantly lower transmission capacities, than can be achieved with grid reinforcements at the 400 kV level, making them lack robustness and future-proofing: For example, continuous additions of new parallel "local roads" will be required to match the expansion of renewable energy and growing electricity consumption from an increased electrification of, for instance, heating and transport sectors.

Finally, a 150 kV or 220 kV connection will require the installation of a number of parallel cables in order to reach sufficient transmission capacity, the total cable system length will grow considerably and will likely create similar voltage distortion problems as those identified for 400 kV cables.

Direct current will increase complexity significantly and increase the risk of faults

For the projects discussed in this report, high-voltage direct current (HVDC) connections, Alternative F, will be so complex that they are not feasible solutions. HVDC would require the installation of many new components, resulting in very complicated control systems and an increased risk of faults. There is a lack of experience of installations of this size, and much research and development must be done before HVDC connections can match the properties of alternating current (AC) grids.

For example, contrary to AC solutions, HVDC connections lack the properties to automatically respond to faults and outages in the transmission grid and activate reserves. An outage of the interconnector between Denmark and England, Viking Link, will require instant import from Germany via the connection between the German border and Endrup to maintain the Danish security of supply.

HVDC connections are used to transport large amounts of energy over long, uninterrupted distances, such as between countries. In Western Jutland, there is a need for "entrances" for generation infeed from, for example, offshore wind power plants, as well as "exits" for demand. Incorporating HVDC solutions as integral parts of the AC grid will necessitate converter stations at each end of a connection and at each "entrance and exit". This will make operation of the electricity grid extremely complex and increase the risk of faults.

Multi-terminal HVDC technology that could reduce the number of converters is still not sufficiently matured and has not yet been tested on a scale matching the set-up required in Western and Southern Jutland.

Offshore cables present the same challenges as land cables

Submarine cables, for example along the western coast of Jutland, present the same basic operational challenges as onshore underground cables. Consequently, it makes no difference system-wise whether connections consist of underground cabling or submarine cables. Problems and risks related to HVDC and 400 kV AC cable connections, respectively, are similar to those described above.

Gas-insulated connections are only undergrounded at very short distances

In addition to Alternatives B-F, the report also discusses the gas-insulated transmission line solution (GIL). GILSs are used, for instance, where installations are situated in underground tunnels in urban area. Worldwide, there is very little experience of directly buried gas-insulated cables and only over very short distances of approximately 1 km. Thus, introducing GIL-technology into a 170 km long route will bring on not only unprecedented operational risk but also complications and risk during installation and commissioning phases.

Perspective: The electricity grid is changing – cables must be used cautiously

The transition to more sustainable energy sources with low carbon footprint mean that the electricity system is undergoing great changes.

Generation based onwind power is already the largest single source of Denmark's electricity supply, and this share will increase further in the years ahead. The change means, in future, security of supply will need to be ensured in r ways other than what is done today. With this aspect in mind, large amounts of energy must be transported from generation sites, often located at sea or far from consumers, to households, businesses, etc. in other regions or neighbouring countries.

This trend is growing not only Denmark, but throughout Europe. The transition to green energy makes it advantageous and necessary to up cross-border exchange of energy. For example, Danish wind power plants can export more when it is very windy, and consumers can import electricity when favourable, or when generation in Denmark is low. The 400 kV grid is the backbone of the transmission grids in both Denmark and the rest of Europe.

The current reinforcement of the transmission grid between Idomlund and Endrup is necessary due to the large expansion of wind energy in Northern and Western Jutland, with the most recent addition being two planned near-shore wind farms with total installed capacity of 350 MW, and expansion is required in order to be able to incorporate these large amounts of renewable energy.

The 400 kV connection between Endrup and the Danish-German border is closely linked with the 770 km Viking Link that will span the North Sea. The connection between Denmark and England will have a capacity of 1400 MW, making it twice the size of Denmark’s largest existing international connection. Viking Link will be a very large component in the Danish transmission grid. Consequently, to prevent a major system supply failure or breakdown in case of an outage of Viking Link, there is a need to strengthen connections between Denmark and Germany so that any sudden loss of large amounts of energy can be replaced from Germany and Central Europe. This 400 kV connection will also contribute to improved market access between Germany and Denmark. Germany is currently expanding the 400 kV transmission grid along the western coast of Germany between Hamburg and Niebüll near the Danish border.

The political aim is for wind energy in 2020 to generate energy at a level corresponding to 50% of Denmark's electricity consumption. By 2030, the share of renewable energy in the electricity system is expected to reach 100 per cent of demand, and electricity will increasingly replace fossil fuels in the transport and heating sectors, for instance by way of electric cars and electric heat pumps in both the district heating industry and private households. The goal is to be a low emission society by 2050.

The trend will require continuous reinforcement and expansion of the overall electricity grid, including the 400 kV grid. For example, the locations of future offshore wind power plants, including the three new offshore wind power plants agreed upon in the Danish Parliament's recent energy policy will necessitate strong electricity motorways in order to ensure that energy reaches consumers, and that they have power available.

The new 400 kV overhead line connection between Idomlund and Endrup is a robust and future-proof solution. The new towers are projected to carry two 400 kV installations, but one will start off as a 150 kV installation to replace the 150 kV overhead line installation that currently makes up the main part of the section, i.e. the one between Idomlund and Karlsgårde. If renewable energy continues to expand as forecasted, factoring in wind power expansion in the North Sea, the 150 kV installation can be upgraded to 400 kV.

Likewise, electricity grid reinforcements will also become necessary in other parts of Denmark.
Existing cable technology only allows underground cabling of a limited amount of 400 kV lines, and underground cabling must therefore be used with caution, taking into account future grid expansions.

The transmission grid is one, large interconnected entity, and a high concentration of underground cabling in one section restricts the use hereof elsewhere. Future transmission grid expansions will most likely also require some degree of underground cabling near conservation areas or urban areas. Moreover, grid connection of future offshore wind farms will add even more to the share of underground cabling in the transmission grid.

1. Introduction

Substantial expansions of the Danish transmission grid and related investments are required in order to accommodate both increasing consumption, increased international energy exchange due to new interconnectors and increasing generation of renewable energy in line with policy targets.

In accordance with Danish national principles for the establishment of transmission lines [1], Energinet has applied for and received approval to build the required grid expansions in Western and Southern Jutland as overhead lines (OHLs), this being the reference technology for transmission of electrical power at the 400 kV voltage level.

However, the establishment of new 400 kV OHLs causes considerable concern in local communities. The feasibility of technology solutions as alternatives to OHLs is likely to be discussed publicly in all future transmission development proposals. In response to these concerns, the Minister for Energy, Utilities and Climate has commissioned Energinet to study the applicability of extended use of 400 kV underground cables (UGCs) as an alternative to the proposed 400 kV OHL projects in Western and Southern Jutland.

The study establishes the merits of operating 400 kV UGCs as part of the approved 400 kV grid expansions in Western and Southern Jutland with regards to technical characteristics, reliability, operation and financial impact.

One of the main objectives of this study is to identify the technically acceptable maximum share of 400 kV UGCs applicable in the 400 kV grid expansion projects in Western and Southern Jutland. In total, four 400 kV OHL/UGC solutions (alternatives A to D) with different UGC shares have been defined:

- The approved 400 kV overhead line solution (Reference/Alternative A);
- The approved 400 kV overhead line solution – with an increased cable share without the need for establishing additional compensation stations (Alternative B);
- The approved 400 kV overhead line solution – with an increased cable share and resulting need for establishing additional compensation stations (Alternative C); and
- Full underground cabling of the current 400 kV connection (Alternative D).

The four 400 kV OHL/UGC solutions (alternatives A to D) are described in Chapter 5.6.

In addition, the report includes a review of transmission solutions based on 150 kV and 220 kV UGCs (alternative E), High Voltage Direct Current (HVDC) links (alternative F) and Gas-insulated transmission lines (GILs) in order to cover all relevant alternatives for the grid expansions in Western and Southern Jutland.

As a prerequisite, all transmission alternatives must be feasible within the Viking Link project schedule, which is set for commissioning in 2023.

The Minister's commissioning letter is included as Annex A.

1.1 Scope of work

In accordance with the Minister's commissioning letter, Energinet has studied the possibilities for an extended application of 400 kV underground cabling in Western and Southern Jutland, including a review of a range of standard and non-standard transmission technologies and voltage levels.

The report is delimited to include a discussion regarding the application of relevant transmission alternatives in order to accommodate the established reinforcement requirements of the transmission grid in Western and Southern Jutland, meaning that it is outside the scope of this report to discuss the validity of these grid reinforcement projects, including the establishment of Viking Link.

The technical analyses regarding the application of 400 kV underground cables have been carried out based on four 400 kV OHL/UGC alternatives with increased shares of 400 kV underground cable to identify relevant technical challenges. Any identified electrical issues are discussed and immediate mitigation measures are identified and analysed. It should be emphasized that explicit mitigation measures can only be specified in conjunction with a design study of a specific project layout.

1.2 Structure of this report

Chapter 1 introduces the background of the report and outlines the structure of this report as well as scope of work.

Chapter 2 introduces the Danish transmission system as well as presenting key figures for the expected development of the transmission grid with an emphasis on the potential development of renewable energy. Finally, Energinet's grid development procedures are described.

Chapter 3 discusses the required grid reinforcements in Western and Southern Jutland, including a discussion on the perspectives for using 150 kV or 220 kV UGCs.

Chapter 4 contains a high-level review of international practice of the application of Extra High Voltage (EHV) UGCs, GIL and HVDC VSC links as alternative transmission line technologies.

Chapter 5 provides a project-specific evaluation of the commercially available EHV transmission technologies. The evaluation includes a comparison of the key techno-economic characteristics of the different technologies from a transmission system perspective.

Chapter 6 presents the results of the study on system-technical performance issues introduced by the application of 400 kV HVAC cables.

Finally, Chapter 7 summarises the key conclusions of the report.

2. The Danish transmission system

This chapter introduces the Danish transmission system. Key figures and operation of the system as well as the planning procedure are described. The purpose is to inform the reader about the context of the two proposed 400 kV transmission lines in Western and Southern Jutland.

2.1 The Danish power system at a glance

The Danish power system, like other power systems worldwide, is undergoing a transformation from a system dominated by centralized thermal power plants to a system incorporating different power generation sources of various sizes and technologies, such as wind power and photovoltaics.

While the power system is being transformed, the laws of physics that determine electrical power flows do not change. To maintain a reliable and economically efficient system, a range of interdependent technical and operational fundamentals must be fulfilled at all times.

The 400 kV transmission grid serves as the backbone of the power system, allowing transportation of large quantities of energy across the country. Major power plants, major consumers, interconnectors and offshore wind power plants are connected to the transmission grid.

Regional sub-transmission grids (132 kV and 150 kV) take power from the 400 kV transmission grid and move it to load-serving substations that serve distribution grids. Major urban centres can have concentrated 132-150 kV grids comprising several load-serving substations in a relatively small geographic area. Alternately, regional sub-transmission grids can serve sparsely populated areas with significant distances between substations. The planned transmission grid at year-end 2024 is shown in Figure 1.

Distribution grids are planned and operated by distribution system operators (DSOs). Energinet and DSOs cooperate in operating the power system and have several interface agreements and joint operating procedures.

The overall power system, including both the transmission- and distribution grids, serves electricity generators and consumers by facilitating the electricity market to ensure that supply of and demand for electricity are physically matched.

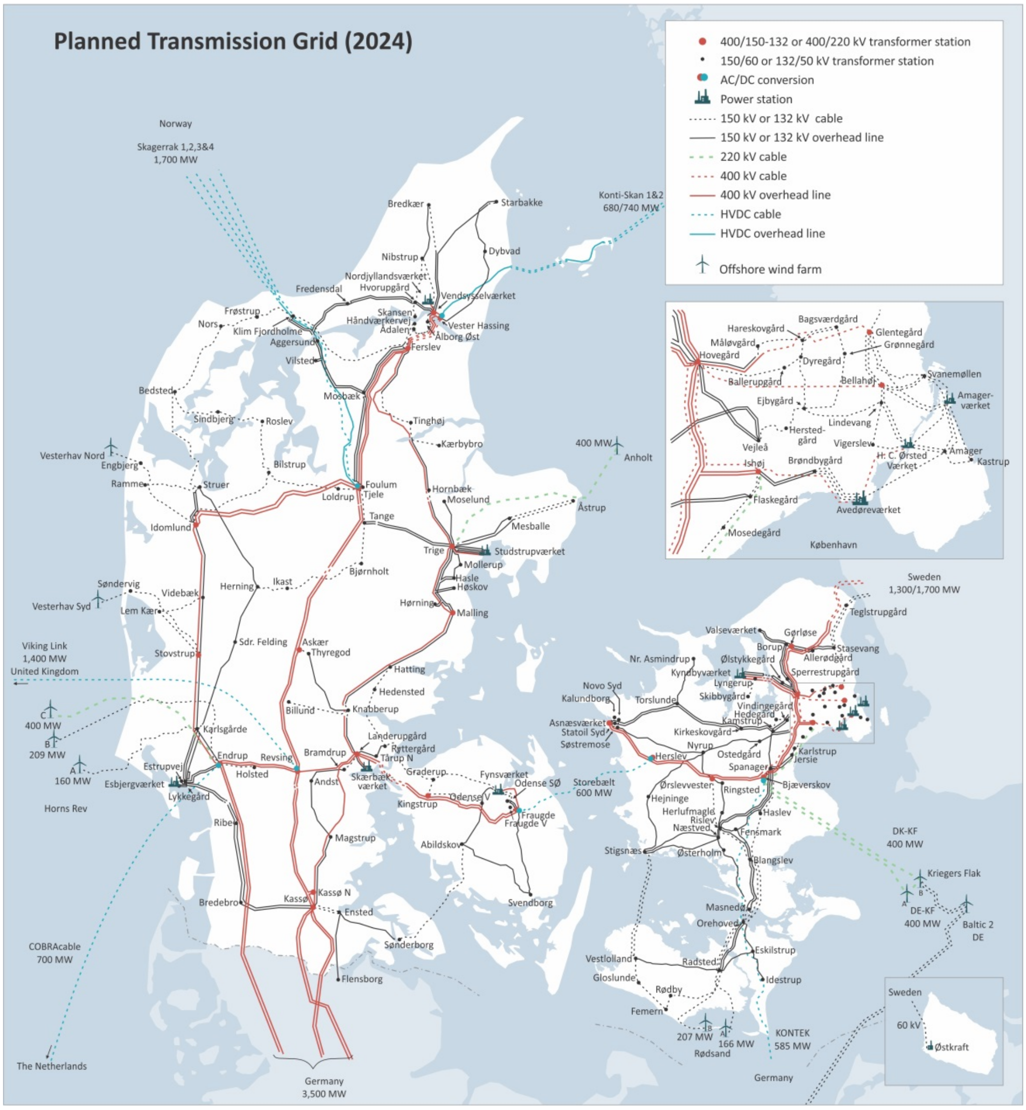

Figure 1 Planned transmission grid - as at year-end 2024

The transmission grid is designed and operated according to international standards[1] to ensure sufficient transmission capacity to transfer power from areas of generation to areas of demand. Limiting factors on transmission capacity include thermal current ratings, voltage constraints and dynamic stability limitations.

For historical reasons, the Danish transmission grid is operated as two separate synchronous systems but at the same frequency. Eastern Denmark is part of the Nordic synchronous system, while Western Denmark is part of the continental European synchronous system. Figure 2 shows the present European synchronous systems. Being part of two synchronous systems, Denmark is interconnected via several HVDC and HVAC interconnectors.

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[1] More information in ENTSO-E grid codes: https://www.entsoe.eu/network_codes/

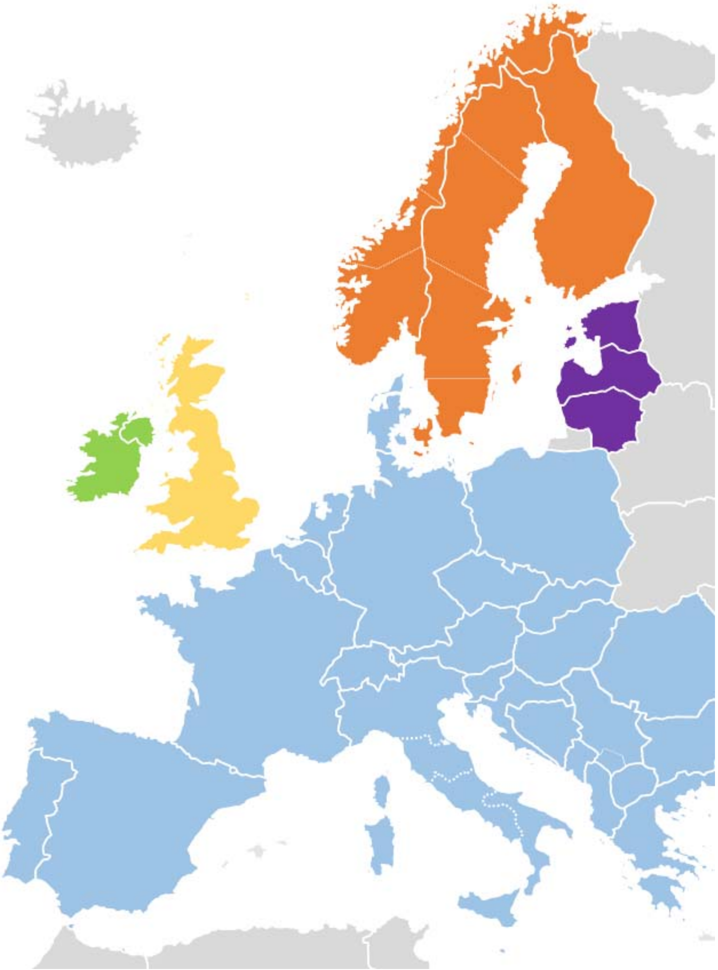


Figure 2 European synchronous systems (ENTSO-E)

The Western part of the Danish transmission grid has high voltage alternating current (HVAC) connections to the synchronous continental European system. Specifically, the connection to Germany consists of four HVAC connections. Export capacity is 1,780 MW, and import capacity is 1,500 MW. By 2023, a total of six 400 kV HVAC connections are planned to be in operation, increasing transmission capacity to 3,500 MW in both directions.

In addition, the Western part of the Danish transmission grid is connected to Sweden and Norway by high voltage direct current (HVDC) connections. The Konti-Skan connection to Sweden consists of two HVDC connections with a total export capacity of 740 MW and an import capacity of 680 MW. The Skagerrak connection to Norway consists of four HVDC connections with a total two-way capacity of 1,700 MW.

A 700 MW HVDC link between Western Denmark and the Netherlands (COBRAcable) is underway with commissioning planned for 2019. The 1,400 MW HVDC link between Western Denmark and Great Britain (Viking Link) is planned to be commissioned in 2023. A more detailed description of the Viking Link project can be found in Chapter 3.1.3.

The eastern part of the Danish transmission grid is connected by HVAC to the synchronous Nordic system. The Øresund Link between Zealand and Sweden consists of four HVAC connections with a total export capacity of 1,700 MW and an import capacity of 1,300 MW.

The Eastern part of the Danish transmission grid is connected to Germany by an HVDC connection, Kontek, which has a capacity of 600 MW. Moreover, Eastern Denmark and Germany will become interconnected via the world's first offshore electricity grid as part of the grid connection concept for the Kriegers Flak offshore wind power plant. This Kriegers Flak combined grid solution (CGS) has a capacity of 400 MW in both directions with commissioning planned for 2019. The connection's export and import capacities will be limited by the power generation levels of the Kriegers Flak offshore wind power plant.

Western Denmark and Eastern Denmark are interconnected by a HVDC link, the Great Belt Link, which has a capacity of 600 MW. The connection is obviously not an actual international connection as it interconnects two Danish market areas. However, it is operated in the same manner and is included in the market on the same terms as other interconnectors.

Denmark has the largest interconnector capacity in Europe relative to domestic electricity consumption, and has considerable energy exchange with neighbouring countries. These interconnections have a major impact on the interaction between generation and demand in the interconnected systems. The connections with neighbouring systems are essential parts of balancing a power system with a large share of renewable generation while they also serve to facilitate a competitive electricity market. Present and future Danish interconnectors are shown in Figure 3.

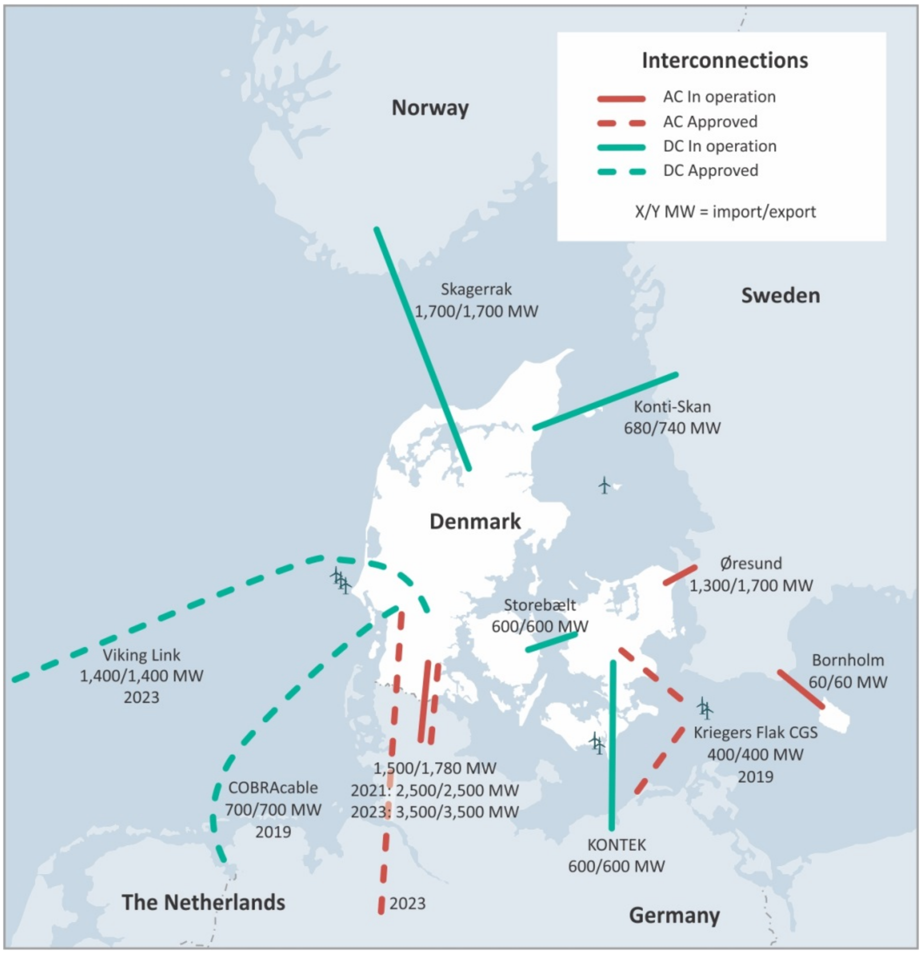


Figure 3 Present and future interconnectors

The Danish transmission system mainly consists of OHLs and air-insulated outdoor substations. However, the use of gas-insulated (GIS) substations in the transmission grid has increased in recent years. Worldwide, UGCs are rarely used for 400 kV transmission lines and only over short distances because of the related technical challenges and high costs due to the high transmission capacity requirements necessitating the installation of several parallel cable circuits.

UGC installations operated at the 132-150 kV voltage level do not introduce similar technical challenges and high costs as with 400 kV UGCs and have therefore been the reference technology at the 132-150 kV voltage level for several years in accordance with the national principles for the establishment of transmission lines. The cable share at this voltage level makes up about half of the transmission lines operated at the 132-150 kV voltage levels.

2.2 Energinet's obligations

Energinet is an independent, state-owned company and is the statutory transmission system operator (TSO) in Denmark.

The responsibilities of Energinet include:

- To operate a reliable and economically efficient transmission grid;
- To plan and develop grid infrastructure, including interconnectors;
- To facilitate integration of renewable energy in Denmark; and
- To facilitate market development.

Development of the transmission grid is one of the central tasks of Energinet as the TSO responsible for planning and operating the main grid in Denmark. Long-term planning and development ensures that the transmission grid and the overall power system fulfil the requirements defined by national and international regulations.

2.3 Energinet's grid development procedure

The transmission grid must be expanded through a coherent, long-term, controlled development, maintaining the security of supply and supporting optimal electricity market functionality. Moreover, expansions must take into account the continued technological development, environmental impact, including landscape considerations, and the socio-economic impact.

As part of the grid development procedure, transmission alternatives are evaluated against a number of key performance objectives, which must be achieved regardless of the particular technology. The objectives for any proposed grid expansion are:

- To comply with system operation guidelines [2] and planning standards [3];
- To provide an environmentally acceptable and cost-effective solution;
- To provide the required transmission capacity;
- To enable future expansions of the transmission grid; and
- To enable future grid connections of renewable generation.

Planning standards are defined and measured in terms of performance of the transmission grid under various contingencies, e.g. a single contingency (N-1) or a double outage contingency (N-1-1). Prediction of the transmission grid contingency performance is established using the results of simulated power flow scenarios, including different load and generation profiles as well as different patterns of interconnector energy exchange.

In addition, system stability must be maintained and power oscillations adequately damped when subjected to severe disturbances such as a three-phase short circuit of a vital transmission line or a three-phase bus bar fault.

2.4 Operational guidelines

The operation of the interconnected continental European synchronous system is founded on the principle that each TSO is responsible for its own system. Within this context, the *N-1-principle* is a well-established practice among European TSOs, which ensures the operational security by foreseeing, that any predefined contingency in one area must not endanger the operational security of the interconnected operation. *Normal* and *exceptional* types of contingencies are considered in the contingency list.

The operational framework covers, for instance, operational procedures, which are important for the operation of the interconnected synchronous continental European system.

2.4.1 Active power reserves

Energinet is obligated to rectify any contingency in the Danish power systems and bring the affected system back into a secure operational state within a limited period of time, including bringing interconnector energy exchange back on schedule. A key enabler in this respect is the active power reserves that must be held at a sufficiently high level to ensure that contingencies do not lead to violation of operational security limits.

The dimensioning contingency is defined as the greatest loss of generation or loss of infeed from HVDC interconnectors that the power system must be able to withstand. In Western Denmark, the dimensioning contingency is the loss of 700 MW.

Manual active power reserves are spread throughout the power system. Energinet has limited knowledge of the locations of the reserves when activating them. As such, no manual power reserves can be assumed to be available to handle grid-related contingencies. Energinet therefore generally only activates reserves to correct for loss of generation or loss of infeed from HVDC interconnectors.

Energinet estimates that it is socioeconomically optimal to design the transmission grid to ensure sufficient transmission capacity to handle any normal grid related contingency without the need to adjust interconnector power flows or generation. Consequently, Energinet has decided not to maintain manual active power reserves to handle grid-related contingencies, such as tripping of a transmission line. Only in the event of a second contingency occurring within the same 24-hour "market period" will it be necessary to change interconnector power flows in line with operational guidelines.

2.5 Grid development plan

Energinet's latest grid development plan, *RUS plan 2017* [4], was published in 2017. The RUS plan presents an overall and long-term development plan for the transmission grid, establishing and coordinating reinvestment, expansion and reconfiguration needs. The plan covers the next 10 years and defines the projected long-term structure of the transmission grid in Denmark.

Energinet's RUS plan 2017 has been prepared in accordance with the Danish national principles for the establishment of transmission lines. According to the revised principles, new 400 kV transmission lines are to be built as overhead lines with the possibility of partial underground cabling as well as underground cabling of 132-150 kV overhead lines in the vicinity of new 400 kV overhead lines.

New 132-150 kV transmission lines are to be established with UGCs. Furthermore, the revised principles stipulate that the 2009 Cable Action Plan [5] no longer applies; however, the possibility of underground cabling of 132-150 kV overhead lines in selected urban areas and areas of particular environmental interest still exists to some extent.

2.6 2018 energy policy and new planning assumptions

In June 2018, the Danish parliament agreed on a new energy policy [6] that defines long-term energy initiatives. The agreement includes a commitment to develop and commission three large new offshore wind power plants with a total capacity of 2,400 MW and further investments in onshore wind and solar energy.

The Danish Energy Agency has prepared a new set of planning assumptions that incorporate the long-term energy ambitions. At the time of writing of this report, the new planning assumptions have not been finalized. Compared with the 2017 planning assumptions, the new planning assumptions primarily differ on the projected amount and the composition of renewable generation.

In recent years, renewable energy has had a significant impact on the need for reinforcement of the transmission grid in Denmark. Thus, it was decided to use the updated assumptions as the basis for the analysis of future requirements for reinforcement of the transmission grid.

2.6.1 Changes compared with 2017 assumptions

Compared with the existing 2017 planning assumptions, the new energy agreement and the revised 2018 planning assumptions forecast the following changes with regard to renewable power generation.

Change in offshore wind power generation capacity:

Offshore wind power [MW]	2018	2024	2028	2031	2040
2017 assumptions	1,142	2,149	2,589	3,023	4,007
2018 assumptions	1,142	2,149	2,789	4,023	7,307
Difference between 2017 and 2018 assumptions	**0**	**0**	**200**	**1,000**	**3,300**

Change in onshore and near-shore wind turbine power generation capacity :

Onshore and near-shore wind power [MW]	2018	2024	2028	2031	2040
2017 assumptions	4,252	6,403	6,235	6,071	6,687
2018 assumptions	4,295	5,498	5,608	5,560	5,528
Difference between 2017 and 2018 assumptions	**43**	**-905**	**-627**	**-511**	**-1,159**

Change in photovoltaics power generation capacity:

Photovoltaics [MW]	2018	2024	2028	2031	2040
2017 assumptions	915	1,103	1,468	2,103	6,050
2018 assumptions	1,040	1,660	2,397	3,257	7,374
Difference between 2017 and 2018 assumptions	**125**	**557**	**929**	**1,154**	**1,324**

Total change in renewable energy sources power generation capacity:

Total power from renewable energy sources [MW]	2018	2024	2028	2031	2040
2017 assumptions	6,309	9,655	10,292	11,197	16,744
2018 assumptions	6,477	9,307	10,794	12,840	20,209
Difference between 2017 and 2018 assumptions	**168**	**-348**	**502**	**1,643**	**3,465**

In general, the new planning assumptions show a significant increase in installed power generation capacity of renewable energy sources compared with the 2017 planning assumptions.

The following sections describe Energinet's expectation with regard to grid connection points of offshore wind power plants.

2.6.2 Offshore wind power plants in planning assumptions

A significant amount of offshore wind power generation capacity is assumed to be installed along the Western coast of Jutland. Expected locations and connection points of the projected wind power plants are shown in Figure 4.

Figure 4 Expected locations and connection points of future offshore wind power plants

2.6.2.1 Existing offshore wind power plants and assumed year of decommissioning

The four oldest offshore wind power plants in Denmark were commissioned during the first decade of the new millennium and are all connected to the transmission grid at the 132 kV and 150 kV levels due to their limited generation capacity. These four offshore wind power plants are assumed to be decommissioned after the concession agreement expires, typically after 25 years.

Offshore location	Capacity [MW]	Year of commissioning	Assumed year of decommissioning	Connection point
Horns Rev A	160	2002	2028	Karlsgårde
Rødsand A	166	2003	2029	Radsted
Horns Rev B	209	2009	2035	Endrup
Rødsand B	207	2010	2036	Radsted
Anholt	400	2013	-	Trige
Total	**1,142**			

2.6.2.2 Offshore wind power plants under construction

Two offshore wind power plants are under construction and will be connected to the 400 kV transmission grid with 220 kV export cables and 400/220 kV transformers at the onshore connection points. These offshore wind power plants are assumed to be in operation in 2040.

Offshore location	Capacity [MW]	Year of commissioning	Assumed year of decommissioning	Connection point
Horns Rev C	407	2019	-	Endrup
Kriegers Flak A+B	600	2022	-	Bjæverskov and Ishøj
Total	**1,007**			

2.6.2.3 New offshore wind power plants

A total of approximately 6,000 MW offshore wind power is assumed to be connected towards 2040. The locations of future offshore wind power plants and their onshore connection points have not been decided at the time of writing this report. Thus, the following locations, commissioning years and connection points only represents qualified projections:

Offshore location	Capacity [MW]	Year of commissioning	Assumed year of decommissioning	Assumed connection point
Ringkøbing A	800	2028	-	Idomlund
Kriegers Flak C	600	2030	-	Bjæverskov + Ishøj
Horns Rev D	800	2031	-	Stovstrup
Ringkøbing B	1,000	2033	-	Idomlund
Jammerbugt A	1,000	2035	-	Ferslev
Rødsand C	400	2037	-	Radsted
Jammerbugt B	800	2038	-	Ferslev
Ringkøbing C	500	2040	-	Idomlund
Total	**5,900**			

3. Project background

In this chapter, the background of the two on-going transmission line projects in Western and Southern Jutland is presented in detail. It is important that the purpose and requirements of the two transmission lines are understood as well as Viking Link's impact on grid expansion requirements. In addition, the determination of voltage level for transmission lines is discussed in view of the future need for grid expansions.

3.1 Required grid expansions in Western Jutland

With unprecedented renewable generation capacity now connected and more projected according to the revised planning assumptions, including new interconnectors, the transmission grid must be developed accordingly.

The transmission grid in the of Denmark is operated as a meshed 150 kV- and 400 kV transmission grid. Initially, the transmission of electricity was handled by the 150 kV transmission grid, but gradually, as the energy transmission rose to a level where more transmission capacity was required, the 400 kV voltage level was introduced in the late 1970’s. The 400 kV grid has taken over the long-distance transmission of electricity, while the 150 kV grid serves as local transmission and to some extent as limited back-up in case of outages in the 400 kV grid.

Historically, the transmission grid has been dimensioned to accommodate regional consumption. In line with the development of renewable generation and increasing power exchange between regions, dimensioning must take into account the transmission capacity demands that this entails.

Onshore wind power plants was first introduced in Denmark in the 1970’s, but accelerated over the following decades and culminated in 2000 with an annual growth of more than 600 MW. Subsequently, development of onshore wind power plants has been more moderate due to various changes in national energy policies. Offshore wind power plants were introduced at the beginning of the 2000s at Horns Rev and Rødsand. There are plans to establish several offshore wind power plants in Western Denmark, where the grid connection points of these power plants will have a major impact on the future development of the transmission grid.

Due to the favourable wind resources in Northwest Jutland, the penetration of wind power is considerably greater in these areas compared to the rest of Denmark. This is clearly shown in Figure 5, where the present and projected locations and installed capacities (accumulated) of wind power plants in 2018 and 2024 are indicated.

Renewable energy is rarely generated where it is actually consumed. The relative low population density, and as a result, the rather limited consumption of electric energy in Western Jutland lead to a significant regional surplus of electrical energy during periods with large wind power generation and low demand. As a result, more and more electrical energy is transmitted over long distances to large urban consumption areas or abroad.

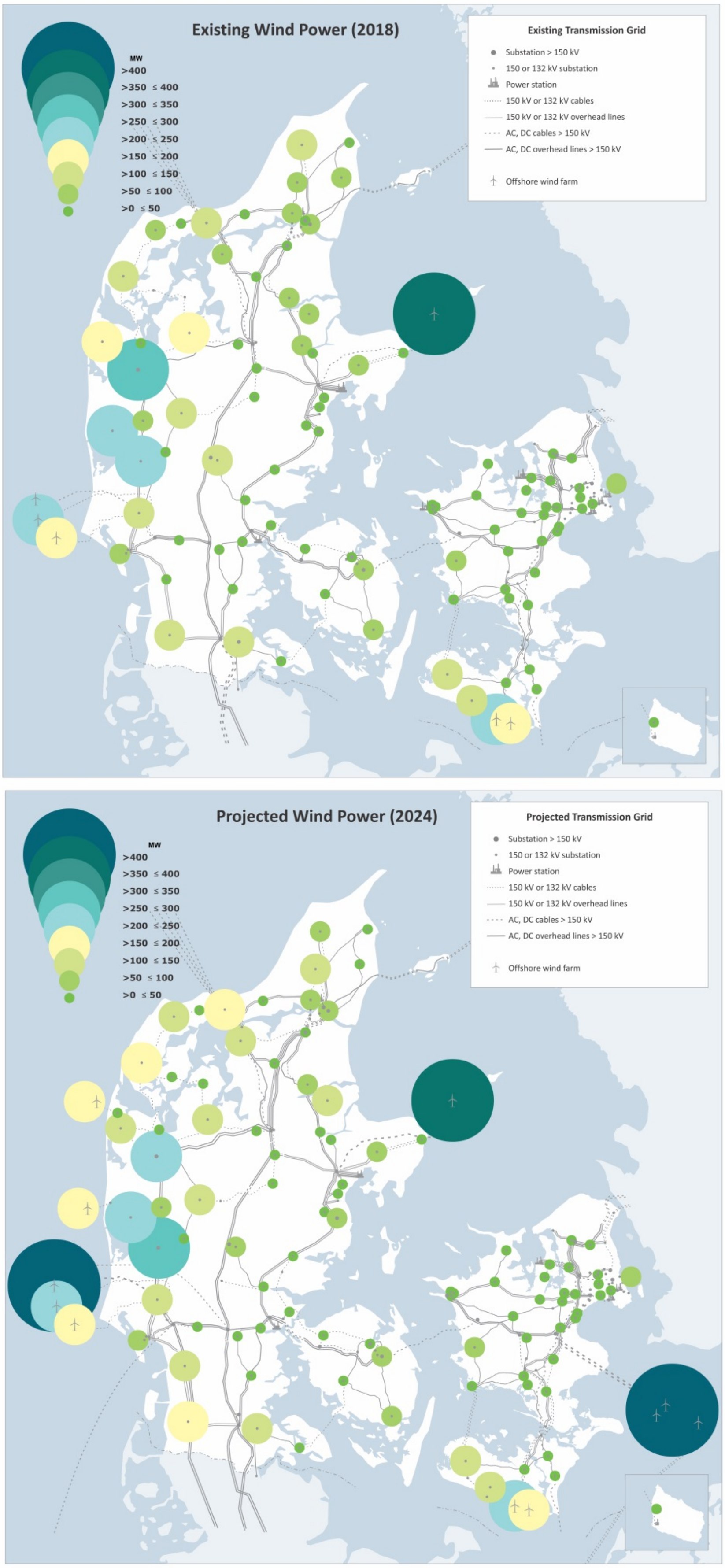


Figure 5 Locations and installed capacities (accumulated) of wind power plants.

Furthermore, more conventional power plants in urban areas are being rebuilt or decommissioned over the next ten years. The demand for electricity and its composition will change up to 2030, depending, in particular, on the expected electricity demand of large consumers like data centres and sector initiatives on electrification of heating and transportation.

These changes to the overall power system impose increased demands on the capacity of the transmission grid that will play a crucial role in the on-going green transition of the energy sector in Denmark.

In order to meet the levels of performance and security of supply required of the transmission grid, the grid must be capable of operating securely with any single electrical circuit out of service according to the *N-1 principle*.

Future energy scenarios to the best of Energinet's projections have been applied to grid models and power flow analysis have highlighted capacity shortfalls and availability of the transmission grid over the next ten years, including the projected expansions of the Danish transmission grid up to 2040. The required reinforcements of the transmission grid in Western and Southern Jutland have been a main theme in Energinet's annual grid development plan for several years.

Studies have shown that the transmission capacity of the existing meshed 150 kV grid in Western Jutland will not meet future transmission capacity required to accommodate the projected renewable generation in the region.

The expected route corridors of the required grid expansions in Western and Southern Jutland are shown in Figure 6.

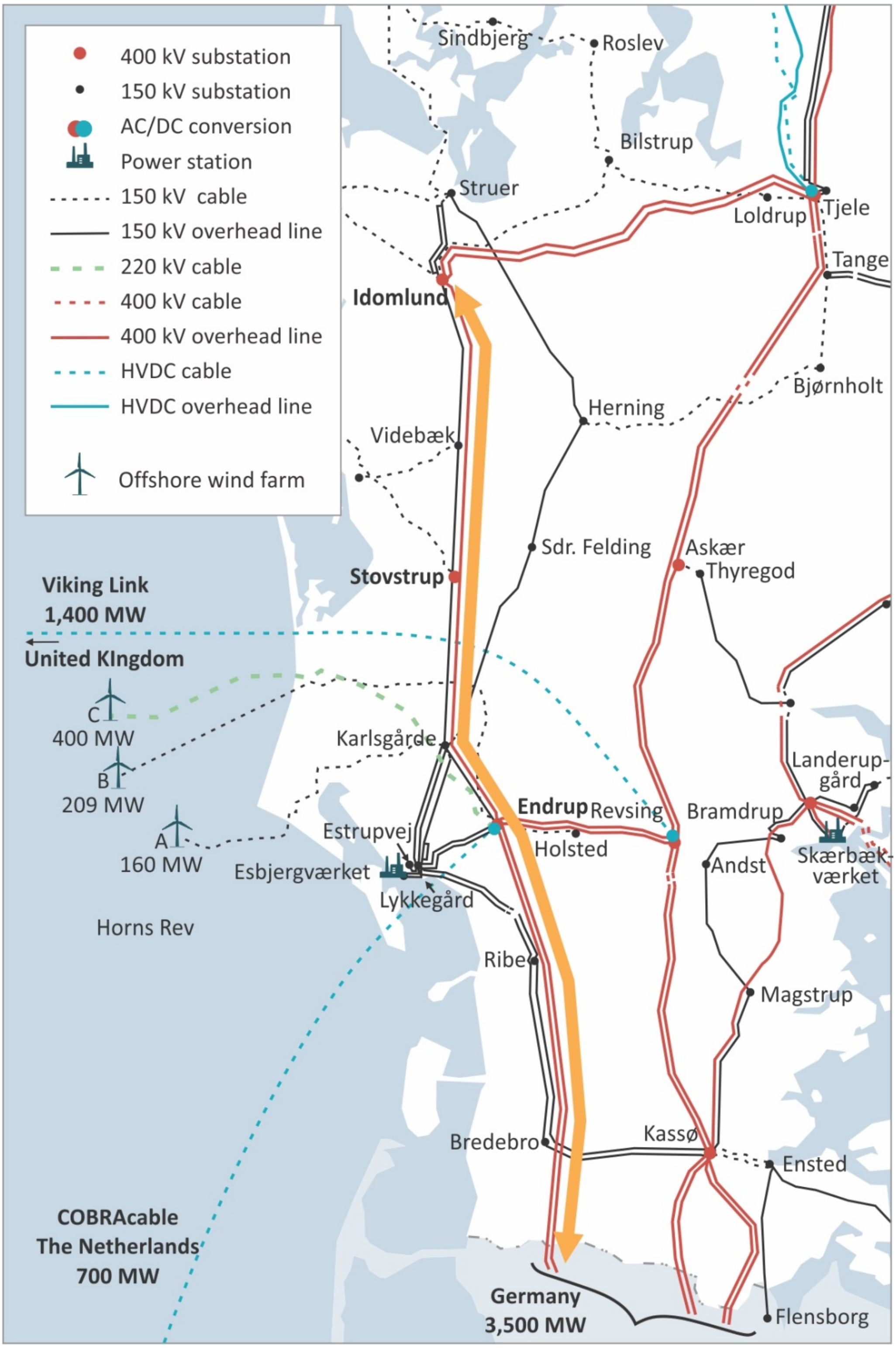


Figure 6 Expected route corridors of the required grid expansions in Western and Southern Jutland.

