SYSTEM IMPACT STUDY

System impact study 380 kV cables Zeeland

TenneT TSO B.V.

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1 INTRODUCTION

The Dutch transmission system operator TenneT is planning to install new 380 kV power connections between Zuid-Beveland and Zeeuws-Vlaanderen in the province of Zeeland. These connections are required to increase the transmission capacity of the 380 kV network in the region. A larger transmission capacity is needed to accommodate the increase of the industrial load in the Terneuzen area, large electrolyzer projects and the connection of large windfarms in Zeeland. More background on the need for the connection and the decision to this by means of a AC connection is described in an assessment prepared by TenneT /4/.

In principle the transmission of electrical power can occur via underground power cables and/or overhead lines. Dutch policy states that new 380 kV connections will be built by means of AC overhead lines. Only in special occasions the applicability of cables can be considered.

The electrical behavior of power cables however differs from the behavior of overhead lines. Because of their behavior the application of power cables needs to be studied in detail before their actual installation. This is especially the case when the nominal voltage is high, the length of the power cable connections is relatively long and large amounts of power need to be transmitted.

For the extension of the 380 kV grid towards Terneuzen several routes are investigated in the Environmental Impact Assessment (EIA), an overview is presented below.

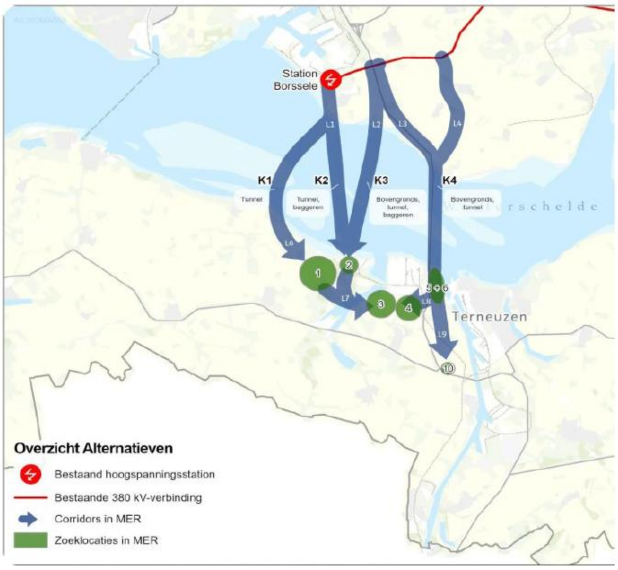


Figure 1 Map with routing options from EIA

All options have been grouped and three main study cases have been defined as shown in Table 1-1.

Table 1-1 Overview Study cases

	Cable length	Variants covered (as specified in the EIA)
Case 1	7	K1T, K2T, K3T, K4T, L1O+K1T
Case 2	10	L1O+K2T, L2O+K3T
Case 3	14	L3O+K4T

TenneT has conducted a system impact study for case study 1 and concluded that crossing the Western Scheldt by means of underground cable is feasible without additional compensation measures, the grid topology and executive summary of that study are included in Appendix C.

TenneT has commissioned DNV to perform an additional system impact study to investigate the electrical feasibility of using a cable for the route across the land on Zuid-Beveland. The request is to investigate the impact of a 14 km (Case study 3) underground cable connection which is the longest alternative under investigation for the planned power connections between Zuid-Beveland and Zeeuws-Vlaanderen. The overall study comprises different sub studies including a steady-state study, an electromagnetic transients study and a power quality study.

The present report states the results of the steady-state study. The steady-state study is only one part of the total system impact study. Final conclusions with respect to the electrical feasibility of the alternative under study can only be drawn once all studies have been completed.

In chapter 2 the scope of the system impact study is presented. In chapter 3 the network under study is described. In chapter 4 a brief introduction of electrical power engineering basics is provided. In chapter 5 the steady-state study is reported in detail. Conclusions are presented in chapter 6, recommendations in chapter 7.

It should be noted that not all topics that are listed in the Input Data Document have been considered yet in the steady-state study because a number of potential obstacles have already been identified during the course of the study.

In chapter 8 a comparison is presented of potential solutions to overcome the obstacles that have been identified during the steady-state study. In a trade-off matrix these potential solutions are ranked against a set of assessment criteria.

2 SCOPE OF SYSTEM IMPACT STUDY

The system impact study performed by DNV comprises the following studies:

- Steady-state study
- Electromagnetic transients (EMT) study
- Power quality study
- Voltage unbalance study
- Stability study
- System restoration study.

An overview of the project approach is depicted in Figure 2-1, items 4, 5, 6 and 7 are separate studies.

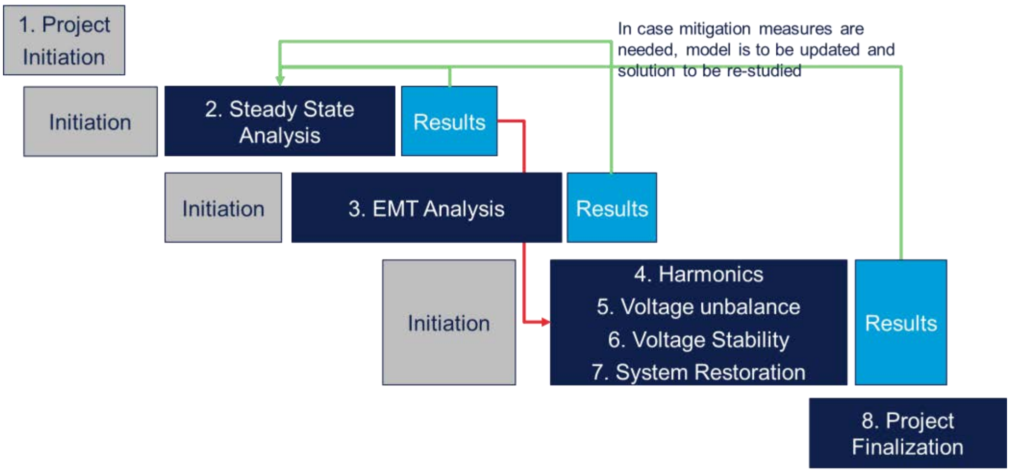


Figure 2-1 Structure of the power system study

The different studies are described in more detail in the sections below.

2.1 Steady-state studies

2.1.1 Objective

The main objective of the steady-state study is to examine the impact of the application of the 380 kV power cables on the voltage profile in the area under study. For proper functioning of the electricity system the voltage, as well as the rapid voltage changes at the different substations under study, should remain within statutory limits, both during normal and contingency conditions. Both steady-state voltages and rapid voltage changes due to switching events are being studied.

2.1.2 Approach

The execution of the steady-state study consists of a number of steps:

1 Modelling of the power system
2 Definition of operation scenarios
3 Definition of contingencies
4 Definition of study cases
5 Running load flow calculations
6 Analysis of calculation results.

The first step of the steady-state study comprises the modelling of the power system under study. For the present study use has been made of a power system model that has initially been developed by TenneT in the power system simulation suite PowerFactory from DIgSILENT GmbH.

The next step consists of the definition of operation scenarios. Operation scenarios are specific combinations of generation dispatch, load dispatch, exchange with foreign countries and network topology.

For the steady-state study also a number of contingencies have to be defined. A contingency is a specific outage of one or more network components e.g. a power transformer or a power connection.

Based on the defined operation scenarios and contingencies a number of study cases can be defined. Each study case comprises of a unique combination of an operation scenario and a contingency.

The actual voltage profiles are studied by running load flow calculations. For each defined study case load flow calculations have been carried out.

The analysis of the load flow calculation results provide insight in the relationship between load dispatch, generation dispatch, voltage levels, network topology, location and size of reactive power compensation devices.

2.2 Starting points for system impact study

All starting points for the system impact study performed by DNV are stated in a TenneT memorandum /1/, from here referred to as the input data document (IDD) version 0.7 The IDD is a collection of data that is relevant to the study. This includes:

1. A chapter on network details that are applicable for all topics of the study (network topology scenarios, operational conditions, the minimum set of contingencies). The items in this chapter have the identifying abbreviation ND
2. A chapter on details of network components. The items in this chapter have the identifying abbreviations based on component type: conductors (C), transformers (T), shunt reactors (SR), circuit breakers (CB), surge arresters (SA)
3. A chapter on details of technical topics to be studied and assessed (assumptions, assessment criteria). The items in this chapter have the identifying abbreviations based on topic: general requirements (GEN), slow voltage variations (LSV), cable discharge (CC), temporary over-voltages (TOV), rapid voltage change (RVC), voltage unbalance (RS3), harmonics (HARM), voltage stability (VST).
   Other topics are also included as sub-chapters
4. Multiple appendices detailing scope, grid topology, scenarios, contingencies, harmonic levels, etc.

The relevant IDD items used for the calculations are referred to in this report by the identifying abbreviation. The IDD is expected to be updated if any additional information is needed or any information is deemed missing.

3 NETWORK UNDER STUDY

3.1 Power system under study

While the entire Dutch network PowerFactory model is being used for the calculations (see Section 2), the focus of the system impact study performed by DNV is on the 380 kV power system in the province of Zeeland and neighbouring areas (IDD, Appendix A). The network under study is based on the active projects in the Zeeland network area in 2035.

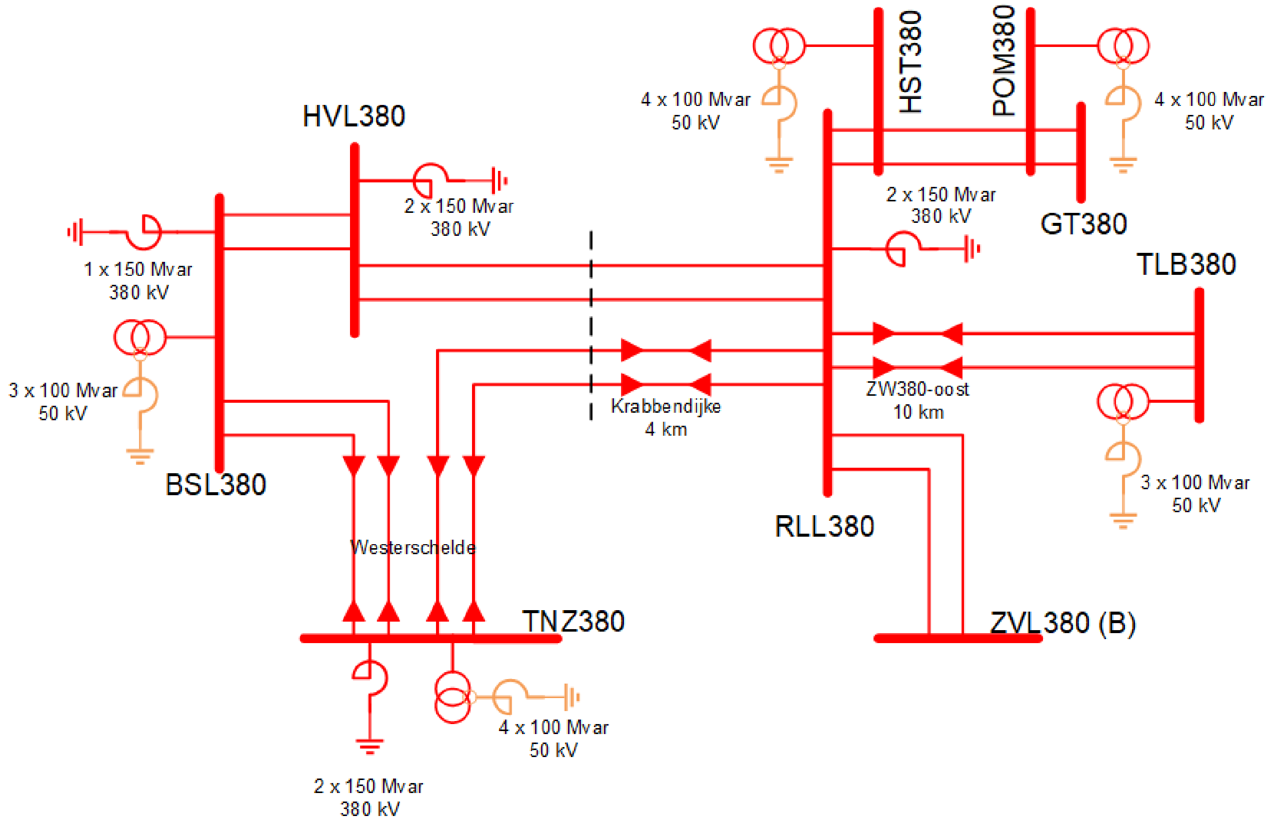


Figure 3-1 Simplified representation of the 380 kV network in focus

The network in focus is depicted in Figure 3-1. This is a simplified topology, showing only the 380 kV substations and circuits for clarity. In line with the IDD the impact of the cable circuits to TNZ380 have been assessed on the following substations (IDD V0.7 LSV10):

1. Borssele 380 kV (BSL380)
2. Haven Vlissingen 380 kV (HVL380)
3. Terneuzen 380 kV (TNZ380)
4. Rilland 380 kV (RLL380)
5. Tilburg 380 kV (TLB380)
6. Halsteren 380 kV (HST380).

