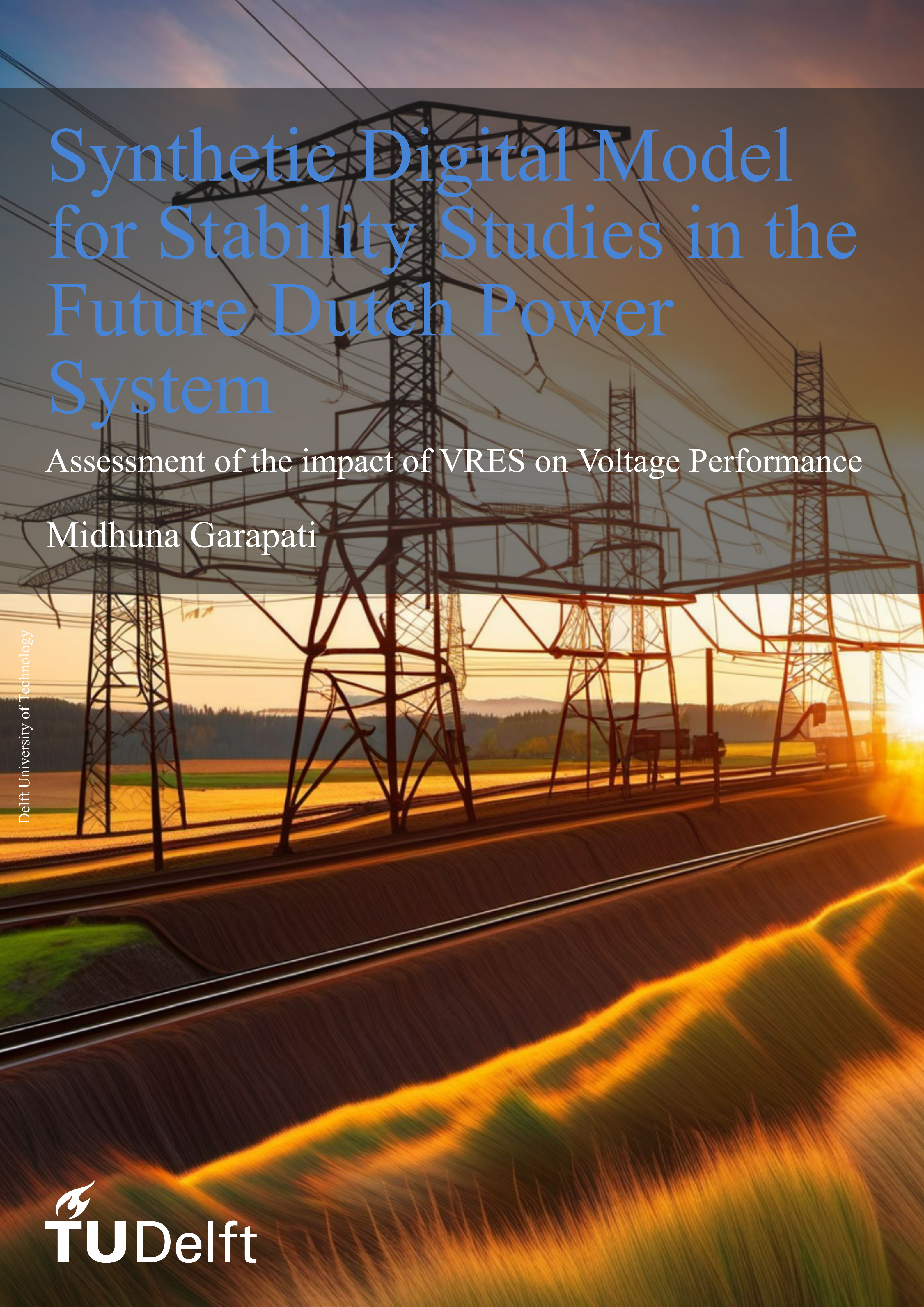

# Synthetic Digital Model for Stability Studies in the Future Dutch Power System

## Assessment of the impact of VRES on Voltage Performance

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Delft University of Technology

TU Delft

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by


Midhuna Garapati


to obtain the degree of Master of Science at the Delft University of Technology, to be defended publicly on 26th June 2024

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TU Delft

# Preface

I had an early understanding that electrification is the magic gateway to a sustainable tomorrow. Therefore here I am, a TU Delft Master's student specialising in *Intelligent Power Systems* realising that only a fundamental change in Power Systems will render this possible. A smart way for Electricity generation, transmission and distribution is one step towards this dream.

The thesis involves development of the dynamic models towards the future implementation of a synthetic model of the Dutch EHV power system which will allow the user to get an understanding of the system as a whole and its behaviour. I was in a discussion with my IEPG team one day and someone said, ”Designing power system models is an art”, and I couldn't agree more. The research is an idea suggested by Dr. Jose Rueda Torres, my professor for Dynamic Stability Studies. I am forever grateful to my professor who came up with the idea after recognising my interests and preferences in field of study. His guidance made me become more confident and skilled enough to design any model. Only after working with him, I realise the immense amount of patience and experience it takes to mentor a very enthusiastic and confused student. One day, I aspire to be just as good.

I am thankful to TU Delft for being the platform to pursue my interests and becoming an important part of my education. My Professors, parents and friends who have been very supportive through the up's and down's during my studies.

*Midhuna Garapati*
*Delft, June 2024*

# Abstract

The need for energy transition entails clear expectations of a significant increase in Variable Renewable Energy Sources (VRES) . However, increased renewable supply introduces challenges due to the integration of Inverter Based Generators (IBG), which can be effectively managed with control modules, such as Exciters.

To ensure power system stability and reliability amid significant advancements, an in-depth understanding of the dynamic behavior of the Dutch Transmission System is essential. This Master's Thesis project aims to investigate the response of the Dutch power system to high penetration of Renewable Energy Sources (RES), with a primary focus on dynamic stability performance. By studying these dynamics, we can better understand and address the challenges posed by the increasing integration of RES.

The Thesis proposes a Synthetic Digital Model of the Dutch Power System in which the generator components are equipped with dynamic models that perform various control functions, to simulate the system's response to any changes. DIgSILENT PowerFactory is a power system analysis software, used to develop this model and to perform various simulations. Dynamic Stability studies evaluates a power system's ability to maintain stability under various operating conditions and disturbances. Following a disturbance, the controllers of the elements determine the dynamic response of the transmission system. While stability is determined by multiple factors, such as the type of a disturbance and its duration, the number of sources in the power system and the power system operating condition (pre-disturbance), controller settings ultimately determine how quickly and effectively a system can respond to disturbances. They help to maintain stability and preventing faults from escalating. Therefore, the design and calibration of these control modules are primarily focused to address the stability challenges and indirectly facilitate smooth integration of VRES.

A case study involving operating under specific conditions of current and future generator dispatches is performed to investigate the impact of change in type of generation, in various scenarios. Successful initialisation of the dynamic models is achieved after multiple parameter tuning and model calibrations. The most basic form of stability assessment is the observation of time response of a specific variable in the model. Thanks to these Dynamic models, the time response of variables like frequency, voltage and rotor angle is observed to be within acceptable limits. However, there are cases in which the model becomes unstable, which are assessed for optimization. Critical disturbances during which the responses are uncontrollably divergent (from original operating point) are identified and recommendations are made at the power system level to effectively beware these faults.

Finally, Voltage Stability Performance is comparatively performed to reflect on the stability performance under low and high predominance of renewable power generation. This evaluates a certain variable under specific operating conditions and checks whether the variable is within acceptable limits. While introducing a fault at each system component, these variables are calculated to recognise all the vulnerable areas of the model. Based on the number of unstable components in the results obtained, recommendations are made on how to decrease this number.

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# 1 Introduction

This chapter introduces the thesis by establishing a problem definition based on identified research gaps. A summary of existing literature is provided to highlight these gaps and offer background information on the Dutch Transmission System and various related topics discussed in the research. The chapter outlines the research objective and scope of the thesis, along with the methodology adopted to address the research questions.