As described in the respective business cases for the ongoing grid reinforcement projects in Western Jutland, a need for reinforcement of the transmission grid on the line between Endrup and Idomlund has been established. Likewise, the establishment of Viking Link and the efforts to improve market integration between North Germany and Jutland require the establishment of a transmission line between the Western parts of the 400 kV transmission grids in Germany and Jutland. These grid reinforcements and Viking link are described in the following sections.

3.1.1 Endrup-Idomlund

Due to the existing onshore renewable generation in Western and Northern Jutland and the addition of offshore wind power plants in the same area, the transmission capacity of the 150 kV transmission grid is fully utilised until the required grid expansions are completed. In daily operation, this may lead to a need for downward regulation (curtailment) of renewable energy. Considering the recent energy policy agreement, additional renewable generation is expected, which will only worsen the situation even further within the next few years. Therefore, grid reinforcements are required in order to facilitate integration of new generation at the substations along the route from Endrup to Idomlund.

Based on the significant resources of the region’s renewable energy potential, expansion of the transmission grid is expected to be required within a 2030 timeframe. The timeline for development of any additional expansions, if required, is dependent on a number of factors, including the rate at which further renewable generation develops in the region.

3.1.2 Endrup-Klixbüll

In order to accommodate the increased demand for energy exchange between Denmark and Germany, the capacity of the existing transmission grids in the Schleswig-Holstein region and the Southern part of Jutland must be increased.

The agreement with the German TSO, TenneT TSO GmbH, stipulates that the joint grid expansion will result in an increase in the capacity for energy trading between Germany and Denmark from 2,500 MW to 3,500 MW. It has been agreed that this expansion, in general, must be made up of an overhead line. The overhead line must consist of two permanent 400 kV circuits, each with an ampacity of at least 3,600 A.

The Danish part of the interconnector will be connected to the German 400 kV transmission grid at the Danish-German border. The German part of the interconnector will be connected to a substation near Klixbüll some 16 km south of the Danish-German border. The 400 kV Endrup-Klixbüll transmission line is part of a major 400 kV grid expansion project in northern Germany involving the installation of approximately 140 km overhead line on a route between Brunsbüttel and the Danish-German border.

The Endrup-Klixbüll interconnector is a prerequisite for the establishment of the 1,400 MW Viking Link. The interconnector will allow an increase in power flow across the border that might occur during the first few minutes after a grid-related contingency. This will facilitate a more efficient utilisation of generation capacity in Denmark and Germany by not requiring increased generation reserves to handle a tripping of Viking Link.

As previously described, it is agreed between TenneT TSO GmbH and Energinet that the Endrup-Klixbull interconnector must be built as a 400 kV transmission line. Consequently, 150 kV and 220 kV transmission alternatives are not considered relevant for the Endrup-Klixbull interconnector.

3.1.3 Viking Link

National Grid Viking Link Limited (NGVL) and Energinet have proposed a new HVDC interconnector between Great Britain and Denmark known as Viking Link, which will connect the existing Danish and British transmission grids.

Viking Link will facilitate a more effective utilisation of renewable energy, access to sustainable electricity generation and improved security of electricity supply. Thus, it will benefit Denmark and Great Britain, as well as the wider European community.

Viking Link is a 1,400 MW HVDC link that connects the transmission systems at Bicker Fen in Lincolnshire, Great Britain and Revsing in Southern Jutland, Denmark, crossing through the territorial waters of both the Netherlands and Germany. Viking Link will be approximately 760 kilometres in total length and is planned to be in operation by 2023.

Viking Link is in line with the European Commission’s aim for an integrated energy market in terms of both electricity costs and security of supply.

3.2 Considerations regarding transmission line voltage level

As part of the evaluation of feasible transmission alternatives for the required reinforcement of the transmission grid in Western Jutland, various solutions have been evaluated. At present, Energinet operates the transmission grid in Jutland and on Funen at three voltage levels; 400 kV, 220 kV and 150 kV. HVAC technology was therefore examined at these voltages, including 150 kV and 220 kV underground cable options. These solutions are described in the following sections.

These transmission alternatives were subject to technical analyses and evaluated and compared against Energinet's planning criteria as outlined in Section 2.3 and repeated below:

- To comply with all system operation guidelines and planning standards;
- To provide an environmentally acceptable and cost-effective solution;
- To provide the required transmission capacity;
- To enable future expansions of the transmission grid; and
- To enable future grid connections of renewable generation.

Each transmission alternative should therefore be robust enough to integrate with the existing 400 kV transmission grid as well as a variety of future transmission developments. Also, the operability of each alternative, which addresses the reliability of the connections, and the alternatives' flexibility with regards to system operational requirements are equally important.

3.2.1 150 kV grid reinforcements

In the business case for the Endrup–Idomlund project, a solution comprising three 150 kV cable circuits between Endrup and Idomlund was evaluated [7]. At the time, it was concluded that having several wind power plants under construction and considering the potential of additional renewable generation in the region, the proposed 150 kV transmission solution was not suitable due to the limited transmission capacity it provided.

Reinforcing the transmission grid in Western Jutland with 150 kV cables will require the establishment of a significant number of cable circuits, not only on the route between Endrup and Idumlund, but also in other parts of the transmission grid. In this context, it should be noted that the transmission capacity of a single 400 kV OHL circuit is equivalent to around five to eight parallel 150 kV cable circuits (depending on the core conductor size).

A 150 kV cable-based solution will require development and establishment of a new topology of the 150 kV transmission grid in Western Denmark in order to accommodate future power flows in the remaining transmission grid. In addition, a 150 kV cable-based solution is not considered robust in relation to future transmission capacity needs, where changes to the current planning assumptions in terms of load and generation will require the establishment of additional 150 kV cable circuits at an additional cost.

Establishing parallel operation of a meshed 150 kV cable grid and the remaining 400 kV transmission grid will introduce unacceptable operational complexity in relation to the control of power distribution between voltage levels, including the risk of operational limitations.

As a prerequisite, all transmission alternatives must be feasible within the Viking Link project schedule, which is set for operation in 2023. Therefore, a 150 kV cable-based solution is not considered an appropriate and long-term solution and is consequently not investigated any further in this report.

3.2.2 220 kV grid reinforcements

A single 220 kV cable circuit can transmit 400-500 MW of active power. Assuming an embedded 220 kV cable grid is to be established on the route between Endrup and Idomlund, there will be a need for a 400/220 kV transformer at both ends for each cable circuit in order to interface with the existing 400 kV grid. In addition, 220/150 kV transformers must be installed in substation Stovstrup to interface with the existing 150 kV transmission grid in Western Jutland.

The introduction of the 220 kV voltage level, i.e. an embedded 220 kV grid in Western Jutland, will, all things considered, increase grid complexity unnecessarily and increase investment costs.

Because of differences in the electrical impedances of the parallel routes comprising the existing 400 kV transmission grid and the considered 220 kV cables circuits between Endrup and Idomlund, the power flow will need to be controlled with phase-shifting transformers (PST) at one end of each cable circuit in series with the 400/220 kV interface transformer.

Due to the lower rating of the 220 kV cables (400-500 MW), four to five 220 kV cable circuits are needed to match the transmission capacity of a single 400 kV OHL circuit. Consequently, to match the long-term transmission capacity requirement in Western Jutland, up to ten 220 kV cable circuits and their associated interface transformers and PSTs will be needed. By comparison, the proposed 400 kV solution will solve the same transmission requirements without the need for any additional transformers (other than those required for 400/150 kV transformation). The principal layout of such a 220 kV solution is shown in Figure 7.

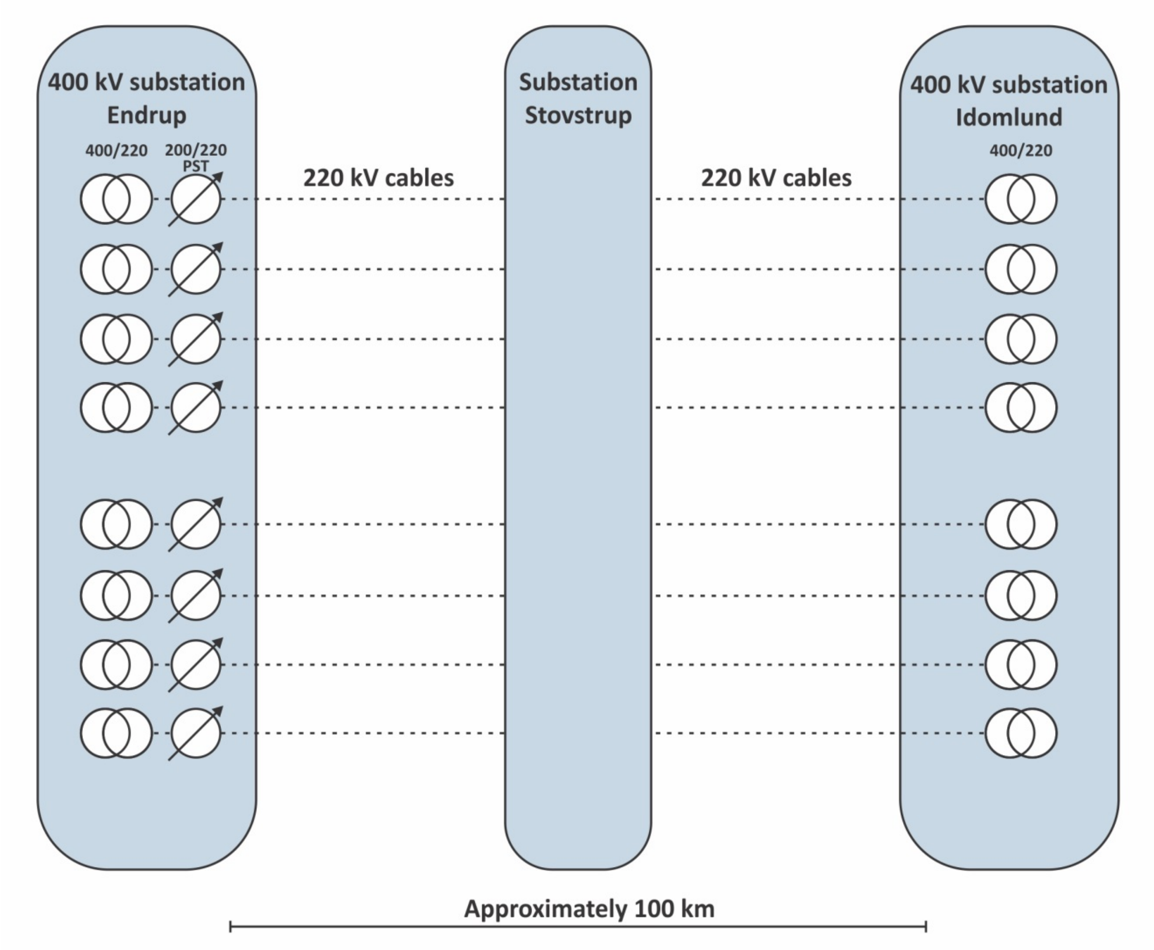


Figure 7: Layout of 220 kV cable circuits to substitute a double circuit 400 kV OHL.

Establishing parallel operation of an embedded 220 kV cable grid and the remaining 400 kV transmission grid will introduce an unacceptable operational complexity in relation to the control of power distribution between voltage levels, including the risk of operational limitations. An extensive 220 kV cable grid would introduce similar technical challenges to those seen in large 400 kV underground cabling projects, including challenges related to power quality and component energization. Finally, a meshed 220 kV cable grid lack the necessary robustness required for future development of the energy system.

The described multiple 220 kV cable circuit alternative is considered neither feasible, sufficiently robust nor achievable within the defined time horizon. Therefore, it is not investigated further in this report.

It should be noted, that the 220 kV voltage level is currently being phased out in Northern Germany as a large number of existing 220 kV transmission lines are being upgraded to the 400 kV voltage level in order to meet future transmission capacity requirements. In addition, the existing 220 kV interconnectors between Germany and Denmark are being upgraded to 400 kV in order to facilitate the increased demand for energy exchange between Denmark and Germany. Consequently, the 220 kV voltage level is not considered part of the future transmission grid in Denmark due to its limited transmission capacity and lack of robustness. Needless to say, the 220 kV voltage level is still considered a suitable level to be used for export cables in connection with future offshore wind power plants.

3.2.3 400 kV grid reinforcements

Pursuing transmission grid expansion with 400 kV transmission lines will facilitate grid connection of the expected offshore wind power plants at Ringkøbing and Horns Rev as well as grid level integration of other types of renewable energy, e.g. major PV power plants or major demand facilities in the region.

It is therefore important to emphasize that during the decision-making stages of grid expansion, Energinet has to take into account not only the specific requirements of the project at hand (as in the current Western and Southern Jutland projects), but also the wider system requirements for setting up a robust, economic, operable and environmentally friendly system.

Based on the evaluation of the individual transmission alternatives, the 400 kV solution is still considered the most efficient alternative due to its built-in robustness and the possibility of integration with the existing transmission grid without the need to introduce additional advanced systems for control and regulation of power flows in the overall transmission grid.

As 400 kV OHL and UGC solutions fulfill the planning criteria outlined in Section 2.3 and in view of the limitations of 150 kV and 220 kV transmission alternatives, only 400 kV HVAC and HVDC transmission alternatives are investigated in depth in this report.

In Section 3.3, future grid expansion is discussed. The purpose of the section is to outline the need for future expansions of the transmission grid in Denmark.

3.3 Future expansions

The impact of the new planning assumptions has been tested on the possible future grid structure presented in RUS plan 2017. The operational scenarios chosen for the studies provide operational considerations for several scenarios, including high and low levels of renewable generation combined with various levels of demand and different patterns of cross-border energy exchanges.

The performance of the transmission grid has been evaluated against Energinet's planning standards and the predefined operational scenarios.

Power flow calculations have been conducted for the following years:

- 2024 (including Viking Link and the Endrup-Klixbüll and Endrup-Idomlund 400 kV transmission lines, no new offshore wind power plants);
- 2028 (including the first new offshore wind power plant at Ringkøbing Fjord connected in Idomlund);
- 2031 (including the second new offshore wind power plant at Horns Rev connected in Stovstrup); and
- 2040 (including all new offshore wind power plants in accordance with Section 2.6.2.3)

Besides the already identified 400 kV grid expansion requirements in the Western and Southern part of Jutland, the following additional 400 kV transmission lines are (according to RUS plan 2017) required in order to accommodate future capacity needs derived from the revised planning assumptions:

1. 400 kV Idomlund-Tjele (circuit 2) required to support increase of wind and solar power in the Western part of Jutland;
2. 400 kV Endrup-Idomlund (circuit 2), required to support increase of wind and solar power in the Western part of Jutland;
3. 400 kV Ferslev-Tjele, required to support an increase in wind and solar power in the northern part of Jutland;
4. 400 kV Ferslev-Vester Hassing, required to support an increase in wind and solar power in the northern part of Jutland;
5. 400 kV Landerupgård-Revsing, required to facilitate the market and ensure supply to the Eastern part of Jutland and Funen;
6. 400 kV Hovegård-Ishøj, required to support the new wind power plants at Kriegers Flak;
7. 400 kV Hovegård-Bellahøj, required to ensure security of supply in the Copenhagen region; and
8. 400 Hovegård-Bjæverskov, required as a general reinforcement of the 400 kV transmission grid.

In Figure 8, required 400 kV grid expansions are highlighted, where green (ID2) indicates the considered Idomlund-Endrup transmission line and amber coloured lines indicate additional grid expansion requirements.

Figure 8 Required expansions of the 400 kV transmission grid (numbers indicate project IDs from the bulleted list on the previous page).

On the list of required 400 kV grid expansions is the installation of a second 400 kV circuit on the existing 400 kV overhead line between the existing substations at Idomlund and Tjele (ID 1). This additional 400 kV circuit effectively links the Western part of the transmission grid with the existing 400 kV backbone of Jutland, thus establishing a redundant (N-1 secure) supply for the 400 kV substation at Idomlund, a prerequisite for grid connection of the assumed Ringkøbing 1 offshore wind power plant (800 MW). The proposed plan is to establish this additional 400 kV circuit by refitting the existing 400 kV Donau towers of the OHL between Idomlund and Tjele, using the same right of way as shown in Figure 9.

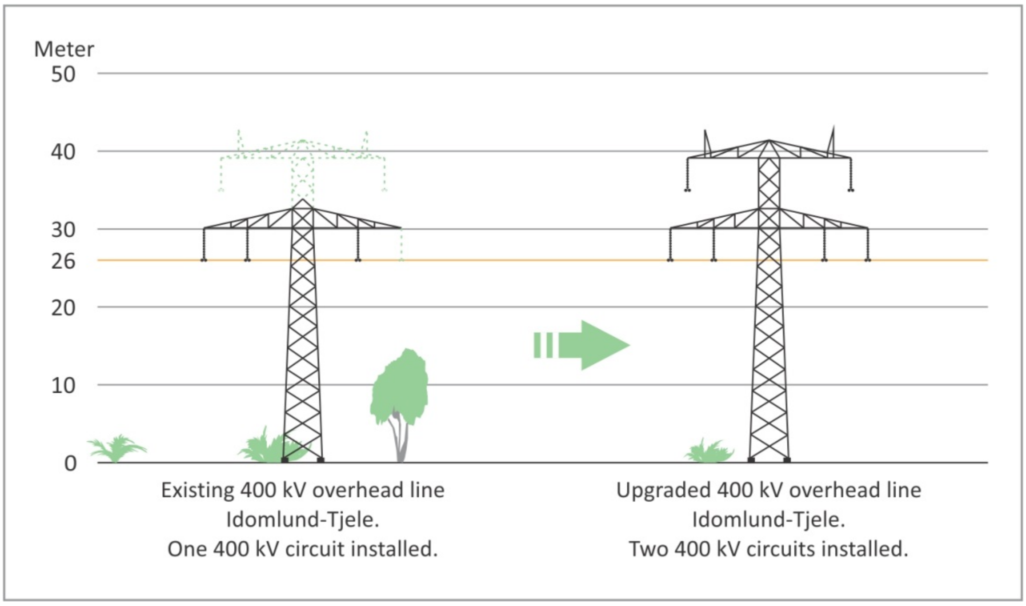


Figure 9 Proposed refitting of existing 400 kV Donau towers.

The analysis also shows that additional transmission capacity is required in the Western part of Jutland due to future grid connections of offshore wind power plants at Ringkøbing and Horns Rev. The required transmission capacity will be established by installing a second 400 kV circuit between the substations at Endrup and Idomlund (ID 2). This expansion should be completed by 2030.

The connection of large-scale offshore wind power plants will result in significant power infeed at the connection points and in the adjacent transmission grid. A firm and long-term strategic development plan for future offshore wind power plants in Denmark will ensure the corresponding development of the transmission grid, facilitating timely coordination and commissioning of necessary grid expansions in relation to the completion of the respective offshore wind plants.

Offshore wind power facilities with capacities of 600-800 MW will require the locations of these facilities to be determined according to a long-term development plan in order to ensure that the transmission grid is developed accordingly with respect to timeliness, robustness and cost-effectiveness. Without such a plan, considerable costs could result from the suboptimal choice of non-robust solutions today.

The specific transmission capacity requirements as well as the optimal time for the commissioning of these 400 kV transmission lines will be analysed in more detail as part of the upcoming RUS plan 2018.

3.4 Summary

To meet future transmission capacity requirements, allowing Denmark to meet its policy objectives and obligations for generation of renewable energy, it is necessary to expand the transmission grid in the Western and Southern parts of Jutland. The primary objectives of the two projects are to facilitate the connection of future renewable generation in the Western part of Jutland and to make it possible to integrate the 1,400 MW HVDC (Viking Link) into the grid. Furthermore, the grid expansions will also be important and integral parts of the transmission grid, necessary to transmit renewable energy as well as meeting the long-term electricity needs of consumers, including securing the supply of large data centres currently under development in the region.

As previously described, the implementation of the national energy policy will lead to a massive expansion of renewable energy generation, where offshore wind power plants are expected to be the dominant contributor. However, the projected expansion of renewable energy in Denmark is subject to considerable uncertainty, which introduces a number of challenges in relation to timely expansion of the transmission grid. Especially challenging is grid connecting future offshore wind power plants, where the choice of location and generation capacity has considerable influence on the capacity requirement in the transmissions grid.

Based on the already established and expected expansion requirements, UGC solutions for the 150 kV and 220 kV voltage levels are not considered relevant technical solutions that satisfy the planning requirements. Generally speaking, the 150 kV transmission grid in Denmark is a sub-transmission and not designed to transport large amounts of energy alongside the 400 kV transmission grid.

The use of 150 kV- and 220 kV transmission grids to transport the large amounts of renewable energy assumed in this report would require major grid expansions in large parts of Jutland. This would extend far beyond the route sections addressed in this report. The use of an embedded 220 kV grid is not recommended either, as this would require advanced control systems, adding to the complexity of the transmission grid, and a large number of additional components to ensure an acceptable power distribution between such new cable circuits and the remaining 400 kV transmission grid.

The 400 kV transmission line alternative is both effective and reliable, which facilitates the transfer of larger quantities of energy on the line while reducing transfer losses relatively. For that reason, Energinet, in line with most European TSOs, has developed a 400 kV infrastructure as the backbone of the transmission grid in Denmark.

4. Transmission line alternatives

This chapter describes different known transmission line technologies. The purpose of the chapter is to provide general background knowledge for the project-specific discussion of transmission line alternatives in Chapter 5.

The following transmission line technologies are included in the review:

- 400 kV HVAC overhead lines (OHLs);
- 400 kV HVAC underground cables (UGCs);
- 400 kV HVAC gas-insulated transmission lines (GILs); and
- High voltage direct current (HVDC).

Alternatives are described based on the relevant parameters affecting the choice of technology for the 400 kV projects studied in this report. These include a general technology description, technical considerations, usability, reliability and environmental impact.

4.1 400 kV HVAC overhead lines

4.1.1 General

Worldwide, the transmission of electrical power is dominated by high voltage alternating current (HVAC) overhead line technology, primarily because it represents the most cost-effective and technically feasible approach to establishing and maintaining a secure transmission grid.

An OHL comprises a conductor suspended from towers made from steel. Insulators used on new overhead lines in Denmark are made from a composite material. The conductors are generally made from aluminium with steel reinforcement in the centre, and the newest 400 kV overhead lines in Denmark are constructed with a triple bundle configuration of conductors. This configuration is typically chosen to reduce acoustic noise, but has the added advantage of reducing losses as well. Experience shows that the reduced losses make up the cost difference between a double and a triple bundle conductor configuration. Due to the noise reduction advantage, it has been decided to construct all new OHLs in Denmark with a triple conductor configuration.

Figure 10 visualises the use of overhead lines. On the left, the existing 150 kV overhead line used on the route between Endrup and Idomlund is shown. On the right, a visualization of the proposed new 400 kV line is shown, assuming the towers are placed in the exact same locations. Figure 11 below shows cross-section drawings of the two OHL towers.

Figure 10 Left: Existing 150 kV OHL between Endrup and Idomlund.

Right: Proposed 400/150 kV OHL.

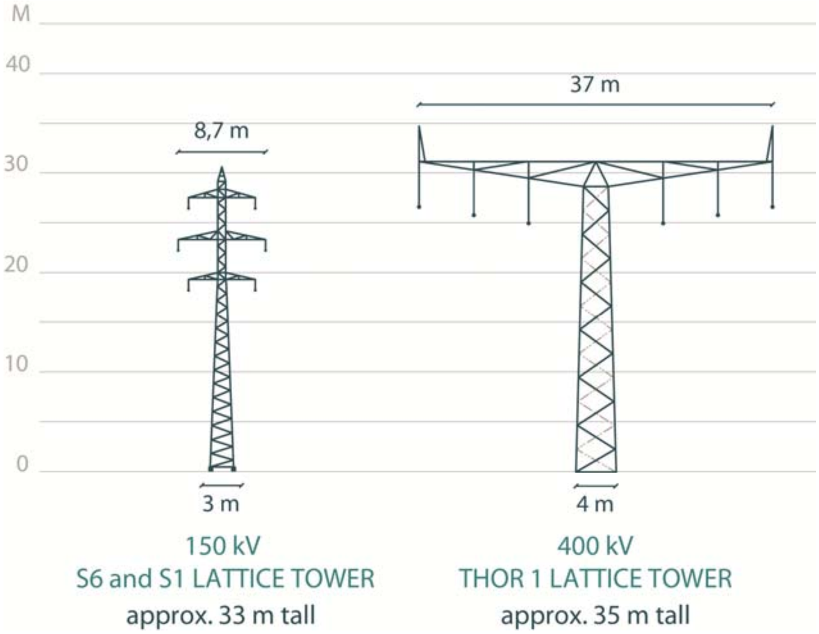


Figure 11: Left: Existing 150 kV OHL tower design between Endrup and Idomlund.

Right: Proposed 400 kV OHL (Thor) tower design.

4.1.2 Reactive power compensation

The demand for reactive compensation of 400 kV OHLs is quite low as the reactive power produced by the line is in the range of approximately 1 Mvar/km. Compensation is normally achieved in Denmark with a single shunt reactor for the whole line. In most cases, shunt compensation is installed at the connecting substations, where shared shunt reactors cover several lines.

4.1.3 Usability

From a technical point of view, OHLs can be used everywhere outside urban areas. The overhead line technology has been developed and improved over decades and today represents a robust and cost-effective solution, which allows for high transmission capacity over long distance. Overhead lines easily integrate in an existing transmission grid and provide a high degree of upgrade flexibility, especially in regions where the required transmissions capacity is expected to increase over time.

4.1.4 Reliability

Overhead lines can develop both temporary and permanent faults. Temporary faults are predominantly caused by bad weather conditions, mostly lightning strikes, but are also occasionally caused by galloping and clashing of conductors in high winds. Salt storms are usually not a problem at the 400 kV level. The experience in Denmark is that very few line faults owe to flying objects, falling trees etc., which may be attributable to the height of the lines compared to those at lower voltage levels and proper pruning of trees in risk zones.

Whenever a fault (short circuit) occurs, the line protection systems are designed to switch off the affected line immediately in order to avoid (or at the very least minimise) equipment damage. Automatic switching sequences (automatic reclosure) are then triggered to re-energize the line and, if a fault proves to be temporary, the OHL circuit is quickly returned to service within a few seconds.

Permanent OHL faults are rare. However, if such a fault occurs, the switching sequences will ensure that the line is switched off permanently, and repair teams are sent to investigate and reinstate the line to an operational condition. This process could take anywhere from a few hours up to a couple of days, depending on the circumstances. If a fault occurs on an OHL in Denmark, normally it will be possible to repair it and get it back into operation within 100 hours.

4.1.5 Environmental impact

The visual impact of an OHL is significant. It is clearly visible in the landscape, and it is clear that it is a foreign element.

Advances in manufacturing technologies and materials mean that designs, that were previously not practically achievable or uneconomic, now have new potential. For new infrastructure, visual amenity can be a key driver in the design. This change has led to a review of more traditional designs, and the development of the Thor tower design, which has been proposed to be used for the 400 kV expansion projects in Western Jutland.

The Thor lattice tower is constructed using pipes instead of the more cost-effective and well-used angled iron. The pipe construction allows for more space between rods, removing sharp edges, which make the overall visual impression less dominant. However, the overhead line will still be visible in the landscape.

This tower design is lower than previous designs, with a maximum height of 32 m from the ground to the cross arm and 36 m from the ground to the tip of the earth wire bearings. Typical distance between towers will be about 330 metres on average (maximum 360 metres).

4.2 400 kV HVAC underground cables

4.2.1 General

Underground cables (UGCs) play an important role in transmission applications, particularly in urban and congested areas, and areas where environmental concerns must be addressed.

Unlike OHLs, underground cables do not use air as an insulating medium. Instead, a specially developed cross-linked polyethylene (XLPE) compound is used. Wind causes movement of air, making it better at transferring heat away from OHL conductors compared to the surrounding soil of cable installations. To compensate for this, the cross-section of cable conductors is generally larger than that of overhead line conductors in order to reduce electrical resistance and heat produced.

The market offers many different cable designs, and the various manufacturers each have a special approach to design and production. Figure 12 shows a cross-section of a cross-linked polyethylene (XLPE) insulated cable as they are typically designed for the transmission grid.

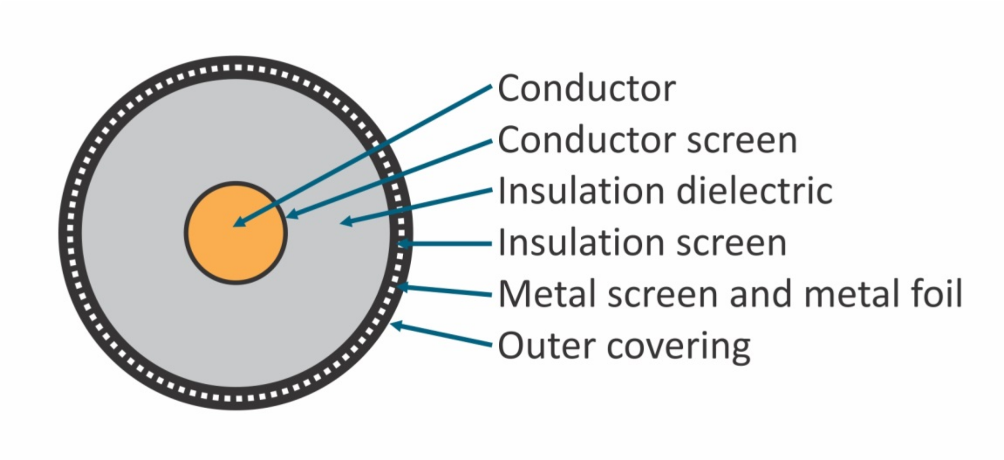


Figure 12: Example design of a single-phase underground cable.

The figure shows the main components of a single-phase underground cable:

- Conductor (aluminium or occasionally copper);
- Conductor screen (semi-conductive layer) (PE);
- Insulation dielectric (cross-linked polyethylene) (XLPE);
- Insulation screen (semi-conductive layer) (PE);
- Metal screen and metal foil (aluminium or copper);
- Outer covering (PE).

Increasing the voltage allows more power to be transmitted but also increases the required cable insulation thickness. In order to match the capacity ratings of 400 kV OHLs, more parallel cable circuits are normally required.

4.2.2 Loadability

The XLPE insulated cables have a large thermal mass compared to overhead lines, and the thermal time constant of a cable installation and the surrounding soils normally allows for significant short-term overloading and moderate long-term overloading, whereas OHLs only allow for limited overloading and only short-term.

For combined OHL/UGC transmission lines, rated capacity of the applied cable system may be lower than rated capacity of the overhead line sections, as the short-term dynamic loadability of the cable system is designed to match the rated capacity of the OHL sections in order to meet required transmission capacity during contingencies for up to 40 hours (see Figure 13).

Significant savings can be achieved with proper optimisation of the rated and dynamic loadability of a cable system. Dynamic loadability ratings are calculated using expected preloading of the cable system and the maximum allowed operating temperature of the conductors and surrounding soil.

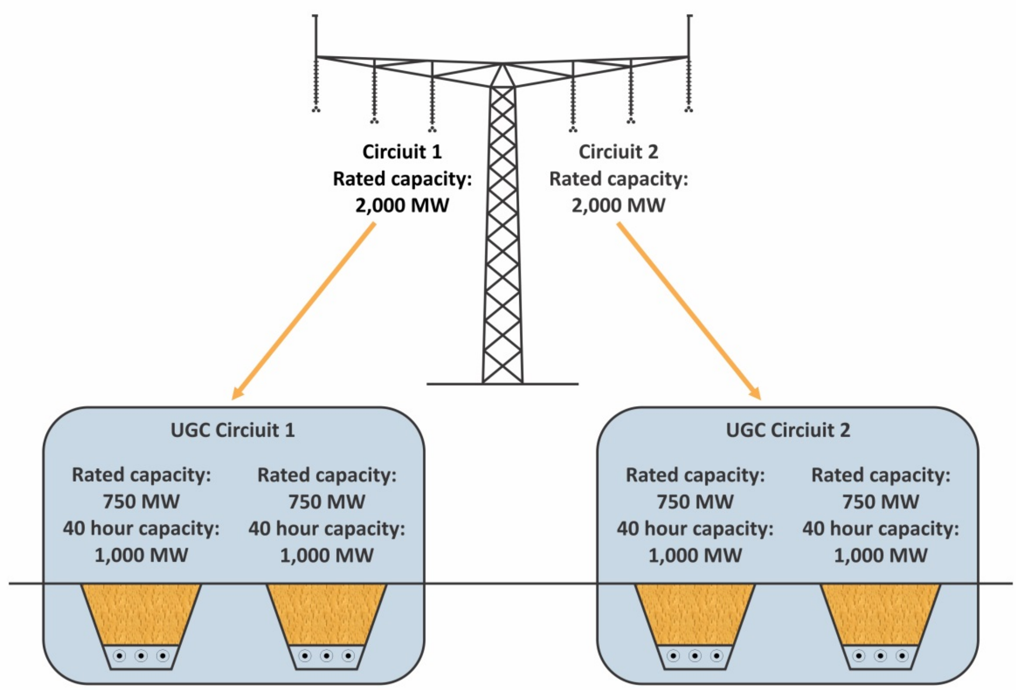


Figure 13: Comparison between capacity of an OHL and corresponding UGL.

To match the rated capacity of a 400 kV double circuit OHL, 12 separate single-core cables in four separate trenches are needed, resulting in a work zone of up to 36 metres wide as indicated in Figure 14. UGCs with a capacity requirement comparable to OHLs will have significant environmental impacts and restrictions along the route. In this declaration area, the construction of buildings or roads or terrain changes is only permissible in exceptional circumstances. Compared to OHLs, cables allow for minor adjustments of the right of way for mitigating local land problems.

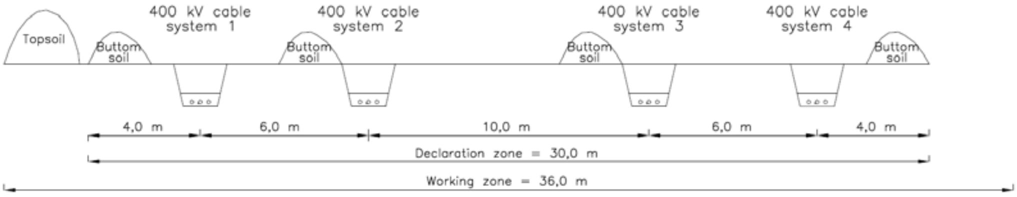


Figure 14: Expected construction and declaration area with two cable systems per OHL system.

4.2.3 Screen system

In long cable systems, single-core cable screens are typically cross-bonded. This is done in order to reduce circulating currents in the screens and reduce losses. A cross-bonded major section is comprised of three minor sections, and in each minor section, screens are cross-bonded as shown in Figure 15. At the end of each major section, screens are bonded and grounded.

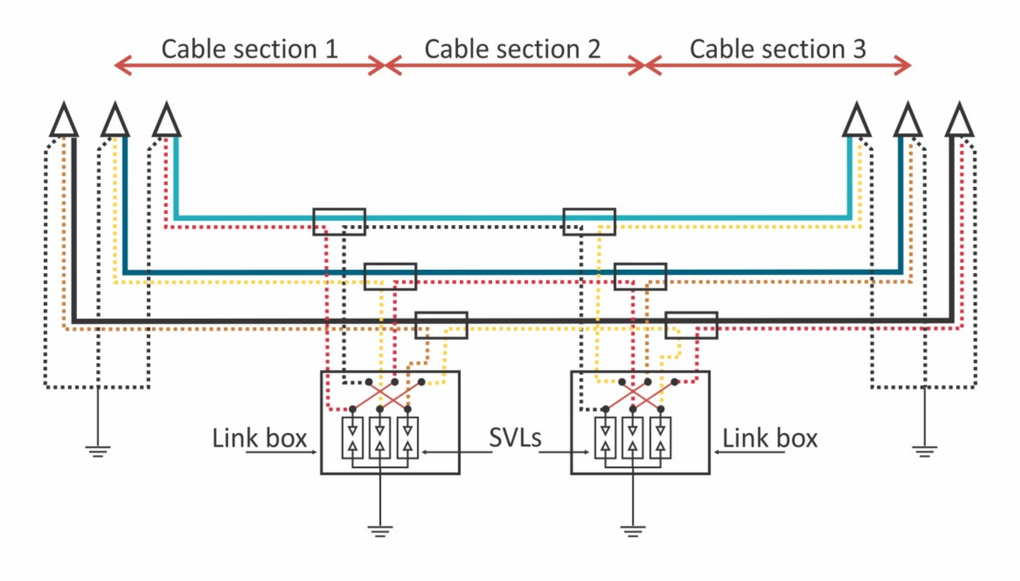


Figure 15 Cross-bonding of underground cables.

In each link box, where physical cross-bonding is done, sheath voltage limiters (SVLs) are placed. The typical distance between link boxes in a 400 kV cable systemcable installation is 1-1.5 km.

4.2.4 Survey of EHV cable systems in service

In 2007, CIGRE conducted a survey [8] on the use of EHV underground cables around the world. The results of the survey are presented in Table 1.

Country	Installed amount of EHV cables
Denmark	52 km
France	2 km
Germany	65 km
Italy	34 km
Japan	123 km
Korea	221 km
Netherlands	7 km
Singapore	111 km
Spain	80 km
United Kingdom	166 km
USA	536 km

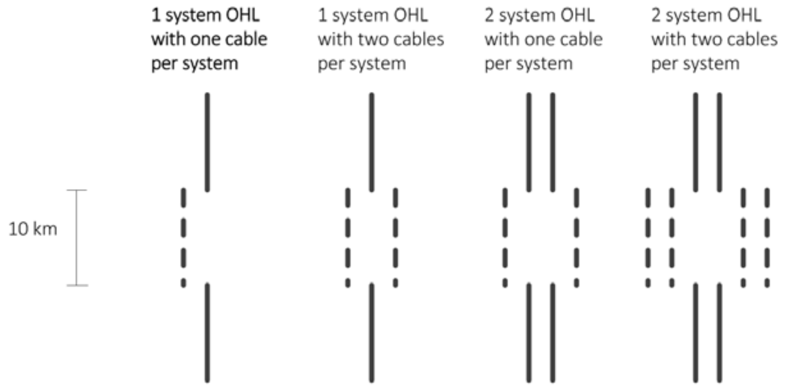
Table 1: EHV underground cables – CIGRE survey – 2007.

In 2017, CIGRE updated the 2007 survey [9], identifying the longest 400 kV cable projects in service in the world. Updated results are shown in Table 2 below.

Figure 16 shows how line length and system length correspond and are defined. The *line length* represents length corresponding to one OHL system. If more cable circuits are used per system, this summed length is presented in the *system length* column.

Country	Year of com-missioning	System name	Number of circuits in the system	Voltage (U_N) [kV]	Capacity [MVA]	Line length [km]	System length [km]
Norway	2017	Kollsnes-Mongstad	1	420	300	30	30
Spain-Morocco	1997	Spain-Morocco Interconnection	1	420	700	28	28
Spain-Morocco	2006	Spain-Morocco Interconnection	1	420	700	33	33
China	2009	Hainan-Guangdong	1	525	740	32	32
Denmark	1997	Copenhagen	1	420	975	22	22
Canada	1984	Bc Hydro-Vancouver	2	525	1,200	38	76
Saudi Arabia /Bahrain	2006	GCCIA Interconnection	2	420	1,200	51	102
United Kingdom	2005	St John's Wood	1	420	1,600	26	26
Japan	2000	Shin-Toyosu Line	2	525	1,800	40	80
Italy	2015	Sorgente-Rizziconi	2	420	2,000	47	95
Netherlands	2015	Randstad	2	420	5,280	20	40

Table 2: EHV underground cables – CIGRE survey - 2017.



Line length	10 km	10 km	20 km	20 km
System length	10 km	20 km	20 km	40 km

Figure 16: Definition of line length and system length.

The updated information on projects completed worldwide shows that the application of EHV underground cables is growing dynamically. The overview shows, that up to now, projects have been implemented mainly in urban areas, as part of underwater crossings or in areas of special environmental interest, which have also been the main drivers for the use of EHV underground cables in Denmark as described in the following sections.

4.2.4.1 Existing 400 kV cables in Denmark

In Denmark, 400 kV underground cables are used in urban areas and to reduce environmental impact in areas of special environmental interest. The locations of existing 400 kV UGCs in Denmark are shown in Figure 17. More details on the 400 kV UGCs installed in Jutland and Zealand are shown in Table 3 and Table 4, respectively.