The list of contingencies is also within the area depicted in Figure 3-1 (see Section 5.3.2). It has been found in a previous TenneT study that contingencies beyond TLB380 have no impact on the results (IDD V0.7, Appendix C).

The depicted shunt-reactors represent the expected installed reactive power capacity in 2035. A further explanation on the shunt reactors at substations relevant to the study can be found in Section 3.3.

It should be noted that the intended name of the 380 kV substation Haven Vlissingen (HVL380) has changed to Nieuwdorp-Liechtensteinweg (NDLS380) during the course of the study. To avoid confusion the name HVL380 is used throughout this report.

3.2 Power connections under study

The objective of the system impact study is to determine if it is possible to realize the connection between Zuid-Beveland and Zeeuws-Vlaanderen via underground 380 kV power cables.

The focus of the study is therefore on the power cable sections of the four circuits connecting the existing substations Borssele (BSL380) and Rilland (RLL380) to the new 380 kV substation Terneuzen (TNZ380):

- 380 kV connection BSL380-TNZ380 Wit
- 380 kV connection BSL380-TNZ380 Zwart
- 380 kV connection TNZ380-RLL380 Wit
- 380 kV connection TNZ380-RLL380 Zwart.

A connection between 380 kV substations usually consists of parallel circuits, which are indicated by a colour (Wit, Zwart).

Table 3-1 shows the main specifications of these four cable circuits. The rest of the cables within the network under study are part of the overall Dutch network PowerFactory model provided by TenneT (see Section 2) and do play a role, as all components of the network, on the overall outcome of the study.

Table 3-1 Main specifications of power cables under study

	Connection			
	BSL380 - TNZ380 Wit	***BSL380 - TNZ380 Zwart***	***TNZ380 - RLL380 Wit***	***TNZ380 - RLL380 Zwart***
Number of cable sections	1	1	2	2
Cable section length [km]	14	14	14	14
Number of single core cables per phase	2	2	2	2
Cable construction	single core	single core	single core	single core
Cross section core [mm^2]	2500	2500	2500	2500
Resistance of single core cable [Ω/km]	0.009	0.009	0.009	0.009
Reactance of single core cable [Ω/km]	0.183	0.183	0.183	0.183
Capacitance of single core cable [μF/km]	0.232	0.232	0.232	0.232

An underground power connection produces a certain amount of reactive power. The total amount of reactive power is determined by the following factors:

- Cable type
- Cable length
- Voltage level
- Number of parallel cables per phase.

Table 3-2 shows the amount of reactive power that is produced by the power cable sections under study (for more information, see Section 4.1). The total amount of reactive power produced by the four power cable sections under study equals 1180 Mvar.

Table 3-2 Reactive power production by power cables under study

	Connection			
	BSL380 - TNZ380 Wit	***BSL380 - TNZ380 Zwart***	***TNZ380 - RLL380 Wit***	***TNZ380 - RLL380 Zwart***
Reactive power production @ 380 kV [Mvar]	295	295	295	295

3.3 Shunt reactors

3.3.1 General

Presently TenneT is applying shunt reactors in its transmission system to absorb the reactive power produced by power cable connections. The absorption of reactive power is required to keep the voltage within the applicable limits.

The shunt reactors are connected either directly to the main busbar or via the tertiary winding of the 380/150/50 kV power transformers. The shunt reactors are located in different substations. For an effective application, the shunt reactors need to be installed in the vicinity of the location where the reactive power is being produced. In section 4.3 more background information is provided with respect to the need for shunt reactors in a power transmission system.

The present and future situation with respect to the installed shunt reactor capacity in each substation under study is described in the following sections.

3.3.2 Shunt reactor capacity

The amount of reactive power that can be consumed by a shunt reactor depends on its capacity. TenneT has standardized the capacity of its shunt reactors. The standardized capacities are listed in Table 3-3.

Table 3-3 Standardized shunt reactor capacities TenneT

Voltage level [kV]	380	50
Shunt reactor capacity at nominal voltage [Mvar]	150	100

The standardized rating of the 380 kV shunt reactors is in line with the standardized rating of the 380 kV capacitor banks used by TenneT. The standard size of the 380 kV capacitor banks is based on the outcome of an RVC study that has previously been performed. From this study it was concluded that when applying capacitor banks with a rating of 150 Mvar TenneT would meet the RVC requirements. For reasons of standardisation TenneT has decided to adopt the same standard size for the 380 kV shunt reactors.

The standardized rating of the 50 kV shunt reactors is based on the rating of the tertiary (50 kV) winding of the standardized 380/150/50 kV power transformers. This rating amounts to 166 MVA. Two third of this rating (100 MVA) is reserved for the connection of shunt reactors.

3.3.3 Shunt reactor placement strategy

TenneT has adopted a strategy with regards to the placement of shunt reactors in its substations. Shunt reactors can be connected either directly to a 380 kV busbar or to the tertiary winding of a 380/150/50 kV power transformer. At a single 380 kV busbar it is allowed to connect either one 380 kV shunt reactor and one 380/150/50 kV power transformer with a 50 kV shunt reactor or two 380/150/50 kV power transformers with a 50 kV shunt reactor The maximum allowed shunt reactor capacity per 380 kV busbar amounts to 250 Mvar. This implies that the maximum allowed shunt reactor capacity in a triple busbar 380 kV substation amounts to 750 Mvar. This requirement ensures that in case of an unexpected outage of a busbar the amount of disconnected shunt reactors is limited and the upper voltage limit is not exceeded.

It should be noted that the available shunt reactor capacity in a substation cannot always be completely assigned to compensation of reactive power produced by power cables at a certain voltage level. The shunt reactor capacity could also be used for reactive power compensation at a different voltage level or for filtering purposes. Furthermore, if the substation is too far away from the power cables that need to be compensated, the allocation of shunt reactors at this remote substation will not contribute to alleviating the reactive power compensation shortage.

3.3.4 Substation Borssele

The number of busbars in substation BSL380 amounts to four. In substation BSL380 presently three shunt reactors are in service. They are connected via the 50 kV tertiary windings of the 380/150/50 kV power transformers and have a rated reactive power of 100 Mvar each.

TenneT is planning to install an additional shunt reactor in BSL380 with a rating of 150 Mvar that will be connected to the 380 kV busbar. Currently this project has not been initiated yet. Their presence is already included in the present study.

3.3.5 Substation Terneuzen

TenneT is planning to realize a new 380 kV substation in Terneuzen (TNZ380). It is expected that this substation will be commissioned in 2035. The planned number of busbars in TNZ380 is three. TenneT is planning to install 6 shunt reactors in TNZ380. Two shunt reactors with a rating of 150 Mvar each will be connected directly to the 380 kV busbar. Four shunt reactors with a rating of 100 Mvar each will be connected to the tertiary windings of the 380/150/50 kV power transformers. All shunt reactors are planned because TenneT is anticipating an increase of reactive power due to the planned cables in Zeeland and Noord-Brabant. The actual amount of shunt reactors to be installed will depend on the actual need.

3.3.6 Substation Rilland

The number of busbars in 380 kV substation RLL380 amounts to three. Presently 380 substation Rilland (RLL380) is fully occupied. However TenneT is planning to install two shunt reactors with a rating of 150 Mvar each that will be connected to the 380 kV busbar. Currently this project has not been initiated yet. Their presence is already included in the present study.

3.3.7 Substation Haven Vlissingen

TenneT is realizing a new 380 kV substation near Vlissingen (HVL380). The planned number of busbars equals three. The expected year of commissioning is 2029. In this substation two shunt reactors will be connected to the 380 kV busbar with a rating of 150 Mvar each. Furthermore, space will be reserved for four 380/150/50 kV power transformers with shunt reactors connected to their tertiaries. For now this is not part of the building scope of HVL380.

3.3.8 Overview of present and future shunt reactor capacity

The present amount of shunt reactor capacity in the region under study is shown in Table 3-4. Also listed is the expected amount of shunt reactor capacity in the year 2035. It should be explicitly mentioned that not all available shunt reactor capacity is available for the 380 kV cables under study. A part is also needed for reactive power compensation of power cables and capacitive customer loads in the 150 kV system.

Table 3-4 Overview of present and future shunt reactor capacity in transmission system in region Zeeland

Substation	***BSL380***		***TNZ380***		***RLL380***		***HVL380***	
Year	2025	2035	2025	2035	2025	2035	2025	2035
Total shunt reactor capacity [Mvar]	300	450	-	700	-	300	-	300
Already located shunt reactor capacity for grid operation [Mvar]	300	300	-	350	-	0	-	0
Available shunt reactor capacity for compensation of new cable section [Mvar]	0	150	-	350	-	300	-	300

4 ELECTRICAL POWER ENGINEERING BASICS

To be able to interpret the results of the system impact study performed by DNV it is crucial to understand the differences between cables and lines. Furthermore, it is important to be aware of the fact that equipment is being used to make the application long underground power cables technically possible. In this chapter the main differences between underground power cables and overhead lines are explained as well as the need for so called reactive power compensation equipment.

4.1 Underground power cables versus overhead lines

Electrical power can be transmitted via so called transmission lines. These can be underground power cables or overhead lines. The electrical behaviour of power cables however differs from the electrical behaviour of overhead lines. To be able to interpret the results of the system impact study performed by DNV it is crucial to understand the differences between cables and lines.

4.1.1 Surge impedance loading

One important parameter of a transmission line is its surge impedance loading (SIL). The SIL is determined by its inductance and capacitance. If the actual loading of the transmission line is equal to the SIL, the transmission line neither produces or absorbs reactive power. If the actual loading is lower than the SIL, the transmission line produces reactive power and has a capacitive behaviour. If the actual loading is higher than the SIL, the transmission line absorbs reactive power and has a reactive behaviour.

4.1.2 Overhead lines

Overhead lines consist of a current carrying conductor that is suspended from towers. The insulation is provided by the air that surrounds the conductor. Because of their construction, overhead lines have a higher inductance than capacitance. Therefore, they have a low surge impedance loading and are mostly loaded above their SIL. Therefore they mostly consume reactive power.

4.1.3 Power cables

Power cables consist of a single or multiple cores and a metal sheath, separated by an insulating material. This construction (two conductors separated by an insulator) results in a relatively high capacitance and high SIL. The actual loading of a power cable is therefore mostly lower than the SIL and thus the power cable mostly produces reactive power. The magnitude of the cable capacitance is determined by the thickness of the insulating layer and the type of insulation material.

The amount of produced reactive power (Q) is determined by its nominal voltage, the cable capacitance and the length of the power cable. The produced reactive power should be consumed by other system components. If the reactive power level in the system is too high, this may impact both the performance of the assets (e.g. damage to insulation, shortening of lifespan) as well as the performance of the system (e.g. reduced power transmission capacity, increased system losses, misoperation of overvoltage protection).

To absorb the reactive power produced by a power cable typically use is made of shunt reactors. These devices have an inductive behaviour i.e. they absorb reactive power. Shunt reactors can be placed in substations or near the cable terminations.

4.1.4 Availability of overhead lines and power cables

In order to calculate the availability of a power connection its failure rate has to be multiplied with the MTTR (mean time to repair). The outcome provides insight in the time the connection is unavailable per km connection per year.

To compare the availability of an overhead line and an underground cable the flowing data is used:

- Failure rate of 400 kV overhead lines: 0.00340 failures/km·yr
- Mean time to failure of 400 kV overhead lines: 4.14 h/failure (European/Nordic reliability compilations).
- A double-circuit results in 2 times the failure rate of a single circuit.
- Failure rate of 300-400 kV XLPE (cross-linked polyethylene cable) per single-circuit, per single-run): 0.0002–0.0006 failures/km·yr (Source: CIGRÉ fleet surveys).
- If two cable runs are used per phase, the number of components (joints, terminations) doubles and so does the failure rate
- The failure rate of two cable circuits in parallel is twice as hight as the failure rate of a single cable circuit
- Mean time to repair (installation in tunnel): 250–400 h typically (this is faster than direct-buried due to access/clean environment).

The results of the availability comparison are summarized in Table 4-1.