## 1.1. Problem Definition

Traditional power system stability is primarily ensured by conventional power plants, which provide essential ancillary services. Despite the rapid increase of Renewable Energy Sources (RES) in the total generation mix, the behavior of the power system is still largely controlled by synchronous generators. This dependency on synchronous generators poses significant challenges for transitioning into a fully renewable power system. The Dutch power system, which aims to be fully renewable by 2045 [1], is in the process of implementing a strategy that includes the integration of large-scale wind and solar power. Therefore, the role of this new integration should be to overcome the inherent limitations associated with decommissioning traditional power plants. This highlights a clear gap between today's emerging technologies and the current understanding of the dynamics of complex power systems [2]. While the plan to achieve this involves numerous steps, including changes in policy and process, it also requires significant technological changes, infrastructure upgrades, and extensive research to ensure power system stability and reliability amidst the fluctuating nature of RESs.

In order to accommodate this unexpected level of integration of VRESs which are highly Inverter-based, adequate research is necessary to avoid disturbances that may trigger a series of events leading to a cascading failure, eventually blackouts. To investigate the effects of various phenomena that affect stability, a Synthetic Digital Model is designed to study the dynamic stability performance of the Dutch Power System under future operating conditions. In order to accommodate this unexpected level of integration of VRESs which are highly Inverter-based, adequate research is necessary to avoid disturbances that may trigger a series of events leading to a cascading failure, eventually blackouts. By examining the influence of the considered control strategies to different controllable devices, suggestions are made to mitigate these instability issues.

## 1.2. State of the Art

While this thesis is designed to study the dynamic stability of a large power system, which may seem very specific, the development and implementation of dynamic models is a broad undertaking involving multiple generator and controller types. The thesis topic can be broadly categorized into three main aspects: renewable integration and power electronics representing the forefront new technologies, digital twins serving as the methodological approach for implementation, and stability serving as the ultimate assessment criterion, thereby discussing the current state of the art in three distinct subsections.

### 1.2.1. Renewable Integration and Power Electronics

The obvious limitations that comes with integration of renewables are majorly tackled in today's research. Currently, power systems are not fully renewable but operate at various levels of renewable energy penetration and aims to be fully renewable in the future; therefore, initial research primarily focused on the stability of these early electrification efforts. [3] discusses the impact of different levels of solar PV penetration in an IEEE 9 bus power system and assesses the transient behavior for different cases.

In wind power systems, a power electronics interface, typically a pulse width modulation (PWM) converter, is positioned between the electrical generator and the power system [4]. This interface regulates the generator's rotational speed, crucial for stabilizing power output amidst varying wind speeds.

For solar generation, DC electricity produced by photovoltaic panels undergoes conversion through a DC-DC converter and subsequent inversion into AC electricity via an inverter. These components ensure efficient energy conversion and compatibility before power is fed into the power system [5].

With time, the PE interfaces were modified for additional functionality and increased efficiency. Today, alongside these advancements, there's a growing emphasis on implementing intelligent control systems to manage the entire energy infrastructure effectively. This includes integrating intelligent functions and robust communication technologies to optimize system operations and ensure seamless integration of renewable energy sources. They are essential to manage intermittency and uncertainties that come with RESs integration by enabling real-time data prediction and analysis [6].

### 1.2.2. Digital Twin and Simulation

The current synthetic model draws inspiration from the Digital Twin concept to implement a comprehensive power system used for steady-state modeling, simulation, and analysis in power system research and development. Given their delicate and vital nature, electrical systems represent crucial infrastructure necessitating comprehensive analyses of various phenomena to effectively design and manage their dynamics. While numerous methods exist for implementing digital twins, their adoption has been delayed due to reliance on standard test systems, particularly for emerging technologies like wind farms, PV systems, HVDC/MVDC systems, and electric vehicles [7]. Although universal standards have been developed, a cross-disciplinary approach such as co-simulation is increasingly advocated to accommodate the advanced integration of sustainable energy supply, particularly in Europe, where distributed and renewable energy resources are prominent [8].

In the large-scale power system implementation of Digital Twins (DT), a wide array of applications emerge, encompassing monitoring, analysis, visualization, and predictive capabilities. While substantial research attention has been directed towards monitoring and online analysis, critical gaps persist in several areas, notably comprehensive exploration in component modeling, integration of IoT sensing devices, and methodologies for real-time data acquisition and processing [9]. This work serves as an example of large-scale power system implementation, intertwining discussions on renewables penetration and component modeling.

### 1.2.3. Power System Stability and Resilience

The current thesis, centered on stability assessment within the context of large-scale dynamic model implementation, investigates benchmark systems aimed at establishing stability tests. With a focus on small-signal stability, the report compares common control strategies and tuning techniques aimed at ensuring system controls synchronize effectively with the generators [10].

The investigation of benchmark systems for stability tests, as pursued in the current thesis, aligns with efforts outlined in another report [11], which focuses on developing a test system for Voltage Stability Analysis and Security Assessment. This complementary study addresses the gap between steady-state tools and static models typically used for Conventional voltage stability studies, highlighting the necessity for dynamic simulation, particularly in scenarios involving post-disturbance controls and voltage instability.

## 1.3. Research Objective and Scope

The synthetic model shall be applied for investigation of possible new forms of dynamic stability phenomenon. In order to address this goal the following research questions are defined.

### 1.3.1. Research Questions

1. How feasible it is to use generic component models and parameters to ensure successful initialisation and correct dynamic simulation?
2. What kind of representative operating conditions and disturbance can exhibit instability risks?
3. Up to which extent Assessment of Voltage Stability Performance metrics from existing literature can provide insights on possible instability phenomena?

### 1.3.2. Research Contributions

- A synthetic digital dynamic (RMS) model for the study of the dynamic active power-frequency performance of the future Dutch Power System. The model includes power electronic interfaced renewable power generation, responsive prosumers (electrolysers), storage, and compensation devices.
- Development of Python Scripts for automated tuning of the Dynamic Test and the simulation of different scenarios and disturbances.
- Python scripts to export results and plot voltage, frequency, and speed responses to compare different study cases and events.
- MATLAB script to calculate performance indices for Voltage Stability Performance.

## 1.4. Approach and Structure of the Report

The research questions outlined in Section 1.3 will be addressed concisely throughout the subsequent chapters. The research approach involves defining clear boundaries and studying the current state of the art, as discussed in Section 1.2, to identify research gaps and motivate this work. The problem statement, derived from a literature survey on issues faced by transmission system operators, assesses the need for Dynamic Stability of the Dutch Power System.

Chapter 1 introduces the thesis, providing an overview of transmission power systems and current operational challenges, along with listing the expected contributions of this work. Following this, Chapter 2 elaborates on the development of the steady-state synthetic model and its underlying data and assumptions.

Chapter 3 discusses the implementation of dynamic models, detailing the methodology and simulation code, along with upgrades included in the case study. Subsequently, Chapter 4 establishes multiple case studies under various operating conditions to analyze critical disturbances and potentially identify optimal working scenarios for the model. Methodology and implementation of Voltage Stability Performance Assessment is also discussed in this chapter.

Analysis of results from each case study informs discussion on mitigation strategies in Chapter 5, where the thesis is comprehensively examined, research questions are addressed, and recommendations for future study are provided.

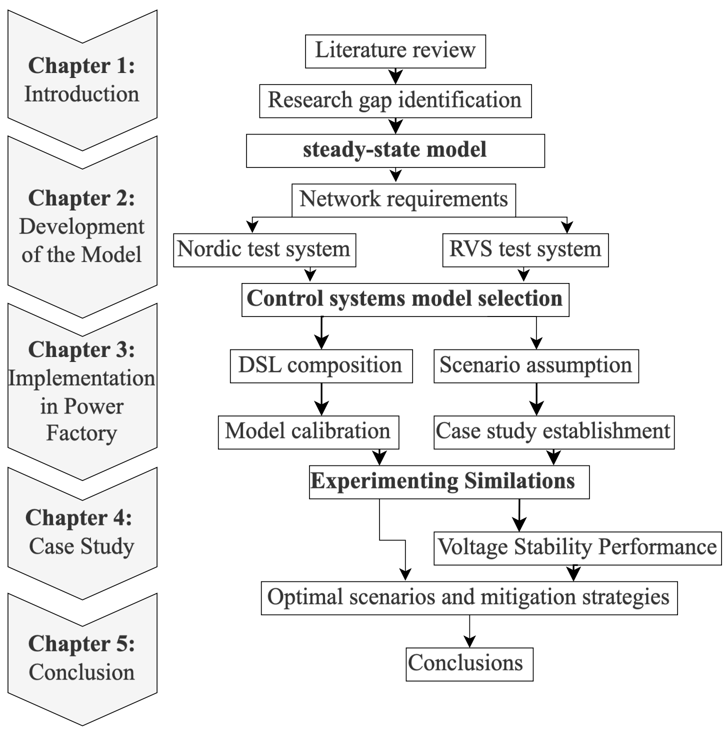



**Figure 1.1:** Thesis process chart depicting the flow of work in each chapter

# 2

# Development of the model

This chapter provides an overview of the steady-state performance of a synthetic model of the Dutch power system. It also details the modeling approach for dynamic plants, tailored to specific generators including synchronous, PV, and wind generators. This chapter offers insights into the Dutch power system prior to the introduction of any transients, thereby laying the foundation for the thesis.

