Master of Science Thesis

A scenario-based voltage stability analysis for external constraints in flow-based capacity calculation

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TenneT Taking power further

Challenge the future

A Scenario-Based Static Voltage Stability Analysis for External Constraints in Flow-Based Capacity Calculation

Master of Science Thesis

For the degree of Master of Science in Electrical Engineering at Delft University of Technology

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Numquam ponenda est pluralitas sine necessitate.

Plurality is never to be posited without necessity.

Ockham's razor, William of Ockham

Executive summary

Since May 2015, flow-based market coupling is introduced within the Central Western Europe region. Flow-based market coupling uses load-flow computations to determine and optimize the cross-border transport capacity available to the power markets. Since DC load-flow computations are used, only the thermal limits of the grid are safeguarded. To allow transmission system operators to set additional limits to safeguard for voltage stability and dynamic stability as well, so-called 'external constraints' can be introduced.

At this moment, the external constraints set by TenneT for the Dutch grid are based on the maximum export and import net positions allowed within the former border-based market coupling mechanism. They include all necessary security measures (i.e. thermal, voltage and dynamic stability), defining a 'worst-case' transport capacity applicable for a longer period, barely taking into account the real-time topology and operating condition of the grid. It results in a transport capacity which is in many cases more stringent than necessary.

This created the need to perform more detailed research in the determination and validity of the external constraints. The desired result was a method to define external constraints which better match the current grid operating point and supply as high as securely possible cross border capacities to the market. This is a desirable situation, because of the foreseen positive effects of enlarged cross border capacities on CWE-region welfare.

The first part of this thesis focused on a voltage stability analysis that could support scenario-based external constraints. It resulted in a scenario-based static voltage stability analysis, using a combination of static load-flow solutions and accompanying contingency analysis to investigate a multitude of scenarios. These scenarios are based on an ENTSO-E reference grid model that has been improved for better accuracy and voltage control possibilities. Three categories of scenario drivers have been taken into account; internal drivers (net import position and load level), external drivers (AC-transit flows and DC-transit flows) and extreme drivers (clustered generation location and border voltages).

The analysis has proven that scenario-based external constraints are a viable concept. Different scenario drivers result in different grid operating points, demanding different security measures. These security measures can be met with smaller margins when scenario-based external constraints are used, increasing the overall efficiency of usage of the grid.

What has proven to be harder than expected is the exact quantification of the voltage stability borders for the Netherlands. Although a general consideration of voltage stability in individual scenarios is possible, the results are not unambiguous enough to put a specific import limit on the boundary between stability and instability.

In general, reactive power balancing seemed to have a larger influence on the voltage stability than scenario drivers. It has to be realized though, that reactive power balancing is influenced by the scenario drivers as well, for example due to the amount of available in-service generators or line-loading due to transit or import flows.

It is important that the stability boundaries become clear before an external constraint set is composed, also including other stability issues, scaling issues and dividing internal problems and import problems. The best way is to start with an as small as possible scenario driver set, since this will keep the analysis work and complexity manageable. Extending to more comprehensive external constraint sets is possible later on since the implementation method has room for extension.

Various methods to translate the results of off-line stability studies towards scenario-based external constraints have been introduced. The most straightforward method uses a format similar to the existing external constraints, varying only the 'Remaining Available Margin' depending on the scenario. More specific external constraint formats are shown to safeguard for specific effects like maximal single border flow, uneven border influence on the remaining available margin and direct integration of AC-transit flows.

It can be concluded that the implementation of scenario-based external constraints is possible in multiple ways and could prove beneficial to cross-border transfer capacity. Implementation work still has to be done, for example the process of matching forecast files to a specific scenario. Also, the amount of allowed complexity has to be determined. Defining scenario-based external constraints can become a vast and complex problem. Starting with 'simple' variants of external constraints is advised, various possibilities to further improve the external constraints can be used later on.

Acknowledgements

List of abbreviations

API	Application Programming Interface
ATC	Available Transfer Capacity
ATC-CC	Available Transfer Capacity - Capacity Calculation
ATC-MC	Available Transfer Capacity – Market Coupling
AVR	Automatic Voltage Regulator (on generators)
CB	Critical Branch
CBCO	Critical Branch/Critical Outage combination
CGM	Common Grid Model
CO	Critical Outage
CWE	Central West Europe
D_{bus}	Business Day
D_{ref}	Reference Day (of FB-CC)
D-1	Day-ahead
D2CF	2-Days Ahead Congestion Forecast Files
DACF	Day-ahead Congestion Forecast Files
ENTSO-E	European Network of Transmission System Operators for Electricity
F_{max}	Maximal allowed Flow on Critical Branch
F_{ref}	Reference Flow during Dref on Critical Branch
FAV	Final Adjustment Value
FB	Flow-based
FB-CC	Flow-based - Capacity Calculation
FB-MC	Flow-based - Market Coupling
FCA	Forward Capacity Allocation
FRM	Flow Reliability Margin
GSK	Generator Shift Key
GUI	Graphical User Interface
HVDC	High-Voltage Direct Current
ID	Intra-day
IEM	Internal Energy Market

IGM	Individual Grid Model
LTA	Long-term Allocations
N-0	Grid situation with all elements activated
N-1	Grid situation with one failed element
NP	Net Position
NRA	National Regulating Authority
NTC	Net Transfer Capacity
NWE	North West Europe
PST	Phase Shifter Transformer
PTDF	Power Transfer Distribution Factors
PU curve	Active Power versus Voltage curve
QU curve	Reactive Power versus Voltage curve
RA	Remedial Action
RAM	Remaining Available Margin
SCADA EMS	Supervisory Control And Data Acquisition - Energy Management System
SoS	Security-of-Supply (region)
TLC	Trilateral Market Coupling
TRM	Transfer Reliability Margin
TSO	Transmission System Operator
TTC	Total Transfer Capacity
UCTE	Union for the Coordination of the Transmission of Electricity
ULTC	Under Load Tap Changers (on power transformers)
VSF	Voltage Sensitivity Factor

Table of contents

Chapter 1

Introduction

Since May 2015, flow-based market coupling (FBMC) is introduced within the Central Western Europe region (CWE-region). This new method of market coupling uses load-flow computation to determine and optimize the interconnector transfer capacity that is available to the power markets. FBMC should improve transfer capacity determination (and as a result improve overall welfare) compared to the current market coupling method based on available transmission capacities (ATC) per individual border.

The capacity calculation process for flow-based market coupling uses DC power flow computations, therefore only safeguarding the thermal limits of the grid. To allow the individual transmission system operators (TSOs) to set additional limits to safeguard for voltage stability and dynamic stability as well, so-called 'external constraints' can be introduced. These constraints are determined in off-line studies and are called 'external' because they are introduced from outside the capacity calculation process.

At this moment, the external constraints set by TenneT for the Dutch grid is based on the maximum export and import net positions allowed within the former ATC-based capacity calculation. The current set of external constraints includes all necessary security measures (i.e. thermal, voltage and dynamic stability) previously included in the total transfer capacity (TTC) value. The TTC was calculated as a 'worst-case' transport capacity applicable for a longer period, barely taking into account the real-time topology of the grid. It results in a transport capacity which is in many cases more stringent than necessary.

This created the need to perform more detailed research into the determination and validity of these external constraints. The desired result is a method to define external constraints which better match the current grid operating point and consequently create the possibility to supply as high as securely possible cross border capacities to the market for each grid operating point. This is a desirable situation, because of the foreseen positive effects of enlarged cross border capacities on CWE-region welfare.

1.1 Thesis research questions

The first objective of this thesis is to give a general overview of the requirements various components should meet to be able to perform a voltage stability analysis in this context. Which kind of limits are applicable to safeguard voltage stability, which conditions should be fulfilled by a grid model to be usable and which load-flow software has the right possibilities to perform the required analysis are a couple of examples that are going to be investigated. Much of this information has not been clearly defined at the start of the thesis project and some clearness on these topics will be given first.

Afterwards, a grid model has to be made suitable for performing the required analysis. The grid model should be adapted so it can serve as a stable and realistic starting point for all scenarios. Combined, this should provide an answer to the following research question:

- *Which grid model is suited for analysis and which adaptations to the model are needed to create a stable and suitable starting point for analysis?*

Afterwards, scenario parameters are used to create a set of scenarios, each scenario being a combination of scenario parameters representing a possible grid operating point. Combined with the starting point in the grid model, a tool combines these two to a complete set of scenarios to be investigated. This step results in a complete set of scenarios that can be investigated on voltage levels for base case (N-0) grid operating point.

To further investigate the scenarios on stability some contingency analysis, stability margin tests or other stability analysis tools will have to be used. Combined with the results of the previous step, this should provide an overview of the overall static voltage stability of the scenario. Based on the combined results, conclusions will be drawn on the acceptability of the scenario and the following research questions should be answered:

- *Which scenario parameters have influence on the voltage stability of the Netherlands?*
- *What are the voltage stability borders in the investigated scenarios?*

The answers on the above research questions will supply information on the limits for voltage stability of the Dutch grid for a set of grid operating points. Also, the results give insight into the influence various scenario drivers have on the voltage stability. The scenario-based approach creates the possibility to supply as high as securely possible cross border capacities to the market for each grid operating point.

The knowledge gathered in this thesis will be used, combined with knowledge about the dynamic stability of the Dutch grid, to define the definitive external constraints for the flow-based capacity calculation process.

Lastly, the resulting stability borders for each scenario should be translated to a format that is compatible with the flow-based capacity calculation process. This will probably also consist of a grouping process to bring down the amount of different sets of flow based parameters. Translation methods towards a flow-based capacity calculation compatible format will be investigated by answering the following research question:

- *How to translate simulations results and accompanying voltage security limits to parameters that are suitable for the flow-based capacity calculation process?*

Additionally, answering these research questions should be done using a structured methodology with an, as much as practically possible, automated process. This creates the possibility to supply a justification of the results to a third party, but this also creates the possibility to easily reassess the external constraints in case of grid changes.

1.2 Thesis outline

The outline of this thesis will largely follow the same line as the research approach described above. Chapter 2 starts with describing the concept of market coupling and the process of capacity calculation involved with market coupling. While the concept of market coupling does not influence voltage stability characteristics of the grid directly, it does represent the system in which the new external constraints should fit. Therefore, knowledge about the market coupling process is important for the translation of study results towards useable external constraints.

Chapter 3 will introduce the theory of power system stability. After defining and describing the categories of power system stability, the common techniques to investigate static voltage stability will be introduced. It concludes with an outline of the research approach based on scenarios, the applied security requirements and tools used for this thesis.

In Chapter 4, the creation of a stable base case model will be described. First, the available grid models will be evaluated and one grid model will be chosen. Afterward, the performed modifications to the grid model will be described. Also, the voltage regulating capabilities apparent in the model will be described.

Chapter 5 discusses the scenario drivers, the automated scenario creation and analysis tools created for this thesis. For each separate scenario drivers, the concept and technical implementation in the model will be discussed. The automated process used to create all the scenarios, run the load-flow calculations and evaluate the results will be described. Lastly, a description of the available analysis tools will be given.

The results of the scenario analysis will be discussed in Chapter 6. Result analysis will be started with a simple module to investigate basic assumptions. Afterwards, the influences of the other scenario drivers will be investigated as well. Also, the method of a scenario based approach used to investigate static voltage stability will be evaluated.

The results of the static voltage stability analysis are not directly compatible with the flow-based capacity calculation process. In Chapter 7, the current method of implementing external constraints in the FB process will be described. Afterwards, two methods of implementing scenario-based external constraints into the capacity calculation process will be introduced.

Finally, Chapter 8 will discuss some conclusions based on the performed research and will give some recommendations for further research and improvement.

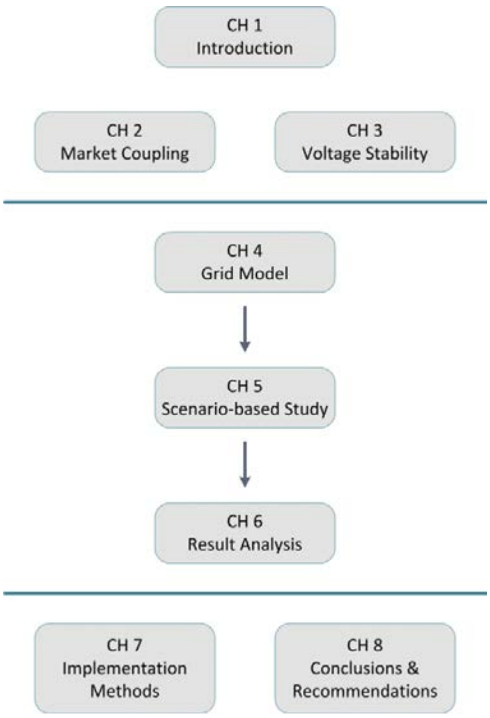

Figure 1: Thesis outline

Chapter 2

Market coupling of electricity systems

Over the last decades, the European Union has worked towards one single European energy market, the Internal Energy Market (IEM)[1]. To create a single European electric energy market it focusses on three concepts; liberalization, independent regulation and supra-national coupling of electricity markets. This is believed to increase economic and technical efficiency and improve security of supply, thus improving European welfare and competitiveness of the European industry.

To this thesis, the concept of supra-national coupling of electricity markets (in short, market coupling) is the most important. This means that not only power systems, but also power markets are connected to each other, as if they are one single system. Finally, it should allow market participants to trade electric energy throughout Europe without restrictions.

In this chapter the process of market coupling is dealt with in more detail. First, we'll focus on the reason market coupling processes are necessary and the steps already taken towards a single European electricity market. Second, the concepts and characteristics of market coupling will be explained. Last, the capacity calculation methods accompanying market coupling process will be discussed in more detail. Also, the need for additional off-line studies like the one in this thesis regarding security issues is clarified.

2.1 Introduction market coupling

The limited amount of cross-border capacity has been holding back the full integration of different national electricity markets into a single market. To overcome the shortage of cross-border capacity TSOs have been investing heavily in new interconnectors over the last years and new ones are planned. Simultaneously, more efficient congestion management and capacity allocation methods are being developed to maximize the economic benefit from electricity trades.

To achieve a single European electricity market by coupling all countries at once would be an impossible task. Power systems are historically nation-orientated with transport bottlenecks on the borders and varied electricity generation fuel mixes, this complicates coupling markets. To overcome these difficulties, an intermediate step towards regional markets of countries with similar properties has been planned, as shown in Figure 49. Afterwards, these regional markets can be combined to one European market.

Figure 2: The creation of a single European electricity market with regional markets as intermediate solution. [2]

Within the project NWE (North Western Europe) Enduring TSOs and power exchanges are working together to replace various individual and in some instances temporary solutions for market couplings or explicit auctions between the CWE, Nordic and UK countries/regions. The goal of the NWE Enduring project is to establish permanent and full price coupling between the CWE and Nordic regions and next to it connect the UK on both day-ahead and intraday markets. Appendix A gives a short overview of previous market coupling processes involving the Dutch electricity markets.

Market coupling is based on the economic principle of supply and demand. Within Europe, electricity prices are varying between countries because of differences in, for example, generation fuel mix, government policies and historic developments. When these markets are coupled the demand of cross-border trades will increase due to these price differences.

Within Market A, with low electricity prices, producers will happily sell to Market B with high electricity prices. Vice versa, consumers in Market B will gladly buy lower priced electricity in Market A. As a result, the difference in electricity prices between both markets will get smaller; a higher price convergence is reached. This is schematically pictured in Figure 3.

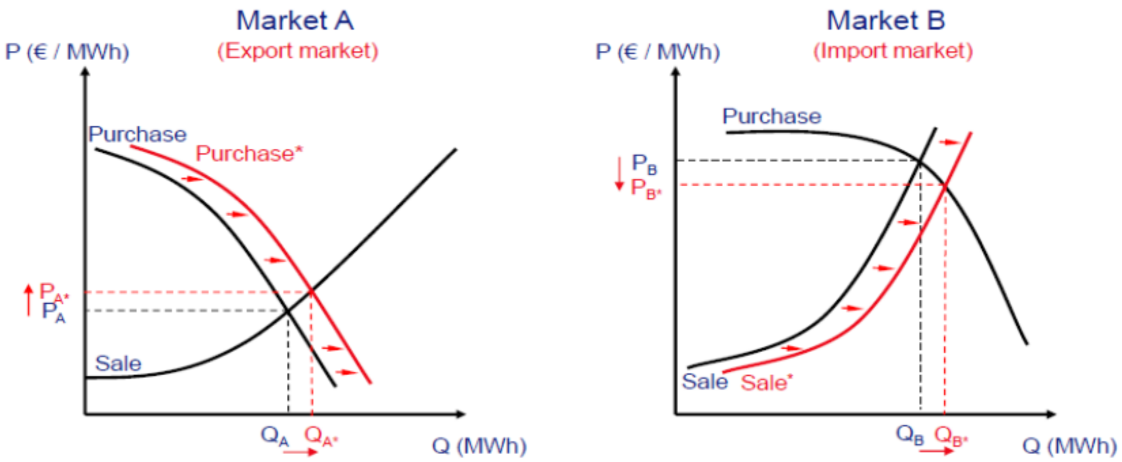

Figure 3: Price development when markets A & B are coupled. [3]

A limiting factor of market coupling is transport capacity between the markets. If there is a shortage of transport capacity, congestion situations will occur and full price convergence cannot be reached. An elaborate example of the effects of congestion on price developments is given in Appendix B.

Market coupling processes try to optimize the transport capacity between markets so congestion situations will be minimized as much as possible and existing infrastructure is used as efficient as possible.

2.2 The concepts of market coupling

Market coupling is a method to manage capacity congestion between neighboring power exchanges, by matching orders of coupled power exchanges and, at the same time, allocate the available cross-border capacity as efficient as possible. This way, two or more electricity market areas can be combined to a single market area. It allows buyers and sellers to combine their trades on power exchanges as if it was one single market area, exactly the European Union's goal of creating a single market throughout Europe.

Cross-border capacity allocation can be done in two ways, implicit or explicit. With explicit auctioning, the electrical energy (traded in MWh) and cross-border transport capacity (traded in MW) are traded separately. This method has a risk of mismatching when energy and transport capacity are not successfully bought for the same timeframe, resulting in less efficient utilization of cross-border capacity.

With implicit market coupling, the transmission capacity auction is integrated into the electrical energy market to minimize the 'mismatching errors'. The flow on a border is forecasted based on market data from the marketplace(s) in the connected markets. When the forecasted flow reaches a transport capacity limit defined by TSOs to safeguard grid security, congestion charges are added to the bid/offer prices.

The way cross-border capacity is allocated is also dependent on the trading timeframe. Electricity trading is divided into several timeframes to cope with trading situations apparent on different moments. Farthest before the delivery day is the Forward Capacity Allocation (FCA) market. In this timeframe, only the right to use cross-border capacity is sold in advance; this can be weeks, months or even years [4].

The main European market for electricity is the day-ahead market. Market participants can implicitly trade electricity and transmission capacity for delivery on the following day. For this thesis, the day-ahead market is the most important one, since it will be the first implementing flow-based capacity calculation.

During the delivery day, market parties can implicitly trade electricity on the intraday market in short timeslots (up to one hour) [5]. This allows them to manage risks or respond to changing conditions (e.g. adapting to wind forecast errors). Finally at real-time, the balancing market is used by the TSOs for several balancing services to make secure grid operation possible [6].

Nowadays, cross border capacity within the CWE is implicitly allocated on the day-ahead market. This means that the resulting prices on the market reflect both the cost of energy (in that specific bidding area) and the cost of congestion (when applicable). A great example of the advantage of implicit auctioning is visible after the introduction of the Tri-lateral Market coupling, as described in Appendix A.

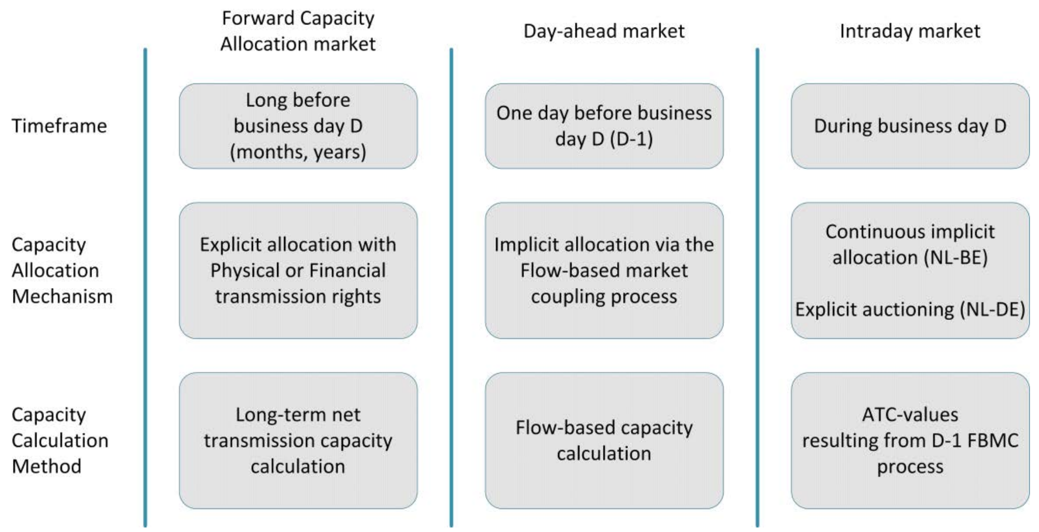

Figure 4: Overview of timeframes, capacity allocation mechanism and capacity calculation methods for market coupling.

The resulting market prices and schedules of the connected market are determined by combining all the bids and offers on the markets with the available capacity defined by the TSOs; a constrained optimization problem. This way, the cost of transmission capacity is integrated in the price differences between the markets. More specifically, if transmission capacity is sufficient available, there is no price difference between the markets and the cost of transmission capacity is zero. On the other hand, is congestion occurs, price differences between the markets occur and TSOs collect congestion charges.

Due to the importance of the available cross-border transport capacity (often the scarce commodity), capacity calculation methods are an important part of the Market Coupling process. Within the CWE region, first the method of ATC-based market coupling (ATC-MC) was used, called after the method of Available Transport Capacity capacity calculation (ATC-CC). This method is replaced by Flow-based market coupling (FB-MC) in May, 2015, again called after the capacity calculation method, Flow-based capacity calculation (FB-CC).

Although processes between ATC-MC and FB-MC differ on more aspects than capacity calculation, they will not be discussed since they are not relevant to this thesis. More details about the complete market coupling processes can be found in [7], [8] or [9].

2.3 Market coupling capacity calculation methods

An important, but separate, element of the market coupling process is the determination of the cross-border transmission capacity available to the market coupling process, done with capacity calculation methods. In the CWE-region the methods of Available Transport Capacity (ATC) capacity calculation and Flow-Based (FB) capacity calculation have been used. The transmission capacity resulting from this calculation method is returned to the 'main' market coupling process, where it is used in the implicit capacity allocation mechanism.

In May 2015, the CWE-region day-ahead market coupling mechanism switched from ATC-based market coupling (ATC-MC) to Flow-based market coupling (FB-MC). This included the switch from ATC-based capacity calculation (ATC-CC) to Flow-based capacity calculation (FB-CC).

The switch from ATC-CC to FB-CC created the need for TSOs to perform additional security investigations; reasons for this are discussed in section 2.3.3. To this aid, the ATC and FB capacity calculation methods will be briefly explained. To this thesis, the flow-based capacity calculation process and its external constraints are the most important. Therefore, an extensive explanation of the use of external constraints will be given in section 2.3.4. The complete FB-CC process will be explained in further detail in appendix C.

2.3.1 Available Transport Capacity capacity calculation

At the basis of the Available Transport Capacity capacity calculation (ATC-CC) lays the Total Transfer Capacity (TTC). The TTC is the maximal cross-border transport capacity allowable with operational security standards. Each TSO individually determines the TTC for each of its borders, in both flow directions. This results in two TTC values per flow direction for each border. The lower of the two values is accepted as the TTC available to the market for that border.

When determining the TTC, TSOs take into account all possible security issues (i.e. thermal, voltage, dynamic) but also phenomena like loop flows, transit flows or foreseen non-availability of connections are considered. As a result cross-border transport up to the TTC is even possible in worst-case scenarios, making it a robust security measure but also one that uses the infrastructure inefficiently.

The Net Transfer Capacity (NTC) available to the markets equals the TTC distracted by a Transfer Reliability Margin (TRM), a reserve on the transport capacity to safeguard grid security. A part of the NTC is offered as long-term capacity (yearly and monthly). The remaining capacity is called the available transfer capacity (ATC) and is offered to the short-term markets, to be used in the implicit auctions on the day-ahead and intraday markets. The capacity not used in the day-ahead market is made available again in the intraday market. Figure 5 depicts this division of cross-border capacities schematically.

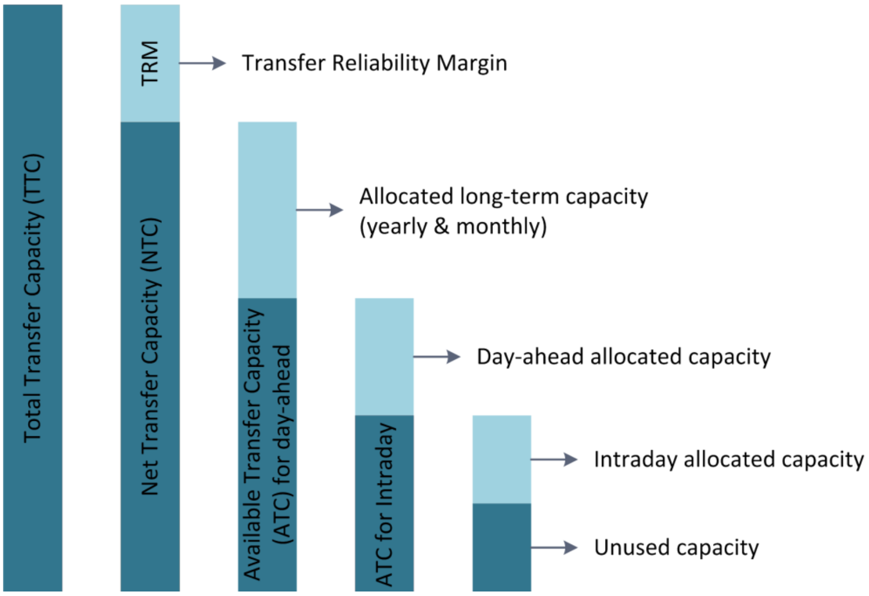

Figure 5: Schematic division of cross-border capacities for ATC-based capacity calculation.

2.3.2 Flow-based capacity calculation

For flow-based capacity calculation, the process of determining the cross-border capacity is changed. All participating TSOs determine their so-called critical branches (CBs), a generator shift key (GSK) and an individual grid model (IGM). The critical branches are transmission lines that are affected by international transactions; it includes the cross-border interconnectors itself but also internal transmission lines. Critical branches are defined for both the normal as well as contingency cases. The generator shift key defines how a change in area net position (the sum of electricity exports and imports of the area) is divided among the generators inside this area. An estimate of the system operating state on business day D is provided in the individual grid model. This contains exchange programs of a reference day, planned network outages, generator schedules, load forecasts and the topology of the network.

All individual CBs, GSKs and IGMs are merged by the European Merging Function to a common grid model (CGM). To account for their physical influences, all other continental ENTSO-E grids are also incorporated (in the form of day-ahead congestion forecasts) in the CGM. The result is a continental European-wide common grid model, the D2CF file.

The common grid model is used to calculate the flow-based parameters; for each critical branch a remaining available margin (RAM) and Power Transfer Distribution Factors ($PTDF$). The remaining available margin is defined as the maximum allowable flow (F_{max}) on a line minus the flow reliability margin (FRM) and the reference flow (F_{ref}, the flow that was dispatched at the reference day); this is schematically depicted in Figure 6. The PTDF represents the change in physical flow on a critical branch resulting from variations in the net position of each hub. They are determined by a sensitivity calculation on the common grid model using the GSK.

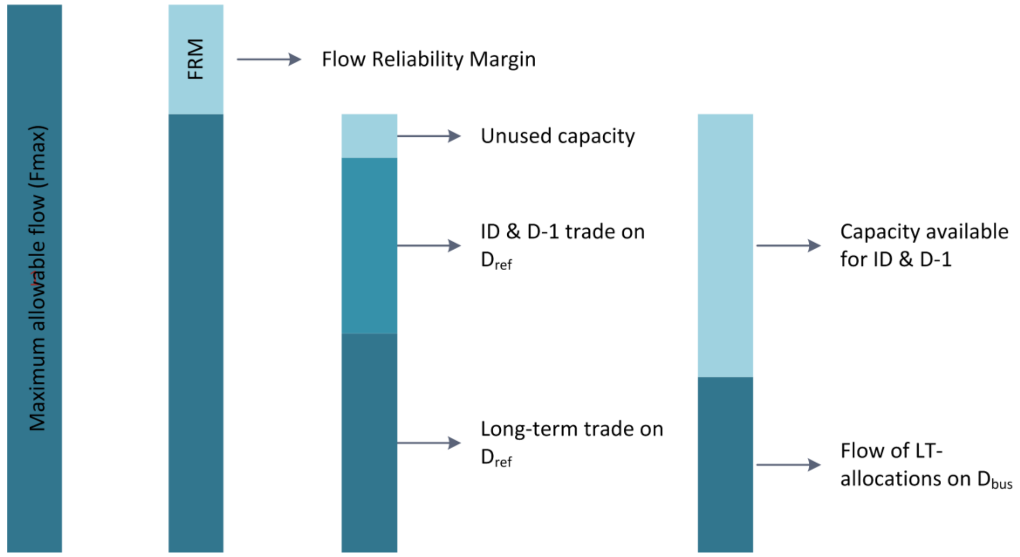

Figure 6: Schematic division of critical branch capacity for flow-based capacity calculation.

To be used for the day-ahead market, the FB parameters have to be adapted to business day D values. This is done by replacing the reference day flows (combined long-term and short-term allocations) by the nominated long-term allocations for business day D. The results are the final RAMs to be allocated on the short-term market (day-ahead and intra-day); also depicted in Figure 6.

Using the final FB parameters, the Flow-based capacity domain available to the market can be determined by combining all the critical branches, resulting in a situation like Figure 7. Since the CWE-region has three possible cross-border exchanges (FR-BE, BE-NL and NL-DE) this would actually be a three-dimensional space. By fixing the 3rd dimension (in this case B>C exchange) to a specific exchange, a more comprehensible illustration remains.

To the market only the Flow-based constraints most-limiting the exchanges are important, after all, bigger exchanges can create unsecure situations and are prohibited. These most-limiting constraints (called non-redundant constraints) together form the Security-of-supply region (indicated in gray). All exchanges and net positions within this region are secure, and therefore available to the flow-based market coupling mechanism. As a comparison, a rectangular shaped capacity domain (ATC domain) results from using the ATC-CC maximal bilateral power flows.

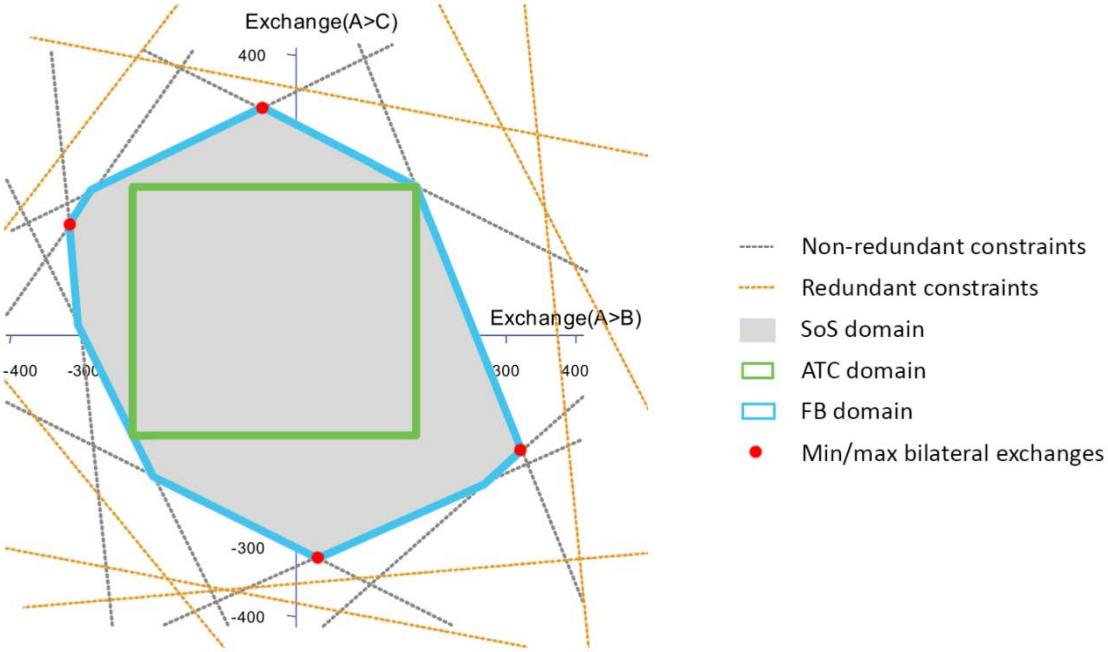

Figure 7: Two-dimensional Flow-based domain, assuming a fixed B>C exchange. The non-redundant constraints determine the Security-of-Supply region, equal to the FB-domain. Also a possible ATC-domain in the same situation is depicted.

2.3.3 Impact of the capacity calculation method switch for the Dutch grid

With ATC-based capacity calculation, each TSO or control area calculates its cross-border exchange capacities towards each of its neighbors, in both directions. Based on these calculations the TSOs agree on the transport capacity for each border and direction combination.

In these separate calculations, all security measures (i.e. thermal, voltage, dynamic) were implicitly included in TTC value. Also, the cross-border capacity was calculated as a 'worst-case' transport capacity applicable for a longer period (not completely taking into account the real-time topology of the grid). This meant the transport capacity in many cases was more stringent than necessary.

As well, phenomena occurring in the neighboring networks influencing the cross-border capacity were hard to include in the calculations. This could for example be transit or loop flows, but also smaller phenomena. Especially in largely meshed networks like the one in continental Europe these phenomena can be quite influential.

Flow-based capacity calculation introduces capacity calculation based on one collective model, the Common Grid Model. Therefore, cross-border effects that before were hard to calculate (transit/loop flows) are now automatically taken into account, removing the necessity to safeguard for these effects with additional limits. This means the existing infrastructure can be utilized more efficiently.

Also, flow-based capacity calculation is a daily process, creating the opportunity to deliver an up-to-date grid model for each day of calculation. This diminishes the need to include a longer period 'worst-case' situation, but a more accurate daily grid situation can be included. Again, this removes the need for overly large security margins. The capacity will be reduced when this is necessary (for example in a situation with a lot of out-of-service lines) but can be enlarged in case of a fully-operating grid.

Because flow-based capacity calculation requires a fully merged network model, the complete market coupling and capacity calculation process involved has inevitably become more complex. A lot of the market coupling steps are outside of the scope of this thesis, and will not be discussed into more detail. The additional steps involved in the capacity calculation process will be discussed in Appendix D.

Although flow-based capacity calculation has clear advantages over ATC-CC, the larger grid used for calculations also imposes some additional difficulties. This means a couple of extra elements have to be considered with FB-CC.

To cope with the complications a larger network imposes and decrease computational times, the flow-based capacity calculation uses DC load-flow analysis. Although much faster than AC load-flow analysis and more easily linearized (as used with PTDFs), this also means security aspects like voltage or dynamic stability cannot be evaluated.

To make sure the capacity calculation results will still meet the requirements on voltage and dynamic stability, this has to be safeguarded explicitly. This is possible via explicitly implemented constraints or 'external constraints', but these have to be well-founded with additional studies.

In short, the switch from ATC-CC towards FB-CC includes;

- Better inclusion of real-time grid situation
- Better inclusion of cross-border influences
- A more complex capacity calculation process
- More efficient use of infrastructure due to better determination of security margins
- Additional measures necessary to safeguard voltage and dynamic security

2.3.4 External constraints in flow-based capacity calculation

The flow-based capacity calculation method is based on the evaluation of remaining available margin on critical branches. Since branches do not represent the complete network or safeguard for all security issues, it might be necessary to implement other specific limitations to guarantee a secure grid operation.

TSOs are able to do this by implementing 'special' or 'artificial' critical branches called 'external constrains' to ensure that the market outcome does not exceed these grid security limits. External constraints are part of the input data that TSOs deliver for the FB-domain calculation. They have the same format as critical branches, with a remaining available margin (RAM) and power transfer distribution factors (PTDFs). In the case of external constraints, the PTDFs will only have the values 0, 1 or -1. For a complete overview of the Flow-based capacity calculation process, see Appendix D.

There are multiple reasons for TSOs to implement external constraints:

- Flow-based capacity calculation is based on DC load flow calculations. Therefore, only thermal limits are taken into account on the critical branches. By implementing external constraints, TSOs can safeguard for other important grid security aspects like voltage stability, dynamic stability or ramping (DC cables, net positions). These constraints are determined by off-line studies (like this thesis) outside the FB parameter computation, hence the name 'external' constraints.

- Flow-based capacity calculation uses a reference situation and variations from this point are calculated in a linearized method with a generation shift key (GSK). Especially with large deviations, differences in dispatch between the linear GSK and the realistic situation will occur. To avoid market results that differ too much from the reference situation, and therefore could induce large additional flows on grid elements, TSOs can limit the GSK shifting region with external constraints.

- Flow-based capacity calculation uses a largely automated process. This means the results of this process cannot always be foreseen in advance. External constraints create the possibility for TSOs to remove specific regions from the flow-based domain. This way they can ensure security of supply even in the case of unexpected flow-based solutions that would otherwise have compromised grid security.

Various methods to determine and implement external constraints are used at this moment:

- **External constraints to limit the import (an import limit constraint) or export (an export limit constraint) to an absolute net position.**
  This type of external constraint is used by the Netherlands (both import and export, $\max|NP| = 4250\ MW$) and Belgium (only import, $\min NP = -4500\ MW$). The values of these limits are determined in off-line studies, taking into account for example voltage stability and dynamic stability.

- **External constraints to limit the deviation from the reference program.**
  Due to linearization (i.e. GSK) in the FB calculation process, FB-results under big deviations are expected to differ too much from the real (non-linear) situation. To safeguard for these errors, the allowed deviation from the reference program is limited. The German TSOs and French TSO use this method combined with absolute import/export limits.

  The German TSOs allow a fixed bandwidth of Δ = 5000 MW from the reference program. Supplementary to that, the final import/export constraint is kept between a certain bandwidth. If the new value ($NP_{ref\,prog}$ +/- Δ) does not reach a minimum value, the constraint is raised to that minimum value; similarly, if the new value exceeds a maximum value, the constraint is lowered to that maximum value. Currently; $export_{min} = 5600\ MW < maxNP_{DE} < export_{max} = 7000\ MW$, and $import_{max} = -6000\ MW < minNP_{DE} < import_{min} = -4400\ MW$.

  The French TSO limits the maximum deviation ('shift' criterion) from the reference program to Δ = 4000 MW. Together with the reference exchanges FR-BE and FR-DE this defines the 'validity' domain. Complementary, an 'acceptability' domain is defined with maximum acceptable net positions. This domain is based on weekly or monthly performed studies on D2CF files representative of relevant exchange directions. The concatenation of these domains determines the final 'acceptable' domain which is applied with external constraints.

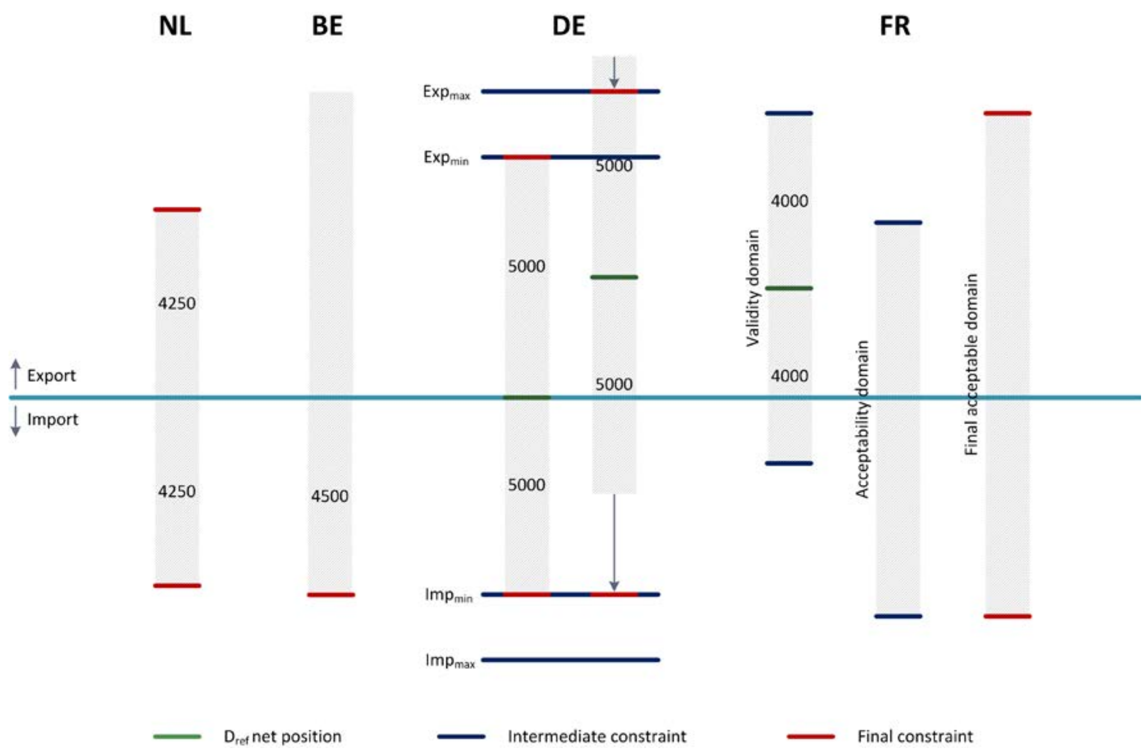

Figure 8: Illustration of various implemented external constraints. The Netherlands has fixed export/import limits, irrespective of D_{ref}-exchanges. Belgium only has an import limit, also irrespective of D_{ref}-exchanges. German combines a scaling bandwidth around D_{ref}-exchanges with an absolute import/export bandwidth. France concatenates a scaling bandwidth around D_{ref}-exchanges and an acceptability domain based on earlier studies (irrespective of D_{ref}-exchanges) into a final acceptable domain.

Chapter 3

Static voltage stability

Nowadays, the power grid should be capable of handling a much broader spectrum of operating points, compared to the traditional 'one-way' situation where energy was transported from centralized and controlled power plants to load centers. Developments like the increased distance between power production and load centers, more and higher capacity interconnectors, power interchanges over longer distances and higher percentages of renewable energy sources have led to this situation.

These developments have resulted in larger differences in grid operating points between low-load situations and high-load situations. This not only has consequences for the active power transport capacity, but also reactive power control challenges arise. The achievement of an acceptable grid voltage profile and sufficient reactive power resources throughout the grid has become more difficult.

Processes like the capacity calculation for market coupling have also become more complicated due to these developments. It is not possible anymore to only consider thermal transport capacities, but also effects on power system stability should be taken into account.

In this chapter, power system stability in general will be introduced first. Second, the specific category of power system stability investigated in this research, static voltage stability, will be described in more detail. Lastly, the chosen approach for this research, investigating the static voltage stability through a scenario based analysis, will be introduced.