Table 4-1 Availability estimation of overhead line and underground cable circuits

Configuration (per route)	Voltage	Failure rate λ (failures/km·yr)	MTTR r (h/failure)	Outage U = λ·r (h/km·yr)
Double-circuit OHL (2 × OHL)	380–400 kV	0.0068 *(= 2 × 0.0034)*	4.14	0.028
Tunnelled XLPE: 2 circuits, each 2 runs/phase	380 kV	0.0008 – 0.0024 *(= 4 × (0.0002–0.0006))*	250 – 400	0.20 – 0.96

Even with 4 runs, the cable route fails around 3 to 8 times less often per km than the double-circuit OHL. Because repairs for the cable takes far longer, the annual outage hours for the tunnelled cable route however are around 7 to 35 times higher per km compared to a OHL.

4.1.5 Overview of main differences between power cables and lines

Table 4-2 provides an overview of the main differences between an underground power cable and an overhead line.

Table 4-2 Main difference between overhead lines and underground power cables

	Connection type	
Aspect	***Overhead line***	***Power cable***
Electrical behaviour	Inductive	Capacitive
Cross section for specific ampacity	Smaller	Larger
Current carrying capacity (for the same cross section)	Higher	Lower

Reactive power	Absorption (loading above SIL)	Generation (loading below SIL)
Outage time	Relatively low	Relatively high

4.2 Relationship between reactive power flow and voltage drops

In a high voltage transmission system the flow of reactive power through a power connection results in a voltage drop. Because the voltage should remain within predefined limits, the flow of large amounts of reactive power through the power system should be prevented. With respect to the reactive power produced by underground power cables this implies that the produced reactive power should ideally be absorbed in the neighbourhood of the power cables. A means to absorb reactive power is the application of shunt reactors.

4.3 Shunt reactors

To absorb the reactive power produced by a power cable typically use is made of shunt reactors. Shunt reactors are placed in parallel with the cables. Shunt reactors can be installed in substations or near the cable terminations. They can be connected directly to the busbars of a substation or via the tertiary winding of a power transformer.

Because of the relationship between reactive power flow and voltage, the application of shunt reactors has a direct impact on the voltage profile of the power system.

5 STEADY-STATE STUDY

In this chapter the set-up and results of the steady-state study are presented.

5.1 Steps in calculation process

For the execution of the steady-state study a stepwise approach has been adopted:

1. To verify if the installed shunt reactor capacity is enough to absorb the reactive power produced by the new 380 kV power cables
2. Execution of load flow calculations for N-0 condition to obtain the voltage profile in the observed area
3. Execution of load flow calculations for the N-1 and N-2 conditions.

Step 1 has already been taken by TenneT. The result is listed in the IDD. TenneT has concluded that there is a shortage of reactive power compensation. Steps 2 and 3 are part of the study performed by DNV.

5.2 Modelling of power system

To run load flow calculations the power system under study needs to be modelled in power system simulation software tool. For the present study the network model has been provided by TenneT. The model has been built in the software tool PowerFactory from DIgSILENT GmbH.

The initial TenneT model has been reviewed by DNV. The model represents the situation in the year 2035.

5.3 Definition of study cases

To study the impact of the 380 kV power cables on the system, a large number of load flow calculations have been carried out. Each calculation is related to a specific state of the power system. i.e. a certain combination of network topology, generation dispatch and load dispatch. A distinction is made between scenarios and contingencies. A scenario describes how the system is used by third parties (dispatch). A contingency relates to the use of the system itself (topology, status of the assets).

TenneT and DNV have defined a large set of study cases to cover all network conditions than can occur in practice. Each case is a combination of a scenario and a contingency.

5.3.1 Definition of Base case

TenneT and DNV have defined a base case. In this base case already a number of network components have been taken out of service. All other defined cases are based on the base case.

The operation scenario for the base case is identical to all other study cases. This operation scenario is described in the IDD and relates to a situation is which the available short circuit power is low (operation scenario: *Far Future_3364_3phs_Weak grid Cable ZL*).

5.3.1.1 Shunt capacitor banks

The present version of the network model contains a number of shunt capacitor banks. An overview of these banks and their status is shown in Table 5-1.

Table 5-1 Overview of shunt capacitor banks

Substation	Shunt capacitor bank	Reactance	Coupled with	On / Off
ZKL380	C11	-32.5 Mvar	Transformer TR421	Off
ZKL380	C21	-32.5 Mvar	Transformer TR422	Off
ZKL380	C31	-32.5 Mvar	Transformer TR423	Off
ZKL380	C41	-32.5 Mvar	Transformer TR424	Off
ZKL380	F01	-70 Mvar	Transformer TR422	On
ZKL380	F02	-70 Mvar	Transformer TR424	On
BSL150	C03-C04-C05	3 × -50 Mvar	Busbar	3 × Off

The shunt capacitor banks and filters that are installed at substation ZKL380 are intended for the offshore wind farms Borssele Alpha and Borssele Beta. They cannot be used for other purposes. The shunt capacitor banks installed at substation BSL150 can be switched off and on individually. Substation BSL150 is connected to substation BSL380 via four 380/150 kV power transformers.

5.3.1.2 Synchronous condensers

The present version of the network model contains several synchronous condensers that are not yet realized. They are located at the substations HVL380, AMH380 and CFE380. To study the impact of adding shunt reactors to the power system, these synchronous condensers have been disabled during the simulations. Initial simulations have shown that if the synchronous condensers are enabled they are in most cases operated at their reactive power limit value. This is not in line with their intended use.

5.3.1.3 Shunt reactors in service

For the assessment of the required amount of additional shunt reactor capacity, it has been assumed that a number of shunt reactors is already in service in the base case. Table 5-2 shows an overview of the assumed shunt reactor capacity that is already in service in the model representing the 2035 situation.

Table 5-2 Assumed shunt reactor capacity in service in 2035

Substation	BSL380	TNZ380	RLL380	HVL380
Shunt reactor capacity in service [Mvar]	450	700	300	300
Shunt reactor capacity in service and available for compensation of new cable sections [Mvar]	150	350	300	300

5.3.2 Definition of contingencies

For the present study TenneT has defined a large number of contingencies. A distinction is made between N-1 and N-2 contingencies. The N-1 contingencies represent the network topologies in which, compared to the base case, one network component is out of service. This can be a power circuit, power transformer, busbar or shunt reactor. The N-2 contingencies represent the network topologies in which two network components are out of service at the same time. This can be a combination of power circuits, power transformers, busbars and shunt reactors. N-2 contingencies relate to the situation in which an outage of one component occurs while another component is out of service for maintenance.

Table 5-3, 5-4, 5-5 and 5-6 give an overview of the network components that have been taken into account when defining the contingencies. The complete overview of defined contingencies is provided in Appendix A.

Table 5-3 Power connections used in definition of contingencies

Component type	Component
Connection	BSL380-TNZ380 W
Connection	BSL380-TNZ380 Z
Connection	BSL380-HVL380 O
Connection	BSL380-HVL380 P
Connection	TNZ380-RLL380 W
Connection	TNZ380-RLL380 Z
Connection	RLL380-TLB380 O
Connection	RLL380-TLB380 P
Connection	HST380-RLL380 W
Connection	HST380-RLL380 Z
Connection	POM380-HST380 W
Connection	POM380-HST380 Z
Connection	GT380-POM380 W
Connection	GT380-POM380 Z
Connection	BSL380-Eurolink
Connection	BSL380-SL10
Connection	BSL380-SL20
Connection	BS30-EPZ1

Table 5-4 Power transformers used in definition of contingencies

Component type	Substation	Component
Power transformer	BSL380	BSL TR401
Power transformer	BSL380	BSL TR402
Power transformer	RLL380	RLL TR411
Power transformer	RLL380	RLL TR412
Power transformer	TNZ380	TR411
Power transformer	TNZ380	TR412

Table 5-5 Busbars used in definition of contingencies

Component type	Substation	Component
Busbar	BSL380	Busbar A
Busbar	BSL380	Busbar A2
Busbar	RLL380	Busbar B
Busbar	TNZ380	Busbar A
Busbar	HVL380	Busbar A

Table 5-6 Shunt reactors used in definition of contingencies

Component type	Substation	Component
Shunt reactor	BSL380	shunt reactor BSL_50kV_SP401 shunt reactor BSL_50kV_SP402 shunt reactor BSL_50kV_SP414 add. shunt reactor BSL380 SP1 add. shunt reactor BSL380 SP2 add.
Shunt reactor	TNZ380	shunt reactor TNZ380 SP1 add. shunt reactor TNZ380 SP2 add. shunt reactor TNZ380 SP3 add. shunt reactor TNZ380 SP4 add.
Shunt reactor	HVL380	shunt reactor HVL380 SP2 shunt reactor HVL380 SP3 add. shunt reactor HVL380 SP4 add.
Shunt reactor	RLL380	shunt reactor RLL380 SP2 shunt reactor RLL380 SP3 add. shunt reactor RLL380 SP4 add.
Shunt reactor	ZKL380	shunt reactor ZKL220F01 shunt reactor ZKL220F02

As shunt reactors are components that are frequently being energized and used at their maximum rating they have an increased unavailability rate. For this reason, the N-2 contingencies also include the situation in which two shunt reactors are out of service at the same time. Also in this situation the amount of reactive power compensation capacity should remain sufficient.

5.4 Set-up of load flow calculations

A large number of load flow calculations has been carried out to analyse the impact of the 380 kV power cables on the voltage profile of the 380 kV system. The starting points for these calculations are mentioned in the following sections.

5.4.1 Load flow settings

In the simulation tool PowerFactory a number of settings need to be selected for the execution of the actual load flow calculations. These settings impact the calculation results. The settings used by DNV have been selected by TenneT and are listed in Table 5-7. The IDD clarifies why these settings have been chosen.

Table 5-7 Selected load flow settings in PowerFactory

Type of calculation	*Fixed shunt reactors*	*Fictitious shunt reactors*
Setting	**Selection**	**Selection**
Calculation method	AC load flow balanced positive sequence	AC load flow balanced positive sequence
Automatic tap adjustment of transformers	Disabled	Disabled
Automatic tap adjustment of shunts	Disabled	Enabled
Consider active power limits	Disabled	Disabled
Consider reactive power limits	Enabled	Enabled

5.4.2 Fictitious shunt reactors

To assess the required amount of reactive power compensation the network model has been expanded with four fictitious 1 Gvar controllable shunt reactors, with a settable step size. The four fictitious shunt reactors have been placed at the substations BSL380, TNZ380, RLL380 and HVL380. During the simulations the fictitious shunt reactors have been allowed to freely change their tap position.

Initially a control step size of 1 Mvar has been used. This allows the fictitious shunt reactors to accurately keep the voltages within limits. The use of these fictitious shunt reactors with small control step leads to good insight into the actual required amount of compensation.

Because TenneT uses fixed shunt reactors with a size of 100 or 150 Mvar also simulations have been carried out with a controls step of 50, 75 and 100 Mvar. These simulations have provided insights into the maximum allowable size of the required additional shunt reactors.

5.5 Assessment criteria

5.5.1 Maximum required reactive power compensation

For each study case the required reactive power compensation at the different substation under study have been calculated. For this the freely tappable fictitious shunt reactors with a control step of 1 Mvar have been applied. Also, the overall maximum value at each substation has been determined. This value is determinative for the required amount of reactive power compensation.

5.5.2 Steady-state voltages within allowable range

The focus of the steady state study is on the impact of the 380 kV power cables on the voltage profile of the 380 kV system in the region. The voltages should remain within the limits stated in the IDD (chapter 4.2, Table 1). Table 5-8 shows the applied steady-state voltage limits for the present study.

Table 5-8 Applicable voltage limits

Voltage level [kV]	380
Lower voltage limit [kV]	361
Lower voltage limit [pu]	0.95
Upper voltage limit [kV]	418
Upper voltage limit [pu]	1.10

5.6 Results of load flow calculations

5.6.1 Required amount of reactive power compensation

By the use of four fictitious controllable shunt reactors in the network model it has been established how much reactive power compensation capacity would be required if the new 380 kV power cables would be installed to keep the voltage within limits. The required amount of reactive power compensation capacity has been calculated for each defined study case. The calculated overall maximum values are shown in Table 5-9. These values represent the calculated maximum values for all contingencies under study (N-0, N-1, N-2). The reactive power values shown in Table 5-9 have been converted to a value at reference voltage of 380 kV, i.e. the voltage at which TenneT specifies the rating of its shunt reactors.

Table 5-9 Required reactive power compensation capacity

Substation	BSL380	TNZ380	RLL380	HVL380	*TOTALS*
Total required reactive power compensation capacity [Mvar]	523	631	497	375	*2026*
Available shunt reactor capacity in 2035 [Mvar]	150	350	300	300	*1100*
Deficit of reactive power compensation capacity in 2035 [Mvar]	-373	-281	-197	-75	*-926*

In can be concluded that the total required reactive power compensation capacity in the substations BSL380, TNZ380, RLL380 and HVL380 to accommodate the use of 14 km long 380 kV cable sections in the four circuits towards TNZ380 is higher than the reactive power compensation capacity that is expected to be available in 2035.