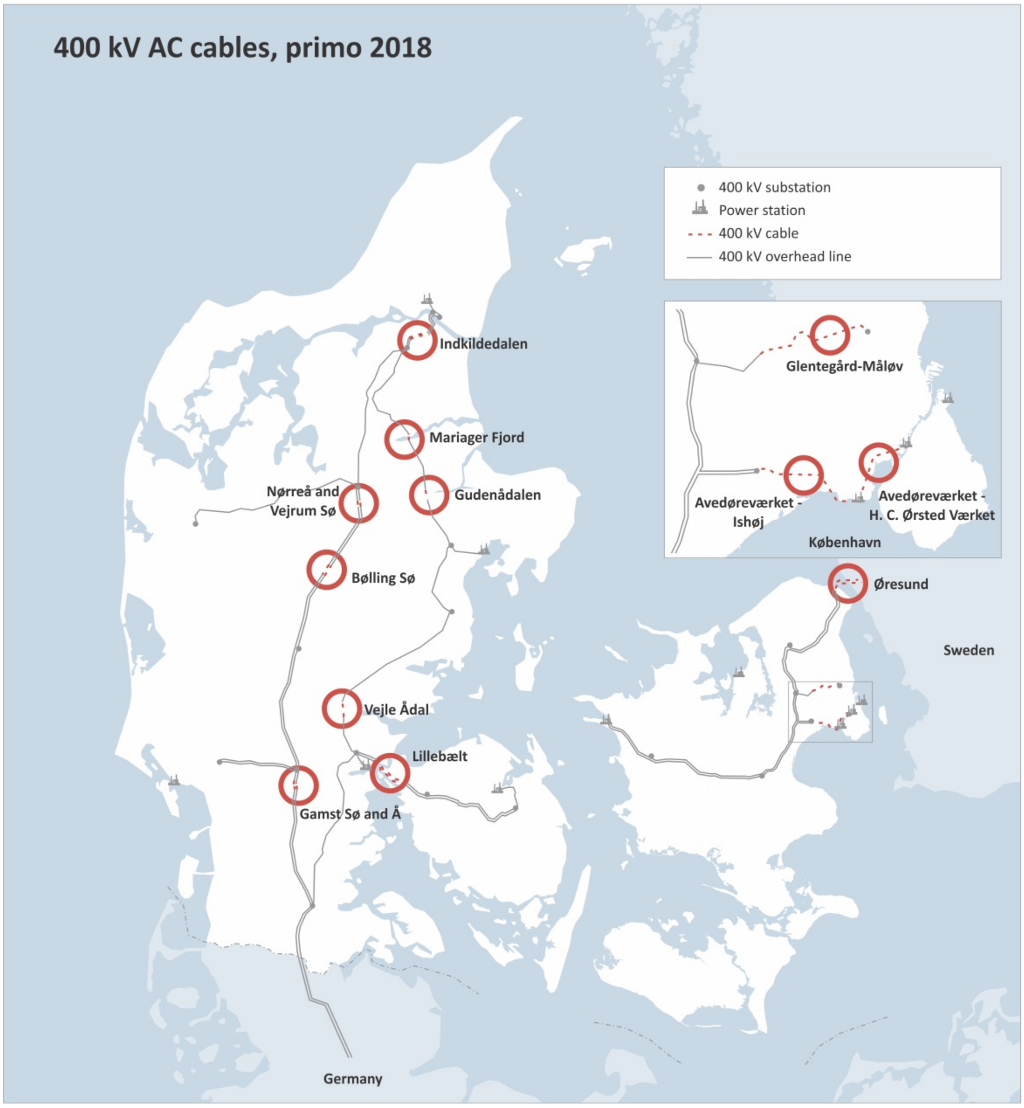


Figure 17: Locations of existing 400 kV underground cables in Denmark.

The majority of these 400 kV underground cables have been installed during the past 20 years.

Region	Year of com-missioning	System name	Number of circuits in the system	Voltage (U_N) [kV]	Capacity [MVA]	Line Length [km}	System Length [km]
Jutland	2004/2015	Indkildedalen	3	420	-	15.8	23.2
Jutland	2004	Mariager Fjord	2	420	-	2.8	5.6
Jutland	2004	Gudenådalen	2	420	-	4.5	8.9
Jutland	2014	Nørreå/Vejrum Sø	2	420	-	3.2	6.4
Jutland	2014	Bølling Sø	2	420	-	9.0	18.0
Jutland	2017	Vejleådal	2	420	-	7.0	14.1
Jutland	2012	Gamst Å/Gamst Sø	2	420	-	4.9	9.8
Jutland	2013	Lillebælt	2	420	-	12,5	24.9
Total						**59.6**	**110.9**

Table 3 Length of 400 kV underground cables in Jutland.

Region	Year of com-missioning	System name	Number of circuits in the system	Voltage (U_N) [kV]	Capacity [MVA]	Line Length [km}	System Length [km]
Zealand	1999	Glentegård-Måløv	1	420	-	12.0	12.0
Zealand	1997	Avedøreværket- H. C. Ørstedværket	1	420	-	8.9	8.9
Zealand	1973/1983	Øresund[2]	1	420	-	9.7	9.7
Zealand	1997	Avedøreværket – Ishøj	1	420	-	12.1	12.1
Total						**42.6**	**42.6**

Table 4 Length of 400 kV underground cables in Zealand.

In total, 115 km line length of underground cable circuits with a total system length of 154 km is installed in Denmark. The 154 system kilometres of 400 kV underground cables equal 462 km of single-core cable.

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[2] The 400 kV cables crossing Øresund are part of the interconnector to Sweden. In the table, length is only summarised for Energinet-owned cables. If Swedish-owned cables are included, the Øresund crossing totals approximately 18 km.

4.2.4.2 Ongoing 400 kV cable installation in Denmark

Energinet is currently installing a 17 km 400 kV cable system between Ishøj and Hovegård substations (planned commissioning in 2018) as part of the grid connection of the Kriegers Flak offshore wind power plant.

4.2.5 Reactive power compensation

Underground cables are inherently capacitive and may require the installation of reactive power compensation when used in HVAC systems. The likelihood that additional reactive compensation will be needed for a particular underground scheme increases with operating voltage and circuit length.

The reactive power production of cable circuits compared to their OHL equivalents is considerably higher (8-10 times). Consequently, shunt reactors are installed at the connecting substations and possible also at one or more intermediate compensation substation(s) along the route, depending on the length of the UGC circuit.

The number of intermediate compensation substations and matching requirements for reactive compensation is determined by the requirement to control the flow of reactive power of cable circuits as well as voltage regulation of the transmission grid. Reducing the number of intermediate substations for an UGC installation makes it more difficult to control the voltage profile of the transmission line and the adjacent transmission grid, as well as decreasing loadability of the cable.

4.2.6 Usability

400 kV HVAC cables are typically used:

- In urban areas, where the use of overhead lines is not feasible and the transmission capacity requirement is so high that a 132-150 kV cable solution would not be sufficient;
- For underwater crossings, like the Øresund sea crossing between Sweden and Denmark, where the distance is too great to use OHLs and HVDC is too expensive; and
- When crossing areas of special environmental interest.

A single 400 kV cable circuit is normally sufficient for transmission lines with capacity requirements of less than 800 MW. Requirements for transmission lines in large, meshed grids are typically different and more demanding than for radial connections to local consumer areas or generation areas, and therefore, overhead line technology is preferred due to its cost-effectiveness compared to underground cables.

Obstacles such as roads, railways, watercourses and other sensitive areas can be crossed using horizontal directional drilling.

4.2.7 Reliability

The limited experience with 400 kV underground cable systems in operation shows that faults typically occur in the beginning of the operational phase and, after a period with low probability of faults, the probability will increase again when approaching end-of-life (a classic U-curve shape).

Cables are often considered maintenance-free, and outages have not played an important role due to the relatively small percentage of UGCs in the transmission grid.

Cable failures are less common than for overhead lines but they do occur. Because most of an underground cable system is inaccessible, fault location can slow the restoration process. An underground cable may require 2-4 weeks to repair once the failure has been located, during which time generation and cross-border exchange might be affected.

4.2.8 Environmental impact

Although underground cable systems have much less visual impact than an OHL, considerable portions of the cable system is still visible above ground, especially at the terminal ends between OHL sections and reactive compensation stations. Underground cable systems are generally less prone to environmental issues than OHLs because they generate less audible noise.

4.3 400 kV HVAC gas-insulated transmission lines (GILs)

4.3.1 General

Gas-insulated transmission lines (GILs) were invented in the early 1970's with the objective of providing a high-capacity transmission system with maximum safety for equipment and personnel in energy tunnel systems. This target was reached by replacing flammable insulation materials (e.g. XLPE and fluid-filled cables) with non-flammable and non-toxic insulating gas. Consequently, the first GIL systems were installed in energy-tunnel systems for cavern and hydro power plants, e.g. the 380 kV GIL system at Schluchsee Pump Storage HPP (1975) which is still in service.

GIL systems have an expected service life of more than 60 years. The insulating gas does not age, and the inbuilt resin insulators are operated in protective gas, preventing oxidation of materials. Issues related to voltage-induced aging of insulators are unknown.

A GIL system consists of two concentric aluminium tubes for each phase. The inner conductor rests on cast resin insulators, which centre it within the outer sheath. This casing is formed from a stable aluminium tube, which ensures a solid mechanical and electro-technical encapsulation of the system. To satisfy the latest environmental and technical aspects, GIL systems are filled with an insulating gas mixture consisting mainly of nitrogen and a small proportion of sulphur hexa fluoride (SF_6). The GIL structure is shown in Figure 18.

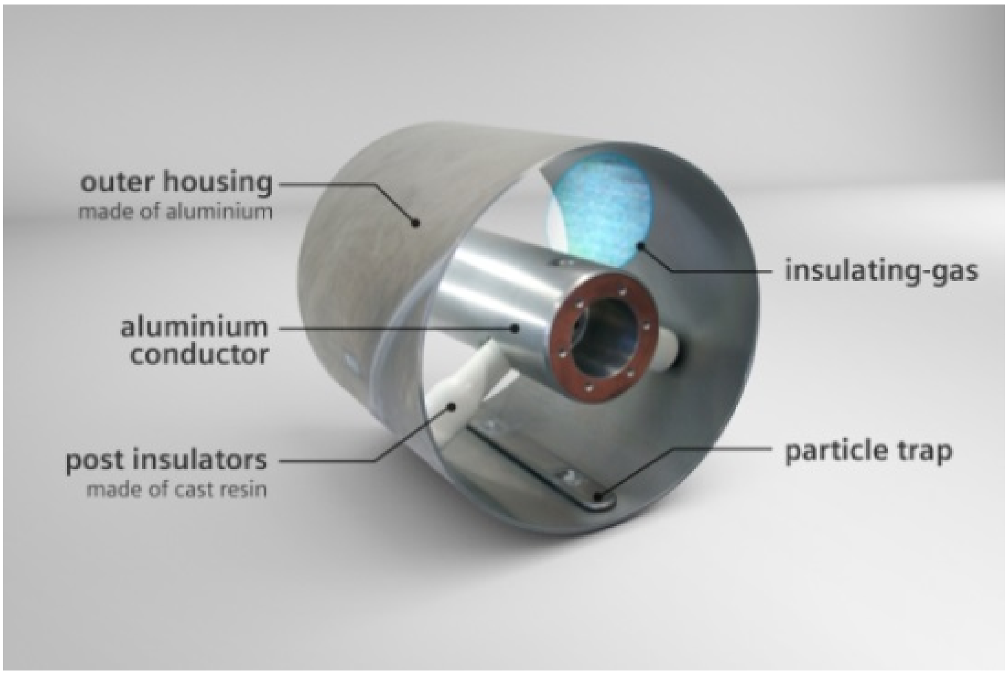

Figure 18 GIL structure (photo: Siemens).

Enclosures are made from a corrosion-resistant aluminium alloy. According to vendors, the GIL solution can be considered a maintenance-free product, implying no need to refill insulating gas during the expected lifetime of a GIL. The enclosure tube is designed to withstand internal arcs so that no external risk results from GIL systems even in the unlikely case of an internal arc. For monitoring and control of a GIL system, secondary equipment is installed to measure gas pressure and temperature. These are the same elements used in gas-insulated switchgear (GIS).

The gas insulation creates a physical similarity to an overhead line, which means that these two system types can be combined very well from an operational perspective. Therefore, gas-insulated transmission lines (GILs) could, in some cases, be an alternative to OHLs and UGCs.

Pure SF_6, which is the preferred insulation medium, will be very expensive due to Danish taxes on SF_6. However, manufacturers offer alternative insulating gas without global warming potential. Environmental concerns still exist though, as the amount of insulating gas required for long-distance GIL systems will be unprecedented, and the toxicological side effects of the associated by-products are unknown.

4.3.2 Survey of GIL systems in service

GIL systems are suitable for partial undergrounding of OHLs, when connecting substations or power plants to the transmission grid, or as a way to save space when connecting major industrial plants to the grid.

The longest 400 kV GIL system, directly buried into the ground, is approximately a 1 km transmission line with two GIL circuits near the airport of Frankfurt. Figure 19 shows the installation.

Figure 19: Two 400 kV GIL systems directly buried in Kelsterbach (photo: Siemens).

4.3.3 Reactive power compensation

Because of the low capacitance of a GIL system, compensating reactors are generally not required, even for long GIL sections. The generation of reactive power of a standard GIL system (approximately 3 Mvar/km) is only one third of what is generated by a 400 kV XLPE cable.

4.3.4 Usability

GIL systems for EHV transmission can be delivered in different designs, suitable to be used as substitutes for OHLs in a variety of configurations. All elements such as tubes, angles and special modules are lightweight and small enough to be transported by comparatively light standard trucks.

As described in Section 4.3.2, GIL systems are predominantly installed in tunnels, but there are commercial solutions available where GIL is directly buried into the ground. This is, however, only used to a limited extent.

There is a lack of experience with long horizontal directional drilling for GIL purposes or the establishment of tunnels for GILs in wetlands.

4.3.5 Reliability

The reliability of GIL systems in controlled environments, such as tunnels, is regarded as very high, although no further statistical information can be given due to a lack of operational experience.

Welded GIL systems are practically maintenance-free with an expected long service live (the first GIL system was installed in 1975). The technology is claimed to have no immediate limitations length-wise, and the same high degree of reliability should be expected when using welded tubes.

In traditional outdoor GIL systems used in switchgear installations, more leakage issues are reported due to leaky joints. However, a welded GIL system for transmission line purposes uses a different technology and no gas leakages should be expected.

4.3.6 Environmental impact

The environmental impact of GIL systems during and after the construction phase is comparable to that of underground cables.

SF_6 is a relatively nontoxic gas used in a number of electrical applications for its inert qualities. The dielectric properties related to its lack of reactivity have led to the extensive use of SF_6 as an insulating gas in switchgear equipment. While SF_6 is inert during normal use, when electrical discharges occur within SF_6-filled equipment, toxic by-products can be produced that pose a threat to the health of workers who are exposed to them.

While SF_6 is the most potent greenhouse gas evaluated, alternative gasses (clean air or Fluoronitrile) without global warming potential might be alternatives in the future. However, the handling of the insulating gasses might require big scale storage and transport capacity, but this has not been investigated further due to the limited application of GIL systems worldwide.

4.4 High Voltage Direct Current (HVDC)

High voltage direct current (HVDC) is a well proven technology for transmitting power efficiently and reliably over long distances. The benefits of long-distance transmission with low losses, combined with features like the ability to connect unsynchronized power systems, have opened up new opportunities for this versatile technology. HVDC has been used in Denmark since 1965, interconnecting Sweden and Jutland (the Konti-Skan link).

4.4.1 General

Two technologies are used for HVDC-transmission:

- Line-commutated converters (LCC) based on thyristors;
- Voltage source converters (VSC) based on transistors.

Today, LCC technology is mainly built for very high power transmission with ultra-high DC voltages (800 kV and above) and overhead DC lines. All HVDC projects under construction in Europe are based on the VSC technology and, being considered the new standard, only this technology will be described in the following.

4.4.1.1 Voltage Source Converters

The VSC technology is based on transistors, mainly insulated-gate bipolar transistors (IGBTs). The state-of-art technology is the Modular Multi-Level Converter (MMC) configuration where the converter comprises a large number of IGBTs connected in series within each leg of the three phases.

The reactive power exchanged between a HVDC VSC link and the HVAC grid can be controlled independently at both ends of the link and within the rating of the link, independent of transferred active power. A HVDC VSC link can support steady state voltage regulation but, more importantly, also provide dynamic voltage support during and after disturbances in the surrounding transmission grid.

Several HVDC VSC links use DC voltages of 320 kV, but links are currently under construction utilizing XLPE cables with DC voltages of up to 525 kV. The DC current is limited by the maximum current allowed by the IGBTs and typically lies in the range of 1,200-2,000 A.

Electrical loss in each converter typically amounts to 0.9-1.1 % of the transferred active power. In addition, losses in the HVDC cables must be considered.

4.4.1.2 Configuration of HVDC links

A HVDC VSC link can be configured in several ways. Many VSC links are symmetrical monopoles where two HVDC cables for plus and minus voltages are used (e.g. +/-320 kV on the 700 MW COBRAcable between Denmark and the Netherlands). To increase power rating, a bipolar configuration is commonly used, like a rigid bipole (as planned for Viking Link) or a bipole with metallic return or ground return. The different options are shown in Figure 20 to Figure 23.

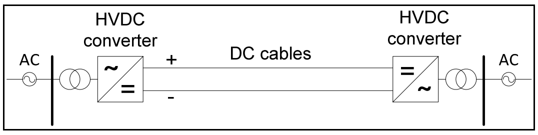

Figure 20: Symmetrical monopole.

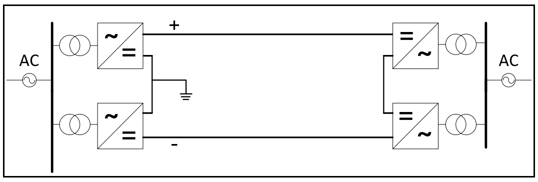

Figure 21: Rigid bipole.

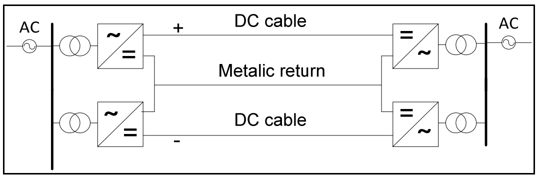

Figure 22: Bipole with metallic return.

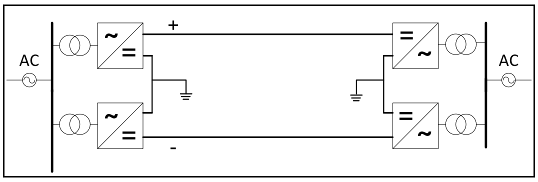

Figure 23: Bipole with ground return.

4.4.1.2.1 Rigid bipole

The rigid bipole only uses two HVDC cables and no ground return conductor (e.g. +/-525 kV for Viking Link). The drawback is that full transmission capacity is lost in case of a cable fault. In the case of a fault in one of the converters, the full transmission capacity is lost until the HVDC cables are reconfigured for monopole operation with one set of converters. If the DC switchyard is equipped with switching devices, half of the transmission capacity can be re-established within a few seconds.

4.4.1.2.2 Bipole with metallic return

The bipole with metallic return requires two HVDC cables and a medium voltage return cable. The advantage is that half of the transmission capacity can be maintained in case of a fault on a cable or in a converter. A disadvantage is the additional cost of the third cable. During maintenance of the converters, monopolar operation is possible without any special DC switching devices.

4.4.1.2.3 Bipole with ground return

The bipole with ground return requires two HVDC cables and an electrode station in each end of the link. During normal operation, no current flows to the ground. During a cable or converter fault, however, monopole operation will require that the full DC current returns through the ground. For long HVDC links, the ground return solution is cheaper than using a metallic return cable but long-lasting ground currents may result in corrosion of metallic pipelines near the electrode stations.

4.4.1.2.4 Multi-terminal HVDC

There is growing interest in VSC-based multi-terminal HVDC schemes due to the advantages they offer over LCC-based multi-terminal HVDC schemes, e.g.:

- The ability to control the power flow through each of the interconnected converter stations and the capability to reverse power flow through a converter station without the need for mechanical DC switches; and
- The advantages inherently offered by VSC over LCC converters such as the ability to connect to passive grids and lower harmonic generation.

The major drawback of VSC-based multi-terminal HVDC schemes is the very limited operational experience with its implementation and operation. Due to this, credible and reliable data regarding expected challenges during installation and operation of a multi-terminal HVDC scheme is sparse due to the very limited number of installations in operation.

One of the benefits of an HVAC transmission line is its flexibility in providing connection points for future generation and consumption along its route. A multi-terminal HVDC link can to some extent be used similarly, thereby enabling the fulfilment of the technical objective of a transmission line between Endrup and Idumlund. The configuration in Figure 24 exemplifies the grid connection of two offshore wind power plants (WP) with the advantage of feeding generation from the HVAC substation Stovstrup (STS) to different AC substations, in this case EDR (Endrup) and IDU (Idomlund).

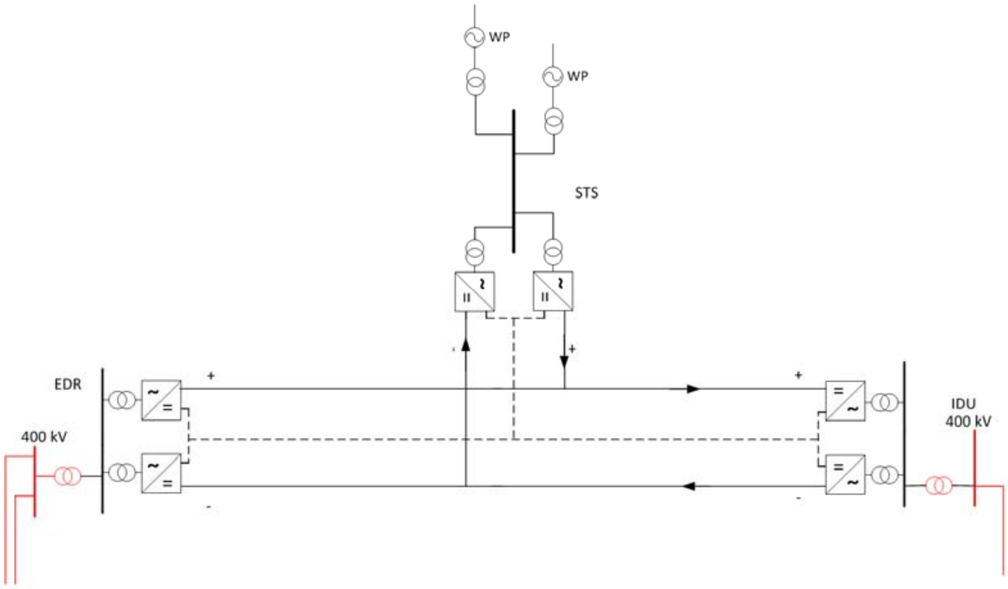

Figure 24: Two three-terminal HVDC links configured as bipoles exemplified using the Endrup-Idomlund transmission line.

The dimensioning contingency in the Danish transmission grid is loss of 700 MW, meaning that any internal fault in an HVDC link used to connect generation to the transmission grid must not lead to a momentary loss of power of more than 700 MW at any time. This limitation must be observed for a multi-terminal HVDC link as an alternative to the HVAC transmission line between Endrup and Idumlund, and, thus, the rating of converters in Stovstrup must not exceed 700 MW.

4.4.1.3 Control functions

By nature, a HVDC VSC link will not react to the loss of a parallel HVAC transmission line by automatically adjusting its flow of active power as would be the case with an HVAC transmission line. Fast control of active and reactive power to support the grid can be achieved with the application of special control functions. There are a few HVDC links around the world where the control systems are designed to emulate an HVAC transmission line but operational experience is limited.

4.4.2 Usability

HVDC links are used in special cases in the transmission grid and the main reasons for selecting HVDC are:

1. Interconnection of two asynchronous power systems;
2. Long distances (including long submarine cables where OHLs are not possible); and
3. Very high levels of power transmitted over very long distances where HVDC is more cost-effective than HVAC transmission.

For power transmission applications other than these three, and particularly over relatively short distances, HVAC rather than HVDC transmission links are normally more economic due to the high cost of converter stations.

The HVDC link across the Great Belt is an example of item 1 above. For other interconnections between the Nordic synchronous system and the Central Europe synchronous system (e.g. Skagerrak), both items 1 and 2 are relevant. In Germany, HVDC links are used to connect large offshore wind power plants located far from shore. This has not been implemented in Denmark to date. In China, for example, several HVDC links have been built to accommodate high levels of power transported over very long distances (item 3).

HVDC transmission does not naturally integrate with HVAC systems and does not impart to the grid the natural resilience of HVAC transmission lines. HVDC is inherently more complex than HVAC in all respects from design, construction, testing, and maintenance to operation. Thus, a meshed HVAC transmission grid with embedded HVDC links will add complexity to future grid planning and expansion.

For these technical reasons, HVDC transmission is normally only used in EHV grids in cases where technical or economic reasons rule out HVAC transmission.

4.4.3 Reliability

The reliability of HVDC links is affected by the frequency and duration of both unplanned and planned maintenance. Unplanned maintenance is a forced outage due to a fault or the failure of an item of equipment. Planned maintenance is typically part of an annual or biannual maintenance schedule or simply a need to do repairs outside normal maintenance plans.

Planned maintenance has a lower impact on the power system as this can be timed to occur when demand is low or reduced transmission requirements are expected. Unplanned maintenance can occur at any time and may have a significant impact on the power system.

ENTSO-E publishes an annual Nordic HVDC Utilisation and Unavailability Statistics [10] in which availability and utilisation of HVDC links connected to the Nordic and Baltic power system are presented with an emphasis on forced outages. The definitions of the abbreviations used to describe reliability are listed in Figure 25. In table 5, statistics for 2016 is presented. Values used are energy values and represent part of the technical capacity.

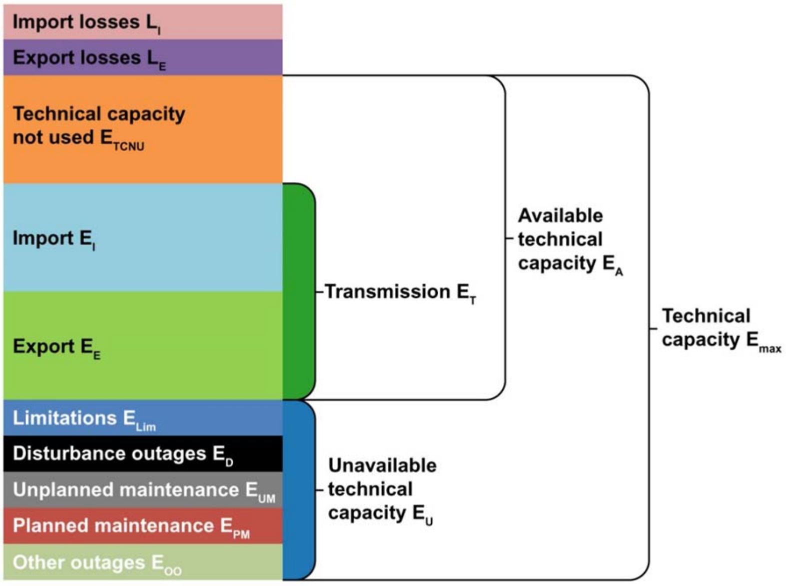

Figure 25: Availability and utilisation categories used in ENTSO-E's HVDC statistics.

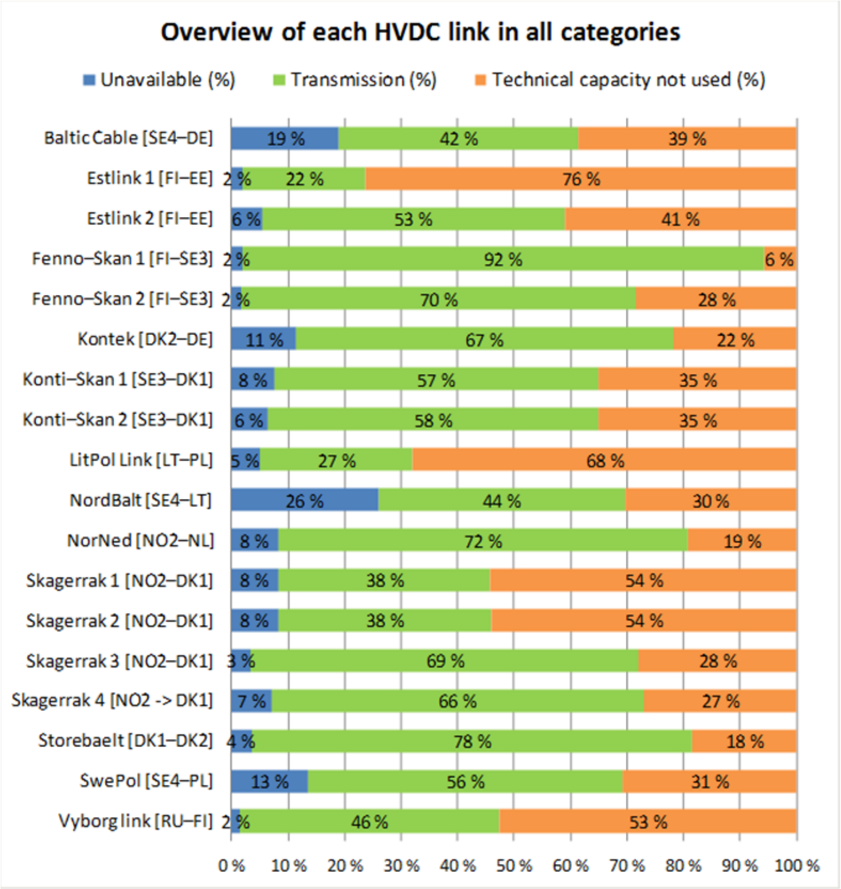

Table 5: Utilisation of Nordic HVDC installations.

Unfortunately, the statistics do not span decades, but the data shows that there are differences in availability. Severe faults lead to quite long unavailability periods due to the complex nature of HVDC installations as well as the risk of DC cable faults.

4.4.4 Environmental impact

The HVAC switchyard of a HVDC link is comparable in character to existing 400 kV substations within the transmission grid. However, the land area of this part of the converter station varies significantly, depending on the HVDC technology employed and the transmission capacity of the HVDC link.

Analyses from the planning phase of the Viking Link project show that the technical installation would cover an area of 42,000 m^2. Figure 26 shows a converter station with a 210 x 200 m^2 footprint.

In total, the substation would cover 20 hectare, or approximately 200,000 m^2, to include necessary parking, rainwater accumulation and shielding planting etc.

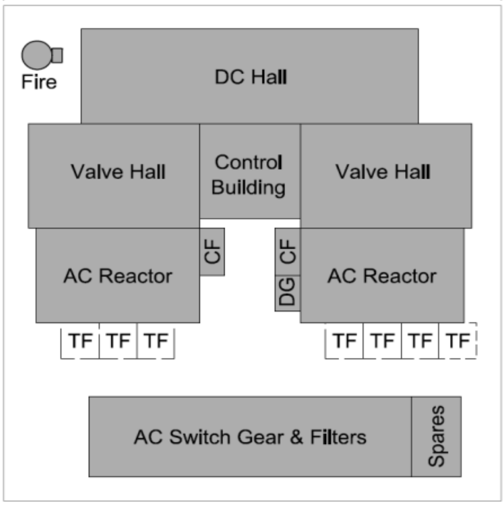

Figure 26 Conceptual layout of a 1,400 MW bi-pole

Figure 27 below visualises the 400 kV Revsing substation following Viking Link's completion.

Figure 27: Visualization of 400 kV Revsing substation after Viking Link's completion.

4.5 Summary

The choice of technology for expanding the transmission grid is based on a number of technical, economic and environmental considerations. In addition, the decision must be based on strategic considerations, especially in areas where future transmission capacity requirements are an important parameter.

In line with the subject of this report, distance, and future transmission capacity requirements are major aspects and, thus, it is important that the technical solution is robust, which will result in a cost-effective long-term development of the transmission grid in Western Jutland.

In this context, an overhead line solution accommodates the transmission capacity requirements and ensures the necessary robustness in relation to the uncertainty of the time of expansion and locations of future offshore wind power plants. OHLs are a proven and reliable technology, and recognized as the preferred solution worldwide despite the obvious visual impact.

The proposed OHL projects in Western and Southern Jutland aim to apply partial underground cabling in areas of natural interest, which ensures that the approved 400 kV OHL solution can be established while taking into account environmental concerns to the greatest extent possible.

GIL systems are currently only used over very short distances. GIL systems buried directly in the ground rather than installed in tunnels are available, which adds potential to the application of GIL systems over long distances. The use and handling of insulating gases will, however, remain a significant challenge.

HVDC is a proven technology and primarily used for bulk power transmission over long distances or for interconnecting asynchronous power systems. The introduction of HVDC VSC technology offers improved technical performance. The application of embedded HVDC links as part of the transmission grid in Western Jutland will introduce considerable complexity with regards to the operation and future development of the transmission grid compared to an HVAC solution.

5. Project-specific considerations regarding the choice of transmission line alternatives

Having identified the need for reinforcement of the transmission grid in Western and Southern Jutland, the first stage of the evaluation of transmission alternatives was to undertake a high-level technical study to identify how these needs could best be met. This section compares the characteristics of the transmission line alternatives described in Chapter 4 and their applicability as part of the described grid reinforcement requirements.

The technology options were subject to technical analysis and comparatively evaluated against the following criteria:

- Usability;
- Technical considerations; and
- Construction schedule.

Different technologies exhibit different electrical characteristics that affect their integration into the transmission grid. Generally, the different characteristics can be technically accommodated but special measures, which increase costs, reduce reliability and increase system complexity, are required.

As already mentioned, the evaluation criteria are assessed at a high level. It is recognised that more detailed development and design is needed to fully identify the impact. The review is based on a range of both generic data and general characteristics, like the ability to integrate with the existing transmission grid, and a range of criteria that can be satisfactorily assessed on a qualitative basis, such as technical considerations, robustness with regard to future expansion/flexibility and risk to project implementation.

Within the scope of this report, cost estimates have been made to facilitate an objective assessment between the costs associated with overhead lines and underground cables as well as between HVAC and HVDC technologies. The cost estimates of the four transmission alternatives are presented and summarized in Section 5.5.

5.1 400 kV HVAC overhead lines

5.1.1 Usability

From a technical point of view, overhead lines can be used anywhere outside urban areas. The technology is simple and electrical issues well known. Moreover, experience gained worldwide on construction and operation of EHV overhead lines has demonstrated the usability and robustness of the technology.

5.1.2 Technical considerations

Neglecting the visual impact, overhead lines can be used for the full route without any further technical considerations including reactive power compensation, voltage control, overvoltages, harmonic amplification, protection etc.

5.1.3 Construction schedule

Overhead lines for the entire route from the Danish-German border to Idomlund can be built within 2½- 3 years.

5.1.4 Summary of project-specific use of OHL technology

From a technical point of view, 400 kV overhead lines have no limitations when all technical aspects are considered. The following advantages have been identified:

- Overhead line technology is easy to integrate into the existing transmission grid;
- Well-proven technology with a high level of reliability;
- Does not affect security of supply for technical reasons such as resonance, etc.; and
- Relatively easy to upgrade or modify as the preferred 400 kV OHL design allows significant flexibility in transmission capacity to accomodate future development of renewable generation in Western and Southern part of Jutland.

No real technical disadvantages to the operability of HVAC OHLs have been identified.

5.2 400 kV HVAC underground cables

5.2.1 Usability

The obvious advantage of underground cable circuits is the potential for reduced visual impact compared to overhead line technologies. Extensive undergrounding of 400 kV transmission lines has not been used anywhere in the world. Globally, 400 kV UGCs are mainly used as part of installations supplying large consumption centres and over short distances, e.g. partial undergrounding.

400 kV underground cables are technically feasible over limited distances, where special environmental issues must be taken into account. From a civil works point of view, it is possible to establish the whole route as an underground cable system; however, from an electrical point of view, operational issues and system impact involve a great deal of uncertainty when incorporating a high cable share in a small electrical system.

5.2.2 Technical considerations

The following sections describe well-known technical issues that must be taken into account when considering the application of long EHV UGSs.

5.2.2.1 Transmission capacity

If a future upgrade is needed to accommodate the projected integration of renewable generation, the increase of transmission capacity with an UGC would be expensive compared to an OHL solution, as it would require the installation of additional 400 kV cable circuits (compared with reconfiguration of an OHL).

5.2.2.2 Reactive power compensation

Full undergrounding of a 400 kV transmission line from the Danish-German border to Idomlund would require the establishment of several compensation installations along the entire route in order to compensate for the charging current from the UGCs. If established as air-insulated outdoor substations, which is Energinet’s current standard for 400 kV substations outside urban areas, each substation would take up 80-100,000 square metres, corresponding to the size of 11-14 football pitches. The base height would be 6-8 metres, but some components for lightning protection, etc. would be approximately 25 metres high. See Figure 28 for an example of the layout of such a compensation installation.

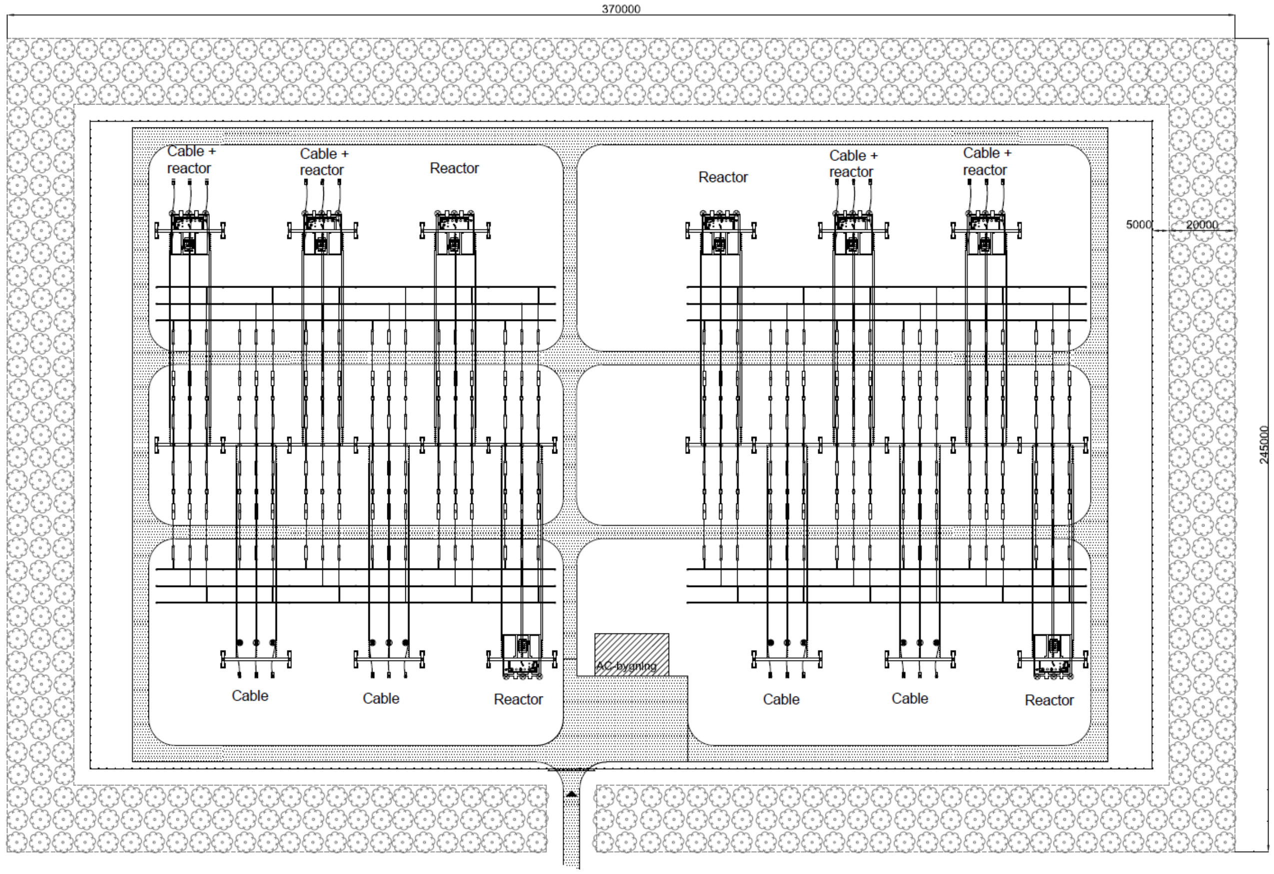

Figure 28: Layout of a compensation installation.

5.2.2.3 Load balancing of the system

Underground cable systems have lower positive sequence impedances [11] as compared to similar overhead lines. As such, they will tend to carry a greater share of the transmitted power when operating in parallel with overhead lines. Detailed analysis must be conducted to establish whether this could effectively be counteracted by inserting reactors in series with cable systems and thereby increasing the apparent reactance of the UGCs.

5.2.2.4 Short-circuit level

A cable solution may result in an increase of the short-circuit level of the transmission grid and thereby exceed the current design limit of 40 kA. If this limit is exceeded, existing components in parts of the transmission grid and at lower voltage levels must be replaced to withstand the elevated short-circuit level. Detailed analysis must be conducted to establish the extent of the required replacement of grid components. In addition, it must be investigated if short-circuit levels can be kept within limits by inserting reactors in series and thereby increasing the apparent reactance of the UGCs.

5.2.2.5 Temporary overvoltage

In an underground cable-based system, the risk of temporary overvoltages (TOV) is higher, as the high capacitance of the UGCs shift resonance points to the low frequency range. This must be considered when evaluating sequences for fault clearing and energization of transformers and shunt reactors as well as load shedding and during black start scenarios.

5.2.2.6 Amplification of background harmonics

A large cable share in the transmission grid increases the risk of resonance and thereby amplification of background harmonics. Resonance conditions may cause high harmonic voltages exceeding planning levels and even ratings of electrical equipment.

For classic HVDC LCC links, the harmonic impedance in the HVAC grid is very important for the harmonic performance of the converter as harmonics currents generated by the LCC may lead to higher harmonic voltage distortion than expected if the HVAC grid impedance is changed to values outside the design specification of the converter. This can give rise to overloading of harmonic filters that may disconnect to protect themselves and, consequently, the harmonic distortion is further increased both locally and globally in the grid. Increased content of harmonic voltages in the grid will negatively affect all customers connected at transmission level.

Harmonic distortion in the transmission grid can result in the distortion of both the current and voltage waveforms. This can lead to poor power quality for consumers. All customers connected to the transmission grid, e.g. wind power plants and large consumers as well as DSOs expect a certain maximum level of harmonic distortion and design their respective plants accordingly. Higher levels than expected can lead to reduction of lifetime of electrical equipment, and in worst-case malfunctions.

5.2.2.7 Effect on existing HVDC link control systems

Large shares of underground cables in the transmission grid will require additional system studies to be performed to ensure HVDC controller stability (wide band stability). For existing HVDC links, it is recommended that the design studies for each HVDC link are updated. The new studies may show that the settings of HVDC control system have to be changed due to the new characteristics of the transmission system.