3.1 Power system stability

Ever since the beginning of the development of power systems, power system stability has been recognized as an important issue for secure system operation. As early as 1920, research has been conducted towards power system stability [10][11][12]. Although transient angle stability has historically been the main field of research, the constant evolvement of power systems, e.g. higher meshed networks, more interconnectors, new generation forms or higher reliability requirements, has led to increased importance of other areas of research such as voltage stability, frequency stability or inter-area oscillations as well.

The expanding field of power system stability created the need for clear definitions and classification of power system stability. It makes a clear understanding possible of different types of stability, the way they are interrelated and consistent use of terminology. Important elements for sound power system design and developing operating criteria, analytical tools and study procedures.

Over the years, many definitions of power system stability have been proposed. A joint task force of CIGRE Study Committee 38 and IEEE Power System Dynamic Performance Committee also created a stability definition and power system stability classification. In this thesis, this classification and definition will be used since it's widely supported and the most recent one. The task force defined power system stability as:

> *Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. [13]*

Today's power systems have a lot of parameters that change constantly, loads, generator outputs, network topology or operating parameters, therefore, they are highly non-linear systems. As a result, not only the character and magnitude of the disturbance but also the initial operating point are all important factors for stability. Small disturbances like load changes or changing PV-systems output happen continuously and the system should adapt to them without problems. More severe disturbances like short-circuits or losing a large generator should be survived by the system as well to deliver the desired level of reliability.

The theory of power system stability uses both differential and algebraic equations with mathematics very similar to other dynamic systems. It is desired that the stability definitions are both useable for more theoretical approaches as well as more practically oriented studies. This matter is beyond the scope of this thesis. Thorough elaboration can be found in the joint task force report [13] or literature like [14]-[16].

3.1.1. Categories of power system stability

Practical power system stability is a single problem, where the complete system should be stable, regardless of the origin of disturbances. More often than not instabilities are a combination of different disturbances, for example a combined active and reactive power imbalance (a tripped large generator) or consecutive disturbances (a tripped line that activates protection systems of other devices).

Due to this stability problems are problems of high dimensionality and complexity. A classification of stability into categories aids to make simplifying assumptions while analyzing specific types of problems or identifying the key factors causing the instability. The classification of power system stability as proposed by the joint task force [13] is based on three considerations:

- *The physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed.*
- *The size of the disturbance considered which influences the method of calculation and prediction of stability.*
- *The devices, processes, and the time span that must be taken into consideration in order to assess stability.*

Figure 9 shows the resulting classification, differentiating categories and subcategories based on these considerations.

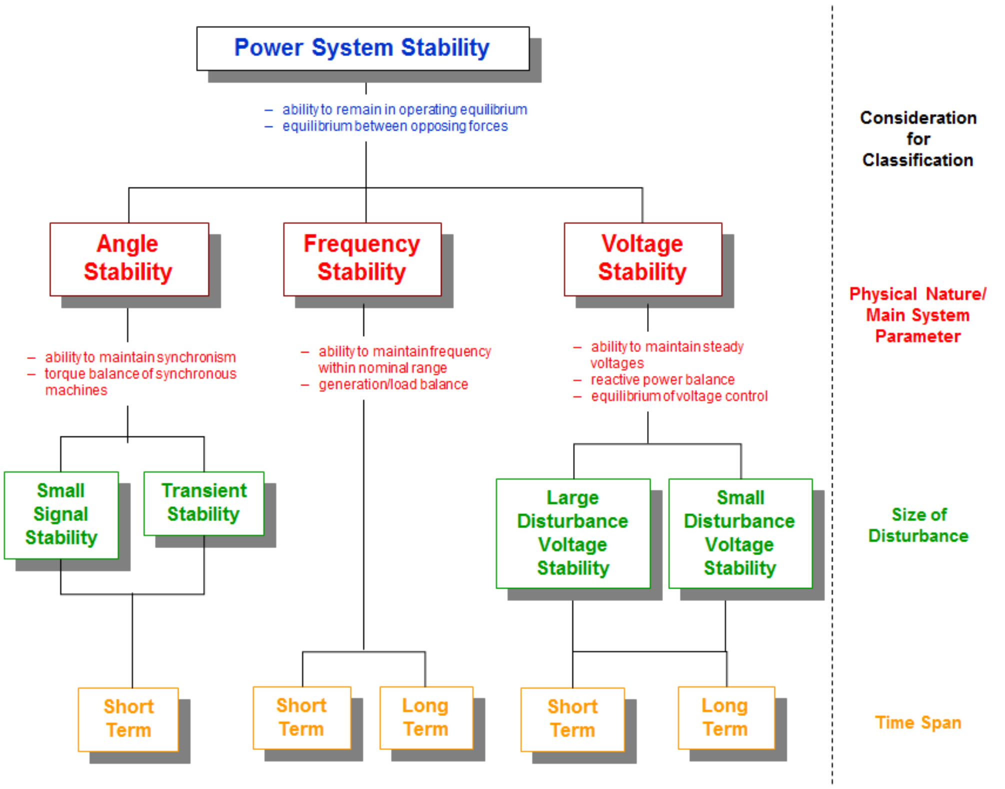

Figure 9: Classification of power system stability.

All three main categories will be briefly introduced, for the sake of completeness and to explain which elements are or are not important to this research. Since we will mainly focus on static voltage stability; this will be more extensively discussed in section 3.2. Further information about the other categories can be found in literature [16]-[18].

Angle stability

During normal operation the total load and total production in the system are balanced. If this balance is disturbed, the kinetic energy in the rotating parts of generators and other rotating machines acts as an energy buffer to overcome this imbalance. Rotor angle stability is the ability of synchronous machines of a power system to keep their synchronism after a disturbance.

There are two kinds of angle stability: Transient instability (or large-disturbance rotor angle instability) and small-disturbance (or small-signal) rotor angle stability. The first is concerned with local and substantial disturbances, which can cause generators to lose synchronism due to lack of synchronizing torque. The latter considers keeping synchronism under small disturbances, indicating sufficient damping of oscillations in regions close to the initial operating point.

Both kinds of angle stability have a timespan in the order of seconds. Therefore the transient behavior of generators should be known and simulations should be done in the time-domain. The analysis in this thesis uses algebraic power flow simulations from operating point to operating point, omitting the behavior in between. Therefore, our simulations give no information about angle stability.

Frequency stability

Whereas angle stability deals with local active power imbalances, frequency stability deals with global ones. When there occurs a large imbalance between the power fed into the system and consumed by the loads (and system losses), this will influence the frequency of the whole system.

For small frequency deviations, the frequency control of generators will regulate the active power output to bring back the frequency within acceptable borders. When deviations become larger, prolonged frequency deviations can cause generators to be disconnected, creating a downwards vicious circle. Instabilities caused by these phenomena are called frequency instability. Both short-term and long-term mechanisms are possible and control and protection characteristics also play an important role in preventing frequency instability.

The synchronous frequency area in Europe is much larger than the CWE-region introducing FBMC. This makes frequency stability a separate issue, concerning the complete synchronous continental Europe region, independent of the market coupling mechanisms used. Therefore, frequency stability is outside the scope of this thesis.

Voltage stability

Voltage stability deals with the ability of a power system to maintain voltages at all buses in the system after disturbances from a given initial operating condition. It depends on the ability to maintain or restore the balance between power demand and supply, both active power and reactive power.

Instability may occur as a progressive fall or rise of voltages at buses, which can lead to loss of load in an area or tripping of transmission lines and other equipment because of violating the equipment voltage bandwidth. When such instabilities occur in a sequence of events this could lead to cascading outages, blackout or abnormally low voltages in a part of the system. This is called a voltage collapse.

The main contributors for voltage instability usually are the loads. After a disturbance, the power consumed by the loads is restored by actions of motor slip adjustment, distribution voltage regulators, tap changing transformers or thermostats. This causes stress on the high-voltage network by increased reactive power consumption, consequently resulting in further voltage reduction. If loads automatically try to restore power consumption in this situation beyond the capability of the transmission network and connected generation, this could lead to a run-down situation and ultimately voltage instability.

In a high loading situation, when active and reactive power flows through the inductive reactances of the transmission network, it leads to a voltage drop between points. This limits the capability of the transmission network for power transfer and voltage support. In this case, reactive power should be supplied to the grid to maintain a stable reactive power balance. Voltage instability could occur when a disturbance increases reactive power demand beyond the capacity of available reactive power resources. For example if a generator hits its field or armature current capability limit and cannot increase reactive power production.

The opposite effect might occur as well in low-loading situations. If transmission networks operate below their surge impedance loading they behave in a capacitive manner. This is especially the case in networks with a lot of cables, which have much higher surge impedance loading and therefore behave capacitive in most cases. In this case voltage instability could be caused by overvoltages due to a lack of absorbing reactive power capabilities.

This becomes an increasing hazard for the Dutch grid as well due to a couple of developments. First, a growing transport capacity of the transmission network to facilitate large, long-distance power transfers (e.g. from German off-shore wind) results in more low-loading situations when there is no wind. Second, an increased production of renewable energy sources causes less conventional generators to be in service resulting in less reactive power control through generators. Last, high voltages in the networks of surrounding countries influence the Dutch grid voltages since they are highly meshed.

Voltage stability can be classified based on two parameters, the size of disturbances and the timeframe of stability problems. For the size of disturbances, the division is:

- *Large disturbance voltage stability* refers to the system stability in case of large disturbances like circuit contingencies, loss of generation or system faults. It is determined by the system characteristics, but also on the behavior of control and protection systems. To determine the large disturbance voltage stability, all effects influencing grid stability are taken into account, also manual remedial actions performed by the operators.
- *Small disturbance voltage stability* refers to the system stability in case of small grid changes like load changes or renewable energy source production fluctuations. This can be analyzed with linearized versions of the system equations and the sensitivity of the grid can be analyzed. Since this thesis focusses on larger disturbances and effects, this category is not taken into account.

Regarding the timeframe of stability problems, the division is:

- *Short-term voltage stability* involves the behavior of fast acting load components such as induction motors, electronically controlled load or HVDC converters. Time-domain simulations with appropriate component transient behavior are required to determine this category, similar to angle stability analysis. Since this research uses algebraic power flow simulations, no information is retrieved about short-term voltage stability.
- *Long-term voltage stability* involves equipment with slower reaction times, like tap changing transformers, reactive power compensation devices or generator current limiters. Stability is usually determined by the resulting outage of equipment, rather than the severity of the initial disturbance.

Instability occurs in several forms, either the post-contingency steady-state operating point is small-disturbance unstable, the long-term power equilibrium is lost (the network has to operate beyond its reactive power capabilities) or remedial actions are applied to late, resulting in lack of reaching a stable post-disturbance point.
This type of voltage stability can be investigated appropriately with static analysis to determine stability margins, identify stability influencing factors, to screen a wide range of system conditions or investigate a large number of scenarios [19]-[22].

For this thesis the main focus will be on long-term and large disturbance voltage stability. The contingencies will consist of outages of grid elements (performing N-1 analysis); this fits the large disturbance category. Also, a lot of different scenarios are considered to determine whether external constraints could be varied based on grid operating conditions. Within these scenarios, changing the operating points of tap changing transformers or reactive power compensation devices is allowed, fitting the long-term voltage stability category.

3.2 Static voltage stability analysis

Static voltage stability analysis uses steady-state snapshots of system conditions at various time frames along the time-domain trajectory to investigate voltage stability. Time derivatives of the state variables are assumed to be zero, and state variables take on values appropriate to the specific time frame. Consequently, the overall system equations reduce to purely algebraic equations allowing the use of static analysis techniques like load-flow solution software.

Stability can be determined in roughly two ways; by conventional power-flow programs for static analysis of voltage stability, computing PU and QU curves at selected load buses. Or, by linearized methods like V-Q sensitivity analysis or Q-V modal analysis that investigate the stability by analyzing the voltage behavior around the operating point. These methods will be explained in more detail in the next section.

Since all time derivatives are zero, the steady state situation of an operating point can be compared easily to given security requirements, as described in 3.3.3. This is also the case for differences between the pre-fault base case and post-fault contingency case. In this respect reference [18] states two important comments on the definition of power system stability which are also valid during this research:

> *It is not necessary that the system regains the same steady state operating equilibrium as prior to the disturbance. This would be the case when e.g. the disturbance has caused any power system component (line, generator, etc.) to trip. Voltages and power flows will not be the same after the disturbance in such a case. Most disturbances that are considered in stability analyses incur a change in system topology or structure. [18]*

and,

> *It is important that the final steady state operating equilibrium after the fault is steady state acceptable. Otherwise protections or control actions could introduce new disturbances that might influence the stability of the system. Acceptable operating conditions must be clearly defined for the power system under study. [18]*

3.2.1 Analysis methods static voltage stability

As described in the previous section, various methods to analyze a power system on voltage stability have been derived. The most important ones mentioned will be shortly described to verify whether they are usable for this research.

Loading margins based on PU & QU curves

One of the first methods of investigating voltage stability was based on PU curves or QU curves. These curves were made up of computing a large number of power flow solutions for a single bus and investigating the behavior of the voltage under changing power influences. Each bus is handled individually; this may distort the stability condition of the complete system. Divergence problems elsewhere in the system might prevent the curve to be finished completely. Also, a large number of curves might need to be created to obtain a complete system overview.

PU-curves (or nose curves) are used to analyze the relation between active power load and voltage for a certain bus. An example of a PU-curve is given in Figure 10. Although for each load with $P_{load} < P_{l,max}$ exist two operating point, only the upper one of the two is of interest (high voltages, lower losses). For $P_{load} > P_{l,max}$ no solutions exist, since this is no stable operating point. The load power margin between the operating point P_{load} and the voltage collapse operating point ($P_{l,max}$ is used as a voltage stability indicator.

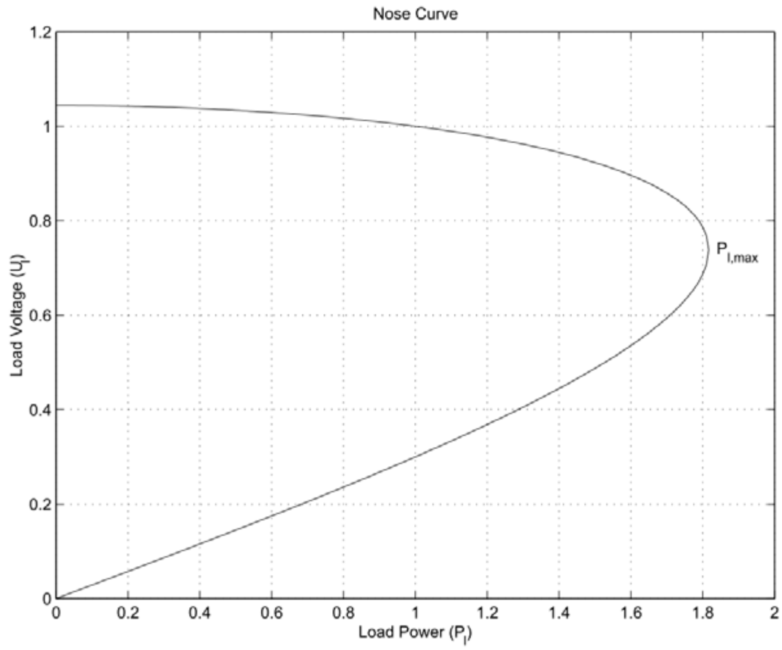

Figure 10: Example of a PU-curve. [18]

QU-curves are used to analyze the amount of reactive power necessary to provide to the network for a given load active power for different load voltages. An example of such a curve is given in Figure 11. In this case, the QU-curve is calculated for a load with unity power factor, this results in a $Q = 0$ at $P_{load} = 1\ p.u.$. Also, for voltages higher than approximately $0.6\ p.u.$ the derivative of the curve is positive, this indicates a stable operation as described in the next method. Sometimes the reactive power margin is used as a stability indicator. This is the MVAr distance from the operating point to the bottom of the QU-curve.

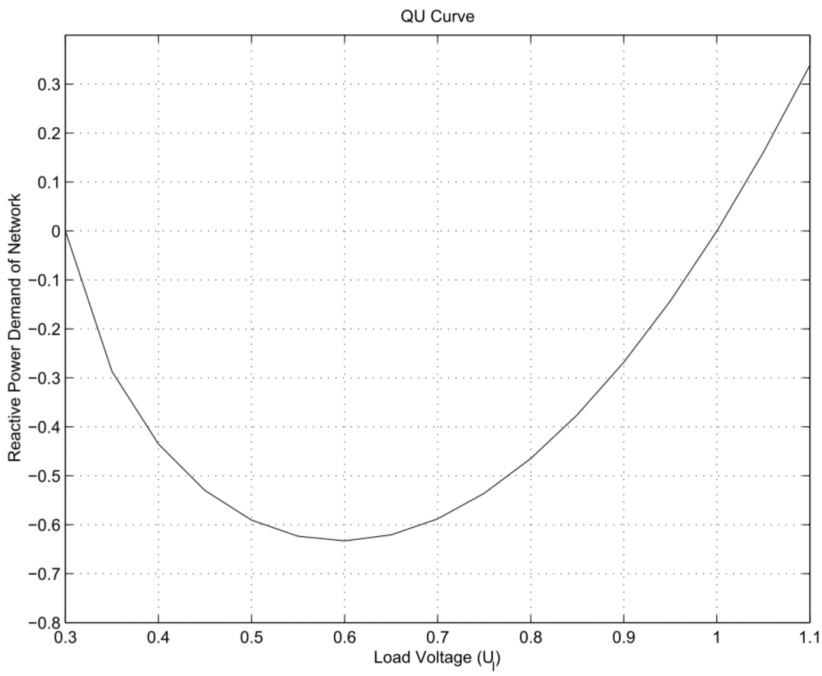

Figure 11: Example of a QU-curve. [18]

Voltage - reactive power sensitivity factor

The voltage sensitivity factor (VSF) is a much used indicator for voltage stability [18][23]. For a bus i, it is given as:

$$VSF_i = \frac{\Delta U_i}{\Delta Q_i}$$

The VSF determines the change in voltage magnitude in a given node as a consequence of a reactive power injection change in that node. The general assumption that a reactive power injection results in voltage increase leads to the stability criterion: $VSF_i > 0$. A VSF can be compared to a QU-curve as the derivative of the curve in a certain operating point.

The property of *voltage regularity* is also applicable for voltage sensitivity factors. This property states that it is reasonable to require an injection of reactive power in any node will not decrease the voltage in any node in the system.

It is possible to enlarge this method towards a complete system, as described in [17]. When this is done, the network constraints may be expressed in the following linearized form:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}$$

Where ΔP, ΔQ, $\Delta\theta$ and ΔV are the incremental changes in bus real power, bus reactive power injection, bus voltage angle and bus voltage magnitude. The elements of the Jacobian matrix give the sensitivity between power flow and bus voltage change.

System voltage stability is affected both by P and Q, which is also visible in the above equation. When P is held constant, the relation between Q and V can be analyzed. With $\Delta P = 0$, equation can be written as:

$$\Delta Q = J_r \Delta V \quad \text{or} \quad \Delta V = J_R^{-1} \Delta Q$$

Where $J_r = \left[J_{QV} - J_{Q\theta}\ J_{P\theta}^{-1}\ J_{PV}\right]$ is the reduced Jacobian matrix of the system. The inverse J_R^{-1} is the reduced V-Q Jacobian where each diagonal element is the V-Q sensitivity at the accompanying bus. This is analogous to the QU curve approach or the voltage sensitivity factor.

For both sensitivities holds the lower the sensitivity, the more stable the system. As stability decreases, the magnitude of the sensitivity increases towards infinity at the stability limit. A negative sensitivity represents an unstable operating point. The magnitudes of the sensitivity do not provide a direct measure for stability, since non-linear effects in the V-Q relationship between different operating situations have to be taken into account as well.

Q-V modal analysis

In addition to the above V-Q sensitivities, voltage stability characteristics of the system can also be identified by computing the eigenvalues and eigenvectors of the reduced Jacobian matrix J_R [17], in the form:

$$J_R = \xi \Lambda \eta \quad \text{or} \quad J_R^{-1} = \xi \Lambda^{-1} \eta$$

Where ξ is the right eigenvector matrix of J_R, Λ is the diagonal eigenvalue matrix of J_R and η is the left eigenvector matrix of J_R. This results in:

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \quad \text{or} \quad \Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q$$

Where ξ_i is the i^{th} column right eigenvector and η_i the i^{th} row left eigenvector of J_R. Each combination of ξ_i, η_i and λ_i represents the Q-V response of the i^{th} mode. Since $\xi^{-1} = \eta$ and with $v = \eta \Delta V$ being the vector of modal voltage variations and $q = \eta \Delta Q$ being the vector of modal reactive power variations, this also be written as:

$$\eta \Delta V = \Lambda^{-1} \eta \Delta Q \quad \text{or} \quad v = \Lambda^{-1} q$$

Λ^{-1} is a diagonal matrix with uncoupled first order equations, therefore the i^{th} modal voltage and the i^{th} modal reactive power variation the above equation can be written as:

$$v_i = \frac{1}{\lambda_i} q_i$$

If $\lambda_i > 0$ then v_i and q_i are in the same direction, the voltage regularity rule is valid and the system is voltage stable. The other way around, if $\lambda_i < 0$ voltage and reactive power are along opposite directions and the system is voltage unstable. In this case the magnitude of λ_i indicates the degree of stability of the i^{th} modal voltage. The smaller a positive λ_i is, the closer it is to instability. When $\lambda_i = 0$ a change in reactive power would result in an infinite voltage change, this is the point of voltage collapse.

The magnitude of the eigenvalues λ can provide a relative measure of the proximity to instability. Due to nonlinearity of the system they do not provide an absolute measure. If a megawatt distance to voltage instability is required, multiple load-flow solutions are necessary where the system is stressed incrementally until it becomes unstable. Complementary modal analysis can be applied to each step, to determine how stable the system is and big the next step size should be. At the voltage collapse point, modal analysis could help identifying the voltage stability critical areas or elements (these should have small λ's).

3.2.2 Shortcomings of existing methods

While all described methods have their advantages and disadvantages, there are a couple of characteristics which are unfavorable for this research. Also, adapting the methods to overcome these disadvantages is not always straightforward. The main disadvantages are: a linearized, bus-based or load-based approach.

Linearized systems are not feasible for a couple of reasons. First, the appearing disturbances will change the system topology and therefore the linearization will not be valid after the disturbance. Also, voltage control possibilities like tap-changing transformers or switched reactive power compensation devices will incur non-linear behavior. As a result, a method that allows large disturbances and stepwise control possibilities is more desirable.

Bus-based methods like PU/QU analysis or nodal voltage sensitivity factors provide the desired information, but are not desirable due to practical reasons. With hundreds of busses in the Dutch grid and many different scenarios these methods would result in immense amounts of data and the need for extensive automation. Due to this, a system-wide method is more desirable.

The last shortcoming to most of the current methods is the fact that the load is the main changing parameter. In this research, the main focus is on voltage stability due to import levels, which makes it desirable to have the import level being the main changing parameter.

Combined, these shortcomings make none of the analyzed methods completely suited for this research. To overcome these shortcomings, conventional power-flow solutions will be used within a scenario based analysis. This does provide a system-wide investigation with multiple scenario drivers and import level as the main changing parameter. To determine the robustness of the system, the base-case analysis will be combined with a contingency analysis.

3.3 Scenario based analysis

The static voltage stability analysis methods introduced in the previous sections are mainly linearized, bus-based or load-dependent. While in this research, the focus is on system wide and import dependent stability issues. Therefore, our approach will be based on a scenario analysis, investigating static voltage stability for all considered scenarios.

During the scenario analysis, using power-flow analysis, bus voltages at substations, equipment loadings and reactive power requirements will be investigated for a range of system operating conditions based on scenario drivers and import level. For any given study, the network configuration, load level, generation schedule and settings of voltage control devices are specified.

Scenarios will be analyzed on two different levels. First, a base-case analysis will be performed with full availability of the system, as described in section 3.3.1. Second, the scenario will be investigated on the robustness during disturbances by a contingency analysis. A large number of grid elements will be disconnected one by one, analyzing the effects this has on the system. The contingency analysis will be described in section 3.3.2.

To determine whether scenarios are acceptable or not the outcomes of the load flow simulations will be compared to the grid security requirements as stated by the Dutch regulator. An overview of these requirements will be given in section 3.3.3. Lastly, in section 3.3.4 a short introduction is given of the tools used to perform this scenario based analysis.

3.3.1 Base case analysis

The base case analysis considers normal system conditions. The main assumptions are a fully operating system (N-0) and all control actions have taken place. Therefore, the system is operating in a true steady-state condition. Consequently, the system can be compared with the security requirements as described in section 3.3.3.

During base case analysis, the system is represented by:

- Loads are represented by constant P and Q; since transformers towards the regional grid operators are not include in the model, tap-changer options of these transformers are not considered.
- Generator active power output is determined by the dispatch function. Reactive power output is determined by the voltage set point of the generator.
- The total system topology is available.
- All control actions are accounted for. This includes: reactive power compensation devices and transformer tap changer or phase shifter settings.

More information on the specifications, modelling considerations and capabilities of the model are described in chapter 4.

3.3.2 Contingency analysis

To analyze the robustness of a power system, performing a contingency analysis is a customary tool. During a contingency analysis, the impact throughout the grid of a failure of one (an N-1 situation) or more elements is analyzed. Different time periods after a contingency can be defined, based on modelling assumptions related to:

- **Loss of generation or load**
  When generation or load is lost during a contingency, which behavior does the model have and how does it compensate for the lost generation/load?
- **Generator Automatic Voltage Regulation (AVR)**

Is a generator AVR able to hold terminal voltages, and is this done within/outside reactive power capabilities?

- **Load behavior**
  Do loads vary as a function of bus voltage? Have distribution system transformer tap changers changed taps?
- **Reactive power compensation devices**
  Are capacitors/reactors switched on or off by voltage relays or operator actions?
- **Transformer under-load-tap-changers (ULTCs)**
  Are ULTCs on automatic control operated? This can be transformers between voltage levels within the transmission system or towards the distribution networks.
- **Phase shifters**
  Are phase shifter transformer angles changed?
- **Operator actions**
  Is the time period of the contingency long enough to give operators the opportunity to perform manual actions or find a new optimized operating point?

To determine the impact of a contingency a solved load-flow solution of a pre-fault situation is compared to one post-fault. Differences in voltage level or loading level are calculated, if the differences exceed requirements as stated in section 3.3.3, they are registered as violations.

3.3.3 Security requirements

To guarantee overall system security, operating economy and quality of supply, the power system has to maintain certain security requirements drawn up by the regulator. This applies to voltage quality, not only voltage levels should be kept within certain boundaries but also limited voltage steps are allowed. But also to power system security issues like for example the maximum loss of loads or generators or duration of black-outs are stated.

The security requirements applicable to the Dutch grid are stated in the 'Netcode Elektriciteit' [24] a document drawn up by the 'Autoriteit Consument en Markt', in line with the Elektriciteitswet 1998 [25]. Requirements on aspects like grid frequency, voltage dips, harmonics, asymmetry, outage size or outage duration are also stated in the 'Netcode'. To this thesis they are not relevant since the load-flow analysis performed does not take into account these aspects. To this thesis, the relevant requirements for the Dutch grid are:

Allowable nominal voltage bandwidth during N-0 and contingency situations

Slow voltage variations;

$U_n - 10\% < \boldsymbol{U} < U_n + 10\%$

With U is the operating voltage and U_n is the nominal voltage, in the Dutch AC-grid 110, 150, 220 or 380 kV. This should apply for 99,9% of the 10-minute average values of one week.

Fast voltage variations;

$\Delta U \leq 3\% \; of \; U_n$, during switching actions

$\Delta U \leq 3\% \; of \; U_n$, during outage of a power transformer, capacitor bank or shunt reactor

$\Delta U \leq 10\% \; of \; U_n$, during outage of a generator unit, large consumer (≥100 MW), substation bus bar or circuit.

With ΔU is the voltage difference between the pre-fault situation and post-fault situation and U_n is the nominal voltage. In specific situations exceptions could apply, but these will not be taken into account in this thesis.

And to a lesser extend:

Allowed nominal transport capacities during N-0 and contingency situations

Circuits and railsystems

$I \leq 100\% \, I_n, \; t \leq \infty,$

Power transformers

$I \leq 110\% \, I_n, \; t \leq \infty,$

$110\% \leq I \leq 110\% - 150\%, t \leq 1 \, hour$, maximum allowable current varies between equipment and situations.

With I is the operating current, I_n is the nominal current and t is the duration of the overloading. Again, in specific situations exceptions could apply, but these will not be taken into account in this thesis.

3.3.4 Tools used to model and analyze power systems

A multitude of tools can be used when analyzing power systems. The main tool will be a load-flow solving application. A programming tool can be used to automate certain tasks, to make sure they are executed in exactly the same structure for a lot of repetitions. Ancillary software like Excel or Notepad will be used to organize data, create result overviews or structurize input data. For this thesis, the two main tools used are:

PSS®E – Power Transmission System Planning Software

The most important piece of software used, since it solves the load-flow equations. For this thesis we have used PSS®E. A couple of advantages of PSS®E are:

- Fast solution of load flow equations compared to DIgSILENT PowerFactory, the other power system analysis software used within TenneT. Since the number of load-flow solutions that will have to be calculated is quite large, this brings down the computing time by a large amount (in the order of days).
- PSS®E has a very extensive Application Program Interface (API) using, among others, the Python programming language. This allows the simulations to be automated with relative ease and creates opportunities to partly automate the result analysis as well.

Downsides are:

- PSS®E has no extensive data management functions. Therefore, the automated scenario analysis will create a lot of different files and a clear file naming scheme is necessary.
- Bad graphic solution presentation. Although it is possible to create graphic grid representations, this function is slow and rigid. Therefore result analysis is mainly done numerical with overview files in Excel.

PSS®E is used in roughly two ways; first, the build-in graphic user interface (GUI) is used to improve the base case model. This only involved one model-file and all changes are made manually and in a sequential way. Once a suitable starting case is achieved (described in Chapter 4), this will serve as the basis of the automated scenario analysis (described in Chapter 5). In this second way of usage, PSS®E is mainly used via the API, bypassing the GUI. This way, the core load-flow calculation functionalities can be used in a function-like manner, operated from the main Python script.

Python

Python is an open-source programming language, used to automate the scenario creation and result analysis. It serves as the interface between input files, scenario creation, load-flow calculations and result processing. It also creates the simulation result overview files automatically. More about the automation of the scenario analysis can be found in Chapter 5.

Chapter 4

Grid model used for study

The results of a scenario analysis can only be as good as the starting case. Model information in the starting case will affect all scenarios originating from it. Therefore, a lot of effort has been put into creating an accurate and stable starting case.

This chapter will focus on the model and information used to create the starting case for the scenario analysis. First, the readily available models will be evaluated and a suitable model will be picked. Second, the incremental steps from rough information towards a finished starting case are described, so they can be repeated in the same manner if this might be necessary. Afterwards, the implemented voltage control possibilities in the model will be described. Last, some remarks will be made about the verification of the resulting model versus real-life expectations.

4.1 Evaluation of available models

A lot of different grid models are being used within TenneT and the international power system community. The available models are mostly optimized for a specific task but none are specifically focusing at static voltage stability regarding international trading or reactive power research. Therefore, an existing model had to be optimized for this task. A short description of the available models will be given, together with their advantages and disadvantages. Also, the model that is used as the base model for the analysis will be introduced.

Asset Management model

Within the Asset Management department of TenneT, a model in Powerfactory is used for all grid studies. A model containing information for dynamic studies is derived from this model as well. The main advantages of this model are the high level of detail and accuracy, and the fact it is commonly used within TenneT. Disadvantages are the lack of foreign networks and the fact it is built in Powerfactory, this requires a translation towards a PSS®E supported model format.

ENTSO-E reference model

Each half year, the ENTSO-E publishes a winter/summer reference model in the UCTE-model format [26]. This model contains network information of the complete synchronous continental Europe network for voltage levels of 110kV and higher. Also the parameters for transmission lines, transformers and other grid elements are included.

Main advantages of this model are the fact the complete European grid is included and its validity is agreed upon as a reference model for European wide studies. Also, the UCTE-format is widely supported, albeit the level of detail might be low.

SCADA EMS Snapshots

The SCADA EMS system the operator use to control the Dutch grid saves a snapshot of the grid each hour. These snapshots are used as a backup of the grid operating point at that specific moment. Although many snapshots are available, earlier attempts to determine the reactive power compensation needs based on snapshots have not been successful due to a lack of accuracy. Also, only the Dutch grid is included in the snapshots.

Model used to create the starting case

For the modelling of the final starting point, it decided to use the reference model as a basis and improve this with the more detailed information of the Asset Management model were necessary. With this approach, it is possible to combine the main advantages of the reference model, the complete European grid topology and widespread acceptance of its validity, but overcome its main downside, the lack of detail. By converting the reference model from the UCTE-format towards PSS®E's own model format, more comprehensive grid elements like shunts can easily be implemented.

4.2 Changes & improvements made to the model

The starting case used for this research is not the standard ENTSO-E reference model, but rather an improved and adjusted one. This section will explain which adaptations have been made and why these adaptations have been necessary.

4.2.1 The need for changes

To acquire a suitable starting case model the reference model has been changed on several elements. These changes are made for multiple reasons. First, the ENTSO-E reference model consists of the whole synchronous continental Europe network. This is needlessly large for this research and negatively influences the model stability. Therefore, the amount of countries included in the model is decreased.

Also, the ENTSO-E reference model uses the UCTE-format, this is converted to PSS®E's own model format to make better use of the built-in capabilities of PSS®E. For example, voltage control capabilities could be better utilized after this conversion. However, these extra capabilities also created the need to add additional grid elements and extended component information.

The unmodified reference model did not meet the demands to be a stable starting case for voltage analysis. The voltage profile in the Netherlands was not correct, modeling of voltage control resources was inadequate, element information was not accurate enough and overall stability was not sufficient. The changes described in the rest of this section have solved these problems.

4.2.2 Changed network size

The ENTSO-E reference model consists of the entire synchronous area of continental Europe. For the performed research, it is needless to include countries as far away from the Netherlands as Greece or Portugal. Additionally, model quality is varying throughout the whole area. This can influence the stability of the resulting model.

Flow-based market coupling only regards the Dutch-German, Dutch-Belgian, Belgian-French and German-French borders. Therefore, a part of the continental Europe grid could be removed without influencing the situation in the Dutch grid too much. This has led to a resizing of the model to include six countries: the Netherlands, Germany, Belgium, France, Switzerland and Denmark.

To remove all the unnecessary parts of the model, the following steps have been taken. First, a load-flow solution was performed for the entire region, after converting the UCTE-formatted source to the '.sav' format used by PSS®E.

With the second step, the unnecessary part of the network was removed, resulting in a model which only contained the desired countries. All countries inside the reference model are individually numbered and the separate networks are connected to each other via fictitious cross-border busses. Therefore it is possible to remove all busses belonging to one country at once.

The third step towards a resized model consisted of the removal of unnecessary busses left after the removal of the unnecessary parts of the network, so called 'grid islands'. After this step, only one large interconnected set of busses consisting of the six countries remains. To obtain this, all of the artificial cross-border busses that are not between or on the border of one of the six remaining countries are removed. Also, all busses or groups of busses not connected to the main network are removed.

The fourth step is used to make sure that the original border flow that existed between a country inside the main network and a removed outside country are staying intact. To achieve this, equivalent loads and generators are connected to the cross-border busses on the outside borders of the main island with the size of the calculated border flow. These generators and load are unchanged during the rest of the analysis.

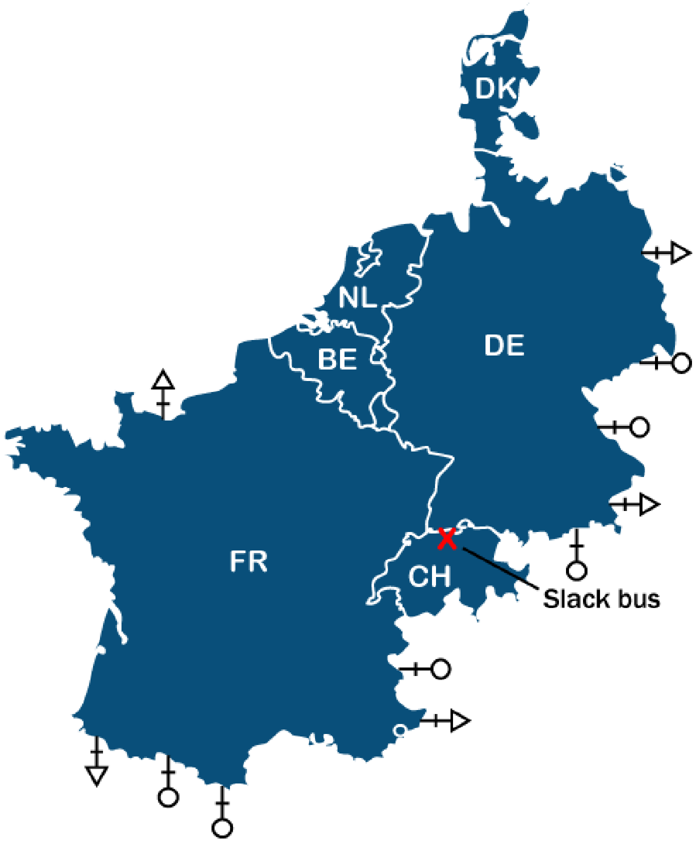

Figure 12: Overview of modelled region, location of slack bus & illustrative cross-border substitutes.

An extra mention has to be made regarding HVDC-links connecting the continental Europe region towards non-synchronous regions within Europe. These are already modelled in the original model as generators and loads connected to X-border busses. This has not changed with these steps. The HVDC-links to the Netherlands (NorNed and BritNed) will be set according to the scenario. Other HVDC-links will stay unadjusted throughout the analysis.

4.2.3 Additional network changes

To further improve the model, some additional changes have been made. The slack bus of the model is relocated from German Rommerskirchen (close to the Dutch border) to a Swiss nuclear power plant in Gösgen. This plant has a sufficiently large power capability to function as slack bus, adapting load-flow solution variances. Also, since Switzerland is being opposite to the Netherlands relative to the axis Germany/France, it is assumed to influence the Dutch grid the least.

Some substations are constructed with a lot of connections between busbars, especially in so-called 1½ breaker design substations or variants. These short, low-impedance connections caused problems for stable load-flow solutions. To avoid this, the short intermediate connections are converted to zero-impedance lines. PSS®E treats busses connected by zero-impedance lines as a one while solving the load-flow, making load-flow solution more stable. At the other hand, during contingency analysis, it is possible to separately fault busses, keeping contingency flexibility intact.

In the original reference model, the NorNed HVDC-cable was importing 700 MW. Since the NorNed operational setting is part of a scenario parameter, the starting case needed to be with the NorNed cable switched off. To avoid a large slack-bus load, Denmark's production was proportionally scaled up 700 MW to overcome the generation loss of NorNed.

4.2.4 Generator data

Although the reference model has a quite extensive set of generators, the completeness and accuracy of the information was not sufficient for this analysis. Problems for example were; missing generators, incorrect or missing power capabilities and incorrect or missing voltage set points. Therefore, all Dutch generators have been reviewed and adapted where necessary. Foreign generators are only adapted if there was a specific need to do so (i.e. to generate AC-transit flows, see Chapter 5).

To determine more accurate generator capabilities, information from various sources is compared to determine the best possible set of data. The main source of information however, was the information from TenneT's dynamical model, which is based on the Asset Management model information.

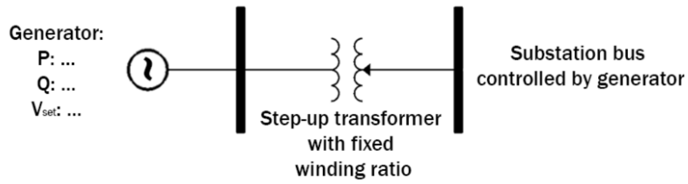

Figure 13: Generator as represented in the starting case.

The typical generator representation in the model is given in Figure 13. Voltage control of the generator is set to control the nearest substation. If a generator is in service, it will use its full reactive power bandwidth to control the voltage at this point. Due to this, correct reactive power bandwidth was an important improvement. Although step-up transformers between the generator and network are capable of controlling the voltage at the generator side by an on-load tap changer, this function is not used since this created convergency issues.

Appendix D.1 depicts the final set of Dutch generators and their capabilities, which are used throughout the analysis. All other Dutch generators that were included in the original reference model are put out-of-service. For foreign generators, information is used from the original reference model.

In the starting case, the cumulative active power production of the generators is scaled to 8100 MW. For generator scaling, the PSS®E function ECDI [27] is used, this function will be explained more extensively in section 5.1.5. Taking into account line losses and loads, this results in a starting case with approximately zero net position.

4.2.5 Load data

The load data included in the reference model is used as a basis for all scenarios. Within the UCTE-format load data can be properly described, consequently, modelling adaptations have not been necessary. Since the reference file originates from a momentary recording of the grid status (a snapshot), absolute load values are connected to reality.

In the starting case, the absolute load level of cumulative Dutch load is scaled to 8000 MW, representing a low-load scenario. All load scaling throughout the analysis is done with a PSS®E-activity SCAL [28]. Active power and reactive power are scaled proportionally; the power factor of the loads is not affected by scaling actions.

Due to these scaling actions, only the division of the cumulative load throughout the Netherlands and the power factor of a load is information used from the reference model. The cumulative level of the load in the Netherlands is based on a one-year analysis of the hourly cumulative load, described in Appendix D.2. The various load levels used will be described in more detail in Section 5.1.2.

4.2.7 Base case transit flow and loop flow removal

The desired net position in the Netherlands of zero MW in the starting case is achieved by load scaling and generator scaling. Despite this, cross-border flows on the interconnectors stayed apparent. This is caused by transit flows or loop flows. Transit flows are defined as power flows from country A to country B while passing other countries. In the Dutch case, for example, this is mainly power flow coming from Germany, going to Belgium or France. Loop flows on the other hand are defined as power flows coming from country A but also going to country A, while passing through country B. For example, flows from Germany entering the Netherlands in the north, but returning to Germany in the south of the Netherlands.

Figure 14: Illustrative transit flows (red arrow) and loop flows (yellow arrow).

In the starting case, these transit and loop flows are undesirable because they influence the individual line loading, and consequently influence reactive power behavior of the network. For the same reason, transit flows are implemented as an external scenario driver, described in section 5.1.3 & 5.1.4. To start with a neutral as possible starting case transit flows and loop flows are cancelled as much as possible. Transit flows are largely cancelled by redispatching groups of generators in the north west of Germany and France. Additionally, phase shifter transformer tap setting adjustments are used to cancel the last part of the transit flows.

4.2.8 Phase shifter transformers

A phase shifter transformer is used to control the flow of power by adjusting the phase angle. Within the CWE-region, they are mainly used to control the power flow on cross-border connections. Regarding the Dutch borders, PSTs are located at various locations depicted in Figure 15, their specifications are described in Table 1. More information on the technical workings of a phase shifter transformer and implementation in the Dutch grid can be found in [29].

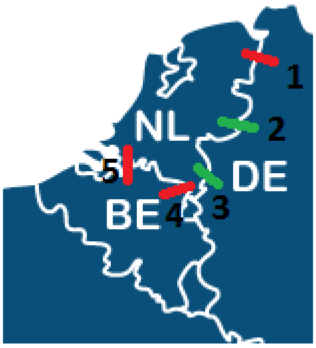

Figure 15: Location of PSTs on Dutch borders.