Case study 3 is considered to be the one with the longest cable section length (14 km). For this reason the focus of the present study has been on this alternative. In the document *Definition lengths cable section in study (Ref 5)* three case studies are defined, an overview is available in Tabel 1-1. From the results shown in the table it can be concluded that the reactive power that will be available in 2035 will be insufficient to accommodate Case study 2 or Case study 3.. In case cables with a length of 10 km (Case study 2) are applied, the required amount of reactive power compensation drops only by 337 Mvar, still leaving a deficit of 589 Mvar. This deficit will still lead to exceedance of the statutory voltage limits.

5.6.2 Voltage levels

For all scenarios, the voltages at the substations under study have been calculated. Figure 5-1 to Figure 5-6 depict the calculated voltages for each substation under study.

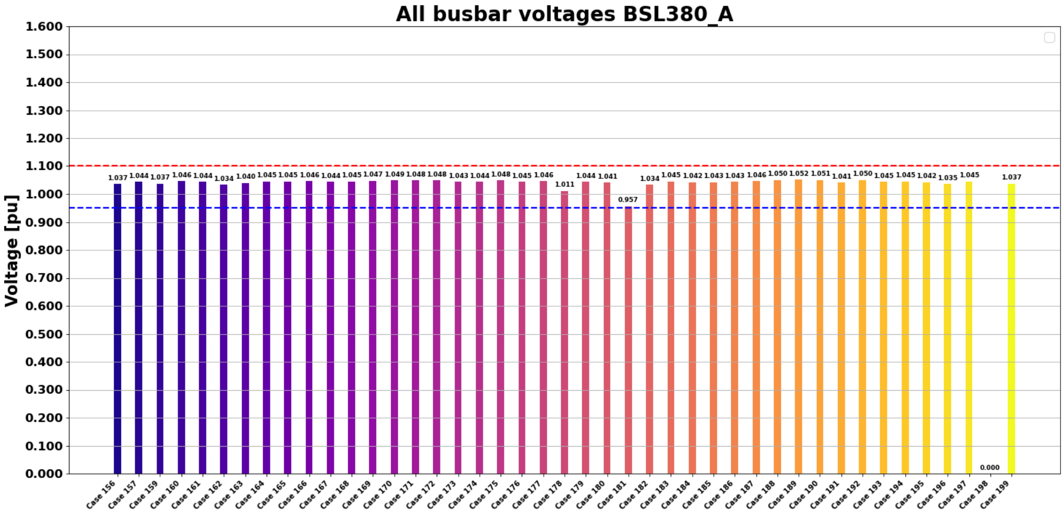


Figure 5-1 All calculated voltages at busbar A of substation BSL380 per study case

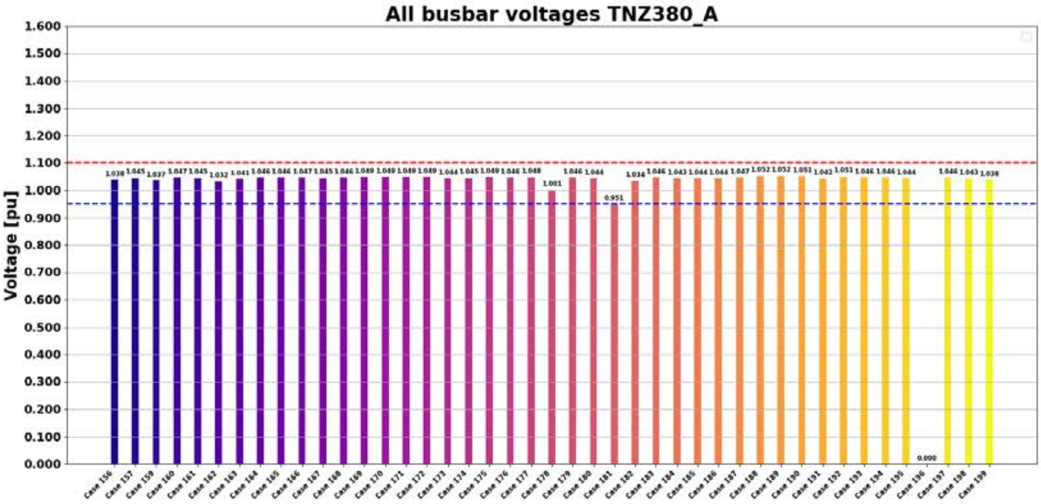


Figure 5-2 All calculated voltages at busbar A of substation TNZ380 per study case

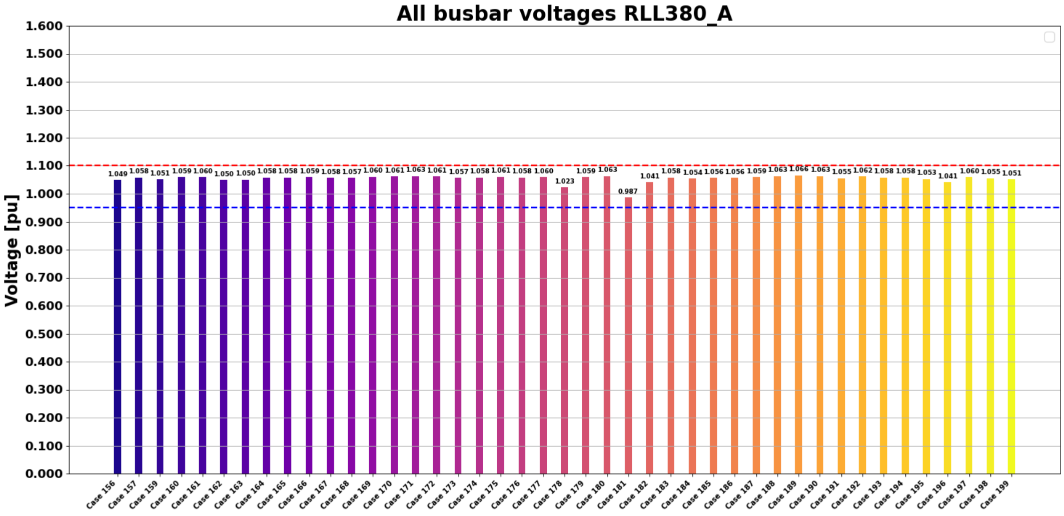


Figure 5-3 All calculated voltages at busbar A of substation RLL380 per study case

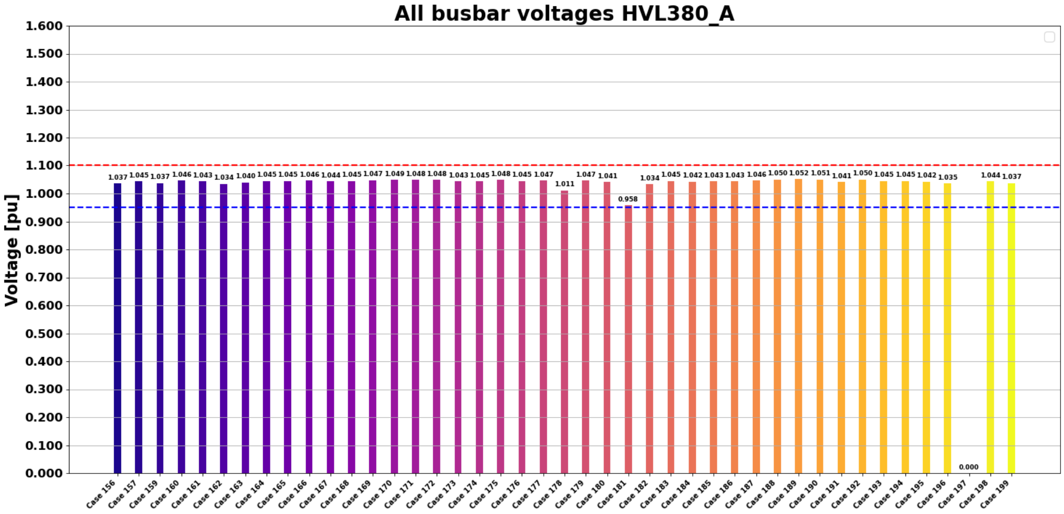


Figure 5-4 All calculated voltages at busbar A of substation HVL380 per study case

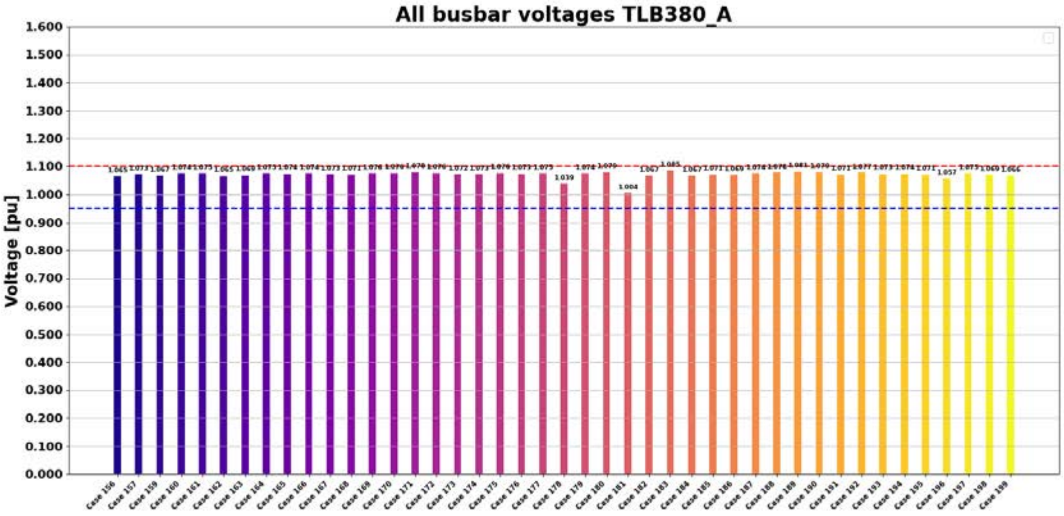


Figure 5-5 All calculated voltages at busbar A of substation TLB380 per study case

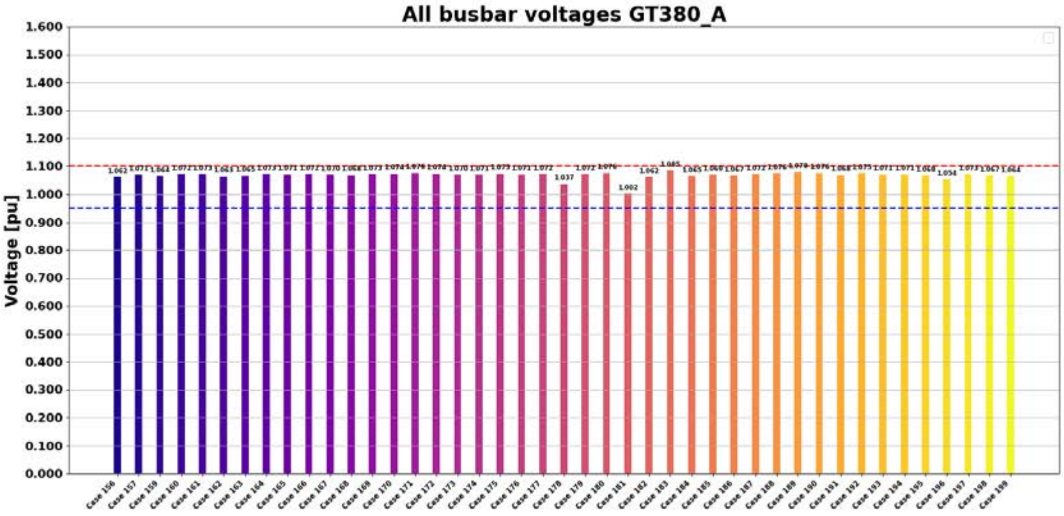


Figure 5-6 All calculated voltages at busbar A of substation GT380 per study case

Figure 5-7 to Figure 5-10 depict per substation under study the voltage distribution for the set of N-1 and the set of N-2 contingencies. The distribution is shown by means of boxplots. The box extends from the first to the third quartile of the calculated voltages. The line in the box indicates the median.