5.2.3 Construction schedule

The two 400 kV transmission lines must be in operation by 2023 due to the commissioning of the Viking Link HVDC link between Great Britain and Denmark, and the required expansion of the 400 kV grid between Northern Germany and Southern Jutland. The foreseen congestions in the existing 150 kV transmission grid in the Western part of Jutland will inevitably lead to curtailment of renewable generation in the region until the required grid expansions is put in operation.

If the projects in the Western part of Jutland are established with a 50 % share of undergrounding, approximately 750 km single-core cable will have to be installed. The estimated construction period from granting of the final permission to the time of commissioning of such a cable installation is minimum 39 months. The unknown production capacity worldwide poses a risk to this time schedule.

5.2.4 Summary of project-specific use of UGC technology

Apart from the obvious visual advantages and maintaining property values, underground cable transmission systems have one primary advantage over overhead lines:

- Reduced maintenance costs as components of underground cable installations require less maintenance as they are not as exposed. However, external equipment like shunt reactors and switchgears will add to the maintenance costs of a 400 kV cable installation.

The application of 400 kV underground cables is relevant for short distances, assuming the technical issues listed in Section 5.2.2 can be mitigated efficiently without setting precedents and limitations for the future development of the Danish transmission grid.

It must be emphasized that the share of underground cables of future 400 kV grid expansion projects must be seen in the context of the accumulated amount of installed cable circuits in the surrounding transmission grid, as this total amount of cables dictates the applicability of EHV cables in a given transmission grid. For the same reason, it is important that any choice between 400 kV underground cables and overhead lines includes a long-term system design perspective.

An increased share of 400 kV underground cables in the transmission grid introduces a series of unknown factors, and thereby considerable risks. Due to limited operational experience of transmission systems with a significant share of underground cables, relevant technical aspects are examined further in Chapter 6.

Attempts to overcome the technical challenges related to underground cables, all originating from the laws of physics, may delay further expansion of renewable generation in Denmark, as there will be a limit to the total amount of 400 kV underground cables which can be established in a transmission grid.

5.3 400 kV HVAC gas-insulated transmission lines (GILs)

5.3.1 Usability

Installation of GIL systems over long distances (>1 km) has not been done anywhere in the world. However, GIL systems buried directly in the ground rather than installed in tunnels are commercially available, which add potential to the use of GIL systems over long distances in the future.

The installation of long GIL systems introduces a number of unknown factors, and thereby considerable risks, due to limited operational experience. Identified risks mainly relate to construction schedules, installation and long-term reliability issues.

For tunnel installations in urban areas, GILs are considered a competitive solution instead of UGCs, especially for high power transmission capacity applications. GIL systems in tunnels add the advantage of personnel safety, as an internal arc (short circuit) between the conductor and the metallic pipe will not cause a pressure rise in the tunnel. In addition, GIL systems are considered fireproof due to the absence of flammable materials.

Figure 29: GILs installed in tunnels (SIEMENS).

5.3.2 Technical considerations

The following sections describe well-known technical issues that must be taken into account when considering the application of GIL systems.

5.3.2.1 Transmission capacity

GIL systems can be designed for a transmission capacity equal to an overhead line, reducing the space needed for the installation as the required transmission capacity can be achieved with a single circuit whereas two circuits are normally required for undergrounded cable systems.

Figure 30: Double circuit GIL installation (Foto: SIEMENS).

5.3.2.2 Reactive power compensation

GIL systems have the advantage of having electrical characteristics similar to those of overhead lines, which is important to system operation. The capacitance of GIL systems is low, allowing long lines to be installed without the substantial need for reactive compensation of an underground cable circuit.

Reactive power compensation of GIL systems does not pose any technical challenges from an operational point of view. Detailed studies will determine the design and optimum location of the required reactive compensation.

5.3.2.3 Load balancing of the system

GIL systems have lower positive sequence impedances as compared to similar overhead lines. As such, they will tend to carry a greater share of the transmitted power when operating in parallel with overhead lines. Detailed analysis must be conducted to establish whether this could effectively be counteracted by inserting reactors in series, thereby increasing apparent reactance of the GIL system.

5.3.2.4 Short-circuit level

A GIL system may result in an increase of the short-circuit level of the transmission grid and thereby exceed the current design limit of 40 kA. If this limit is exceeded, existing components in parts of the transmission grid and at lower voltage levels must be replaced to withstand the elevated short-circuit level. Detailed analyses must be conducted to establish the extent of the required replacement of grid components. In addition, it must be investigated if short-circuit levels can be kept within limits by inserting reactors in series, thereby increasing apparent reactance of the GIL-system

5.3.2.5 Temporary overvoltage

The risk of temporary overvoltages (TOV) related to GIL systems is considered low; however, detailed analyses must be conducted to establish whether special countermeasures are required for each individual case.

5.3.2.6 Amplification of background harmonics

The risk of amplification of background harmonics related to GIL systems is considered low; however, detailed analyses must be conducted to establish whether unacceptable amplification might occur.

5.3.2.7 Effect on existing HVDC links control systems

The application of long GIL systems is not expected to introduce any risk towards HVDC controller stability (wide band stability).

5.3.3 Construction schedule

A detailed construction schedule of a very long GIL system has not been prepared, but a time schedule for the installation of a 5 km GIL system comprising two circuits (a total of 30 km single phase tubes) has been developed.

The expectation is that the discussed length of 5 km can be installed and commissioned within 3 years. Installation and commissioning of the entire length of the proposed 400 kV transmission lines with GIL technology within the timeframe available seems extremely unlikely.

5.3.4 Summary of project-specific use of GIL technology

The application of long, directly buried GIL systems as part of the required expansion of the transmission grid in Western and Southern Jutland is considered very risky due to the limited operational experience available. Identified risks mainly relate to construction, installation and long-term reliability issues of directly buried GIL systems.

It must be recognized that GIL systems offer several advantages over underground cables as the electrical characteristics of GIL systems are similar to overhead lines, thus reducing the basic challenges related to high capacitance of underground cables as described in Section 5.2.2.

One of the main unknown issues for long GIL systems is the mechanical behaviour in the soil during installation and operation. The reliability of GIL systems in tunnel installations has proven high; however, the reliability of long, directly buried GIL systems must be established before this installation method should be used for long-distance GIL installations.

The expectation is that a length of 5 km can be installed and commissioned within 3 years; Installation and commissioning of the entire length of the proposed 400 kV transmission lines with GIL technology within the timeframe available seems extremely unlikely.

Due to the lack of operational experience of long GIL systems, the significant additional cost and the construction schedule, GIL systems are not considered a feasible transmission alternative as part of the required expansion of the transmission grid in Western and Southern Jutland.

5.4 High Voltage Direct Current (HVDC)

5.4.1 Usability

The next sections describe issues related to the operation of embedded HVDC links in a Danish context with an emphasis on the Endrup-Idomlund project and special aspects to be considered. As described in Section 3.3, the future transmission capacity in Western Jutland will require the establishment of two 400 kV AC circuits between Endrup and Idomlund which constitutes the reference for the evaluation of the HVDC transmission alternative.

Lately, HVDC projects are being developed in Sweden and Germany with long HVDC transmission lines used onshore to provide bulk transport of energy in parallel with existing HVAC grids.

The Swedish SouthWest Link project consists of 180 km of 400 kV HVAC OHLs and two 600 MW HVDC links based on VSC technology. The HVDC lines consist of a 190 km underground HVDC cable and 60 km HVDC OHLs. With a capacity of 2 x 600 MW, the SouthWest Link is supposed to reduce the differences in energy prices caused by a regional deficit of energy. For the discussion in this report, it is important to notice that the nominal power of each individual link is less than the dimensioning contingency in Southern Sweden (700 MW).

The German projects SuedLink and SuedOst Link are in the planning and design phase. Suedlink consists of two 2,000 MW links between Brunsbüttel northwest of Hamburg to Heilbronn north of Stuttgart. The distance between those points is around 600 km. According to TenneT TSO GmbH, the expected timeframe for commissioning is 2025.

SuedOstLink consists of a 2,000 MW link over a distance of around 580 km from Sachsen-Anhalt to Bavaria. According to TenneT TSO GmbH, the expected timeframe for commissioning is 2025. It should be noted that the nominal power of each individual link is less than dimensioning contingency in Germany (3,000 MW).

Please note that the objectives of the Swedish and German grid expansion projects and the expansion projects in Western Denmark are quite different. As mentioned, the main purpose of the Swedish and German projects is the facilitation of bulk energy transport from point to point, whereas the Danish project between Endrup and Idomlund aims to reinforce the transmission grid as well as to accommodate an increase in renewable power generation in Western part of Jutland.

In Germany, HVDC VSC technology is in some cases used to connect offshore wind power plants to the 400 kV transmission grid. Mainly because the distances from the onshore connection point to the offshore wind power installations are too long for HVAC transmission. Also, the capacity of the wind power plant might require the installation of more parallel HVAC cables, making this solution less cost-efficient compared to a single offshore HVDC link.

Another reason is that the dimensioning contingency in central Europe allows for the utilisation of HVDC links with larger capacity, thereby leading to more cost-effective solutions compared to smaller HVDC links feasible in Denmark.

5.4.2 HVAC versus HVDC reinforcement

Overall, the objective of the project-specific considerations is to accommodate the identified substantial need for an expansion of the 400 kV transmission grid in order to facilitate the integration of large amounts of renewable energy and fully utilise interconnector capacity. In this context, it is important to understand the fundamental differences between HVAC and HVDC technology to understand the criteria used to approve or reject various transmission technologies in the final section. Therefore, basic HVAC versus HVDC reinforcement concepts are discussed in detail in the following sections.

5.4.2.1 HVAC reinforcement

To demonstrate the differences between HVAC and HVDC when it comes to system performance, the example below assumes that wind power generation comparable to two 700 MW offshore wind power plants is connected at Stovstrup substation and that the proposed 400 kV transmission line between Endrup and Idomlund is operated with two 400 kV circuits. The scenario involves high wind power generation and northbound flow as illustrated in Figure 31. The left illustration shows the power flow during normal operation, and the right illustration shows the power flow during a contingency (N-1) involving an unscheduled tripping of one of the 400 kV circuits of the proposed Idomlund-Stovstrup transmission line. The size of the arrows indicates the level of pre-contingency active power flow and post- contingency active power flow.

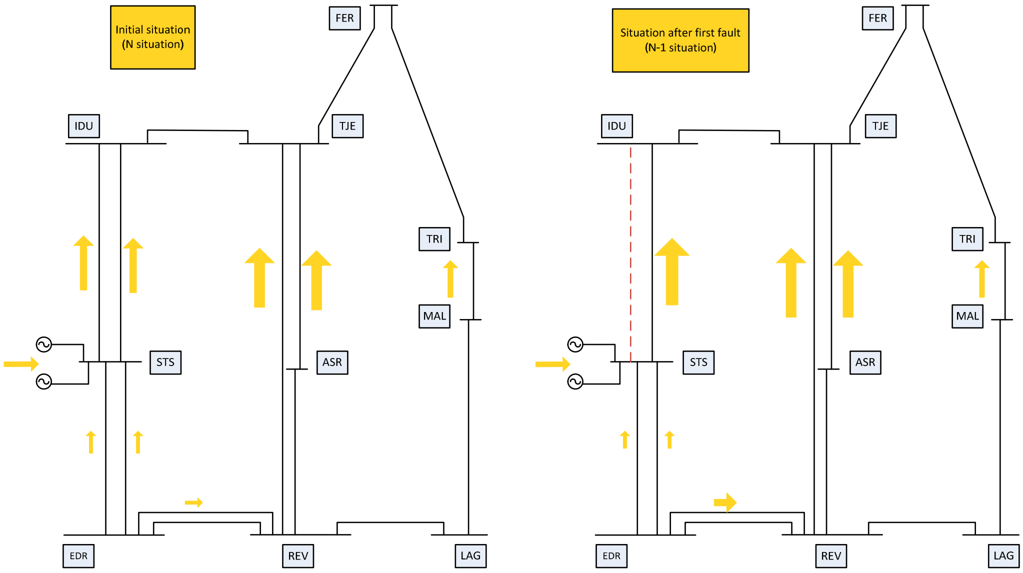

Figure 31: N-0 and N-1 scenarios (HVAC reinforcement).

Due to the nature of a HVAC-based transmission grid, a contingency (fault) on a transmission line (red dashed line in the right illustration) will automatically lead to a redistribution of active power flow between the remaining parallel transmission lines within the grid. The largest share of the pre-contingency active power flow is inherently taken over by the remaining 400 kV circuit between Idomlund and Stovstrup, while load on other parallel transmission lines is impacted by this contingency to some degree.

5.4.2.2 HVDC reinforcement

All HVDC converters dedicated to connecting wind power plants to the grid are limited to 700 MW because of the dimensioning contingency in DK1, as described in Section 2.4.1.

Assuming the same boundary conditions as in the HVAC example above, an HVDC solution with similar amounts of wind power generation connected to Stovstrup substation requires at least two 700 MW HVDC links.

In Figure 32, the left illustration shows the power flow during normal operation, whereas the right illustration shows the power flow during a contingency (N-1) on the HVDC links and in the surrounding HVAC transmission grid due to a DC cable fault between Stovstrup and Idomlund. The size of the arrows indicates the level of pre-contingency active power flow and post- contingency active power flow.

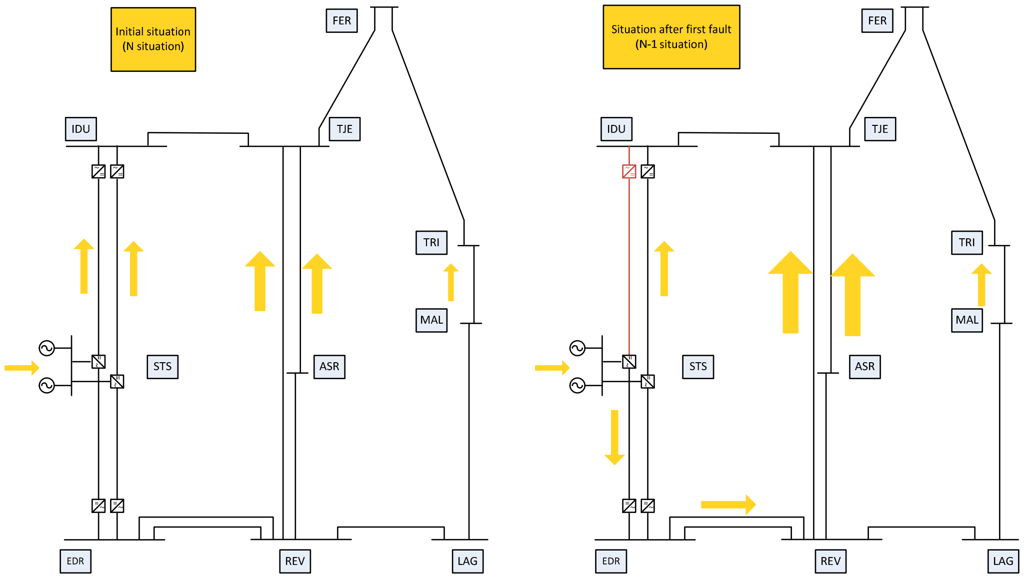

Figure 32: N-0 and N-1 situation (HVDC reinforcement).

The example shows that if one of the HVDC links between Idomlund and Stovstrup trips in a situation with high wind power generation and a pre-scheduled northbound power flow, the northbound loading on the existing parallel 400 kV HVAC transmission lines increases. To avoid overloading on the transmission lines due to this load increase, additional HVDC capacity must be established in order to maintain a secured pre-contingency active power flow before a contingency (fault) occurs.

As an overall design criterion, an embedded HVDC multi-terminal link concept must be sufficiently robust and flexible in terms of accommodating long-term transmission capacity in Western and Southern Jutland. In addition, such a concept must be proven reliable and stable in order to withstand the defined *normal* and *exceptional* types of contingencies without compromising the security of supply. Without carrying out detailed grid studies, it is estimated that a 1,000 MW HVDC link between Revsing and Tjele would be sufficient to withstand the defined contingencies, thus bringing the transmission capacity of the HVDC multi-terminal link concept on a par with the 400 kV HVAC alternative.

The evaluation of the embedded HVDC multi-terminal link concept is based on the layout shown in Figure 33.

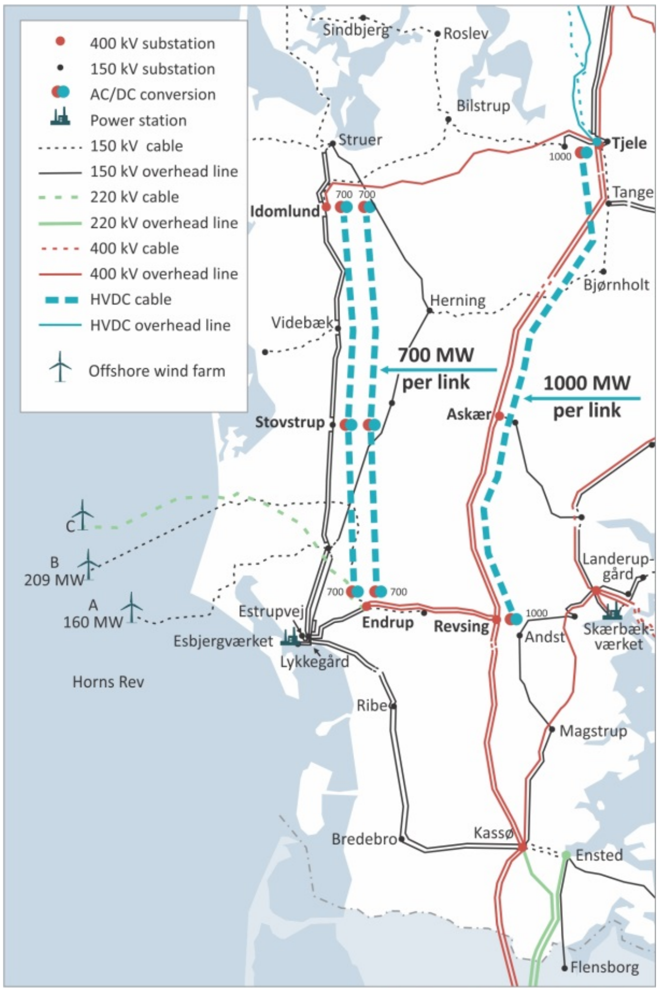

Figure 33: Layout of embedded HVDC multi-terminal link concept

5.4.3 Conclusion on HVDC system design

It is estimated that in order to comply with planning assumptions related to the new energy agreement, it would be necessary to implement at least two embedded multi-terminal HVDC links plus one embedded HVDC link along the existing route between Revsing and Tjele. Moreover, additional embedded multi-terminal HVDC links will be required in conjunction with new offshore wind power plants. Finally, development of the transmission grid will still be required in order to ensure the security of supply and to facilitate onshore renewable generation in the region.

5.4.4 Control of an HVDC system

One challenge related to HVDC control is that the transmitted power flow of an embedded HVDC link does not automatically follow the load and flow directions of the surrounding HVAC grid.

A 2 x 1,000 MW HVDC VSC link is in operation between France and Spain with an angle-difference control scheme implemented in order to emulate the performance of parallel HVAC transmission lines. It is outside the scope of this report to determine whether a similar angle-difference control scheme would be sufficient input for a controller algorithm involving several embedded HVDC links in the Danish transmission grid. Detailed studies would be required in order to design a feasible and robust controller concept in case an advanced HVDC scheme is to be implemented as part of the required reinforcement of the transmission grid in Western Jutland.

Assuming the HVDC links presented in Section 5.4.2.2 are to be controlled in real time using traditional digital and analogue inputs, the control system will need to be very complex in order to manage a very large variety of real time power flow scenarios and contingencies. This algorithm would have to include the following transmission lines and components (the list is not exhaustive):

- 400 kV HVAC transmission line Askær-Revsing;
- 400 kV HVAC transmission line Askær-Tjele;
- 400 kV HVAC transmission line Revsing-Tjele;
- 400 kV HVAC transmission line Kassø-Revsing (1+2)
- 400 kV HVAC transmission line Endrup-Revsing (circuit 1+2);
- 400 kV HVAC transmission line Idomlund-Tjele (circuit 1+2[3]);
- 400 kV HVAC transmission line Landerupgård-Revsing[4]
- Viking Link (1,400 MW HVDC link)
- Cobracable (700 MW HVDC link)
- 400 kV HVAC transmission line Kassø-Landerupgård;
- 400 kV HVAC transmission line Landerupgård-Malling;
- 400 kV HVAC transmission line Malling-Trige; and
- Parts of the North German 400 kV transmission grid.

A global control system, designed to control the suggested HVDC links embedded in a meshed HVAC transmission grid, does not exist anywhere in the world. Some technical limitations must be expected to surface when several embedded HVDC links interact in the same HVAC grid area [12].

The additional complexity of the HVDC concept and the required control functions increase the complexity of the operation of an already complex system. A further operational risk associated with HVDC systems is that a control failure can have significant impact on the integrity of the transmission grid.

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[3] No agreement has been made for system 2 as of the publication of this report.

[4] No agreement has been made for this line as of the publication of this report.

5.4.5 Offshore-based HVDC reinforcement

Situating cables offshore instead of onshore has been discussed by the public. Figure 34 shows comparable onshore and offshore HVDC installations with all the converters placed onshore, as an alternative for a 400 kV transmission line between Endrup and Idomlund. From a technical point of view, the solutions are similar.

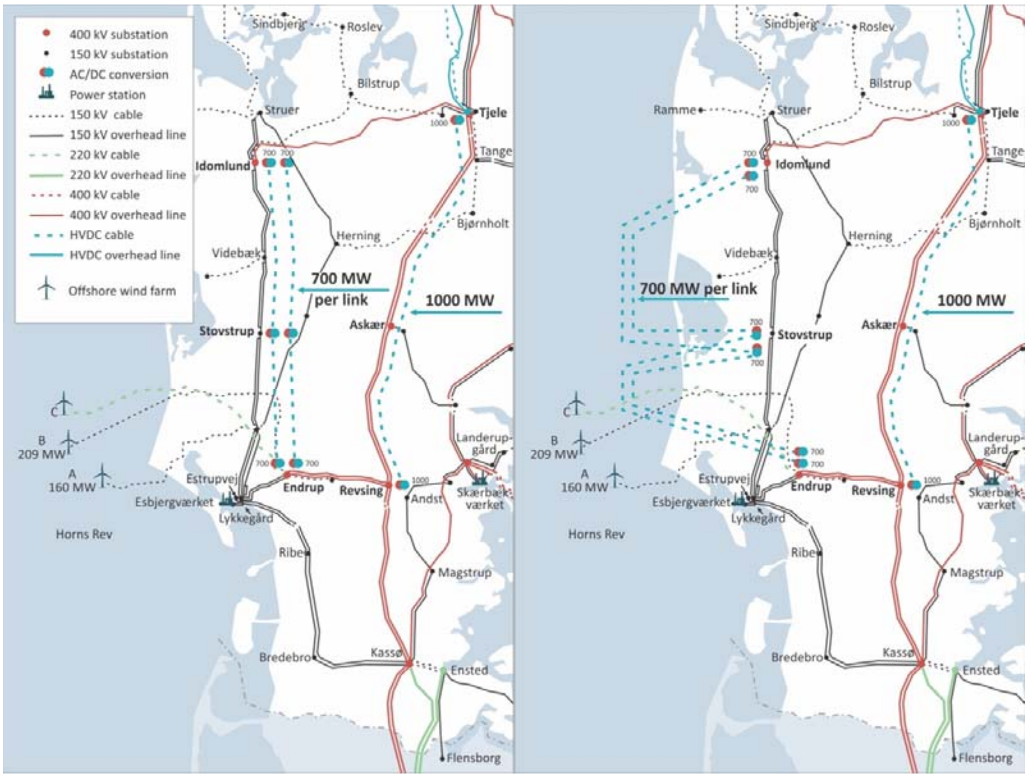

Figure 34: HVDC installation with the same function as a landing facility for power generation.

Assuming the converter installations were to be established in Stovstrup using DC cables installed partially onshore and offshore, the total length of the DC cable circuits would be exceed that of an onshore route directly between converter installations.

5.4.6 Construction schedule

The construction time for the described HVDC installations is estimated as more than 5 years, not including the analysis and design phases as well as the approval process and environmental impact study. Installation and commissioning of a HVDC concept comprising several embedded multi-terminal HVDC links within the timeframe available seems very unlikely.

5.4.7 Summary of project-specific use of HVDC technology

The application of embedded HVDC links will add unprecedented technical and operational complexity. The operation of a multi-terminal HVDC grid will require the development and implementation of advanced control algorithms. No references to existing comparable HVDC controller scheems have been identified.

A meshed HVAC transmission grid with embedded HVDC links would add to the complexity of future grid planning and grid expansions. Not knowing the exact locations and quantities of renewable energy to be transported makes it very challenging to design robust HVDC solutions that are both agile and capable of accommodating the uncertainties associated with wind power development in Denmark.

As described in Section 3.1.2, the agreement between TenneT TSO GmbH and Energinet stipulates that the interconnector between Endrup and Klixbüll must be established as a 400 kV transmission line; hence, the HVDC option is not a relevant transmission alternative for this transmission line.

Working with a timeframe until the end of 2023, the establishment of embedded HVDC links is considered very risky and challenging, and thus, embedded multi-terminal HVDC links are not considered a feasible transmission alternative as part of the required expansion of the transmission grid in Western and Southern Jutland.

5.5 Financial aspects

Cost estimates in this report mainly relate to transmission technology and component ratings currently used in Danish transmission grid. However, there are exceptions to this with regard to GILs and HVDC technology. Despite the very limited application of GIL systems in Denmark at present, cost estimates for the use of this technology have been included.

Only investment costs (CAPEX) are considered in the comparison of the transmission line alternatives for the two projects in question. Operational costs, such as maintenance costs and capitalized losses, are not considered because this requires more analyses than possible within the limited timeframe set to prepare this report.

Cost estimates are, wherever possible, based on supplier estimates and known costs of the most recent projects or on-going projects indexed to present day values. That being said, estimates presented are necessarily subject to changes in prices commanded in international markets.

To the extent possible, cost estimates have been developed on a “bottom-up” basis – i.e. by identifying costs of base components (unit prices) and then adding them to establish an overall cost estimate.

5.5.1 Cost estimates – 400 kV HVAC overhead lines

400 kV OHLs are the most cost-effective way to establish the required transmission capacity in the transmission grid. For comparison between the various transmission technologies, the estimated investment costs of the application of OHLs on the two routes between Endrup and Idomlund and between Endrup and the Danish-German border without partial undergrounding are given below (in 2015 prices adjusted for inflation):

- Endrup-Idomlund: 1,540 mDKK;
- Endrup-German border: 960 mDKK.

Both estimates include costs of necessary extensions of substations, compensation to landowners and all other related project costs.

As part of a future upgrade of the proposed 400/150 kV combined transmission line between Endrup and Idomlund with an additional 400 kV circuit as described in Section 3.3, the 150 kV circuit installed along the 400 kV circuit will be undergrounded. The installation of these 150 kV cable circuits constitutes the main cost for upgrading the combined 400/150 kV transmission line. A rough estimate of investment costs for the described 150 kV grid expansion amounts to 800-1,000 mDKK.

5.5.2 Cost estimates - 400 kV HVAC underground cables

It is commonly accepted that one of the most important reasons for the limited use of cables at the EHV level is the significant additional costs compared with overhead lines.

Energinet has estimated costs for undergrounding the 400 kV transmissions lines Endrup-Idomlund and Endrup-German border with different shares (lengths) of partial undergrounding. Investment costs are highly dependent on the number of parallel cable circuits necessary to meet the required transmission capacity of the 400 kV transmission lines being undergrounded. In this case, cost estimates are based on the assumption of a standard layout comprising two cable circuits per overhead line circuit.

The share of undergrounding has a significant impact on investment costs as does the decision whether to underground one long section or several short sections.

It should be emphasized, that stated cost estimates must not be considered final because of a number of uncertainties associated with the cost of base components. Furthermore, additional costs related to the installation of necessary mitigation measures, such as harmonic filters etc., can only be estimated based on a concrete cable layout.

As stated in Chapter 6, alternatives C and D are not technical feasible, and thus, no price estimates have been prepared for these alternatives.

5.5.2.1 Partial undergrounding of the 400 kV transmission line Endrup – Idomlund

Investment costs of the considered 400 kV OHL/UGC alternatives with different shares of partial undergrounding of the line length between Endrup and Idomlund are estimated and presented in Table 6.

As stated in Chapter 6, alternatives C and D are not technical feasible, and thus, no price estimates have been prepared for these alternatives.

Undergrounding of the 150 kV parts of the OHL is estimated using standard 150 kV equipment and 150 kV cables.

Solution	Alternative A	Alternative B	Alternative C	Alternative D
Investment costs (2018 prices) [mDKK]	1,680[5]	1,900[6]	-	-

Table 6 Cost estimates of partial undergrounding of the Endrup – Idomlund transmission line.

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[5] Investment costs from the business case corrected for inflation.

[6] Investment cost without considering cost for mitigation of harmonic amplification.

5.5.2.2 Partial undergrounding of the 400 kV transmission line between Endrup and the Danish-German border

Investment costs of the considered 400 kV OHL/UGC alternatives with different shares of partial undergrounding of the line length between Endrup and the Danish-German border are estimated and presented in Table 7.

As stated in Chapter 6, alternatives C and D are not technical feasible, and thus, no price estimates have been prepared for these alternatives.

Solution	Alternative A	Alternative B	Alternative C	Alternative D
Investment costs (2018 prices) [mDKK]	1,240[7]	1,400[8]	-	-

Table 7 Cost estimates of partial undergrounding of the Endrup-Klixbüll transmission line.

5.5.3 Cost estimates - 400 kV HVAC gas-Insulated transmission lines (GIL)

The investment costs of a GIL transmission line is high compared to 400 kV underground cables. To be compatible with a 400 kV UGC circuit, the requirement for transmission capacity must at least equal the transmission capacity of more 400 kV underground cable circuits, and even then, the investment costs of a GIL installation will be considerably higher.

Without a tender process, the assumption is that investment costs of a GIL installation is 2-3 times the investment costs of a comparable 400 kV UGC installation.

5.5.4 Cost estimation - High Voltage Direct Current (HVDC)

Technical and financial uncertainties related to the establishment of HVDC links are quite different from those of HVAC transmission lines. Due to the limited number of manufacturers, financial uncertainties are significant.

A worldwide procurement process is possible for HVAC transmission line equipment, which is not the case for non-standard HVDC systems such as the described multi-terminal concept. Therefore, HVDC costs would remain rough estimates until the finalisation of an actual procurement process.

Another uncertainty factor that will influence costs is the number of converters. Twelve converters in total would be required, including four converters for Viking link, and two of these converters would be installed on the British side of the link. All converters would have to be established by 2023. The demand for several HVDC links within a limited timeframe will most likely affect total investment costs.

HVAC transmission lines have an inherently higher built-in capacity and add more flexibility to the system compared to an HVDC concept. Therefore, the investment costs of HVAC and HVDC solutions are not directly comparable.

Without taking these price uncertainties into account, an estimate of the costs of two 700 MW multi-terminal links and one 1,000 MW HVDC link totals approximately 11,500 mDKK.

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[7] Investment costs from the business case corrected for inflation.

[8] Investment costs without considering cost for mitigation of harmonic amplification.

5.6 Discussion

As set out in detail in Chapter 1 of this report, Energinet has carried out a review process, which considered a number of transmission technologies, considering the nature and parameters of the required grid expansions in Western Jutland. These include the application of HVAC overhead lines and HVAC underground alternatives as well as HVDC technology.

The objective was to review the applicability of each of the above transmission technologies, identify the relative advantages and disadvantages of each and then assess these against the requirements of the grid expansion projects in Western and Southern Jutland in order to identify any technically feasible alternatives.

The review is based on a qualitative assessment of the criteria defined in Chapter 5 with all criteria being of equal importance. The summary analysis matrix is shown in Table 8 and the applied rating scale in Table 9.

Technology Criterion	HVAC OHL	HVAC UGC	HVAC GIL	HVDC
Usability	5	3	3	2
Technical considerations	5	1	3	1
Construction schedule	5	4	1	1
Environmental impact	1	4	3	4
Financial aspects	5	3	1	1

Table 8 Summary analysis matrix.

Rating	Description
1	Least preferred, high difficulty, unacceptable
2	Major technical challenges, difficult, poor acceptability and very risky
3	Known technical challenges, difficult, limited acceptability and high risk
4	Known technical challenges, acceptable and some risk
5	Preferred, no technical challenges, fully acceptable and low risk

Table 9 Applied rating scale of the analysis matrix.

The evaluation of the summary matrix showed that overhead lines offer the most acceptable technical solution when assessed against the selection criteria adopted, and is thus the currently preferred transmission technology for the grid expansions in Western and Southern Jutland.

The environmental impact of a transmission project depends on the characteristics of the crossed area. The visual impact is clearly more dominant in the case of OHLs. UGCs may have significant local impact. In areas of special interest, this may be prohibitive for UGCs and rerouting may be required, directly adding to costs. However, though for different reasons, this also applies to OHLs, and conclusions should only be reached based on the results of specific environmental impact assessments (EIA).

The application of embedded HVDC links has been proven very complicated. HVDC links do not provide the same robustness as HVAC solutions. In addition, replacing 400 kV transmission line projects in Western Jutland with HVDC installations will increase costs approximately fivefold. In this case, HVDC has been assessed, but rejected, due to the added operational complexity, higher costs and limitations of future expansion with regard to integration of renewable generation. For converter ratings and route lengths as discussed for Denmark, embedded HVDC links do not offer technical and economic advantages in transmission projects.

GIL is a promising technology with obvious electrical advantages compared to underground cables. However, there is a lack of operational experience with directly buried GILs in open landscapes and in areas of special environmental interest, including a lack of experience of long horizontal directional drilling for GIL purposes or the establishment of tunnels for GILs under such areas. Applied over long distances, GILs appear not to be an alternative for overhead lines and underground cables.

5.7 Conclusion on choice of transmission line alternatives

Overhead lines offer the most acceptable technical solution when assessed against the selection criteria adopted, and is thus the current preferred transmission technology to be adopted for the grid expansions in Western and Southern Jutland.

It is recognised that, from an environmental point of view with special regard to areas of special environmental interest, it will be necessary to establish the 400 kV transmission lines as combined OHL/UGC lines. Compared to other technologies, 400 kV UGCs are considered the only real alternative to OHLs with respect to the grid expansion projects in Western and Southern Jutland, as the required transmission capacity can be achieved more cost-effectively with the application of standard UGC solutions.

The review process also showed that full undergrounding of the grid reinforcements projects in Western and Southern Jutland would be subject to significant constraints, particularly in respect of system operation.

In view of the above conclusions, it was decided only to conduct detailed analysis of project-specific solutions, based on a combination of HVAC OHL/UGC transmission lines.

One of the objectives of this study is to identify the technically acceptable maximum share (length) of 400 kV UGCs that can be adopted for the grid reinforcements projects in Western and Southern Jutland.

One of the main objectives of this study is to identify the technically acceptable maximum share of 400 kV UGCs applicable in the 400 kV grid expansion projects in Western and Southern Jutland. In total, four 400 kV OHL/UGC solutions (alternatives A to D) with different UGC shares have been defined:

- The approved 400 kV overhead line solution (Reference/Alternative A);
- The approved 400 kV overhead line solution – with an increased cable share without the need for establishing additional compensation stations (Alternative B);
- The approved 400 kV overhead line solution – with an increased cable share and resulting need for establishing additional compensation stations (Alternative C); and
- Full underground cabling of the current 400 kV connection (Alternative D).

Under consideration of the possible routes for the approved combined 400 kV OHL/UGC transmission lines, a range of cable shares ranging between 6 % and 100 % with the remaining part of the circuit modelled as an overhead line, have been analysed. It should be noted that the locations and exact lengths of the individual cable sections (splits) are to be defined during the environmental impact assessment (EIA), which is outside the scope of this report. The four OHL/UGC alternatives studied for the two 400 kV projects are shown in Figure 35 and Figure 36. The defined cable shares are shown in Table 10 and Table 11.

400 kV transmission line - Endrup-Idomlund

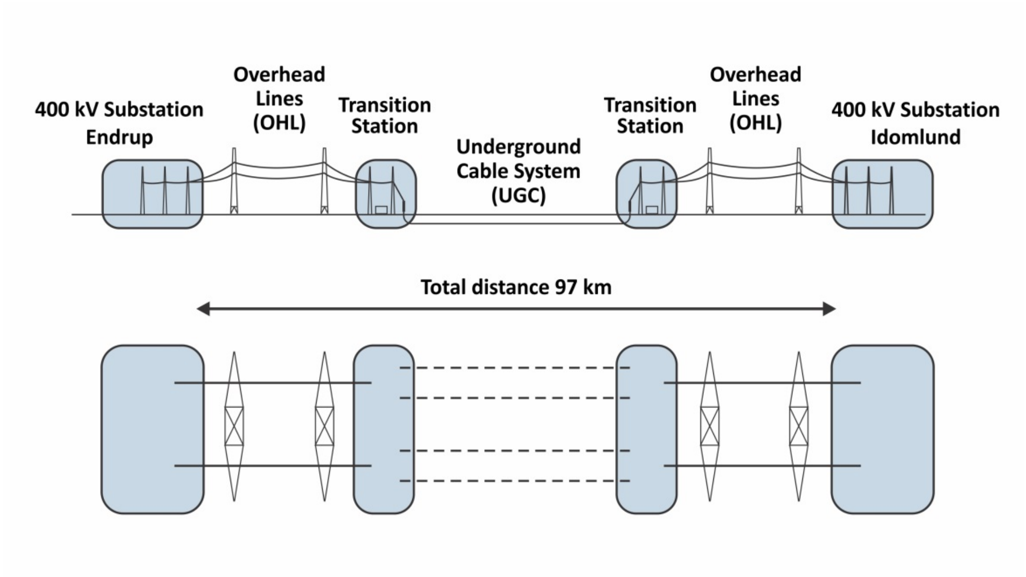

Figure 35 400 kV transmission line - Endrup-Idomlund.

Alternative	Share of UGC	Share of OHL	Total distance
A	6 km (approx. 6 %)	91 km (approx. 94 %)	97 km
B	15 km (approx. 15.5%)	82 km (approx. 85 %)	97 km
C	48.5 km (approx. 50 %)	48.5 km (approx. 50 %)	97 km
D	97 km (100 %)	No OHL sections included	97 km

Table 10 Defined cable shares (Endrup-Idumlund).

400 kV transmission line - Endrup-Klixbüll

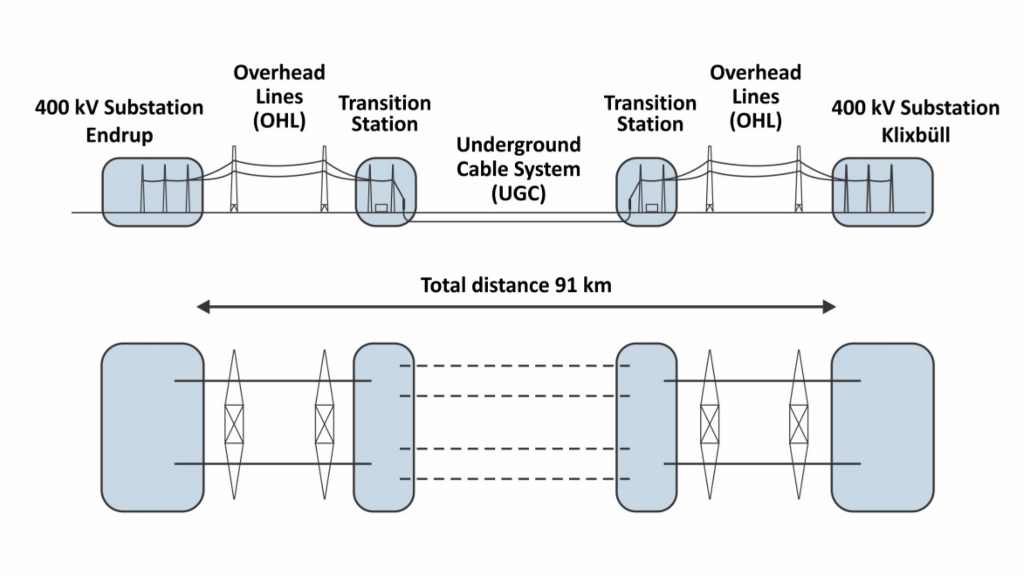

Figure 36 400 kV transmission line - Endrup-Klixbüll.

Alternative	Share of UGC	Share of OHL	Total distance
A	10 km (approx. 11 %)	80.6 km (approx. 89 %)	91 km
B	11 km (approx. 12.3 %)	79.5 km (approx. 87.7 %)	91 km
C	37.3 km (approx. 41.2 %)	53.3 km (approx. 58.8 %)	91 km
D	91 km (100 %)	No OHL sections included	91 km

Table 11 Defined cable shares (Endrup-Klixbüll).

Please note, that the German part[9] of the 400 kV transmission line Endrup-Klixbüll is included in the calculated cable shares. Exclusion of the German part will make the cable shares on a par with the Endrup-Idomlund 400 kV transmission line.

The consequences of introducing the defined cable shares in the Danish system will be discussed in detail in Chapter 6.

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[9] The German part of the 400 kV transmission line Endrup-Klixbüll will be built as an overhead line with a length of approximate 16 km.

6. Technical performance issues introduced by the application of long HVAC cables

6.1 Introduction

Safe and reliable operation of a power system depends on many factors. One such factor is the approach used in the system planning stage. For example, any grid development project that introduces components that may give rise to overvoltages upon their energization or that may negatively affect power quality will need to undergo a series of system and component level studies in the project's design stage to detect such issues, and plan and design mitigation measures accordingly.

A representative example of this is the installation of unsymmetrical transmission lines that may give rise to excessive negative sequence voltages in the system. This whole approach of establishing good system integrity is generally referred to as system technical performance. The main focus of such an undertaking is to establish possible outcomes of interactions between the power system and its components, with particular reference to transient and dynamic conditions. However, the area of interest spans such different issues as steady state, power quality, electromagnetic compatibility, lightning and system stability.