## 2.1. Overview of Synthetic Model

An overview of the base model which was originally created to perform steady-state analysis is essential to gain an understanding of the idea behind the digital synthetic model of the Dutch power system. It provides information regarding the system components, component parameters and operating conditions, that were assumed during the development of the model which is relevant to the current thesis.

The synthetic model used for steady-state simulations is developed in PowerFactory. The power system topology is designed using publicly available data from Tennet and hoogspanningsnet.nl [12]. The model includes system components such as bus terminals, generators, transmission lines, loads, interconnections, electrolysers, transformers, phase-shifting transformers, and static reactive power compensation devices. It is further extended to incorporate renewable energy sources, batteries, and other relevant elements.

Initial simulations are performed for the Base Model using installed capacities and peak demands during 2017-2019, to check whether the model imitates the real-world power system. Interconnections are modeled as loads and are set to a negative active power dispatch when there is in-feed into the power system. For the 2030 model, the 110/150kV power system's generators are modeled using single aggregated generators for each technology type as opposed to the base model. Gas and WKK(Cogeneration - combined heat and power (Warmte-krachtkoppeling)) generators are aggregated into one gas generator. For wind and solar generators, static generators are used. Extra impedance was added to High Voltage (HV) areas by adding extra transmission to avoid parallel flows and consequent overloading of certain transformers [12].

The model offers a foundation for creating a more accurate digital replica of the Dutch power system and serves as a tool for exploring potential future advancements such as the installation of VRES and system flexibility in the case study. The thesis also suggests locations for installing electrolysers to alleviate congestion. As expected the introduction of VRES poses a challenge for the steady-state performance of the power system. Flexibility measures should be introduced if decentralized projects grow, like solar generation. However, if the centralized projects grow, such as offshore wind, there will be an increase in power flows between extra high-voltage regions.

The scenarios used for simulations in the current research are derived from the original thesis to avoid repeated testing and utilize optimal scenarios already concluded. Table 2.1 concisely refers to these conclusions, aiding the analysis before selecting study cases relevant to the current research context. The power system topology in Figure 2.1 helps identify the locations and regions mentioned in Table 2.1.

**Table 2.1:** Analysis of each case considered for the Steady-state stability and conclusions drawn from the case study that are considered while choosing the cases for the current research

| Scenarios | Assumed operating conditions | Reflections from qualitative analyses |
|---|---|---|
| **Peak Demand 2017** | To simulate power flow using data from historical dispatch for 2017 | A large amount of generation capacity in the north leads to power flows going from North to South with overloading at certain transformers and generators |
| **Peak Demand 2018** | Similarly, to use 2018 dispatch for simulating power flow | The reactive power losses are less than that of 2017 (1141 Mvar compared to 1744Mvar) |
| **Low Demand 2019** | To compare the critical components among their three dispatches | Much less reactive power losses when compared to the previous two dispatches |
| **TCA** | When the generation within one region is increased to 90% while the other regions evenly distribute the remaining generation is Transfer Capacity Analysis. What the power flow would be if there is a high amount of export or import of power from/to a specific region | Initial power flow, peak demand scenario of 2018 was used, static generators not used for re-dispatching. The critical components that are overloaded remain same as that of the base case. |
| **A0** | 2030 Base case, only wind, no IC | Large transport of electricity from offshore wind farms towards more inland connections. Large exports from Zeeland to Brabant |
| **B0** | 2030 Base Case, only solar, no IC | Large transport can be seen from the North of the Netherlands to the South due to a larger amount of solar generation being installed in the North |
| **C0** | 2030 Base case, mix solar and wind, no IC (to investigate high VRES simultaneously with peak demand) | High power flows between Zeeland and Brabant. No elements are loaded above 73% |
| **Case A1-7** | Wind as the only source of electricity generation for high demand, Electrolyser cases | A4 being the best, electrolyser of 6.5GW equally distributed(most beneficial, 2,17 at each location) |
| **Case B1-7** | Solar as the only source of electricity generation for high demand, Electrolyser cases | Undervoltages in Groningen and Drenthe(installed capacity of solar in Groningen and Drenthe) combined with low demand and insufficient transformer capacity between HV and EHV |
| **Case B1-7*** | 6.5GW electrolyser case, 75% solar generation | There is an increased active power flow between regions compared to the base scenario B0. Most favorable scenario B6, electrolyser at MVL380 and EEM380 |
| **Case C1-7** | A mix of high wind and some solar generation during peak demand, Electrolyser cases | From both the initial power flows and contingency analysis C5 and C6 are the better cases |
| **Case D1-7** | A mix of wind and solar for average winter capacity factors for high demand, Electrolyser cases | Compared to all the cases D2 is the best one with minimal losses and overloading of elements |
| **Case E1-7** | A mix of wind and solar for average summer capacity factors for high demand, Electrolyser cases | Overloading of transformers between EHV and HV power system |
| **Case F1-7** | No VRES generation, average demand, and selfsupplying | Less a number of critical elements in the power system except one transformer. OPF, the decline in generation dispatched in the North |
| **Case G1-7** | No VRES generation, peak demand and full use of interconnections | No stability with huge losses in the power system and many overloaded components |