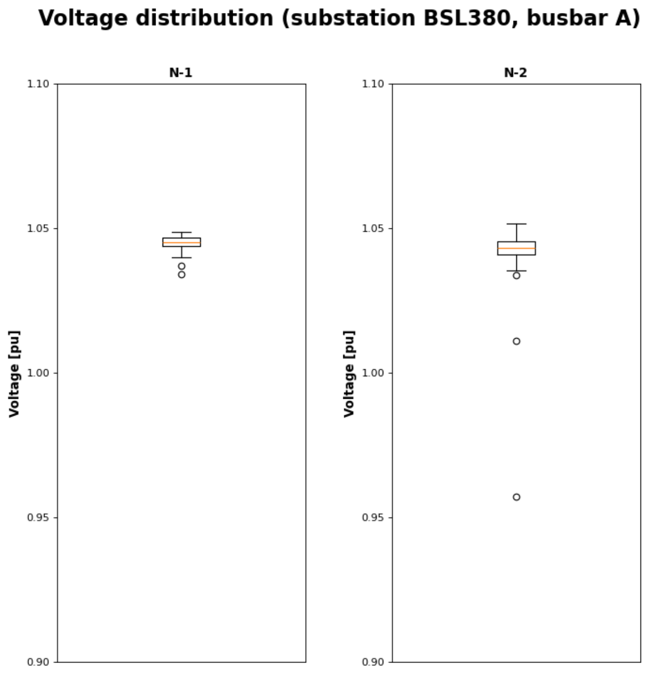


Figure 5-7 Distribution of voltages at substation BSL380

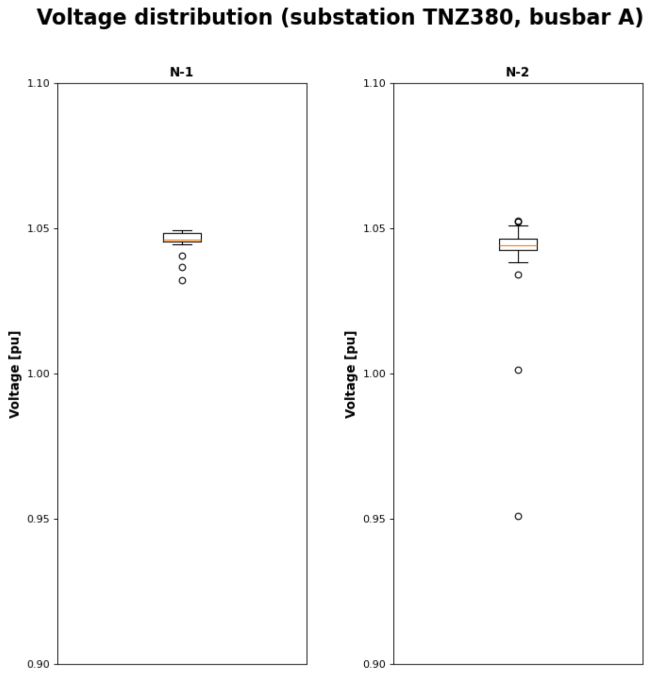


Figure 5-8 Distribution of voltages at substation TNZ380

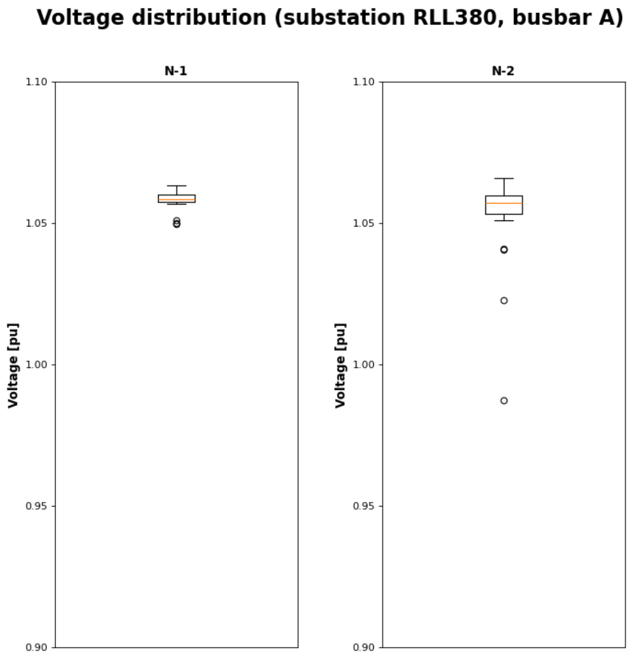


Figure 5-9 Distribution of voltages at substation RLL380

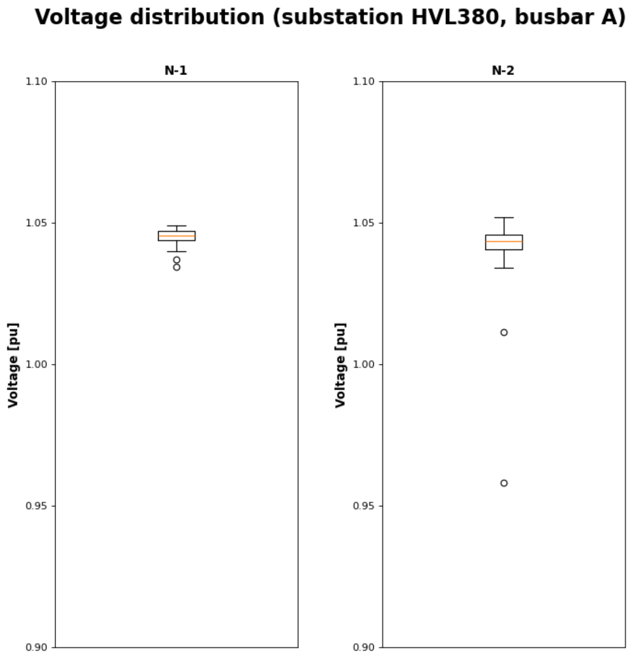


Figure 5-10 Distribution of voltages at substation HVL380

The overall minimum and maximum voltage levels and the associated scenarios are summarized in Table 5-10.

Table 5-10 Calculated minimum and maximum voltages at substations under study (1 p.u.=380 kV)

Substation	**BSL380**	**TNZ380**	**RLL380**	**HVL380**	**TLB380**	**GT380**
MINIMUM VOLTAGES						
Minimum voltage [pu]	0.957	0.951	0.987	0.958	1.004	1.002
Study case	181	181	181	181	181	181
Contingency type	N-2	N-2	N-2	N-2	N-2	N-2
First contingency component type	Line	Line	Line	Line	Line	Line
First contingency component	TNZ380 - RLL380 W	TNZ380 - RLL380 W	TNZ380 - RLL380 W	TNZ380 - RLL380 W	TNZ380 - RLL380 W	TNZ380 - RLL380 W
Second contingency component type	Line	Line	Line	Line	Line	Line
Second contingency component	TNZ380 - RLL380 Z	TNZ380 - RLL380 Z	TNZ380 - RLL380 Z	TNZ380 - RLL380 Z	TNZ380 - RLL380 Z	TNZ380 - RLL380 Z
MAXIMUM VOLTAGES						
Maximum voltage [pu]	1.052	1.052	1.066	1.052	1.085	1.085
Study case	189	189	189	189	183	183
Contingency type	N-2	N-2	N-2	N-2	N-2	N-2
First contingency component type	Shunt reactor	Shunt reactor	Shunt reactor	Shunt reactor	Line	Line
First contingency component	HVL380 SP1	HVL380 SP1	HVL380 SP1	HVL380 SP1	HST380 - RLL380 W	HST380 - RLL380 W
Second contingency component type	Shunt reactor	Shunt reactor	Shunt reactor	Shunt reactor	Line	Line
Second contingency component	RLL380 SP1	RLL380 SP1	RLL380 SP1	RLL380 SP1	HST380 - RLL380 Z	HST380 - RLL380 Z

The calculation results show that all calculated voltage remain with the required range of 0.95 -1.10 p.u provided that the total reactive power compensation as mentioned is available.

In all substations under study the minimum voltage occurs when both circuits between TNZ380 and RLL380 are out of service.

5.6.3 Rating of additional shunt reactors

As stated previously in Section 5.4.2, TenneT makes use of shunt reactors with a fixed size of 100 or 150 Mvar, meaning that they can only produce either their maximum reactive power, or 0 Mvar. Therefore, once the total required reactive power was established, additional calculations were conducted to determine the allowable maximum size of the additional shunt reactors to be installed, and how many such fixed shunt-reactors would be required.

A number of additional load flow calculations have been carried out with fictitious shunt reactors having step sizes of 50, 75 or 100 Mvar. The calculation results have shown that in case the control step is 50 Mvar all voltages in the substations under study remain within limits. However, if the control step is 100 Mvar this is no longer the case.

These results imply that in case the required additional reactive power compensation capacity would by realised by fixed shunt reactors, the maximum size of these shunt reactors should be around 50 Mvar.

5.6.4 Rapid voltage change levels

The switching of power connections or reactive power compensation equipment could result in a change of the voltage level in the substations. The magnitude of the voltage change should remain below a limit value-. A distinction is made between the steady state voltage change ΔUss and the voltage change ΔUmax during the switching oscillation. The applicable limits are stated in Table 5-11. Additional requirements are stated in the IDD (RVC1 up to RVC12).

Table 5-11 Applicable rapid voltage change (RVC) limits

Voltage level [kV]	380
ΔUss limit [%]	10
ΔUss limit [%]	3 (in situations without outages of production, large customers or connections)
ΔUmax limit [%]	5 (in situations without outages of production, large consumers or connections)

The steady state voltage change can be estimated/calculated in different ways: manually, or via a simulation software.

5.6.4.1 Manual calculation of ΔUss

The steady state voltage change ΔUss depends on two parameters:

- The magnitude of the short-circuit power Sk at the substation where the switching is performed
- The reactive power rating Q of the component that is being switched

The steady state voltage change ΔUss can be estimated by means of the following formula:

$$\Delta U_{ss}[\%] = 100 * \frac{Q\ [Mvar]}{S_k[MVA]}$$

The reactive power production of a single 380 kV cable circuit is shown in Table 5-12 for 3 different cable lengths.

Table 5-12 Reactive power production of 380 kV cable

Cable length [km]	10	14	18
Total reactive power production of cable circuit [Mvar]	210	295	379

The relationship between ΔUss and the short circuit current magnitude is depicted in Figure 5-11 for three different lengths of 380 kV cable circuits. It can be seen that for a 14 km long 380 kV cable circuit, consisting of two 380 kV cables, the steady state voltage change will remain below the limit value of 3 % if the short circuit current is always higher than 15 kA. For a 18 km long 380 kV cable circuit the steady state voltage change will remain below the limit value of 3 % if the short circuit current is always higher than 19 kA.

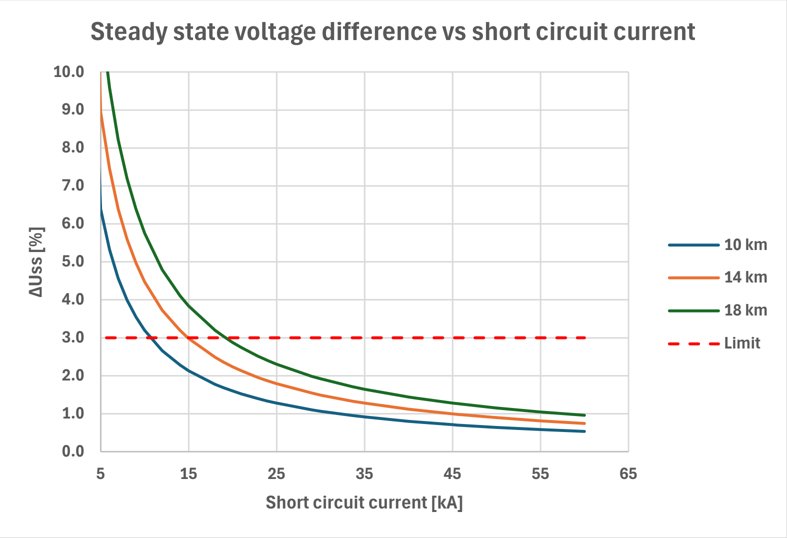


Figure 5-11 Steady state voltage change versus short circuit current (U=1.0 p.u.)

The worst-case scenario with respect to the steady state voltage change occurs when the voltage level is at the upper voltage limit (1.1 p.u.). The relationship between ΔUss and the short circuit current magnitude is depicted in Figure 5-12.