	Border:	PSTs:	Angle Range:	
1	Meeden – Diele	2x 1000 MVA	+40.0°	-40.0°
2	Hengelo – Gronau	No PSTs	-	-
3	Maasbracht - Rommerskirchen	No PSTs	-	-
4	Maasbracht – van Eyk	2x 1400 MVA	+24.5°	-24.5°
5	Borselle/Geertruidenberg - Zandvliet	1x 1400 MVA	+24.5°	-24.5°

Table 1: Specifications of the PSTs on the Dutch borders.

The ENTSO-E reference model has correctly modelled phase-shifter transformers included, but the automatic flow control settings had to be enabled. The automatic flow control adjusts the tap positions and thereby the winding angle, to reach the desired flow. This is used for the cancellation of the last part of the AC-transit flow through the Netherlands in the starting case. In this case, all cross-border flow set points were set to zero, to determine three sets of PST angles for the various load levels, the result depicted in Table 2.

Borders		LOW-LOAD			MID-LOAD			HIGH-LOAD		
		MW	MVAr	PST angle (degree)	MW	MVAr	PST angle (degree)	MW	MVAr	PST angle (degree)
Meeden	Diele	-1.1	-79.2	-0.59	-1	-140.5	3.97	-0.9	-136.6	5.2
Meeden	Diele	-1.1	-79.3	-0.59	-1	-140.5	3.97	-0.9	-136.7	5.2
Hengelo	Gronau	-0.3	40.5	--	36.6	-9	--	66.5	-36	--
Hengelo	Gronau	1.1	40.7	--	38.2	-8.7	--	68.4	-35.5	--
Maasbracht	Siersdorf	136.7	-39	--	74.7	-81.5	--	27.7	-114.7	--
Maasbracht	Rommerskirchen	-165.9	-68.8	--	-211.2	-100.9	--	-245.8	-126.1	--
Borselle	Zandvliet	453.7	-68.8	15.21	603.5	-174.8	16.51	572.3	-144.7	16.4
Geertruidenberg	Zandvliet	-449.2	113.9	*	-597.3	190	*	-567.3	149.7	*
Maasbracht	Van Eyck	-0.4	22.4	1.48	-0.4	0.2	0.97	-0.3	-17.6	0.58
Maasbracht	Van Eyck	4.3	157.1	13.33	3.8	153	12.89	3.6	141.7	12.53
Total border flow		-22.2	39.5	--	-54.1	-312.7	--	-76.7	-456.5	--
NL-DE flow		-30.6	-185.1	--	-63.7	-481.1	--	-85	-585.6	--
NL-BE flow		8.4	224.6	--	9.6	168.4	--	8.3	129.1	--

Table 2: Cross-border flows and PST-settings for zero transit-flow scenarios.

Table 2 shows two other remarkable effects. On the German-Dutch border, only the Meeden-Diele cross-border connection power flow can be controlled since this is the only German-Dutch connection that has a PST installed. This results in some remaining cross-border flows on the other two connections that cannot be controlled. Also, on the Zandvliet Belgian-Dutch cross-border connection a loop flow remains active. This is due to the PST location in Zandvliet, as depicted in Figure 16.

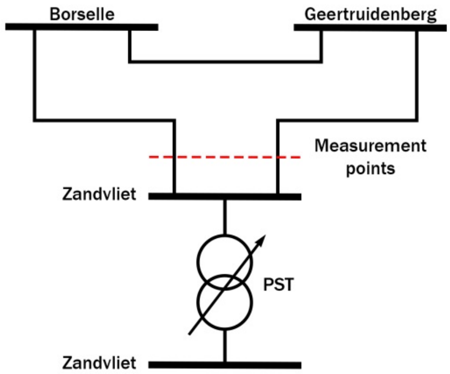

Figure 16: Grid lay-out at Zandvliet-Borselle-Geertruidenberg triangle. Since the phase shifter transformer cannot control the flows at the measurement point side of the busbar, a loop flow keeps existing.

The automatic flow control is also used to distribute power flows, to achieve an equal distribution of power flows over all German-Dutch cross-border connections. This is also done to prevent overloading on the Meeden-Diele PSTs, which 1000 MVA rating is quite limiting in certain scenarios. Using PSS®E's automatic flow control it is possible to mimic this operator behavior. Using the following formula, the desired cross border flow of the Meeden-Diele PSTs is determined:

$$Single\ circuit\ cross\ border\ flow = (\,Transit\ flow_{DE-NL} + \frac{2}{3} * Net\ position\,)/6$$

In this formula, both transit flow and net position are scenario dependent values. The resulting desired cross border flow is used as flow set point of the controllers of the Meeden-Diele PSTs. Because of the transport capacity limit, this value is limited to maximal 1000 MW.

4.3 Voltage control possibilities in the model

In real life, one of the tasks of the power system operators is to maintain a desired voltage profile throughout the grid. With resources like reactors, capacitors, tap-changers or generator voltage controllers they can control the voltage at specific points by injecting or absorbing reactive power and changing transformer winding ratios. Operators can make and activate these decisions manually, based on operator experience, a process this research tried to recreate with the voltage control process described in this section.

4.3.1 Voltage control process

During normal operation, operators have sufficient time to optimize the grid operating point. Therefore, we assume the usage of voltage control possibilities will be the most efficient as possible. This is the starting point of the base case simulations in this research to investigate the maximal possibilities of the grid regarding static voltage stability in this optimal situation.

In contingency situations however, the main focus of this research is in the period directly after the contingency and before operators can operate the voltage control devices. This gives an indication how severe the contingency situation is. Therefore, in this research the usage of voltage control devices in the post-contingency situation will be identical to the pre-contingency situation. Only automatic voltage control of the generators will change settings, because this is done automatically.

There are three main methods of voltage control implemented in the process. The first are voltage controlled shunt devices, reactors and capacitors that absorb reactive power from or deliver reactive power to the grid. The second are tap-changers on distribution transformers that change the voltage ratio between the high and low voltage side. The third are specific voltage set points for generators voltage controllers. All three will be discussed in more detail in the upcoming paragraphs.

Since all three methods use automatic control processes, an important aspect was preventing counteractive measures. To avoid this as much as possible, a specific load-flow solving sequence is used. First, the control devices will be set to a load-level specific default setting and the load-flow will be solved without changing them to obtain a rough approximation. Second, two solving sequences will be performed with only the shunt devices active or only the tap changers active. Last a final solving sequence will be performed with both the shunt devices and tap changers active to correct for the last contradictions. Generator voltage set points will be taken into account each solving iteration; therefore no special attention is needed. More detailed description of the implementation of this method can be found in Chapter 5.2.

4.3.2 Generator voltage set points

Most generators are equipped with automatic voltage regulators (AVR). The AVR actively controls the output voltage of the generators. This can be used to reach a desired voltage at the generators point of common coupling, but also to control the voltage in a nearby substation. The last method is mainly used in this research, with generators given a voltage set point for a nearby substation. An overview of these set points is given in Appendix D.1.

Only in-service generators control their voltage set point. This is important because the number of in-service generators is expected to influence voltage stability. Whether a generator is active and at which active power level is depending on the scenario. Reactive power level of the generator is depending on the voltage set point given and the voltage at that specific bus. If the reactive power capabilities are insufficient to control the voltage to the set level, the generator will produce or absorb the maximal amount of reactive power possible. During the load-flow solution, the reactive power level is automatically determined. Therefore, no specific solving considerations are necessary.

4.3.3 Switched shunts

To control reactive power, reactive power compensation devices are installed in the Dutch grid. In case of static voltage control, they are an important resource available to the operators to control the voltage throughout the grid.

Different types of compensation devices exist. In the Dutch grid, only relatively simple switchable reactors and capacitors are installed. They can only deliver static or passive voltage control. Since this analysis focusses on static voltage stability in the Dutch grid only, this is no limitation for this research.

Reactive power compensation devices can be installed in several ways. In the Netherlands reactors are at this moment connected to the tertiary winding of a transformer. This can either be a 380kV/220kV/50kV or a 380kV/150kV/50kV transformer. Devices can also be connected directly to a busbar, this is done with capacitors and will be done in future projects with reactors as well due to a limited number of transformers.

In Dutch substations, it is common to have multiple transformers with shunts attached to its tertiary winding or multiple blocks of capacitors, as depicted in Figure 17. In real-life, operators can switch them on one-by-one, since they are all separately switchable. This results in the ability to stepwise increase or decrease the reactive power in steps the size of the corresponding shunt.

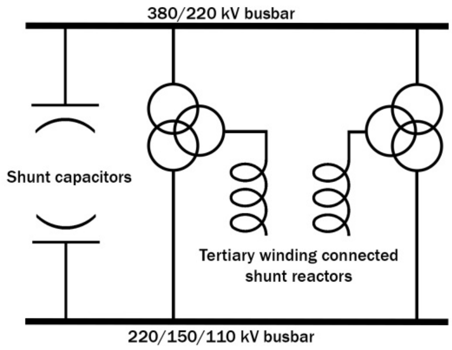

Figure 17: Real-life connection methods of compensation devices. Capacitors are directly connected to the substation busbar. Reactors are connected to the tertiary winding of transformers.

Reactive power compensation devices like reactors and capacitors are not supported in the UCTE-format [30]. As a work-around, the shunt devices are modelled as loads in the reference model. They can be identified by having zero active power but a fixed non-zero reactive power. A downside to this method is the lacking voltage dependency of reactive power injection. In reality, the actual compensation capability of shunt devices is dependent on the actual voltage. The included 380kV and 220kV shunts in the reference model are put out-of-service, since they are replaced by manually added shunts.

PSS®E's model format does support switched shunts with automatic voltage control. This function is used to model the compensation devices in the 380kV and 220kV networks. Although it is possible to create separate switched shunts connected to each tertiary winding like in reality, this proved to be undesirable because of conflicting voltage control behavior. With similar voltage bandwidths all devices at the same substation switched at the same moment, creating an all on/all off setting only.

To avoid this, all devices in a substation of the same type are implemented in the model as one switchable shunt device with multiple blocks. This way, the voltage control of this aggregate device can switch the blocks one-by-one, mimicking the behavior of an operator. Only downside is the changed connection point, directly to a busbar instead of to a tertiary winding of a transformer. This aggregate connection method is schematically depicted in Figure 18. Appendix D.3 contains a table of the reactive power compensation devices implemented in the model.

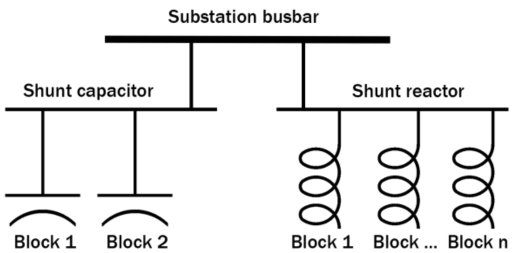

Figure 18: Implementation schematic of aggregated shunt devices.

4.3.4 Tap changer transformers

The power transformers in the Dutch system are equipped with tap changers. Tap changers are used to change the winding ratio between the primary and secondary side of the transformer. By changing the tap changer ratios the operators can change the voltage level at one side respective to the other. In this analysis, the same behavior is implemented with automatic voltage control by PSS®E.

Most of the power transformers in the Dutch grid are three winding models. Three winding transformers are not supported in the UCTE-format, but star-delta transformations are used to implement each winding as a separate two-winding transformer. The resulting ‘primary’ winding is at the high voltage level and contains the tap changer. The ‘secondary’ winding has a fixed ratio between the high and middle voltage level. The ‘tertiary’ winding has a fixed ratio as well, but due to the relocation of shunt devices, the tertiary windings are not used in this analysis. The resulting transformer model is depicted in Figure 19.

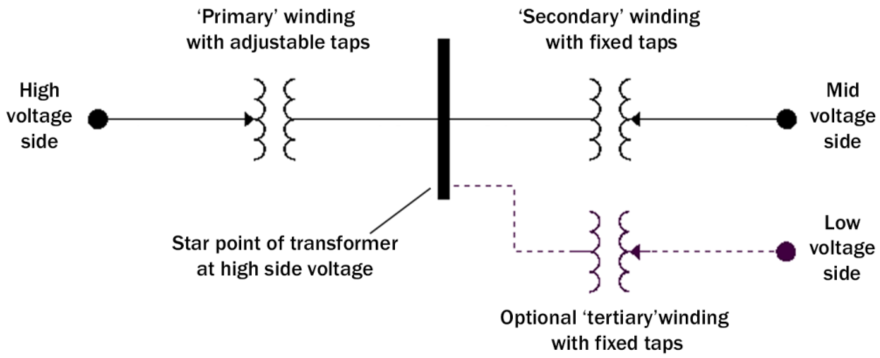

Figure 19: Schematic implementation of two- and three- winding transformers.

The 380kV and 220kV networks are linked with six 380kV/220kV transformers, three in substation Ens, two in substation Eemshaven and one in substation Meeden. All are stepwise controlling the voltage level at the 220kV side of the transformer. Their voltage control range is between 1.02 p.u. and 1.06 p.u..

All 380kV/150kV or 220kV/110kV transformers are controlling the secondary side between a 1.02-1.06 p.u. range. Transformers between the 150kV/110kV network and lower voltage levels are not modelled. Connections of regional network operators are modelled as loads connected with the 150kv/110kV substations.

4.4 Verification of the resulting model

The original ENTSO-E reference model did not suffice for this analysis. To improve the models usability, a lot of improvements have been described in this chapter. In this section, the original and improved model will be compared. Also, we will elaborate on the possibilities to verify the resulting model to reality.

One of the main issues in the original model was the lacking voltage control possibilities. This resulted in unrealistically high and low voltages throughout the network. By improving, enabling or adding the voltage control resources in the model, an improved voltage profile within the Netherlands has been achieved. An overview of the spread in original and final voltages is given in Figure 20.

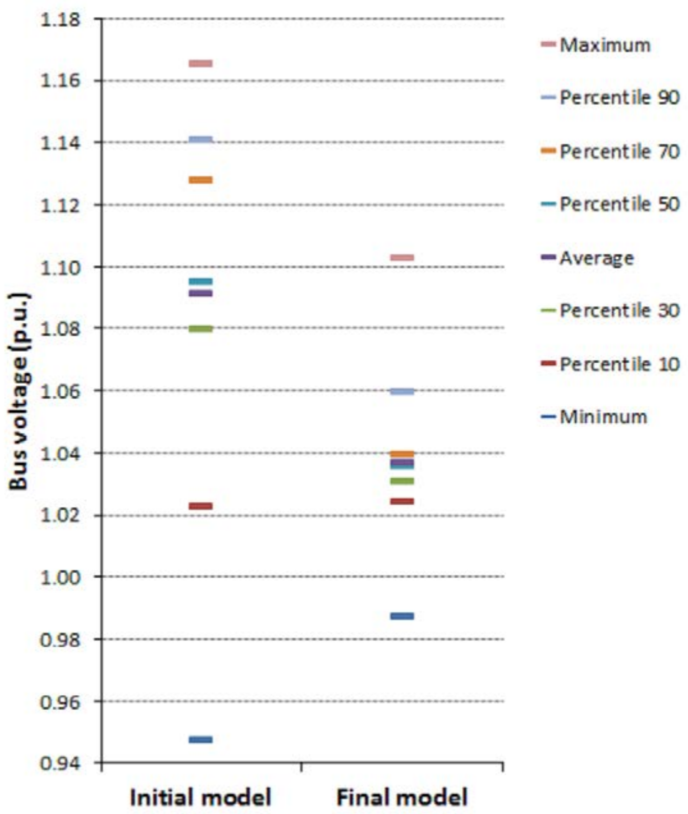

Figure 20: Substation bus voltage comparison between the unmodified ENTSO-E reference model and the final starting case of the scenario based analysis.

The final model shows a substation voltage division with most of the substation voltages in the range of 1.02 - 1.06 p.u.. Some extremes still exist, but these are mainly connected to fictitious star point busses (see Figure 19) or generator busses. This is big improvement compared to the original model, which had substation voltages ranging from below 1.00 p.u. till as high as 1.15 p.u..

The final voltage profile is in line with operator experiences in the real network. Similar to reality, voltages in the north of the Netherlands are a bit higher than the rest of the network. All voltages are in a range of around 1.02 - 1.08 p.u., a range in line with operator experience. Also, the grid behaved in line with real grid behavior when generator or shunt settings were manually adjusted.

Verification of the resulting model with a snapshot of a real grid situation has not been possible due to a couple of reasons. First, the final model has a starting case of zero net position and low-load. A real situation with this grid operating point hardly ever occurs. If this would have occurred, grid topology, generator set points and other grid elements should have been exactly the same before a realistic comparison is possible. Also, the recorded snapshots itself has a relatively big fault margin; therefore a snapshot does not contain a 100% correct representation of the grid. Finally, the advantage of a full verification did not outweigh the amount of uncertainties involved and expected amount of work it would take.

In the end, it is decide to accept the fact verification with a real grid situation was not possible. The fact the model behaved in line with real grid behavior and the voltage profile is in line with operator experience are considered sufficient to use this as a final starting case for the scenario based analysis.

Chapter 5

Scenario based static voltage stability study

As introduced in Chapter 3.3, a scenario based analysis will be used to analyze voltage stability in the Dutch grid. This way, the large variation of possible grid operating points can be investigated with a structured and reproducible method. Also, the cause of voltage stability problems can be accounted to a specific influence.

Scenario drivers will be used to define the scenarios. A scenario driver represents an influence on the Dutch grid that could influence voltage stability. Six scenario drivers have been defined; load level, net position, AC-transit, DC-transit, generator location and border voltage. These drivers will be described in more detail in the next section. A single scenario will always contain one setting of a scenario driver, therefore a scenario can be indicated as;

$$Scenario\ x \begin{pmatrix} Net\ position(x) \\ Load\ level(x) \\ AC-transit(x) \\ DC-transit(x) \\ Generator\ location(x) \\ Border\ voltage(x) \end{pmatrix}$$

An automated process will be used to ensure that each scenario is generated in the same manner. A script has been developed which combines the starting case model described in Chapter 4 with all the scenario drivers described in the next section. This results in a dataset of scenarios which will serve as the basis for the result analysis of Chapter 6. The automated creation of scenarios will be described in Chapter 5.2.

Complementary to the dataset of scenarios, a couple of tools have been made to ease the analysis of results. These results overview tools are created simultaneously with the scenario dataset. The resulting tools will be described in Chapter 5.3.

5.1 Scenario drivers

The scenario drivers used in this analysis can be divided in three categories; internal, external and extreme scenario drivers. The internal scenario drivers are based on effects that occur internally, in this case the load level and net position of the Dutch network. Both influence the operating point in the network with a source inside the same network. Also, they are always apparent; a grid operating point will always have a certain amount of load or a net position (even in the unrealistic case of a zero setting).

The external scenario drivers are based on phenomena taking place outside and independent of the Dutch network, whilst still influencing the grid operating point of the Dutch network. In this analysis, two sources of transit flows are considered. Transit flows caused by power flows over AC-interconnectors and transit flows caused by the HVDC-interconnectors connected to the Dutch grid.

Last, extreme scenario drivers are added to the scenario analysis. These scenario drivers are not so much 'realistically' occurring phenomena, but more focused at investigating the stability of the grid while taken to a hypothetical extreme operating point. The first driver is focusing on the influence of generator location on the voltage stability; the second focusses on the effect of varying border voltages.

In this section, the focus will be on the conceptual description of the driver, the frequency these effects will occur and the implementation method in the model. The expected influences of a scenario driver will be introduced in Chapter 6, after which the results of the analysis will be used to verify if these expectations hold.

5.1.1 Net position

Changing net position is the main scenario driver of this research. At this moment, the Dutch external constraints are based on net positions which are regarded as the maximal net positions possible whilst safeguarding grid stability. This will be the case with scenario-based external constraints as well; therefore the net position stays the most important scenario driver.

At this moment, the maximal net position allowed by TenneT is 4250 MW, regardless whether this is import or export. Driven by low German energy prices, scenarios with an import between 2 to 4 GW are the most common grid situations [31].

The net position directly relates to the amount of power import or export the Netherlands has at a certain moment, as stated in the following formula:

$$Net\ position_{NL} = Total\ exchange_{NL-DE} + Total\ exchange_{NL-BE}$$

In this case, export flows or export net positions are positive values and import flows or import net positions are negative values. From a generation and load balance point-of-view, the net position can also be calculated with:

$$Net\ position_{NL} = Total\ generation_{NL} - (Total\ load_{NL} + Line\ losses_{NL})$$

This approach is used to implement net position as a scenario driver. The total generation in the Netherlands is varied using PSS®E's economic dispatch function. This way, a generation deficit is created and the power balance is restored by increased import. Total generation in Germany, France and Belgium is proportionally scaled with the same amount, to maintain the same total generation of the whole network and avoid a heavy slack node loading.

$$\Delta\ Generation_{NL} + \Delta\ Generation_{FR,BE,DE} = 0$$

In this research eight different net positions will be investigated for each scenario, starting with a 0 GW net position (no import/export) towards a -7 GW net position (large import). Export situations are not investigated; in these situations the number of in-service generators will be large and a lack of voltage stability resources is less likely compared to import situations.

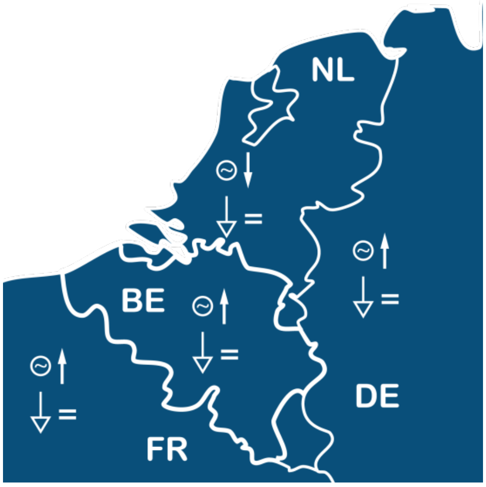

Figure 21: The net position of the Netherlands is set by varying the generator production inside and outside the Netherlands.

5.1.2 Load level

The load level of an operating point has influence on various parameters that determine voltage stability. It influences line loading and therefore reactive power behavior of connections. But also the number of in-service generators will increase with a higher loading level (assuming a stable net position), which will increase reactive power compensation resources. Therefore, load level is included as a scenario driver in this research.

To determine the absolute level of the load, an analysis of the Dutch load has been made, added in Appendix D.2. This contains all hourly load levels between the start of October 2013 and the end of September 2014. Three load level divisions have been made, one for the total set of loads, one for loads in peak hours (8:00hr-20:00hr) and one for loads in off-peak hours (20:00hr-8:00hr).

Low-load is set at 8 GW, this is at the 25%/75% point of all load point and at 50%/50% level of the off-peak loads. Medium-load is set at 10 GW, this roughly 50%/50% of the total load division. High-load is set at 12 GW, this is a rather extreme load level setting on the 90%/10% border of all load levels.

The loads in the Dutch grid are scaled using the build-in scaling functions of PSS®E. This function proportionally scales all loads within the Netherlands towards the desired cumulative load level. Active power and reactive power are scaled proportionally; the power factor of the load is not adjusted.

A varying load level also has an effect on the cumulative production of the generators. The total generation of the Dutch generators is given by:

$$Total\ generation_{NL} = Load\ level_{NL} + Line\ losses_{NL} + Net\ position_{NL}$$

Where, line losses are roughly estimated at 100 MW for each scenario and the net position is scenario dependent. For example, in a low-load and zero net position scenario, this would result in a generator set point of 8.1 GW (8 GW of load and 0.1 GW of line losses). Generators settings or load levels in the rest of the network are not affected by a changed load level.

Figure 22: Different load levels in the Netherlands are created by proportionally scaling the loads towards a new cumulative load level.

5.1.3 AC-transit

As described in section 4.2.7 transit flows are power flows from country A to country B while passing other countries. Although transit flows do not change the net position, generator level or load level of the intermediate country, it does induce additional line loading in the intermediate country. This influences the grid operating point in the intermediate country and therefore AC transit flows are included as an external scenario driver. These transit flows are called AC-transit flows because they are originating from AC cross-border connections, opposed to the HVDC originating transit flows described in the next section.

In the Dutch case, the most occurring AC transit flows are originating from German-Belgian or German-French power flows. Therefore, only north-south transit flows are implemented, with a power flow level of 2 GW and 4 GW. A schematic overview of AC-transit flows is given in Figure 23.

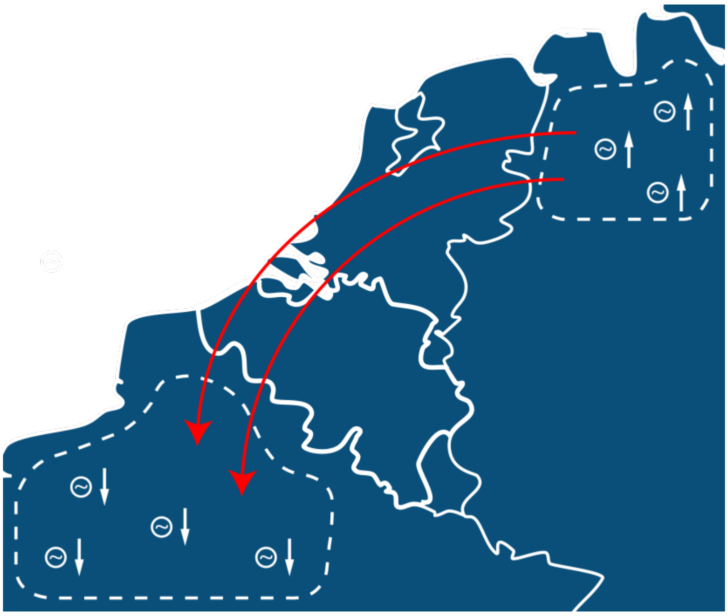

Figure 23: Generation of an AC-transit flow through the Netherlands by redispatching generation from the Northwest of France to the Northwest of Germany.

To create the AC-transit flow, generation is redispatched from a set of generators in the Northwest of France to a set of generators in the Northwest of Germany. This creates a generation deficit in the

Northwest of France, and a generation surplus in the Northwest of Germany, inducing additional power flows in the system. It results in an additional import power flow on the Dutch-German border and an export power flow of the same level on the Dutch-Belgian border. Some examples of AC-transit situations are given in Table 3, the sets of generators are included in Appendix D.1.

Borders		0 GW Transit flow		2 GW Transit flow		4 GW Transit flow	
		MW	MVAr	MW	MVAr	MW	MVAr
Meeden	Diele	-0.6	-79.3	-352.6	-64.9	-698.9	-30.8
Meeden	Diele	-0.6	-79.3	-352.9	-64.9	-699.3	-30.8
Hengelo	Gronau	14.2	32.3	-363	60.7	-723.1	94.7
Hengelo	Gronau	15.7	32.4	-361.6	60.9	-721.8	94.7
Maasbracht	Siersdorf	122.4	-52.3	-79.7	-22.0	-263.3	-221.3
Maasbracht	Rommerskirchen	-172.6	-78.8	-450.3	-55.3	-703.1	-229.2
Borselle	Zandvliet	452.6	-65.7	727.5	-65.7	991.1	427.9
Geertruidenberg	Zandvliet	-451.3	112.5	100.9	107.1	633.3	388.3
Maasbracht	Van Eyck	-3.2	153.2	504.8	142.3	1019.2	538.0
Maasbracht	Van Eyck	1.3	15.6	620	7.1	1125	334.6
Total border flow		**-22.1**	-9.4	**-6.9**	105.3	**-40.9**	1366.1
NL-DE flow		**-21.5**	-225.0	**-1960.1**	-85.5	**-3809.5**	-322.7
NL-BE flow		**-0.6**	215.6	**1953.2**	190.8	**3768.6**	1688.8

Table 3: AC-transit flows in a 0/2/4 GW transit flow scenario. Other scenario drivers are set at low-load, zero net position, merit order generator schedules, no DC-transit and normal border voltage.

5.1.4 DC-transit

DC-transit flows are comparable with AC-transit flows, but in this case they do not originate from AC interconnectors, but from HVDC interconnectors. The combination of the 700MW NorNed interconnector and the 1000MW BritNed interconnector are modelled to cause a transit flow between the Eemshaven region and the Maasvlakte region. This situation is illustrated in Figure 24.

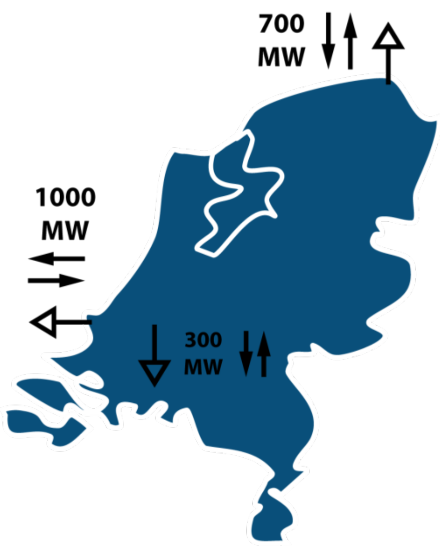

Figure 24: Overview of implementation method for DC-transit flows. BritNed and NorNed can be used in two directions and a cumulative Dutch load adjustment is made to overcome the nominal power difference of the HVDC-interconnectors.

This transit flow is either in north-south direction or south-north direction, dependent on the HVDC operating points (as depicted in Table 4). In reality, the north-south DC-transit flow is the most common due to cheap hydropower in Norway and high energy prices in the UK.

HVDC-interconnectors are modelled as loads in the reference model, which is sufficient for this investigation. Since the NorNed and BritNed cable do not have the same transport capacity, the Dutch load level is adjusted by 300 MW to avoid net position differences.

HVDC interconnector settings	No DC-transit		N-S DC Transit		S-N DC Transit	
	MW	MVAr	MW	MVAr	MW	MVAr
NorNed	0	0	-700	175	700	175
BritNed	0	0	1000	-75	-1000	-75
Load adjustment	0	0	-300	--	300	--

Table 4: HVDC-interconnector settings for the DC-transit situations. Since the interconnectors are modelled as a load, a negative value indicates import and a positive value export of energy.

5.1.5 Generator location

In the Netherlands, generation is more and more concentrated on a couple of locations. As a result, large power plants are concentrated in the Maasvlakte area and Eemshaven area. This could create a situation where voltage support resources are only available at those areas, while the rest of the network can only depend on shunt resources.

To investigate the effect of these extreme situations of generation concentration on the voltage stability, the generator location scenario driver is included. The possible settings of this driver are: a 'neutral' setting with generator division based on historic operating hours, an Eemshaven concentrated setting with generators concentrated in the north of the Netherlands and a Maasvlakte concentrated setting with generators concentrated in the southwest of the Netherlands.

The 'neutral' setting of this scenario is based on historic operating hours of the Dutch generators. Over a six-month period, the operating hours of the Dutch generators are determined. Generator priorities are based on the amount of operating hours. Generators with the highest amount of operating hours received the lowest priority number, this means they will be in service most of the time.

Figure 25: Overview of generation location extreme settings. Priority regions of Maasvlakte (left) generation division and Eemshaven (right) generation division.

The two 'extreme' settings of this scenario driver do not have a connection with realistic operating hours. They are included to investigate the impact of the hypothetical situations with generation concentrated at specific point in the grid.

The center points of these settings are the Maasvlakte and the Eemshaven. The generators in these locations receive the lowest priority. Several priority rings are created around the center points, to ensure the total generator capacity is large enough compared to the load. The more distanced from the center point, the higher the priority. This results in a set of in-service generators which is always as concentrated around the center points as possible, schematically depicted in Figure 25.

To implement the scenario driver in the automated scenario creation, the economic dispatch function (ECDI) of PSS®E is used. This function determines the in-service generators based on priority numbers. It will put generators in-service, starting with the lowest priorities, until a given production level is reached. The priority numbers for each generation pattern is given in Appendix D.1.

5.1.6 Border voltage

The Dutch network is relatively small, strongly meshed and has a large amount of cross-border transport capacity. Therefore, the other parts of the synchronous European network influence the grid operating point in the Dutch grid quite heavily. This is especially true for nearby networks like the German and Belgian one. Although agreements have been made on the grid condition of the cross-border connections, the difference between the maximal and minimal settings is significant. This scenario driver is included to investigate the sensitivity of the Dutch grid to changes of the voltages at the border.

Figure 26: Border generator setup for forced border voltages.

Three border voltage situations are considered. The border voltages in the 'neutral' situation are determined by the outcomes of the load-flow solution. No specific border voltage is forced on the grid. Both of the 'forced' border voltage settings use generators to control the voltage at the border, with a voltage set point of 1.0 p.u. for a low border voltage situation and 1.1 p.u. for a high border voltage situation.

At each substation directly across the Dutch border, a generator is added to fix the voltage at a certain level. These generators have a large reactive power bandwidth, zero active power input and a given voltage set point.

5.2 Automated scenario creation & contingency analysis

To ensure each scenario is created in a similar manner, an automated process is used to generate the dataset of scenarios. This script uses the Python scripting language to control the application programming interface (API) functions of PSS®E, these tools are introduced in section 3.3.4. The complete script is provided in a separate document.

The process is roughly divided in three parts. First, all the necessary data is set up to start creating the scenarios. This includes creating an overview file with all scenarios that have to be included in the dataset. Second, all the individual scenarios are created, their load-flow solution is calculated and their voltage control resources are optimized. Last, an additional contingency analysis is performed on each scenario. For a single scenario, this process is depicted in Figure 27.

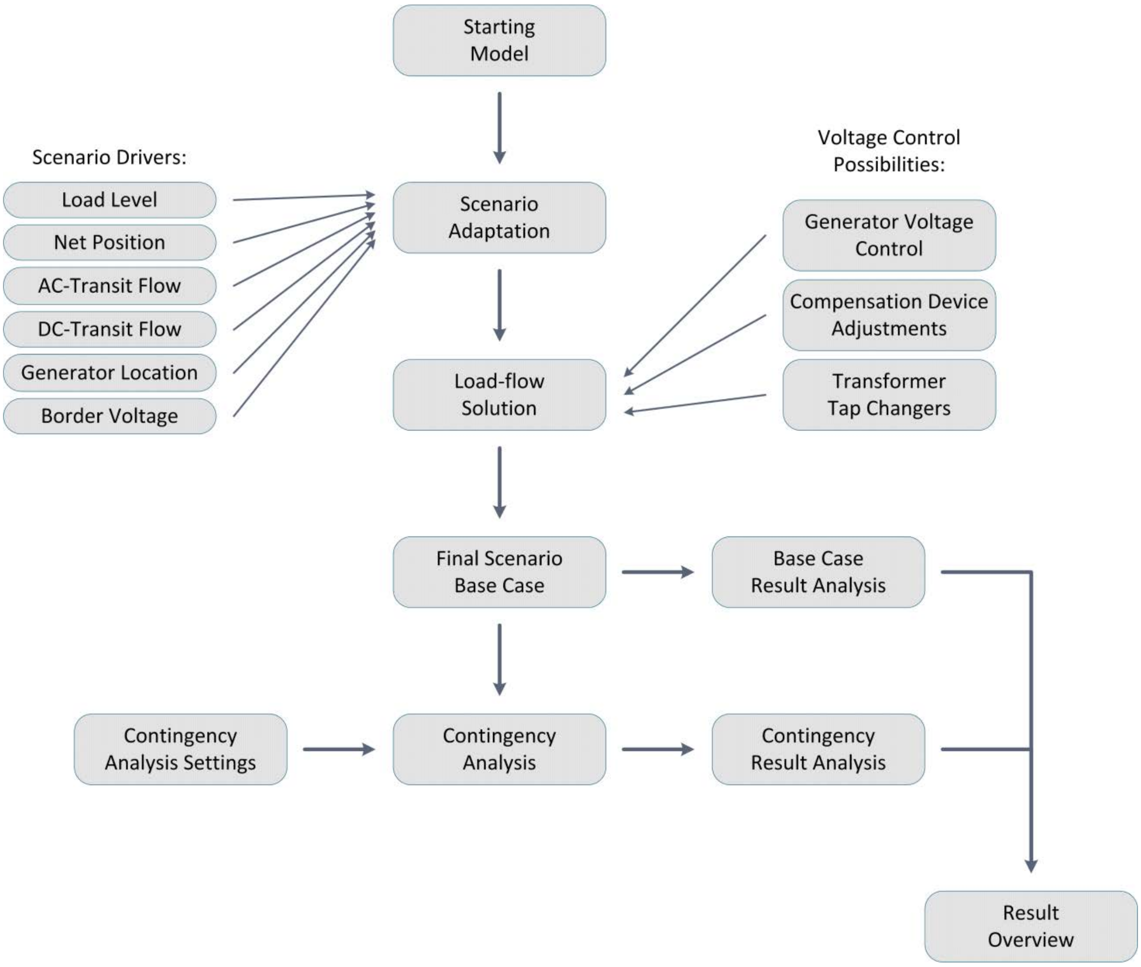

Figure 27: Process of creating and analyzing one single scenario. This process is repeated for each scenario in the dataset. First, the starting model is adapted to the desired scenario driver settings. Next, the voltage control possibilities are optimized and the base case load-flow solution is calculated. Complementary, a contingency analysis is calculated for each scenario. Finally, all base case and contingency results are organized into the various result overviews.

Scenario setup

The first step in the process of creating a dataset with scenarios consists of choosing the scenario driver settings. For each scenario driver, all desired possibilities should be given. Next, the script creates all possible combinations of the scenario drivers and combines this together with filenames and scenario drivers settings in one big setup-file. This setup-file is used as the basis for the loop creating all scenarios in the second step. Manually removing or adding scenarios is possible at this point, to further customize the amount of scenarios created.

Scenario creation

The script runs a large loop over all desired scenarios, creating a single scenario at a time. The creation of a single scenario starts with the starting case model described in Chapter 4. Subsequently, the adaptions necessary to enforce all the scenario drivers are made one-by-one. Each scenario driver has an individual function to adjust the model, these functions use the implementation method described in CH5.1 to achieve the desired scenario driver influence in the scenario.

After all scenario drivers are implemented in the model, the load-flow solution is performed. This includes multiple steps; first, a rough approach solution is calculated. Next, the tap changer adjustments and shunt settings are automatically determined by the voltage control processes to optimize the use of voltage control possibilities. Generator reactive power settings are calculated automatically for each iteration of the load-flow solution. When all voltage control possibilities are applied, the final load-flow solution is calculated. This result is saved and analyzed as the final scenario base case.

Contingency analysis

Complementary to the base case analysis of each scenario, a contingency analysis is performed. This is performed by the automatic contingency analysis function in PSS®E, ACCC [32]. This function performs contingency analysis based on a given set of contingencies and creates a database with a comparison of pre-contingency and post-contingency values throughout the model.

For this analysis, only busbar faults of Dutch substations are taken into account. When a busbar fails, all lines connected to the busbar are put out of service. Therefore, busbar faults can be considered as quite severe contingencies and additional line faults are not required. Extending the contingency analysis with other types of contingencies is still possible.

5.3 Result analysis tools:

With the script described in section 5.2, a dataset of 1944 scenarios is created. To handle the enormous amount of data produced, a set of result overviews has been created. These overviews are generated after the creation of the scenarios, using the same script. The script gathers and organizes specific data of each scenario and puts this in various overviews. Three different levels of overviews are generated, depicted in Figure 28.

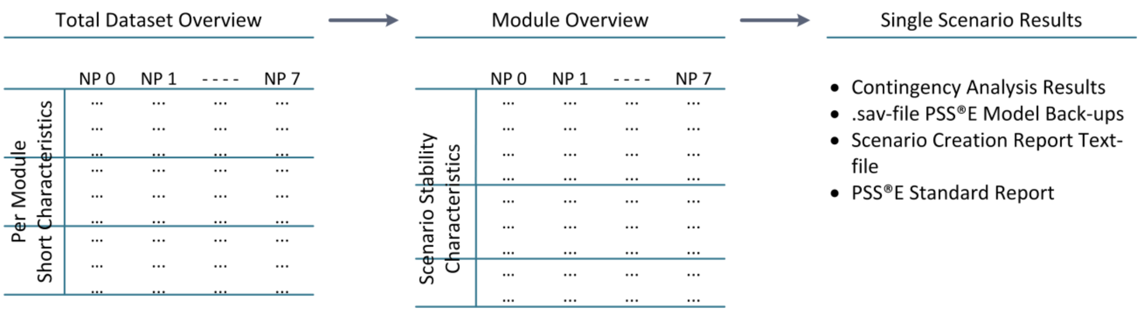

Figure 28: Overview of different result analysis tools.

Total dataset overview

A complete overview of all scenarios is given in the total dataset overview. Although the level of detail is low, it is very usable to get a first impression of the stability of a scenario and to check if all scenarios are created successfully (convergent load-flow solutions).

The overview contains all scenarios, which are organized per module. For each scenario, some key parameters are available; scenario number, scenario driver settings and net position. Information about the accuracy of the load-flow solution (total mismatch) is included to check whether the scenario is created successfully. Also, an overview of the amount and type of contingency analysis violations is given. Finally, some reactive power compensation margin information is given to identify the remaining voltage control possibilities in the base case. An example of the scenario overview is given in Appendix E.1.

Module overview

The main result analysis tool is the module overview. These overviews are used to compare a single module, consisting of all scenarios with the same scenario drivers settings, except a varying net position. This way, the differences between scenarios with increasing net position can easily be identified. An example of the module overview is given in Appendix E.2.

This overview includes more detailed information of the module's scenarios. A summary with the module characteristics, scenario drivers, settings, filenames etc. is given first. Afterwards, several categories of information are included:

Area totals: This category includes information on area totals of the Dutch grid like generation totals, load totals, shunt totals, line losses & charging and cross-border exchange for active and reactive power.

Shunts: Information about the utilization of the shunt equipment. Number of capacitors and reactors active, but also their total reactive power set point, maximal and minimal positions and margins between these positions are included.

Generators: Information regarding Dutch generators; number of generators active, active power and reactive power production and margin between maximal/minimal productions.

Tie-lines: Power flow of various border crossings (P&Q) but also HVDC interconnectors. Resulting net positions are also included.

Voltage profile: Overview of the voltages of the most important substations in the Netherlands. This gives a quick overview of the voltage profile throughout the Netherlands.

Border voltage: Overview of the voltages of the substations directly across the borders, at the foreign side of the AC-interconnectors.

Contingency results: Overview of the number and type of violations of the contingency analysis.

Additionally to the module overview, each file contains more detailed information on the active generators, reactive power compensation devices settings, interconnector flows, area totals and contingency analysis results.

Single scenario results

Complementary to the various overview files, a couple of per scenario result files are also available. First, a text-based report file is generated during the creation of the scenario; this contains all information about the exact actions which are performed by PSS®E.

Also, the detailed information about the contingency analysis is saved on a per-scenario basis. The main element is the database containing the voltages for all busses and flows for each connection in both pre-contingency and all post-contingency situations. Based on this data, the amount of violations, severity of violations and locations of violations can be determined. Also, some automatic reports about the contingency analysis are created by PSS®E.

Chapter 6

Scenario result analysis

With the model and system described in Chapter 4 and Chapter 5 modules and scenarios are created. This resulted in a dataset of 1944 scenarios, divided in 243 modules, dependent of 0 GW – 7 GW net import levels and various scenario drivers. In this chapter, specific modules from this dataset will be used to investigate separate effects on voltage stability.