## 2.1.1. Power system Topology

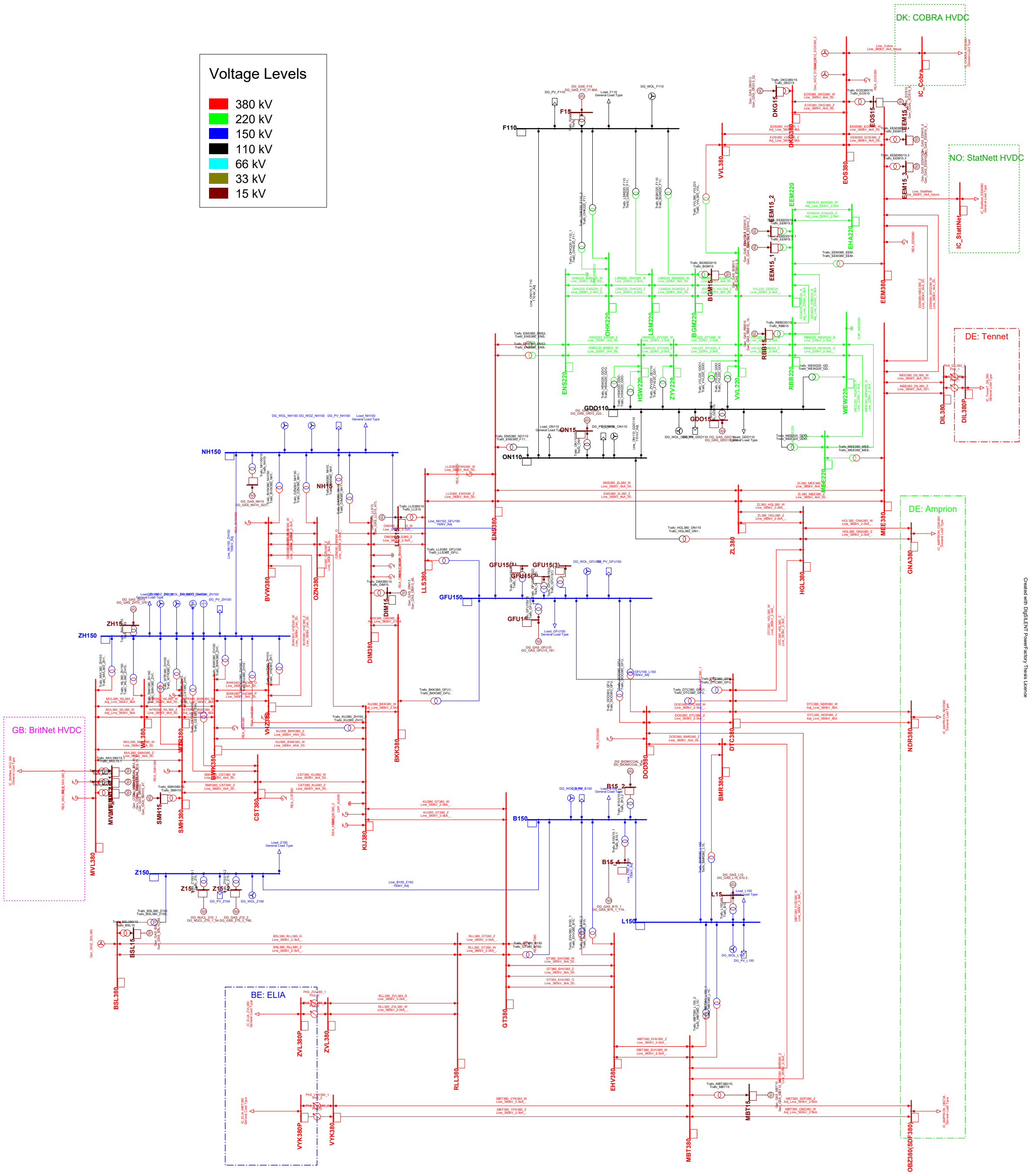



**Figure 2.1:** Single-line diagram of the power system according to Voltage levels

## 2.2. Steady-state Performance

The model is divided into different geographical regions as shown in Figure 2.2. A simplified geographical diagram of the 220/380kV connections was created in PowerFactory which is the single-line diagram of the synthetic model.

In scenarios where offshore wind generation is high, an optimal approach involves evenly distributing the 10 GW of installed capacity across Eemshaven, Maasvlakte, and Borssele. However, if there are significant transit flows from North to South and West to East, the most favorable setup is to allocate one electrolyser each to Eemshaven and Maasvlakte, with a capacity of 5 GW. Conversely, in situations with abundant solar generation, it is preferable to have at least 5 GW of electrolyser capacity located in Eemshaven to mitigate congestion issues arising from high Variable Renewable Energy Sources (VRES) generation, particularly solar. If a choice arises between Maasvlakte and Borssele for electrolyser placement, Maasvlakte experiences fewer congestion problems. Yet, if both locations are viable, introducing a smaller electrolyser in Borssele can aid in directing power flow between Noord-Brabant and Zeeland during extensive periods of offshore wind generation. This strategy is advantageous, considering single-location scenarios with 10 GW of electrolyser capacity result in heightened congestion concerns.

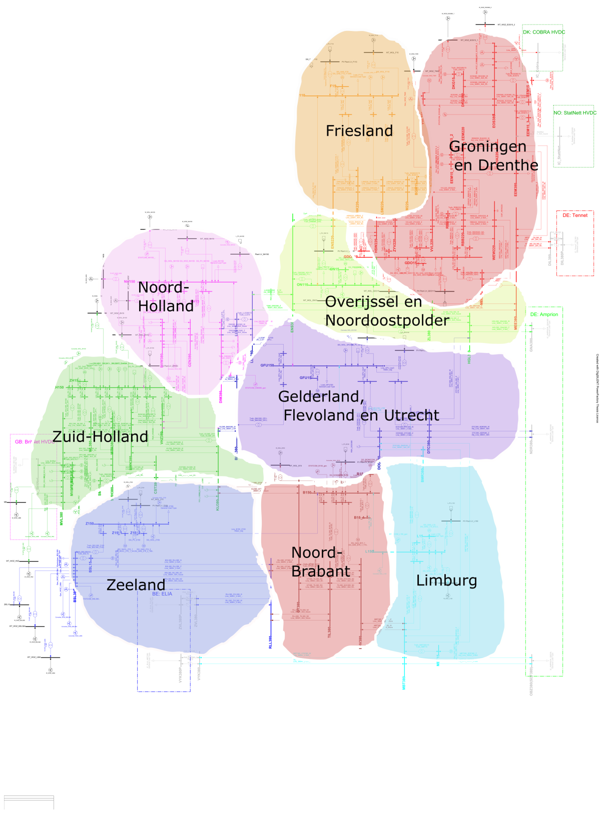



**Figure 2.2:** Division of zones within the single line diagram

## 2.3. Dynamic Stability Performance

*Transient stability* is the power system's ability to maintain synchronism in the face of a serious transient disturbance [13]. The degree of the disturbance and the system's initial operating state both affect stability.

The operating condition of the Power System is described by the phase angle and magnitude of the terminal voltage at buses along with active or reactive power that flows in each line [14]. When these magnitudes stay constant with respect to time, the system is in *steady-state* operating condition. Any change to this causes a sudden *disturbance* in the quantities mentioned above.

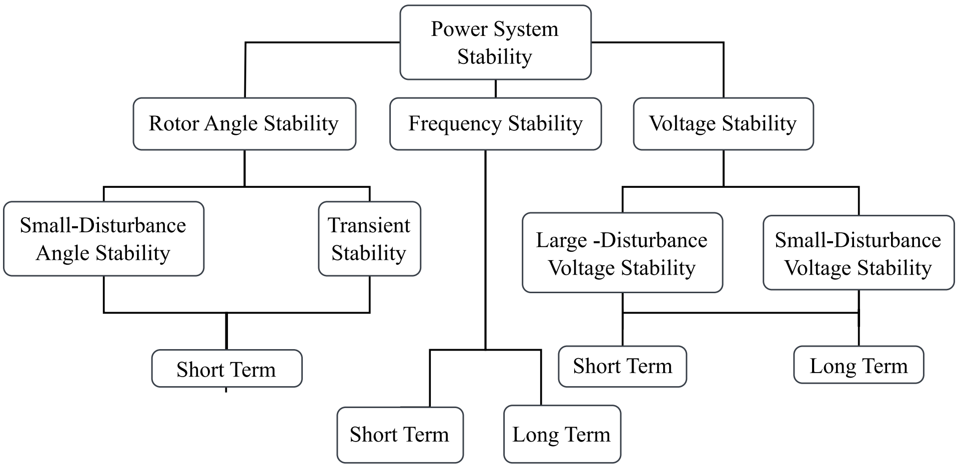



**Figure 2.3:** Classification of Power System Stability [13]

**Rotor Angle Stability** refers to a synchronous machine's ability to maintain synchronism both under normal operating conditions and following a disturbance. When synchronous machines experience increased angular swings, this can lead to a loss of synchronism, indicating potential instability within the system [14]. Large excursions of generator rotor angles specifically pertain to transient stability, which addresses the system's ability to withstand short-term disturbances such as faults or sudden changes in load. Maintaining rotor angle stability is crucial for ensuring the reliable operation of power systems and preventing widespread outages.

**Voltage Stability** is the system maintaining an acceptable range of voltages at all buses under base case operating conditions [14]. Further classified into small disturbance and large disturbance voltage stability. When there is a sudden load change or a large disturbance, the transmission power system's ability to retain stability is transient stability, important to prevent voltage collapse and blackouts.

**Frequency Stability** is the ability to maintain the frequency within a suitable level when a system is under duress due to a large imbalance between generation and load. As opposed to voltage stability, frequency stability is calculated by the overall response of the power system. The high addition of VRES has a major impact on Frequency Stability.

As the research progresses, these three types of stability are discussed and also calculated in Voltage Stability Performance with respect to the Dutch power system.

### 2.3.1. Dynamic Stability in Renewable Energy Systems

In Renewable energy systems, dynamic stability refers to the ability of the system to maintain stable and reliable operation despite fluctuations and uncertainties that are inherent to sources such as solar and wind power. As opposed to conventional power generation sources, renewable energy generation is much more variable and intermittent thus leading to challenges in power system stability.