Energinet has conducted in-house studies for many years focusing on the classic power system structure with large power plants and transmission circuits using OHLs. However, the observation of a rather peculiar de-energization waveform in 2004 of a 400 kV line between two northern Danish substations Trige and Fjertselv illustrated in Figure 37, increased the focus of Energinet on the design, planning and operation of UGC systems.

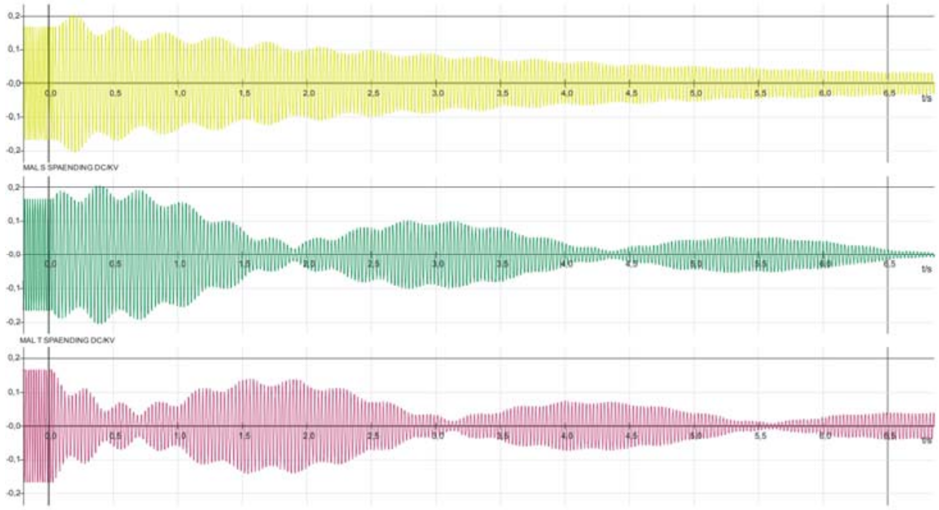


Figure 37 Voltage profile observed in 2004 after the de-energization of a 400 kV hybrid line.

This trend was further motivated by the Danish 2009 cable action plan that led to the start-up of a comprehensive R&D programme (DANPAC) dedicated to the study of issues related to replacing OHLs with UGCs at component and system level. The necessity originated from the significant differences in electrical behaviour of UGCs compared to OHLs, with the potential impact on the system evaluated as very high. Clearly, improving knowledge was key, and five years were spent studying the subject.

One leg of the DANPAC project was related to practical issues of undergrounding cables. The resulting product was the 'Cable Handbook' – an extensive handbook in Danish that describes all aspects of undergrounding cables from a practical perspective [5]. The other, academic leg of the project consisted of five PhD projects with four of these centred on system-related aspects and cable modelling for system studies In terms of academic publications, DANPAC resulted in five PhD dissertations, 32 conference articles and journal papers and one book [13] [14] [15] [16] [17] [18].

Since the DANPAC project ended, Energinet has been strongly involved in international working groups and technical forums with special focus on CIGRE working groups within equipment, technology and system-related study committees (A2, C4, B1 and B4).

In concrete cable projects, Energinet handles all design-related component issues in relation to cable installations as well as broad system-related designs in system level studies. In-house load flow, short circuit, dynamic, electromagnetic transient (EMT) and power quality studies are carried out.

The rest of this chapter focuses on technical analysis and is written based on experience gained over time from DANPAC, international collaboration and knowledge sharing platforms such as CIGRE as well as from the cable and hybrid line projects designed, constructed, commissioned and operated by Energinet.

The following sections discuss the technical issues found by Energinet to be most relevant to the west coast 400 kV transmission projects. The selected topics for further discussion are:

- Voltage and reactive power control
- Temporary overvoltage following:
    - Transformer energization
    - Clearing of faults
    - System islanding
- De-energization of transmission lines
- Transmission line energization (switching overvoltages)
- Power quality issues with focus on voltage harmonics

Other issues are also pertinent, but the existence of well-tested and proven solutions makes these less relevant to this report. For instance, issues such as trapped charge on UGCs following de-energization could in certain circumstances introduce complications. However, use of inductive voltage transformers by Energinet as a countermeasure to ensure that trapped charges are discharged before any subsequent energization, eliminates any possible issue. This is an easy and cost-effective solution to a potential problem. As a result, the issue is less pertinent to this report, but nevertheless it is handled in the design stage of the transmission line projects when specific construction decisions are made. Adopting similar reasoning, issues such as transient recovery voltage (TRV), induced voltage, and voltage unbalances are not included in the following discussion either.

6.2 Voltage- and reactive power control

The reactive power generated by a transmission line affects the voltage profile along it. Long OHLs and UGCs require reactive power compensation to maintain a satisfactory steady-state voltage regulation under various load conditions. This section seeks to investigate the voltage profiles for the Endrup-Idomlund and Endrup-Klixbüll lines at no load and in connection with induced voltage steps during line energisation.

6.2.1 Voltage Profiles

6.2.1.1 No-load voltage profile

At no load operation, the reactive power generated by a transmission line reach its maximum value, as the loading of the line does not lead to a loss of reactive power. For no load operation of a symmetrical line with fixed voltage at both ends, the voltage peaks at the line's midpoint. UGCs generate more reactive power than OHLs due to the higher capacitance per unit length, therefore leading to a higher voltage rise along the UGC. With use of distributed reactive compensation, the voltage profile shows less variation from one end to the other compared to a layout having compensation placed only at the ends of a line.

6.2.1.1.1 No-load voltage profiles of EDR400STSV and EDR400KLIS

During no-load operation assuming a fixed voltage of 410 kV at the end terminals, the voltage profiles for the Alternatives A, B, C and D along the lines Endrup-Stovstrup and Endrup-Klixbüll are as shown in Figure 38. It should be noted that all voltage profiles shown in Figure 38 represent situations where the cables are fully compensated by the inclusion of fixed shunt compensation. In Alternative D, compensation is accomplished by including one compensation substation on Endrup-Stovstrup and three compensation substations on Endrup- Klixbüll. In Alternative C one compensation substation is included on Endrup-Stovstrup. For Alternatives A, B and C, two compensation substations are included on Endrup-Klixbüll.

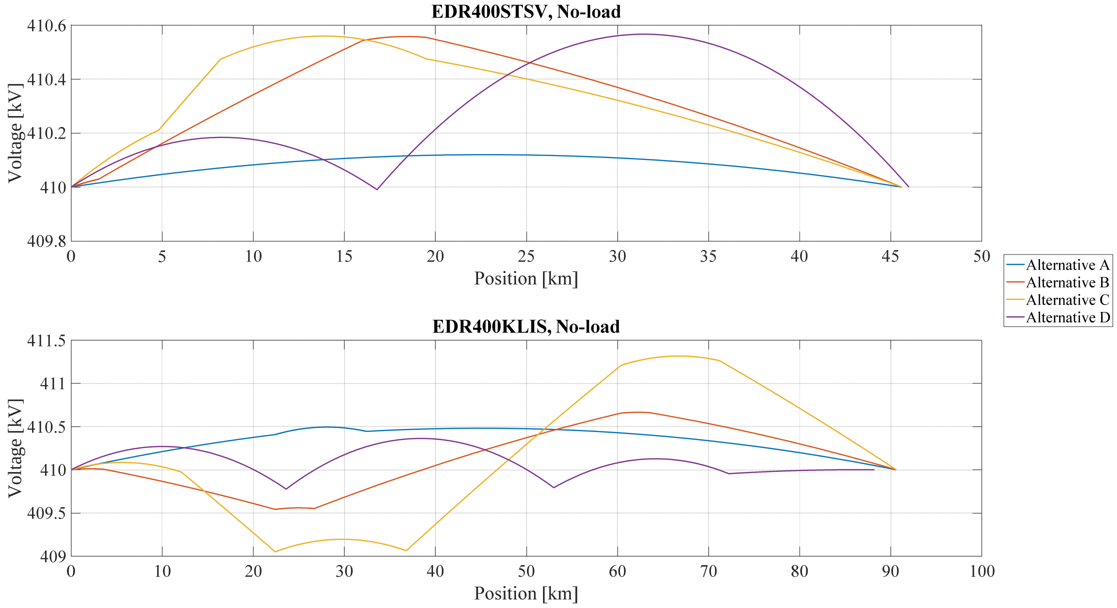


Figure 38: No-load voltage profiles of Endrup-Stovstrup and Endrup-Klixbüll at a fixed voltage of 410 kV at both end terminals. Approximately 100 % reactive compensation is applied.

Endrup- Stovstrup

For Alternative A, only a short part of the lines is UCG, which leads to a voltage profile with small variations on both transmission lines. For Alternatives B and C, the share of OHLs and UGCs are more equally divided. This leads to a larger voltage variation with the given distribution of reactive power compensation. Even though Alternative D represents a fully undergrounded line and hence produces the largest amount of reactive power, the voltage variation is limited due to the several compensation substations on the line.

Endrup- Klixbüll

The lowest voltage variation is found for Alternative A, which also contains the least share of UGC, whereas alternatives B and C show the highest voltage variations. On the other hand, Alternative D yields voltage variations similar to those of Alternative A. This is due to the even distribution of reactive power compensation compared to Alternatives B and C. The location of compensation is clearly seen in Alternative C and D.

6.2.1.2 Open end voltage profile

When a line is energized from one end only, and the reactive power generation of the line is not fully compensated there may be a significant voltage rise along the line a phenomenon defined as Ferranti effect. It is assumed that the amount of reactive power compensation is fixed to a maximum of 50 % from the line due to Energinet’s zero-miss mitigation policy. This leads to an unbalance of reactive power of the cable at energisation.

By combining OHLs and UGCs in a single circuit (hybrid circuit) the voltage profile along the line is affected. This is especially relevant when energising a hybrid transmission line from the OHL’s side, as this leads to higher voltage than energizing from the UGC’s side. This occurs due to flow of reactive power generated by the cable through the OHL’s larger reactance. Higher open end overvoltages might be observed in Alternatives B and C compared to D due to this phenomenon.

6.2.1.2.1 Open end voltage profiles of EDR400STSV and EDR400KLIS

In a situation where Endrup-Stovstrup is to be energized it will most likely be from Endrup, which has a higher short circuit capacity as compared to Stovstrup. If Endrup-Klixbüll is to be energized it may be from either end. Since there is an OHL section on the German side of the border, energisation from Klixbüll will cause the largest voltage variation. The voltage profiles for Endrup-Stovstrup and Endrup-Klixbüll are shown in Figure 39. The lines are approximately 50 % compensated.

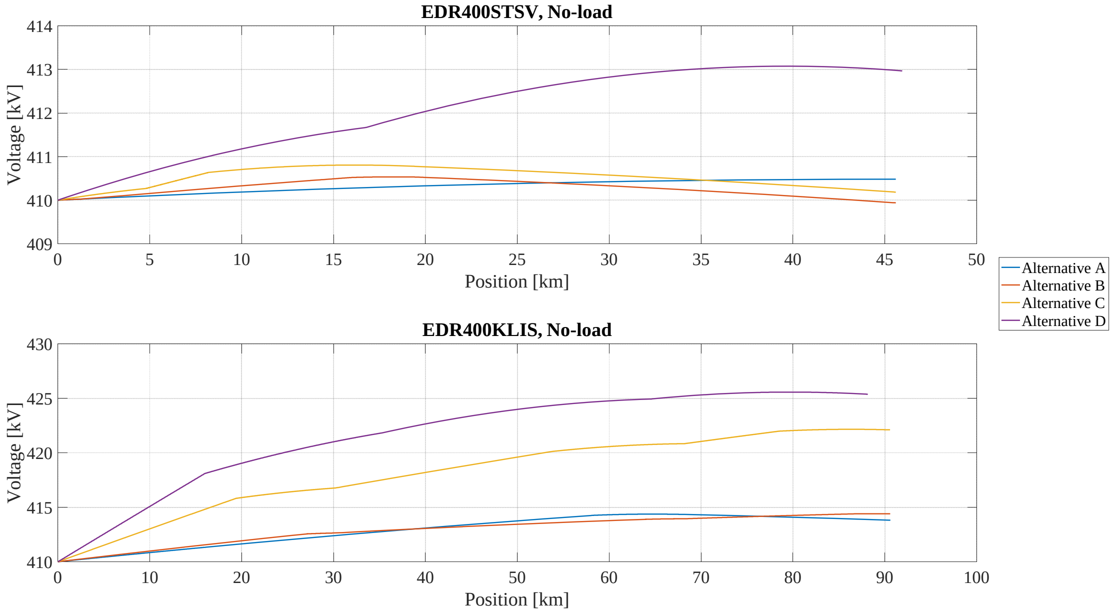


Figure 39: Open end voltage profiles of Endrup-Stovstrup with the Stovstrup end open and Endrup-Klixbüll with the Endrup end open. For both the voltage is fixed at 410 kV at the end which is connected to the grid.

Endrup- Stovstrup

For Alternatives B and C, some of the reactive power compensation is located at the line side of the circuit breaker in Stovstrup while most of the cable length is located nearer to Endrup, which is the reason for the decreasing voltage towards Stovstrup. In Figure 39 the largest voltage occurs for Alternative D.

Endrup- Klixbüll

For Endrup-Klixbüll, the voltage increase along the line for Alternative C and D is 12 kV and 15 kV, respectively. As is shown in the figure, the open end voltages are above 420 kV, which is Energinet's design limit. Considering that the operational voltage limit in Denmark is 420 kV, the open end voltages can reach to 435 kV in some cases. One method for avoiding voltages above the design limit is to reduce the voltage at energisation. This may be unacceptable from an operational point of view. Another method is to enable energisation of shorter line sections. This will require additional system components and increase the system's complexity.

6.2.2 Voltage steps

Voltage step is the change in voltage at the transmission line's connection point when energising the line. With the present zero-miss design philosophy applied, there will be a flow of reactive power to the adjacent transmission grid at energisation of a line. The longer the line and the more of the length that is laid as cable, the larger the reactive power imbalance will be. Hence it is relevant to look at the magnitudes of voltage steps at line energisation for all alternatives.

According to Energinet's grid planning standards, a maximum voltage step of 4 % is allowed during normal operation. A 400 kV UGC circuit generates approximately 11 Mvar/km per cable at 410 kV. Assuming the lines are 50 % compensated the relationship between the short circuit power of the grid and the maximum allowable cable length is shown in Figure 40 in order to comply with the 4 % voltage step at energization.

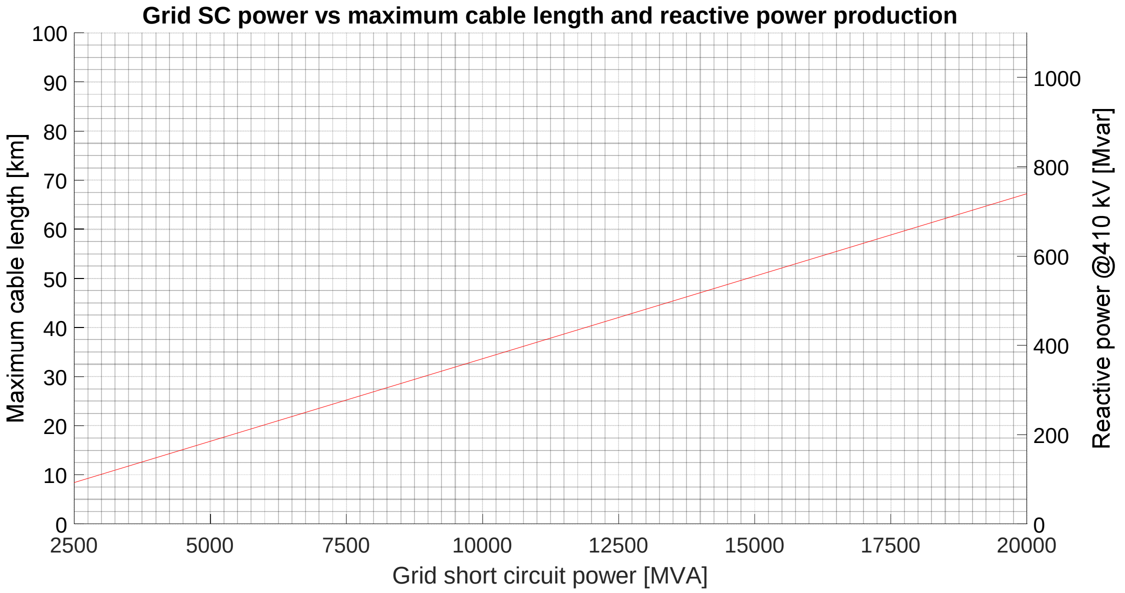


Figure 40: Relationship between grid short circuit power and connected reactive power, which is approximated to an equivalent 400 kV double circuit cable length provided with 50 % compensation, for a voltage jump of 4 %.

Assuming a short circuit power of 5000 MVA, which represents a low grid strength scenario, the maximum length of a line with two circuits per phase would be approximately 17 km in order not to violate the voltage step criterion.

6.2.2.1 Discussion on energisation of lines of the four Alternatives

As the voltage steps are dependent on the generated reactive power, it is relevant to analyse the reactive power generation for the lines in the different alternatives. It can be shown that, without compensation, a single UGC produces 11 Mvar/km and OHLs produce 0.76 Mvar/km, both operating at 410 kV. It is safe to assume that two cables per phase are required to achieve equal power transfer capacity (in OHL vs UGC) and that the cable sections are 50 % compensated. This gives the generated reactive power as shown in Table 12.

	Idomlund-Stovstrup, [Mvar]	Endrup-Stovstrup, [Mvar]	Endrup-Klixbüll, [Mvar]
Alternative A	87	77	136
Alternative B	119	106	182
Alternative C	307	272	451
Alternative D	575	511	835

Table 12: Generated reactive power at energisation assuming 50 % reactive compensation of the cables for all Alternatives.

Including the short circuit power of the grid, it is possible to estimate which lines will produce higher voltage steps at energisation compared to permissible level. Estimation assumes the full line length is energized as one circuit. In Table 13 the minimum short circuit power at Idomlund, Endrup and Klixbüll is shown.

	Sk”min, [MVA]
Idomlund, Idomlund-Stovstrup open	3,465
Endrup, Endrup-Klixbüll open	5,816
Endrup, Endrup-Stovstrup open	8,747
Klixbüll, Endrup-Klixbüll open	5,247

Table 13: Minimum short circuit power at the end terminals of the lines.

Given the reactive power generation per line shown in Table 12 and assuming minimum short circuit power conditions as given in Table 13, the resulting voltage steps can be calculated as shown in Table 14.

Voltage jump [%]	Idomlund-Stovstrup, from Idomlund	Endrup-Stovstrup, from Endrup	Endrup-Klixbüll, from Endrup	Endrup-Klixbüll, from Klixbül
Alternative A	2.5	0.9	1.6	2.6
Alternative B	3.4	1.2	2.1	3.5
Alternative C	8.9	3.1	5.2	8.6
Alternative D	16.6	5.8	9.5	15.9

Table 14: Calculated voltage jumps when energising the lines during minimum short circuit power conditions.

It can be observed in Table 14 that the voltage steps for Alternative A and B are below the allowed 4 % limit. However, in Alternatives C and D the voltage steps exceed the limit. Therefore, in order to be able to energise the lines of Alternatives C and D, changes must be made to the entire cable circuit layout. This could be the introduction of one or more intermediate compensating substations, so that only part of the lines will be energised at any one time. This will, however, add to the complexity of the system including its operation. Another option would be to change the zero-miss mitigation strategy. By employing automatic sequential closing at voltage peak zero-miss can be avoided [19]. However, this will cause maximum switching overvoltage and, due to breaker pole-spreading, it is not feasible to fully compensate the line. Another option is to apply sequential breaker opening when a single-phase fault is detected [19]. However, this will compromise the back-up protection scheme currently applied since coordination between all primary and back-up protection is not feasible at the scale needed.

6.2.3 Discussion/conclusion

The analyses conducted in this section do not show any issues for no-load operation regardless of the Alternative. On the other hand, open end voltages and voltage steps are above the design limit in Alternatives C and D. To solve the issues regarding open end overvoltages and voltage steps, the excessive reactive power generation at energisation must be reduced. One solution is to add intermediate compensation points, allowing energisation of shorter line parts. However, this solution requires more system components and hence an increased system complexity. An alternative solution would be a revision of design philosophy regarding mitigation of zero-miss, to allow for a higher rate of reactive power compensation. However, this is associated with several problems that cannot be accepted

6.3 Temporary overvoltages

The addition of UGCs to the transmission grid is known to lower system resonant frequencies due to the UGC’s high capacitance [20]. In this context, it is a matter of concern if the connection of UGCs in any of the considered alternatives on the west coast project will lead to critical temporary overvoltages (TOVs) occurring. TOVs occur in high voltage systems due to the excitation of the grid's resonances, which may be characterised by very high or very low impedances (namely parallel and series resonances). TOVs caused by excitation of parallel resonances occur when a harmonic current is injected at the resonant frequency.

Most commonly, this situation arises during energization of large power transformers as these draw very large currents (referred to as inrush currents) from the grid and are rich in low order harmonic content [21] [22] [23]. Any parallel resonance at these low frequencies may result in critical temporary overvoltages. In a similar way, simultaneous re- energization (usually referred to as pseudo- energization) of power transformers after post-fault voltage recovery may lead to increasingly high TOVs.

TOVs are characterized by lower voltage magnitudes than switching and lightning overvoltages. TOVs are, however, equally critical to the transmission system due to their long duration, which may lead to failure of high voltage components due to thermal stress. An example of a TOV is presented in Figure 41. Surge arresters (SAs), designed to mitigate switching and lightning overvoltages, are the weakest components in relation to TOVs, as their energy discharge capabilities may be surpassed within a few seconds [20]. Magnetic components, such as power transformers or shunt reactors, are also susceptible to TOVs as overfluxing in the magnetic core results in overheating, however they are less sensitive compared to surge arresters [24].

It is worth mentioning that TOVs typically spreads to larger parts of the power system. Therefore they have the potential to affect many components increasing the consequence. This is contrary to high frequency overvoltages which typically are more local of nature due to higher damping.

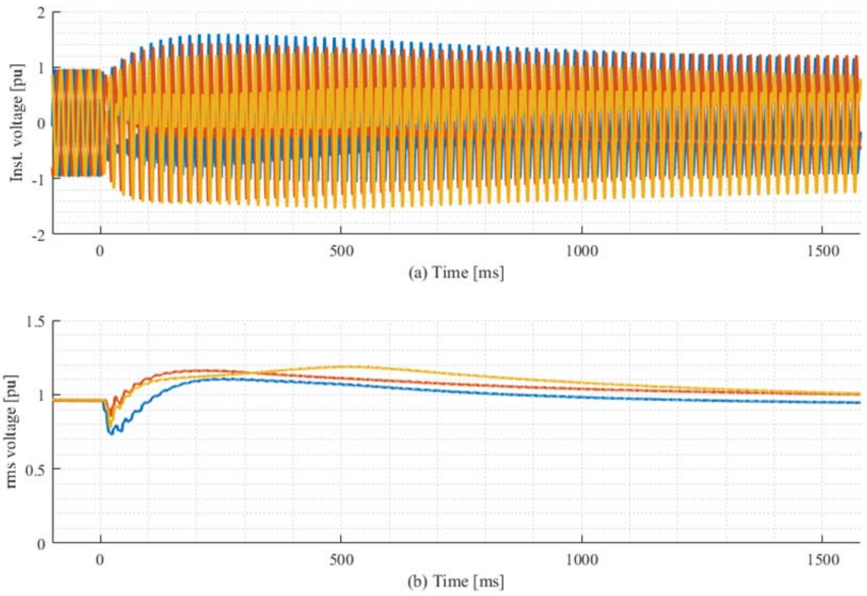


Figure 41 Example of TOV after transformer energization.

The following sections present assessments of TOVs resulting from excitation of parallel resonances during transformer energization fault clearance or system islanding. These assessments aim to describe differences between alternatives A, B, C and D in order to identify any possible system impact.

6.3.1 TOVs during energization of power transformers

The purpose of this section is to evaluate the risk of TOVs associated with transformer energization in each of the alternatives considered for the west coast project. In order to accomplish this target, the impedance spectra of the grid electrically close to the west coast area is investigated. Furthermore, potential low order harmonic resonances are identified and any differences between alternatives are highlighted.

In general, the power system operates in a planned state where responses to foreseen or possible contingencies have already been thought out. In the Danish transmission system, the planned state covers N-0 or N-1 situations, i.e. when the system operates under intact conditions or with a single unplanned circuit outage. Transformer energization is more likely to occur during N-0 and N-1 situations simply because the system mostly operates in the planned state as opposed to the rare, abnormal system configuration states. However, specific care must be exercised in special system configurations, and black start situations are classic examples of this. Typically, these are highly critical system configurations as the short-circuit power level is low, causing relatively high system impedance, and resonances shifted towards lower frequencies. The following sections present an analysis of these system configurations, and discussions are provided on the implications of each case.

6.3.1.1 Methodology

Simulation studies are conducted using Energinet’s PowerFactory system model. The initial objective is to evaluate the impedance spectra of the relevant grid area. Simulations are performed for several cases, covering possible grid configurations in which transformer energization may take place. These include different alternatives, different system demand levels, various combinations of harmonic filters in service and a number of N-1 and black start grid configurations. For each case, the magnitude of impedance as seen from the relevant busbars is evaluated at and around 100, 150 and 200 Hz in order to identify potential resonances around these frequencies. In order to determine critical cases, the magnitude of impedance at the aforementioned frequencies is evaluated and compared with a number of screening impedance levels. Based on established working experience, the screening levels applicable to the Danish transmission system are found to be 400 Ohms at 100 ±10 Hz, 600 Ohms at 150 ±10 Hz and 2,400 Ohms at 200 ±10 Hz. If the magnitude of the impedance at one of these frequencies exceeds the screening level, additional studies are initiated.

6.3.1.2 Energization of large transformers during N-0 and N-1

As a starting point, the frequency dependent impedance seen from the 400 kV substations and offshore platforms located close to the west coast is analysed during N-0 and N-1 grid configurations for alternative A, B, C and D. Figure 42 shows the frequency dependent magnitude of impedance as seen from the IDU400 node. Each colour represents a system demand level (namely high, medium and low short circuit power scenarios), for which multiple grid configurations are shown. The results indicate that there is no resonance above the screening levels for any of the relevant low order harmonics, which implies that no critical TOVs are likely to occur during transformer energization. The same conclusion can be drawn for the rest of the 400 kV substations.

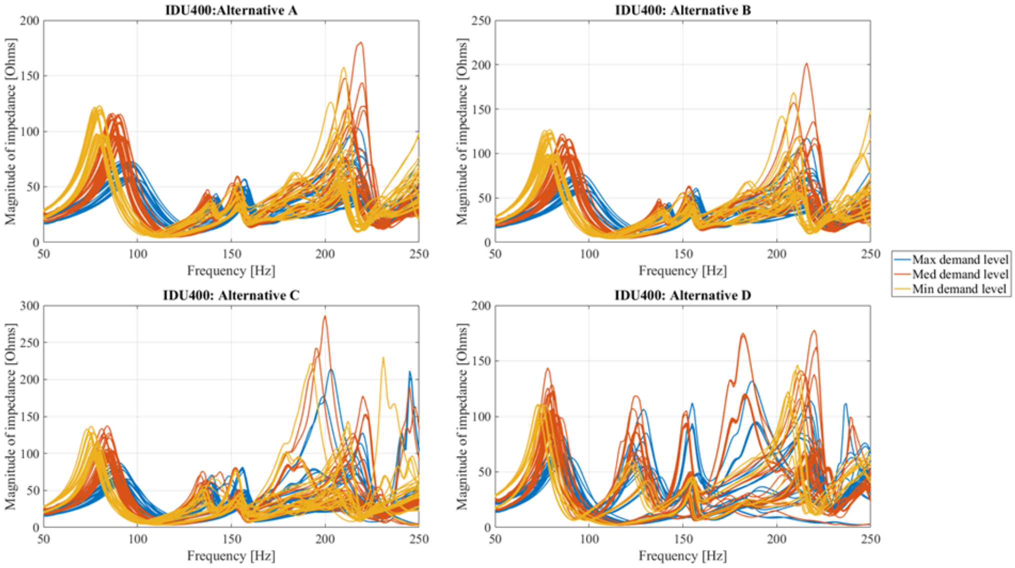


Figure 42 Frequency dependent impedance seen from IDU400 for different N-0 and N-1 scenarios.

Figure 43 shows the frequency dependent impedance as seen from node Horns Reef B 150 kV for different N-0 and N-1 scenarios. It appears that the system frequency response indicates a relatively large resonance between 150 to 200 Hz. However, this level is within the threshold value established and thus not of major consequence. It also appears that there is no significant frequency shifting of this resonance depending on the system demand level or the investigated alternative, which indicates that the resonance is mostly determined by the long land and submarine cables that connect Horns reef B 150 kV to substation Endrup 150 kV. In other words, this observed resonance is not a new introduction, and it is highly likely that it is already present in the current grid configuration. A similar conclusion can be extended to Horns Reef C 220 kV.

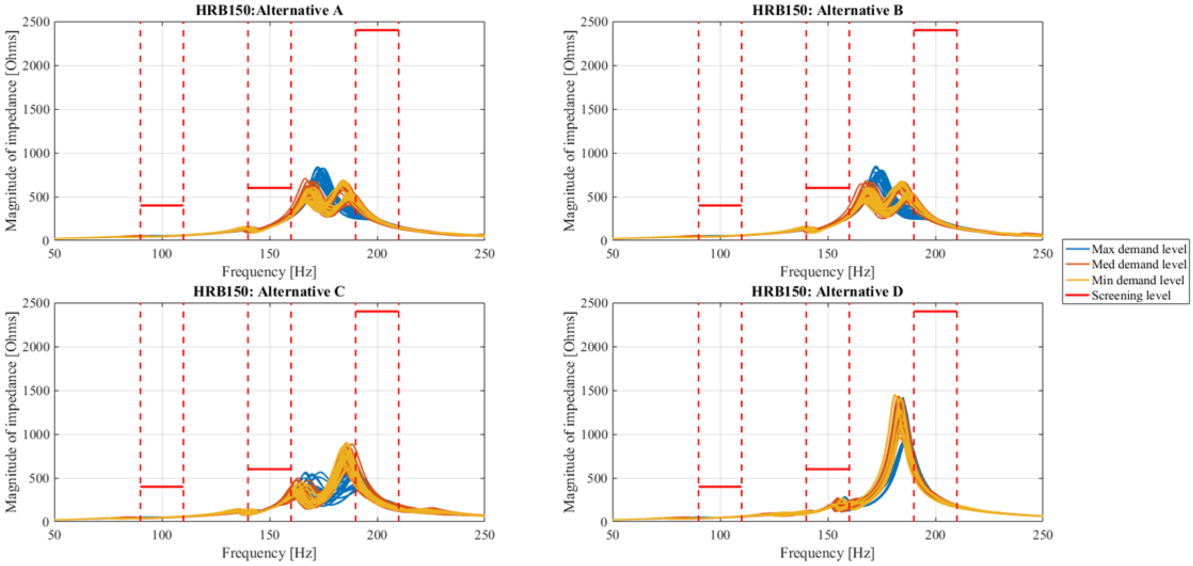


Figure 43 Frequency dependent impedance seen from Horns Reef B for different N-0 and N-1 scenarios.

The analysis indicates that the system behavior with respect to its frequency response to planned conditions under N-0 and N-1 grid configurations is relatively robust and unlikely to give rise to critical TOVs. Furthermore, not much difference is observed between the various alternatives.

6.3.1.3 Energization of large transformers during black start

This section examines the possibility of TOVs when large system transformers are energised through the west coast transmission lines during a grid black start situation. It is assumed that black start can either be initiated from Germany (KLIS400 and northward) or from the Danish power plants at Studstrupværket (MKS) and Nordjyllandsværket (NVV) towards TJE400, IDU400 and southward. As the situation is based on a depleted system configuration, the Energinet PowerFactory model is reduced to the substations of interest, placing an external grid at TJE400 when black-starting from Denmark and at KLIS400 when energising from Germany. Furthermore, it is known that the short-circuit level of the external grids will heavily affect the location and magnitude of resonances seen at the transformer terminals. Therefore, for black start cases, it is decided to not only evaluate the different alternatives and grid configurations, but also to vary the short-circuit level of the external grids. It should be noted that external grids are represented by voltage sources and power frequency Thévenin's equivalent impedances. This implies that the impedance seen at frequencies above 50 Hz will lack damping, and the approach will therefore tend to produce conservative results. However, as the main objective is to uncover differences between the various alternatives of the west coast project, and this conservativeness applies to all alternatives, the approach can be safely used.

Figure 44 shows the frequency dependent impedance seen from STSV400 under different grid configurations and short-circuit levels that may come to be during a black start from Germany. It appears that for all alternatives, there is at least one grid configuration that causes the screening level to be exceeded for a certain short-circuit level, meaning that critical TOVs might arise when energising a transformer from STSV400. Analyses of the rest of the substations of interest indicate similar results and hence the same conclusions. Actually, for alternatives A and B, resonance is located between 100 and 150 Hz, whereas this is located between 50 and 100 Hz for alternatives C and D. This conclusion is valid for all substations of interest, grid configurations analysed and short-circuit levels taken into consideration. Exceptions to the above conclusions include TJE400 in alternative D when energising from Germany, and REV400 and EDR400 in alternative D when energising from Denmark, where no risk of TOVs was seen.

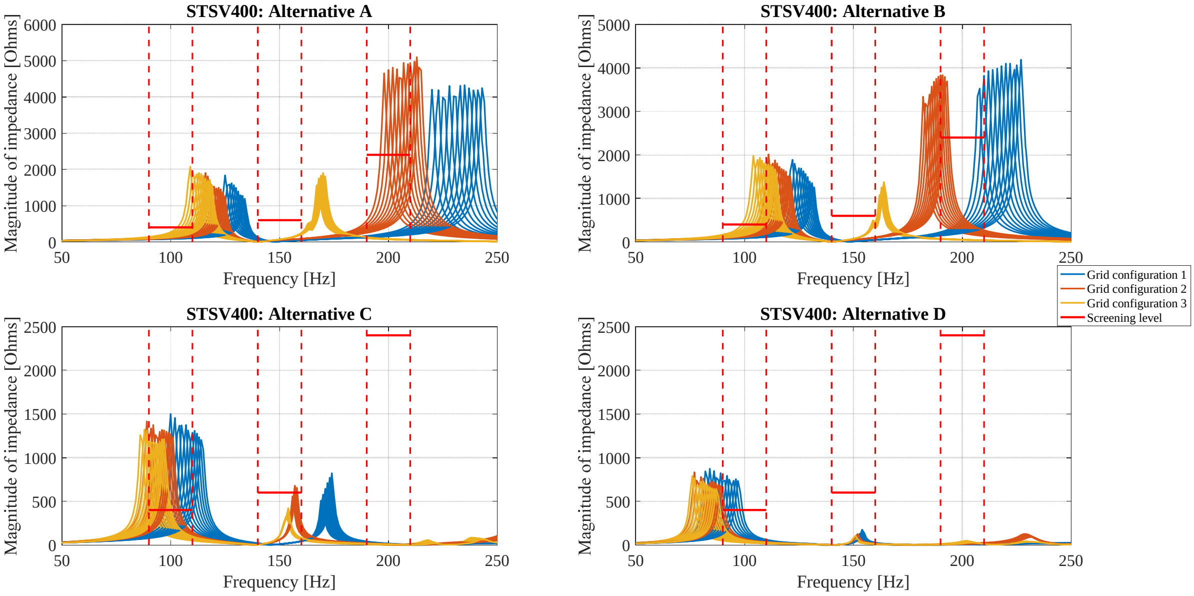


Figure 44 Frequency dependent impedance seen from STSV400 for different black start scenarios.

It was previously explained that there is a risk of shifting resonance to critical frequency bands in at least one short-circuit level and grid configuration, independent of the investigated substation and alternative. Consequently, it is extremely important to carry out a detailed black start study for the selected alternative during the project execution stage in order to identify safe combinations of short-circuit level (i.e. synchronous machine in operation) and grid configuration (i.e. transmission lines in operation) where such operation can be executed. In summary, it can be stated that no alternative has a clear advantage respect to the others in terms of location and magnitude of low order harmonic resonances.

6.3.2 TOVs after clearance of faults

During the course of a fault, the voltage seen at nearby busbars and hence the transformers connected to it, is close to zero. Following fault clearance, transformers go through re- energization, usually referred to as pseudo-energization, and can be heavily driven into saturation depending on the instant of fault clearance (i.e. the re-energization instant). This owes to the fact that the transformer cores retain a level of flux, with remanent flux as high as 0.8 p.u. in such pseudo-energization cases [21]. In such cases, inrush current drawn by the transformers can reach levels matching those of a normal energization (depending on the fault clearance time, i.e. voltage point-on-wave). Due to the number of transformers that can be simultaneously re-energised in this way, the TOVs that occur during faults may be more severe when compared to the energization of a single transformer.

Impedance scans performed in the transformer energization study did not show any critical low order harmonic resonance during N-1 configurations, in which the system will most likely be operating after a fault is cleared. Given the relatively low probability of faults, other rare and problematic system configurations such as black start are not considered for the evaluation of the alternatives. Therefore, it can be concluded that no critical TOV is likely to occur due to faults regardless of the alternative. This must, however, be confirmed during the project-specific study phase in order to account for rare system configurations in the assessment.

6.3.3 TOVs after system islanding

When a fault occurs in the transmission system, the protection systems open the relevant breakers in order to isolate the fault. This could be the isolation of a line, of a transformer or of other equipment. In radial or poorly meshed grids, the loss of transmission lines may lead to a significant reduction in the short-circuit power seen from the busbars electrically close to the fault. In these situations, large TOVs resulting from the superposition of different frequency components might occur. The magnitude of these TOVs is more likely to be high if islanding leads to the appearance of low order harmonic resonances in the remaining system, as these would be excited by the re- energization of nearby transformers.

The 400 kV substations located in the west coast area, with the exception of STSV400, are all in a highly meshed grid. Furthermore, impedance scans performed in the transformer energization study do not show any critical low order harmonic resonances during N-0 or N-1 system configurations. Therefore, it can be safely inferred that no critical TOV is likely to arise due to system islanding following fault clearance.

6.3.4 Discussion and Conclusions

This section has evaluated the risk of TOVs associated with transformer energization as a direct action or as part of fault clearance and system islanding for each of the alternatives considered for the west coast project. Results obtained for N-0 and N-1 grid configurations indicate that none of the analysed conditions give rise to critical TOVs in any of the alternatives. However, energization of transformers during rare system

configurations with radial grid structure and low short-circuit level and system damping, such as black start, may potentially cause critical TOVs due to the presence of low order harmonic resonances.
The analysis carried out indicates that no alternative has a clear-cut advantage over the others in respect of the risk of critical TOVs occurring, as this is found to be highly unlikely during planned system operational configurations. However, during very low short-circuit level and system damping situations under specific configurations; it is possible to observe situations that result in critical TOVs. For these cases, project-specific transformer energization studies are required in order to identify safe grid configurations.

6.4 Overvoltage following line de-energization

When a compensated transmission circuit is disconnected from the power system, the disconnected circuit will resonate at its natural frequency as energy exchange between capacitive and inductive elements take place. Furthermore, capacitive coupling between OHL conductors and inductive coupling between the UGC and OHL conductors and shunt reactor windings will give rise to slow modulated overvoltage [20] [25] [26]. The magnitude, frequency and duration of overvoltage will depend on circuit parameters which in turn depend on circuit's physical construction, the ratio between UGCs and OHLs, and the degree of reactive compensation.

Another point of interest is overfluxing in shunt reactors connected directly to a transmission line. Flux in the reactor core is proportional to voltage and inversely proportional to frequency. The natural frequency of the de-energised, compensated line is inversely proportional to the square root of the degree of compensation with natural frequencies of 50 Hz at 100 % compensation, 36 Hz at 50 % compensation and 15 Hz at 10 % compensation. Depending on the voltage/frequency ratio and overfluxing duration, a shunt reactor can be overheated and, in worst cases, damaged. Nonetheless, there is currently only limited published literature that deals with assessment of overfluxing in magnetic components. In this context, CIGRE Electra No. 179 [24] provides TOV withstand envelopes as overfluxing is the main constraint. However, these envelopes are only applicable under power-frequency overvoltages and therefore not useful for other frequencies.

As the four alternatives for the west coast project all apply different UGC/OHL ratios, it is relevant to determine if any of them give rise to unacceptable overvoltage and in return, reactor flux levels during de-energization. This is done in the following sections.

6.4.1 Slow, modulated overvoltages following line de-energization

As an example, phase-to-ground voltages following de-energization of the 50 km transmission line between Idomlund and Stovstrup constructed as alternatives A, B, C or D are shown in Figure 45.

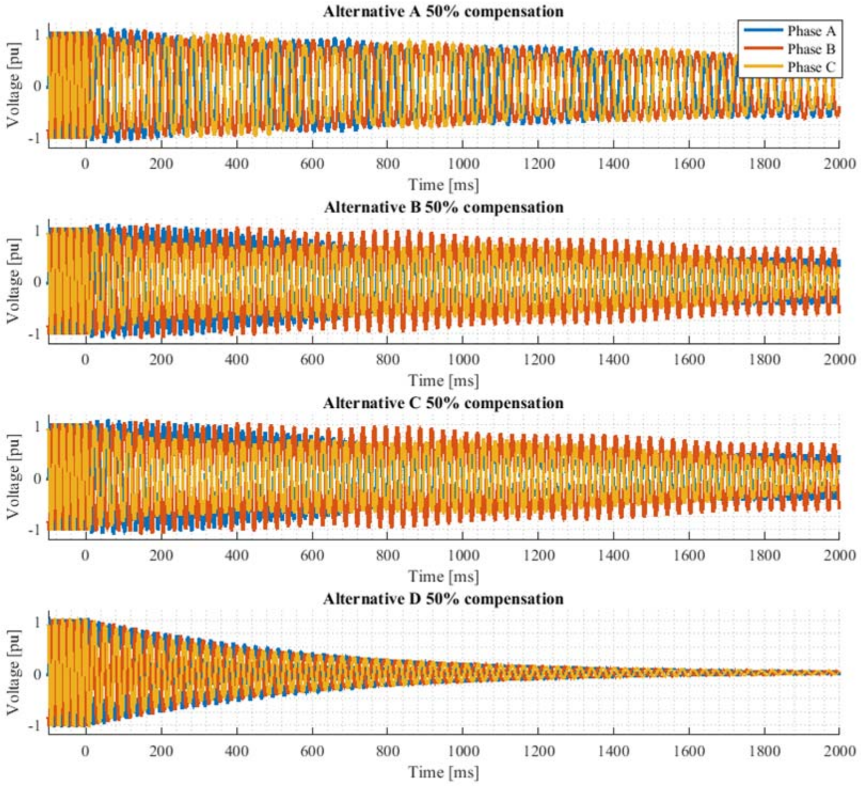


Figure 45 Phase-to-ground voltages after de-energization of transmission line between Idomlund and Stovstrup constructed as alternatives A, B, C or D.