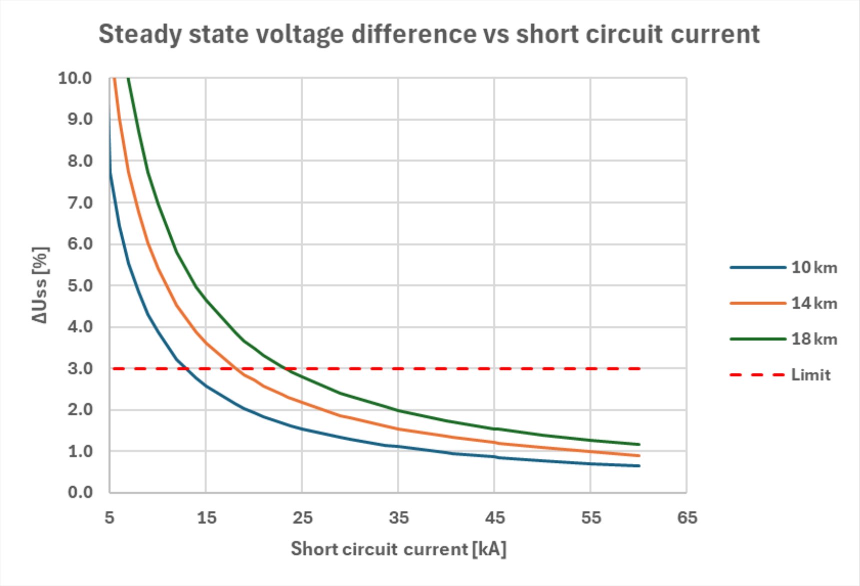


Figure 5-12 Steady state voltage change versus short circuit current (U=1.1 p.u.)

It can be seen that for a 14 km long 380 kV cable circuit, consisting of two 380 kV cables and operated at a voltage level of 1.1 p.u., the steady state voltage change will remain below the limit value of 3 % if the short circuit current is always higher than 18 kA. In case of a 18 km long 380 kV cable the minimum short circuit requirement is 22.9 kA.

The minimum available short circuit power at the substations under study has been determined by running short circuit calculations for all operation scenarios. The results are shown in Table 5-13.

Table 5-13 Minimum short circuit current at substations under study

Substation	BSL380	TNZ380	RLL380	HVL380
Minimum short circuit current [kA]	20.9	21.9	29.0	23.4

From the table it can be concluded that for the 18 km long 380 kV cable case the minimum short circuit current in the substations BSL380 and TNZ380 is too low, implying that for this case the RVC limits could be exceeded. The 18 km case corresponds to the connections between substations TNZ380 and RLL380 that include a 4 km cable section near Krabbendijke.

The calculated minimum short circuit currents do not differ much from the required minimum values. This implies that in case the short circuit current level decreases and/or the total length of the 380 kV cable sections increases, the rapid voltage change levels need to be re-evaluated.

5.6.4.2 Calculation of ΔU_{ss} via network model (pending)

6 CONCLUSIONS OF STEADY STATE STUDY

The results of the steady-state study lead to the following conclusions:

- The total required reactive power compensation capacity in the substations BSL380, TNZ380, RLL380 and HVL380 to accommodate the new 14 km long 380 kV cable sections in the four new circuits to TNZ380 is higher than the reactive power compensation capacity that will be available in 2035. Additional reactive power compensation is therefore needed
- The required amount of additional reactive power compensation can currently not be realized in the 380 kV substations under study, based on TenneT's assessment of available space and TenneT's shunt reactor placement policy
- If no additional measures are taken to realize the required reactive power compensation capacity, it will not be possible to realize the four new circuits to substation TNZ380 with 14 km long underground cable sections included in each circuit by the year 2035. The shortage of reactive power compensation capacity could result in exceedance of the voltage limits
- Neither will it be possible to realize the new circuits to substation TNZ380 with 10 km long underground cable sections (Case study 2) included in each circuit by the year 2035. Also in this alternative the shortage of reactive power compensation capacity could result in exceedance of the voltage limits
- The installation of additional reactive power compensation equipment requires additional physical space in the existing and planned 380 kV substations. Presently insufficient additional space is available.

7 RECOMMENDATIONS

Based on the results of the steady-state study the following recommendations are given:

- A solution should be found for the deficit of reactive power compensation capacity before the other technical issues, part of this system impact study, can be addressed
- If it is not possible to mitigate the deficit of reactive power compensation capacity by installing additional shunt reactors, other potential solutions should be investigated e.g. direct connection of shunt reactors to power cable terminations, application of dynamic reactive power compensation, use of different AC power cable type.

8 STEADY STATE SOLUTIONS TRADE-OFF MATRIX

8.1 Introduction

The main conclusion of the steady-state analysis is that the total required power compensation capacity in the substations BSL380, TNZ380, RLL380 and HVL380 to accommodate the new 14 km long 380 kV cable sections in the four new circuits to TNZ380 is higher than the reactive power compensation capacity that will be available in 2035. Because of this the voltage cannot be kept within the limits. From a technical perspective this is not acceptable and measures are therefore required in order to install a 14 km cable section while keeping the voltage levels within the limits.

The current 14 km of AC cable requires more reactive power compensation than available. Therefore an assessment of potential solutions to overcome this deficit have been assessed.

An inventory has been made of potential solutions. They are listed in a trade-off matrix (TOM) which is added as appendix B to this report. The aim of the trade-off matrix is to compare potential solutions to overcome the identified problems and rank them against a set of assessment criteria. The TOM includes the main disadvantages of the listed solutions in order to determine if a number of solutions can already be disregarded at this stage. In case a disadvantage applies to all solutions it is not listed.

The expected deficit of reactive power compensation capacity amounts to 926 Mvar in 2035. Based on reactor sizes of 100 or 150 Mvar, this would mean 7 to 10 additional reactors would have to be installed. The study already indicated that reactors of 50 Mvar might also be needed, this will even increase the number of installed reactors. Without major modifications and a change in TenneT policy, that is not possible in the existing substations.

8.2 Reference case

The listed remaining solutions are compared to the Marked solution. The Marked solution is a connection from BSL380 to TNZ380 which consist of a combination of approximately 7 km of overhead line (OHL) and a 7 km underground AC cable to cross the Western Scheldt estuary. This solution was studied before (Reference 4: TenneT Memorandum EPN-2026-004) and it was concluded sufficient reactive power will be available in the grid to support this option.

8.3 Grouping of solutions

The list of potential solutions have been grouped into the following categories:

- Solutions which provide additional reactive power compensation
- Non technical solutions

For all solutions it should be noted that reactive power compensation is always location specific. To be effective, reactive power must be compensated in the area where it is generated.

8.4 New grid design or technology for TenneT grid

The following solutions are either new to the TenneT grid or currently not used for this purpose by TenneT. Introducing new technology or design changes in the TenneT grid generally involves a process in which the impact must be assessed. Specifications must then be drawn up and experience gained. Then a procurement process starts. Adding technologies that are new in the TenneT grid will also impact the complexity of operational procedures.

This group also includes several solutions which would require a change in the way current grid/substations are designed to accommodate more space for reactive power compensation. Most solutions mentioned below require the acquisition of additional land and permits. The feasibility of these proposed solutions must however always be checked against the maximum amount of reactive power that can be connected to a 380 kV substation. When adding more reactive power in existing substations the impact of a fault will also increase. A busbar fault in a substation should not lead to a loss of too much reactive power compensation capacity, as this introduces a risk of exceeding the voltage limits.

To put the planning of these solutions into perspective: to realize a new substation including permitting typically takes around 10 years. The execution timeline does not necessarily present a constraint in itself. However, in the broader context of the grid development, an additional execution window, which may, or may not affect other planned works in the vicinity, risks delays in timelines of meeting critical grid expansions, which affects grid security over the long term. This consideration should be evaluated in context of other possible alternatives.

8.4.1 STATCOM in existing substation

A STATCOM (Static Synchronous Compensator) is a device that is used in power systems to quickly stabilize voltage levels by injecting or absorbing reactive power. It is intended to support the grid and keeping the power flow smoothly, especially during sudden changes or disturbances in the grid. The STATCOM is a very useful inclusion in a grid when there are these challenges relating to the dynamic grid stability. However, in the context of compensating the reactive power of the longer cable system, a STATCOM would not be considered a commercially feasible alternative, compared to a switchable reactive power compensation device, like a reactor.

When considering integration, it is important to consider not only the installation itself, but also its integration into the environment. A typical 300 Mvar STATCOM requires a hall of around 1.000 m^2 excluding transformers, cooling units, etc which would require another 500-1.000 m^2. Given the current deficit multiple STATCOM’s would be needed.

Figure 8-1 Example of a 300 Mvar GE STATCOM (source: GE Verona.com)

8.4.2 Direct connection of shunt reactors at cable terminations

Currently shunt reactors are located at substation sites. It is also possible to connect the shunt reactors at other locations, nearby existing equipment like cable terminations or at the tunnel entry/exit. Those locations would have to be extended to facilitate the shunt reactors and any auxiliary equipment needed. They can be considered as small substations with the sole purpose to facilitate shunt reactors for reactive power compensation. This solution requires the purchase of land and changes to spatial planning agreements.

Either switchable or non-switchable shunt reactors could be used. In case non-switchable shunt reactors are used, the reactors are not available when the power cable is switched off. In case of switchable shunt reactors the reactors can remain in service, even when the power cable is switched. In this case the switchable shunt reactors can still be used for reactive power compensation in other nearby parts of the grid.

8.4.3 Expansion of the 380 kV power system

To accommodate more shunt reactors without increasing the current maximum number of reactors per station the existing 380 kV power system could be extended with additional substations. This would mean building additional substations and connections. Figure 8-2 shows an example of a 380/150 kV substation. This solution posed the network operator with many challenges: the need for new locations, high investment costs, long permitting procedures, visual impact etc.

Figure 8-2 Example of a 380/150 kV substation (Diemen)

8.4.4 Adjustment of existing substation design

Adjusting the existing substation design would at first require expansion of the current design, acquire additional land adjacent to the station. Furthermore, the policy regarding the maximum amount of reactive power compensation that can be facilitated at a substation must be reconsidered, because new operational risks are introduced with this option. The applicability of this solution might require a change (and rebuilding) of the substation design as the standard triple busbar substation design is no longer compliant.

8.4.5 Overview of physical space in substations

Several suggested solutions rely on the availability of additional bays in the substations either within the existing station area or adjacent to it. In Table 8-1 an overview of the substations in the area and the availability to accommodate additional reactors. It can be concluded that limited physical space may be available but not sufficient to accommodate the required additional reactors. In addition, in order to comply with other requirements of the Grid Code, such as the voltage step, TenneT has a policy for the maximum number of coils/capacitors per substation as described in section 3.3.3. At the TNZ380 this maximum is already planned for 2035 and included in the calculations. At HVL380, it would be possible to install 400 Mvar additional capacity within the TenneT policy, of which maximum 200 Mvar could be used for compensation for additional cables. However this would not be sufficient to cover the shortage of reactive power compensation capacity neither for the 11 or 14 km cable options. New operational risks would be introduced with this option and the impact needs to carefully assessed. The applicability of this solution might require a change (and rebuilding) of the substation design as the standard triple busbar substation design is no longer compliant.

Table 8-1 Overview of physical space in substations

	Status	Existing lay-out	Options for expansion
BSL380	Existing station	1 bay available	Complex, would require changes to existing layout
TNZ380	Under development, final location to be confirmed	May be space for some additional compensation, plots are still to be acquired	Depends on final location
RLL380	Existing station	No additional availability within current layout	Limited, due to existing 150kV station in the North, TenneT is already acquiring land south of the station to facilitate existing expansion plans, in addition Stedin plans to build a MV substation.
HVL380	Under construction	In total 25 bays will be available, of which 1 spare bay intended as spare customer field not yet allocated. Limited additional space may be available.	No additional space available

8.5 Non-technical solutions

8.5.1 Buy reactive power compensation from the market

Third-party generators can also be used to compensate for reactive power. However, these must be present in the area and their availability must be guaranteed at all times in order to ensure security of supply. In this scenario TenneT would buy in reactive power compensation and would mean TenneT would rely on external parties for compensation. These could be existing installations or new commercial suppliers who install additional reactive power in new or existing substations or plants, such as STATCOMs, for the purpose of selling it. Currently no generation units are available against a reasonable price. It is not to be expected that new commercial suppliers will install new reactive power compensation equipment for the present project only. This will only be the case if the new compensation equipment could also be used to alleviate reactive power compensation deficits in other parts of the grid. These new assets also require space which will not be available for other developments.

8.5.2 Accept reactive power compensation deficit

TenneT has policy rules in place to comply with the Netcode requirements, also with regards to reactive power compensation. Failure to comply with these rules jeopardises security of supply. Allowing any sort of exceptions to this policy will set a precedent that will be impossible to reverse. The planning and operation of the Dutch grid depends on strict adherence to this policy, which has a legacy far exceeding this single project.

8.6 Other measures

Two additional alternatives were mentioned during the brainstorming session:

- Shunt reactors with a smaller capacity for more precise regulation of the voltage
- Controllable shunt reactors instead of fixed ones.

These suggested “measures” can reduce the need for reactive power compensation. By applying shunt reactors with a smaller capacity or controllable shunt reactors the amount of installed reactive power compensation can be better matched with the actual need.

The suggested measures will contribute but will however not solve the need for additional compensation. As such they are not considered as real solutions and therefore not included in the TOM.