#### Solar PV Systems

Solar Energy is established as the most cost-effective and efficient. However, it comes with certain major disadvantages. Even though there is an increased adoption of Solar PV systems, integration is not as smooth. Various such challenges are listed in Table 2.2. Therefore, to enhance the dynamic stability of the solar PV systems, controllers are designed, discussed in Section 2.5.2.

**Table 2.2:** Dynamic Stability Challenges of Solar PV systems

| S.No | Issue | Effect |
|---|---|---|
| 1 | Non-Transmittable | Cannot generate power on demand. Output depends on weather conditions. Highly fluctuated. Challenging for power system operators to match supply and demand [15]. |
| 2 | Power Quality | Fluctuations in solar irradiance cause variations in voltage and frequency. This will affect power quality. It will lack reliability and stability[16]. |
| 3 | Voltage and Phase-angle stability | Intermittency in generation will consequently also cause angular and voltage instability [16]. |
| 4 | Reactive Power Support | No reactive power support. Additional equipment like storage technologies are needed [15]. |
| 5 | Fault Ride-Through | Controls designed for PV systems should allow minimum contingencies like short circuits and power system faults [17]. |
| 6 | Reverse Power Flow | When high PV penetration is the case, reverse power flow may occur causing instability which is challenging[18]. |

**Wind Systems**

A record 35% increase in wind energy production in the Netherlands, resulting in approximately 4.7 GW of installed offshore wind capacity, indicates much bigger plans in the coming years[19]. The large-scale deployment and transportation of this wind energy to the Dutch energy systems present significant challenges. It involves heavy infrastructure to ensure the most profitable delivery of electricity while preventing congestion. To ensure efficient conversion, transport, and storage of wind energy, many shortcomings must be addressed [20].

While it is paramount to consider the lack of inertia of conventional generators in wind systems, other dynamic factors must also be analyzed, as described in Table **??**.

**Table 2.3:** power system Integration Challenges of Wind Energy

| S. No | Issue | Effect |
|---|---|---|
| 1. | Wind Predictability | Changes with wind direction and speed challenging to estimate demand and supply reliability issues [21]. |
| 2. | Power Quality | Due to voltage fluctuations and harmonics. Will affect the stability and power system performance [21]. |
| 3. | Voltage and Angular stability | Mainly due to integration of large-scale wind farms. Requires specialized control strategies to improve stability [21]. |
| 4. | Reactive Power Support | To maintain power system voltage within acceptable limits. Essential for stability and requires coordination [21]. |
| 5. | Generation Intermittency | Generation is highly dependent on weather conditions, leading to fluctuations in supply and less efficiency and consistency in meeting the demand[22]. |
| 6. | Planning of power system Integration | Requires heavy planning by operators to integrate a growing share of wind energy. Involves enhancement of transmission infrastructure, system flexibility [23]. |

## 2.4. Development of the model for Dynamic simulation

With the help of Anouk's model as a base, not many configurations or settings were changed to develop the dynamic model [12]. Only DIgSILENT Simulation Language (DSL) models of synchronous generators and static generators were modeled and added. The development process is defined in the flowchart shown in Figure 2.4.

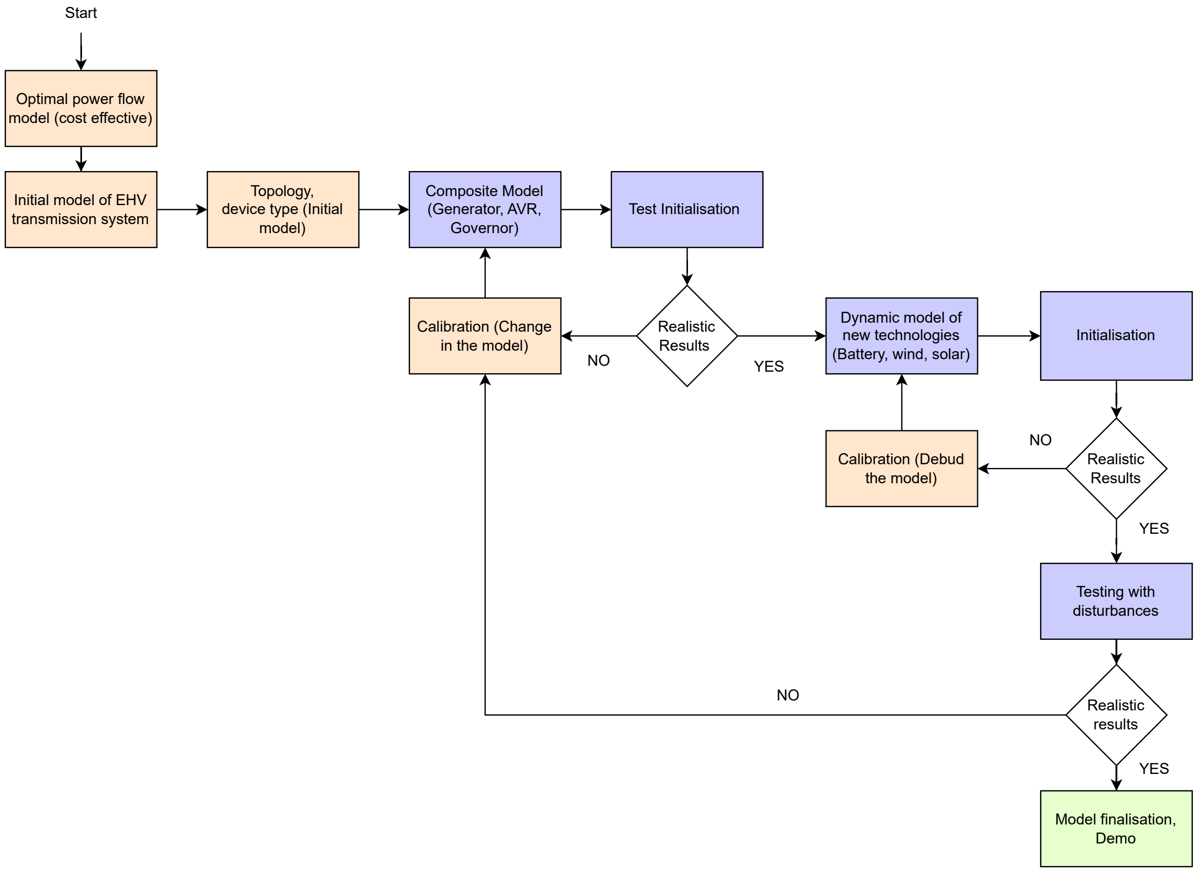



**Figure 2.4:** Development process of the Dynamic simulation model. The Orange color blocks depict initial model consideration and calibration, blocks in purple show the addition of models, and green shows the final model

The synthetic model developed for power flow (steady-state) performance studies serves as the starting point and undergoes thorough topology analysis. While this model is valid for steady-state power system studies, it lacks the information needed to simulate dynamic behavior over time. Therefore, each transmission component and equipment is meticulously modeled and analyzed for further development.

A composite model tailored to the specifics of each power system component, such as exciters and governors, is created. Following initialization, initial test results are examined for favorability. If favorable, dynamic models for new technologies, such as wind and solar, are integrated. Subsequent initial tests are conducted and calibrated accordingly. Events and disturbances are then introduced to validate the dynamic models. Finally, the model undergoes further refinement and additional testing.

When subjected to a disturbance, the system response contains huge changes in the generator rotor angles. Because non-linear power-angle relationships, such as faults or sudden load changes can affect the ability of generators to adjust their rotor angles to maintain synchronism.

To ensure dynamic stability the power system should be able to match the output of generators with changing demand and make adjustments in real-time to counteract disturbances and maintain stability.

## 2.5. Power system Requirements

Basic system requirements from any efficient power system involves the following regulations set by the government and compliance with the transmission code set by the TSO. Technically the power system needs to reach the Capacity Outlook vision and congestion management expected from the system.

A requirement of power system operation is to balance the electricity supply and the demand at any time, including power system losses. A properly designed and operated power system should be able to maintain this balance both under normal conditions (steady state) as well as after disturbances (dynamic) [14].