The figure shows that the highest voltage occurs in Alternative A, followed by B and C, however, none of the overvoltages being critical. Overvoltage peaks in Alternative A because this has the highest share of OHLs and resulting increased capacitive coupling. Mutual capacitance between phases in a UGC system is negligible, because a metallic sheath is used and the ground acts as an equipotential surface. Therefore, no modulated overvoltages are seen in the Alternative D voltage profile, and voltage is decaying slowly at its natural frequency. In any case, the time constant of decay is dependent on losses in line components. For all four alternatives, overvoltages are generally not critical with the highest phase-to-ground voltage for Alternative A at 1.2 p.u. peak in phase B.

The respective flux in the shunt reactor is shown in Figure 46.

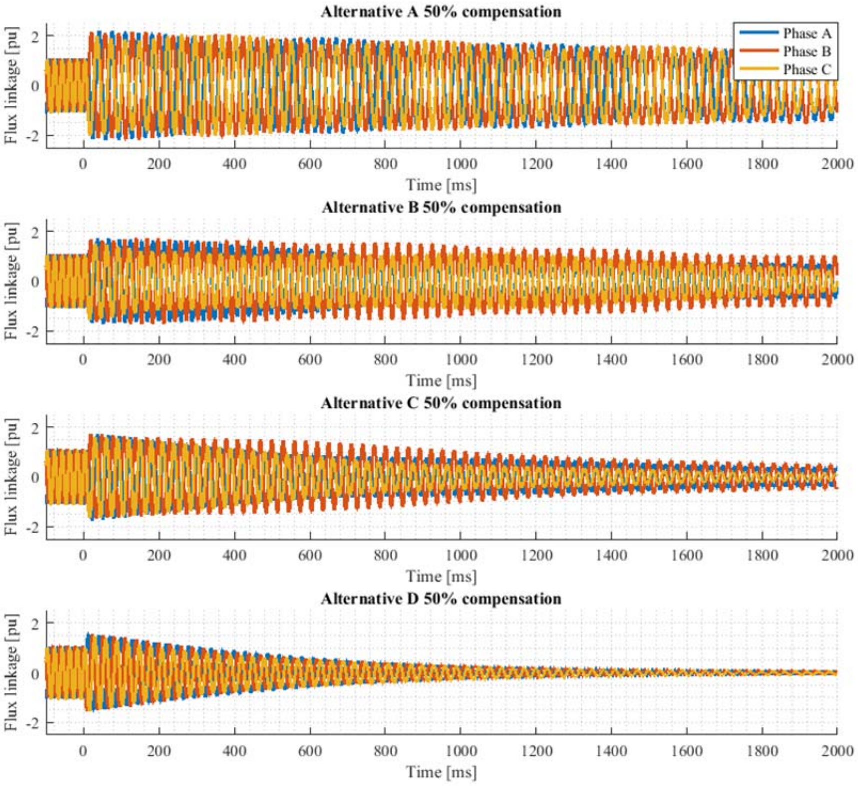


Figure 46 Relative flux linkage after de-energization of the transmission line between Idomlund and Stovtrup constructed as alternatives A, B, C or D.

Flux in a shunt reactor increases after de-energization by the grid frequency to natural frequency ratio. Furthermore, due to modulated voltage in the hybrid line-based alternatives (A, B and C), flux is further increased when modulated voltage reaches its maximum. Especially in Alternative A, flux is limited as a shunt reactor is saturated.

6.4.2 De-energization with variable shunt reactors

From an operational perspective, equipping the line with variable shunt compensation instead of fixed compensation, as discussed in Section 6.2, is preferable. This is especially true for hybrid-based alternatives A, B and C. However, as shown in the previous section these are also the alternatives most prone to shunt reactor overfluxing due to the increased share of long OHL segments.

Decreasing the compensation degree decreases natural line frequency and leads to elevated flux levels resulting in faster heating of the reactor. An example is depicted in Figure 47 where line-side phase-to-ground voltage, reactor flux and reactor currents are shown following de-energization of a 25 % compensated line.

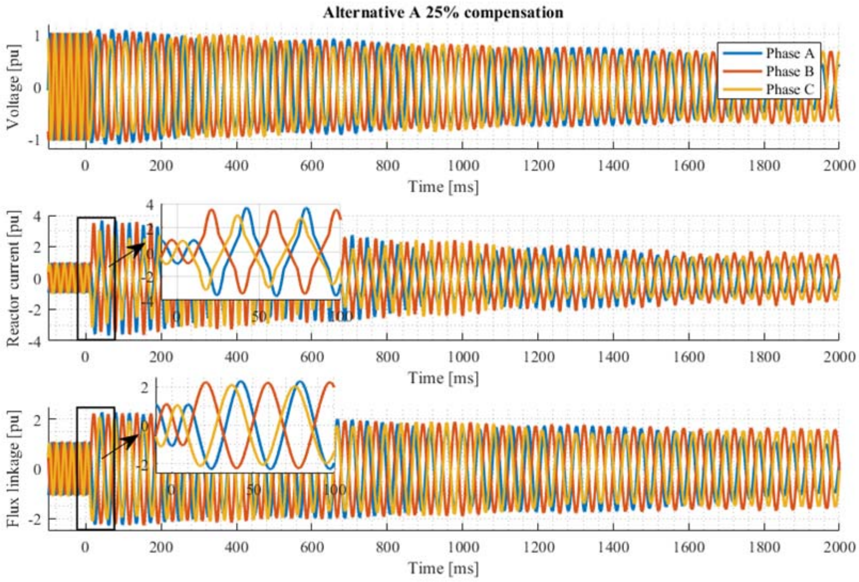


Figure 47 Line voltages, reactor current, and relative flux linkage following de-energization of transmission line between Idomlund and Stovtrup constructed as Alternative A with 25 % compensation.

Reactor currents become heavily saturated and exceed 1 p.u. for 6-7 seconds after disconnection, and flux takes an equal amount of time to return to rated levels. This can be critical for a reactor and that risk should be mitigated. One mitigation option for is to add a circuit breaker in line with the shunt reactor so that it can be isolated following de-energization of the line. However, this introduces other complexities compared to a fixed connected shunt reactor. Disconnection of a shunt reactor following line de-energization hinders the operation of delayed auto-reclose (DAR). DAR is an important operational facility that brings a line back following spurious trip of the line. Another option is to increase the nominal flux levels in the reactor core by overdimensioning. This will, however, drive up shunt reactor costs and should be avoided, if possible.

6.4.3 Discussion and conclusion

This section describes how de-energization of hybrid lines with long OHL sections can result in low frequency modulated overvoltages due to the OHL's mutual capacitance. Shunt reactor flux levels will increase during de-energization as flux is proportional to voltage and inversely proportional to frequency. Flux levels are strongly dependent on the level of compensation with levels increasing as the compensation degree decreases. Especially for alternatives A and B with low compensation levels, the shunt reactor will be driven heavily into saturation. However, with limited duration and no recognized international standard governing this matter, related criticality is difficult to determine. It is sufficient to say that there is a high risk of overfluxing being an issue and detailed discussion with shunt reactor manufacturers must take place before any categoric conclusions can be made. For UGC-based lines, de-energization issues are of less critical importance due to low flux levels and short overflux duration.

In conclusion, introducing variable shunt reactors in the hybrid line design requires special attention for alternatives A, B and possibly C. No such issue exists for Alternative D.

6.5 Line switching overvoltages

energization overvoltage characteristics for UGC systems differ significantly from those of OHL systems. The main differences are lower electromagnetic wave velocity, the use of cross-bonding in UGC systems and differences in surge impedances [16] [27].

In OHLs systems, the inter-phase modal wave propagates at the speed of light. In UGC systems, the equivalent coaxial modal wave propagates at 2/3 of this velocity due to the influence of main insulation permittivity. In general, the reduced UGC wave velocity gives rise to reduced characteristic frequencies in the voltage and current profiles following energization. However, contrary to an OHL, cross-bonding of a UGC sheath used for long high voltage cables gives rise to a large number of additional high frequency components in the profiles. These additional high frequency components exist because each wave that encounters a cross-bonding point will reflect and refract, thus giving rise to a very large number of reflections seen from any point in the UGC.

The low surge impedance of cables is relevant, as it determines the ratio of reflected and refracted waves at surge impedance discontinuity points. Typical values for cable coaxial surge impedances are 25-50 Ω compared to 350-400 Ω for OHL. The resulting overvoltage profile following energization is determined both by these factors and by the structure of the power system to which they are connected. This makes it very difficult to predict overvoltage profiles for specific transmission lines. However, it is Energinet's experience that, unless a resonance is excited by the action, overvoltages following UGC energization are comparable to or lower than overvoltages on OHLs of equal length.

Three of the four alternatives under study for the west coast lines are hybrid solutions (i.e. incorporate both UGCs and OHLs). It is well known that a propagating electromagnetic wave will be significantly affected (reflected and refracted) by the surge impedance discontinuity point between OHLs and UGCs because of their very different values. This strongly affects the voltage profile after energization of hybrid lines. As alternatives A, B and C are hybrid-line structures, overvoltages following the energization of hybrid lines are investigated.

6.5.1 Case definitions

It is desirable to have access to all component and system level detail data in a representative overvoltage study. This is not the case for the west coast projects at the time of writing this report so a series of generic simulations have been carried out using the 50 km 400 kV Stovstrup-Idomlund line as a study case example. The purpose of the study is to compare overvoltages following energization for all four alternatives.

As mentioned, alternatives A, B or C are hybrid lines. Any hybrid line can be constructed using an arbitrary number of OHL and cable sections but, as the layout of the lines is not fixed at the time of writing this report, the hybrid line structures shown in Figure 48 T_3, T_4, T_5 and T_6 are assumed. The pure UGC structure in Figure 48 T_1 represents alternative D, and the pure OHL structure in Figure 48 T_2 is also included for comparative purposes.

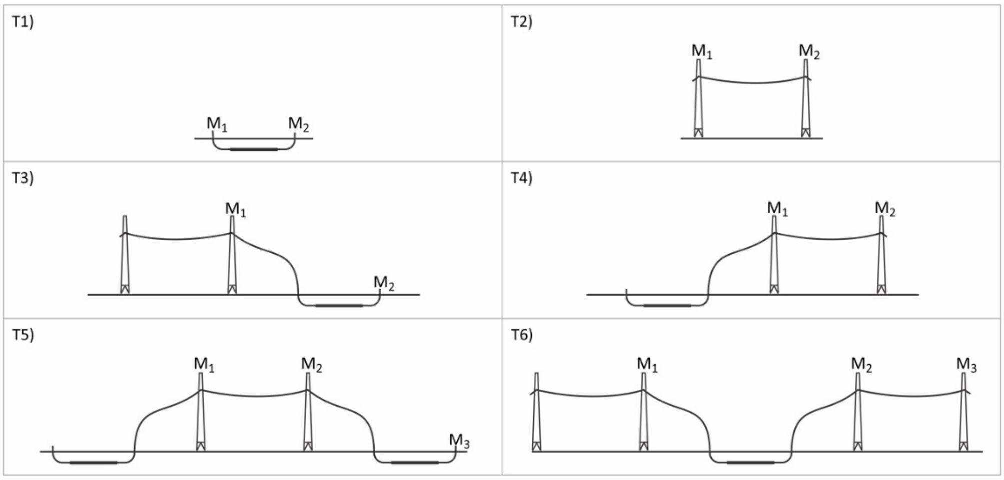


Figure 48 Topology of line to be energised – M_x marks measuring location x.

The lengths of the line segments in Figure 48 T_1 and T_2 are fixed at 50 km to represent the Stovstrup-Idomlund line and is not varied. The lengths of the UGC and OHL segments in Figure 48 T_3 and T_4 are determined by the ratios defined for alternatives A, B and C. The two UGC segments in Figure 48 T_5 and two OHL segments in Figure 48 (T_6) are assumed to be similar in length and varied at the UGC and OHL ratio defined for alternatives A, B and C (see Section 5.7 for a detailed description of the alternatives).

Since the surge impedance of the line energization end substation will impact the resulting overvoltage profile, two different substation configurations are investigated for each line topology shown in Figure 48:

1. A substation where the transmission line feeding the substation is constructed using a 400 kV Thor tower OHL (as referred to as OHL-based substation); and
2. A substation where the transmission line feeding the substation is constructed with a single cable circuit (as referred to as UGC-based substation).

For each of the six line topologies (Figure 48) with two possible energization end substation configurations and on all four alternatives, 200 line energization simulations have been conducted. Voltage in each phase was recorded at the measuring points marked by an 'M_x' in Figure 48. The instant of switching varies, following a uniform distribution over a power frequency period, and breaker poles vary, following a normal distribution with mean value 0 ms and a standard deviation of 1 ms. No surge arresters were included in the study.

6.5.2 Energization of pure OHL or UGC circuits

Time domain voltages obtained at M_2 are plotted under line topology T_1 and T_2 (see Figure 48) and for an UCG-based and OHL-based energization end substation are shown in Figure 49.

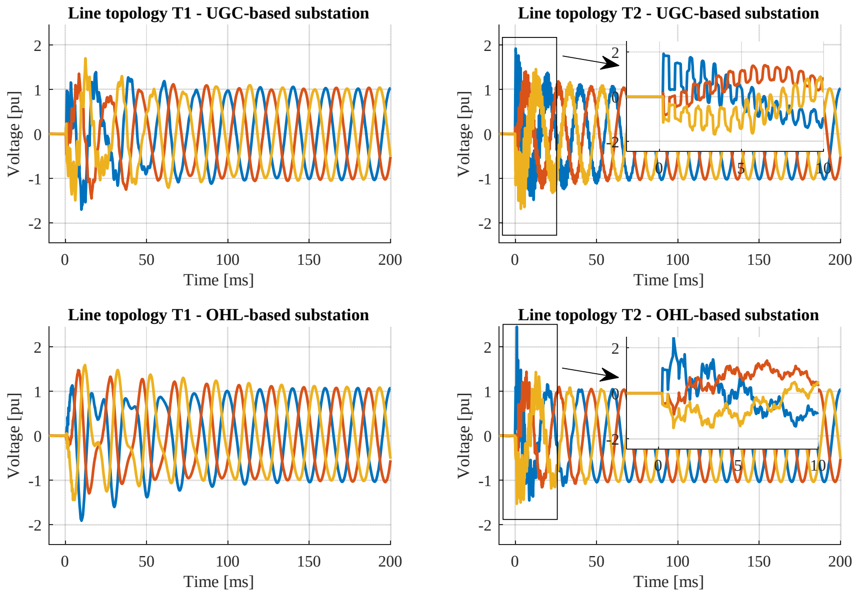


Figure 49 Time domain voltages obtained at M_2 under line topology T1 and T2 with the energized line connected to a UCG-based or OHL-based substation.

The waveforms shown in Figure 49 are representative of the normal switching transient behaviour in UGCs and OHLs. The UGC (line topology T_1) is a lower frequency transient damped rather slowly whereas the OHL (line topology T_2) is in a high frequency fast damped form. The substation configuration has some influence, with the OHL-based configuration being the one leading to the longest sustained overvoltage.

Voltages at M_1 and M_2 under line topology T_1 and T_2 (see Figure 48) are shown in Figure 50. The figure displays the highest, the 98 percentile (often used for insulation coordination), the median, the 25 percentile and the minimum voltages using boxplots.

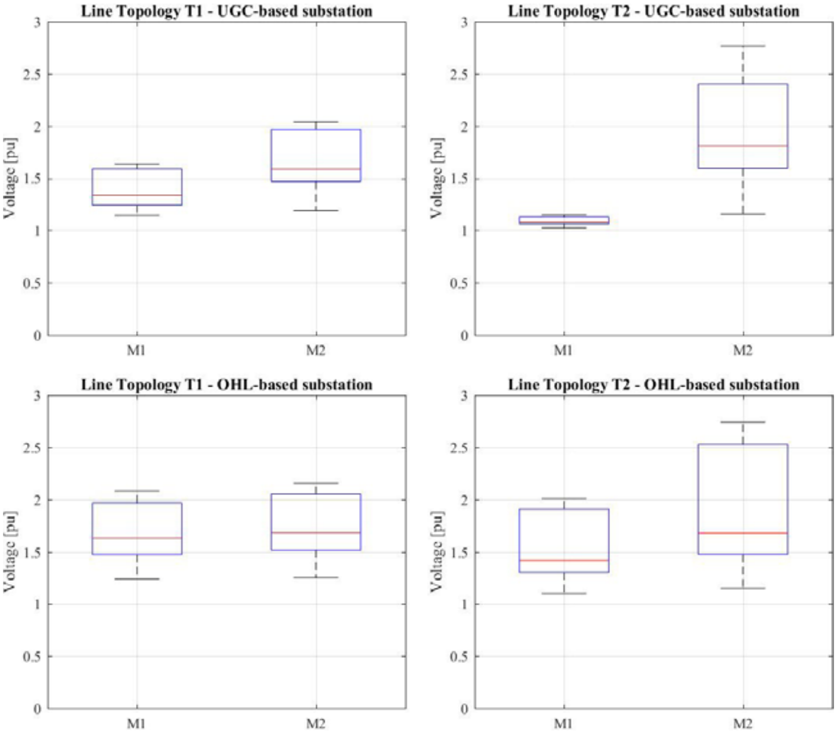


Figure 50 Highest, 98 percentile, median, 25 percentile and minimum overvoltage for energization of 50 km UGC or OHL connected to a UGC-based or OHL-based energizing substation. Measuring points defined as in Figure 48.

Results indicate that low switching overvoltages are to be expected when energizing long AC UGCs. The top and bottom left figures that show energization of UGCs display lower overvoltages at the open end (M_2) than energization of OHLs. This is an advantage and especially important for UGCs as the insulation material is non-self-restoring.

Open-end voltages of nearly 3 p.u. are seen when OHLs are energised (top and lower right figures) irrespective of the UGC or OHL based energizing substation. It is also important to notice that the overvoltage at the energizing end (M_1 in the top right figure) is low. This is an added advantage, as this voltage will affect all substation-connected components during energization, when energizing OHLs connected to cable-based substations.

6.5.3 Energization of hybrid circuits

Similar boxplots of overvoltage resulting from energization of hybrid lines (line topology T_3-T_6 in Figure 48) when energized through a cable-based substation are shown in Figure 51.

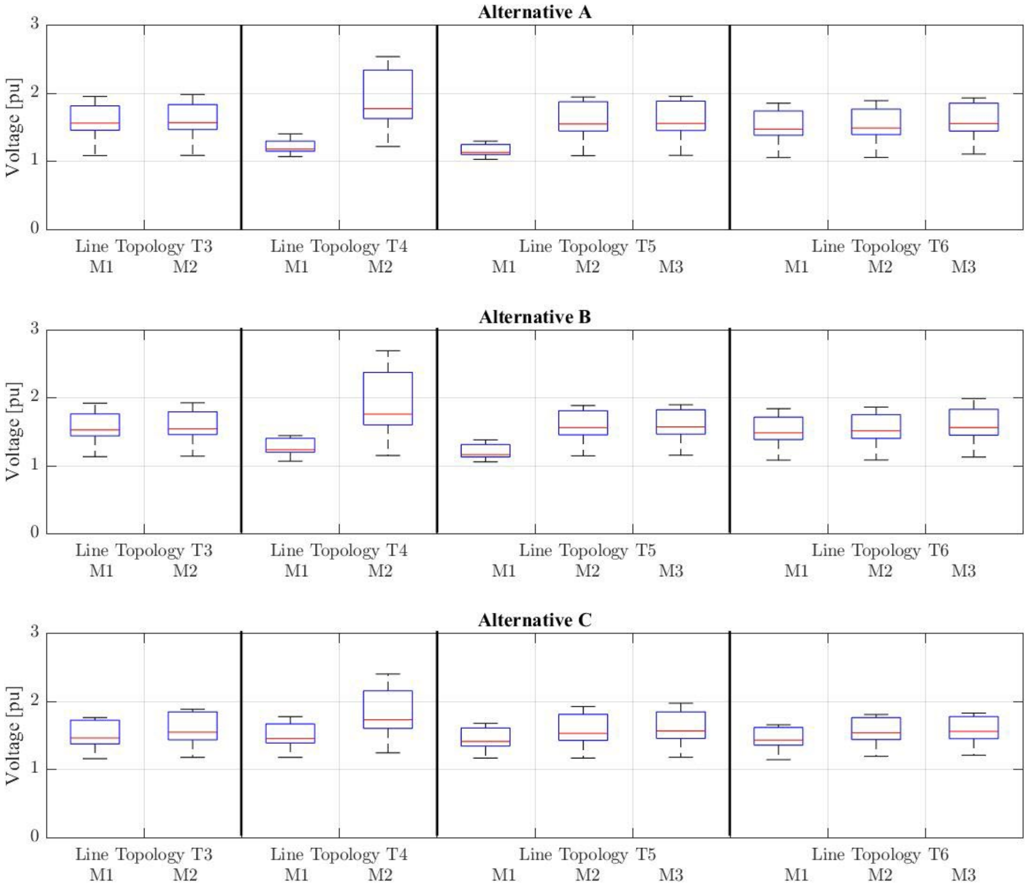


Figure 51 Highest, 98 percentile, median, 25 percentile and minimum overvoltage for energization of 50 km hybrid line under different configurations energized via a UGC-based substation. Measuring points defined as in Figure 48.

Figure 51 shows that line topology T_4 will give rise to the highest open-end voltage. Hybrid line topology T_4 is similar to the energization of an OHL connected to an UGC-based substation which also gave rise to the highest overvoltage in the previous section with just OHLs and UGCs. It should also be noted that the distribution of overvoltages between the three alternatives for the same line topology is quite similar with a tendency towards lower voltages for Alternative C. This result also matches results from the previous section well, where energization of a UCG resulted in lower overvoltages than the OHL.

It is Energinet's technical policy to install surge arresters in line with equipment utilizing solid insulation material. Based on experience, the overvoltages estimated here are at levels where the solution offered by this policy is sufficient to reduce overvoltages to acceptable levels. This must, however, be confirmed in the design stage of the transmission line projects.

Equivalent results assuming energization via an OHL-based substation are shown in Figure 52.

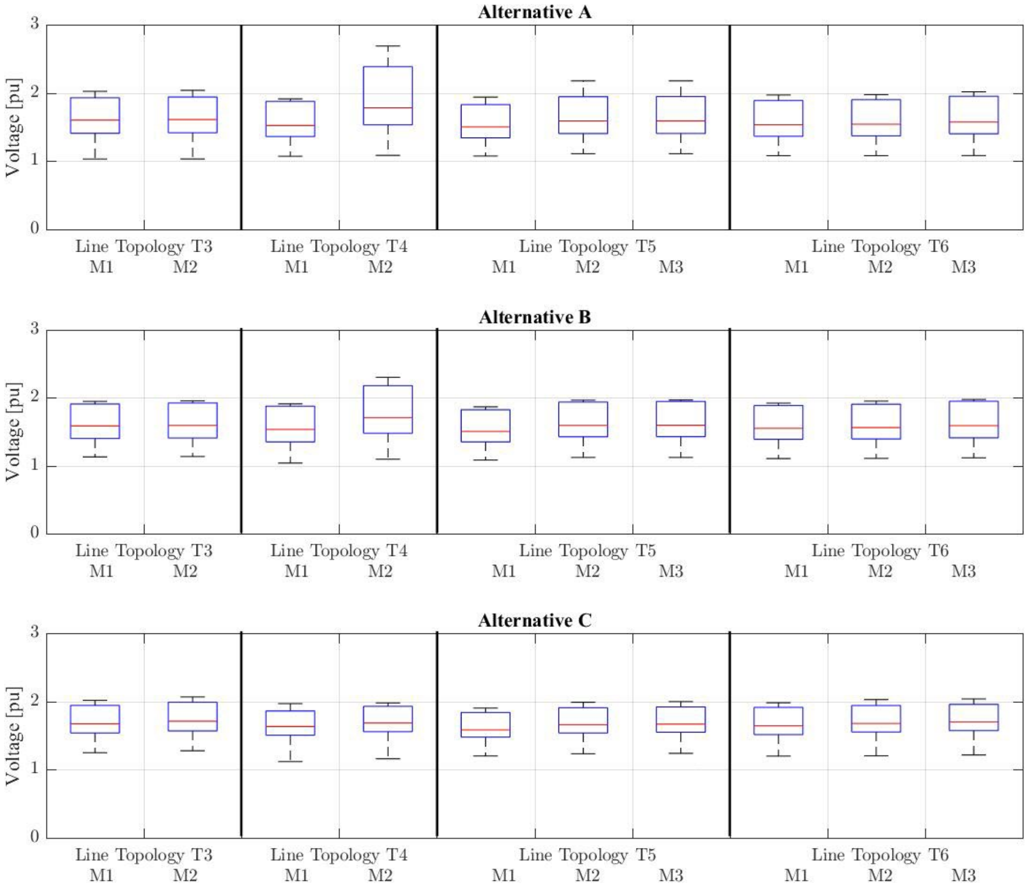


Figure 52 Highest, 98 percentile, median, 25 percentile and minimum overvoltage for energization of 50 km hybrid line under different configurations connected to an OHL-based substation. Measuring points defined as in Figure 48.

Results in Figure 52 show that overvoltage distribution is very similar, regardless of whether hybrid lines are energised from an OHL-based substation (Figure 52) or a cable-based substation (Figure 51). The main difference between the two alternatives is that the cable-based substation cases have the lowest voltage in the hybrid line/substation intersection point (M_1). The explanation can be found in the section on energization of pure OHLs and UGCs.

6.5.4 Discussion and conclusion

This section shows that UGC energization generally gives rise to switching overvoltages of a lower magnitude than in an equivalent OHL. The same can be said for a hybrid line where the UGC/OHL configuration when the hybrid circuit ends with an OHL.

Results show that the UGC and OHL ratio (the choice of alternative) does not influence overvoltages critically. This is because the geometrical structure of UGCs or OHLs will determine wave propagation characteristics, including the lines' surge impedances. The large differences between UGC and OHL surge impedances means that wave reflection coefficients will be very similar, regardless of the OHL and UGC types. Consequently, it can be stated that results in this section are of a general nature.

In conclusion, when resonance conditions are not present, a pure UGC-based line is more attractive seen from an energization overvoltage point of view. However, overvoltages established by the energization of hybrid circuits are all below levels that can be handled by the installation of surge arresters in front of all UGC and at the line end of OHLs in some cases in line with Energinet's technical policy.

6.6 Power quality-related issues (study-based discussion)

Power quality, loosely defined, is the manifestation of any problem in voltage, or current, or frequency deviations that results in failure or mis-operation of electrical equipment. In most cases, the term is used interchangeably with voltage quality. For reference, a good voltage waveform is defined as one that has/is:

- a constant sinusoid wave shape
- a constant fundamental frequency only
- a symmetrical form in three-phase power systems
- a constant rms value unchanged over time
- resilient to load changes
- reliable and available when required

There are various power quality categories that cover waveform distortion and variations. For the purpose of this report, however, only harmonics are considered for further analysis and explanation.

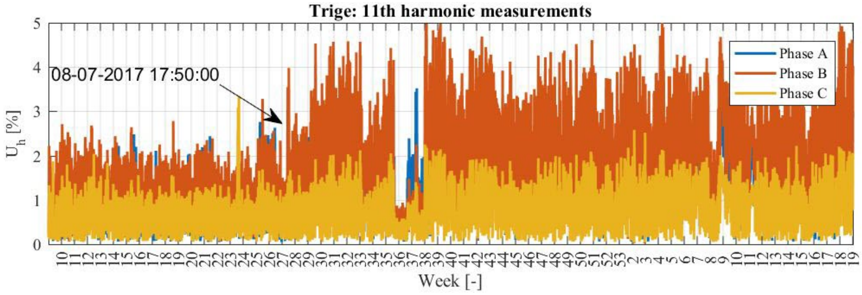
The term harmonics has a varied definition but the one applicable to electric power systems is a sinusoidal component of a periodic wave or quantity having a frequency that is an integer multiple of the fundamental frequency. The fundamental frequency of the Danish system is 50 Hz and, hence, any waveform that has a frequency as an integer multiple of 50 is classified as harmonic.

Energinet's responsibility

Energinet is responsible for the coordination of the overall power quality at transmission level in Denmark. One of the primary power quality parameters of interest is, as in most other countries, harmonic voltage distortion. In order to maintain an acceptable power quality, Energinet issues emission limits for harmonics for all new connections. Energinet is responsible for limiting the amplification of pre-existing harmonics caused by high-voltage grid expansion projects and monitors harmonic content of the system using a specially-developed power quality monitoring system for high and extra high voltage. For coordination purposes, Energinet has adopted the indicative planning levels in IEC 61000-3-6 [28].

6.6.1 Power quality in general and experience of the Danish grid

On 8 July 2017 at 17:50, Energinet commissioned two parallel 400 kV UGC systems of 8 km in the Vejle-Ådal area to partially replace overhead lines. Immediately after, significantly increased harmonic voltages were observed at Trige and Fraugde 400 kV substations. Increases were primarily seen in the 11th harmonic order, and time series measurements from both 400 kV substations are shown in Figure 53. Notice that the change of phase C in Trige is insignificant compared to Fraudge, indicative of the unbalanced nature of the phenomenon.



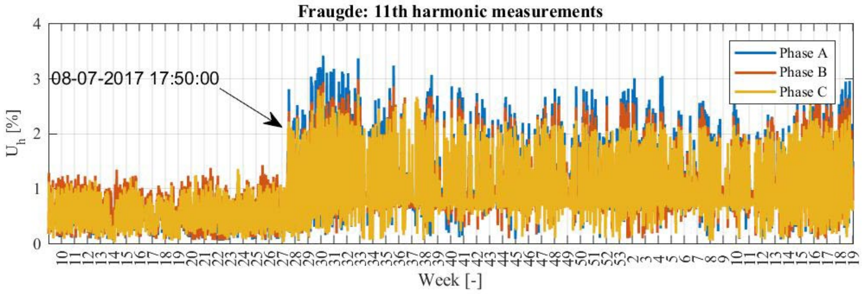


Figure 53: Harmonic measurements of 11th harmonic as 10-minute averages at the Fraugde and Trige 400 kV substations from week 10, 2017, until week 19, 2018.

After the Vejle-Ådal UGCs were commissioned, the 11th harmonic voltages exceeded the planning level in Trige, while the 11th harmonic voltages in Fraugde were within the planning level despite significant amplification. A solution to the problem is currently being designed.

The location of the Vejle-Ådal UGCs in relation to Trige and Fraugde 400kV substations are shown in Figure 54. It should be noted that the electrical distance from Vejle-Ådal to Fraugde and Trige is 80 km and 90 km, respectively, resulting in a total route length of 170 km from Fraugde to Trige. It is important to note this detrimental impact of such relatively short 400 kV UGCs on the power quality of a large geographic area.

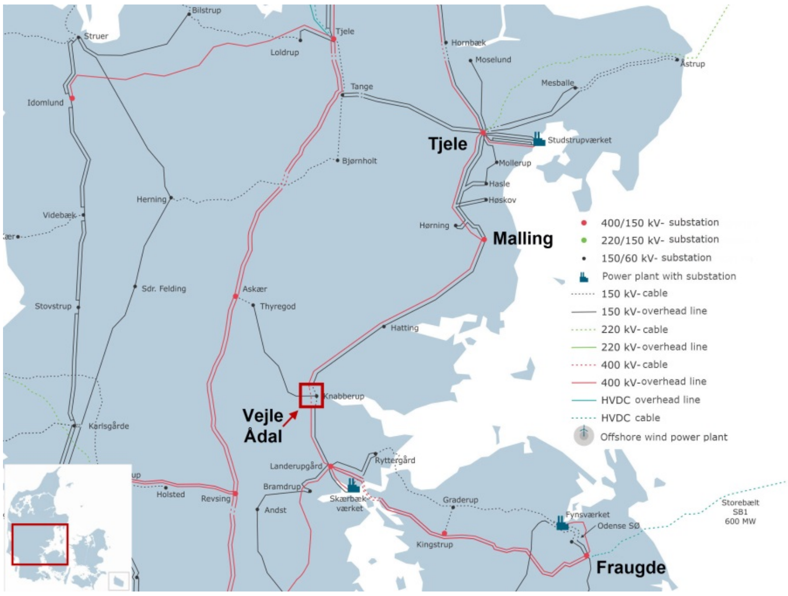


Figure 54: Location of the Vejle-Ådal UGCs in relation to Fraugde and Trige 400kV substations.

The amplification of the 11th order harmonic voltages is caused by a change in the transmission system's harmonic impedance due to the commissioning of the Vejle-Ådal UGCs. The high capacitance of the UGC shifts system resonances to lower frequencies. Energinet was after the incident able to identify this shift of resonances and the subsequent amplification of harmonic voltages using the in-house harmonic system model.

Since Vejle-Ådal had such an impact on the system, the concern is that a large share of 400 kV UGCs in the west coast projects could cause similar issues. The experience with the Danish grid shows, that especially the 5th, 7th, 11th and 13th harmonics are critical. This is because the existing distortion levels for these harmonics are at approximately 50-60 % of IEC planning levels. Hence, the primary concern is that long HVAC cables will cause system-wide amplification at these frequencies. Therefore, an analysis is conducted to identify the potential impact that different west coast alternatives would have on harmonic distortion in the transmission system.

6.6.2 Assessment of system level harmonics in a meshed transmission grid

Evaluating harmonic amplification in a meshed transmission system is a complicated task. Variation in input parameters, lack of component and system data as well as unknown sources of harmonics all make very accurate studies difficult to conduct. No agreed international method exists, and typically each TSO develops in-house methods for such assessments.

Typically, these methods are developed for the specifics of the system under consideration. Similar to other European TSOs, Energinet has developed a system level screening method to identify harmonic resonance issues and evaluate acceptability or impact of various connections. This developed method is used to evaluate the impact of the west coast projects on voltage harmonic distortion in the system.

The method is based on frequency domain harmonic propagation studies carried out using Energinet’s PowerFactory model for the Danish transmission system of Jutland/Funen (DK1). Simulations are conducted to calculate harmonic voltages, which are then utilised to establish harmonic voltage gain factors. Gain factors represent the relative changes in harmonic voltages when the transmission system’s impedance is changed by, for example, the commissioning of new transmission lines, under the assumption that harmonic injections into the grid before and after the change to the system are the same. Gain factors are used to assess how the west coast alternatives differ in their impact on the background level of harmonic voltages in the transmission system.

The aim of the on-going analysis is to determine the impact each of the west coast alternatives will have on the power quality of the Danish system. This analysis is a screening study, meaning that the results will be only indicative. The study can, however, be used to form a technically sound opinion of the expected overall system harmonic performance due to each of the four west coast alternatives. Following a final decision on the choice of circuit, a full, detailed design-specific harmonic study will be required in order to estimate the system impact of the chosen alternative and to consider possible mitigation methods and costs.

6.6.2.1 Set-up of harmonic model

Component modelling

All OHLs as well as the west coast UGC are modelled using distributed wide-band (frequency dependent resistance and inductance) models with input parameters given based on a geometrical representation of the lines (phase quantity representation); cross-bondings are implemented manually. All other cables in the system are modelled based on power frequency impedance and susceptance, in general referred to as an equivalent-pi model.

In order to capture their frequency dependency, the distributed model is applied where a long-line approximation is introduced based on the use of hyperbolic functions. This makes the cable models exact-pi as recommended by in [29]. Loads are modelled according to [30] and frequency-dependent damping in transformers and shunt reactors is included as described in [29]. Synchronous generators and synchronous condensers are modelled as described in [29].

Representation of harmonic background distortion

Two traditional approaches may be used for the representation of harmonic background distortion:

- A voltage source behind system impedance at the point of interest
- Multiple current sources distributed around the system to achieve measured distortion at the point of interest.

Both approaches have advantages and limitations.

In general, the first approach can adequately predict modification to background harmonics due to changes in the system when connections are of the radial type. The method involved in the first approach is a calculation of system impedance at the point of interest prior to and after system changes. It provides a good indicator of possible modification of background distortion, but it is not conclusive as all distortion is assumed to centre at the calculation point whereby any change to the flow of harmonic currents to that point is completely ignored.

The second approach is based on distributed harmonic current sources and assumes that sources of harmonic currents are rather well-known in the system. In most cases, this is not true as the majority of harmonic currents at transmission level originate from lower voltage level grids. However, in the presence of known recognised large harmonic sources, the method is more accurate for estimating background harmonic distortion. For the particular system under assessment, the level of harmonic current injection from known LCC HVDC converter stations at their characteristic harmonics is more pronounced than that originating in lower voltage grids by at least a factor.

Therefore, the second estimation approach was selected to work out gain factors as a result of investigating the four alternatives. As part of the approach, harmonic current sources were connected at the three 400 kV substations where LCC HVDC converters are in operation (namely Vester Hassing, Tjele and Fraugde). Furthermore, current sources are connected to most 150 kV busbars supplied directly by 400 kV substations to represent harmonic background distortion propagating from lower voltage levels. In total, 14 current sources are used in the analysis where their contributions are added as described in 6.6.2.2. Only positive sequence current injections with a frequency resolution of 5 Hz were used.

Operational scenarios

The studies are conducted for three operational scenarios; high, medium and low system demand levels. For each operational scenario, nine different HVDC filter configurations at three LCC HVDC converter locations are considered, resulting in 27 study cases per alternative scenario. None of the operational scenarios, evaluated in full detail, considers N-1 contingencies. A discussion of the impact of N-1 contingencies is available in Section 6.6.2.6.

Base case alternative

To assess potential harmonic amplification for the alternatives, a common reference case is needed. The configuration of the existing system cannot be used as a base case reference point simply because it is topologically different from the investigated alternatives (e.g. Stovstrup does not exist until after the west coast project). Therefore there is a need for a base case that is topologically identical to the investigated alternatives but different in content (i.e. same connection from A to B but with a completely different set of parameters). With this in mind, the base case alternative is defined as the west coast project constructed using only OHLs. This is chosen, as OHLs do not cause major harmonic amplification issues as evidenced by the vast majority of commissioning cases. The validity of the approach is verified by evaluating the harmonic distortion in existing 400 kV substations in Western and Southern Jutland with the west coast transmission lines modelled as mentioned (pure OHL). Taking the line in and out of services, it is confirmed that an effect on the level of harmonics is seen, but it is limited.

6.6.2.2 Methodology of analysis

Estimation of harmonic gain factors

The angles of the harmonic current components injected at different locations are unknown relative to each other. To account for this, the harmonic voltages that result from each individual source in the system are added using the general IEC summation law with the recommended α-coefficients [28]. As mentioned, 14 current sources are used for the analysis; hence the resulting harmonic voltages are calculated as shown in Eq. 1 [28].

$$U(h) = \sqrt[\alpha]{\sum_{1}^{14} U_i(h)^{\alpha}} \qquad \textit{Eq. 1}$$

Using Eq. 1, harmonic voltages are calculated at every 400 kV substation in DK1 for each of the five alternatives (A, B, C, D and base). Based on these harmonic voltages, harmonic gain factors can then be calculated for each alternative with Eq. 2.

$$G(h) = \frac{\left|U_{Alt_X}(h)\right|}{\left|U_{Alt0}(h)\right|} \qquad \textit{Eq. 2}$$

where Alt_x indicates alternatives A, B, C or D, and Alt_0 represents the base case.

As an example, gain factors calculated for the Idomlund 400 kV substation are shown in Figure 55. Gain factors are calculated for each alternative for one operational scenario with the nine different filter configurations.

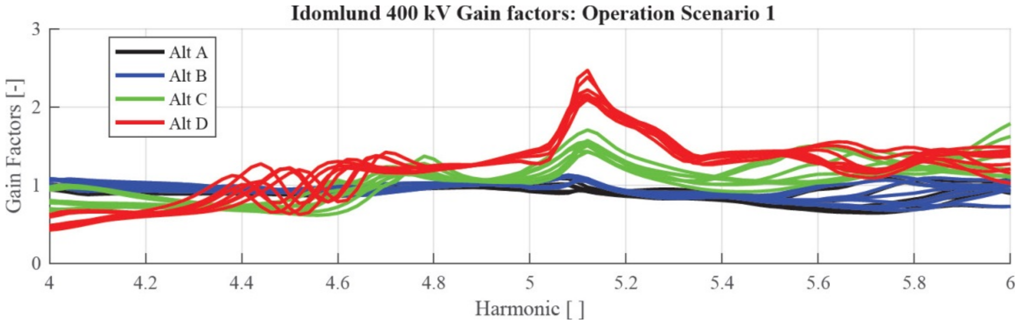


Figure 55: Idomlund 400 kV substation gain factors calculated for the frequency range 200 Hz-300 Hz.

The figure shows that gain factors can vary significantly in magnitude for this relatively narrow frequency range. Model inaccuracies are known to lead to shifts of frequency of resonance points and, consequently, in the location of any particular gain factor. Furthermore, none of the grid expansion components' parameters are available at the project planning stage, which contributes to the uncertainty of the resonance frequencies. Typically, the model predicts accurately if, for instance, high gain factors will occur in a certain frequency range.

In a screening study where the goal is to evaluate harmonic behaviour at system level, it is important to take the frequency uncertainty into account. From experience, gain factors in cable-based systems can be determined within ± 50 Hz with good accuracy.

6.6.2.3 System level data processing

In Energinet's experience, the 5 % highest gain factors identified using Energinet's harmonic system model are very unlikely to occur in practice and especially unlikely in UGC systems. To account for this, the highest 5 % gain factors are removed from the evaluation. Furthermore, assuming that all of the considered operational scenarios are equally likely to occur, the 95th percentile gain can be related to the IEC 61000-3-6 planning levels limiting the 95th percentile harmonic voltages.