8.7 Impact of expansion of the TenneT grid

In table 8-2 and overview is provided to provide insight in the impact of expanding the grid with additional substations to facilitate additional compensation for reactive power. During the subsequent study phases additional measures may be identified. The budget estimate for additional substation is provide by TenneT and is based on a 800 m^2 substation layout with 4 reactors and additional equipment.

Table 8-2 Estimated impact additional substations for reactive power compensation

	Additional stations	**Financial impact**	**Land needed**	**Impact on planning**
Case study 1 (7 km)	No additional stations	NA	NA	NA
Case study 2 (10 km)	One additional station	265 MEUR	800 m^2	IBN 2034
Case study 3 (14 km)	Two additional stations	530 MEUR	1.600 m^2	IBN 2034

8.8 Next steps

After identifying possible solutions, each solution should be systematically assessed and compared. This can be achieved by ranking the options against a clearly defined set of criteria—such as feasibility, cost, expected (environmental) impact, risks, impact on planning, and alignment with current policies.

After a decision is made, the solution should be implemented in the model and Steady state calculations will be repeated to validate the solution. Then the Steady state study can continue with the final steps followed by the subsequent study phases to identify if any additional measures are needed

9 ELECTROMAGNETIC TRANSIENTS STUDY (PENDING)

10 POWER QUALITY AND HARMONICS STUDY (PENDING)

11 REFERENCES

/1/ TenneT Memorandum PU-AMT 24-131. System Impact Study: Zeeland 380 kV Cable connections (BTR) – Input Data Document. Version V.0.7.

/2/ Notitie Reikwijdte en Detailniveau 380 kV netuitbreiding Zeeuws-Vlaanderen.

/3/ Handreiking aanleg 220/380 kV hoogspanningsverbindingen. Ministerie van Klimaat en Groene Groei. July 2025.

/4/ TenneT Memorandum EPN-2026-004. Assessment of possible options to realize the required transmission capacity towards Zeeuws-Vlaanderen V2

/5/ EPN-2026-008 Definition of lengths cable section in study

APPENDIX A

Overview of defined contingencies

Case index	Contingency type	Contingencies				Comments
		Connection(s)	Shunt reactor(s)	Transformer(s)	Busbar(s)	
156	N-0	-	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are in service
157	N-0	-	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
159	N-1	BSL380-TNZ380 Wit	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
160	N-1	BSL380-HVL380 Oranje	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
161	N-1	RLL380-HVL380 Oranje	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
162	N-1	RLL380-TNZ380 Wit	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
163	N-1	RLL380-TLB380 Oranje	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
164	N-1	RLL380-HST380 Wit	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
165	N-1	RLL380-ZVL380 Wit	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
166	N-1	BSL380-Eurolink	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
167	N-1	BSL380-SL10	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
168	N-1	BS30 EPZ1	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
169	N-1	-	TNZ_50kV_SP411	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
170	N-1	-	HVL380 SP1	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
171	N-1	-	RLLL380 SP1	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
172	N-1	-	BSL_50kV_SP401	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
173	N-1	-	ZKL220 F01	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
174	N-1	-	ZKL220 F02	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
175	N-1	-	-	BSL380 TR401	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
176	N-1	-	-	RLL380 TR411	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
177	N-1	-	-	TNZ380 TR411	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
178	N-2	BSL380-TNZ380 Wit BSL380-TNZ380 Zwart	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
179	N-2	BSL380-HVL380 Oranje BSL380-HVL380 Paars	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
180	N-2	RLL380-HVL380 Oranje RLL380-HVL380 Paars	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
181	N-2	RLL380-TNZ380 Wit RLL380-TNZ380 Zwart	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
182	N-2	RLL380-TLB380 Oranje RLL380-TLB380 Paars	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
183	N-2	RLL380-HST380 Wit RLL380-HST380 Zwart	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
184	N-2	RLl380-ZVL380 Wit RLL380-ZVL380 Zwart	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
185	N-2	BSL380-SL10 BSL380-SL20	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
186	N-2	BSL380-SL10 BS30 EPZ1	-	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
188	N-2	-	TNZ_50kV_ SP411 TNZ_50kV_SP412	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
189	N-2	-	HVL380 SP1 RLL380 SP1	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
190	N-2	-	BSL_50kV_SP401 BSL_50kV_SP402	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
191	N-2	-	ZKL220 F01 ZKL220 F02	-	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
192	N-2	-	-	BSL380 TR401 BSL380 TR402	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
193	N-2	-	-	RLL380 TR411 RLL380 TR412	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
194	N-2	-	-	TNZ380 TR411 TNZ380 TR412	-	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
195	N-2	RLl380-ZVL380 Wit	-	-	RLL380 Busbar B	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
196	N-2	BSL380-TNZ380 Zwart	-	-	TNZ380 Busbar A	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
197	N-2	BSL380-HVL380 Paars	-	-	HVL380 Busbar A	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
198	N-2	BSL380-HVL380 Paars	-	-	BSL380 Busbar A	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service
199	N-2	BSL380-TNZ380 Zwart	-	-	BSL380 Busbar A2	Shunt reactors HVL380 SP2 and RLL380 SP2 are out of service

To keep track of all individual simulations that have been performed , use has been made of unique case numbers. Only the relevant cases are shown in the table. For this reason case numbering does not start from 1.

APPENDIX B
Trade-off matrix

	Potential solutions						
	Reference case	Solutions for reactive power deficit				Non-technical solutions	
		New technology or design for TenneT grid					
	0	1a	1b	1c	1d	2a	2b
Criteria	Case study 1: Overhead Line (on land)+ 7km Cable (crossing)	Other reactive power compensation methods: STATCOM (in existing substation)	Directly connect shunt reactors at the power cable ends, or transition points / tunnel entry (small substation)	Extend the 380 kV power system to accommodate more shunt reactors (additional substation, as no space in existing)	Adjust the existing substation design to accommodate more shunt reactors.	Other reactive power compensation methods: Buy (existing) reactive power	Accept certain unbalance
Maturity		-- New for TenneT, new as reactive power compensation				-- At this moment no generation units available at reasonable price, depedency on external party, less robust TenneT becomes dependent on market developments. If new commercial initiatives would be initiated, location cannot be influenced (effectiveness less certain).	
		- Complex operation produceres	- Complex operation produceres	- Complex operation produceres			
Environmental / Stakeholder impac	- Bird victims (draadslachtoffers)		- Increased size of substation	-- New location is required	- Additional land is needed		
	-- Visual impact		-- Visual impact	-- Visual impact	- Environmental impact due to noise		
			-- New location is required	-- New location is required			
Budget		-- Much more expensive than static solutions (5-6 times more expensive)	- Investment needed in (small) substation	-- High investment cost		-- Generator continuos running Operational costs for auxiliary services - to be contracted - will increase outside TenneT's control.	
Planning/MER		-- No specifications available, takes more time (~10yrs from spec to implementation)	-- ~10 years incl permits for new substation	-- ~10 years incl permits for new substation		- Initiatives for commercial reactive power compensation will propably be too late as the market will follow demand with a delay.	-- Needs to be studied
Comply with TenneT policy		-- Would require TenneT policy change, takes more time			-- "Requires change in policy, resulting in extensive substation modifications"		- Requires change in policy
System integrity studies(stability, compliance, additional studies needed)		-- No specifications available, takes more time					--
Impact on security of supply							-- Impact on voltage stability, NON-compliance with grid code

APPENDIX C

Grid topology and Executive summary System impact study 7km (Case study 1)

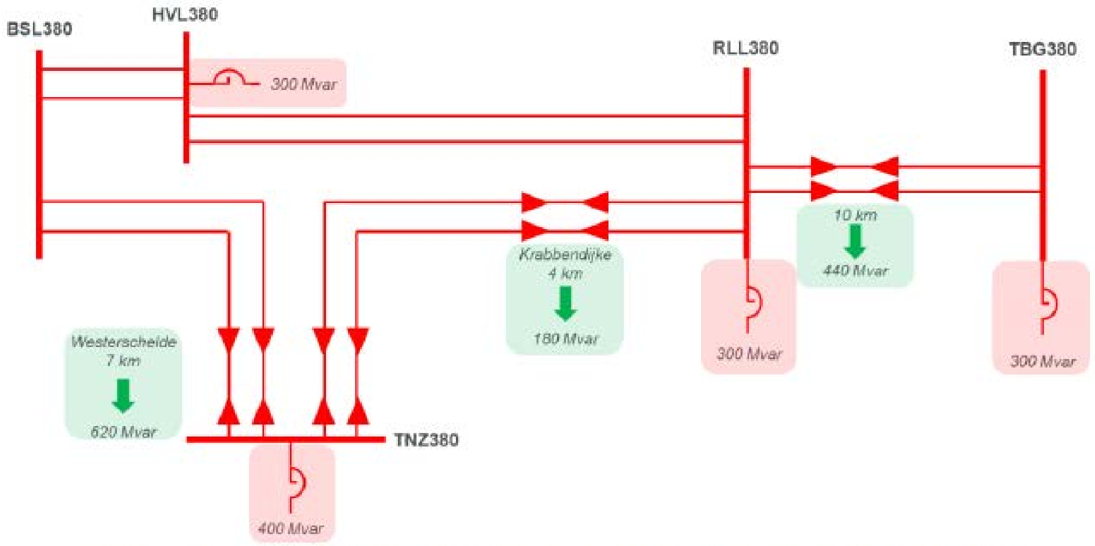
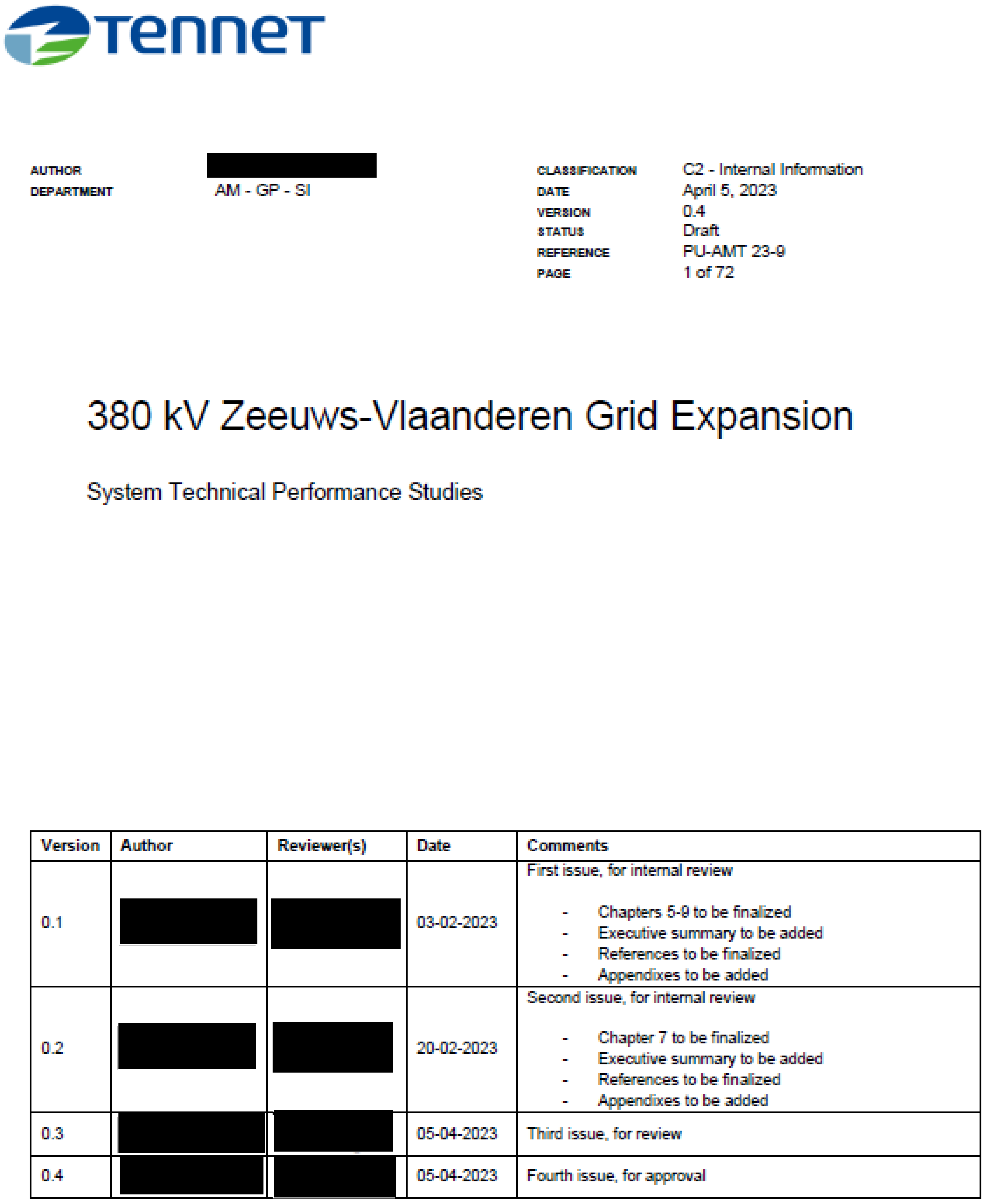