Therefore the major requirements from a power system control are:

- Constant frequency
- Constant voltage level at the connection point
- Reliability to deliver power with continuity
- Adequate power delivery while being resilient against disturbances
- Controlling harmonics in the power system

The Dutch transmission system is inherently dynamic, with both active and reactive power demands continuously fluctuating even under normal operating conditions. This variability necessitates constant adjustment and monitoring to maintain system stability. Additionally, power systems frequently experience disturbances due to their extensive network of interconnected machines and components spanning vast geographical areas. These disturbances can arise from various sources, including faults, load changes, and the integration of renewable energy sources. Ensuring the stability and reliability of the transmission system in such a dynamic environment is critical for preventing outages and maintaining efficient power delivery.

**Inertia**

The increase in share of distributed and inertia-less generators means requirements for balancing and system stabilization. Typically in a Synchronous Generator-dominated power system, the SGs release the kinetic Energy stored in the rotor as an inertia response following a large disturbance. Also, SGs participate in the primary and secondary frequency control by increasing or decreasing their active power generation [24]. The rate of change of frequency (RoCoF) and frequency nadir (i.e., angle) are inversely proportional to the system inertia. In power systems with low levels of synchronous generation, there are low levels of system inertia which results in higher RoCoF and lower frequency nadir [25].

To achieve comprehensive control over the power system, it is imperative to deploy control devices on several levels from generation and transmission to the consumer end, can be observed in Figure 2.5. Therefore while managing the power system, it is easier for the operator to monitor and regulate, by narrowing down the issue at all crucial points in the power system.

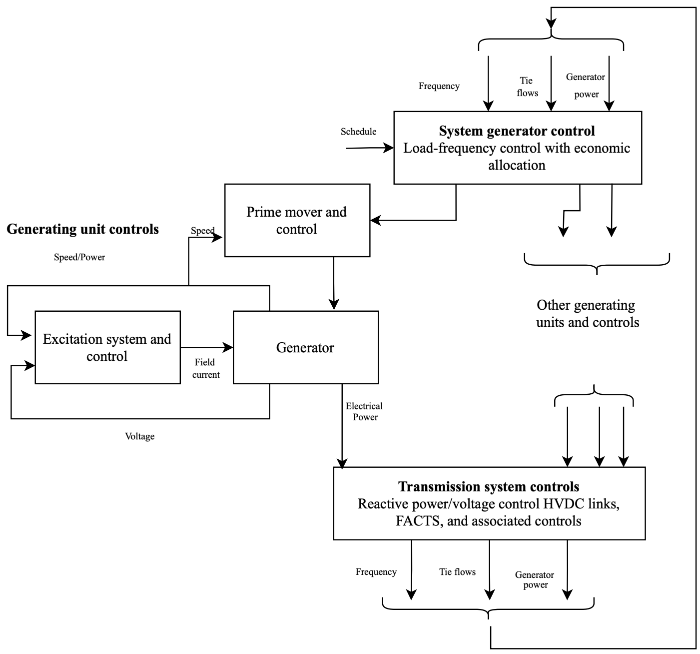



**Figure 2.5:** Subsystems of a Power system and its associated controls [13]

**Voltage**
To deliver continuity and reliability in power transmission, it is important that the system voltages are maintained within acceptable limits, which is challenging in case of high penetration of Renewable Energy sources. Technologies like Photovoltaic and variable-speed wind turbines cannot ride-through the voltage dip during disturbances, unlike synchronous generators. They cannot absorb or inject reactive power in response to voltage changes. However, with sufficient Battery energy storage systems, power system-forming inverters can be used to regulate reactive power in response to voltage changes [25].

All the requirements discussed above pave the way for selecting the type of control systems various generators need. Beyond the technical requirements from power generating entities and the power system itself, multiple other factors must be considered when developing the model. While it is not in the context of current research, it is also crucial to account for reasonable costs incurred by system operators, both for implementation and maintenance of the system.

**Table 2.4:** power system Connection Requirements applicable to synchronous power generating modules [26]

| Requirement category | Description |
|---|---|
| **Post Fault Active Power Recovery** | The amount of time after the clearance of a fault is post-fault active power recovery. Active power generation needs to be quickly restored to minimize frequency deviations |
| **Reactive power capability at maximum active power** | Synchronous power-generating modules should supply reactive power within the limits established by the relevant system operator |
| **Reactive power capability below maximum active power** | The generating module should be able to operate within the specified P-Q capability curve during operation below maximum active power |
| **Voltage Control system** | The facility owner and relevant TSO should commonly agree the parameters of the voltage control system. Should include Automatic voltage regulator, power system stabilizer function, UEL and OEL |

*Power Park Module* or *PPM means a unit or ensemble of units generating electricity, which is either non-synchronously connected to the power system or connected through power electronics, and that also has a single connection point to a transmission system, distribution system including closed distribution system or HVDC system.[26]*

**Table 2.5:** power system Connection requirements applicable to Power Park module [26]

| Requirement Category | Description |
|---|---|
| **Synthetic Inertia Capability** | Due to the lack of inherent inertia in PPM systems, they do not contribute to the inertia of the power system. This requirement is introduced so PV park modules (PPM) can mimic the inherent inertia from synchronous generator |
| **Post-fault active power recovery** | A condition on period in which the PPM provides the active power needed for recovery after clearance of a fault avoid large frequency excursions |
| **Provision of fast fault current** | The ability of the power park module to provide fast fault current when a three-phase fault occurs. Additional reactive current is provided when the voltage deviation at terminals is larger than 10% |
| **Priority to Active or Reactive power contribution** | The module should prioritize either active power or reactive power contribution during faults. These priorities are set by the relevant TSO |
| **Reactive power capability at maximum active power** | Should be able to provide reactive power within the specified limits in the capability curve of the specific generator |
| **Reactive power capability below maximum active power** | During the operation of the Power park module below its maximum active power capacity, the reactive power contribution will be determined by the relevant TSO |
| **Reactive power control modes** | The selection of control mode between Voltage control mode, reactive power control mode, and power factor control mode is determined by the system operator |
| **Power oscillations damping control** | Ability to damp out power oscillations. During different control modes, the characteristics should not negatively affect power oscillations |

### 2.5.1. Synchronous Generators

The requirements of excitation systems vary from power system requirements and generator requirements. The power system requirements previously analyzed are considered when choosing the type of dynamic simulation models used for specific control tasks for each type of generator. The stability requirements are discussed in Table 2.6 along with power system Connection Requirements.

**Table 2.6:** Stability requirements from the synchronous generator control models [26]

| Power system Requirement | Synchronous Generator Control System Features |
|---|---|
| **Dynamic Stability** | • Stable operation under varying operating conditions<br>• Rapid response and resilience against disturbances<br>• Meet the desired reliability and availability, by incorporating the necessary level of redundancy, internal fault detection, and isolation capability. |
| **Voltage Regulation** | • Supply and automatically adjust the field current of the synchronous generator to maintain the terminal voltage<br>• Maintaining voltage within acceptable limits<br>• Determining the voltage level of the connection point at which the power generating module will be connected. |
| **Frequency Response** | • Excitation system with practically instantaneous response with high ceiling voltages.<br>• Meet the short-term capability of the generator without exceeding the limits. |
| **Power System Stabilization** | • Controlling field voltage to damp system oscillations.<br>• Substantial enhancement of the overall system dynamic performance.<br>• Provide limiting and protective functions as required to prevent damage to itself, the generator, and other equipment. |
| **Speed Governor** | • Normal speed/load control, overspeed control, and overspeed trip.<br>• Stabilise exponential increase in speed during frequency events. |

**Exciter**

The primary role of an excitation system is to supply direct current to the field winding of a synchronous machine. By regulating the field voltage, the excitation system controls the field current, which is crucial for the machine's performance. Additionally, the excitation system performs essential control and protective functions, ensuring the overall stability and reliability of the power system..

*An exciter provides DC power to the synchronous machine field winding, constituting the power stage of the excitation system.*[13]

The IEEE-type AC1A exciter is an AC excitation system that uses alternators as sources of the main generator excitation power. It is a type of field-controlled, alternator-rectifier excitation system. According to [27], for large power system stability studies, IEEEAC1A is ideal due to its simplest form. The exciter is used for Conventional synchronous generators in [11].