In this type of harmonic screening study, it is not only relevant to know the 95th percentile harmonic voltage gain factor per harmonic, but also to gather information about the distribution of other gain factors resulting from the study as the distribution of these will give an estimate of the expected likelihood of potential amplification. The 25th, 50th, 75th and 95th percentile harmonic gain factors are determined for the four alternatives for most 400 kV substation (13 substations were evaluated) in the western Danish transmission grid for the 5th, 7th, 11th and 13th harmonics (the dominating harmonic orders in Denmark).

As an example, Figure 56 shows a boxplot for the distribution of the 5th harmonic gain factors for the four alternatives at Idomlund 400 kV substation.

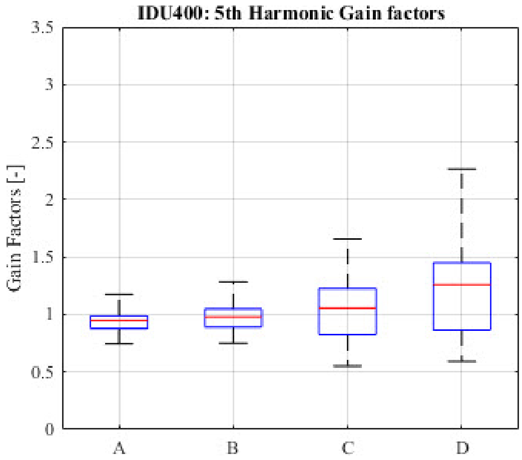


Figure 56: Boxplot showing the 95th (top black line), 75th (top blue line), 50th (red line), 25th (bottom blue line) and 5th (bottom black line) percentiles of gain factors estimated for the 5th harmonic order at Idomlund 400 kV substation.

Figure 56 shows that alternatives A and B lead to 95th percentile harmonic gain factors of 1.25 and 1.4, respectively, and that gain factors are below 1.05 for 75% of the scenarios studied. Alternatives C and D have 95th percentiles of 1.65 and 2.25, respectively. Furthermore, the figure shows that 25% of scenarios for alternative D will give rise to gains above 1.5. These results show that as the share of UGC increases, it is more likely that high gain factors will occur.

Similar results for all the substations under investigation and for the four harmonic orders of interest are provided in Appendix B.

The above graphical result only describes one harmonic frequency in one substation; it does not give a full picture of how the overall power quality will be affected at a system level by the different transmission line alternatives. Therefore, it is necessary to evaluate all of the critical harmonic frequencies for all of the substations of interest in a way that can be visualised easily and quickly.

For this purpose, the harmonic gain factors are placed into categories depending on the magnitude of the 95th percentile of the harmonic gain factor for each harmonic order. These categories are shown in Figure 57.

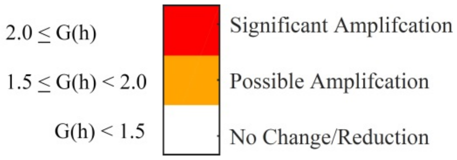


Figure 57: Categories for harmonic gain factor evaluation.

A gain of 2 or above will cause harmonic voltages to exceed the IEC planning level, considering that the average harmonic distortion level of the 5th, 7th, 11th and 13th harmonics already occupies 50% of the planning level today. Exceeding the planning level for any harmonic calls for action and is therefore marked as critical as no harmonic headroom remains. Between 1.5 and 2, amplification may or may not be problematic depending on existing levels, meaning that this category represents a risk which must be properly assessed and handled. Harmonic gain factors below 1.5 can be handled and are therefore labelled insignificant.

In the following sections, the results of the system level harmonic assessment are presented for the substations of interest.

6.6.2.4 System level assessment of the influence of the west coast project alternatives

Utilising the method for harmonic assessment described in Sections 6.6.2.2 and 6.6.2.3, the harmonic gain factors are estimated for alternatives A, B, C or D at most 400 kV substations for the 5th, 7th, 11th and 13th harmonics for most 400 kV substations in Jutland and Funen. Results are presented in Figure 58 where substations are sorted according to their geographical locations based on closeness to the west coast transmission lines.

The aim is to give a visual impression of the spread of amplification from the two 400 kV transmission lines in question.

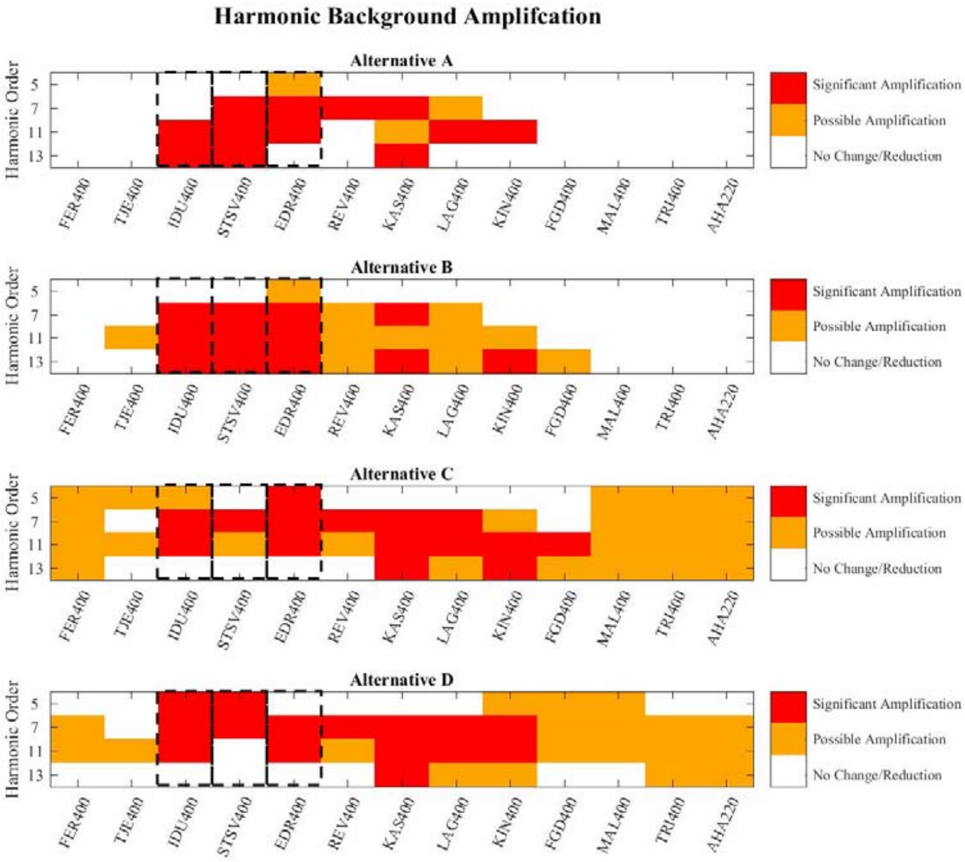


Figure 58: Illustration of 95th percentile gain factors for the alternatives. White indicates 95 percentile value below 1.5, orange indicates value between 1.5 and 2.0 and red indicates 95 percentiles above 2.0. Dashed black rectangles indicate west coast substations. A frequency band of ± 50 Hz is used.

Figure 58 illustrates that all of the west coast alternatives can cause significant harmonic amplification. For alternatives A and B, amplification is primarily local around the substations where the 400 kV west coast lines are connected as was the case for Vejle-Ådal discussed earlier in this section. The main difference between these alternatives is that alternative B may possibly cause amplification in substations geographically further from the west coast transmission lines. Both alternatives C and D lead to significant amplification in nearly all substations included in the study. There are no significant differences between alternatives C and D, as both will very likely lead to excessive harmonic levels at the system level. The implication of these results is discussed in Section 6.6.4.

6.6.2.5 Harmonic mitigation through the use of passive filters

In the previous section, it was determined that the alternatives presented will very likely cause harmonic amplification with a tendency towards more substations being affected as the share of UGCs increases. An analysis is therefore conducted to determine the effect of introducing passive harmonic filters at system level. As filters are known to impact system resonances and anti-resonance can cause problems at other frequencies than the tuning frequency only damping type (C-type) filter with a low quality factor are utilised [31] [32]. It is important to note that the aim of the mitigation screening study is to examine the system level effect of harmonic filters, not to design a full solution scheme for each alternative.

System level effect of passive harmonic filters

For this investigation, filters listed in Table 15 are added to the alternatives. Furthermore, shunt reactors are added to compensate reactive power from the filters. It should be noted that, for comparison purposes, the filter solution proposed for all alternatives is identical. Results are presented in Figure 59.

Substation	Filter type	Tuning frequency	Size	Quality factor
Idomlund	C-type	550 Hz	100 Mvar	2
Stovstrup	C-type	350 Hz	100 Mvar	2
Stovstrup	C-type	550 Hz	100 Mvar	2
Endrup	C-type	350 Hz	100 Mvar	2
Endrup	C-type	550 Hz	100 Mvar	2

Table 15 Filters and shunt reactors added to alternatives A, B, C and D to investigate harmonic mitigation with C-type filters.

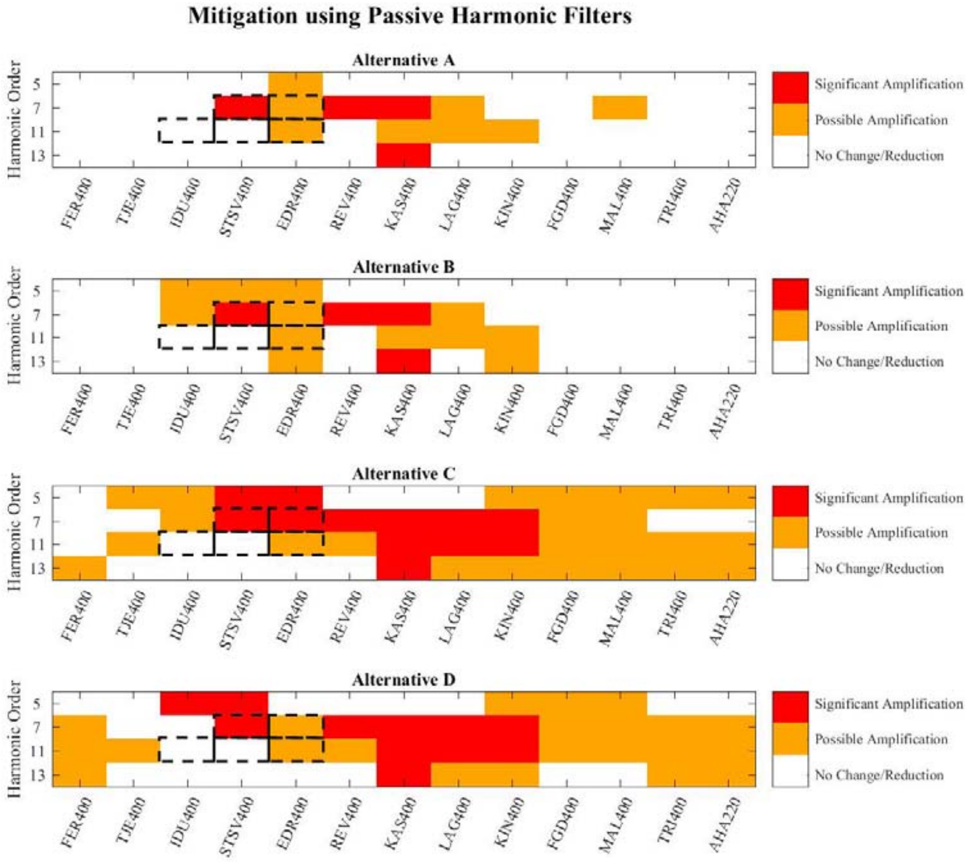


Figure 59: Illustration of 95th percentile gain factors for the alternatives with C-type harmonic filters for alternatives A, B, C and D. Dashed black rectangles show substations and tuned frequencies for added harmonic filters.

In order to illustrate the impact the tested filters have in harmonic amplification Figure 60 is created. The figure compares graphically Figure 58 to Figure 59. A green marking indicates positive impact of a filter where negative is marked by red. The effect is positive if a red square changes to orange or white or if an orange square changes to white. Filter’s location and tuning frequencies are marked by dashed lines.

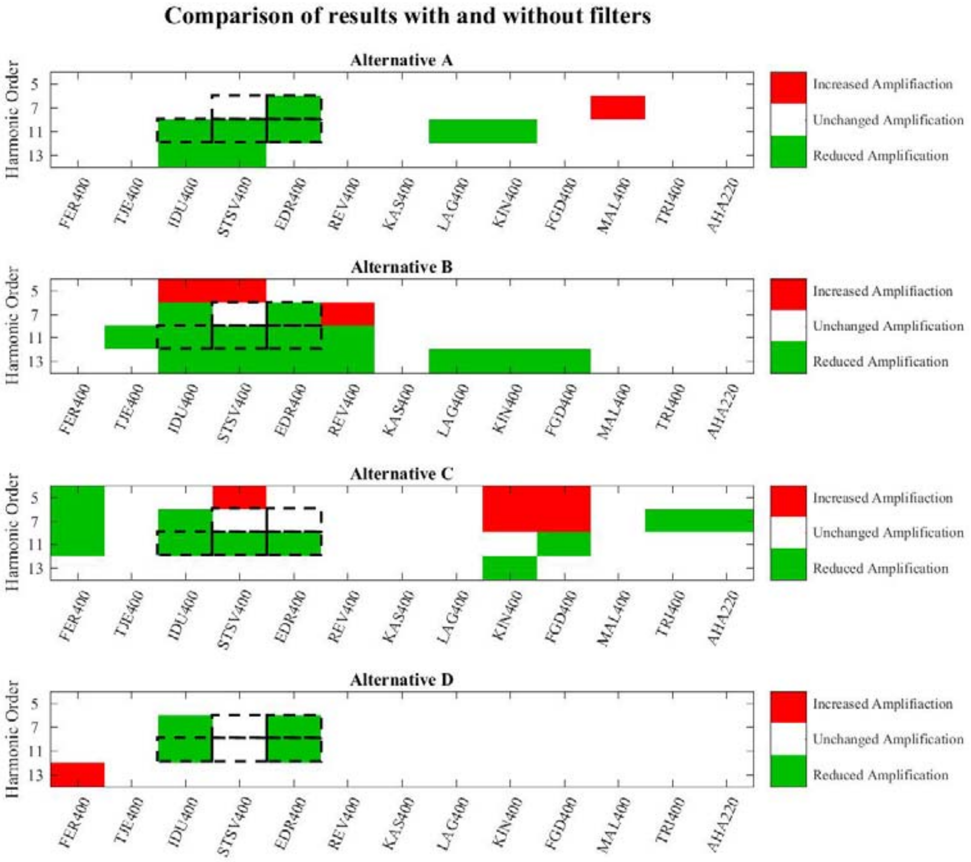


Figure 60: Comparison between 95th percentile gain factors for the alternatives without filters and with C-type harmonic filters. Dashed black rectangles show substations and tuned frequencies for added harmonic filters.

Results show that passive harmonic filters improve the system’s power quality, as these mitigate harmonic amplification. For alternatives A and B, the positive effect of the filters is in general more wide-spread in the system. For alternative C it is relatively local and for alternative D, the effect is only seen at the substations where the filters are installed. It is interesting to observe, that the filter tuned at the 11th order located in IDU400, STSV400 and EDR400 (west coast substation) for alternative A and B act to reduce the amplification of the 13th order harmonic as well; this effect is not seen in alternatives C and D.

Taking into account that the amount of UGC is correlated with more widespread harmonic amplification in the system and that the filters only have a local effect in the high UGC share alternatives, it is expected that the number of filters needed to resolve the issues at system level increases with the amount of UGC. Achieving a robust solution in these alternatives may be a very challenging task simply due to the number of filters needed, hence likely increasing the risk of harmonic amplification at other frequencies at other location (anti-resonance) than the targeted, as observed especially for alternative C (notice that this effect does not appear in alternative D). It is also of interest to mention the need of filter redundancy in order to uphold planning levels during, for example, planned filter maintenance.

6.6.2.6 Impact of N-1 contingencies

The results presented so far have been conducted for intact grid scenarios only. However, during day to day operation of the system, contingency situations arise, due to either planned maintenance or faults. Such contingencies are known to change the system's harmonic behaviour, especially if major transmission lines are out of service.

Contingencies usually lead to more extreme conditions by changing the amplification of particular harmonic frequencies or by shifting resonance frequencies. To illustrate the point, gain factors are calculated at Endrup 400kV under alternative D for the three N-1 contingencies listed in Table 16. Gain factors are calculated with reference to alternative D under intact grid condition and are shown in Figure 61.

Contingency:	Line out of service
Contingency 1	Endrup-Germany 400 kV line
Contingency 2	Endrup-Stovstrup 400 kV line
Contingency 3	Idomlund-Tjele 400 kV line

Table 16 Contingencies considered for analysis for harmonic amplification.

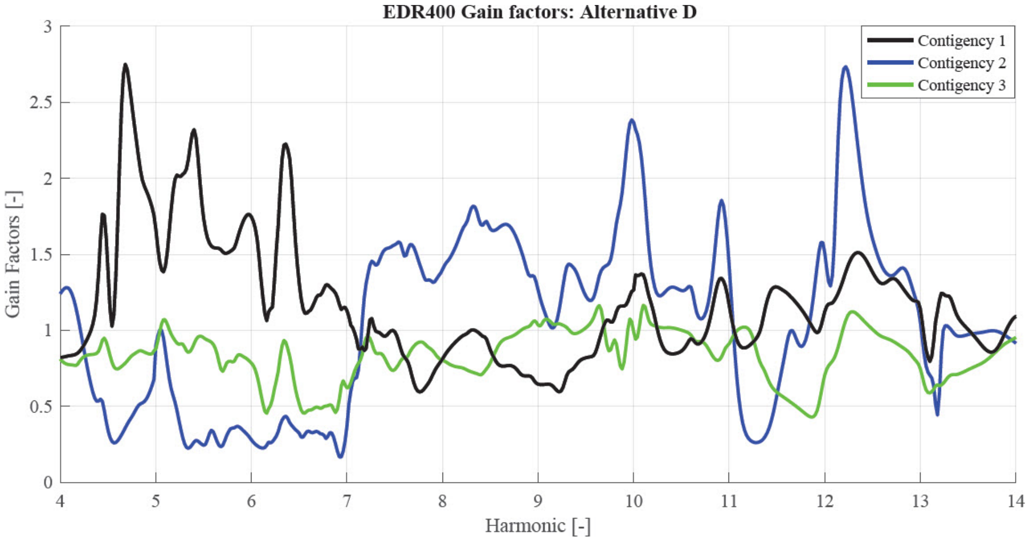


Figure 61: Gain factors for Endrup 400 kV substation calculated for alternative D under three N-1 contingencies.

Figure 61 shows that amplification can change drastically, as resonance conditions are altered by the N-1 grid configuration. In the figure, especially contingencies 1 and 2 result in very different gain factors compared to intact grid, as these contingencies represented outage of the Endrup 400 kV lines to Germany and Stovstrup, respectively. Inversely, contingency 3 shows minor changes as gain factors are 1 or below. This is an outage of the 400 kV lines between Idomlund and Tjele substations, located far from Endrup substation.

Clearly, outages of components close to the substation have the greatest influence on harmonic voltage distortion in that substation. Generally, Energinet experiences that contingencies may cause significant changes in the local harmonic voltage amplification. This is expected to occur to an equal degree with the four alternatives. However, alternatives C and D are challenging as they are very likely to cause system-wide amplification for intact grid. Since contingencies cause significant local changes in the level of amplification, any contingency in the system becomes relevant to these alternatives. For alternatives A and B, a reduced number of contingencies may prove problematic, as their initial harmonic amplifications are close to the west coast transmission lines.

6.6.2.7 Harmonic mitigation through the installation of high ampacity cables

A method to reduce the impact of UCG on harmonic background amplification is to replace the hitherto assumed UGC type (2 x 2,000 mm^2 Al) with a different type provided with larger cross-section and a lower resistivity core material (1 x 2,500 mm^2 Cu). This UGC type, with approximately twice the transmission capacity of the original, will reduce UGC length by 50 % in all alternatives. To achieve sufficient transmission capacity, the UGCs are, however, placed with a distance of 1 m compared to the traditionally used 0.4 m. This increases the mutual inductance leading to an increased positive sequence inductance of the UGC system hence shifting resonances to lower frequencies. Results of this analysis are presented in Figure 62.

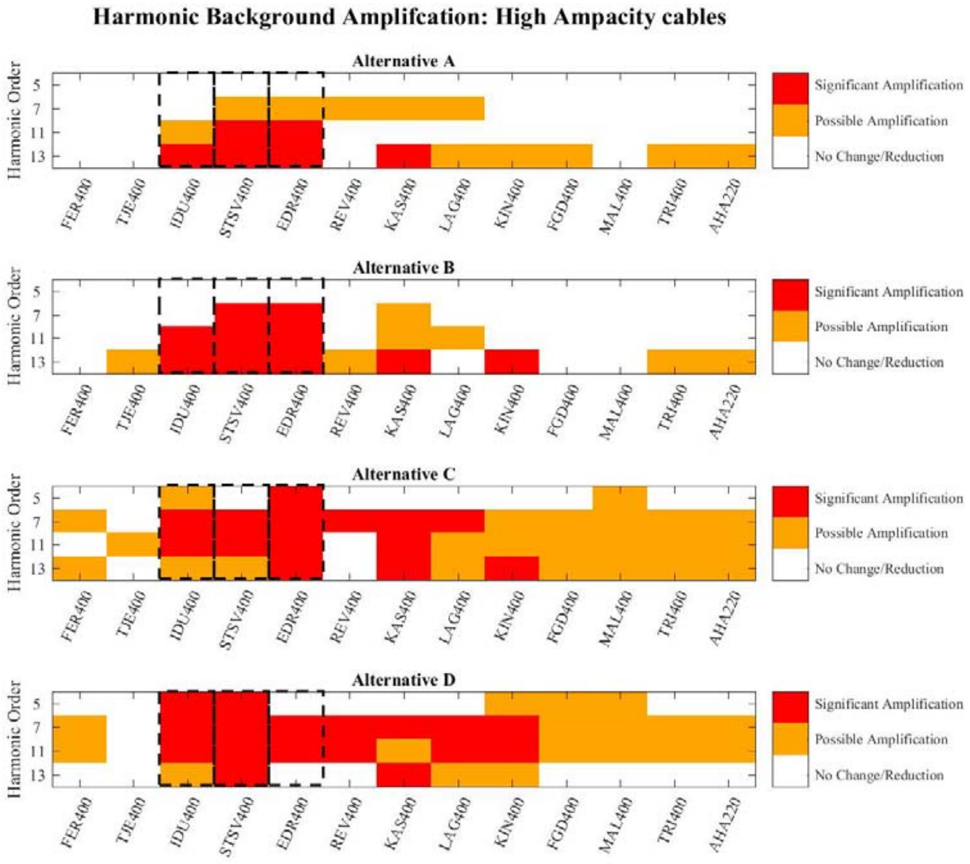


Figure 62: Illustration of 95th percentile gain factors for the alternatives using a high ampacity UGC. Dashed black rectangles show west coast substations.

The results show a reduction in harmonic amplification in alternatives A and B and little to no reduction in alternatives C and D. The reduction identified in alternatives A and B are due to the reduction in total capacitance added to the system being higher than the increase of inductance. When the total included UGC exceeds a certain amount, the positive effect wears off. A similar result was identified with the 2x2000 mm^2 Al UGCs, where results show that the amplification on a system level was worse in alternative C compared to D. Overall, it can be concluded that reducing total UGC length by using larger UGC cross-section reduces harmonic amplification as long as the installed cable length is limited. The technology is therefore of interest for the 400 kV west coast projects.

6.6.3 Emerging technologies for mitigation of harmonics

6.6.3.1 Active filtering

Active filtering of harmonics at high and extra high voltage levels using power electronics is an emerging technology that is showing promise. Because the active filter is controlled by software, the solution is more flexible compared to a passive filter solution designed for specific performance. Such flexibility is valuable when handling uncertainties in the analysis of the impact on the system's harmonic performance when extensive grid reinforcements similar to those on the Danish west coast are made.

Active filters are often implemented as shunt-connected STATCOMs. A STATCOM is typically employed for dynamic voltage stability and reactive power compensation issues, but can also be used for active filtering. The technology has been successfully tested for radially connected off-shore wind power plants.

However, in a meshed grid, the control objective of the active filter becomes more difficult to determine, and issues such as grid impedance variations and connection voltage level become important. The control objective could be, for instance, to reduce two or three harmonic voltage components at the STATCOM's local busbar. This can be done by injecting harmonic current at the frequencies of interest, giving rise to harmonic voltage in phase opposition to the ones existing in the system. However successful, this would be at the expense of the harmonic voltage distortion at other remote busbars (propagating effect as with passive filters).

No active filter-based solution has been implemented to mitigate harmonics at transmission system level in a meshed grid anywhere in the world today. Based on this and the premonition that a significant number of STATCOM units will be required to mitigate at system level, an active filter based solution is viewed as non-feasible for the west coast project.

6.6.4 Discussion on the impact of elevated harmonic distortion

6.6.4.1 Existing and new connectees

Energinet's practice for coordinating harmonic distortions caused by transmission-connected facilities is to allocate each connectee a certain share of the available harmonic headroom. The headroom is determined as the difference between the adopted planning levels and the existing background distortion level at the relevant point of connection

It is then the responsibility of the connectee to make the necessary investments to ensure that such limits are not exceeded. If there is little or no harmonic headroom available, harmonic emission limits issued to connectees become very strict, resulting in increased investment costs (both in terms of equipment and land requirements) for the connectee.

This poses a special risk to future large scale consumers-, DSO -, wind -, or solar power plant connections. For existing plants connected at transmission level, the effects are similar to all other transmission level components. In severe cases, the equipment of connected facilities can experience reduced lifetimes, increased losses associated with harmonics and even mis-operation.

In conclusion, undergrounding large parts of the transmission grid simultaneously could therefore involve a significant risk for both existing and new connectees in Denmark.

6.6.4.2 The transmission system

Elevated harmonic distortion in the grid increases losses and potentially reduces component life time thus increasing socioeconomic costs. However, existing HVDC are also affected.

Harmonic filters in an LCC HVDC scheme fulfil two duties; act as harmonic filters to reduce harmonic current originating from the converter station and provide reactive power support to the HVDC converter station. Without this reactive power support, the ability of HVDC stations to transfer active power is limited because of voltage issues in the grid.

Overloading of LCC HVDC converter station filters with excess harmonic current due to increased distortion will result in the protection system of the filter tripping the filter. A reactive power controller (RPC) will then, if no reserve filter is available, regulate active power transfer of the HVDC link downward to avoid overloading of the remaining filters caused by harmonics from the converter. If the overloading is caused by an increase in the background harmonics the remaining filters may also be tripped due to overloading causing a cascade event. If the remaining filters are not affected by the tripped filter, they will stay in service, but harmonic distortion will increase due to the tripped filter.

6.6.4.3 HVAC-connected neighbouring countries

Another concern in relation to cable undergrounding is the HVAC-connected German transmission system's influence on power quality. Previous sections have shown that the cable share in the west coast projects will significantly impact harmonic amplification throughout most of the Danish transmission system. Such impact will, with some certainty, propagate into the German transmission system. This poses a potentially risk for the German system as well as Energinet as the responsible party and cannot be estimated without detailed studies using harmonic models of each two countries.

6.6.5 Discussion and conclusion

Experience from the Danish transmission grid shows that short 400 kV UGC can have a system-wide impact on the amplification of harmonic voltages. This was identified and observed for the Vejle-Ådal cables which led to significant amplification of 11th harmonic voltages over a large geographical area.

For the ongoing analysis, four alternatives (A, B C and D) for the west coast project was investigated to determine the level of impact each would have on the power quality of the Danish transmission system. It was established that increasing the share of UGC will cause significant harmonic amplification of critical frequencies over a widespread area. Alternatives A and B with 10 % and 15 % UGC showed harmonic amplification concentrated in the vicinity of the west coast substations, while alternatives C and D with 50 % and 100 % UGC were found to cause system-wide harmonic amplification. Alternative C was found to be the worst case, as this alternative caused amplification of most harmonics and in the most 400 kV substations.

The analysis has investigated the use of passive harmonic filters for the mitigation of harmonic amplification. This showed that specific harmonic frequencies can be mitigated, but the design of the filter solution becomes increasingly complex with the amount of cable, especially in alternatives C and D, due to the large number of filters required. Using a cable with higher transmission capacity can be used to reduce the required UGC lengths by half but will only have a positive effect for alternatives A and B, and little to no effect for alternatives C and D.

The harmonic assessment shows that an increased share of UGC in the west coast transmission lines will give rise to system wide-spread harmonic amplification and as a consequence thereof increased complexity of mitigation solutions. It is shown that as the share of UGC increases, the amplification spreads to a wider area of the transmission system which complicates mitigation significantly.

6.7 Discussion of outcome of technical studies

The continued expansion and development of the transmission grid in Denmark must at all times be accomplished without compromising system security and quality of supply. The technical solutions chosen and implemented must be technically robust to be a part of the expected development plan of the overall transmission system, while introducing minimum operational risk.

With this premise in mind, results of the technical analyses carried out demonstrate that issues are highly likely to be encountered when the share of UGCs increase. In particular, deterioration of power quality will have a limiting effect on the possibility to use UGC.

The identified challenges in terms of power quality, owing to an increased use of UGC, not only give rise to local issues in the area directly affected by the new transmission lines, but also to other parts of the transmission system. Use of UGC to the extent defined in alternatives C or D is expected to negatively affect power quality in most of the western Danish system and possibly northern Germany.

Consequently, the issues introduced cannot merely be mitigated locally but must be handled at system level. As this requires an increased number of mitigation measures, the design and functional specification of such a system becomes extremely complicated. This is the case even before considering contingencies and the requirement for redundancy as these assets become vital for the safe and secure operation of the system, not only in Denmark but also in Germany. Added to this is the complexity of introducing, operating and controlling a large number of reactive power compensation units both to compensate the harmonic filters and the UGC and again the question of redundancy requirements

From an overall system development perspective, the sequential commissioning of a number of smaller UGC projects is more desirable than the commissioning of a single large UGC installation. The reason for this is the numerous technical uncertainties, which must be handled all at once in case of one large UGC project. It is also beneficial that new design conditions, such as measurements of harmonic voltages or measurements of transmission line impedance of a commissioned installation, may be established fairly systematically for small sequential UGC projects at every milestone providing increased certainty for the future expansion and development of the grid.

In practice considering the grid expansion rate expected for the Jutland-Funen grid, such a sequential expansion is not possible. The planned expansions of the 400 kV grid must be expected to coincide with grid expansions at lower voltage levels including the connections of future offshore wind power plants typically using long cables. Furthermore, the trend of transmission level connected consumers seems to increase rapidly which is a further complication.

The power quality analysis shows that a high total amount of UGC added in the transmission grid has a negative impact on most of the system's power quality. Therefore, a significant number of harmonic filters are required to ensure mitigation. As a consequence the possibility of designing robust mitigation solutions is far more complex. As such, the discussion of policy on the use of UGC cannot be limited to each individual project but must be considered for all coinciding projects to ensure the necessary robustness. This will make it possible to ensure a more appropriate long-term coordination of power quality in the transmission system.

It is of importance to note the possibility of using a cable type with increased transmission capacity for current and future 400 kV transmission line projects. This has less negative impact on widespread harmonic amplification as the total amount of cable is reduced. However, the use of this type of cable, introduces new challenges with regard to transportation and installation due to cable size and considerably heavier weight. Besides, there are no applicable international testing standards for this cable type and it is only offered by a limited number of suppliers. It is, however, estimated that these challenges can be overcome, and having both this solution as well as the possibility of using passive harmonic filters provides flexibility to the design stage for new 400 kV transmission lines.

Based on the above arguments, use of UGC for a large share of the current 400 kV grid reinforcement projects in Western and Southern Jutland is found to be associated with unacceptable operational risks. With reference to a corresponding risk evaluation use of UGC up to the share defined in Alternative B is evaluated as feasible options on the basis of a mitigation measure that could be designed, managed and commissioned in due time.

7. Conclusion

The first public hearing phase in connection with the establishment of the 400 kV connection in Western and Southern Jutland between Holstebro and the Danish-German border spurred local concern, demands for full underground cabling and subsequent doubts in the public as to whether finances, technology or geography determines the feasibility of underground cabling at the 400 kV level. Moreover, a wish was expressed for an investigation into possible alternatives to the proposed 400 kV overhead line solution. On this basis, a technical report was requested regarding alternatives to the approved overhead cable connection.

A technical report has been prepared, providing a description of and quantifying the total need for expansion and the systematic task to be performed in the future by the electricity infrastructure in Western and Southern Jutland, as regards integration of renewable energy, maintaining security of supply, and facilitating the electricity market at the transmission level. The report describes the structural composition of the electricity system in Denmark and examines the relationship between the existing system and the need to expand the 400 kV electricity transmission grid. Lastly, the report provides a review of Danish and international practice relating to the use of cables at the transmission level.

The technical report clarifies the potential use of the following technical solutions in connection with the realisation of the identified need for expansion in Western and Southern Jutland:

- The approved 400 kV overhead line solution (Reference/Alternative A);
- The approved 400 kV overhead line solution – with an increased cable share without the need for establishing additional compensation stations (Alternative B);
- The approved 400 kV overhead line solution – with an increased cable share and resulting need for establishing additional compensation stations (Alternative C);
- Full underground cabling of the current 400 kV connection (Alternative D);
- Perspectives for using 150 kV or 220 kV cable systems with full underground cabling (Alternative E); and
- Perspectives for using direct current connections (HVDC) with the laying of necessary cable systems underground or offshore (Alternative F).

In addition, an investigation was made into the possible use of gas-insulated transmission lines (GILs).

The main report conclusions are summarised below:

400 kV overhead line solution with varying cable share (alternatives A-D)

The possibility of increased 400 kV underground cabling has been examined for the defined alternatives A, B, C and D. The conclusion is that it is possible to underground up to 15 % of the total distance, corresponding to alternative B. Further underground cabling will result in significant and unacceptable risks to the electricity grid due to system wide amplification of harmonics. Maintaining harmonic distortion within utilized planning levels is extremely important for asset lifetime and a compatible operation. Deviation from planning levels will eventually cause miss-operation to a level that may possibly compromise the security of supply.

Perspectives for using 150 kV or 220 kV cable systems with full underground cabling (Alternative E)

Use of 150 kV or 220 kV cable systems will require massive restructuring of the transmission grid in Jutland due to a need for very extensive grid reinforcements. Establishing parallel operation of meshed 150 kV or 220 kV cable grids and the remaining 400 kV transmission grid will introduce an unacceptable operational complexity in relation to the control of power distribution between voltage levels, including the risk of operational limitations. Establishing extensive 150 and 220 kV cable grids would introduce technical challenges similar to those seen in large 400 kV underground cable projects, including challenges related to power quality and component energization. Finally, meshed 150 kV or 220 kV cable grids lack the necessary robustness required for future development of the energy system.

Perspectives for using high-voltage direct current (HVDC) connections with the laying of necessary underground cable systems onshore or offshore (Alternative F)

HVDC connections incorporated as integral parts of the transmission grid will result in unacceptable technical and operational risks due to the required control algorithms necessary for embedded HVDC connections to emulate the electrical behaviour of an HVAC transmission system. Such control algorithms have not been implemented anywhere world-wide. In addition, there is a general lack of experience of the use of embedded multi-terminal HVDC connections on the scale required in the relevant grid reinforcement projects.

Use of gas-insulated transmission lines

Worldwide, there is no experience of the use of long gas-insulated power lines directly undergrounded. The solution is currently only used for very short distances of up to approximately 1 km. Therefore, introducing gas-insulated transmission lines in a 170 km section presents an unacceptable risk.

Perspectives for using 400 kV cables in connection with long-term grid expansion plans

Using 400 kV underground cabling must be evaluated from a system perspective, since current cable technology only allows for limited use in the system. Consequently, underground cabling must be used with caution, taking into account future grid expansion plans, which also factor in any need for underground cabling near conservation areas or urban areas. It is hence important to ensure that the possible cable share is used where it is most needed.

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Appendix A – commissioning letter

Energi-,
Forsynings- og
Klimaministeriet

Chairman Lars Barfoed
Energinet
Tonne Kjærsvej 65
7000 Fredericia

The Minister

Date
17 July 2018

Case no. 2018-498

Technical report on the use of cable systems in the expansion of the 400 kV grid in Southern and Western Jutland

Dear Lars Barfoed,

The first public phase in connection with the establishment of the 400 kV connection in Southern and Western Jutland has spurred local concern and demands for full underground cabling. Some doubts have been expressed in the public sphere as to whether finances, technology or geography determines the feasibility of underground cabling at the 400 kV level. On this basis, I have asked Energinet to prepare a technical report that provides a review of the possibilities for expanded underground cabling and other alternative cabling solutions.

Attached here is the synopsis of the report, which has been prepared in collaboration with Energinet, and which specifies the contents of the technical report.

Energinet is requested to submit a first draft of the report on 17 September, and to deliver a final version on 28 September 2018. Please send the final report in a Danish and English version.

Best regards

Lars Chr. Lilleholt

Lars Chr. Lilleholt

Ministry of Energy, Utilities and Climate

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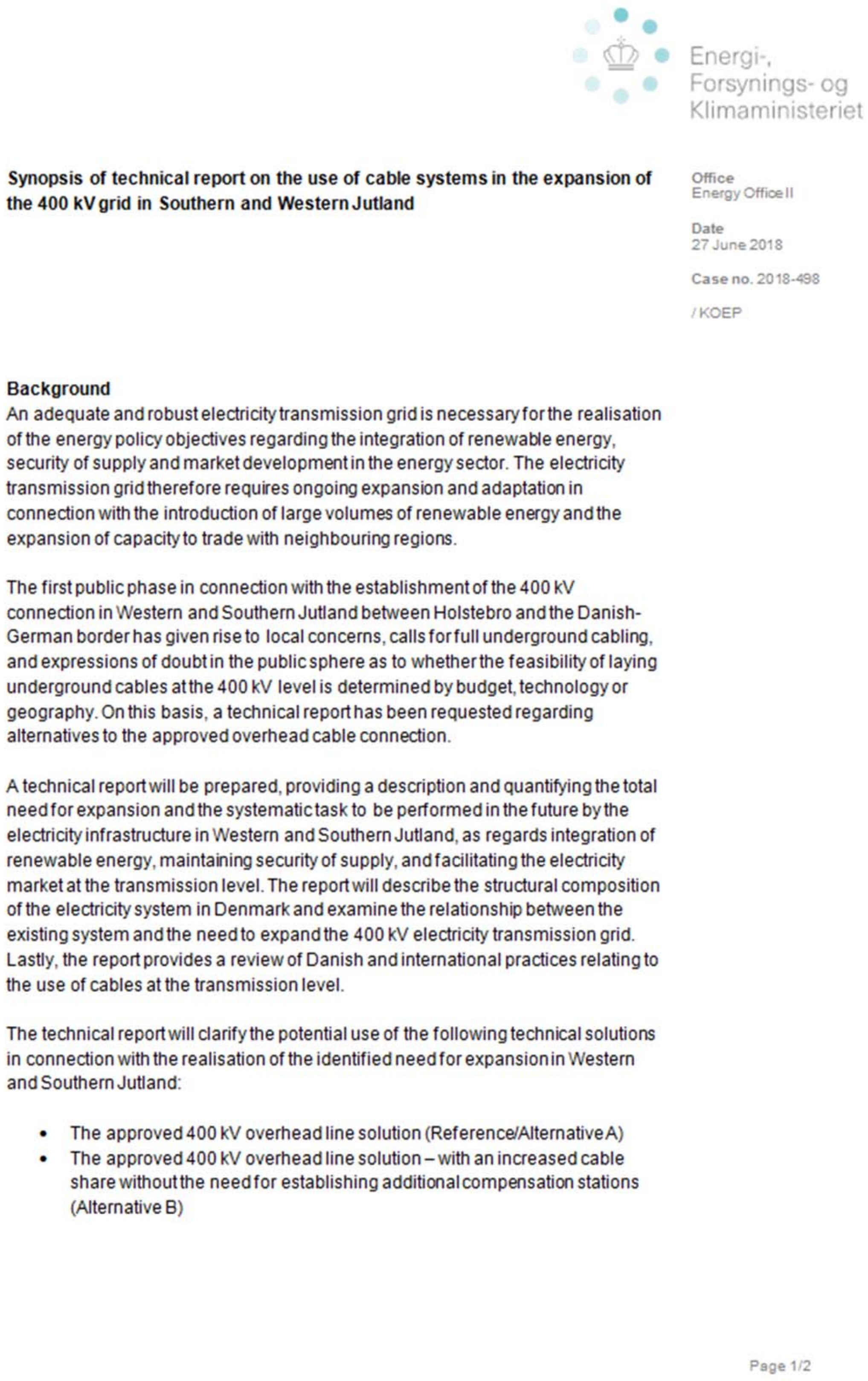


Energi-,
Forsynings- og
Klimaministeriet

Synopsis of technical report on the use of cable systems in the expansion of the 400 kV grid in Southern and Western Jutland

Office
Energy Office II

Date
27 June 2018

Case no. 2018-498

/ KOEP

Background

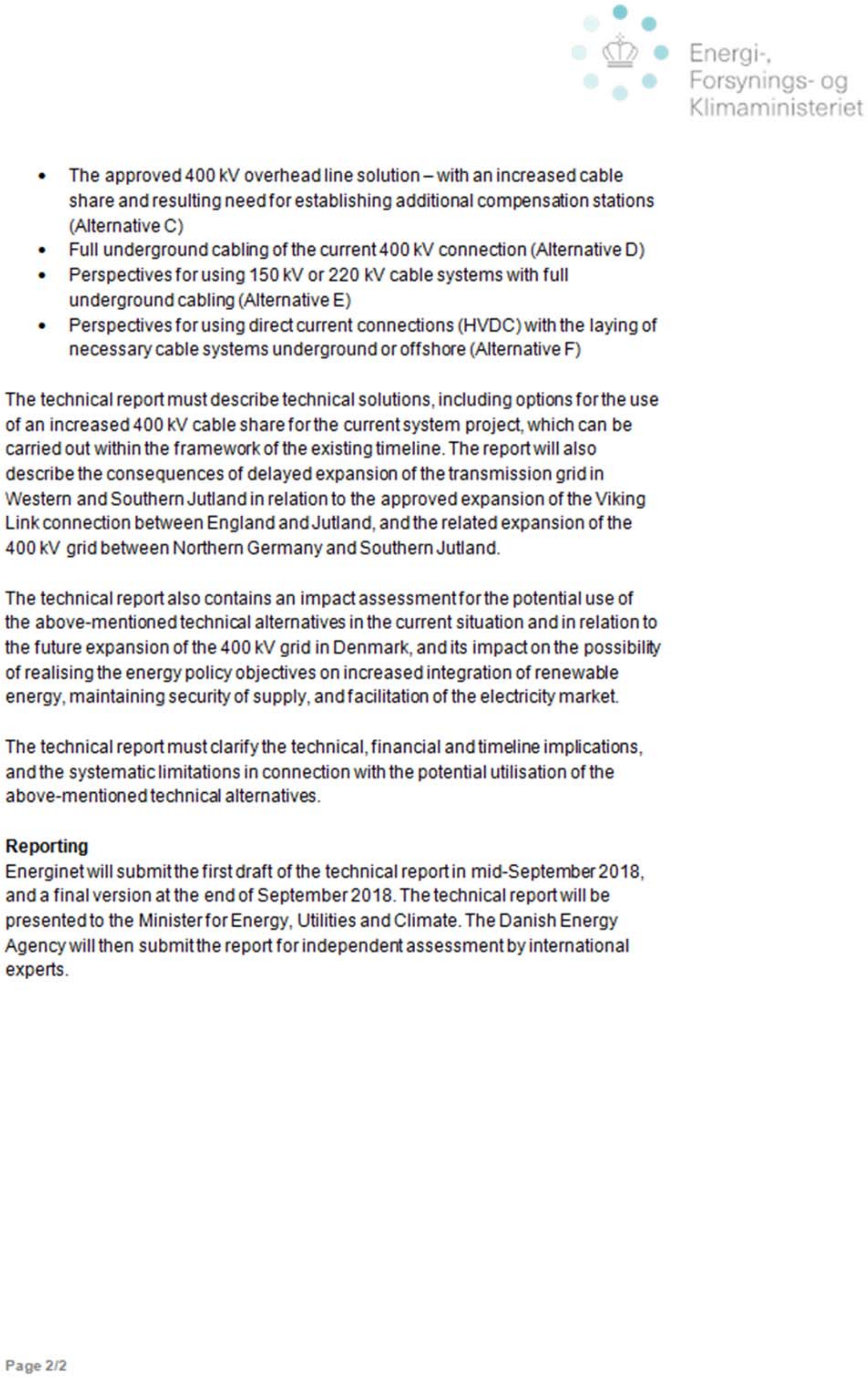
An adequate and robust electricity transmission grid is necessary for the realisation of the energy policy objectives regarding the integration of renewable energy, security of supply and market development in the energy sector. The electricity transmission grid therefore requires ongoing expansion and adaptation in connection with the introduction of large volumes of renewable energy and the expansion of capacity to trade with neighbouring regions.