First, a basic module will be investigated on general effects which will occur for each module. This includes the effect of higher/lower net position of the Dutch grid on voltage profile and line loading, but also the availability of reactive power compensation devices versus reactive power behavior of conventional generation.

Afterwards, the effects of various scenario drivers will be investigated. After describing the reason of including the scenario driver and the prospective effects on system voltage stability, modules will be investigated to verify if these assumptions hold.

Scenario drivers can be divided in three categories. First the load level and net import position of the Dutch grid will be handled. These drivers represent effects that occur internally in the Dutch grid; hence they can be considered implicit scenario drivers. Second, the effects of AC-transit flows and DC-transit flows are investigated. Contrary to the implicit scenario drivers, these influences occur independently from the Dutch grid and have their origin outside the Netherlands; therefore considered as explicit scenario drivers. Last, two extreme scenario drivers are included to get an estimation of the overall stability margin of the Dutch grid. These scenario drivers will represent localized generation schedules or extreme border voltages.

During the evaluation of the scenarios the main emphasis will be on voltage problems. This could be high voltages or low voltages, but also significant voltage deviations during contingencies or between scenarios. The requirements will be the ones described in section 3.3.3. Voltage levels will be the main investigated property since line loading is already included in the FB-CC process. Nevertheless, line loading properties provide information about the system operating point and therefore might indicate a cause for voltage level problems.

6.1 The effect of net position and load level implicit scenario drivers

The load level and the net position of the system are properties that are implicitly apparent in the net operating point. Therefore, it is an obvious point to start investigating the voltage properties of the system. In the next section, the assumed effects on the grid properties for load level and net position are described. These assumptions will be checked using selected modules afterwards.

Assumed effect of load level and net position

Regarding load level, it is expected that most voltage stability problems will occur during low-load situations. There are two main reasons for this. First, during low-load situations, the grid will shift towards capacitive behavior since even overhead line natural loading levels are not reached. This causes an increased voltage when there are not enough reactive power absorbing capabilities. At this moment, these effects are already experienced in the north of the Netherlands, where low-load and high border voltages combined cause voltages up to 1.10 p.u.

Second, during low-load less conventional generation will be running compared to higher load situations. Via contracting, conventional generation is an important source of reactive power control capabilities. Having less conventional generation running will lower the reactive power controlling possibilities throughout the grid and therefore a lack of control capabilities to absorb high voltages will occur faster.

When the net position rises, this effect becomes even stronger. A higher import level is expected to further decrease the amount of conventional generators running in the Dutch grid, therefore diminishing the amount of reactive power compensation capabilities even further.

At the other hand, a rising import level also results in rising line loading, because the distance between generation and load is increased. Higher line loading would result in a more inductive behavior of the grid, therefore lowering reactive power absorption necessity when the grid approaches natural line loading. At the other hand, this would result in larger reactive power production needs if the grid moves towards a highly loaded, inductive behavior.

An important remark is the fact that a low amount of running conventional generators could also influence dynamic stability in the Dutch grid due to a shortage of conventional inertia. Because of this, final external constraints will be dependent on dynamic stability investigations as well. For this research we only investigated voltage stability and dynamic stability issues are out of scope.

Concluding, for a low-load situation with increasing import, it is expected to result in relatively high voltages overall, with rising voltages in case of high import due to the lack of absorbing reactive power compensation.

Low-load scenario with increasing import position

As a starting point a module with low-load (8 GW) will be investigated, there is no AC or DC transit effect active, generation pattern is based on merit order and border voltages are defined by the model. Within this setting, only the net position scenario driver is active, increasing the net import position from 0 to 7 GW. The results of the load-flow studies are depicted in Table 5, the number of running generators and their output is clearly declining with increasing import levels while the sum of import + generator output stays stable. Also visible is the decreasing bandwidth of reactive power compensation by generators (Q_{max}/Q_{min}). The assumption of less available generators and therefore, less reactive power capabilities clearly holds.

GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-1314.3	-769.1	-718.1	-171.4	-143.5	-40.3	31.3	51.8
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

Table 5: Overview of the generator characteristics.

Although the amount of generators decreases, the influence on the voltage level is marginal. In Table 6, voltages throughout the Netherlands and on its borders are depicted for each import level.

The voltages of a selection of 380kV and 220kV substation busbar voltages are depicted. Although a small selection of the 1000+ voltage measurements for the Netherlands, it does give a good insight in the voltage development.

VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.071	1.097	1.099	1.098	1.097	1.091	1.086	1.086
MEEDEN380C	1.078	1.095	1.097	1.096	1.094	1.088	1.084	1.084
ZWOLLE380A	1.079	1.081	1.083	1.084	1.084	1.078	1.077	1.080
HENGELO380A	1.077	1.076	1.077	1.076	1.077	1.072	1.069	1.070
ENS380A	1.075	1.075	1.078	1.079	1.079	1.074	1.075	1.080
DIEMEN380A	1.066	1.065	1.065	1.065	1.065	1.062	1.057	1.068
BEVERWIJK380A	1.063	1.063	1.061	1.056	1.057	1.055	1.043	1.059
KRIMPEN380A	1.070	1.068	1.061	1.057	1.057	1.058	1.053	1.062
MAASVLAKTE380A	1.072	1.071	1.060	1.060	1.060	1.066	1.061	1.071
BORSELLE380B	1.050	1.050	1.063	1.061	1.061	1.059	1.055	1.058
GEERTRUID380A	1.059	1.057	1.056	1.054	1.052	1.051	1.048	1.056
EINDHOVEN380A	1.064	1.062	1.061	1.060	1.060	1.058	1.054	1.057
MAASBRACHT380A	1.069	1.067	1.067	1.065	1.066	1.062	1.058	1.057
DOETINCHEM380A	1.076	1.070	1.071	1.070	1.073	1.065	1.061	1.062
EEMSHAVEN220A	1.047	1.039	1.041	1.040	1.039	1.037	1.042	1.042
MEEDEN220A	1.050	1.039	1.042	1.042	1.039	1.041	1.042	1.044
VIERVERLATEN220A	1.049	1.040	1.042	1.042	1.041	1.038	1.042	1.042
ENS220A	1.052	1.039	1.042	1.042	1.042	1.037	1.039	1.042
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.084	1.093	1.094	1.093	1.091	1.086	1.082	1.080
GRONAU	1.076	1.075	1.076	1.075	1.076	1.071	1.068	1.068
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.071	1.070	1.070	1.069	1.069	1.066	1.064	1.063
VANEYK1	1.066	1.064	1.064	1.063	1.063	1.059	1.055	1.055
VANEYK2	1.069	1.067	1.066	1.065	1.065	1.061	1.058	1.057
ZANDVLIET	1.051	1.050	1.055	1.053	1.052	1.050	1.046	1.047

Table 6: Overview of Dutch voltage profiles for increasing import net position.

A couple of remarks are possible for these voltage profiles. Overall, the voltages are within the 1.00-1.10pu boundaries. With increasing import net position, voltage levels stay roughly the same. The voltage profile throughout the Netherlands, with higher voltages in the north and lower voltages in the south, is similar to what is experienced in real-life.

A voltage level bandwidth of 1.04 – 1.10 p.u. is somewhat high, but this is normal for low-load situations. Also, operators generally keep voltages a bit higher than 1.00 p.u. to have a little voltage dip margin and because voltages in the German grid are generally a bit higher than Dutch voltages.

Notable is the voltage step in the north between 0 GW and 1 GW import net position. This is caused by the fact that two in-service Magnum generator located in Eemshaven are turned off. As a result, 400 MVAr of absorbed reactive power is lost, resulting in a voltage rise. Looking at the border voltages, the influence of higher line loading is visible. Higher import levels have a clear decline in voltage level as a result.

An explanation for the stability of the voltage profile can be found in the reactive power shunts. Table 7 shows that most of the lost reactive power generation from the generators is compensated by shunt devices, keeping the total reactive power generation roughly stable. Apparently, there is no shortage of reactive power capabilities in these scenarios and therefore voltages can be kept stable.

SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	9	14	15	20	21	21	20	19
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-400.0	-770.0	-895.0	-1345.0	-1420.0	-1420.0	-1345.0	-1245.0

Table 7: Overview of reactive power shunt device settings for a low load module.

Lastly, a look at the contingency analysis results to determine the stability margin. The only violations which occur are high voltage violations, situations with voltage levels higher than 1.10 p.u.. Considering the high voltage levels in the north of the Netherlands and the fact that in this overview, transformer star points and generator connections are not removed, the amount of violations is very acceptable. The same is valid for the base-case violations; these are all on machine transformer connections or transformer star points and therefore, can be neglected.

VIOLATIONS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
BC V-Viol(<1.0 or >1.1):	3	2	1	1	1	1	0	0
Contingency analysis:								
Total violations:	89	263	410	242	162	31	26	35
High V viols:	89	263	410	242	162	31	25	35
High V dev viols:	0	0	0	0	0	0	0	0
Low V viols:	0	0	0	0	0	0	0	0
Low V dev viols:	0	0	0	0	0	0	1	0

Table 8: Overview of violations during base-case and contingency situations.

Influence of varying load-level on the voltage profile

As explained above, the assumed effect of the load level will mainly influence the amount of in-service generators and line loading level throughout the Netherlands. A higher number of in-service generators increases reactive power capabilities, which should result in better voltage control. Higher line loading will initially result in an operating point closer to natural line loading resulting in a more neutral reactive power behavior. Eventually it could also result in high reactive power absorption in highly loaded situations, with lower voltages as a result.

To investigate the influence of load level, the module with low-load and increasing import net position, analyzed in the previous section will be compared with its medium load and high load counterparts. These modules have the same scenario driver settings except the load-levels (and accordingly generation level) are 10 GW load in the medium load case and 12 GW load in the high load case.

MEDIUM LOAD								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running Generators (#)	31	30	28	25	22	19	16	13
P generation (MW)	10099.9	9100.1	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0
Q generation (MVAr)	-538.4	-629.2	-761.5	-231.5	-280.7	-125.1	-190.7	24.8
Reactive power bandwidth								
Qmax (MVAr)	7785.6	6992.0	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8
Qmin (MVAr)	-3415.1	-3150.6	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3
HIGH LOAD								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running Generators (#)	36	34	31	30	28	25	22	19
P generation (MW)	12100.1	11100.0	10099.9	9100.1	8100.0	7100.0	6100.1	5100.0
Q generation (MVAr)	-362.3	-408.7	-203.0	-205.6	-308.7	99.2	130.0	283.7
Reactive power bandwidth								
Qmax (MVAr)	9468.4	9103.1	7785.6	6992.0	6051.0	4824.7	4244.7	2912.6
Qmin (MVAr)	-4264.6	-4049.4	-3415.1	-3150.6	-2535.1	-1697.2	-1449.4	-1114.0

Table 9: Overview of generator characteristics for medium and high load modules.

From the overviews given in Table 9, it is very clear that, as expected, the amount of in-service generators is rising with a rising load level. Similar to the low load-level module, this relation holds:

$$Load\ level\ (MW) + Line\ losses\ (MW) = Generation\ (MW) + Import\ (MW)$$

Due to the rising amount of in-service generators, the reactive power bandwidth is also larger.

Another remarkable effect is the shift in reactive power generation. Compared to the low-load situation, it is clearly visible that the generators are absorbing less reactive power, or even produce reactive power. Apparently, the voltage dampening effects of absorbing reactive power are less needed.

The same effect is visible for reactive power compensation devices. Table 10 shows that for higher load levels, the number of active reactors decreases, while more capacitors become active. As a result, the total behavior of shunts is becoming more and more voltage-increasing than voltage-damping.

MEDIUM LOAD								
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Reactors Active (#)	8	8	8	12	12	12	12	11
Capacitors Active (#)	4	4	4	4	4	4	4	4
BSW Nom (MVAr)	-175.0	-175.0	-175.0	-475.0	-475.0	-475.0	-475.0	-400.0
HIGH LOAD								
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Reactors Active (#)	6	6	6	6	6	9	9	8
Capacitors Active (#)	6	6	6	6	6	6	6	6
BSW Nom (MVAr)	300.0	300.0	300.0	300.0	300.0	75.0	75.0	150.0

Table 10: Overview of shunt devices settings for medium and high load modules.

The voltage profiles in medium load and high load shows a consistent effect with the generator and shunt behavior. Overall, voltages are decreasing for increasing load levels, despite the fact that generators and shunt devices behave less voltage decreasing. This clearly shows the influence the network (and the accompanying loading of the network) on the voltage profile throughout the Netherlands.

Again clearly visible is the switch off of the Magnum generators in Eemshaven in the medium load situation. Instead of between a 0 GW and 1 GW import net position, this happens between 2 GW and 3 GW import, but the same voltage step is visible. For high load this is also visible, between 4 GW and 5 GW import, but due to generally lower voltages, the effect is less visible.

Another remarkable effect is the fact that the border voltages are barely effected by load-level differences. Apparently, the load-level changes have mainly internal consequences, but not so much on cross-border lines. The cross-border lines seem to be more influenced by the increasing line loading effects of higher import.

MEDIUM LOAD								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.071	1.071	1.071	1.092	1.090	1.085	1.082	1.078
MEEDEN380C	1.078	1.078	1.078	1.091	1.089	1.085	1.081	1.077
ZWOLLE380A	1.078	1.077	1.077	1.079	1.078	1.077	1.074	1.072
HENGELO380A	1.077	1.076	1.076	1.075	1.074	1.073	1.070	1.066
ENS380A	1.074	1.073	1.073	1.073	1.072	1.072	1.070	1.070
DIEMEN380A	1.065	1.065	1.065	1.065	1.065	1.065	1.064	1.065
BEVERWIJK380A	1.060	1.061	1.061	1.061	1.060	1.061	1.060	1.061
KRIMPEN380A	1.059	1.064	1.064	1.062	1.059	1.063	1.062	1.064
MAASVLAKTE380A	1.055	1.066	1.066	1.064	1.060	1.068	1.067	1.075
BORSELLE380B	1.050	1.050	1.050	1.050	1.060	1.059	1.058	1.055
GEERTRUID380A	1.052	1.052	1.053	1.052	1.052	1.054	1.052	1.051
EINDHOVEN380A	1.058	1.059	1.060	1.059	1.058	1.058	1.056	1.053
MAASBRACHT380A	1.067	1.067	1.067	1.065	1.064	1.063	1.061	1.056
DOETINCHEM380A	1.077	1.077	1.076	1.075	1.074	1.073	1.070	1.063
EEMSHAVEN220A	1.045	1.044	1.045	1.033	1.032	1.037	1.037	1.034
MEEDEN220A	1.048	1.048	1.048	1.033	1.031	1.034	1.038	1.033
VIERVERLATEN220A	1.047	1.046	1.047	1.035	1.033	1.037	1.037	1.035
ENS220A	1.057	1.057	1.057	1.044	1.043	1.043	1.043	1.041
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.085	1.084	1.083	1.089	1.087	1.084	1.080	1.076
GRONAU	1.076	1.075	1.075	1.074	1.073	1.072	1.069	1.065
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.070	1.070	1.070	1.069	1.068	1.067	1.065	1.062
VANEYK1	1.064	1.064	1.064	1.062	1.061	1.060	1.058	1.053
VANEYK2	1.066	1.067	1.067	1.065	1.064	1.063	1.060	1.055
ZANDVLIET	1.048	1.048	1.049	1.048	1.052	1.051	1.048	1.045

Table 11: Voltage profiles for medium load scenarios.

HIGH LOAD								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.070	1.070	1.070	1.070	1.070	1.078	1.076	1.078
MEEDEN380C	1.077	1.076	1.076	1.075	1.075	1.079	1.076	1.077
ZWOLLE380A	1.076	1.075	1.073	1.073	1.073	1.073	1.071	1.071
HENGELO380A	1.074	1.073	1.071	1.070	1.069	1.068	1.066	1.065
ENS380A	1.073	1.072	1.070	1.070	1.069	1.069	1.069	1.069
DIEMEN380A	1.067	1.066	1.065	1.065	1.065	1.065	1.065	1.065
BEVERWIJK380A	1.069	1.067	1.064	1.065	1.065	1.065	1.064	1.064
KRIMPEN380A	1.064	1.061	1.060	1.064	1.064	1.062	1.060	1.058
MAASVLAKTE380A	1.060	1.055	1.055	1.065	1.065	1.061	1.060	1.061
BORSELLE380B	1.050	1.050	1.050	1.050	1.050	1.050	1.058	1.053
GEERTRUID380A	1.053	1.052	1.052	1.052	1.052	1.052	1.052	1.048
EINDHOVEN380A	1.057	1.057	1.057	1.056	1.056	1.055	1.054	1.050
MAASBRACHT380A	1.065	1.064	1.063	1.062	1.061	1.059	1.057	1.053
DOETINCHEM380A	1.075	1.073	1.070	1.069	1.068	1.066	1.064	1.063
EEMSHAVEN220A	1.040	1.039	1.039	1.038	1.038	1.042	1.042	1.044
MEEDEN220A	1.042	1.041	1.042	1.041	1.041	1.040	1.044	1.045
VIERVERLATEN220A	1.040	1.039	1.038	1.037	1.038	1.040	1.040	1.042
ENS220A	1.053	1.052	1.050	1.049	1.050	1.050	1.050	1.050
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.084	1.083	1.082	1.081	1.079	1.080	1.077	1.075
GRONAU	1.073	1.072	1.071	1.070	1.069	1.067	1.065	1.064
ROMMERSKIRCHEN	1.081	1.082	1.081	1.081	1.081	1.080	1.080	1.078
SIERSDORF	1.069	1.069	1.068	1.067	1.066	1.065	1.063	1.060
VANEYK1	1.062	1.062	1.060	1.059	1.058	1.056	1.054	1.051
VANEYK2	1.065	1.064	1.063	1.062	1.061	1.059	1.057	1.053
ZANDVLIET	1.048	1.048	1.048	1.048	1.048	1.047	1.049	1.043

Table 12: Voltage profiles for high load scenarios.

6.2 The effect of AC-transit and DC-transit explicit scenario drivers

Contrary to load level or net position, the causes of transit flows are mainly externally driven and occur independent from the Dutch grid. The effects of AC cross-border line transport driven transit flows and HVDC interconnectors driven transit flows will be investigated to see how these transit flows influence the Dutch grid.

Assumed effect of transit flows on the Dutch grid

Transit flows do not affect the Dutch loads or generators, their operating point will not change due to transit flow influences (except for generator reactive power output). Therefore, the same bandwidth of reactive power capabilities is available for both generators and shunt devices.

The expected influence of transit flows will mainly involve the line loading of the Dutch grid. A 'superposition' of extra power flow caused by the transit flows on top of the regular line loading influences the reactive power behavior of the grid. The higher loaded lines will act more inductive, therefore, in general voltages will be lower or less reactive power compensation will be used.

In low-load situations, this might be beneficial since transit flows can cause the network to operate more towards the natural loading point (decreasing reactive power compensation needs). At the other hand, in high-load situations it might result in overloaded lines due to the combination of high internal line loading and transit flows.

These assumptions hold for both types of transit flows. Differences are expected at the influences locations. The sources of the DC-transit flow, the HVDC-interconnectors, come ashore in the Eemshaven and Maasvlakte. Therefore, the biggest influence is expected in these locations, since the estimated 1 GW influence is relatively small in the rest of the network.

The AC-transit flow is much larger (up to 4 GW). Obviously, influences are expected at the cross-border connections which experience additional power flows. Otherwise, the main North-South connections within the Netherlands are expected to experience extra power flows as well.

Evaluation of AC-transit flow effects

As expected, the number of in-service generators, active power production or reactive power bandwidth does not change in AC-transit situations. Regarding the reactive power generation, the 0 GW and 2 GW AC-transit flow situations behave very similar. Both the generators and compensation devices have more or less the same settings for both scenarios. Apparently, the influence of 2 GW AC-transit is not big enough to require very different reactive power compensation settings.

The 4 GW AC-transit flow scenarios at the other hand show much less absorption of reactive power. In the 0 GW import case this is mainly visible for the generators, in higher import scenarios, it's the shunt devices which have lower reactive power absorption. Apparently, the extra line loading generated by the AC-transit flow is big enough to remove the network from the far capacitive end of behavior.

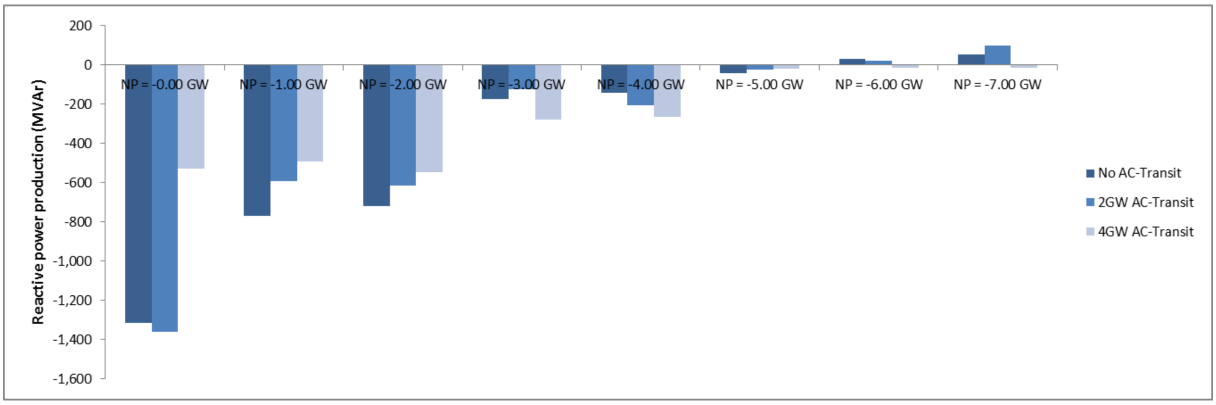

Figure 29: Total generator reactive power production for AC-Transit situations with various net positions (NP).

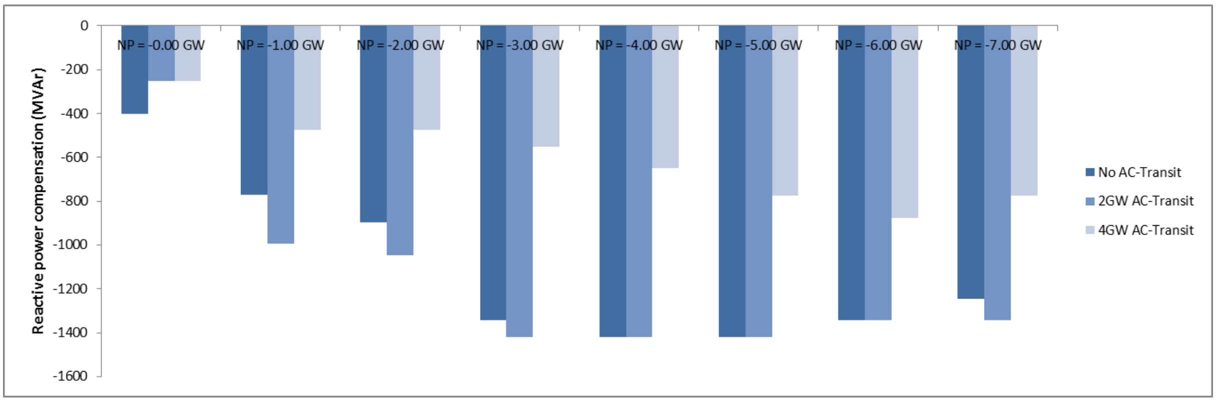

Figure 30: Total shunt devices reactive power production for AC-transit situations with various net positions (NP).

The same phenomenon is visible when looking at the voltage profiles. Especially for lower import situations, the voltage profiles for the 0 GW and 2 GW AC-transit flow situations are more or less the same. For higher import positions however, the total line loading starts to increase and differences in voltage level become apparent. For the 4 GW AC-transit scenarios, the same amount of total line loading is reached for lower import net positions, therefore the voltage differences start increasing much earlier.

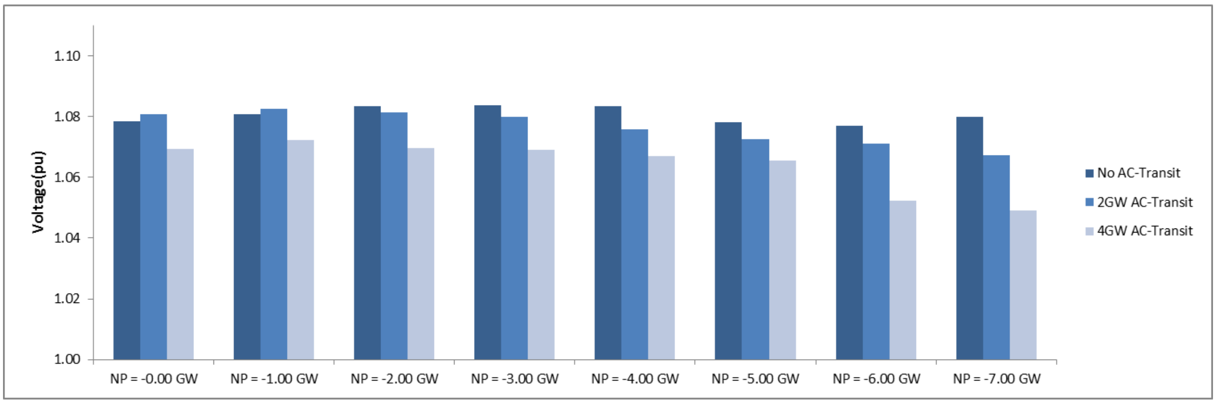

Figure 31: Voltage profile for Zwolle380.

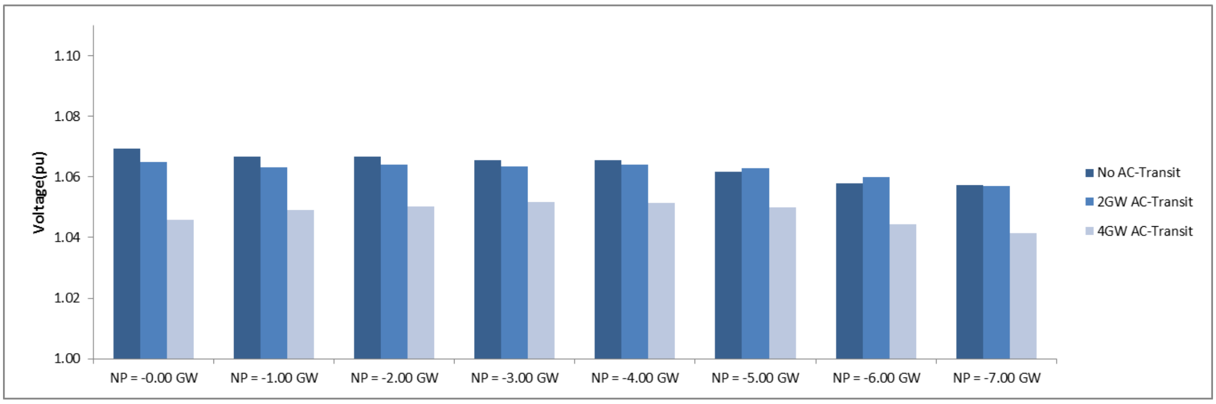

Figure 32: Voltage profile for Maasbracht380

When looking at the cross-border voltages, the same relation of voltage level versus total line loading is visible. With small drops in voltage for the 2 GW AC-transit flow scenario or higher import scenarios and higher voltage drops as the total power flows in these lines increases.

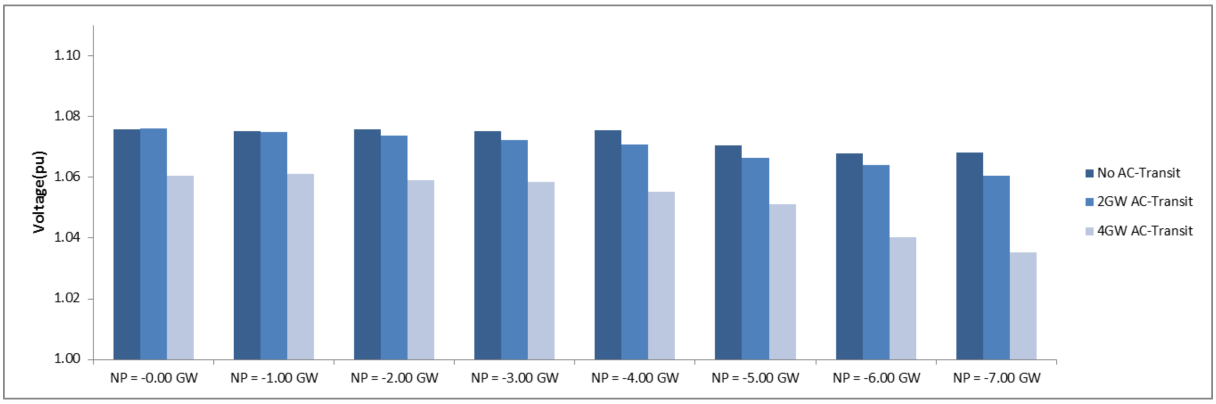

Figure 33: Voltage profile for the cross-border connection at Gronau.

LOW LOAD, 2GW N-S AC-TRANSIT								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.071	1.096	1.094	1.091	1.083	1.078	1.079	1.079
MEEDEN380C	1.079	1.094	1.092	1.089	1.082	1.077	1.076	1.075
ZWOLLE380A	1.081	1.083	1.081	1.080	1.076	1.073	1.071	1.067
HENGELO380A	1.077	1.076	1.075	1.073	1.072	1.067	1.065	1.061
ENS380A	1.079	1.078	1.077	1.076	1.072	1.070	1.070	1.066
DIEMEN380A	1.069	1.065	1.065	1.065	1.061	1.065	1.058	1.056
BEVERWIJK380A	1.066	1.062	1.062	1.056	1.054	1.058	1.043	1.043
KRIMPEN380A	1.071	1.064	1.062	1.058	1.057	1.065	1.059	1.061
MAASVLAKTE380A	1.074	1.065	1.060	1.061	1.060	1.073	1.067	1.069
BORSELLE380B	1.050	1.050	1.063	1.062	1.064	1.067	1.064	1.069
GEERTRUID380A	1.059	1.055	1.057	1.055	1.055	1.060	1.055	1.058
EINDHOVEN380A	1.062	1.059	1.061	1.061	1.061	1.063	1.059	1.058
MAASBRACHT380A	1.065	1.063	1.064	1.064	1.064	1.063	1.060	1.057
DOETINCHEM380A	1.075	1.070	1.069	1.067	1.069	1.062	1.059	1.055
EEMSHAVEN220A	1.047	1.039	1.036	1.034	1.039	1.035	1.035	1.036
MEEDEN220A	1.051	1.039	1.036	1.035	1.040	1.036	1.035	1.037
VIERVERLATEN220A	1.050	1.041	1.039	1.037	1.039	1.036	1.035	1.037
ENS220A	1.055	1.041	1.040	1.039	1.037	1.035	1.033	1.040
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.083	1.091	1.088	1.085	1.080	1.075	1.072	1.071
GRONAU	1.076	1.075	1.074	1.072	1.071	1.066	1.064	1.061
ROMMERSKIRCHEN	1.079	1.079	1.079	1.080	1.080	1.080	1.079	1.078
SIERSDORF	1.066	1.066	1.066	1.066	1.066	1.065	1.064	1.061
VANEYK1	1.061	1.060	1.061	1.060	1.061	1.060	1.057	1.055
VANEYK2	1.064	1.062	1.063	1.063	1.064	1.063	1.060	1.057
ZANDVLIET	1.048	1.047	1.055	1.055	1.056	1.059	1.056	1.058

Table 13: Voltage profiles for the low-load, 2 GW N-S AC-transit scenarios.

LOW LOAD, 4GW N-S AC-TRANSIT								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.070	1.080	1.074	1.074	1.074	1.074	1.063	1.060
MEEDEN380C	1.072	1.077	1.072	1.071	1.070	1.070	1.060	1.057
ZWOLLE380A	1.069	1.072	1.070	1.069	1.067	1.066	1.052	1.049
HENGELO380A	1.062	1.063	1.061	1.060	1.057	1.053	1.042	1.037
ENS380A	1.070	1.072	1.070	1.070	1.068	1.068	1.054	1.052
DIEMEN380A	1.065	1.065	1.065	1.065	1.067	1.066	1.047	1.051
BEVERWIJK380A	1.063	1.063	1.062	1.063	1.063	1.062	1.042	1.047
KRIMPEN380A	1.066	1.067	1.066	1.068	1.066	1.064	1.052	1.056
MAASVLAKTE380A	1.069	1.070	1.068	1.072	1.069	1.072	1.060	1.064
BORSELLE380B	1.050	1.050	1.056	1.060	1.064	1.064	1.060	1.063
GEERTRUID380A	1.052	1.053	1.055	1.058	1.058	1.056	1.048	1.052
EINDHOVEN380A	1.050	1.052	1.054	1.056	1.056	1.054	1.047	1.047
MAASBRACHT380A	1.046	1.049	1.050	1.052	1.051	1.050	1.044	1.042
DOETINCHEM380A	1.058	1.060	1.059	1.059	1.057	1.051	1.041	1.035
EEMSHAVEN220A	1.046	1.039	1.035	1.043	1.033	1.045	1.049	1.043
MEEDEN220A	1.048	1.040	1.034	1.040	1.033	1.046	1.051	1.039
VIERVERLATEN220A	1.049	1.042	1.038	1.044	1.036	1.045	1.048	1.043
ENS220A	1.057	1.047	1.045	1.046	1.042	1.044	1.046	1.043
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.070	1.071	1.067	1.064	1.063	1.062	1.054	1.051
GRONAU	1.061	1.061	1.059	1.058	1.055	1.051	1.040	1.035
ROMMERSKIRCHEN	1.067	1.069	1.069	1.070	1.070	1.070	1.068	1.067
SIERSDORF	1.049	1.051	1.052	1.053	1.053	1.052	1.048	1.046
VANEYK1	1.040	1.044	1.045	1.047	1.047	1.046	1.041	1.039
VANEYK2	1.042	1.046	1.048	1.050	1.050	1.049	1.044	1.042
ZANDVLIET	1.037	1.039	1.046	1.051	1.054	1.055	1.052	1.055

Table 14: Voltage profiles for the low-load, 2 GW N-S AC-transit scenarios.

Evaluation of DC-transit flow effects

Although the main assumption of the effect of DC-transit flow is the same as for AC-transit flow, which is higher overall line loading, the differences between the two might be of interest. Especially whether the relatively small amount of the DC-transit flow is important and which areas are affected compared to AC-transit flow.

Equal to the AC-transit flow situation, the number of in-service generators, active power production or reactive power bandwidth stays the same for various DC-flow situations. The reactive power production from generators stays roughly the same, but the reactive power compensation shunts do vary per situation.

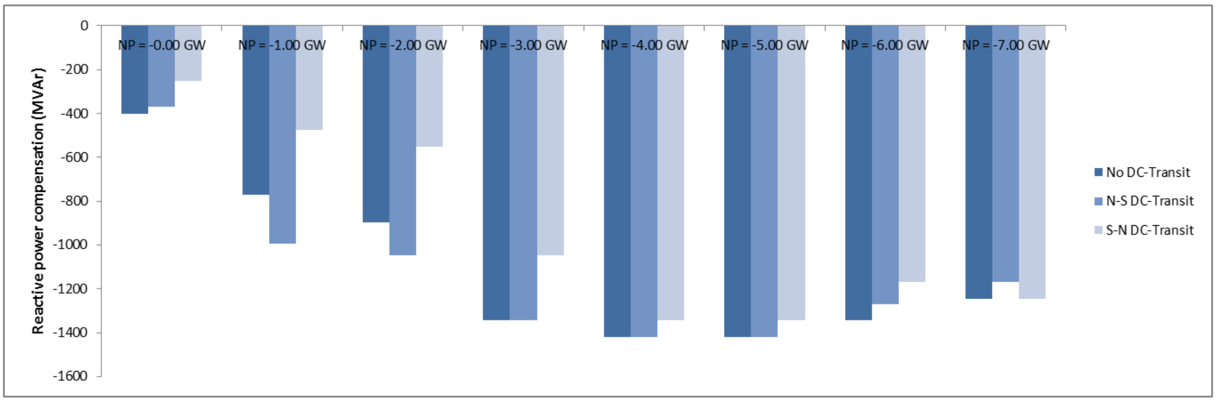

Figure 34: Total shunt devices reactive power production for DC-transit situations with various net positions (NP).

The voltage profiles for the various DC-transit scenario driver settings are very similar, with voltage differences of around 0.01 pu. Only in the north of the Netherlands, close to the NorNed connection point Eemshaven, voltage differences become substantial. The reason for this could be local power flows. In the neutral case, the NorNed cable is switched off therefore, P = 0 and Q = 0. In the N-S case, Norned produces 700 MW but absorbs 175 MVAr at the same time. In the S-N case, it consumes 700 MW and absorbs 175 MVAr.

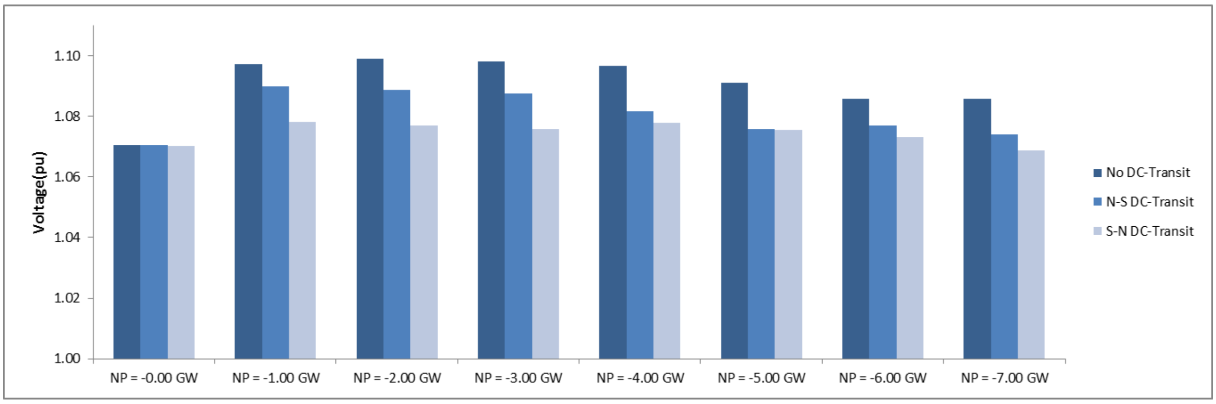

Figure 35: Voltage profile for the Eemshaven380 substation for various DC-transit situations.

Border voltages are only affected in the areas close to the HVDC-interconnector connection points. For the lower import levels (0 - 3GW) this influences is not yet visible. For higher import levels (5-7 GW) these influences are visible on substations as Meeden and Zandvliet. Apparently, the additional power flow of around 1 GW is significant in these areas, while the rest of the grid absorbs the extra power flow more easy.

LOW LOAD, N-S DC-TRANSIT								
VOLTAGE PROFILE	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
EEMSHAVEN380A	1.070	1.090	1.089	1.088	1.082	1.076	1.077	1.074
MEEDEN380C	1.079	1.091	1.090	1.089	1.084	1.078	1.078	1.074
ZWOLLE380A	1.080	1.082	1.082	1.082	1.079	1.074	1.074	1.071
HENGELO380A	1.078	1.077	1.077	1.078	1.075	1.070	1.068	1.065
ENS380A	1.077	1.078	1.078	1.078	1.076	1.071	1.072	1.070
DIEMEN380A	1.069	1.065	1.065	1.065	1.062	1.060	1.055	1.058
BEVERWIJK380A	1.066	1.062	1.062	1.056	1.055	1.054	1.041	1.050
KRIMPEN380A	1.071	1.063	1.061	1.057	1.055	1.054	1.048	1.052
MAASVLAKTE380A	1.074	1.065	1.060	1.060	1.060	1.063	1.056	1.060
BORSELLE380B	1.050	1.050	1.062	1.060	1.059	1.056	1.052	1.052
GEERTRUID380A	1.060	1.054	1.055	1.053	1.051	1.048	1.044	1.047
EINDHOVEN380A	1.065	1.061	1.062	1.060	1.059	1.056	1.052	1.051
MAASBRACHT380A	1.070	1.067	1.067	1.067	1.065	1.061	1.057	1.054
DOETINCHEM380A	1.075	1.072	1.071	1.074	1.072	1.064	1.061	1.058
EEMSHAVEN220A	1.048	1.035	1.034	1.033	1.040	1.034	1.045	1.032
MEEDEN220A	1.051	1.036	1.034	1.033	1.041	1.035	1.042	1.033
VIERVERLATEN220A	1.050	1.039	1.037	1.037	1.042	1.035	1.044	1.033
ENS220A	1.054	1.041	1.040	1.040	1.040	1.035	1.039	1.034
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.085	1.091	1.090	1.089	1.085	1.080	1.078	1.074
GRONAU	1.076	1.076	1.075	1.076	1.074	1.069	1.067	1.064
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.072	1.070	1.070	1.070	1.069	1.066	1.063	1.060
VANEYK1	1.067	1.064	1.064	1.064	1.062	1.058	1.054	1.051
VANEYK2	1.070	1.067	1.067	1.066	1.065	1.061	1.057	1.053
ZANDVLIET	1.051	1.049	1.055	1.052	1.051	1.047	1.043	1.041

Table 15: Voltage profiles for the low-load, N-S DC-transit scenarios.

LOW LOAD, S-N DC-TRANSIT								
VOLTAGE PROFILE	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
EEMSHAVEN380A	1.070	1.078	1.077	1.076	1.078	1.075	1.073	1.069
MEEDEN380C	1.079	1.081	1.080	1.079	1.080	1.077	1.075	1.071
ZWOLLE380A	1.079	1.076	1.075	1.075	1.074	1.072	1.072	1.072
HENGELO380A	1.077	1.074	1.074	1.072	1.069	1.066	1.064	1.063
ENS380A	1.076	1.072	1.071	1.071	1.071	1.070	1.072	1.072
DIEMEN380A	1.065	1.065	1.065	1.065	1.058	1.061	1.059	1.062
BEVERWIJK380A	1.062	1.062	1.062	1.061	1.049	1.055	1.052	1.053
KRIMPEN380A	1.070	1.069	1.070	1.061	1.054	1.061	1.059	1.062
MAASVLAKTE380A	1.075	1.074	1.075	1.065	1.060	1.072	1.071	1.074
BORSELLE380B	1.050	1.050	1.066	1.063	1.060	1.061	1.059	1.058
GEERTRUID380A	1.058	1.057	1.062	1.056	1.051	1.054	1.052	1.055
EINDHOVEN380A	1.062	1.062	1.065	1.062	1.058	1.059	1.057	1.056
MAASBRACHT380A	1.068	1.067	1.069	1.066	1.063	1.061	1.058	1.056
DOETINCHEM380A	1.075	1.073	1.072	1.070	1.064	1.060	1.058	1.056
EEMSHAVEN220A	1.046	1.038	1.037	1.036	1.035	1.033	1.032	1.040
MEEDEN220A	1.051	1.040	1.039	1.037	1.036	1.035	1.033	1.042
VIERVERLATEN220A	1.048	1.040	1.039	1.040	1.036	1.034	1.033	1.041
ENS220A	1.052	1.046	1.045	1.044	1.035	1.034	1.034	1.037
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.085	1.086	1.084	1.083	1.082	1.079	1.076	1.072
GRONAU	1.076	1.074	1.073	1.072	1.068	1.066	1.064	1.062
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.081	1.081	1.080	1.079
SIERSDORF	1.070	1.070	1.071	1.070	1.068	1.066	1.064	1.062
VANEYK1	1.065	1.064	1.065	1.063	1.060	1.058	1.056	1.053
VANEYK2	1.068	1.067	1.068	1.066	1.063	1.061	1.058	1.056
ZANDVLIET	1.050	1.050	1.059	1.055	1.052	1.052	1.049	1.048

Table 16: Voltage profiles for the low-load, S-N DC-transit scenarios.