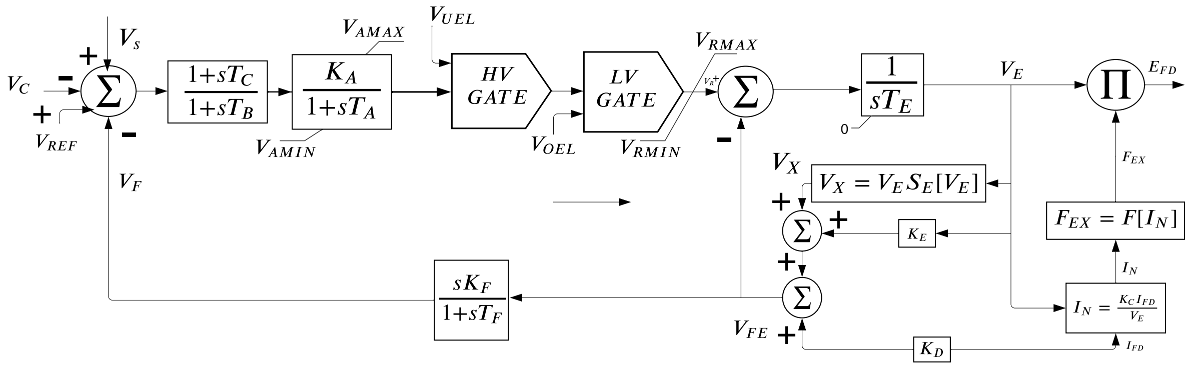



**Figure 2.6:** IEEE Type AC1A excitation system [27]

**Governor**
The IEEEG1 model, recommended by IEEE for steam turbines, accurately depicts the parameters of turbine and governor systems. Incorporating a Deadband, IEEEG1 serves as a comprehensive model of the steam turbine system, encompassing both the speed governor and turbine stages [28]. The governing systems for steam turbines perform three fundamental functions: normal speed/load control, overspeed control, and overspeed trip. Additionally, these systems manage several other critical functions, including start-up/shutdown procedures and auxiliary pressure control. The governor's speed control function ensures that the generating unit can effectively operate in parallel with other units, ensuring proper load distribution [13].

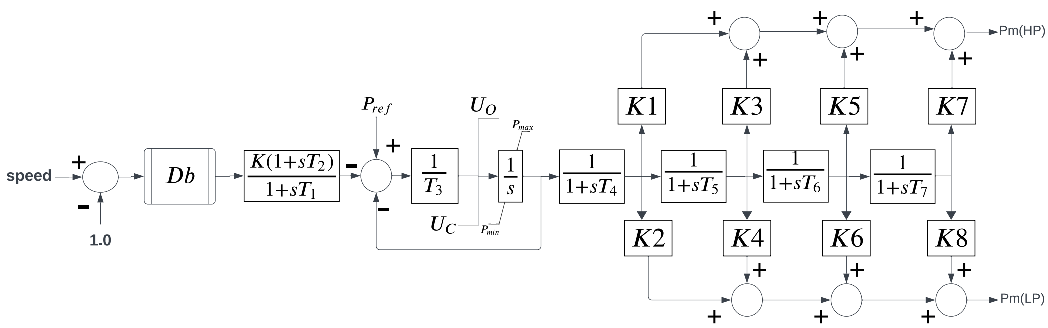



**Figure 2.7:** Simple steam turbine-governor model IEEEG1 [29]

**Power System Stabilizer**
Power system stabilization is achieved by damping system oscillations. The system. It helps to enhance the small-signal stability performance of the power system [13]

*The power system stabilizer (PSS) uses auxiliary stabilizing signals to control the excitation system to improve power system dynamic performance* [13]

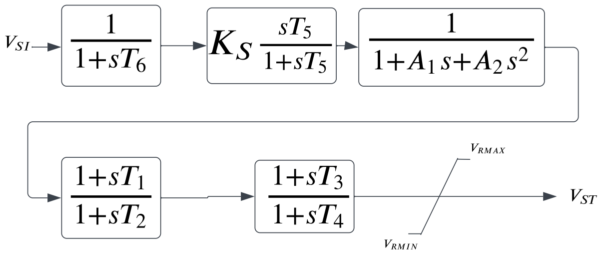


**Figure 2.8:** IEEE Type PSS1A power system stabilizer [27]

A PSS detects oscillations in the power system's electrical variables, such as voltage and frequency, and produces control signals to dampen these oscillations, thereby stabilizing the system. These signals are then injected into the system's excitation system. The PSS helps maintain system stability under small disturbances, ensuring smooth and stable operation. During large disturbances, such as faults at terminals or sudden load changes, the PSS adjusts the excitation system signals to quickly restore the generator's stability and prevent wider system disruptions. The voltage regulator of the exciter receives these control signals, which modulate the generator's field current, directly influencing the generator's electrical output and providing supplemental damping.

### 2.5.2. Photovoltaic Systems

The *WECC Generic PV Plant Model* is a positive-sequence model representing the essential dynamic behavior of large-scale PV systems. Developed by the WECC Renewable Energy Modeling Task Force, this model enables the assessment of PV plants' impact on the dynamic stability of the power system. The Western Electricity Coordinating Council (WECC) is a regional entity responsible for compliance monitoring, enforcement, and overseeing reliability planning and assessments. Initially developed to validate models by comparing simulated responses to actual measurements at power stations, the WECC Generic PV Plant Model is now used for various PV-related studies [30].

Unlike the control modules for Synchronous Generators that are standardized by "IEEE Recommended", different PV plant models are proposed by various manufacturers. For simulations and software applications, Large-scale PV generation is therefore implemented due to the availability of the customer-provided utility PV power system. The Dynamic Model includes:

1. **REGC_A**: To provide current injections, the generator converter module balances the current commands with the power system boundary conditions.
2. **REEC_B**: Real and reactive power references are converted into commands for current flow by the electrical control.
3. **REPC_A**: Then, the plant controller module will generate real and reactive power references using values from the power system solution.

The REPC_A is an optional module that usually uses the values provided by the power system solution to generate active and reactive power references for the electrical control module. Since the PV systems work on local control of Constant V, the functionality of REPC_A is rendered unnecessary for the current studies. The major functionalities like closed-loop voltage regulation and closed-loop reactive power regulation are also indirectly provided by REEC and REGC combined. Large-scale PV systems are highly complex configurations. While the intricate details of the design of each component are not essential for dynamic studies, the function of each module are discussed in this section.

The interconnection between the three modules is shown in Figure 2.9. The variables used in Figure 2.9 are described in Table 2.7.

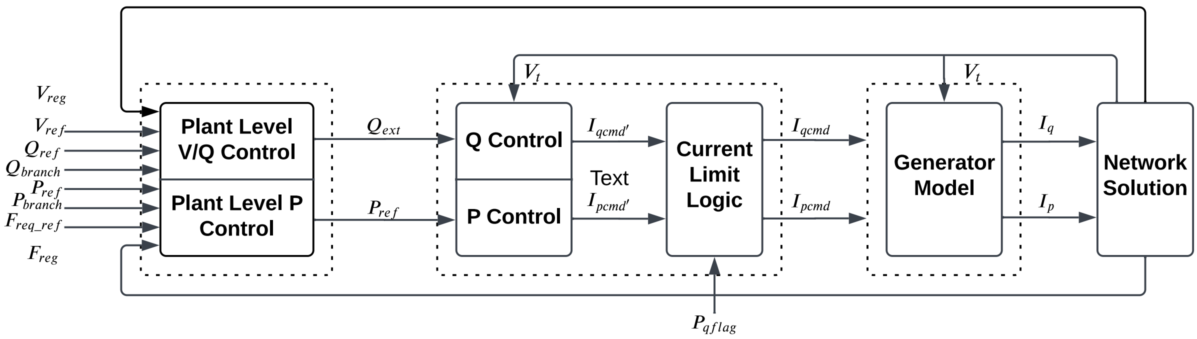



**Figure 2.9:** Block Diagram Showing Different Modules of the WECC Generic Models [31]

**Table 2.7:** Definition of parameters shown in Figure 2.9

| Parameter | Description |
|---|---|
| $V_req$ | Regulate bus voltage |
| $V_ref$ | Regulated bus initial voltage |
| $Q_ref$ | Regulated branch initial reactive power flow |
| $Q_branch$ | Branch reactive power flow for plant Q regulation |
| $P_ref$ | Active power command from plant controller |
| $F_req_ref$ | Initial frequency deviation |
| $Freq$ | Frequency deviation |
| $Q_ext$ | Reactive power command from plant controller |
| $V_t$ | Terminal voltage |
| $I_qcmd'$ | Desired reactive current command |
| $I_pcmd'$ | Desired active current command |
| $Pqflag$ | Active or reactive current priority flag |
| $I_qcmd$ | Actual reactive current command |
| $I_pcmd$ | Actual active current command |
| $I_q$ | Reactive terminal current |
| $I_p$ | Active terminal current |

**REEC_D**

REEC_D is the module used to represent the electrical controls of the inverters. The active and reactive power signals are sent from REPC module with the feedback of terminal voltage and generator power output. These are given as real reactive current commands to the REGC module by REEC. The model diagram of REEC_D is shown in Figure 2.10.