The first public phase in connection with the establishment of the 400 kV connection in Western and Southern Jutland between Holstebro and the Danish-German border has given rise to local concerns, calls for full underground cabling, and expressions of doubt in the public sphere as to whether the feasibility of laying underground cables at the 400 kV level is determined by budget, technology or geography. On this basis, a technical report has been requested regarding alternatives to the approved overhead cable connection.

A technical report will be prepared, providing a description and quantifying the total need for expansion and the systematic task to be performed in the future by the electricity infrastructure in Western and Southern Jutland, as regards integration of renewable energy, maintaining security of supply, and facilitating the electricity market at the transmission level. The report will describe the structural composition of the electricity system in Denmark and examine the relationship between the existing system and the need to expand the 400 kV electricity transmission grid. Lastly, the report provides a review of Danish and international practices relating to the use of cables at the transmission level.

The technical report will clarify the potential use of the following technical solutions in connection with the realisation of the identified need for expansion in Western and Southern Jutland:

- The approved 400 kV overhead line solution (Reference/Alternative A)
- The approved 400 kV overhead line solution – with an increased cable share without the need for establishing additional compensation stations (Alternative B)



- The approved 400 kV overhead line solution – with an increased cable share and resulting need for establishing additional compensation stations (Alternative C)
- Full underground cabling of the current 400 kV connection (Alternative D)
- Perspectives for using 150 kV or 220 kV cable systems with full underground cabling (Alternative E)
- Perspectives for using direct current connections (HVDC) with the laying of necessary cable systems underground or offshore (Alternative F)

The technical report must describe technical solutions, including options for the use of an increased 400 kV cable share for the current system project, which can be carried out within the framework of the existing timeline. The report will also describe the consequences of delayed expansion of the transmission grid in Western and Southern Jutland in relation to the approved expansion of the Viking Link connection between England and Jutland, and the related expansion of the 400 kV grid between Northern Germany and Southern Jutland.

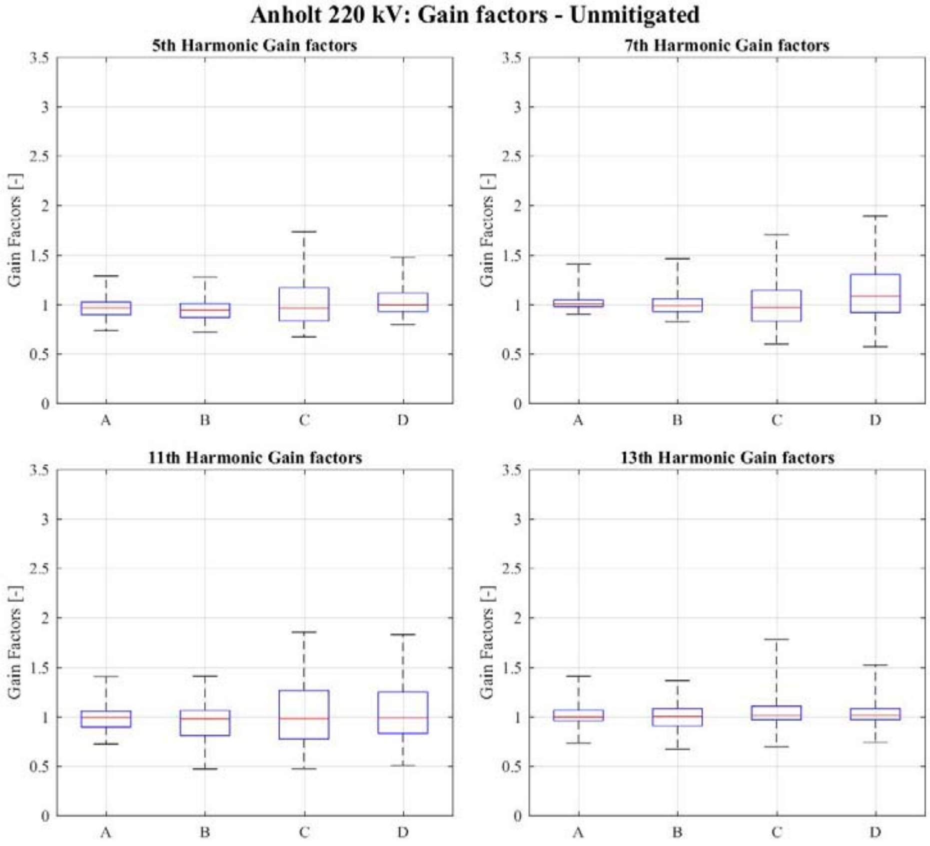
The technical report also contains an impact assessment for the potential use of the above-mentioned technical alternatives in the current situation and in relation to the future expansion of the 400 kV grid in Denmark, and its impact on the possibility of realising the energy policy objectives on increased integration of renewable energy, maintaining security of supply, and facilitation of the electricity market.

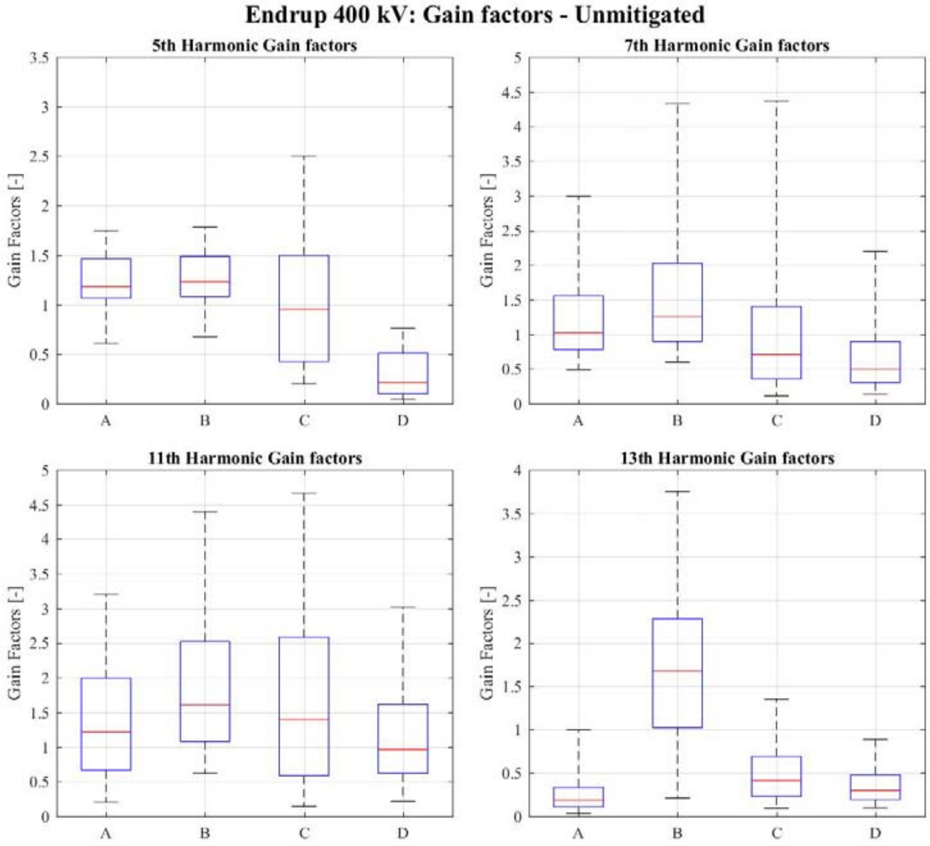
The technical report must clarify the technical, financial and timeline implications, and the systematic limitations in connection with the potential utilisation of the above-mentioned technical alternatives.

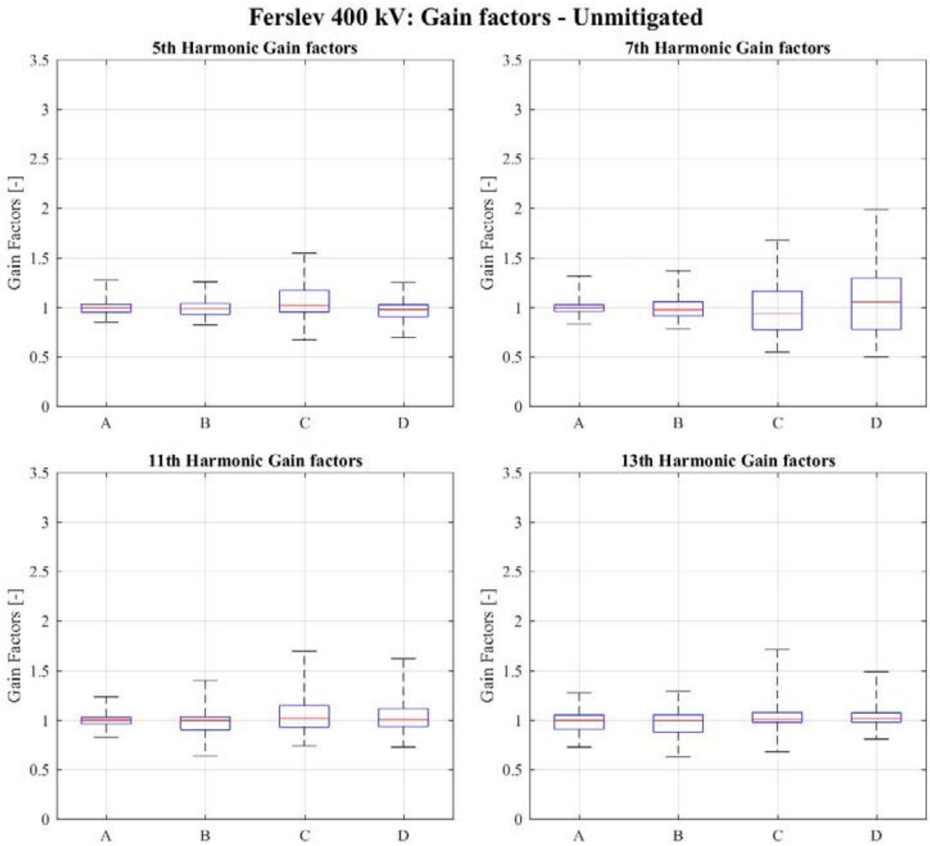
Reporting

Energinet will submit the first draft of the technical report in mid-September 2018, and a final version at the end of September 2018. The technical report will be presented to the Minister for Energy, Utilities and Climate. The Danish Energy Agency will then submit the report for independent assessment by international experts.

Appendix B – Box plots analysis of harmonic amplification



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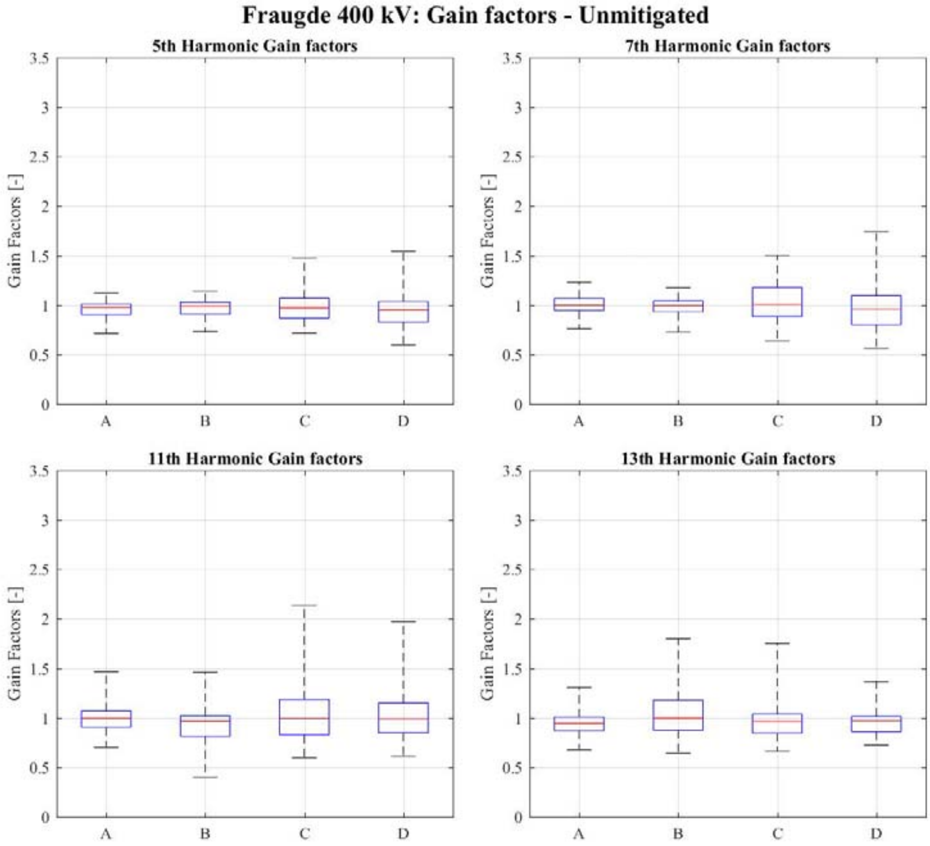
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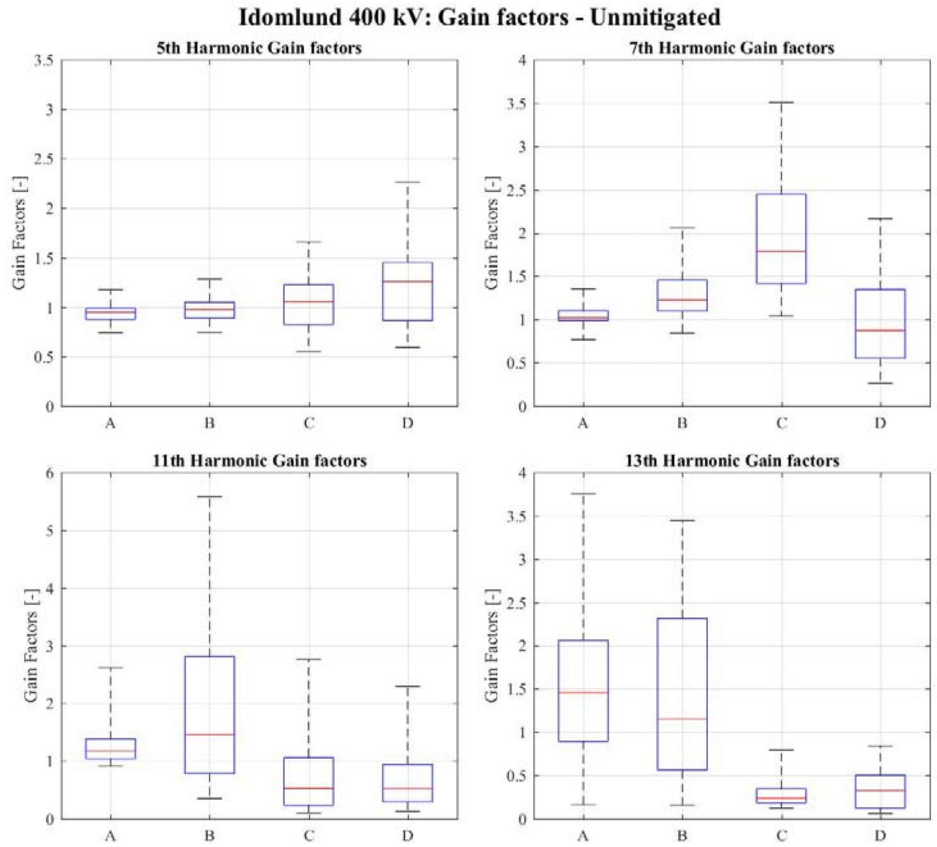
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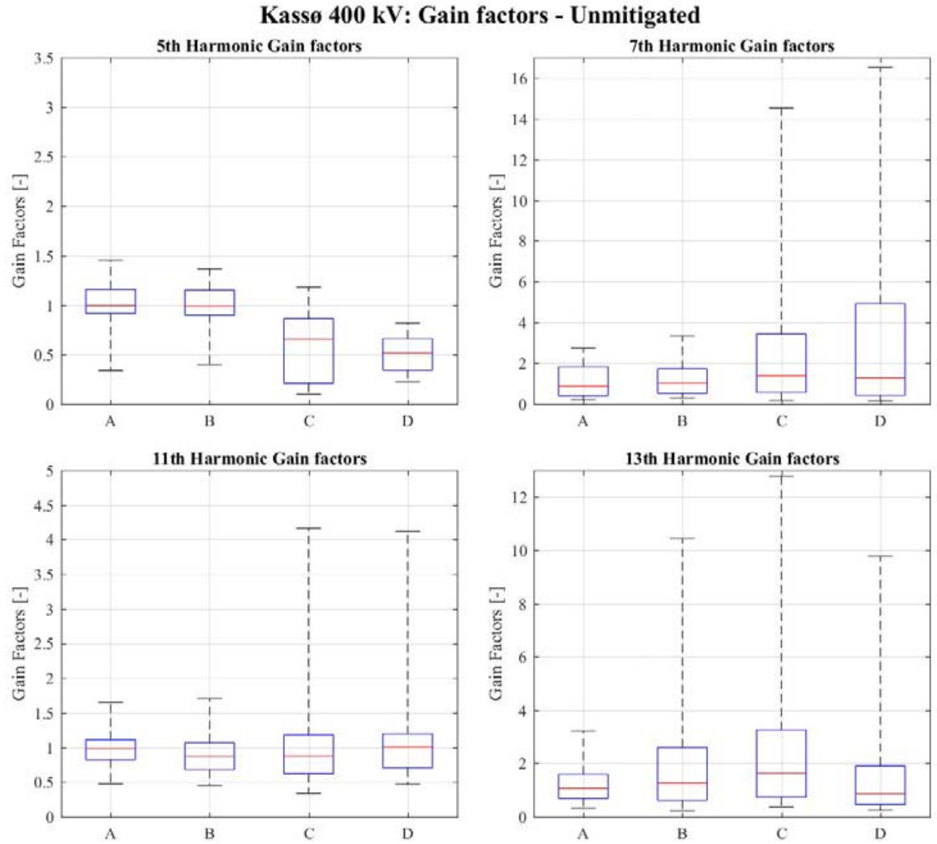
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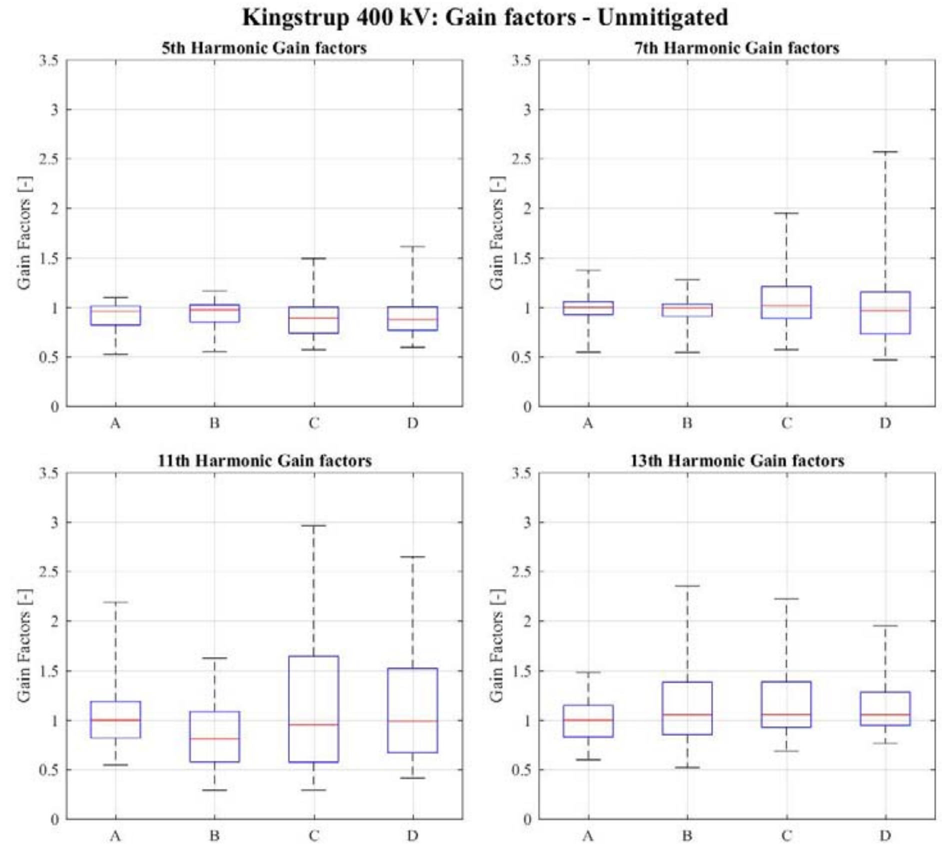
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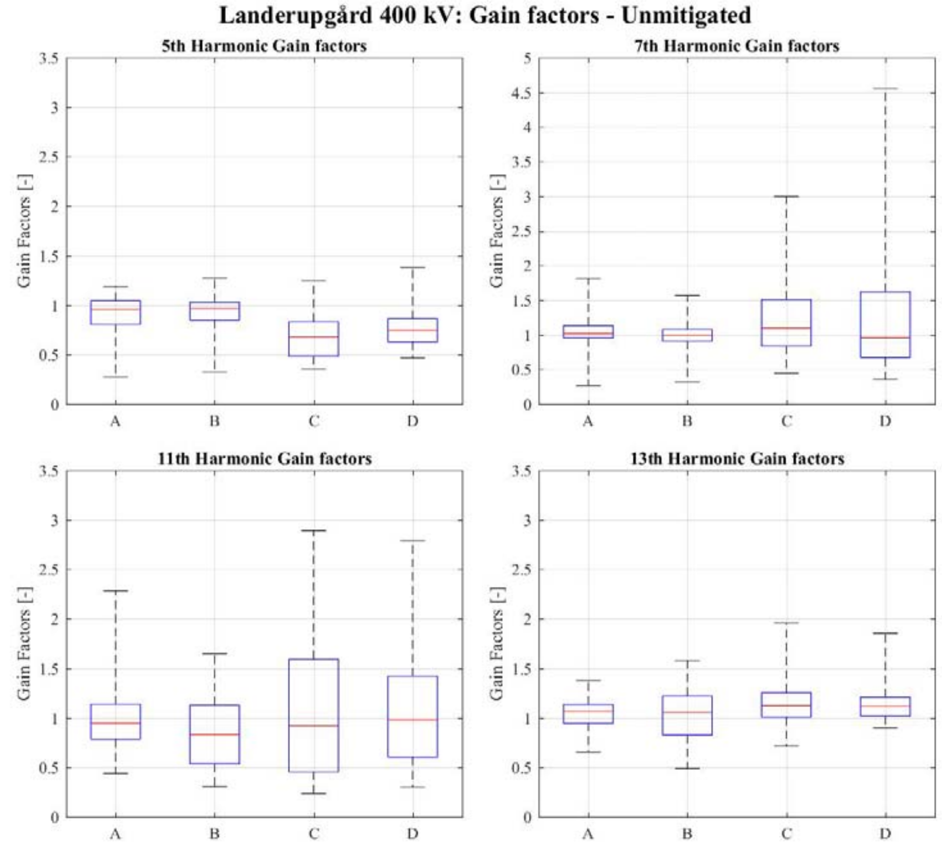
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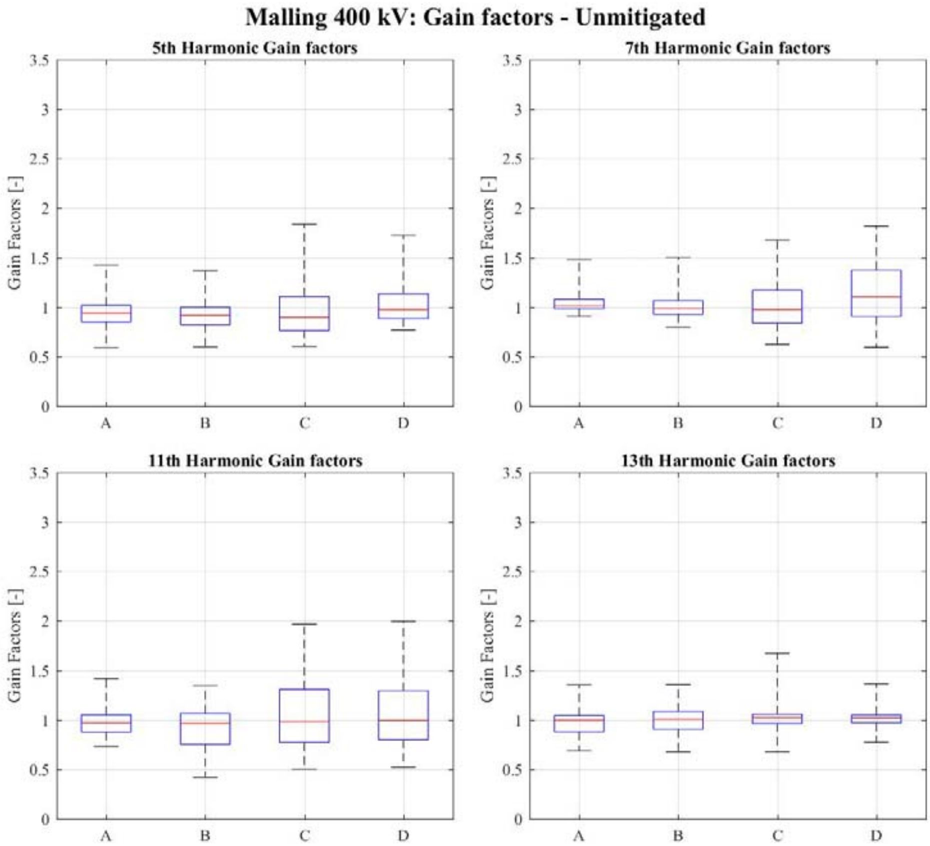
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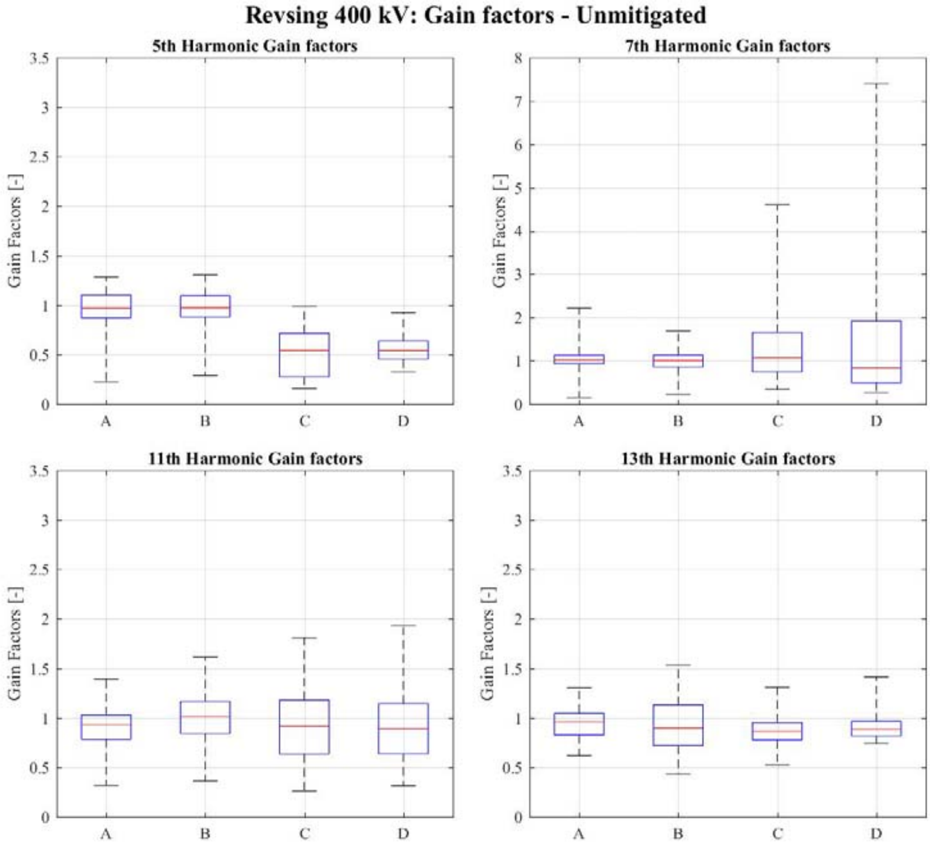
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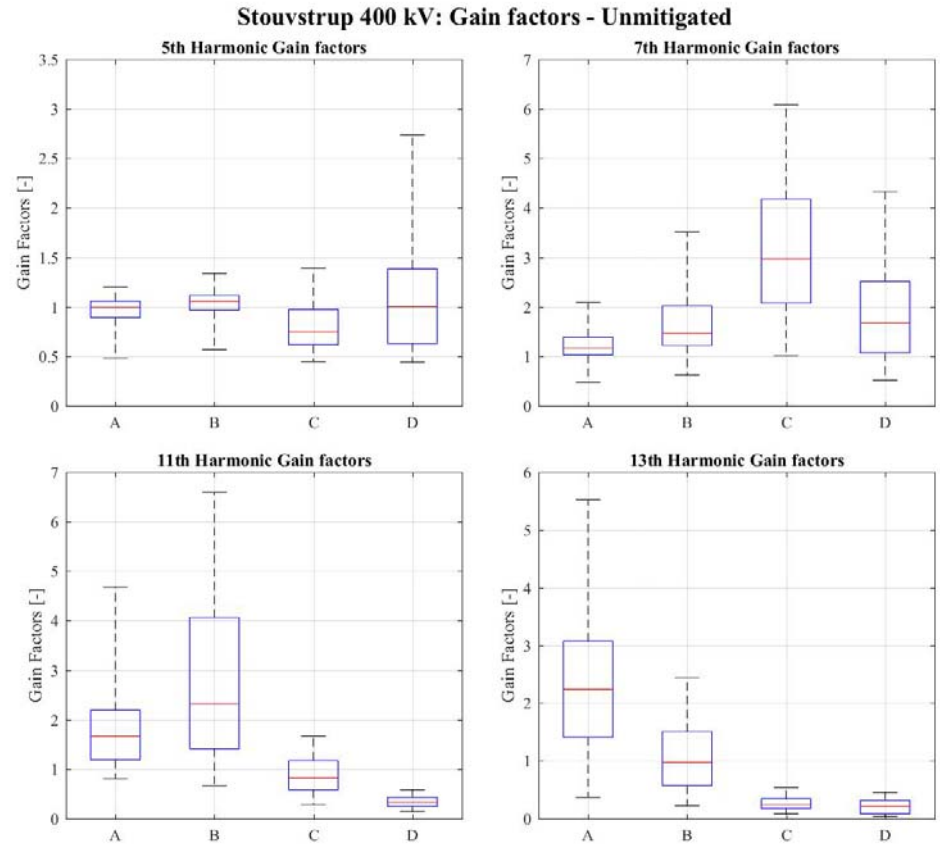
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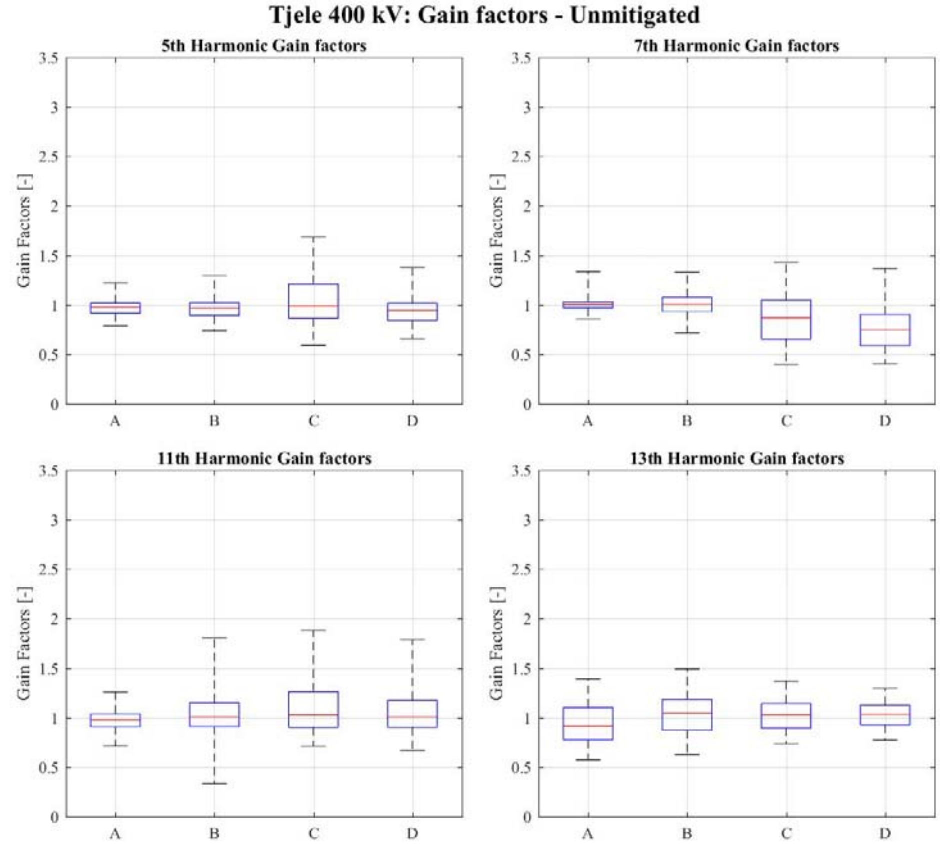
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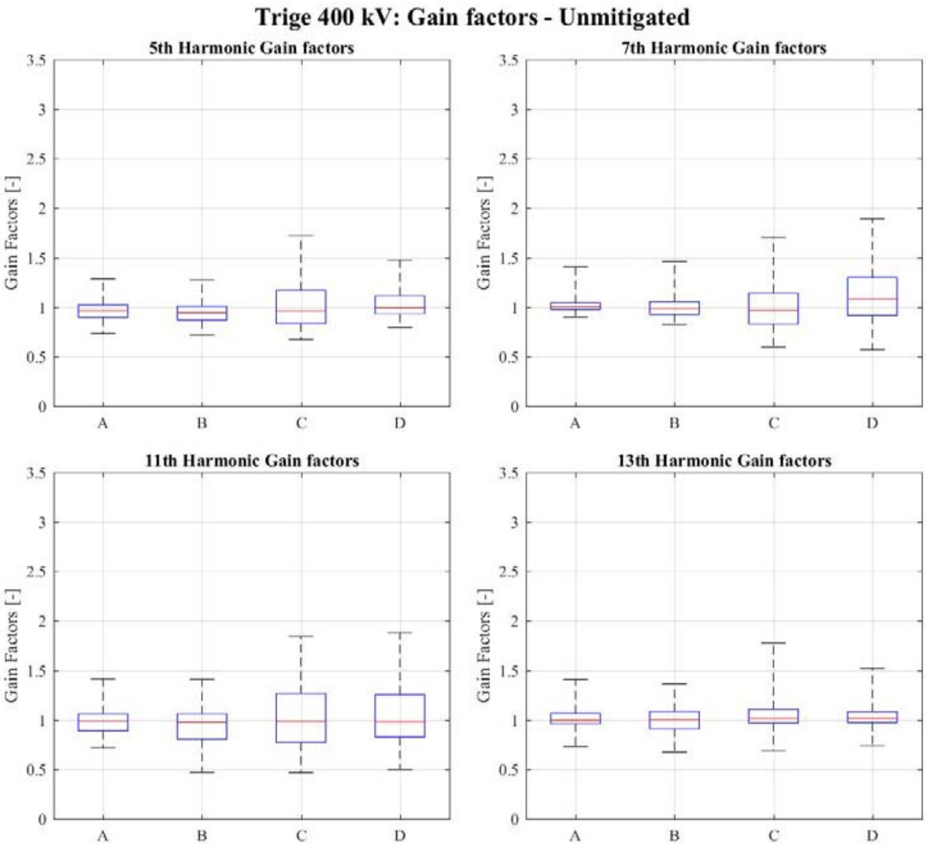
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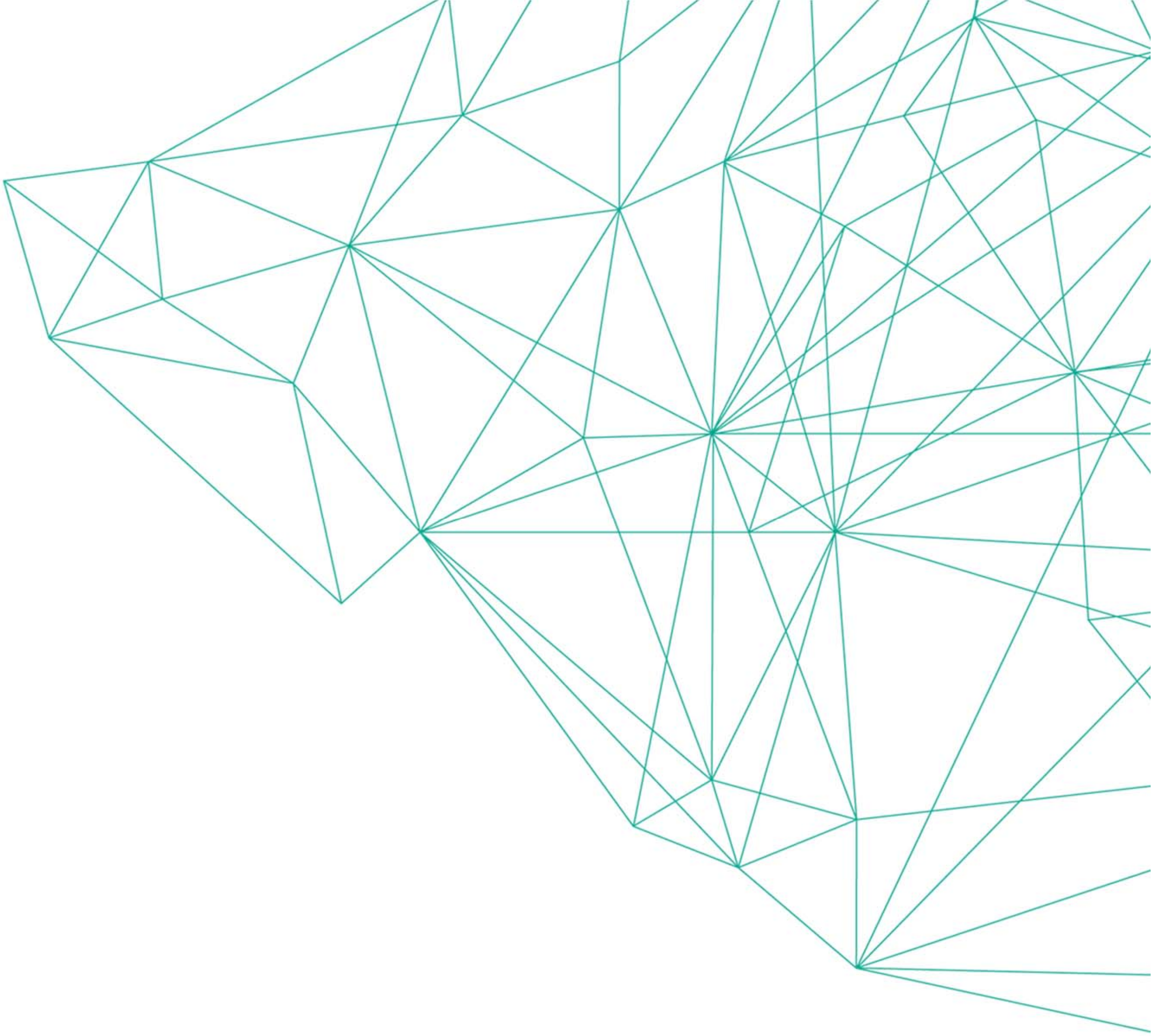

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Date: 28 September 2018