Overall, it can be concluded that DC-transit flows have much less influence than AC-transit flows, mainly because of the smaller size. Nevertheless, it could cause local problems due to its operating point. Especially since they are connected with areas that contain a large amount of conventional generation. Therefore, they should surely be included in the model in some way. Whether this is combined with AC-transit or as a generator/load is of less importance.

6.3 The effect of generation location and border voltage extreme scenario drivers

To check the effects of some more extreme scenario drivers, scenarios with concentrated generation patterns and with adapted border voltage have been included. Since these drivers are included to get an idea about the stability margin for a certain phenomenon, the assumed effects and results will be analyzed in a more qualitative way compared to the other drivers.

Effect of concentrated generator locations on the Dutch grid

Like shunt devices, generators are producing or absorbing reactive power. When all in-service generation is located in one region, the rest of the network has to rely on shunt devices only. Since the generation in the Netherlands gets more and more centralized around three areas (Eemshaven, Maasvlakte and Borselle) this could become a realistic scenario in the future. A couple of things are remarkable when looking at the results for the concentrated generation locations.

Overall, the assumption that voltage control will be influenced clearly holds, this could lead to overvoltages as well. When looking at the Maasvlakte scenario, the overvoltages in the Eemshaven area are clearly visible. The low-load situation, no voltage control capabilities from generators, high border voltages and a lacking amount of shunt devices leads to voltages higher than 1.10 pu. At the other hand, the Maavlakte area itself has voltages at or close to the generator voltage set points, indicating sufficient control capabilities.

LOW LOAD, MAASVLAKTE CONCENTRATED GENERATION								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.099	1.099	1.101	1.099	1.095	1.094	1.090	1.084
MEEDEN380C	1.097	1.096	1.098	1.096	1.093	1.092	1.088	1.082
ZWOLLE380A	1.083	1.082	1.084	1.082	1.083	1.083	1.080	1.077
HENGELO380A	1.077	1.077	1.076	1.076	1.075	1.074	1.071	1.068
ENS380A	1.077	1.076	1.079	1.077	1.080	1.079	1.078	1.076
DIEMEN380A	1.056	1.058	1.063	1.060	1.063	1.065	1.061	1.060
BEVERWIJK380A	1.047	1.049	1.054	1.052	1.056	1.058	1.047	1.049
KRIMPEN380A	1.056	1.057	1.060	1.062	1.062	1.063	1.059	1.059
MAASVLAKTE380A	1.060	1.060	1.060	1.060	1.055	1.055	1.060	1.065
BORSELLE380B	1.050	1.060	1.064	1.067	1.066	1.064	1.059	1.052
GEERTRUID380A	1.052	1.052	1.057	1.062	1.062	1.062	1.057	1.052
EINDHOVEN380A	1.055	1.057	1.060	1.065	1.065	1.064	1.059	1.053
MAASBRACHT380A	1.062	1.063	1.064	1.066	1.065	1.064	1.059	1.054
DOETINCHEM380A	1.072	1.072	1.069	1.071	1.069	1.067	1.064	1.061
EEMSHAVEN220A	1.041	1.040	1.033	1.032	1.036	1.038	1.034	1.041
MEEDEN220A	1.041	1.040	1.036	1.035	1.038	1.038	1.033	1.042
VIERVERLATEN220A	1.042	1.041	1.037	1.035	1.037	1.039	1.036	1.041
ENS220A	1.041	1.040	1.041	1.039	1.035	1.041	1.040	1.039
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.095	1.094	1.094	1.092	1.090	1.088	1.084	1.079
GRONAU	1.076	1.076	1.075	1.075	1.074	1.073	1.070	1.067
ROMMERSKIRCHEN	1.081	1.081	1.081	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.067	1.068	1.068	1.069	1.069	1.068	1.065	1.061
VANEYK1	1.059	1.060	1.061	1.063	1.062	1.061	1.057	1.052
VANEYK2	1.062	1.063	1.064	1.066	1.065	1.063	1.059	1.054
ZANDVLIET	1.049	1.054	1.057	1.059	1.058	1.056	1.050	1.044

Table 17: Voltage profiles for the Maasvlakte concentrated generation scenarios. Overvoltages due to lacking voltage control capabilities are visible in the Eemshaven region while the voltages at the Maasvlakte area are all in line with generator voltage set points.

When looking at the Eemshaven concentrated case, it is remarkable that the voltages in the region are relatively low compared to the 'normal' merit order scenarios. Finally, enough reactive power capabilities are available in the Eemshaven region to decrease the voltages to acceptable levels. In the rest of the network, there are no voltage problems either. Since a lot of reactive power shunt devices (especially reactors) are installed in the south western part of the Netherlands (around the Randstad) and a lot of loads are located in this place, this is plausible.

LOW LOAD, EEMSHAVEN CONCENTRATED GENERATION								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.070	1.070	1.070	1.070	1.070	1.070	1.070	1.070
MEEDEN380C	1.068	1.064	1.061	1.059	1.066	1.069	1.071	1.062
ZWOLLE380A	1.063	1.059	1.052	1.042	1.061	1.063	1.066	1.032
HENGELO380A	1.064	1.061	1.056	1.051	1.064	1.062	1.064	1.036
ENS380A	1.066	1.064	1.056	1.043	1.064	1.063	1.064	1.017
DIEMEN380A	1.065	1.065	1.065	1.047	1.068	1.064	1.058	0.997
BEVERWIJK380A	1.062	1.062	1.061	1.047	1.063	1.056	1.053	0.984
KRIMPEN380A	1.066	1.067	1.066	1.054	1.068	1.059	1.062	0.995
MAASVLAKTE380A	1.073	1.074	1.073	1.061	1.075	1.064	1.072	0.998
BORSELLE380B	1.070	1.070	1.068	1.058	1.066	1.058	1.057	1.010
GEERTRUID380A	1.065	1.065	1.063	1.053	1.064	1.056	1.057	1.002
EINDHOVEN380A	1.068	1.068	1.065	1.056	1.066	1.057	1.057	1.013
MAASBRACHT380A	1.068	1.067	1.065	1.059	1.065	1.058	1.057	1.029
DOETINCHEM380A	1.067	1.065	1.059	1.053	1.065	1.058	1.058	1.025
EEMSHAVEN220A	1.040	1.043	1.045	1.047	1.039	1.036	1.035	1.036
MEEDEN220A	1.041	1.041	1.041	1.042	1.040	1.040	1.040	1.035
VIERVERLATEN220A	1.037	1.036	1.035	1.037	1.035	1.035	1.036	1.029
ENS220A	1.046	1.042	1.036	1.037	1.042	1.044	1.047	1.009
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.078	1.075	1.073	1.070	1.074	1.074	1.074	1.065
GRONAU	1.065	1.063	1.059	1.054	1.065	1.063	1.064	1.041
ROMMERSKIRCHEN	1.082	1.082	1.081	1.080	1.081	1.080	1.080	1.073
SIERSDORF	1.070	1.070	1.068	1.065	1.068	1.064	1.063	1.046
VANEYK1	1.065	1.064	1.062	1.056	1.062	1.056	1.054	1.028
VANEYK2	1.067	1.067	1.065	1.059	1.064	1.058	1.057	1.030
ZANDVLIET	1.061	1.061	1.059	1.051	1.057	1.050	1.048	1.011

Table 18: Voltage profiles for the Eemshaven concentrated generation scenarios. Lower voltages are clearly visible in the Eemshaven region now sufficient voltage control capabilities are available. High line loading starts becoming a problem for high import scenarios. This will get even more critical in higher load level or transit flow scenarios.

Nevertheless, the Eemshaven concentrated scenario does have problems regarding line loading. Since the load in the north of the Netherlands is very low, most of the generated power has to be transported to the center part of the Netherlands. This is where most of the load is located. These larger distances between generation and load cause high line loading problems.

In this low-load scenario this effect is already visible, the 7 GW import scenario did not converge correctly due to this. When scenarios with higher load levels or, especially, additional north-south transit flow are considered, overloaded lines are a major problem. The Zwolle-Ens-Lelystad-Diemen trajectory is the easiest overloaded, since this is exactly in the middle between the loads (Randstad) and Eemshaven generation. In the Maasvlakte concentrated generation scenarios this problem is much less visible due to shorter distances between generation and load.

Effects of high/low border voltages on the Dutch grid

The northwest European network is heavily meshed; therefore, the operating points of the neighboring networks have a large influence on the Dutch network operating point. To examine the influence of the voltage levels in the neighboring networks, the border voltage gets fixed at 1.0 p.u. and 1.1 p.u.; roughly the same difference each way.

With a very high border voltage, the voltage control systems are used to their full capacity to try to lower/raise voltages levels. This is clearly visible in Figure 36 and Figure 37. When looking at the voltages however, this does not seem to help much. Especially the regions close to the border (Maasbracht, Eemshaven) experience the same voltage levels as the border voltages.

Therefore, it is easy to conclude that it is counterproductive to try to control the voltages when the set voltage at the border is that strong. In these cases, it is better to (partially) accept the voltages of the neighboring networks than to fight a lost battle with full capacity of voltage control capabilities.

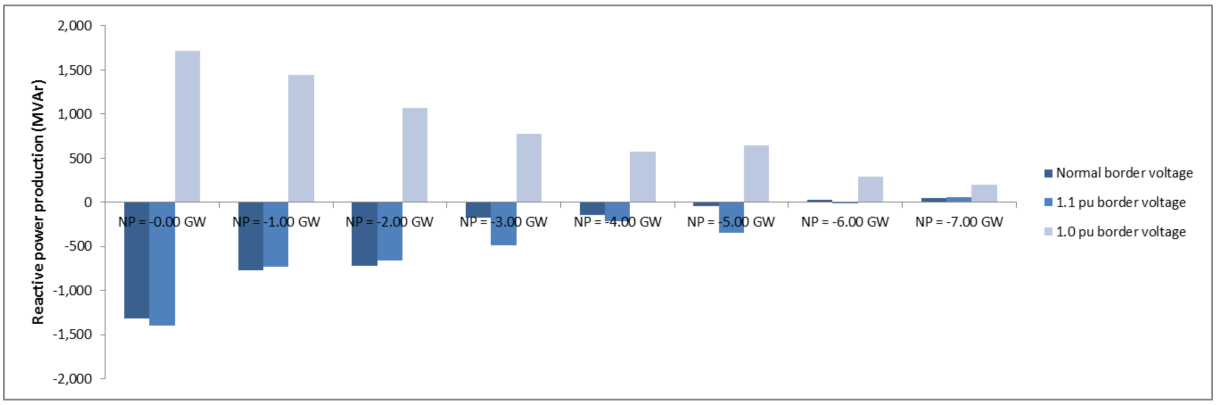

Figure 36: Generator reactive power output for border voltages scenarios. In case of high respectively low border voltages, the generators absorb respectively produce reactive power to their maximum capability.

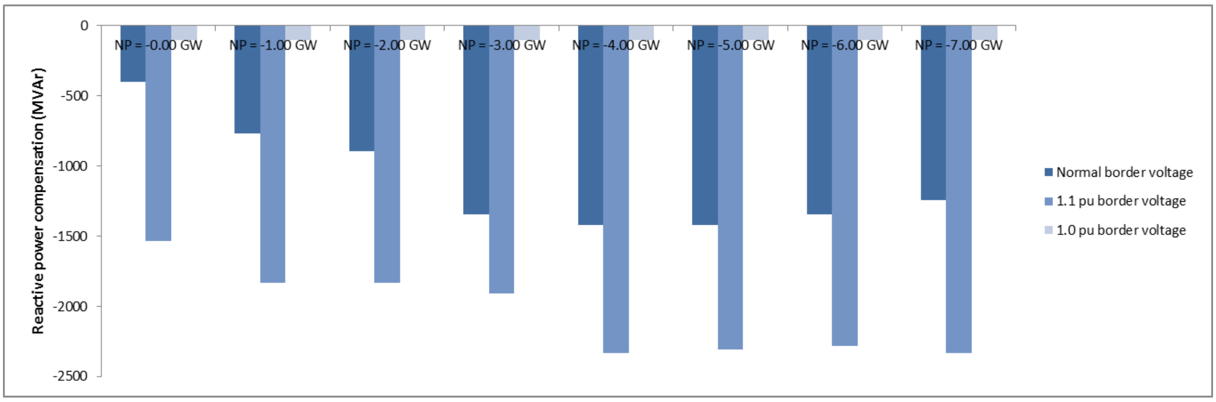

Figure 37: Reactive power shunt devices for border voltage scenarios. For high border voltages, all reactors throughout the network are in-service. Vice versa, for low border voltages, they are all out-of-service.

Chapter 7

Translation of scenario results to flow-based external constraints

A couple of elements have to be considered when external constraints are defined. First, the external constraints set should safeguard for complete grid stability. Only voltage stability analysis is not sufficient, dynamic stability, scaling errors and other security influencing elements should be considered as well. The most limiting element of these elements will determine the final external constraints.

Therefore, this voltage stability analysis alone does not suffice if new, scenario dependent external constraints have to be defined. Additional studies, for instance on dynamic stability, minimum inertia or the linearization errors of the FB-CC process have to be conducted before a complete picture of Dutch grid stability could be given.

Second, the results of off-line studies are often not directly applicable in the flow-based capacity calculation process. Therefore a translation has to be made from off-line study results towards a format usable in the capacity calculation process, in this case a combination of PTDFs and RAM.

The translation for the voltage stability analysis in this thesis is relatively straightforward because of the use of net position as the main scenario driver. This is largely in line with the current implementation of the external constraints. For each module (combination of scenario drivers excluding net position) the largest secure net position could be defined, this net position could be used in the FB-CC process.

Last, the external constraints can be implemented in the flow-based capacity calculation process in different ways. Although an external constraint will always be a combination of PTDFs and RAM, a lot of variants are possible in this regard.

This chapter will focus on this last element. First, the current method of external constraints implementation will be explained and the effect external constraints have on the FB-domain will be demonstrated. Afterwards, two new methods of implementing external constraints will be introduced.

At the moment, these new implementation methods are only conceptual. New exact external constraints cannot be defined because the results of this analysis are not unambiguous enough and voltage stability alone is sufficient enough. Therefore, a proof-of-concept will be given in this chapter, but a new set of external constraints or detailed implementation examples are not possible.

7.1 Current implementation method and effect of external constraints in FBCC

The principle of external constraints is already explained in Chapter 2. In this section, we'll focus on the effect the external constraints have on the Flow-based domain. This will provide a clear starting point for the implementation of scenario based external constraints, as will be introduced in the next two sections.

The same 2D example flow-based domain we used in Chapter 2 will be used throughout this chapter. In reality, the flow-based domain is a 3D body, with the exchange between B and C on the third axis. For the sake of clarity, this B-C exchange will be fixed throughout this chapter, so the FB-domain can be represented by a cross section of this body. Consequently, the constraints, which are depicted as lines in this example, would be planes in reality.

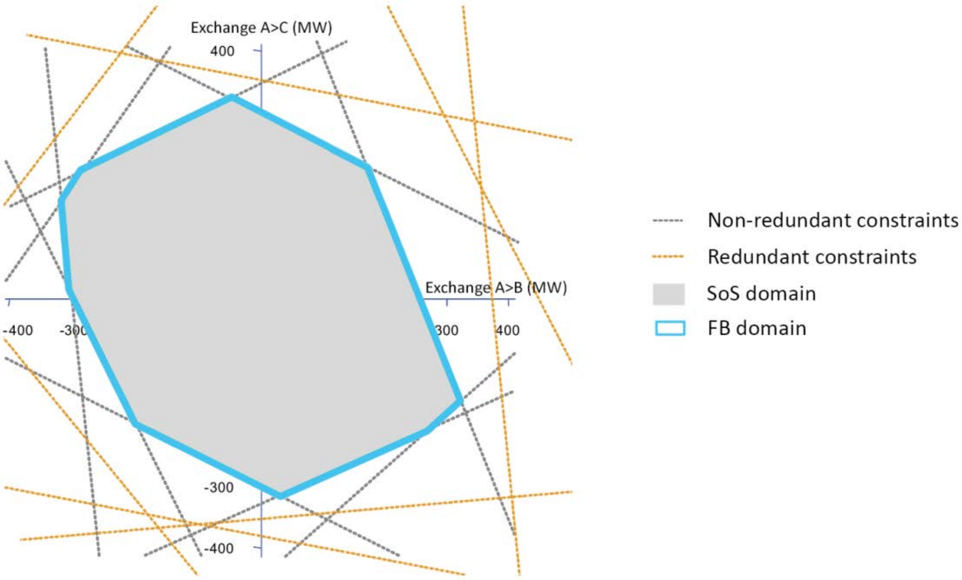

Figure 38: Flow-based domain, without external constraints, as introduced in Chapter 2. The non-redundant constraints determine the borders of the Flow-based domain, which contains all the possible clearing positions for the market.

Figure 38 depicts the original FB-domain. Each individual constraint represents the thermal limits of a line or other grid element, therefore, the combination of most-limiting constraints will form the Security-of-Supply (SoS) region (indicated in yellow). This is also the FB-domain available to the market coupling mechanism.

Current implementation method of external constraints in the capacity calculation process

As explained earlier, TSOs can introduce external constraints to safeguard for other issues affecting grid security (i.e. voltage stability, dynamic stability, inaccuracies due to scaling effects et cetera). External constraints are introduced in the system in the same way as 'normal' constraints; as a combination of power transfer distribution factors (PTDFs) and remaining available margin (RAM). In the capacity calculation process there is no distinction between internal and external constraints. At this moment the external constraints implemented by TenneT are based on a maximum net position of 4250 MW (import or export).

A net position dependent constraint is implemented using PTDFs of 1 or -1 for each of the country's borders, depending on the reference direction of the power flow on the border. The RAM-PTDF-exchange relation is given by the formula:

$$RAM_{new} = RAM_{old} + \sum_{x = all\ zones\ except\ A} (Exchange_{A-x} * PTDF_{A-x})$$

For example, Country A accepts a maximal export net position of 400 MW. This results in a RAM of 400 MW in a neutral (net position = 0 MW) starting case. Using a PTDF of -1 for A->C exchanges, a 200 MW exchange would result in a RAM of 200 MW:

$$RAM_{new} = RAM_{old} + (Exchange_{A-C} * PTDF_{A-C}) = 400 + (200 * -1) = 200$$

Combinations of exchanges are possible as well, an A->C exchange of 200 MW combined with an A->B exchange of -100 MW would result in a new RAM of 300 MW. This is in line with the accompanying net position of 100 MW. Also, when the reference exchange would be C->A instead of A->C, the PTDF would become 1 and an export flow from A to C would become a negative exchange.

As a result of this implementation method, external constraints will always be represented by 45°/135° lines (relative to the x-axis) in the upper right and lower left quadrant. For example the external constraint depicted in Figure 39 left, each position on this line results in a net position of 400 MW export for country A:

$$Net\ position_{A} = Exchange_{A-B}\ (MW) + Exchange_{A-C}\ (MW) = 400\ MW$$

Effect of external constraints on the Flow-based domain

When a TSO introduces an external constraint, two situations are possible. In the first situation, TSO A introduces an external constraint with a net position limit of 400MW (i.e. exporting). This situation is depicted in Figure 39 left. In this case, the external constraint is a redundant constraint, since there are more limiting constraints already. The external constraint will not have an influence on the available capacity for the market.

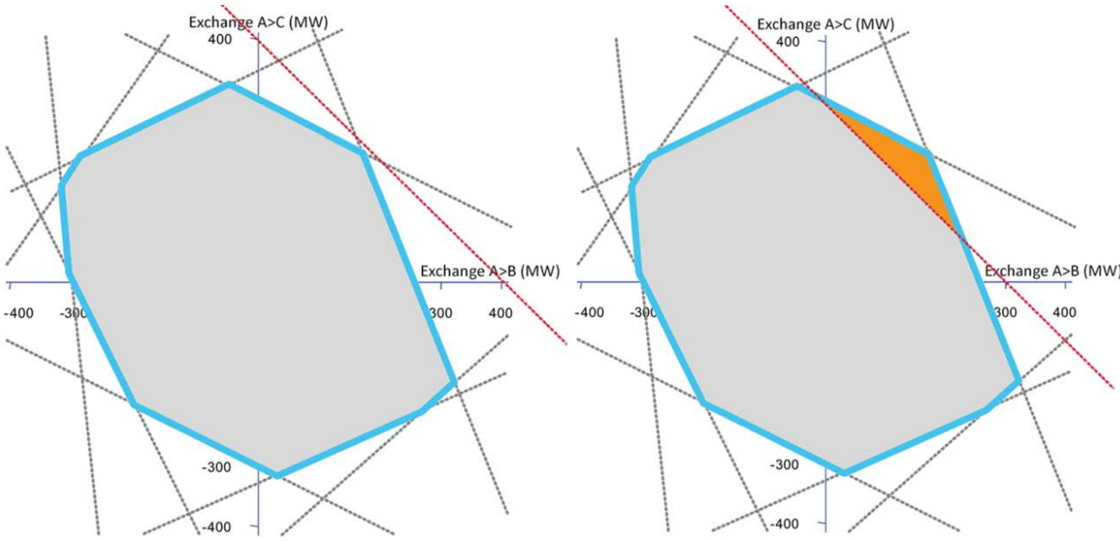

Figure 39: Two possible situations when a TSO introduces an external constraint, non-limiting the FB-domain (left) or limiting the FB-domain(right).

In the second situation, TSO A introduces an external constraint with a net position limit of 300MW. This situation is depicted in Figure 39 right. Without the external constraint the orange area was inside the SoS-region and therefore would be a possible clearing position for the market. However, based on the off-line studies supporting the external constraint, the orange area would be an unsecure situation and should not be available to the market. When the external constraint is introduced, it becomes the most-limiting constraint, influencing the FB-domain. The resulting FB-domain is depicted with the purple line in Figure 40. The unsecure orange area is now outside the FB-domain, no longer available to the market.

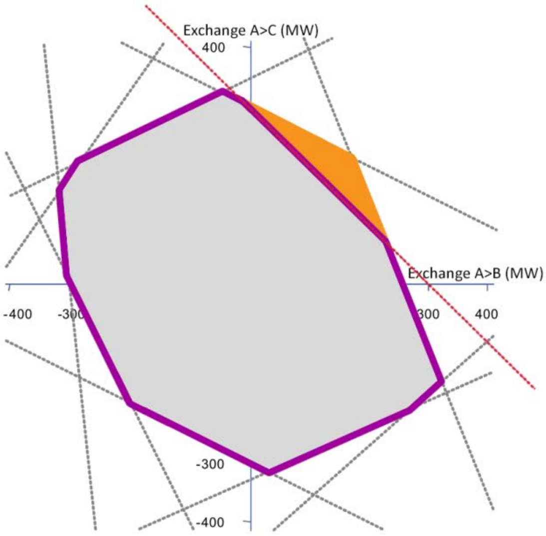

Figure 40: Resulting FB-domain of the situation where the TSO introduces a limiting external constraint.

Limitation of the current implementation method of external constraint

The current implementation method of external constraints has a couple of limitations. First, only two external constraints are implemented, one for a maximal import net position and one for a maximal export net position. Therefore, these constraints should safeguard for all scenarios. Chapter 6 has shown that grid operating points can be very different between scenarios, therefore current external constraint inevitable maintain an unnecessary large security margin for some scenarios.

Also, the external constraints currently implemented are solely focused on absolute net position, regardless of the origin or destination of cross-border flows or other influential flows apparent in the grid operating point. All are all based on PTDFs of -1 and 1 combined with a RAM till the maximal net position. As a result, the external constraints have only one possible shape; 45°/135° lines.

For both limitations, a solution is suggested in the next sections. First, a method to adapt the external constraints to the scenarios is introduces. This reduces the need for unnecessary large security margins. Second, a method is introduced to adapt the shape of the external constraint more towards the actual insecurity. This reduces the need to exclude unnecessary large areas from the flow-based domain.

7.2 Method 1: Scenario dependent external constraints

In the current implementation method of external constraints, only two external constraints are introduced, one to limit the maximal export net position and one to limit the maximal import net position. These should provide additional grid security for all possible grid operating scenarios. This could result in needlessly large security margins or 'false positive' limitation of the market, some sort of mismatching of the external constraints and flow-based domain. After all, the location of the external constraints is not dependent on the grid operating point and consequently flow-based domain.

For example a situation could occur where the external constraint limits the market, while in that particular grid operating point, no security issues would have arisen if the external constraints would have been exceeded. Some example situations are schematically depicted in Figure 41.

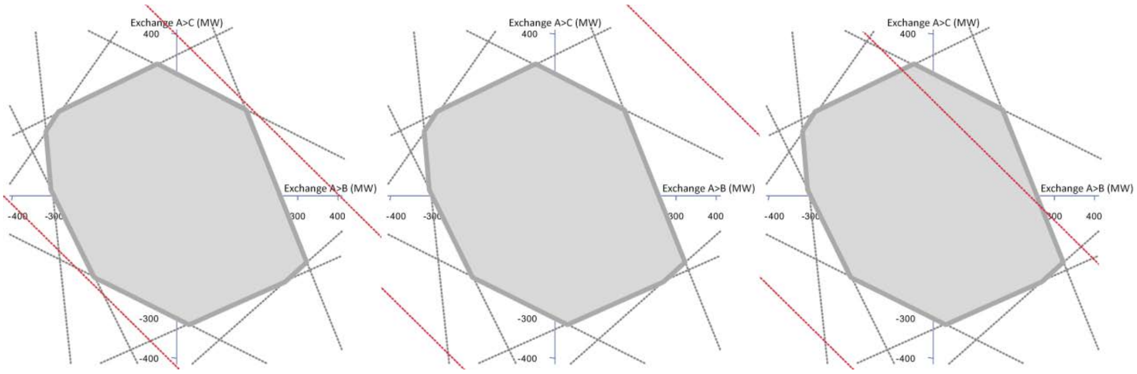

Figure 41: Various possible results with grid operating point independent external constraints. Left shows the ideal situation with external constraints in line with the fb-domain derived from internal constraints. In the middle picture a possible but harmless situation. External constraints are less strict than the flow-based domain. In the right picture an undesirable situation where the external constraint limits the flow-based domain significantly, while this not might be necessary. The exception in this situation will be when this external constraint is really determined for this grid operating point and exceeding it will pose security issues.

To overcome this situation, a scenario-dependent external constraint could be introduced. This would result in a specific external constraint for a grid operating point. A couple of elements will be considered; the implementation method in the flow-based process, the effect scenario based external constraints have on the flow-based domain and matching the grid operating point forecast to the scenario based external constraint.

Implementation in the flow-based process and effect on the flow-based domain

To minimize the amount of changes necessary to the current implementation method, scenario-based constraints are implemented in the same way as the current external constraints. The PTDFs will be similar for each external constraint, but the RAM will vary depending on the grid operating point. Essentially, the maximal net position (either import or export) will vary according to the grid operating point. An example overview of grid operating points versus PTDFs/RAM combination is depicted in Figure 42.

Grid operating point / Scenario	RAM (MW)	PTDF NL-DE	PTDF NL-BE	PTDF BE-FR	PTDF DE-FR
Scenario #1 Export	X_1	-1	-1	0	0
Scenario #1 Import	Y_1	1	1	0	0
Scenario #2 Export	X_2	-1	-1	0	0
Scenario #2 Import	Y_2	1	1	0	0
⋮	⋮	⋮	⋮	⋮	⋮

Figure 42: Example of how a scenario-based external constraint set could look like. For different grid operating points/scenarios (or groups thereof), external constraints with different RAMs but identical PTDFs will be implemented.

Due to a changing RAM but similar PTDFs, all external constraints will stay parallel to each other. Compared to the current implementation method, this effect is depicted in Figure 43. Obviously, the flow-based domain will be different for each scenario as well due to changing grid operation points.

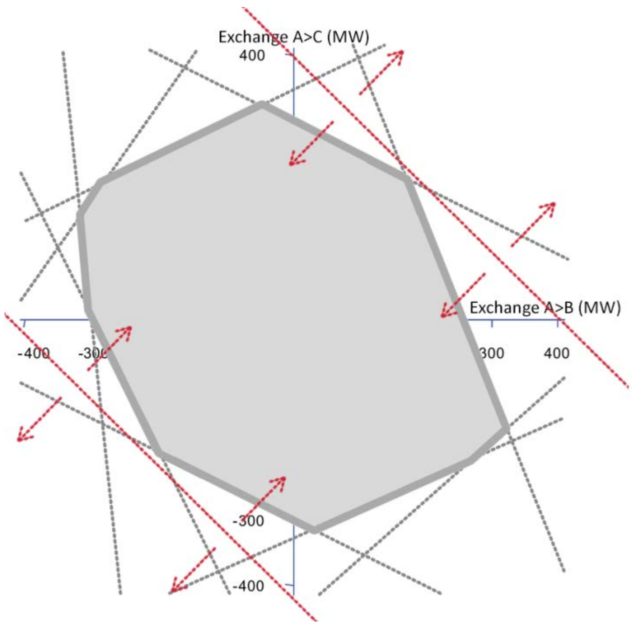

Figure 43: Effect of changing the RAM for external constraints. The external constraints will shift up or down, parallel to the original constraints.

Matching forecasted grid operating point with external constraints determined in off-line study

Using off-line studies, external constraints can be made for a variety of different scenarios. An additional process is necessary to match one of the predefined scenarios (and consequently their external constraints) with the forecast of the grid operating point at the business day. To do this, a 'matching process' has been defined.

Figure 44 shows a process overview of the whole matching process. Roughly, it can be divided in three parts. First, during off-line studies, a set of external constraints has to be defined. This starts with defining various scenario drivers. These will be used to define scenarios for the stability analysis. Finally, external constraints can be determined for each scenario. This approach is used in this thesis as well.

Second, the grid forecast has to be analyzed to see which of the scenarios matches with it the best. This uses the D2CF files provided on a daily basis by the flow-based process. The grid forecast included in this file has to be analyzed on characteristics similar to the scenario drivers like load level, generator dispatch, exchanges and transit flows. Afterwards, the scenario with the same scenario driver characteristics can be determined and its off-line determined external constraints will be the one valid for this grid forecast. These external constraints will be the one used in the flow-based capacity calculation process to determine the final flow-based domain.

Additionally, a feedback loop can be implemented to improve this process. For instance, the scenario drivers can be changed if specific grid effects turn out to be influence grid stability more than expected or less than expected. Also, the way of analyzing and matching the D2CF grid forecast could be improved based on first experience.

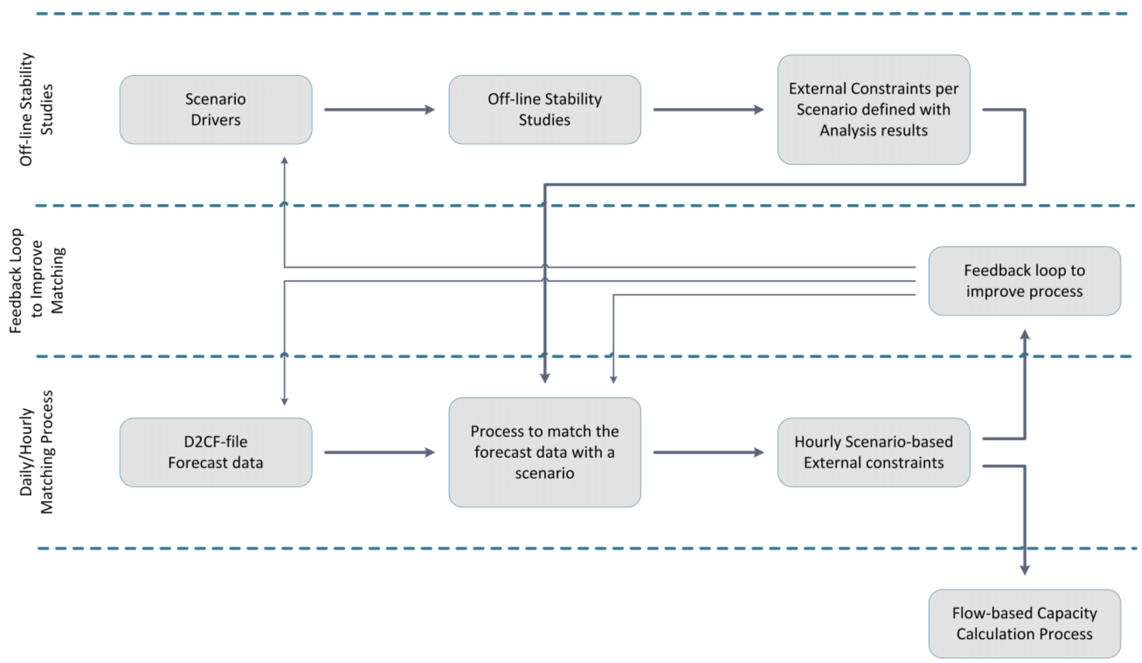

Figure 44: Overview of the matching process of the scenario-based external constraints with the daily grid forecasts used in the flow-based capacity calculation process.

Remarks on scenario-based external constraints

The main advantage of this scenario-based external constraint method is the relative ease of implementation in the current flow-based capacity calculation process. Only the RAM of the external constraint changes, all other elements stay the same. Within TenneT, the process of matching the grid operation point from the D2CF-files and the external constraint set from off-line studies should be developed. Since this is an internal process, this should be relatively straight-forward.

Also, this system of scenario-based constraints will probably profit from most of the quick-wins, delivering relatively big gains compared to the amount of effort necessary. It can be started relatively simple, with a small amount of possible external constraints, and extended into more detailed external constraints sets later on. This way a solid and incremental implementation process can be defined.

The main difficulty of this system will be the determination of exact RAMs for specific grid operating points. As is shown in Chapter 6, grid operating points in different scenarios do vary considerably, but putting an exact number on the maximal import net position is difficult. This requires a reliable grid model and clear load-flow results, something that has proven difficult to obtain.

Also, the complexity of the problem rises quickly when implementing several scenario drivers because of the large amount of scenarios possible, which all have different outcomes and a lot of data. This will make the determination of a complete external constraint set a very labor intensive problem.

7.3 Method 2: Implementation of scenario dependability inside FB-CC mechanism

Method 1 introduces an implementation of scenario-based external constraints in the flow-based capacity calculation process. Nevertheless, all these external constraints are still with the 135°/45° orientation and the specific external constraint has to be determined externally from the FB-CC process. This method introduces some concepts to change this as well.

These concepts allow the external constraints to be defined in a way that the least possible amount of unnecessary market space is removed because unsecure market space can be removed locally. In the end, this could deliver the most accurate secure market space, alas at a high cost of increased complexity.

Implementation methods in the flow-based capacity calculation process do not have to be different from the method introduced in the previous section. Still, a forecasted grid operating point can be combined with a predefined external constraint set. But in this case, the external constraints can be even more tailor-made to the grid operating point.

Another difference with method 1 is the fact that the possibilities in this section are mainly conceptual. To implement these concepts, a very high accuracy of the offline studies is crucial. As shown in Chapter 6 this is hardly the case at this moment. Also, various stability phenomena should be combined and each requires its own off line studies. As a result, a lot of effort is required to compile a complete set of external constraints. Therefore, the chances that these possibilities will be used in the near-future are very small. Nevertheless they are introduced here, because it gives a good insight in the vast possibilities of external constraints in the flow-based capacity calculation which are not yet exploited.

7.3.1 Flexible orientation of external constrains

Method 1 only uses a variable RAM per scenario, but the PTDFs for each external constraint are the same for similar import/export situations. By changing the PTDFs as well a much larger set of external constraint shapes is possible.

External constraints until now have always had a 135°/45° orientation, caused by PTDFs of 0, 1 or -1. This is a result of the choice to use net positions as the main external constraint driver. But other drivers, like maximal cross-border flow or a variable influence per cross-border connection could be implemented as well with the following methods.

Maximal single cross-border flow constraints

When the maximal amount of transport for one border should be limited, this is possible by introducing a non-zero PTDF for only this exchange direction. At a neutral starting point, the RAM should be the maximal allowable flow and the RAM is influenced by;

$$RAM_{new} = RAM_{old} + (Exchange_{A-B} * PTDF_{A-B})$$

Where $Exchange_{A-B}$ is the cross-border flow for that specific border and the accompanying $PTDF_{A-B}$ for that border is 1 or -1 (depending on the reference direction). This would result in external constraints as depicted in Figure 45.

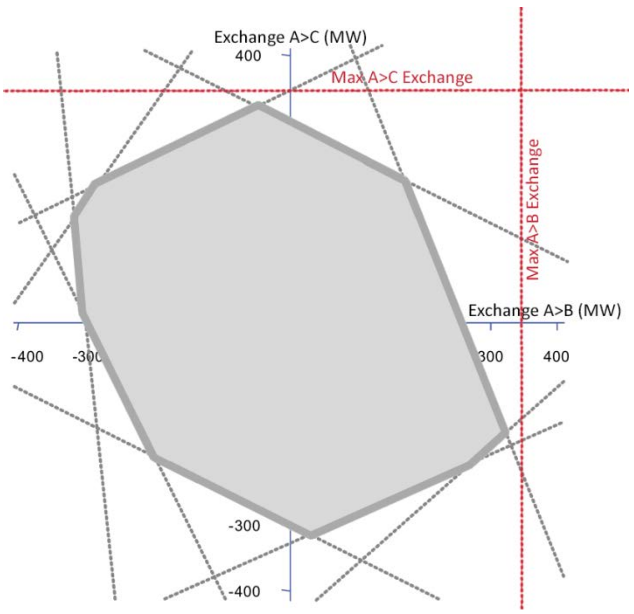

Figure 45: Maximal cross-border exchange constraints for a single border using a non-zero PTDF for only 1 exchange direction.

For example, with a neutral point RAM of 500 MW, a cross border exchange between A and B of 200 MW would result in: $RAM_{new} = 300 = 500 + (200 * -1)$. In this case, the $PTDF_{A-B}$ is -1 since the reference direction is from A to B.

An external constraint of this type is comparable with the Available Transfer Capacity (ATC) technique. In both cases, the available transport capacity is determined on a per-border basis.

Variable cross-border exchange influence on Remaining Available Margin

Using the net position as the main driver for external constraints, the implicit assumption is made that the influence of cross-border flow on stability issues is the same, regardless of the division of flows between borders. This might not be the case when one cross-border connection to a country is much stronger than another cross-border connection. To implement this effect the PTDFs can be adjusted to create an external constraint with different sensitivities for various cross-border flows.

In this case, the RAM can't be connected to a single cross-border flow or net position anymore. It is the representation of a combination of the cross-border flows on multiple borders. Again, departed from a neutral start point, the RAM should be the maximal allowable combined flow and the RAM is influenced by;

$$RAM_{new} = RAM_{old} + (Exchange_{A-B} * PTDF_{A-B}) + (Exchange_{A-C} * PTDF_{A-C})$$

For example, let's assume the combined starting point for the RAM is 200 MW. Also, cross-border flow on the A-B border is twice as influential compared to the A-C cross-border flow. This would result in a $PTDF_{A-B}$ of -1 and a $PTDF_{A-C}$ of -0.5. This will result in a maximal cross-border flow of 400 MW on the A-C border ($RAM_{new} = 0 = 200 + (400 * -0.5)$) and a maximal cross-border flow of 200 MW on the A-B border ($RAM_{new} = 0 = 200 + (200 * -1)$). Combinations of cross-border flows are possible as well, as is depicted in Figure 46. The external constraint represents the points where the RAM is zero. The point halfway the external constraint for example represents a cross-border flow of:

$$RAM_{new} = RAM_{old} + (Exchange_{A-B} * PTDF_{A-B}) + (Exchange_{A-C} * PTDF_{A-C})$$

$$0 = 200 + (100 * -1) + (200 * -0.5)$$

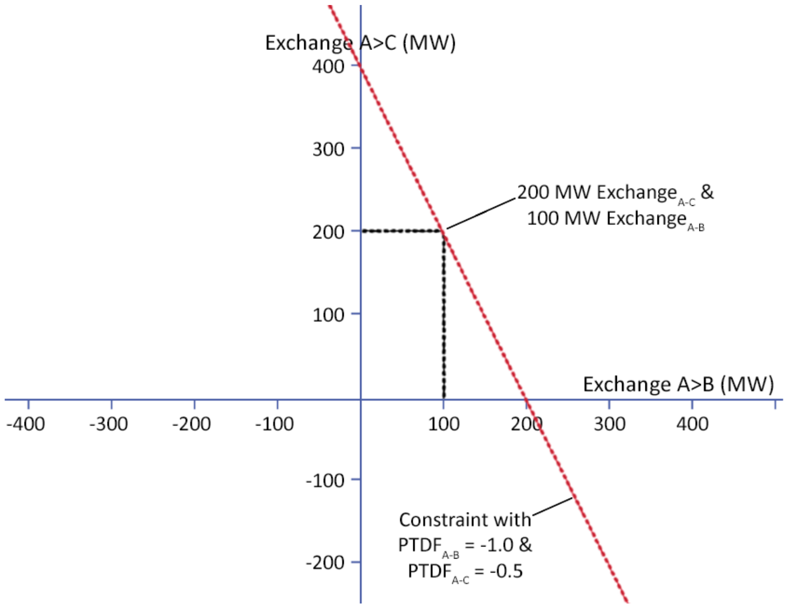

Figure 46: An external constraint using a different PTDF for A-C and A-B exchanges.

Using various PTDFs for different exchange directions, external constraints in all orientations could be implemented. This creates the possibility to trim the flow-based domain very accurately to the necessary security measures. As a result, as little as necessary grid operating points are removed from the market clearing possibilities.

7.3.2 Internal compensation of external constraints for scenario driver effects

Besides trying to shape the external constraints as much to the real stability limits as possible, another option could be to implement the effects a scenario driver has on the external constraints values inside the FB-CC.

Especially the effects of external scenario drivers, caused by trading behavior of other countries are suitable to be implemented in the external constraint determination in this way. The most important external scenario driver, the AC-transit flows, will be used in this section to demonstrate this.

There is no need any more to include the AC-transit as a dependability in the external constraint set when the effects of AC-transit flows are directly incorporated in the external constraints. This will reduce the complexity of the matching process of forecasted grid operating point and off-line study scenario. At the other hand, it will add complexity to the determination of the external constraint itself.

Adapting for AC-transit inside the flow-based capacity calculation process

An AC-transit through the Netherlands is caused by power flows resulting from Germany-Belgium or Germany-France trade actions. These trade actions are incorporated in the FB-CC PTDFs as well. Previously, these PTDFs were considered zero for Dutch external constraints, but to incorporate the AC-transit effect directly in the external constraints they will become non-zero.

To directly incorporate the effect of the AC-transit on country A's external constraints, the previously used RAM-formula can be adapted to:

$$RAM_{new} = RAM_{old} + (Exchange_{A-x} * PTDF_{A-x}) + (Exchange_{x-y} * PTDF_{x-y})$$

Where the *x-y* exchanges are all exchanges not incorporating country A. Let's assume that the exchange of B-C results in a transit flow through A of 40% the exchange size. Also, the influence of the transit flow is such that this reduces the available transport capacity in the same way normal exchange does. As a result, the $PTDF_{B-C}$ will be 0.40. If necessary, these PTDF's can be multiplied by an influence factor if a transit flow of x MW should not lead to an x MW adaption of the RAM.