Figure 4. Simplified representation of the 380 kV grid topology under study



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PAGE	1 of 72

380 kV Zeeuws-Vlaanderen Grid Expansion

System Technical Performance Studies

Version	Author	Reviewer(s)	Date	Comments
0.1	[redacted]	[redacted]	03-02-2023	First issue, for internal review - Chapters 5-9 to be finalized - Executive summary to be added - References to be finalized - Appendixes to be added
0.2	[redacted]	[redacted]	20-02-2023	Second issue, for internal review - Chapter 7 to be finalized - Executive summary to be added - References to be finalized - Appendixes to be added
0.3	[redacted]	[redacted]	05-04-2023	Third issue, for review
0.4	[redacted]	[redacted]	05-04-2023	Fourth issue, for approval

Executive Summary

In order to facilitate the developments in the South West of the Netherlands with respect to transport capacity, a major grid expansion towards Zeeuws-Vlaanderen is required in the 380 kV Zeeland network. More specifically, the preferred variation from grid development perspective, which was in Q4 2021 evaluated and selected to be further studied, includes the following changes:

- A ring structure is formed between the existing 380 kV substations Borssele (BSL380) and Rilland (RLL380) and the new 380 kV substation Terneuzen (TNZ380).
- A T-split is introduced in two circuits of the 4-circuit overhead line connection BSL-RLL380 at a distance of 7 km from BSL380. This results in the connections BSL-TNZ380 and TNZ-RLL380, i.e. four circuits connect TNZ380 to the 380 kV grid.
- The new 4-circuit connection between the T-split and TNZ380 is 14 km long and it crosses the Westerschelde, which is approximately 3.5 km to 7 km wide.
- The 150 kV grid at the Terneuzen area is decoupled from the 150 kV Zeeland grid and it forms a load-pocket, which is connected to TNZ380.

For the crossing of the Westerschelde, one alternative is that it is realized by means of an overhead line. Another alternative is that the crossing is realized by means of underground cables. For the latter, two options are considered:

- _Option 1_: introducing four 380 kV underground cable circuits of 3.5 km each for the crossing of shipping lanes of the Westerschelde;
- _Option 2_: introducing four 380 kV underground cable circuits of 7 km that will cover the complete Westerschelde crossing. Eventually this covers 50% of the new 4-circuit connection between the T-split and TNZ380.

In order to evaluate the impact on the technical performance of the transmission grid when partially cabling the new 380 kV ring configuration between the BSL380, TNZ380 and RLL380 substations, a series of studies was conducted that covered the following system and component aspects:

1. Voltage profile in the part of the 380 kV grid under study, based on the defined reactive power compensation scheme;
2. Rapid voltage changes (RVC) during the switching of the overhead line – underground cable circuits and of the 380 kV shunt reactors;
3. Harmonic resonance temporary overvoltages (TOVs) during power transformer energization of fault conditions;
4. Circuit breaker capacitive currents and current zero-miss phenomena;
5. Harmonic impedance profile in the part of the 380 kV grid under study.

NOTES

- **For the purposes of this technical study, it was agreed that first Option 2 would be analysed (introduction of maximum cable length). If this analysis were to conclude that the risks due to the occurring grid phenomena would not be acceptable, Option 1 could still be studied.**

- **In order to perform this technical study, detailed assumptions had to be made regarding possible routing and installation. This does not imply that any routing or construction is already preselected. The RCR participation process will be used to develop a possible trace. Then it will be checked whether this study results are still applicable or that (parts of) the study should be repeated.**

Based on the findings of the complete analysis, the following conclusions are drawn per study item:

	A. General	
	Conclusion	**Elaboration**
A1	It can be concluded that the partly cabling of the 380 kV grid expansion towards Zeeuws-Vlaanderen seems feasible with respect to the system technical performance aspects, as analysed in this study. It needs to be noticed that this conclusion applies to the new 4-circuit connection to TNZ380 and based on the assumption that each of the 380 kV cable sections will have a maximum length of 7 km.	n/a
	B. AC load flow analysis	
	Conclusion	**Elaboration**
B1	The defined reactive power compensation scheme provides sufficient voltage control and, therefore, no mitigation actions or changes in the scheme are deemed necessary.	In all defined scenarios, N-0, N-1 and N-2 system conditions were considered, when calculating the voltage values at the 380 kV substations of interest. Despite the already elevated values under N-0 conditions (i.e., close to 1.05 pu), the voltages did not exceed the defined limits except for few specific N-2 contingencies. These system conditions are regarded extreme and, therefore, the risk of exceeding the voltage limits is accepted.
	C. RVC analysis	
	Conclusion	**Elaboration**
C1	For all simulation cases, the calculated dU_{ss} and dU_{max} values did not exceed the defined limits. Therefore, no risk is identified and no mitigation actions are deemed necessary.	n/a
	D. TOV analysis	
	Conclusion	**Elaboration**
D1	For all simulation cases, the calculated TOVs did	n/a

	not exceed the defined limits. Therefore, no risk is identified and no mitigation actions are deemed necessary.	
	E. 380 kV circuit breaker aspects	
	Conclusion	**Elaboration**
E1	The calculated capacitive currents did not exceed the preferred maximum value given in the IEC standard.	n/a
E2	For all the defined cases, no current zero-miss was calculated. Therefore, no risk is identified and no mitigation actions are deemed necessary.	n/a

Based on the findings of the complete analysis, the following recommendations are given per study item:

	A. Project realization timeline	
	Recommendation	**Elaboration**
A1	Should a significant change occur in the timeline, especially with respect to the sequence of realizing the 380 kV cable projects, the validity of the findings of each study item should be evaluated and, when deemed necessary, the analysis of a study item should be re-conducted.	This study and its findings were based on a number of starting points and assumptions, as defined and agreed upon with AMT-GP-NL. An important starting point was related to the realization timeline of all relevant projects in the area of study.
	B. AC load flow analysis	
	Recommendation	**Elaboration**
B1	Should a significant change occur in any of the starting points or assumptions, the AC load flow analysis should be conducted again in order to re-evaluate the voltage profile within the study area.	The findings and the conclusions of the AC load flow analysis are valid for the given starting points and assumptions, especially with respect to: • the length of the 380 kV cable sections within the ring configuration between the BSL380, TNZ380 and RLL380 substations; • the defined reactive power compensation

		scheme; • the defined network scenario corresponding to the minimum/maximum short circuit power and load conditions.
B2	For future analyses and according to an internal technical agreement, the following aspects should be considered, as a way towards the definition of a standard calculation methodology/policy for AC load flow calculations: • Evaluation of the end solution of the DIgSILENT Power Factory calculation with respect to the transformer tap positions; • Differences in the AC load flow calculations, when the transformer taps are kept fixed at their neutral positions.	For the AC load flow calculations, the automatic tap adjustment option was active for all 380 kV power transformers.
B3	For future analyses and according to an internal technical agreement, the following should be considered: • Extended representation of the foreign grids, as they could have a significant impact on the resulting AC load flows and, therefore, on the resulting voltage profiles in the grid.	In the defined DIgSILENT Power Factory network model used for the AC load flow analysis, the foreign grids were represented by simplified power frequency equivalents.
B4	It is strongly recommended to analyse a) the actual operating voltage levels in the 380 kV grid and b) the currently applied reactive power compensation schemes and operational actions, e.g., automatic tap adjustments of the 380 kV power transformers, switching of reactive power shunt elements, switching of cable circuits. Such an analysis can provide important information to be used as input, especially when defining and studying the effectiveness of reactive power compensation schemes for new 380 kV cable sections.	n/a

	C. RVC analysis	
	Recommendation	**Elaboration**
C1	Should longer 380 kV cable sections or 380 kV shunt reactors of higher MVAr rating be considered, the RVC analysis should be conducted again.	The findings and the conclusions of the RVC analysis are valid for the given starting points and assumptions, especially with respect to: • the length of the 380 kV cable sections within the ring configuration between the BSL380, TNZ380 and RLL380 substations; • the power rating of the 380 kV shunt reactors (150 MVAr); • the defined network scenario corresponding to the minimum/maximum short circuit power and load conditions.
	D. TOV analysis	
	Recommendation	**Elaboration**
D1	Should longer 380 kV cable sections be considered, the TOV analysis should be conducted again.	The findings and the conclusions of the TOV analysis are valid for the given starting points and assumptions, especially with respect to: • the length of the 380 kV cable sections within the ring configuration between the BSL380, TNZ380 and RLL380 substations; • the defined network scenario corresponding to the minimum/maximum short circuit power and load conditions.
D2	It is recommended that a study should be conducted, aiming to the definition of a screening limits for harmonic resonance TOV studies. These screening limits could be based either on a two-parameter level, i.e., harmonic resonance frequency and impedance amplitude, or a three-parameter level, i.e., harmonic resonance frequency, impedance amplitude and total MVA rating of power transformers connected in parallel to a specific substation.	The selected representative TOV worst-cases considered system conditions with a first parallel resonance close to the 3rd and the 4th harmonic respectively. The resulting TOVs are dependent on the total MVA rating of power transformers connected in parallel to a 380 kV substation.

E. 380 kV circuit breaker aspects		
	Recommendation	**Elaboration**
E1	Should longer 380 kV cable sections be considered, the circuit breaker capacitive current analysis should be conducted again.	The findings and the conclusions of the 380 kV circuit breaker capacitive current analysis are valid for the given starting points and assumptions, especially with respect to the length of the 380 kV cable sections within the ring configuration between the BSL380, TNZ380 and RLL380 substations.
E2	It is strongly recommended that the capacitive current interrupting capability of the 380 kV circuit breakers is re-evaluated by the circuit breaker technologist(s) during the basic design phase, when more detailed information is available with respect to the 380 kV cable sections, e.g., section length, cable type, etc.	n/a
E3	It is strongly recommended that transient recovery voltage (TRV) aspects are studied for the 380 kV cable circuit breakers during the basic design phase, when more detailed information is available with respect to the 380 kV cable sections, e.g., section length, cable type, etc.	n/a
F. Harmonic impedance analysis		
	Recommendation	**Elaboration**
F1	It is strongly recommended that a complete harmonic analysis is performed, based on the harmonic impedance calculations of this study. The harmonic analysis should consider possible updates of the currently applied methodology.	In this study, the implementation of the complete harmonic analysis methodology was not possible due to the following limitations: • One of the study starting points is that the Zeeuwse-Vlaanderen grid expansion towards TNZ380 will follow the commissioning of the ZW380-Oost and ZW380-West projects. Therefore, it is not possible to define a reference system configuration that will facilitate the methodology. Even if the existing system configuration was considered as the

		reference configuration (i.e., ZW380-Oost and ZW380-West not in operation), it would have possibly led to incorrect or misleading conclusions. In such a case, the harmonic analysis would consider the impact on the THD of all 380 kV cable sections at once (i.e., ZW380-Oost, Krabbendijke and TNZ380) and not only of the 380 kV cable sections to TNZ380. • The latest available power quality data refer to the year 2022. The starting point of this study refers to the year 2035 and, similarly to the above, no measurement data is there that considers the 380 kV cable sections at Krabbendijke and ZW380-Oost. Therefore, the starting points for conducting the harmonic analysis would significantly deviate from reality, which could result in incorrect conclusions and recommendations.
F2	Due to the given uncertainties, it is strongly recommended to consider the following actions during the basic design of the project: • Reserve space at either BSL380, HVL380, TNZ380 or RLL380 for a redundant harmonic filter (i.e., two filter bays) and for reactive power compensation (i.e., two shunt reactor bays), taking into consideration the integration/noise production to the environment. • Install Power Quality (PQ) meters at the new circuit bays at BSL380, TNZ380 and RLL380.	n/a
G. Switching overvoltages		
	Recommendation	**Elaboration**
G1	It is strongly recommended that a switching overvoltage study is conducted during the basic design phase, when more detailed information is available with respect to the 380 kV cable	Slow-front overvoltages due to the switching of a mixed 380 kV OHL-UGC circuit could result in excessive overvotlages, which could stress the insulation of substation components, of the cable

	sections, e.g., section length, cable type, etc. Such a study should consider all relevant parameters, e.g., statistical simulations, substation of switching, application of auto-reclosing protection schemes, etc.	system and its accessories or the overhead line insulation. Also, these overvoltages could prove themselves important for the proper selection of the 380 kV surge arresters to be installed at the cable terminations at the OHL-UGC transition points.

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