For example, country A has a neutral point RAM of 400 MW. It exchanges 100 MW with country B and 100 MW with country C. Similar to earlier settings, this will result in a new RAM of:

$$RAM_{new} = RAM_{old} + (Exchange_{A-B} * PTDF_{A-B}) + (Exchange_{A-C} * PTDF_{A-C})$$
$$= 400 + (100 * -1) + (100 * -1) = 200$$

Now country B exchanges 200 MW with country C and the resulting transit flow will be incorporated in the external constraint:

$$RAM_{new} = RAM_{old} + (Exchange_{B-C} * PTDF_{B-C}) = 200 + (200 * -0.4) = 120$$

The result of this is stepwise depicted in Figure 47. Also note that the AC-transit is direction dependent, with an exchange from country C to country B ($Exchange_{B-C} = -200$), RAM_{new} would become 280 MW.

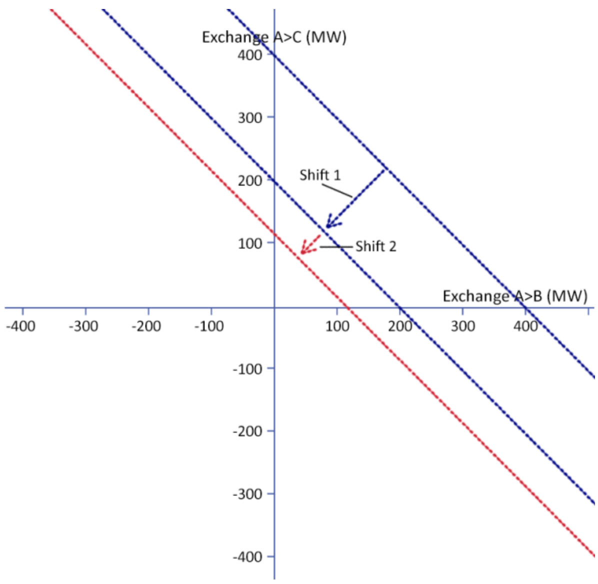

Figure 47: Example influence of directly implemented AC-transit influence in external constraint. Shift 1 is caused by country A's own exchanges. Shift 2 is cause by the transit flow through country A by a trading between country B & C.

Load-flow solutions performed when implementing the AC-transit scenario driver in the script (see Chapter 5.1.3) have shown that the resulting power flow from Germany-Belgium or Germany-France trading through the Netherlands is quite stable. For Germany-Belgium, about 55% of the resulting power flow passes through the Netherlands, for Germany-France this is about 30%, schematically depicted in Figure 48. Although these numbers vary depending on generator dispatch and load distribution in both countries, they will be used as a first approach.

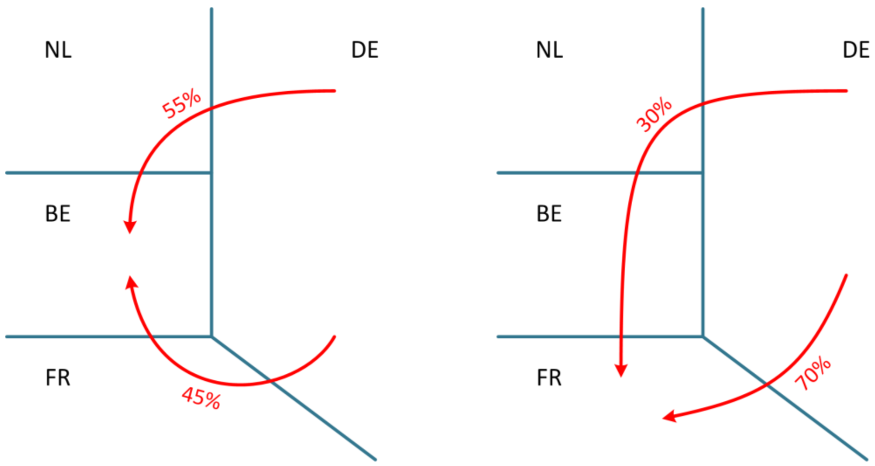

Figure 48: Transit flow division for Germany-Belgium exchanges (left) and Germany-France exchanges (right).

In the CWE-case, this would mean the $PTDF_{Germany-Belgium} = -0.55$ and the $PTDF_{Germany-France} = -0.30$ for Dutch external constraints. This means, if a 1000 MW trade is made between Germany and Belgium, 550 MW will pass the Netherlands as a transit flow. In total, the RAM-formula for the Netherlands will result in;

$$RAM_{new} = RAM_{old} + (Exchange_{NL-BE} * PTDF_{NL-BE}) + (Exchange_{NL-DE} * PTDF_{NL-DE}) + (Exchange_{DE-BE} * PTDF_{DE-BE}) + (Exchange_{DE-FR} * PTDF_{DE-FR})$$

Where the first two exchanges are exchanges influencing the Dutch net position (similar to earlier examples). The last two exchanges are only involving the Netherlands through transit flows.

Chapter 8

Conclusions & recommendations

This chapter will conclude the work done in this thesis. First, a short summary of the work done in this thesis is given combined with an answer on the initial research questions. Afterwards, the main conclusions drawn from the work in this thesis will be described. Lastly, some recommendations for the continuation of this research topic work will be given.

An initial remark has to be made regarding the division of work. During this thesis, it became clear that the work was dividable in two separate parts. One is the concept of scenario-based external constraints, the flow-based process and the implementation of scenario-based external constraints in the flow-based capacity calculation. The other is the static voltage stability analysis that supports the off-line study towards a set of scenario-based external constraints, in this case for voltage security. Conclusions and recommendations can be divided in these two categories as well.

8.1 Summary of the work

The first part of this thesis focuses on the structure of a voltage stability analysis that could support scenario-based external constraints. Also, the following research question had to be answered:

- *Which grid model is suited for analysis and which adaptations to the model are needed to create a stable and suitable starting point for analysis?*

This resulted in the usage of a static voltage stability analyses, using a combination of static load-flow solutions and accompanying contingency analysis to investigate static voltage stability for a multitude of scenarios.

These scenarios are all based on a 'starting' case model. Since none of the available models was directly suitable for this analysis, as a result a modified ENTSO-E reference model has been used. This way, we could maintain the advantages of the ENTSO-E reference model; it's verification throughout European fora, it's inclusion of the complete synchronous European grid and relative ease of use in automation processes. But also, we could overcome the downsides of the ENTSO-E reference model by improving the accurateness of generator capabilities, adding reactive power compensation devices and implementing automatic voltage control possibilities.

Using this 'starting' case model, a data set of scenarios has been made. With an automated process, the 'starting' case model was adapted to each combination of scenario drivers. This resulted in a data set of 1944 different scenarios (243 modules with rising import level). Using this data set, the following two research questions could be answered:

- *Which scenario parameters have influence on the voltage stability of the Netherlands?*
- *What are the voltage stability borders in the investigated scenarios?*

Three categories of scenario drivers have been taken into account; internal drivers (net import position and load level), external drivers (AC-transit flows and DC-transit flows) and extreme drivers (clustered generation location and border voltages). The influences these drivers have on voltage stability are described in the next section, since these are among the main conclusions of this thesis. To aid the analysis, a couple of result overview tools have been created as well.

Lastly, methods to translate the results of off-line studies towards external constraints have been investigated, used to answer the last research question:

- *How to translate simulation results and accompanying voltage security limits to parameters that are suitable for the flow-based capacity calculation process?*

First, the current method of external constraint implementation is described and the effect on the flow-based domain is shown. Afterwards, a couple of concepts have been described to translate the scenario-based analysis results towards external constraints. These concepts start relatively simple, with only one variable (the remaining available margin) changed compared to current external constraint. But more detailed adaptions can be made as well, as shown by concepts with changing power transfer distribution factors (PTDFs) or implementing scenario driver influences into the PTDFs.

8.2 Conclusions

The conclusions of the research can be divided in three parts, which will be described one-by-one. First, the concept of a scenario-based external constraint will be evaluated. Second, the results of the voltage stability analysis will be discussed. Lastly, conclusions regarding the translation of analysis results in the flow-based capacity calculation process will be described.

The concept of scenario-based external constraints

As a proof-of-concept, the analysis in this thesis has proven that scenario-based external constraints are a viable concept. In Chapter 6 is shown that different scenario drivers result in different grid operating points. Various grid operating points also demand different security measures. These security measures can be met with smaller margins when scenario-based external constraints are used, increasing the overall efficiency of usage of the grid.

In the future, with an increasing amount of renewables, increased cross-border transport possibilities and less predictable loads, the range of different grid operating points will become even larger. Although this will make the determination of scenario-based external constraints even more complex, the benefits will also become larger.

What has proven to be harder than expected is the exact quantification of the voltage stability borders for the Netherlands. Although a general consideration of voltage stability in individual scenarios is possible, the results are not unambiguous enough to put a specific import limit on the boundary between stability and instability.

To complicate this even more, a lot of different phenomena are influencing the results. For example, local stability problems occur in scenarios. Although this results in violation of the security requirements, these problems are not import driven and therefore specific safeguarding with external constraints is not desirable.

Also, in some scenarios the origin of voltage problems was due to inductive behavior of (very) high loaded lines. Although the resulting voltage violations are valid, it is unlikely that these scenarios would have been allowed in the flow-based domain. This is because these scenarios would have already been excluded from the flow-based domain based on the thermal line limits (represented by internal constraints).

In general, reactive power balancing seemed to be a larger influence on the voltage stability than scenario drivers. It has to be realized though, that reactive power balancing is influenced by the scenario drivers as well. For example, due to the amount of available in-service generators or line-loading due to transit of import transports.

When not taking into account these other influences, clear voltage stability problems have not been encountered. On the contrary, importing levels up to the maximal 7 GW seemed to be no problem voltage stability wise. It has to be remarked that line loading internal constraints probably would not allow these scenarios.

Apart from the ambiguous results of voltage stability, the large amount of scenarios and analysis thereof has proven to be a major hurdle in this research. Although some analysis tools were developed, the large variety of violation reasons made manual, in-depth and very time consuming analysis of each scenario necessary.

Results of the scenario voltage stability analysis

As indicated in the previous section, the voltage stability analysis results are not unambiguous enough to determine an exact number for the external constraints. Instead of a hard boundary between stable and unstable scenarios, the grey area in between was very large and other effects influenced voltage stability as well. Nevertheless, the general effects of a scenario driver on the grid were visible. For each separate scenario driver, the following effects were visible.

The net import position of the Netherlands was supposed to be the main influencing scenario driver and expected to create stability issues for larger import levels. This effect has not been confirmed by the stability analysis. A decrease in reactive power capabilities by a lower number of in-service generators is visible. But this does not create issues because shunt device capabilities are sufficiently available and the increased line loading lowers the need for absorbing reactive power. Large import does not lead to excessive line loading because this is evenly divided throughout the gird.

Load level influence is mainly as expected. Low load results in high voltages, although this seems to originate more from capacitive behavior of overhead lines than from lack of reactive power resources. Medium load has a nice balance between in-service generators and line loading; these scenarios can be considered the most stable. High load level experiences quickly situations with high line loading, especially in combination with other drivers. The resulting inductive line behavior is the main voltage influencer.

AC-transit flows are causing a lot of extra line loading through the Dutch grid, which is also the main cause of problems related to AC-transit flows. Especially the lines Diemen-Lelystad-Zwolle are influenced by AC-transit flows. The effects however are more related to inductive behavior of highly loaded lines and reactive power balancing. Therefore, a lot of these problems will also be solved by the normal internal constraints or by improving the reactive power capacities at these locations.

DC-transit flows have the same effect of AC-transit flows, mainly extra line loading. However, the influence of the HVDC-lines is with maximal 1000MW power flow not that considerable. Therefore, it should simplify the scenario based analysis when the HVDC-lines would be taken into account as generator or loads. This will have the same effect but decreases the amount of scenarios a factor of three.

As expected, the extreme scenario drivers did influence the grid heavily, especially the resulting effects were interesting, not so much the exact outcomes. Regarding the generation concentrated around one area, the Eemshaven scenarios stood out. In this case, large transports will occur from the north of the Netherlands towards the Randstad. As a result, the voltages in the north became more stable with medium imports because these imports meant the line loading was better divided. High line loading effects resulting from high-import Eemshaven generation combined with AC-transit flows proved to be an especially toxic cocktail, these scenarios were the only resulting in divergent load-flow solutions.

The border voltage scenarios have mainly proven the fact that the Dutch grid can be considered highly meshed with the Belgian and German grid. With high border voltage differences, the reactive power cross-border transports became very high because of this. Also, reactive power compensation devices capacity was not enough to overcome these problems. It seems that adapting more to the cross-border voltage is a more sensible solution than trying to compensate for the big voltage difference.

Implementation of external constraints in the flow-based capacity calculation process

Although the voltage stability analysis did not result in a set with specific import limits per scenario, some concepts to translate the off-line study results towards external constraints have been introduced.

The most straightforward method is to use the same format of external constraint as the currently implemented constraint combined with a process that matches the grid forecast to the corresponding scenario's external constraints. Also, a couple of external constraint implementations are shown to safeguard for specific effects like maximal single border flow, uneven border influence on the remaining available margin and direct integration of AC-transit flows.

All in all, it can be concluded that the implementation of scenario-based external constraints is possible in multiple ways. Although not directly applicable, some implementation work still has to be done, it would not pose the biggest difficulty while implementing scenario-based external constraints.

8.3 Recommendations for future work

Similar like the conclusions, the recommendations for future work can be divided into two parts, one for the voltage stability analysis and one for the scenario-based external constraints in general.

Recommendations on voltage stability analysis work

The voltage stability analysis performed in this research has not resulted in clear boundaries of voltage stability for the scenarios. It is important that these boundaries become clear before an external constraint set is composed. Also, other stability issues and scaling issues have to be investigated in order to include all security risks.

The analysis of scenarios has proven to be a large amount of work. Therefore, the best way is to start with an as small as possible scenario driver set. This will keep the analysis work and complexity manageable. Extending to more comprehensive external constraint sets is possible later on since the implementation method has room for extension.

Regarding voltage stability, additional work has to be done to divide stability issues. Is it required or desired to take into account internal non-import related stability problems or reactive power balancing problems when defining external constraints? Also, it has to be determined which scenarios are excluded by the flow-based process on a thermal limit basis.

Lastly, when performing a contingency analysis, it is advised to include specific contingencies like; the loss of only a generator or compensation device, the loss of only a cross-border line and other non-busbar contingencies that could harm voltage stability. Also, a lot of dispensable contingencies could be removed, mainly 110kV/150kV substation contingencies. This would decrease the amount of data for contingency analysis greatly, leading to easier result analysis

Recommendations on scenario-based external constraints

Scenario-based external constraints are a viable idea and probably beneficial to cross-border transfer capacity or grid usage. However, it is not yet implementable; the process of matching a D2CF forecast file to a specific scenario still has to be defined.

Also, the amount of allowed complexity has to be determined. Defining scenario-based external constraints can become a vast and complex problem. Starting with ‘simple’ sorts of external constraints is advised. A lot of possibilities to further improve the external constraints can be used later on.

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Appendices

Appendix A: Historic development of market coupling involving the Netherlands

To achieve a single European electricity market by coupling all countries at once would be an impossible task. Power systems are historically nation-orientated with transport bottlenecks on the borders and varied electricity generation fuel mixes, this complicates coupling markets. To overcome these difficulties, an intermediate step towards regional markets of countries with similar properties has been planned, as shown in Figure 49. Afterwards, these regional markets can be combined to one European market.

Figure 49: The creation of a single European electricity market with regional markets as intermediate solution. [2]

Trilateral Market Coupling

On the 21st of November 2006, the Trilateral Market Coupling (TLC) was launched successfully, coupling the day-ahead markets of The Netherlands, Belgium and France. It was the first step towards a regional market including the Netherlands and the first initiative to couple not only countries, and therefore separate TSOs, but also three separate power exchanges (APX, Belpex and Powernext).

Parts of the cross-border capacity on the France-Belgium and Belgium-The Netherlands borders were allocated implicitly by the three power exchanges. Market prices and trading volumes were based on available cross-border capacity of all TSO's and order books of all power exchanges in the coupled region. This replaced the explicit day-ahead trading on these borders. Long term allocation and intraday trading mechanisms did not change.

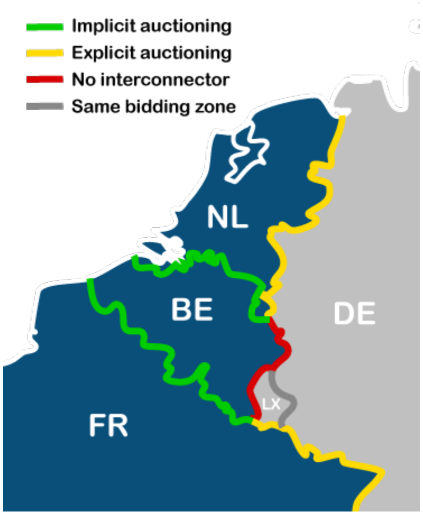


Figure 50: Trilateral Market Coupling region

The introduction of TLC involved several new concepts and served as a test case for larger European market coupling. For example, it was the first time independent power exchanges used a system of implicit trading without the use of a supranational market operator (like Nordpool). This required intensive co-operation between the three power exchanges and three TSOs additionally supported by governments, European Commission, regulators and market parties.

The results of TLC show the large advantages of market coupling and implicit trading. Figure 51 shows the great increase in price convergence between the Dutch and French market. Before TLC was introduced a price difference was nearly always apparent. After TLC introduction price differences were 0 €/MWh for 68% of the time. Figure 52 shows that price differences also occurred when sufficient transport capacity was available, due to mismatched trading of transport capacity and energy. These price differences disappear completely after TLC is introduced. Price differences are only apparent when transport capacity is insufficient.

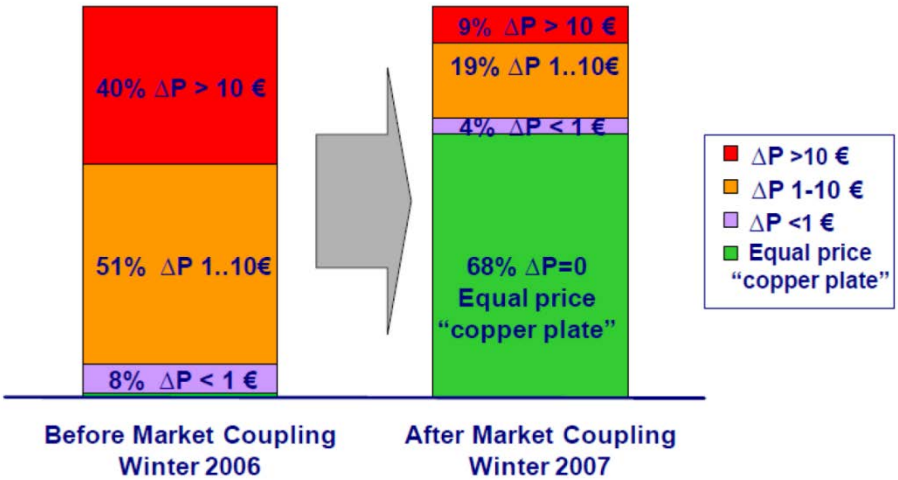


Figure 51: Before TLC, there are always price differences between the Dutch and French power markets. After TLC is introduced, price differences are for a large part disappeared. [3]

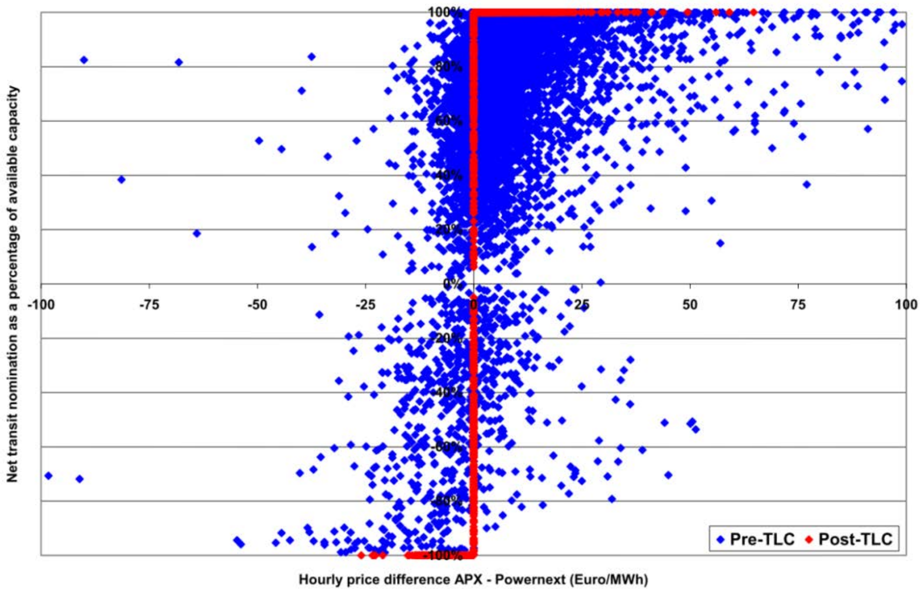


Figure 52: TLC's implicit (red) market coupling shows no price differences as long as transport capacity is sufficient (net transit nomination < available capacity). Explicit (blue) market coupling shows unnecessary price differences when sufficient transport capacity is available due to mismatched trading. [3]

Central Western European Market Coupling

On the 9th of November 2010, the Central Western European (CWE) market coupling initiative started, expanding the TLC region with Germany (and Austria). The day-ahead electricity markets of Belgium, France, Germany and the Netherlands are coupled by a price coupling mechanism close to the TLC market coupling mechanism. Since the region now contains four large and meshed electricity systems, the complexity is increased further.

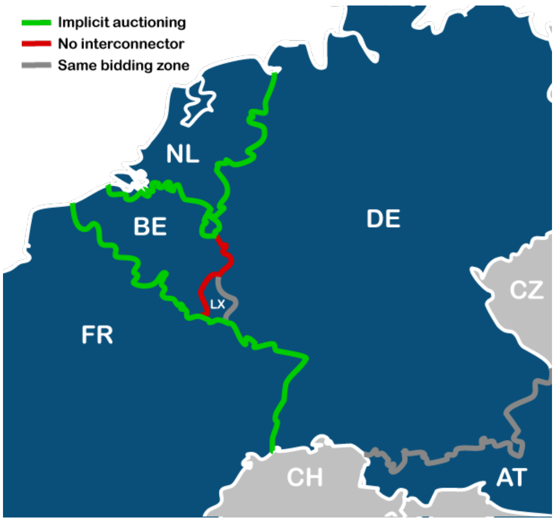


Figure 53: Central Western Europe Market Coupling region

For CWE market coupling, price convergence results similar to the TLC results are obtained. In Figure 54 the price differences between Germany and the Netherlands are depicted schematically. Approximately 75% of the time, no price difference between Germany and the Netherlands exist after CWE market coupling is introduced.

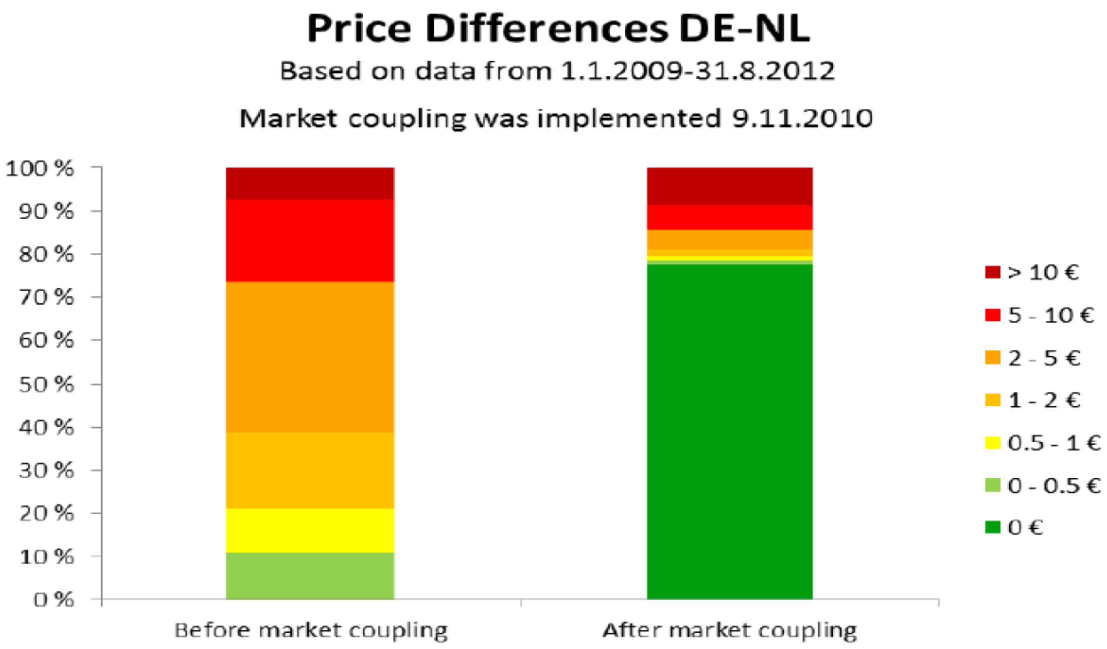


Figure 54: Price difference results for the German-Dutch border before and after CWE market coupling. [3]

Appendix B: Economic principle of market coupling

Market coupling relies on the principle of supply and demand. A two-market example can be used to explain the economic principle of market coupling. Although simplified, it depicts the economic principle behind market coupling clearly. Regarding power markets this means the markets with low(er) energy prices exports to the markets with high(er) energy prices.

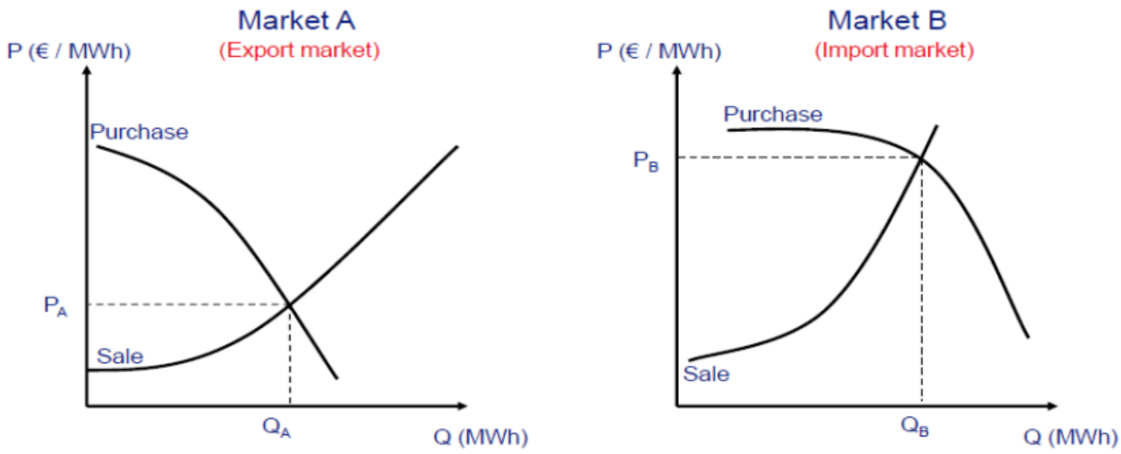


Figure 55: Supply & demand in uncoupled markets A & B. [3]

Figure 55 depicts the initial situation before market coupling, there is no connection between markets A and B. In this situation both markets are behaving independently and their supply and demand curves intersect at a different price.

When these markets are connected, the energy demand in the lower priced market A will increase, resulting in a higher clearing price. The additionally purchased energy on market A will be sold on market B, therefore increasing the supply of energy on market B. Market B will experience a lower clearing price as a result of this. Figure 56 shows this development schematically.

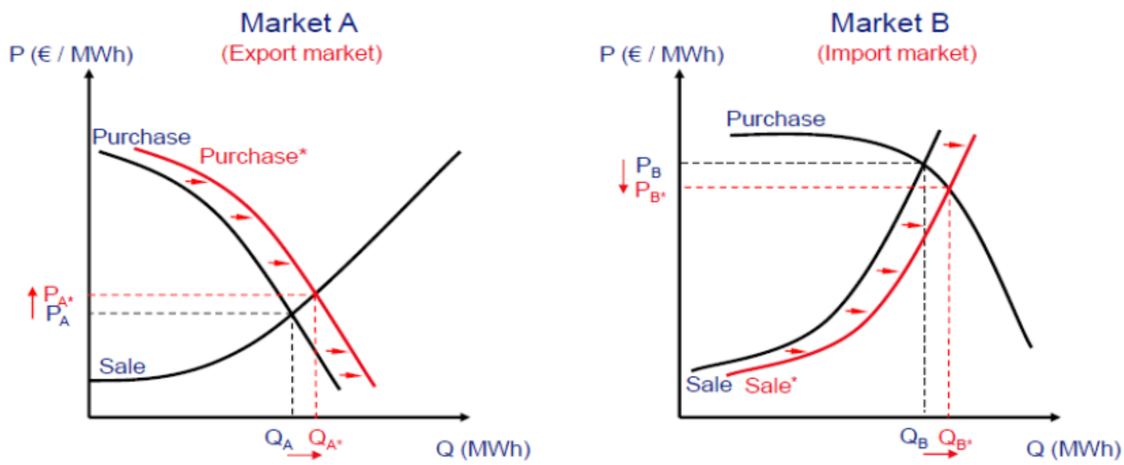


Figure 56: Price development when markets A & B are coupled. [3]

The amount of energy that can be transferred from market A to market B is limited by the physical transmission capacity between the markets. Therefore, two resulting equilibrium situations are possible. The first, a situation with enough interconnecting capacity, is depicted in Figure 57. In this situation, congestion (a shortage of transmission capacity) does not occur and the demand curve in market A and supply curve in market B will shift until the prices in both markets are equal. This situation is said to have full price convergence or a 'copper-plate' situation.

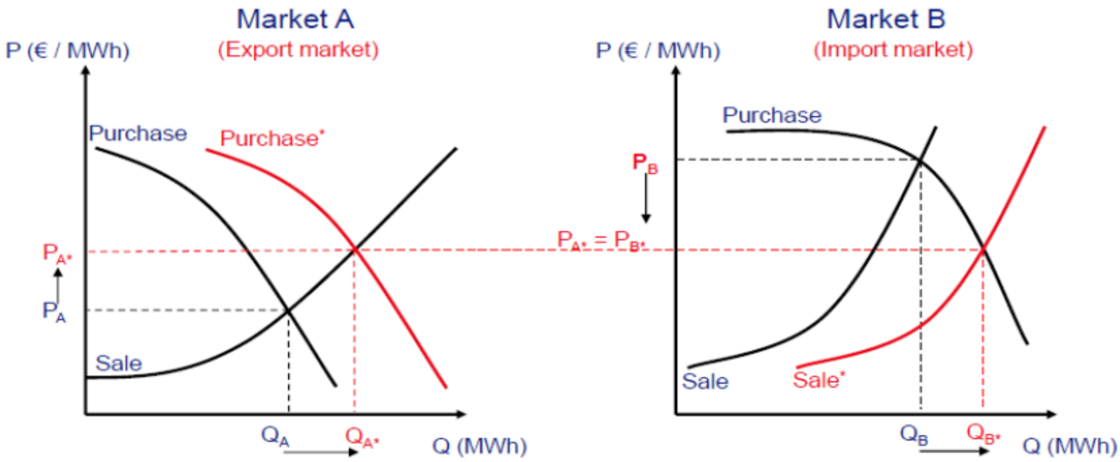


Figure 57: Clearing situation without congestion (copper plate situation) resulting in fully converged prices between markets A & B. [3]

The second situation, depicted in Figure 58, occurs when the transmission capacity is not sufficient to let the markets overcome the price differences. Therefore, it is not possible to reach full price convergence between markets A and B. The demand curve of the exporting market and the supply curve of the importing country will shift till they reach the transmission capacity limit. Further price convergence is not possible and a certain price difference $P_{B*} - P_{A*} = \Delta P$ remains in place.

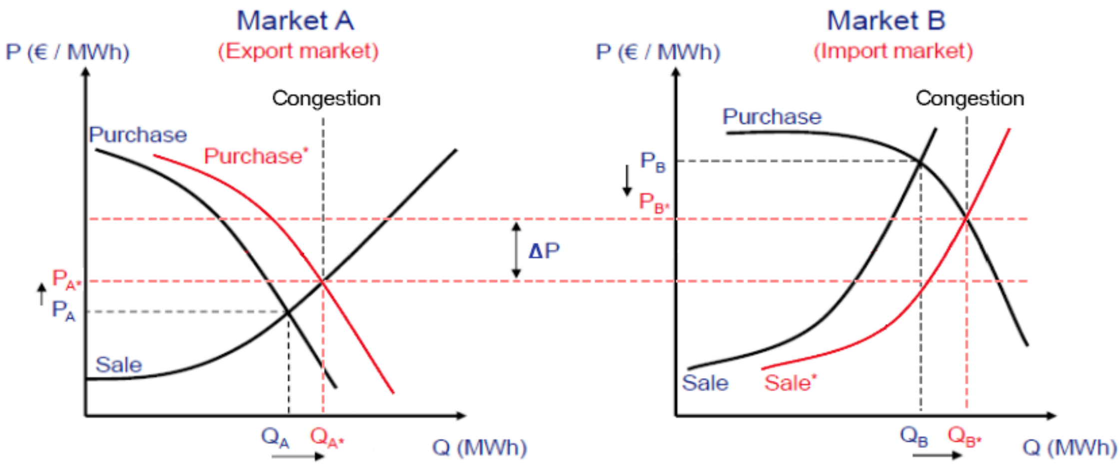


Figure 58: Clearing situation with congestion, markets are shifting until the transport capacity limit is reached but a price difference keeps existing.

Appendix C: Flow based capacity calculation process

This section will describe the Flow Based Capacity Calculation (FBCC) process in more detail. First, the input data necessary for the calculations will be discussed. Special emphasis will be put on the external constraints, since they are of extra importance for this thesis. Subsequently, the coordinated process to calculate the flow-based parameters and determine the flow-based domain will be described.

C.1 FB-CC; Input data

The flow-based capacity calculation process is a quite complicated process, not only due to the size of the grid or complexity of the calculations, but also due to the multitude of TSOs involved, all using their own methods, models and other processes. To avoid mismatching problems, input data and data formats are strictly defined. TSOs have to deliver the following input data upfront so it can be used in the calculation of the FB-domain.

Critical branch/Critical outages (CBCOs)

TSOs specify the technical parameters of relevant network constraints in a CB-file. Network constraints are combinations of network elements combined with contingencies which are significantly impacted by CWE cross-border trades and therefore are monitored in the capacity calculation process.

Such a network element is called a Critical Branch (CB) and is defined by a line (either internal or cross-border) or a transformer, combined with an operational situation (e.g. N, N-1, busbar faults or others depending on TSO risk policies). The Critical Outage (CO) can be a trip of a line, cable, busbar, transformer or other network elements.

Combinations of a CB and a CO (a CBCO) are determined by each CWE TSO for its own network. This selection is based on the impact CWE cross-border trade has on the network element and on operational experience. If the sensitivity factor of a CBCO is bigger than 5%, the CB is considered to be significantly impacted by CWE cross-border trade, and the CBCO is included in the CB-file. In cases justified to the other TSOs and the NRAs, TSOs can include CBCOs that do not meet the 5% threshold value.

The sensitivity factor of a CBCO is based on the Power Transfer Distribution Factor (PTDF) of the corresponding network element. More information about the selection of CBCOs can be found in [33] and [9].

Other characteristics of a CB or CBCO included in the CB-file are;

$\boldsymbol{I_{max}}$ The maximum allowable current is the physical limit of a CB, determined by each TSO in line with its operational criteria. If a temporary overload is allowed during specific outages, the CBCO I_{max} for that outage will differ from the CB I_{max}. I_{max} can be varied to compensate for weather conditions.

$\boldsymbol{F_{max}}$ The maximum allowable power flow in MW of a CBCO. It is given by the formula:

$$\boldsymbol{F_{max} = \sqrt{3} * I_{max} * U * \cos\varphi * 10^{-3}}\ [\boldsymbol{MW}]$$

Where I_{max} is the maximum allowable current, U is the reference voltage level for the CB and $\cos\varphi$ is set to 1.

FAV The Final Adjustment Value; this value can be set by TSOs to adjust the remaining available margin (RAM) on a CB for specific reasons, based on operational skills and experience, if this cannot be introduced in the flow-based system.

RAs Remedial actions; Actions that are allowed during the FB parameter calculations to optimize or maximize the available market capacity while ensuring a secure power system operation. Each RA is connected to one CBCO combination and taken into account by the FB parameter calculation. Remedial actions can be either explicit or implicit. Explicit RAs are for example, changing the tap position of a phase shifter transformer (PST), topology changes (putting in/out service of network elements or switching network elements to other bus bar) or post-fault redispatching. When conditional RAs do not lead to a concrete change in load flow, an implicit RA (implemented as a FAV) can be used. PST tap position optimization is part of the remedial actions.

Generator Shift Key (GSK)

The Generation Shift Key (GSK) represents the effect a changing net position of a bidding area has on the output of generating units in the same bidding area. Line loading differences due to changing generator output can be calculated more accurately in the load-flow calculations with the GSK. GSK values can very every hour and are given in dimensionless units. For example, a unit with a GSK-value of 0.05 will account for 5% of the hub's net position change.

Every TSO creates a GSK for each hour, representing the best forecast of the generator characteristics in its control area. In the Netherlands, a 'selective GSK' methodology is applied. This methodology divides generator units into three categories based on operational hours in a previous period; rigid (mostly on), swing (flexible) and idle (mostly off) generators. The number of flexible generators needed to match maximum import and export positions can be limited with this division. Also, the units are selected on the best possible forecast considering generation schedules, generator outages and historical operational hours. Detailed information about the selective GSK methodology can be found in [33].

Flow Reliability Margin (FRM)

TSOs will never be completely accurate when predicting the operating conditions of the grid two days in advance. Sources of these uncertainties are for example; external exchanges, approximations in the FB-methodology like a GSK or differences between forecasts and realized programs. Therefore, the TSOs must hedge against uncertainties of capacity calculation by applying reliability margins.

This is done by defining a Flow Reliability Margin (FRM) for each critical branch. The FRM quantifies the uncertainty in the capacity calculation process by statistically comparing the flow-based model results to real-time measurements. This way, the FRM can be as small as possible, but also prevent that TSOs will be confronted with flows that exceed the maximum allowed flows in their system due to calculation uncertainties. Inevitably, the FRM reduces the remaining available margin (RAM) on the critical branches available to the market, but this is necessary to safeguard grid security. Detailed information about the calculation of the FRM can be found in [9].

2-Days Ahead Congestion Forecast files (D2CF files)

The 2-Days Ahead Congestion Forecast files are a best estimate of the state of the CWE electric system for each hour of execution day D. Each participating TSO provides for its zone an hourly D2CF file that contains:

- Net exchange programs for a reference day (a recent day with similar characteristics). The exchanges should include the programs for DC-connections.
- A best estimation for the topology of the grid as foreseen until D-1, including planned grid and interconnector outages (i.e. effective grid model of day D).

- A best estimation for the forecasted load, load pattern, wind generation and solar generation.
- A best estimation for generating units, this includes outages and expected production which is in line with outage planning, forecasted load and reference progam, and expected total generation.
- Phase shift transformer tap position is neutral, justified exceptions are allowed.

Each hourly local D2CF file has to be balanced in terms of production and consumption, in line with the reference program. Imbalances will be adjusted by each TSO by adapting production and/or load.

C.2 FB-CC; External constraints

The flow-based capacity calculation method is based on the evaluation of remaining available margin on critical branches. Since critical branches do not represent the complete network it might be necessary to implement other specific limitations to guarantee a secure grid operation.

TSOs are able to do this by implementing 'special' or 'artificial' critical branches called 'external constrains' to ensure that the market outcome does not exceed these grid security limits. External constraints are part of the input data that TSOs deliver for the FB-domain calculation. They have the same format as critical branches, with a remaining available margin (RAM) and power transfer distribution factors (PTDFs). In the case of external constraints, the PTDFs will only have the values 0, 1 or -1.

There are multiple reasons for TSOs to implement external constraints:

- Flow-based capacity calculation is based on DC load flow calculations. Therefore, only thermal limits are taken into account on the critical branches. By implementing external constraints, TSOs can safeguard for other important grid security aspects like voltage stability, dynamic stability or ramping (DC cables, net positions). These constraints are determined by off-line studies (like this thesis) outside the FB parameter computation, hence the name 'external' constraints.

- Flow-based capacity calculation uses a reference situation and variations from this point are calculated in a linearized method with a generation shift key (GSK). Especially with large deviations, differences in dispatch between the linear GSK and the realistic situation will occur. To avoid market results that differ too much from the reference situation, and therefore could induce large additional flows on grid elements, TSOs can limit the GSK shifting region with external constraints.

- Flow-based capacity calculation uses a largely automated process. This means the results of this process cannot always be foreseen in advance. External constraints create the possibility for TSOs to remove specific regions from the flow-based domain. This way they can ensure security of supply even in the case of unexpected flow-based solutions that would otherwise have compromised grid security.

Various methods to determine and implement external constraints are used at this moment:

- **External constraints to limit the import (an import limit constraint) or export (an export limit constraint) to an absolute net position.**
  This type of external constraint is used by the Netherlands (both import and export, $\max|NP| = 4250\ MW$) and Belgium (only import, $\min NP = -4500\ MW$). The values of these limits are determined in off-line studies, taking into account for example voltage stability and dynamic stability.

- **External constraints to limit the deviation from the reference program.**
  Due to linearization (i.e. GSK) in the FB calculation process, FB-results under big deviations are expected to differ too much from the real (non-linear) situation. To safeguard for these errors, the allowed deviation from the reference program is limited. The German TSOs and French TSO use this method combined with absolute import/export limits.

  The German TSOs allow a fixed bandwidth of Δ = 5000 MW from the reference program. Supplementary to that, the final import/export constraint is kept between a certain bandwidth. If the new value ($NP_{ref\ prog}$ +/- Δ) does not reach a minimum value, the constraint is raised to that minimum value; similarly, if the new value exceeds a maximum value, the constraint is lowered to that maximum value. Currently; $export_{min} = 5600\ MW < maxNP_{DE} < export_{max} = 7000\ MW$, and $import_{max} = -6000\ MW < minNP_{DE} < import_{min} = -4400\ MW$.

The French TSO limits the maximum deviation ('shift' criterion) from the reference program to Δ = 4000 MW. Together with the reference exchanges FR-BE and FR-DE this defines the 'validity' domain. Complementary, an 'acceptability' domain is defined with maximum acceptable net positions. This domain is based on weekly or monthly performed studies on D2CF files representative of relevant exchange directions. The concatenation of these domains determines the final 'acceptable' domain which is applied with external constraints.

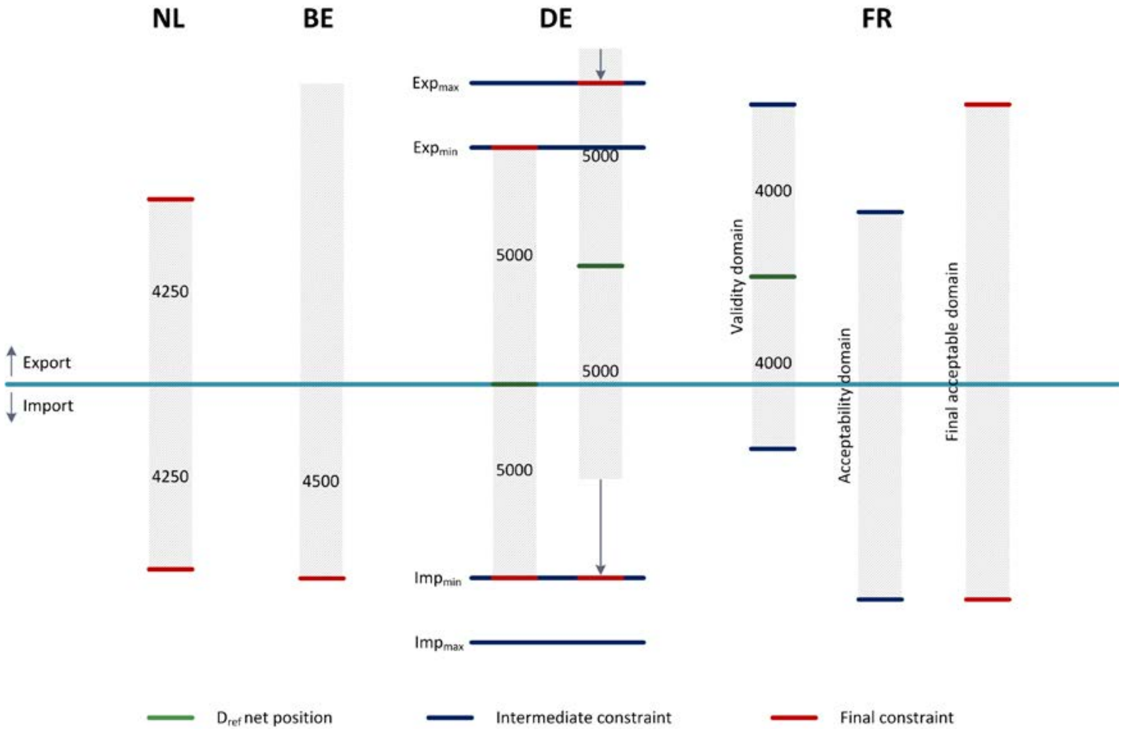


Figure 59: Illustration of various implemented external constraints. The Netherlands has fixed export/import limits, irrespective of D_{ref}-exchanges. Belgium only has an import limit, also irrespective of D_{ref}-exchanges. German combines a scaling bandwidth around D_{ref}-exchanges with an absolute import/export bandwidth. France concatenates a scaling bandwidth around D_{ref}-exchanges and an acceptability domain based on earlier studies (irrespective of D_{ref}-exchanges) into a final acceptable domain.

C.3 FB-CC; Flow-based parameters calculation and flow-based domain determination

All previous input data is used to calculate the flow-based parameters, which are used as input to determine the flow-based domain. First, the individual D2Cf-files are merged into a common grid model. Subsequently, the common grid model is used to calculate the flow-based parameters for the reference day. After the flow-based parameters are adjusted to the business day values, they are used to determine the final flow-based domain. The flow-based domain is representing all allowed possibilities for the market to clear, and as such returned to the market coupling allocation process.

Creating the Common Grid Model (CGM)

The individual D2CF files are merged into one single model, which is the basis for all subsequent flow-based calculations. This model is called the Common Grid Model (CGM), representing a best forecast of the corresponding hour of execution day D. It consists of:

- The single D2CF data sets from Elia (BE), RTE (FR), TenneT (NL), TenneT (DE), TransnetBW (DE), Amprion (DE), 50Hz (DE) and APG (AT).
- The Day Ahead Congestion Forecast (DACF) files of non-participating TSOs of continental Europe. They are included to take into account the physical influences of these grids when calculating CWE grid transfers.
- Injections in the model representing DC-cables linked to other control blocks.

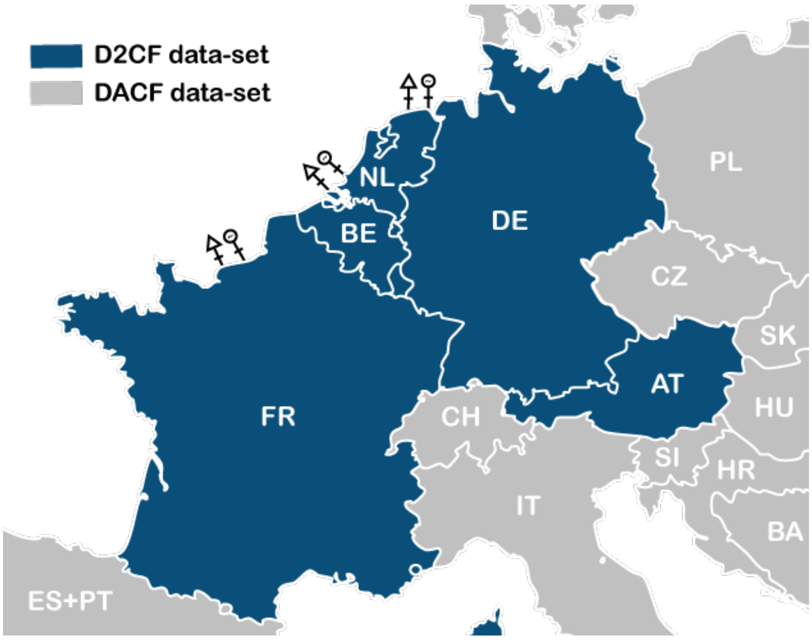


Figure 60: Overview of data-sets included in the Common Grid Model.

During the merging process consists of a couple of steps, to obtain a stable final model. First, the individual data sets are checked for load flow convergence and format, Second, the import/export balance is checked according to scheduled balance of the reference timestamp and, if necessary, adjusted.

Third, during the actual merging process, the interconnector statuses are checked. To reach matching reference day net positions, the CWE control blocks will be scaled using the corresponding GSK. Complementary to this, sanity checks are performed during the merging process. More information about both the D2CF-files and CGM can be found in [9], specific information about the Netherlands in [33].

After merging the individual grid models into the CGM, all TSOs check whether their CB-file is consistent with the CGM. Especially the remedial actions described in the CB-file have to be checked, to make sure the RAs are available in the forecasted grid situation.

Calculation of the flow-based parameters

The flow-based parameters are calculated during a centralized computation. After gathering and preparing all necessary input data (i.e. the CGM, CBCO-set, GSK and external constraints) the resulting calculations can be linearized, allowing for much faster, but less detailed, DC load flow analysis. The calculation output is a set of 2 parameters for each critical branch:

- **Remaining Available Margin (RAM)**
  The remaining available margin of a critical branch is the maximum allowable additional line loading for that branch. It results from the following equation:
  $$RAM = F_{max} - F_{ref} - FRM - FAV$$
  Where F_{max} is the maximum allowable line loading, FRM is the flow reliability margin and FAV is the final adjustment value, all following from the CB-file. F_{ref} is the reference flow, this reflects the calculated line loading with the exchange programs of the reference day. During parameter adjustment this will be replaced by business day D line loading.

- **Power Transfer Distribution Factors (PTDFs)**
  The Power Transfer Distribution Factor of a critical branch is the effect a variation in the net position of a market area has on the line loading of that specific critical branch. It is calculated by varying the exchange programs, and therefore net positions, of each market area.

  All possible zone variations are calculated by scaling the regions production up or down with the GSK. Because the GSK directly influences the generation at specific nodes, the GSK has an important influence on the line loadings around that node, and therefore on the PTDFs.

  PTDFs characterize the linearization of the model and subsequent calculation steps are all linear. Changes in line loading are calculated by multiplying the change in net position with the corresponding PTDF.

  $$RAM_{new} = RAM_{old} + (\Delta NP_A * PTDF_A)$$

  For example, a net position shift of 100 MW in zone A has a line loading effect of 10 MW on a branch, the zonal PTDF of A is said to be 10% or 0.10. A more detailed example of the calculation of PTDF's can be found in [34]. In this case, the PTDFs are zone-to-zone PTDFs, more information on various forms of PTDFs can be found in [35].

After determination of the flow-based parameters, a two-step control process is performed by the TSOs. First, each TSO has to check the FB-parameters to see if the FB-domain can be enlarged by replacing or changing Remedial Actions. If necessary this could also be cross-border Remedial Actions in collaboration with neighboring TSOs. The goal of this step is to maximize the FB-domain, and therefore capacity available to the market, whilst respecting or increasing the security of supply.

Second, based on these renewed CB-files a new set of FB-parameters is calculated resulting in the largest possible FB-domain respecting the security-of-supply domain. This result is distributed among the TSOs as a grid model, so it can be checked by the TSOs. For example on grid security in specific points by replacing the GSK with other generating patterns, AC load flow analysis for reactive power flows, equipment voltage limits, voltage stability or other security controls. After this last check (and possibly adaption) the final FB-domain gets calculated.

Flow-based parameter adjustment to business day D values

Up till now, all calculations have been done with the reference day exchange. The last step that has to be performed before the final FB-domain get determined, is replacing these reference day exchanges with business day D values.

All the reference exchanges (the final values, indifferent of timeframe) are replaced by the long-term allocated capacity (LTA) of business day D. This is done by calculating the line loading influence of the difference in exchange programs;

$$F_{ref_{new}} = F_{ref_{old}} - \sum_{i=hub} PTDF_i * (Refprog_i - LTA_i)$$

Where $F_{ref_{new}}$ and $F_{ref_{old}}$ are critical branch specific flows and $Refprog_i$ and LTA_i are zone-to-zone exchanges of which the line-loading influence on the critical branch is described in the associated $PTDF_i$.

The resulting RAM available for the day-ahead market on this critical branch is calculated with the formula:

$$RAM_{new} = F_{max} - F_{ref_{new}} - FRM - FAV$$

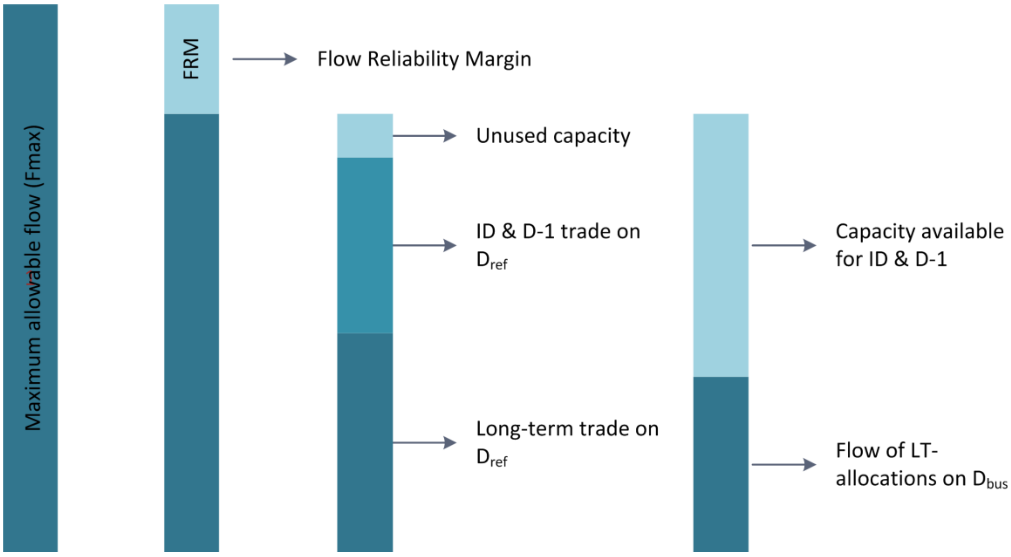


Figure 61: Schematic division of critical branch capacity for flow-based capacity calculation, assuming FAV = 0.

These results are checked if RAM_{new} < 0. If this is the case, the long-term allocated capacity exceeds the FB-domain, possibly creating an unsecure situation. In this case the LTA inclusion mechanism becomes active, described in [36][37].

As soon as the Long-Term Nominations (LTN) of day D are known, a similar step is performed to update the FB-domain from the Long-Term allocated situation to the effectively nominated situation.

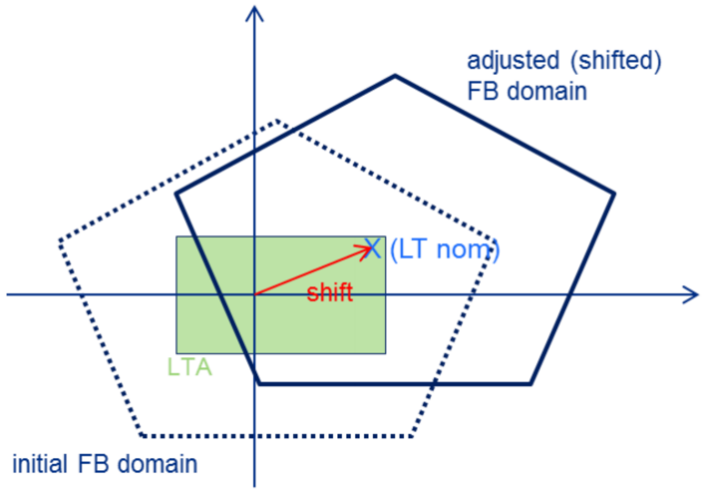


Figure 62: Shift of the FB-domain from the long-term allocated situation to the long-term nominated situation. [7]

Determination of the final FB-capacity domain

After the FB-parameters are finalized, the Flow-based capacity domain available to the market can be determined by combining all the critical branches. Each critical branch has a specific RAM as a function of the exchanges on the borders (influence calculated with the PTDF). This specifies what exchanges and net positions can be facilitated by the CB under market coupling without endangering grid security.

A single critical branch is schematically visualized in Figure 63, by a single constraint line. This is the boundary between allowable and non-allowable net positions for this critical branch. A position on the 'outside' of the line would overload the critical branch, endangering grid security. Logically, only positions 'inside' of the critical branch are allowed.

When all critical branches are combined, a situation like Figure 63 could arise. Since the CWE-region has three possible cross-border exchanges (FR-BE, BE-NL and NL-DE) this would actually be a three-dimensional space. By fixing the 3rd dimension (in this case B>C exchange) to a specific exchange, a more comprehensible illustration remains.

To the market, only the Flow-based constraints most-limiting the exchanges are important, after all, bigger exchanges can create unsecure situations. These most-limiting constraints (called non-redundant constraints) together form the Security-of-supply region (indicated in yellow). All exchanges and net positions within this region are secure, and therefore available to the market coupling mechanism.

In case of Flow-based market coupling, the complete Security-of-supply (SoS) region is available to the market coupling mechanism. Also indicated in Figure 63 is a possible ATC-region in this situation. The ATC-CC is based on maximum border capacity; therefore it will always be rectangular shaped, excluding areas that would otherwise be within the SoS-region. This easily indicates the advantage of more efficient use of cross-border capacity with FB-MC over ATC-MC, creating more trading opportunities for the market.

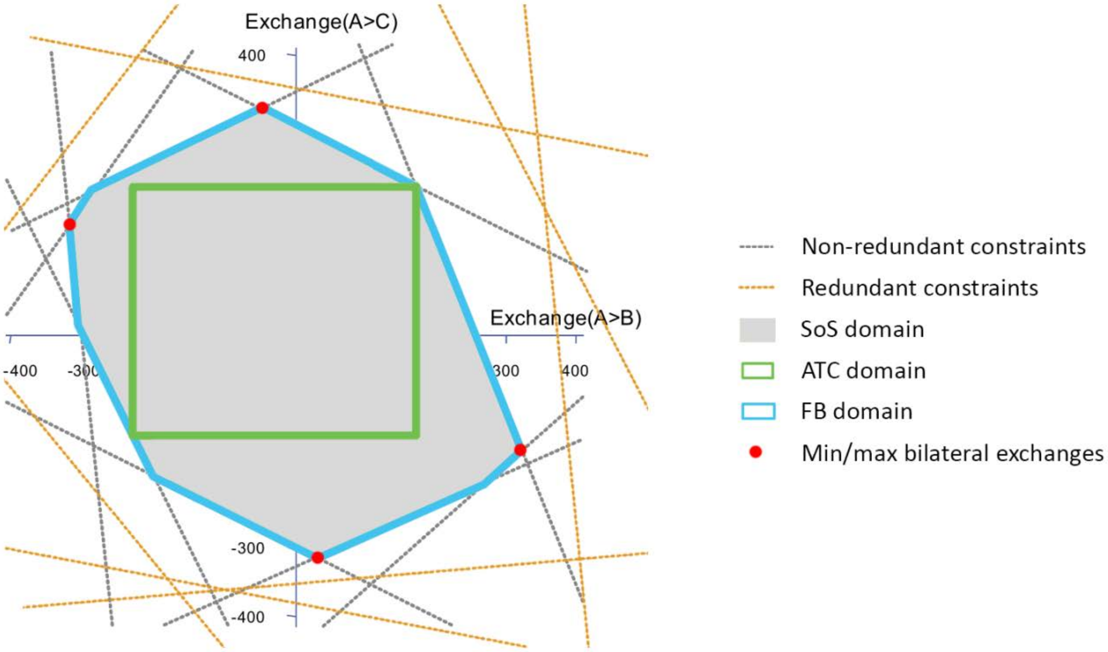


Figure 63: Two-dimensional Flow-based domain, assuming a fixed B>C exchange. The non-redundant constraints determine the Security-of-Supply region, equal to the FB-domain. Also a possible ATC-domain in the same situation is depicted.

Appendix D: Model data:

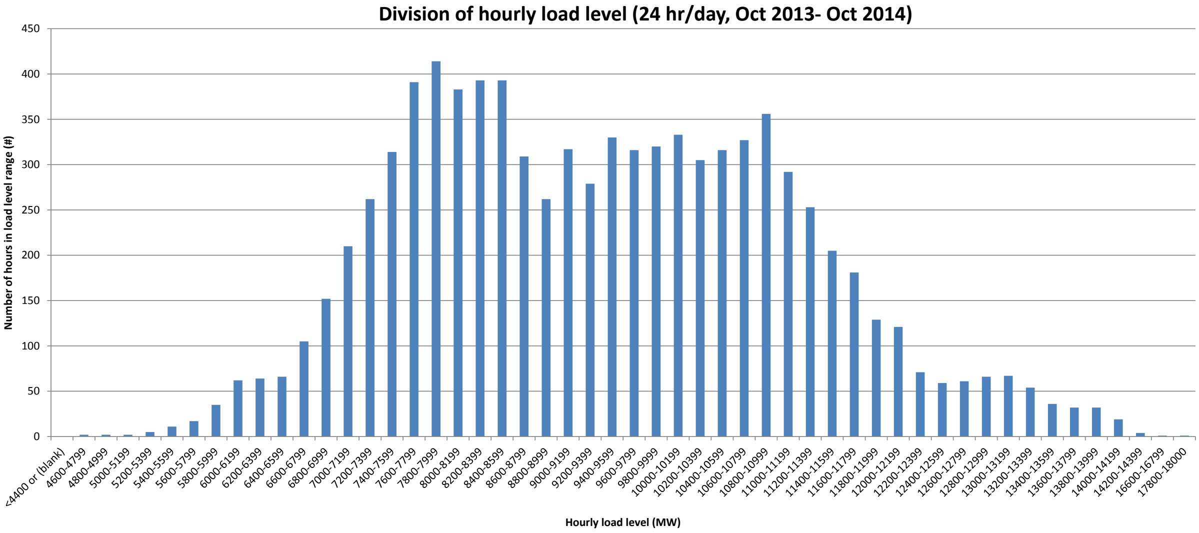
D.1 Generators

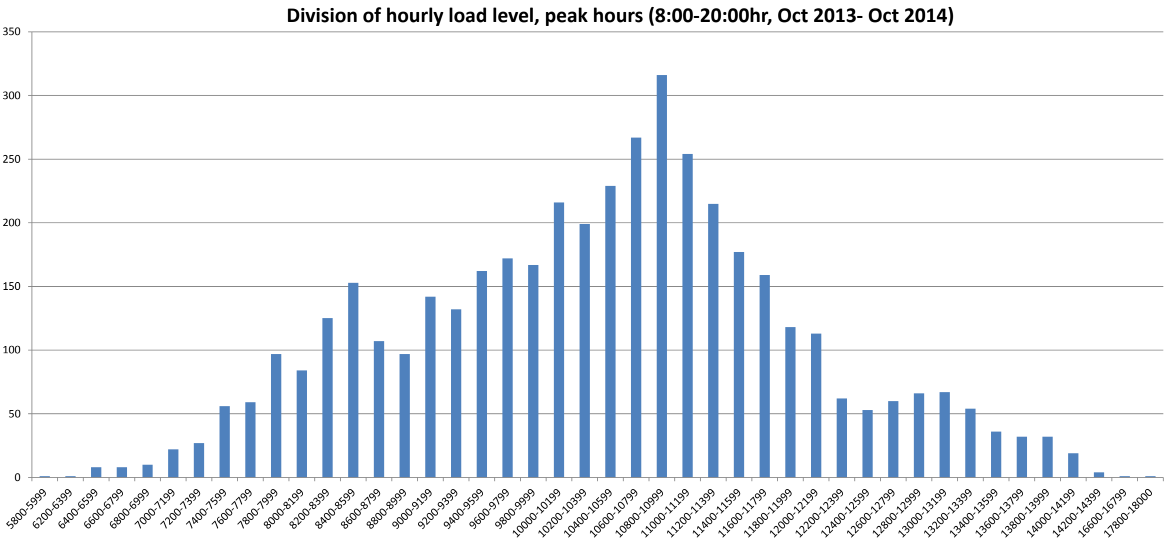
The following generators in the Netherlands are used throughout the analysis. Other generators are shut down. The amount of in-service generators is depending on load level and generation pattern. Each generation pattern uses its own priority list of generators, to control the in-service generators. Generators are put into service until the necessary production level, with the lowest priority generators switched in first.

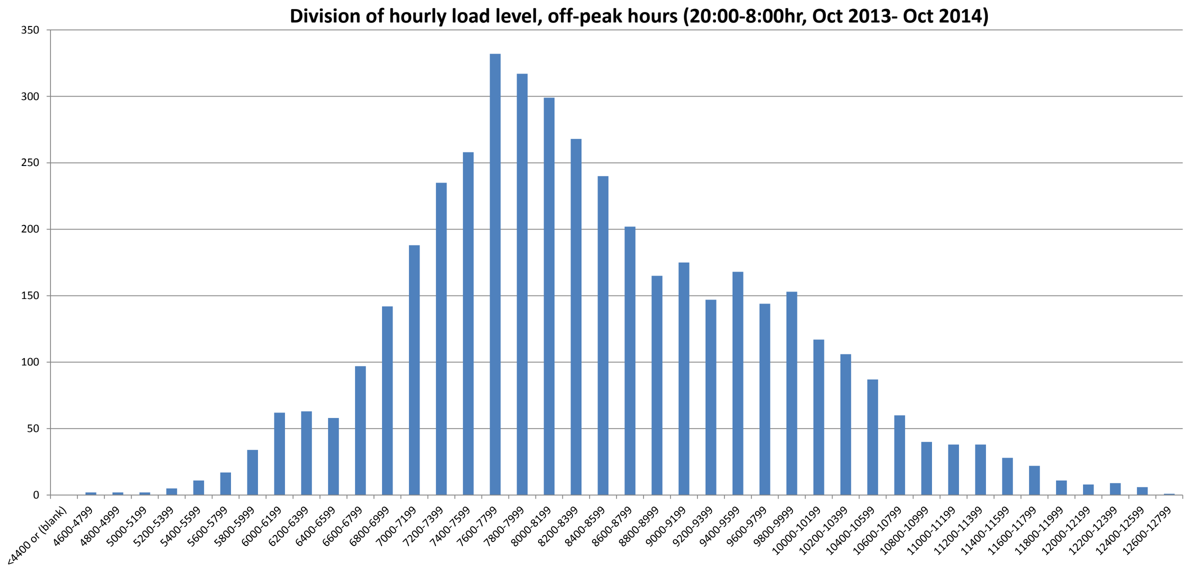
In-service generators are controlling the voltage at the rail of the nearest substation (connection point), within their reactive power capabilities towards the voltage control set point.

Power plants:		Power capabilities:				Voltage control setpoint	Merit order generation pattern	Eemshaven generation pattern	Maasvlakte generation pattern
Generator name	Connection point	PMax (MW)	PMin (MW)	QMax (Mvar)	QMin (Mvar)	VSched (p.u.)	Priority	Priority	Priority
AkzoNobel Hengelo WKK	Hengelo 150kV	56.3	0	6.3	6.3	1	12	999	999
Amercentrale 8	Geertruidenberg 150kV	650	0	126.9117	-126.9117	1.04	4	999	3
Amercentrale 9	Geertruidenberg 380kV	620	0	658.75	-116.25	1.0521	26	5	3
Borssele Coal	Borssele 150kV	460.28	0	39.2535	33.2535	1.055	999	999	4
Borssele Nuclear	Borssele 150kV	525	0	168.7782	-31.2218	1.055	53	999	4
Centrale Maasvlakte MPP1 Eon	Maasvlakte 380kV	500	0	625	-187.5	1.06	25	999	2
Centrale Maasvlakte MPP2 Eon	Maasvlakte 380kV	500	0	625	-187.5	1.06	12	5	2
Centrale Maasvlakte MPP3 Eon	Maasvlakte 380kV	1117.05	0	1083.2	-473.9	1.06	97	999	2
Centrale RoCa	Ommoord 150kV	269.75	0	295	-88.5	1.0438	37	999	3
Clauscentrale-C	Maasbracht 150kV	600.6	0	770	-231	0.9872	81	5	999
Cluster Velsen IJmond	Velsen 150kV	396	0	261.6224	-23.3776	1.03	11	4	999
Cluster Velsen VN-24	Velsen 150kV	499	0	600	-180	1.03	66	4	999
Cluster Velsen VN-25	Velsen 150kV	144	0	20.3121	18.3121	1.03	27	4	999
Diemen 33	Diemen 150kV	250	0	262.3	-131.7	1.0509	94	3	5
Diemen 34	Diemen 380kV	433.6	0	440	-200	1.065	19	3	5
Eemscentrale 3	Eemshaven 220kV	358	0	447.5	-134.25	1.07	64	1	999
Eemscentrale 4	Eemshaven 220kV	358	0	447.5	134.25	1.07	54	1	999
Eemscentrale 5	Eemshaven 220kV	358	0	447.5	-134.25	1.07	47	1	999
Eemscentrale 6	Eemshaven 380kV	358	0	447.5	-134.25	1.07	65	1	999
Eemscentrale 7	Eemshaven 380kV	358	0	447.5	-134.25	1.07	71	1	999
Eemshavencentrale RWE1	Eemshaven Oudeschip 380kV	900	0	875	-500	1.07	999	2	999
Eemshavencentrale RWE2	Eemshaven Oudeschip 380kV	900	0	875	-500	1.07	999	2	999
Elsta	Terneuzen 150kV	462.2	236	236.5446	-91.4554	1.06	1	999	4
Enecogen-1	Maasvlakte 380kV	400	0	350	-200	1.06	52	999	2
Enecogen-2	Maasvlakte 380kV	400	0	350	-200	1.06	999	999	2
Gelderland 13	Nijmegen 150kV	617.4	0	160.2586	-89.7414	1.03	15	4	999
Hemweg 8	Hemweg 150kV	680	0	545	-300	1.03	51	4	5
Hemweg 9	Hemweg 150kV	432.9	5	440	-200	1.03	59	3	5
Lage Weide 6	Utrecht Lage Weide 150kV	160	0	15.2294	-15.2294	1.0555	51	4	5
Lage Weide 6	Utrecht Lage Weide 150kV	90	0	86.5	-47	1.0555	999	4	5
Maasstroom Energie	Simonshaven 380kV	435.2	0	350	-200	1.055	94	999	1
Maasvlakte Electrabel Powerplant	Maasvlakte 380kV	793.65	0	793.65	-264.55	1.055	47	999	2
Magnumcentrale 1,2,3	Eemshaven Oudeschip 380kV	1663.2	0	1650	-1200	1.07	38	2	999
Maximacentrale 4	Lelystad 380kV	416	0	325	-200	1.065	11	3	999
Maximacentrale 5 + 32	Lelystad 150kV	536	0	374.999	-250	1.04	48	3	999
Merwedekanaal 12	Utrecht Lage Weide 150kV	224	0	241	-93	1.04	91	4	5
Moerdijk 1	Moerdijk WKC 150kV	345	0	154.56	-30.64	1.04	2	999	3
Moerdijk 2	Moerdijk WKC 150kV	465.7	102.454	459	-200	1.04	2	999	999
PerGen 1	Geervliet 150kV	135	0	48.3372	-31.6628	1.04	1	999	1
PerGen 2	Geervliet 150kV	135	0	48.3372	-31.6628	1.04	19	999	1
Rijnmond Energie	Rotterdam Waalhaven 150kV	832	410	737.2	-233.4	1.0479	88	999	1
Sloecentrale 1	Borssele 380kV	445	0	391	-215.5	1.05	36	999	4
Sloecentrale 2	Borssele 380kV	445	0	391	-215.5	1.05	40	999	4
Swentibold	Graetheide 150kV	298	0	29.786	27.786	1.04	2	999	999

D.2 Load level







D.3 Reactive power compensation devices

Substation	**Steps**	**Voltage control range**	
		Vhigh (p.u.)	Vlow (p.u.)
Reactors			
Beverwijk 380kV	2x -100 MVAr	1.08	1.03
Bleiswijk 380kV	3x -100 MVAr	1.08	1.03
Crayestein 380kV	2x -100 MVAr	1.08	1.03
Diemen 380 kV	2x -100 MVAr, 1x -50 MVAr, 1x -45 MVAr	1.08	1.03
Dodewaard 380kV	2x -100 MVAr, 1x -45 MVAr	1.08	1.03
Doetinchem 380kV	2x -45 MVAr	1.08	1.03
Eemshaven 380kV	2x -75 MVAr	1.08	1.03
Ens 380kV	5x -75 MVAr	1.08	1.03
Geertruidenberg 380kV	2x -75 MVAr	1.08	1.04
Krimpen a/d IJssel 380kV	2x -100 MVAr, 1x -45 MVAr	1.08	1.03
Meeden 380kV	1x -75 MVAr	1.08	1.03
Maasvlakte 380kV	1x -100 MVAr, 1x-50 MVAr	1.08	1.04
Simonshaven 380kV	1x -100 MVAr	1.08	1.04
Wateringen 380kV	3x -100 MVAr	1.08	1.03
Capacitors			
Diemen 380kV	2x 150 MVAr	1.08	1.03
Dodewaard 380kV	1x 150 MVAr	1.08	1.03
Eemshaven converterstation 380kV	2x 106 MVAr	1.08	1.03
Ens 220kV	2x 150 MVAr	1.08	1.03
Krimpen a/d IJssel 380kV	2x 150 MVAr	1.08	1.03
Weiwerd 220kV	1x 150 MVAr	1.08	1.03

Appendix E: Result analysis files:

E.1 Scenario overview example

SCENARIO OVERVIEW								
MODULE: 1	Module parameters: M001_LOW-L_ACOFF_DCOF_MRIT_BVUM							
Scenarionr:	1	2	3	4	5	6	7	8
Netto pos:	-0.00 GW	-1.00 GW	-2.00 GW	-3.00 GW	-4.00 GW	-5.00 GW	-6.00 GW	-7.00 GW
Convergency:	0.06	0.10	0.38	0.31	0.24	0.11	0.06	0.05
BC V-Viol(<1.0 or >1.1):	3	2	1	1	1	1	0	0
ACCC-Viol:	117	290	433	267	266	79	219	206
RPCD-margin(Cap):	9177.2	7775.8	7269.8	5841.0	5408.8	4514.0	3780.8	3366.8
RPCD-margin(Ind):	3695.8	3033.1	2711.3	2472.6	2258.7	2091.0	2014.2	1988.2
MVAr Interchange:	65.4	213.7	365.1	447.0	581.5	569.4	612.5	833.8
MODULE: 2	Module parameters: M002_LOW-L_ACNS2_DCOF_MRIT_BVUM							
Scenarionr:	9	10	11	12	13	14	15	16
Netto pos:	-0.00 GW	-1.00 GW	-2.00 GW	-3.00 GW	-4.00 GW	-5.00 GW	-6.00 GW	-7.00 GW
Convergency:	0.03	0.06	0.14	0.14	0.26	0.23	0.06	0.08
BC V-Viol(<1.0 or >1.1):	3	3	1	1	1	1	0	0
ACCC-Viol:	149	1195	121	71	46	79	191	225
RPCD-margin(Cap):	9072.5	7825.9	7317.6	5869.0	5472.6	4497.8	3788.9	3417.8
RPCD-margin(Ind):	3800.5	2983.0	2663.4	2444.5	2194.9	2107.2	2006.1	1937.2
MVAr Interchange:	221.9	320.3	404.2	428.6	481.0	521.0	559.5	643.0
MODULE: 3	Module parameters: M003_LOW-L_ACNS4_DCOF_MRIT_BVUM							
Scenarionr:	17	18	19	20	21	22	23	24
Netto pos:	-0.00 GW	-1.00 GW	-2.00 GW	-3.00 GW	-4.00 GW	-5.00 GW	-6.00 GW	-7.00 GW
Convergency:	0.04	0.13	0.11	0.18	0.13	0.29	0.10	0.05
BC V-Viol(<1.0 or >1.1):	1	1	1	1	3	0	2	2
ACCC-Viol:	30	69	29	36	34	44	192	909
RPCD-margin(Cap):	8241.9	7203.6	6676.6	5154.6	4760.4	3846.3	3354.5	2964.5
RPCD-margin(Ind):	4631.1	3605.3	3304.4	3159.0	2907.1	2758.7	2440.6	2390.5
MVAr Interchange:	562.7	675.1	670.4	728.6	769.1	803.0	624.3	662.3
MODULE: 4	Module parameters: M004_LOW-L_ACOFF_DCNS_MRIT_BVUM							
Scenarionr:	25	26	27	28	29	30	31	32
Netto pos:	-0.00 GW	-1.00 GW	-2.00 GW	-3.00 GW	-4.00 GW	-5.00 GW	-6.00 GW	-7.00 GW
Convergency:	0.08	0.21	0.28	0.06	0.16	0.21	0.06	0.05
BC V-Viol(<1.0 or >1.1):	3	3	1	1	1	1	0	0
ACCC-Viol:	120	1149	49	56	43	43	142	430
RPCD-margin(Cap):	9134.9	7871.3	7349.1	5784.4	5414.1	4445.7	3670.2	3281.8
RPCD-margin(Ind):	3738.2	2937.6	2631.9	2529.1	2253.4	2159.3	2124.8	2073.2
MVAr Interchange:	199.4	291.8	417.9	529.5	572.6	544.5	617.7	706.0
MODULE: 5	Module parameters: M005_LOW-L_ACNS2_DCNS_MRIT_BVUM							
Scenarionr:	33	34	35	36	37	38	39	40
Netto pos:	-0.00 GW	-1.00 GW	-2.00 GW	-3.00 GW	-4.00 GW	-5.00 GW	-6.00 GW	-7.00 GW
Convergency:	0.08	0.07	0.06	0.07	0.11	0.43	0.05	0.24
BC V-Viol(<1.0 or >1.1):	3	3	1	1	1	0	4	2
ACCC-Viol:	119	1044	28	36	47	51	411	506
RPCD-margin(Cap):	8916.1	7857.3	7318.1	5767.3	5338.5	4317.4	3613.8	3268.8
RPCD-margin(Ind):	3956.9	2951.6	2662.9	2546.2	2329.0	2287.6	2181.2	2086.2
MVAr Interchange:	294.8	329.6	392.3	423.2	446.8	493.9	601.7	504.8

E.2 Module overview example

MODULE-OVERVIEW	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Generator-set:	Merit-order							
Load-level:	LOW-L							
Load-level (MW):	8000							
AC-T Direction:	----							
AC-T Size (MW):	0							
DC-T Direction:	----							
DC-T Size (%):	0							
Border Voltage:	UnModified							
Sourcefile:	C:\Users\Thijs\Desktop\Runs\Run 8\Dataset 19 Full set test\20140115_1030_RE3_UX1_RUN8_STEP7.sav							
PY-file:	C:\Users\Thijs\Desktop\Runs\Run 8\Dataset 19 Full set test\Rerunner.py							
Date:	11-Apr-2015 07:09:30							
Contingency Analysis:	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Convergency-check:	0.06	0.10	0.38	0.31	0.24	0.11	0.06	0.05
AREA NL TOTALS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Gen (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Load (MW)	8000.0	8000.0	8000.0	8000.0	8000.0	8000.0	8000.0	8000.0
Bus Shunt (MW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Line Shunt (MW)	18.9	18.9	18.9	18.8	18.8	18.8	18.7	18.8
Line Losses (MW)	93.4	103.3	89.8	87.5	80.7	92.4	109.9	108.5
Interchange (MW)	-12.3	-1022.3	-2008.6	-3006.3	-3999.6	-5011.2	-6028.5	-7027.3
Gen (MVAr)	-1314.3	-769.1	-718.1	-171.4	-143.5	-40.3	31.3	51.8
Load (MVAr)	1596.1	1596.1	1596.1	1596.1	1596.1	1596.1	1596.1	1596.1
Bus Shunt (MVAr)	477.7	922.1	1048.1	1546.9	1630.2	1633.7	1526.5	1444.6
Unused (prev line shunt)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
rging - Line Shunts(MVAr)	5384.7	5370.6	5351.0	5339.6	5333.8	5352.0	5324.7	5369.4
Line Losses (MVAr)	1931.2	1869.6	1623.5	1578.2	1382.4	1512.5	1620.9	1546.7
Interchange (MVAr)	65.4	213.7	365.1	447.0	581.5	569.4	612.5	833.8
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
BSW Max (MVAr)	1412.0	1412.0	1412.0	1412.0	1412.0	1412.0	1412.0	1412.0
Cap. Margin (MVAr)	1812.0	2182.0	2307.0	2757.0	2832.0	2832.0	2757.0	2657.0
BSW Nom (MVAr)	-400.0	-770.0	-895.0	-1345.0	-1420.0	-1420.0	-1345.0	-1245.0
Reac. Margin (MVAr)	2475.0	2105.0	1980.0	1530.0	1455.0	1455.0	1530.0	1630.0
BSW Min (MVAr)	-2875.0	-2875.0	-2875.0	-2875.0	-2875.0	-2875.0	-2875.0	-2875.0
Capacitors Active	3	3	3	3	3	3	3	3
Reactors Active	9	14	15	20	21	21	20	19
GENERATORS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Active Generators	28	25	22	19	16	13	11	5
Pmax	8458.0	7248.2	6490.5	5235.5	4341.6	3167.9	2355.9	1252.9
P +marg	358.0	148.2	390.4	135.5	241.6	67.9	255.9	152.9
Pgen	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
P -marg	7761.6	6761.5	5761.6	4761.5	3761.5	2761.6	1761.6	761.6
Pmin	338.5	338.5	338.5	338.5	338.5	338.5	338.5	338.5
Qmax	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Cap. Margin	7365.2	5593.8	4962.8	3084.0	2576.8	1682.0	1023.8	709.8
Qgen	-1314.3	-769.1	-718.1	-171.4	-143.5	-40.3	31.3	51.8
Reac. Margin	1220.8	928.1	731.3	942.6	803.7	636.0	484.2	358.2
Qmin	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4
TIE-LINES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
NL -> BE (MW)	-29.9	-355.5	-766.1	-1157.8	-1549.8	-1903.6	-2261.5	-2655.3
NL -> DE (MW)	19.8	-663.9	-1239.3	-1842.8	-2442.0	-3096.4	-3751.8	-4351.7
Total AC NP (MW)	-10.0	-1019.3	-2005.4	-3000.7	-3991.8	-5000.0	-6013.3	-7007.0
AC-Transit (MW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EEM->FED (MW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MVL->GRA (MW)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total NP (MW)	-10.0	-1019.3	-2005.4	-3000.7	-3991.8	-5000.0	-6013.3	-7007.0
NL -> BE (MVAr)	200.2	211.4	276.3	325.4	385.8	433.7	482.8	621.1
NL -> DE (MVAr)	-234.2	-90.1	-2.0	57.2	152.5	128.7	165.7	301.2
Total AC NP (MVAr)	-34.0	121.3	274.2	382.6	538.3	562.4	648.5	922.4
AC-Transit (MVAr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EEM->FED (MVAr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MVL->GRA (MVAr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total NP(MVAr)	-34.0	121.3	274.2	382.6	538.3	562.4	648.5	922.4

VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
BC V-Viol(<1.0 or >1.1):	3	2	1	1	1	1	0	0
EEMSHAVEN380A	1.071	1.097	1.099	1.098	1.097	1.091	1.086	1.086
MEEDEN380C	1.078	1.095	1.097	1.096	1.094	1.088	1.084	1.084
ZWOLLE380A	1.079	1.081	1.083	1.084	1.084	1.078	1.077	1.080
HENGELO380A	1.077	1.076	1.077	1.076	1.077	1.072	1.069	1.070
ENS380A	1.075	1.075	1.078	1.079	1.079	1.074	1.075	1.080
DIEMEN380A	1.066	1.065	1.065	1.065	1.065	1.062	1.057	1.068
BEVERWIJK380A	1.063	1.063	1.061	1.056	1.057	1.055	1.043	1.059
KRIMPEN380A	1.070	1.068	1.061	1.057	1.057	1.058	1.053	1.062
MAASVLAKTE380A	1.072	1.071	1.060	1.060	1.060	1.066	1.061	1.071
BORSELLE380B	1.050	1.050	1.063	1.061	1.061	1.059	1.055	1.058
GEERTRUID380A	1.059	1.057	1.056	1.054	1.052	1.051	1.048	1.056
EINDHOVEN380A	1.064	1.062	1.061	1.060	1.060	1.058	1.054	1.057
MAASBRACHT380A	1.069	1.067	1.067	1.065	1.066	1.062	1.058	1.057
DOETINCHEM380A	1.076	1.070	1.071	1.070	1.073	1.065	1.061	1.062
EEMSHAVEN220A	1.047	1.039	1.041	1.040	1.039	1.037	1.042	1.042
MEEDEN220A	1.050	1.039	1.042	1.042	1.039	1.041	1.042	1.044
VIERVERLATEN220A	1.049	1.040	1.042	1.042	1.041	1.038	1.042	1.042
ENS220A	1.052	1.039	1.042	1.042	1.042	1.037	1.039	1.042

BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.084	1.093	1.094	1.093	1.091	1.086	1.082	1.080
GRONAU	1.076	1.075	1.076	1.075	1.076	1.071	1.068	1.068
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.071	1.070	1.070	1.069	1.069	1.066	1.064	1.063
VANEYK1	1.066	1.064	1.064	1.063	1.063	1.059	1.055	1.055
VANEYK2	1.069	1.067	1.066	1.065	1.065	1.061	1.058	1.057
ZANDVLIET	1.051	1.050	1.055	1.053	1.052	1.050	1.046	1.047

ACCC-RESULTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Total violations:	658	301	440	278	274	85	257	244
High V viols:	89	263	410	242	162	31	25	35
High V dev viols:	544	14	9	14	10	10	40	38
Low V viols:	0	0	0	0	0	0	0	0
Low V dev viols:	25	24	21	22	102	44	192	171

Appendix F: Data of investigated modules

Module 1: Low-load, all neutral

	LOW LOAD							
GENERATORS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-1314.3	-769.1	-718.1	-171.4	-143.5	-40.3	31.3	51.8
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

	LOW LOAD							
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Reactors Active (#)	9	14	15	20	21	21	20	19
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-400.0	-770.0	-895.0	-1345.0	-1420.0	-1420.0	-1345.0	-1245.0

	LOW LOAD							
VOLTAGE PROFILE	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
EEMSHAVEN380A	1.071	1.097	1.099	1.098	1.097	1.091	1.086	1.086
MEEDEN380C	1.078	1.095	1.097	1.096	1.094	1.088	1.084	1.084
ZWOLLE380A	1.079	1.081	1.083	1.084	1.084	1.078	1.077	1.080
HENGELO380A	1.077	1.076	1.077	1.076	1.077	1.072	1.069	1.070
ENS380A	1.075	1.075	1.078	1.079	1.079	1.074	1.075	1.080
DIEMEN380A	1.066	1.065	1.065	1.065	1.065	1.062	1.057	1.068
BEVERWIJK380A	1.063	1.063	1.061	1.056	1.057	1.055	1.043	1.059
KRIMPEN380A	1.070	1.068	1.061	1.057	1.057	1.058	1.053	1.062
MAASVLAKTE380A	1.072	1.071	1.060	1.060	1.060	1.066	1.061	1.071
BORSELLE380B	1.050	1.050	1.063	1.061	1.061	1.059	1.055	1.058
GEERTRUID380A	1.059	1.057	1.056	1.054	1.052	1.051	1.048	1.056
EINDHOVEN380A	1.064	1.062	1.061	1.060	1.060	1.058	1.054	1.057
MAASBRACHT380A	1.069	1.067	1.067	1.065	1.066	1.062	1.058	1.057
DOETINCHEM380A	1.076	1.070	1.071	1.070	1.073	1.065	1.061	1.062
EEMSHAVEN220A	1.047	1.039	1.041	1.040	1.039	1.037	1.042	1.042
MEEDEN220A	1.050	1.039	1.042	1.042	1.039	1.041	1.042	1.044
VIERVERLATEN220A	1.049	1.040	1.042	1.042	1.041	1.038	1.042	1.042
ENS220A	1.052	1.039	1.042	1.042	1.042	1.037	1.039	1.042
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.084	1.093	1.094	1.093	1.091	1.086	1.082	1.080
GRONAU	1.076	1.075	1.076	1.075	1.076	1.071	1.068	1.068
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.071	1.070	1.070	1.069	1.069	1.066	1.064	1.063
VANEYK1	1.066	1.064	1.064	1.063	1.063	1.059	1.055	1.055
VANEYK2	1.069	1.067	1.066	1.065	1.065	1.061	1.058	1.057
ZANDVLIET	1.051	1.050	1.055	1.053	1.052	1.050	1.046	1.047

	LOW LOAD							
VIOLATIONS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
BC V-Viol(<1.0 or >1.1):	3	2	1	1	1	1	0	0
Contingency analysis:								
Total violations:	89	263	410	242	162	31	26	35
High V viols:	89	263	410	242	162	31	25	35
High V dev viols:	0	0	0	0	0	0	0	0
Low V viols:	0	0	0	0	0	0	0	0
Low V dev viols:	0	0	0	0	0	0	1	0

Module 82: Medium load, all neutral

	MEDIUM LOAD							
GENERATORS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Running Generators (#)	31	30	28	25	22	19	16	13
P generation (MW)	10099.9	9100.1	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0
Q generation (MVAr)	-538.4	-629.2	-761.5	-231.5	-280.7	-125.1	-190.7	24.8
Reactive power bandwidth								
Qmax (MVAr)	7785.6	6992.0	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8
Qmin (MVAr)	-3415.1	-3150.6	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3

	MEDIUM LOAD							
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Reactors Active (#)	8	8	8	12	12	12	12	11
Capacitors Active (#)	4	4	4	4	4	4	4	4
BSW Nom (MVAr)	-175.0	-175.0	-175.0	-475.0	-475.0	-475.0	-475.0	-400.0

	MEDIUM LOAD							
VOLTAGE PROFILE	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
EEMSHAVEN380A	1.071	1.071	1.071	1.092	1.090	1.085	1.082	1.078
MEEDEN380C	1.078	1.078	1.078	1.091	1.089	1.085	1.081	1.077
ZWOLLE380A	1.078	1.077	1.077	1.079	1.078	1.077	1.074	1.072
HENGELO380A	1.077	1.076	1.076	1.075	1.074	1.073	1.070	1.066
ENS380A	1.074	1.073	1.073	1.073	1.072	1.072	1.070	1.070
DIEMEN380A	1.065	1.065	1.065	1.065	1.065	1.065	1.064	1.065
BEVERWIJK380A	1.060	1.061	1.061	1.061	1.060	1.061	1.060	1.061
KRIMPEN380A	1.059	1.064	1.064	1.062	1.059	1.063	1.062	1.064
MAASVLAKTE380A	1.055	1.066	1.066	1.064	1.060	1.068	1.067	1.075
BORSELLE380B	1.050	1.050	1.050	1.050	1.060	1.059	1.058	1.055
GEERTRUID380A	1.052	1.052	1.053	1.052	1.052	1.054	1.052	1.051
EINDHOVEN380A	1.058	1.059	1.060	1.059	1.058	1.058	1.056	1.053
MAASBRACHT380A	1.067	1.067	1.067	1.065	1.064	1.063	1.061	1.056
DOETINCHEM380A	1.077	1.077	1.076	1.075	1.074	1.073	1.070	1.063
EEMSHAVEN220A	1.045	1.044	1.045	1.033	1.032	1.037	1.037	1.034
MEEDEN220A	1.048	1.048	1.048	1.033	1.031	1.034	1.038	1.033
VIERVERLATEN220A	1.047	1.046	1.047	1.035	1.033	1.037	1.037	1.035
ENS220A	1.057	1.057	1.057	1.044	1.043	1.043	1.043	1.041
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.085	1.084	1.083	1.089	1.087	1.084	1.080	1.076
GRONAU	1.076	1.075	1.075	1.074	1.073	1.072	1.069	1.065
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.070	1.070	1.070	1.069	1.068	1.067	1.065	1.062
VANEYK1	1.064	1.064	1.064	1.062	1.061	1.060	1.058	1.053
VANEYK2	1.066	1.067	1.067	1.065	1.064	1.063	1.060	1.055
ZANDVLIET	1.048	1.048	1.049	1.048	1.052	1.051	1.048	1.045

Module 163: High load, all neutral

GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
	HIGH LOAD							
Running Generators (#)	36	34	31	30	28	25	22	19
P generation (MW)	12100.1	11100.0	10099.9	9100.1	8100.0	7100.0	6100.1	5100.0
Q generation (MVAr)	-362.3	-408.7	-203.0	-205.6	-308.7	99.2	130.0	283.7
Reactive power bandwidth								
Qmax (MVAr)	9468.4	9103.1	7785.6	6992.0	6051.0	4824.7	4244.7	2912.6
Qmin (MVAr)	-4264.6	-4049.4	-3415.1	-3150.6	-2535.1	-1697.2	-1449.4	-1114.0

SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
	HIGH LOAD							
Reactors Active (#)	6	6	6	6	6	9	9	8
Capacitors Active (#)	6	6	6	6	6	6	6	6
BSW Nom (MVAr)	300.0	300.0	300.0	300.0	300.0	75.0	75.0	150.0

VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
	HIGH LOAD							
EEMSHAVEN380A	1.070	1.070	1.070	1.070	1.070	1.078	1.076	1.078
MEEDEN380C	1.077	1.076	1.076	1.075	1.075	1.079	1.076	1.077
ZWOLLE380A	1.076	1.075	1.073	1.073	1.073	1.073	1.071	1.071
HENGELO380A	1.074	1.073	1.071	1.070	1.069	1.068	1.066	1.065
ENS380A	1.073	1.072	1.070	1.070	1.069	1.069	1.069	1.069
DIEMEN380A	1.067	1.066	1.065	1.065	1.065	1.065	1.065	1.065
BEVERWIJK380A	1.069	1.067	1.064	1.065	1.065	1.065	1.064	1.064
KRIMPEN380A	1.064	1.061	1.060	1.064	1.064	1.062	1.060	1.058
MAASVLAKTE380A	1.060	1.055	1.055	1.065	1.065	1.061	1.060	1.061
BORSELLE380B	1.050	1.050	1.050	1.050	1.050	1.050	1.058	1.053
GEERTRUID380A	1.053	1.052	1.052	1.052	1.052	1.052	1.052	1.048
EINDHOVEN380A	1.057	1.057	1.057	1.056	1.056	1.055	1.054	1.050
MAASBRACHT380A	1.065	1.064	1.063	1.062	1.061	1.059	1.057	1.053
DOETINCHEM380A	1.075	1.073	1.070	1.069	1.068	1.066	1.064	1.063
EEMSHAVEN220A	1.040	1.039	1.039	1.038	1.038	1.042	1.042	1.044
MEEDEN220A	1.042	1.041	1.042	1.041	1.041	1.040	1.044	1.045
VIERVERLATEN220A	1.040	1.039	1.038	1.037	1.038	1.040	1.040	1.042
ENS220A	1.053	1.052	1.050	1.049	1.050	1.050	1.050	1.050
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.084	1.083	1.082	1.081	1.079	1.080	1.077	1.075
GRONAU	1.073	1.072	1.071	1.070	1.069	1.067	1.065	1.064
ROMMERSKIRCHEN	1.081	1.082	1.081	1.081	1.081	1.080	1.080	1.078
SIERSDORF	1.069	1.069	1.068	1.067	1.066	1.065	1.063	1.060
VANEYK1	1.062	1.062	1.060	1.059	1.058	1.056	1.054	1.051
VANEYK2	1.065	1.064	1.063	1.062	1.061	1.059	1.057	1.053
ZANDVLIET	1.048	1.048	1.048	1.048	1.048	1.047	1.049	1.043

Module 2: Low load, NS AC 2GW, all neutral

LOW LOAD, 2GW N-S AC-TRANSIT								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running Generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-1359.6	-594.2	-616.0	-124.5	-207.3	-24.0	23.2	100.8
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, 2GW N-S AC-TRANSIT								
SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	7	16	17	21	21	21	20	20
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-250.0	-995.0	-1045.0	-1420.0	-1420.0	-1420.0	-1345.0	-1345.0

LOW LOAD, 2GW N-S AC-TRANSIT								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.071	1.096	1.094	1.091	1.083	1.078	1.079	1.079
MEEDEN380C	1.079	1.094	1.092	1.089	1.082	1.077	1.076	1.075
ZWOLLE380A	1.081	1.083	1.081	1.080	1.076	1.073	1.071	1.067
HENGELO380A	1.077	1.076	1.075	1.073	1.072	1.067	1.065	1.061
ENS380A	1.079	1.078	1.077	1.076	1.072	1.070	1.070	1.066
DIEMEN380A	1.069	1.065	1.065	1.065	1.061	1.065	1.058	1.056
BEVERWIJK380A	1.066	1.062	1.062	1.056	1.054	1.058	1.043	1.043
KRIMPEN380A	1.071	1.064	1.062	1.058	1.057	1.065	1.059	1.061
MAASVLAKTE380A	1.074	1.065	1.060	1.061	1.060	1.073	1.067	1.069
BORSELLE380B	1.050	1.050	1.063	1.062	1.064	1.067	1.064	1.069
GEERTRUID380A	1.059	1.055	1.057	1.055	1.055	1.060	1.055	1.058
EINDHOVEN380A	1.062	1.059	1.061	1.061	1.061	1.063	1.059	1.058
MAASBRACHT380A	1.065	1.063	1.064	1.064	1.064	1.063	1.060	1.057
DOETINCHEM380A	1.075	1.070	1.069	1.067	1.069	1.062	1.059	1.055
EEMSHAVEN220A	1.047	1.039	1.036	1.034	1.039	1.035	1.035	1.036
MEEDEN220A	1.051	1.039	1.036	1.035	1.040	1.036	1.035	1.037
VIERVERLATEN220A	1.050	1.041	1.039	1.037	1.039	1.036	1.035	1.037
ENS220A	1.055	1.041	1.040	1.039	1.037	1.035	1.033	1.040
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.083	1.091	1.088	1.085	1.080	1.075	1.072	1.071
GRONAU	1.076	1.075	1.074	1.072	1.071	1.066	1.064	1.061
ROMMERSKIRCHEN	1.079	1.079	1.079	1.080	1.080	1.080	1.079	1.078
SIERSDORF	1.066	1.066	1.066	1.066	1.066	1.065	1.064	1.061
VANEYK1	1.061	1.060	1.061	1.060	1.061	1.060	1.057	1.055
VANEYK2	1.064	1.062	1.063	1.063	1.064	1.063	1.060	1.057
ZANDVLIET	1.048	1.047	1.055	1.055	1.056	1.059	1.056	1.058

LOW LOAD, 2GW N-S AC-TRANSIT								
VIOLATIONS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
BC V-Viol(<1.0 or >1.1):	3	3	1	1	1	1	0	0
Contingency analysis:								
Total violations:	125	1167	101	41	2	24	7	15
High V viols:	125	1167	101	41	2	24	6	14
High V dev viols:	0	0	0	0	0	0	0	0
Low V viols:	0	0	0	0	0	0	0	0
Low V dev viols:	0	0	0	0	0	0	1	1

Module 3: Low load, NS AC 4GW, all neutral

LOW LOAD, 4GW N-S AC-TRANSIT								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running Generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-528.9	-491.9	-545.0	-280.0	-265.1	-17.5	-12.3	-15.9
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, 4GW N-S AC-TRANSIT								
SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	7	10	10	11	12	13	14	13
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-250.0	-475.0	-475.0	-550.0	-650.0	-775.0	-875.0	-775.0

LOW LOAD, 4GW N-S AC-TRANSIT								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.070	1.080	1.074	1.074	1.074	1.074	1.063	1.060
MEEDEN380C	1.072	1.077	1.072	1.071	1.070	1.070	1.060	1.057
ZWOLLE380A	1.069	1.072	1.070	1.069	1.067	1.066	1.052	1.049
HENGELO380A	1.062	1.063	1.061	1.060	1.057	1.053	1.042	1.037
ENS380A	1.070	1.072	1.070	1.070	1.068	1.068	1.054	1.052
DIEMEN380A	1.065	1.065	1.065	1.065	1.067	1.066	1.047	1.051
BEVERWIJK380A	1.063	1.063	1.062	1.063	1.063	1.062	1.042	1.047
KRIMPEN380A	1.066	1.067	1.066	1.068	1.066	1.064	1.052	1.056
MAASVLAKTE380A	1.069	1.070	1.068	1.072	1.069	1.072	1.060	1.064
BORSELLE380B	1.050	1.050	1.056	1.060	1.064	1.064	1.060	1.063
GEERTRUID380A	1.052	1.053	1.055	1.058	1.058	1.056	1.048	1.052
EINDHOVEN380A	1.050	1.052	1.054	1.056	1.056	1.054	1.047	1.047
MAASBRACHT380A	1.046	1.049	1.050	1.052	1.051	1.050	1.044	1.042
DOETINCHEM380A	1.058	1.060	1.059	1.059	1.057	1.051	1.041	1.035
EEMSHAVEN220A	1.046	1.039	1.035	1.043	1.033	1.045	1.049	1.043
MEEDEN220A	1.048	1.040	1.034	1.040	1.033	1.046	1.051	1.039
VIERVERLATEN220A	1.049	1.042	1.038	1.044	1.036	1.045	1.048	1.043
ENS220A	1.057	1.047	1.045	1.046	1.042	1.044	1.046	1.043
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.070	1.071	1.067	1.064	1.063	1.062	1.054	1.051
GRONAU	1.061	1.061	1.059	1.058	1.055	1.051	1.040	1.035
ROMMERSKIRCHEN	1.067	1.069	1.069	1.070	1.070	1.070	1.068	1.067
SIERSDORF	1.049	1.051	1.052	1.053	1.053	1.052	1.048	1.046
VANEYK1	1.040	1.044	1.045	1.047	1.047	1.046	1.041	1.039
VANEYK2	1.042	1.046	1.048	1.050	1.050	1.049	1.044	1.042
ZANDVLIET	1.037	1.039	1.046	1.051	1.054	1.055	1.052	1.055

LOW LOAD, 4GW N-S AC-TRANSIT								
VIOLATIONS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
BC V-Viol(<1.0 or >1.1):	1	1	1	1	3	0	2	2
Contingency analysis:								
Total violations:	3	41	2	9	7	13	2	2
High V viols:	3	41	2	9	7	13	2	2
High V dev viols:	0	0	0	0	0	0	0	0
Low V viols:	0	0	0	0	0	0	0	0
Low V dev viols:	0	0	0	0	0	0	0	0

Module 4: Low load, DC-Transit N-S, Rest neutral

LOW LOAD, N-S DC-TRANSIT								
GENERATORS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-1301.9	-639.5	-647.5	-114.9	-148.8	28.1	67.0	61.8
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, N-S DC-TRANSIT								
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Reactors Active (#)	9	16	17	20	21	21	19	18
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-370.0	-995.0	-1045.0	-1345.0	-1420.0	-1420.0	-1270.0	-1170.0

LOW LOAD, N-S DC-TRANSIT								
VOLTAGE PROFILE	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
EEMSHAVEN380A	1.070	1.090	1.089	1.088	1.082	1.076	1.077	1.074
MEEDEN380C	1.079	1.091	1.090	1.089	1.084	1.078	1.078	1.074
ZWOLLE380A	1.080	1.082	1.082	1.082	1.079	1.074	1.074	1.071
HENGELO380A	1.078	1.077	1.077	1.078	1.075	1.070	1.068	1.065
ENS380A	1.077	1.078	1.078	1.078	1.076	1.071	1.072	1.070
DIEMEN380A	1.069	1.065	1.065	1.065	1.062	1.060	1.055	1.058
BEVERWIJK380A	1.066	1.062	1.062	1.056	1.055	1.054	1.041	1.050
KRIMPEN380A	1.071	1.063	1.061	1.057	1.055	1.054	1.048	1.052
MAASVLAKTE380A	1.074	1.065	1.060	1.060	1.060	1.063	1.056	1.060
BORSELLE380B	1.050	1.050	1.062	1.060	1.059	1.056	1.052	1.052
GEERTRUID380A	1.060	1.054	1.055	1.053	1.051	1.048	1.044	1.047
EINDHOVEN380A	1.065	1.061	1.062	1.060	1.059	1.056	1.052	1.051
MAASBRACHT380A	1.070	1.067	1.067	1.067	1.065	1.061	1.057	1.054
DOETINCHEM380A	1.075	1.072	1.071	1.074	1.072	1.064	1.061	1.058
EEMSHAVEN220A	1.048	1.035	1.034	1.033	1.040	1.034	1.045	1.032
MEEDEN220A	1.051	1.036	1.034	1.033	1.041	1.035	1.042	1.033
VIERVERLATEN220A	1.050	1.039	1.037	1.037	1.042	1.035	1.044	1.033
ENS220A	1.054	1.041	1.040	1.040	1.040	1.035	1.039	1.034
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.085	1.091	1.090	1.089	1.085	1.080	1.078	1.074
GRONAU	1.076	1.076	1.075	1.076	1.074	1.069	1.067	1.064
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.072	1.070	1.070	1.070	1.069	1.066	1.063	1.060
VANEYK1	1.067	1.064	1.064	1.064	1.062	1.058	1.054	1.051
VANEYK2	1.070	1.067	1.067	1.066	1.065	1.061	1.057	1.053
ZANDVLIET	1.051	1.049	1.055	1.052	1.051	1.047	1.043	1.041

Module 7: Low load, DC-Transit S-N, Rest neutral

LOW LOAD, S-N DC-TRANSIT								
GENERATORS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-1129.6	-686.9	-733.6	-276.8	-161.1	24.5	-5.4	61.2
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, S-N DC-TRANSIT								
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Reactors Active (#)	7	10	11	17	20	20	18	19
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-250.0	-475.0	-550.0	-1045.0	-1345.0	-1345.0	-1170.0	-1245.0

LOW LOAD, S-N DC-TRANSIT								
VOLTAGE PROFILE	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
EEMSHAVEN380A	1.070	1.078	1.077	1.076	1.078	1.075	1.073	1.069
MEEDEN380C	1.079	1.081	1.080	1.079	1.080	1.077	1.075	1.071
ZWOLLE380A	1.079	1.076	1.075	1.075	1.074	1.072	1.072	1.072
HENGELO380A	1.077	1.074	1.074	1.072	1.069	1.066	1.064	1.063
ENS380A	1.076	1.072	1.071	1.071	1.071	1.070	1.072	1.072
DIEMEN380A	1.065	1.065	1.065	1.065	1.058	1.061	1.059	1.062
BEVERWIJK380A	1.062	1.062	1.062	1.061	1.049	1.055	1.052	1.053
KRIMPEN380A	1.070	1.069	1.070	1.061	1.054	1.061	1.059	1.062
MAASVLAKTE380A	1.075	1.074	1.075	1.065	1.060	1.072	1.071	1.074
BORSELLE380B	1.050	1.050	1.066	1.063	1.060	1.061	1.059	1.058
GEERTRUID380A	1.058	1.057	1.062	1.056	1.051	1.054	1.052	1.055
EINDHOVEN380A	1.062	1.062	1.065	1.062	1.058	1.059	1.057	1.056
MAASBRACHT380A	1.068	1.067	1.069	1.066	1.063	1.061	1.058	1.056
DOETINCHEM380A	1.075	1.073	1.072	1.070	1.064	1.060	1.058	1.056
EEMSHAVEN220A	1.046	1.038	1.037	1.036	1.035	1.033	1.032	1.040
MEEDEN220A	1.051	1.040	1.039	1.037	1.036	1.035	1.033	1.042
VIERVERLATEN220A	1.048	1.040	1.039	1.040	1.036	1.034	1.033	1.041
ENS220A	1.052	1.046	1.045	1.044	1.035	1.034	1.034	1.037
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.085	1.086	1.084	1.083	1.082	1.079	1.076	1.072
GRONAU	1.076	1.074	1.073	1.072	1.068	1.066	1.064	1.062
ROMMERSKIRCHEN	1.082	1.082	1.082	1.082	1.081	1.081	1.080	1.079
SIERSDORF	1.070	1.070	1.071	1.070	1.068	1.066	1.064	1.062
VANEYK1	1.065	1.064	1.065	1.063	1.060	1.058	1.056	1.053
VANEYK2	1.068	1.067	1.068	1.066	1.063	1.061	1.058	1.056
ZANDVLIET	1.050	1.050	1.059	1.055	1.052	1.052	1.049	1.048

Module 6: Low load, AC-Transit 4 GW, DC-Transit N-S, Rest neutral

LOW LOAD, 4GW N-S AC-TRANSIT, N-S DC-TRANSIT								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-233.7	-458.9	-531.7	-165.7	-103.4	170.4	-28.8	-60.2
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, 4GW N-S AC-TRANSIT, N-S DC-TRANSIT								
SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	7	9	7	8	10	11	10	9
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-250.0	-400.0	-250.0	-350.0	-500.0	-600.0	-500.0	-400.0

LOW LOAD, 4GW N-S AC-TRANSIT, N-S DC-TRANSIT								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.070	1.070	1.079	1.073	1.071	1.067	1.051	1.047
MEEDEN380C	1.070	1.069	1.076	1.070	1.068	1.065	1.049	1.045
ZWOLLE380A	1.067	1.069	1.070	1.067	1.065	1.062	1.046	1.039
HENGELO380A	1.060	1.061	1.063	1.060	1.058	1.052	1.039	1.032
ENS380A	1.068	1.070	1.070	1.068	1.067	1.066	1.049	1.041
DIEMEN380A	1.065	1.065	1.065	1.065	1.064	1.065	1.050	1.046
BEVERWIJK380A	1.063	1.063	1.062	1.063	1.061	1.062	1.044	1.042
KRIMPEN380A	1.066	1.067	1.066	1.068	1.063	1.064	1.058	1.060
MAASVLAKTE380A	1.070	1.070	1.070	1.074	1.066	1.072	1.066	1.069
BORSELLE380B	1.050	1.050	1.057	1.061	1.063	1.064	1.062	1.063
GEERTRUID380A	1.052	1.053	1.055	1.058	1.056	1.056	1.051	1.052
EINDHOVEN380A	1.050	1.052	1.054	1.056	1.053	1.053	1.048	1.046
MAASBRACHT380A	1.045	1.048	1.050	1.051	1.049	1.048	1.043	1.039
DOETINCHEM380A	1.056	1.058	1.059	1.058	1.056	1.049	1.038	1.031
EEMSHAVEN220A	1.044	1.043	1.052	1.047	1.045	1.041	1.038	1.036
MEEDEN220A	1.047	1.045	1.054	1.048	1.046	1.043	1.039	1.037
VIERVERLATEN220A	1.047	1.045	1.054	1.050	1.047	1.044	1.039	1.037
ENS220A	1.055	1.047	1.058	1.056	1.054	1.052	1.039	1.044
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.069	1.067	1.069	1.064	1.062	1.059	1.048	1.044
GRONAU	1.059	1.060	1.061	1.059	1.056	1.050	1.038	1.032
ROMMERSKIRCHEN	1.066	1.068	1.069	1.069	1.069	1.069	1.068	1.066
SIERSDORF	1.048	1.051	1.052	1.052	1.051	1.050	1.047	1.044
VANEYK1	1.039	1.043	1.045	1.046	1.045	1.044	1.040	1.036
VANEYK2	1.041	1.045	1.047	1.049	1.048	1.047	1.043	1.040
ZANDVLIET	1.038	1.040	1.047	1.052	1.053	1.055	1.054	1.055

Module 9: Low load, AC-Transit 4 GW, DC-Transit S-N, Rest neutral

LOW LOAD, 4GW N-S AC-TRANSIT, S-N DC-TRANSIT								
GENERATORS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-432.8	-519.1	-608.7	-285.2	-228.5	-2.7	-49.0	-0.5
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, 4GW N-S AC-TRANSIT, S-N DC-TRANSIT								
SHUNTS	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
Reactors Active (#)	7	7	7	10	12	13	13	15
Capacitors Active (#)	3	3	3	3	3	3	3	5
BSW Nom (MVAr)	-250.0	-250.0	-250.0	-500.0	-700.0	-800.0	-800.0	-675.0

LOW LOAD, 4GW N-S AC-TRANSIT, S-N DC-TRANSIT								
VOLTAGE PROFILE	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
EEMSHAVEN380A	1.070	1.079	1.077	1.072	1.070	1.067	1.056	1.060
MEEDEN380C	1.073	1.078	1.076	1.071	1.069	1.066	1.055	1.059
ZWOLLE380A	1.071	1.073	1.071	1.069	1.067	1.064	1.053	1.057
HENGELO380A	1.063	1.064	1.063	1.061	1.058	1.052	1.041	1.043
ENS380A	1.070	1.073	1.070	1.069	1.068	1.067	1.057	1.062
DIEMEN380A	1.065	1.065	1.065	1.065	1.066	1.066	1.053	1.066
BEVERWIJK380A	1.063	1.063	1.062	1.062	1.062	1.063	1.049	1.058
KRIMPEN380A	1.068	1.068	1.068	1.068	1.062	1.069	1.061	1.062
MAASVLAKTE380A	1.073	1.073	1.073	1.074	1.067	1.081	1.072	1.072
BORSELLE380B	1.050	1.050	1.056	1.060	1.062	1.066	1.064	1.066
GEERTRUID380A	1.052	1.053	1.055	1.058	1.055	1.060	1.055	1.057
EINDHOVEN380A	1.050	1.052	1.054	1.056	1.055	1.057	1.052	1.053
MAASBRACHT380A	1.046	1.050	1.051	1.053	1.052	1.052	1.048	1.048
DOETINCHEM380A	1.059	1.061	1.061	1.060	1.057	1.051	1.042	1.047
EEMSHAVEN220A	1.046	1.050	1.051	1.047	1.045	1.042	1.044	1.036
MEEDEN220A	1.048	1.052	1.053	1.048	1.047	1.044	1.046	1.037
VIERVERLATEN220A	1.049	1.050	1.053	1.050	1.049	1.046	1.045	1.039
ENS220A	1.057	1.049	1.058	1.056	1.056	1.053	1.047	1.048
BORDER VOLTAGES	**NP = -0.00 GW**	**NP = -1.00 GW**	**NP = -2.00 GW**	**NP = -3.00 GW**	**NP = -4.00 GW**	**NP = -5.00 GW**	**NP = -6.00 GW**	**NP = -7.00 GW**
DIELE	1.071	1.072	1.069	1.064	1.062	1.059	1.051	1.052
GRONAU	1.061	1.062	1.061	1.059	1.055	1.050	1.040	1.040
ROMMERSKIRCHEN	1.067	1.069	1.070	1.071	1.070	1.071	1.069	1.069
SIERSDORF	1.049	1.052	1.053	1.054	1.053	1.053	1.051	1.050
VANEYK1	1.041	1.045	1.047	1.048	1.047	1.048	1.044	1.045
VANEYK2	1.043	1.047	1.049	1.051	1.050	1.051	1.047	1.048
ZANDVLIET	1.036	1.038	1.045	1.050	1.052	1.056	1.055	1.057

Module 10: Low load, Maasvlakte concentrated generation, Rest neutral

LOW LOAD, MAASVLAKTE CONCENTRATED GENERATION								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running Generators (#)	22	20	14	12	10	8	7	4
P generation (MW)	8100.0	7100.0	6100.0	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	285.3	57.1	-169.1	82.7	-261.8	-390.5	-49.0	129.6
Reactive power bandwidth								
Qmax (MVAr)	6805.7	6245.9	5796.4	5010.7	4310.7	3060.7	2267.1	1087.2
Qmin (MVAr)	-2619.2	-2372.5	-2253.3	-2010.2	-1610.2	-1235.2	-970.6	-433.4

LOW LOAD, MAASVLAKTE CONCENTRATED GENERATION								
SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	12	13	14	15	15	15	19	21
Capacitors Active (#)	3	3	3	3	3	3	3	3
BSW Nom (MVAr)	-595.0	-670.0	-770.0	-870.0	-870.0	-870.0	-1295.0	-1420.0

LOW LOAD, MAASVLAKTE CONCENTRATED GENERATION								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.099	1.099	1.101	1.099	1.095	1.094	1.090	1.084
MEEDEN380C	1.097	1.096	1.098	1.096	1.093	1.092	1.088	1.082
ZWOLLE380A	1.083	1.082	1.084	1.082	1.083	1.083	1.080	1.077
HENGELO380A	1.077	1.077	1.076	1.076	1.075	1.074	1.071	1.068
ENS380A	1.077	1.076	1.079	1.077	1.080	1.079	1.078	1.076
DIEMEN380A	1.056	1.058	1.063	1.060	1.063	1.065	1.061	1.060
BEVERWIJK380A	1.047	1.049	1.054	1.052	1.056	1.058	1.047	1.049
KRIMPEN380A	1.056	1.057	1.060	1.062	1.062	1.063	1.059	1.059
MAASVLAKTE380A	1.060	1.060	1.060	1.060	1.055	1.055	1.060	1.065
BORSELLE380B	1.050	1.060	1.064	1.067	1.066	1.064	1.059	1.052
GEERTRUID380A	1.052	1.052	1.057	1.062	1.062	1.062	1.057	1.052
EINDHOVEN380A	1.055	1.057	1.060	1.065	1.065	1.064	1.059	1.053
MAASBRACHT380A	1.062	1.063	1.064	1.066	1.065	1.064	1.059	1.054
DOETINCHEM380A	1.072	1.072	1.069	1.071	1.069	1.067	1.064	1.061
EEMSHAVEN220A	1.041	1.040	1.033	1.032	1.036	1.038	1.034	1.041
MEEDEN220A	1.041	1.040	1.036	1.035	1.038	1.038	1.033	1.042
VIERVERLATEN220A	1.042	1.041	1.037	1.035	1.037	1.039	1.036	1.041
ENS220A	1.041	1.040	1.041	1.039	1.035	1.041	1.040	1.039
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.095	1.094	1.094	1.092	1.090	1.088	1.084	1.079
GRONAU	1.076	1.076	1.075	1.075	1.074	1.073	1.070	1.067
ROMMERSKIRCHEN	1.081	1.081	1.081	1.082	1.082	1.081	1.080	1.079
SIERSDORF	1.067	1.068	1.068	1.069	1.069	1.068	1.065	1.061
VANEYK1	1.059	1.060	1.061	1.063	1.062	1.061	1.057	1.052
VANEYK2	1.062	1.063	1.064	1.066	1.065	1.063	1.059	1.054
ZANDVLIET	1.049	1.054	1.057	1.059	1.058	1.056	1.050	1.044

LOW LOAD, MAASVLAKTE CONCENTRATED GENERATION								
VIOLATIONS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
BC V-Viol(<1.0 or >1.1):	4	3	25	1	1	1	1	1
Contingency analysis:								
Total violations:	1817	875	23919	1116	142	107	46	109
High V viols:	1817	875	23919	1116	142	107	45	108
High V dev viols:	0	0	0	0	0	0	0	0
Low V viols:	0	0	0	0	0	0	0	0
Low V dev viols:	0	0	0	0	0	0	1	1

Module 19: Low load, Eemshaven concentrated generation, Rest neutral

LOW LOAD, EEMSHAVEN CONCENTRATED GENERATION								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running Generators (#)	18	15	12	10	8	7	6	4
P generation (MW)	8099.9	7100.0	6100.0	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	599.3	1075.6	1234.9	1024.8	443.6	73.3	-183.6	242.0
Reactive power bandwidth								
Qmax (MVAr)	8185.1	7429.8	6517.5	5637.5	4537.5	3987.5	3112.5	1790.0
Qmin (MVAr)	-3974.2	-3534.4	-3002.8	-2602.8	-1802.8	-1402.8	-902.8	-537.0

LOW LOAD, EEMSHAVEN CONCENTRATED GENERATION								
SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	13	13	13	12	12	16	15	26
Capacitors Active (#)	3	3	3	3	4	4	3	2
BSW Nom (MVAr)	-775.0	-775.0	-775.0	-675.0	-550.0	-870.0	-920.0	-1965.0

LOW LOAD, EEMSHAVEN CONCENTRATED GENERATION								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.070	1.070	1.070	1.070	1.070	1.070	1.070	1.070
MEEDEN380C	1.068	1.064	1.061	1.059	1.066	1.069	1.071	1.062
ZWOLLE380A	1.063	1.059	1.052	1.042	1.061	1.063	1.066	1.032
HENGELO380A	1.064	1.061	1.056	1.051	1.064	1.062	1.064	1.036
ENS380A	1.066	1.064	1.056	1.043	1.064	1.063	1.064	1.017
DIEMEN380A	1.065	1.065	1.065	1.047	1.068	1.064	1.058	0.997
BEVERWIJK380A	1.062	1.062	1.061	1.047	1.063	1.056	1.053	0.984
KRIMPEN380A	1.066	1.067	1.066	1.054	1.068	1.059	1.062	0.995
MAASVLAKTE380A	1.073	1.074	1.073	1.061	1.075	1.064	1.072	0.998
BORSELLE380B	1.070	1.070	1.068	1.058	1.066	1.058	1.057	1.010
GEERTRUID380A	1.065	1.065	1.063	1.053	1.064	1.056	1.057	1.002
EINDHOVEN380A	1.068	1.068	1.065	1.056	1.066	1.057	1.057	1.013
MAASBRACHT380A	1.068	1.067	1.065	1.059	1.065	1.058	1.057	1.029
DOETINCHEM380A	1.067	1.065	1.059	1.053	1.065	1.058	1.058	1.025
EEMSHAVEN220A	1.040	1.043	1.045	1.047	1.039	1.036	1.035	1.036
MEEDEN220A	1.041	1.041	1.041	1.042	1.040	1.040	1.040	1.035
VIERVERLATEN220A	1.037	1.036	1.035	1.037	1.035	1.035	1.036	1.029
ENS220A	1.046	1.042	1.036	1.037	1.042	1.044	1.047	1.009
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.078	1.075	1.073	1.070	1.074	1.074	1.074	1.065
GRONAU	1.065	1.063	1.059	1.054	1.065	1.063	1.064	1.041
ROMMERSKIRCHEN	1.082	1.082	1.081	1.080	1.081	1.080	1.080	1.073
SIERSDORF	1.070	1.070	1.068	1.065	1.068	1.064	1.063	1.046
VANEYK1	1.065	1.064	1.062	1.056	1.062	1.056	1.054	1.028
VANEYK2	1.067	1.067	1.065	1.059	1.064	1.058	1.057	1.030
ZANDVLIET	1.061	1.061	1.059	1.051	1.057	1.050	1.048	1.011

LOW LOAD, EEMSHAVEN CONCENTRATED GENERATION								
VIOLATIONS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
BC V-Viol(<1.0 or >1.1):	1	1	1	0	0	0	0	660
Contingency analysis:								
Total violations:	1065	1077	1057	55	105	49	16	3
High V viols:	1065	1076	1057	55	105	49	16	0
High V dev viols:	0	0	0	0	0	0	0	0
Low V viols:	0	0	0	0	0	0	0	2
Low V dev viols:	0	1	0	0	0	0	0	1

Module 28: Low load, Border voltage 1.1 p.u., Rest neutral

LOW LOAD, BORDER VOLTAGE 1.1 p.u.								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	-1399.8	-725.8	-657.2	-484.1	-213.1	-341.4	-4.1	59.6
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, BORDER VOLTAGE 1.1 p.u.								
SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	23	27	27	28	33	29	32	33
Capacitors Active (#)	3	3	3	3	3	1	3	3
BSW Nom (MVAr)	-1535.0	-1835.0	-1835.0	-1910.0	-2330.0	-2305.0	-2285.0	-2330.0

LOW LOAD, BORDER VOLTAGE 1.1 p.u.								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.071	1.104	1.106	1.102	1.104	1.093	1.100	1.100
MEEDEN380C	1.084	1.102	1.103	1.100	1.101	1.095	1.099	1.099
ZWOLLE380A	1.087	1.089	1.089	1.089	1.087	1.087	1.090	1.090
HENGELO380A	1.095	1.095	1.095	1.095	1.095	1.094	1.095	1.095
ENS380A	1.080	1.078	1.077	1.077	1.074	1.077	1.079	1.080
DIEMEN380A	1.065	1.065	1.065	1.065	1.063	1.067	1.062	1.064
BEVERWIJK380A	1.057	1.057	1.056	1.059	1.057	1.059	1.049	1.052
KRIMPEN380A	1.067	1.066	1.064	1.072	1.061	1.067	1.064	1.068
MAASVLAKTE380A	1.065	1.064	1.062	1.075	1.060	1.073	1.069	1.074
BORSELLE380B	1.078	1.077	1.091	1.093	1.095	1.092	1.094	1.098
GEERTRUID380A	1.070	1.069	1.070	1.076	1.069	1.072	1.071	1.075
EINDHOVEN380A	1.081	1.081	1.083	1.086	1.082	1.082	1.083	1.084
MAASBRACHT380A	1.093	1.093	1.094	1.095	1.094	1.092	1.092	1.092
DOETINCHEM380A	1.086	1.085	1.085	1.086	1.086	1.083	1.084	1.083
EEMSHAVEN220A	1.044	1.045	1.034	1.040	1.035	1.054	1.039	1.039
MEEDEN220A	1.045	1.045	1.033	1.041	1.039	1.055	1.040	1.042
VIERVERLATEN220A	1.045	1.046	1.037	1.039	1.037	1.053	1.038	1.038
ENS220A	1.044	1.043	1.040	1.031	1.038	1.047	1.031	1.032
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
GRONAU	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
ROMMERSKIRCHEN	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
SIERSDORF	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
VANEYK1	1.095	1.095	1.095	1.096	1.095	1.094	1.094	1.094
VANEYK2	1.095	1.095	1.095	1.096	1.095	1.094	1.095	1.094
ZANDVLIET	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100

Module 55: Low load, Border voltage 1.0 p.u., Rest neutral

LOW LOAD, BORDER VOLTAGE 1.0 p.u.								
GENERATORS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Running generators (#)	28	25	22	19	16	13	11	5
P generation (MW)	8100.0	7100.0	6100.1	5100.0	4100.0	3100.0	2100.0	1100.0
Q generation (MVAr)	1717.9	1438.4	1066.4	774.6	577.3	645.1	291.1	199.8
Reactive power bandwidth								
Qmax (MVAr)	6051.0	4824.7	4244.7	2912.6	2433.3	1641.8	1055.1	761.6
Qmin (MVAr)	-2535.1	-1697.2	-1449.4	-1114.0	-947.2	-676.3	-452.9	-306.4

LOW LOAD, BORDER VOLTAGE 1.0 p.u.								
SHUNTS	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
Reactors Active (#)	7	7	7	7	7	7	7	7
Capacitors Active (#)	4	4	4	4	4	4	4	4
BSW Nom (MVAr)	-100.0	-100.0	-100.0	-100.0	-100.0	-100.0	-100.0	-100.0

LOW LOAD, BORDER VOLTAGE 1.0 p.u.								
VOLTAGE PROFILE	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
EEMSHAVEN380A	1.070	1.044	1.044	1.044	1.043	1.041	1.033	1.032
MEEDEN380C	1.051	1.036	1.036	1.036	1.035	1.033	1.026	1.024
ZWOLLE380A	1.049	1.044	1.045	1.045	1.043	1.043	1.029	1.028
HENGELO380A	1.017	1.015	1.016	1.015	1.015	1.014	1.009	1.009
ENS380A	1.062	1.059	1.059	1.060	1.057	1.059	1.036	1.035
DIEMEN380A	1.065	1.065	1.065	1.065	1.061	1.064	1.038	1.038
BEVERWIJK380A	1.062	1.062	1.061	1.060	1.057	1.060	1.033	1.032
KRIMPEN380A	1.066	1.065	1.061	1.053	1.052	1.057	1.041	1.041
MAASVLAKTE380A	1.069	1.068	1.064	1.060	1.060	1.070	1.054	1.054
BORSELLE380B	1.047	1.047	1.030	1.025	1.026	1.026	1.023	1.023
GEERTRUID380A	1.052	1.052	1.049	1.033	1.032	1.034	1.024	1.023
EINDHOVEN380A	1.037	1.037	1.036	1.025	1.025	1.024	1.018	1.016
MAASBRACHT380A	1.018	1.017	1.017	1.014	1.013	1.011	1.008	1.006
DOETINCHEM380A	1.027	1.025	1.025	1.024	1.024	1.018	1.014	1.013
EEMSHAVEN220A	1.041	1.034	1.035	1.035	1.034	1.045	1.037	1.038
MEEDEN220A	1.038	1.033	1.034	1.033	1.032	1.045	1.037	1.043
VIERVERLATEN220A	1.044	1.038	1.038	1.038	1.037	1.047	1.039	1.040
ENS220A	1.051	1.047	1.047	1.047	1.046	1.050	1.042	1.042
BORDER VOLTAGES	NP = -0.00 GW	NP = -1.00 GW	NP = -2.00 GW	NP = -3.00 GW	NP = -4.00 GW	NP = -5.00 GW	NP = -6.00 GW	NP = -7.00 GW
DIELE	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
GRONAU	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
ROMMERSKIRCHEN	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
SIERSDORF	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
VANEYK1	1.014	1.014	1.014	1.011	1.011	1.009	1.007	1.005
VANEYK2	1.014	1.014	1.014	1.011	1.011	1.010	1.007	1.005
ZANDVLIET	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000