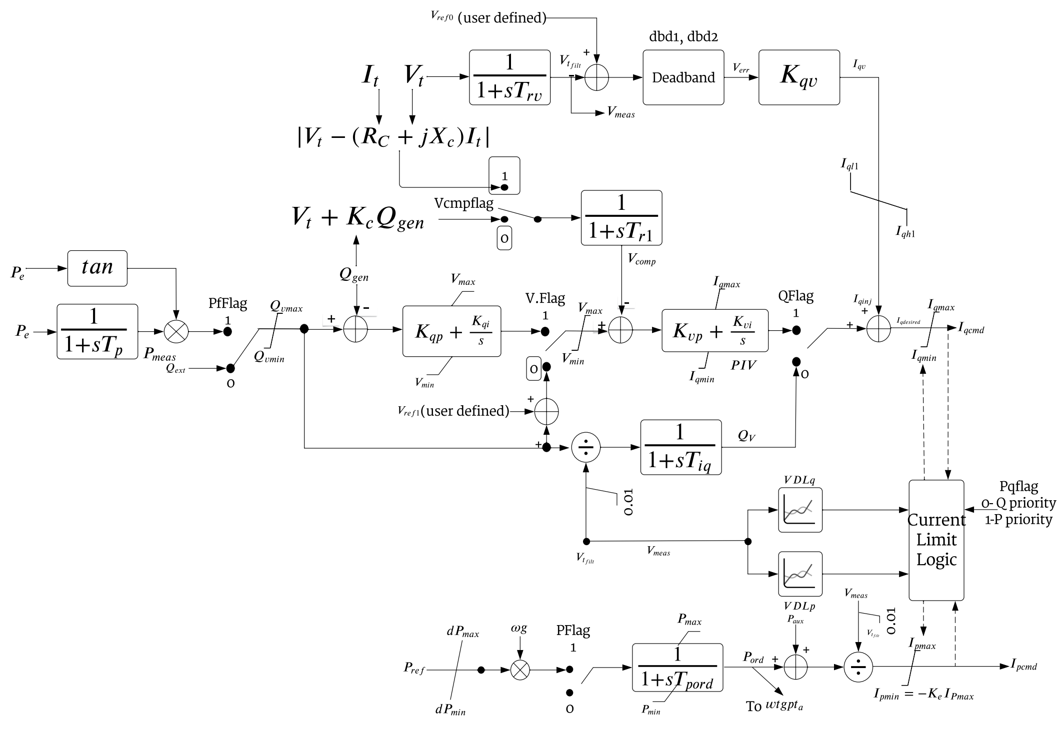



**Figure 2.10:** Block diagram of the Renewable Energy Electrical Control Model REEC_D [32]

**REGC_B**

REGC_B is the module that is used to represent the generator/converter interface with the power system. REGC processes the real and reactive current commands. Then it injects the outputs of real and reactive current into the power system model. The model diagram of REGC_B is shown in Figure 2.11.

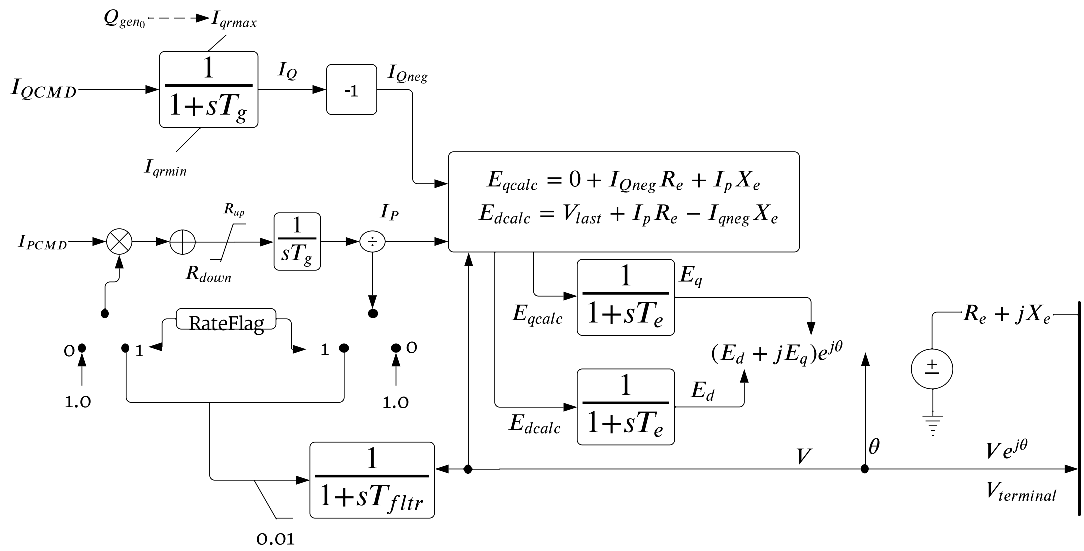


**Figure 2.11:** Model of Renewable Energy Generator Converter REGC_B [33]

**Weak power system Option**

A weak power system option is added to help stabilize the wind turbine at the point of interconnection [34]. It majorly addresses concerns such as Low-frequency voltage/power oscillations from small signal disturbance and top increase FRT capability- fault ride through voltage/power stably restored after fault is cleared.

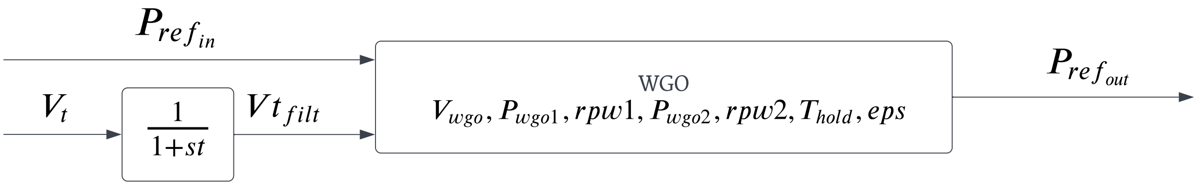


**Figure 2.12:** WTGWGO: WECC Weak Grid Option Control [34]

None of these modules contain an inverter for plant protection. Conventional generator protection models can be used to represent voltage and frequency protection settings. To be precise, only the REGC module is sufficient to implement the simulation. However, the rest of them enable enhanced control functionality.

## 2.5.3. Wind Systems

With the increasing integration of wind energy into power systems, Transmission System Operators (TSOs) and Distribution System Operators (DSOs) are increasingly focused on researching the stability of power systems using dynamic models of wind power generation. Generic models have been developed for three different control systems used in wind generation systems: the IEC Type 4B Wind Turbine Controller (WTC), Virtual Synchronous Machine (VSM), and Droop Control System.

The comparison of simulation results among these three control systems serves to validate their accuracy and effectiveness specifically for large-scale power systems and power system stability analyses.

- **IEC Type 4B**: Ensures optimal power generation
- **Virtual Synchronous Machine**: Imitates a synchronous generator
- **Droop Control System**: Imitates a governor in Synchronous Generator dynamic model.

Because of their advantages—high efficiency, high power density, and dependability—type 4 WTG generators are recommended. Emerging technologies that can address such stability issues include power system-forming controls for inverter-based winter wind turbine generators, which reduce power system inertia and weaken the power power system. Higher penetration of wind power in a conventional power system is made possible by these controls. As a result, an analysis is conducted comparing the simulation outcomes of power system forming and power system following controls.

The Type 4 wind turbine represents a significant advancement in wind energy technology, featuring a variable speed design and employing either synchronous or asynchronous generators connected to the power system through a full-scale power converter. While it excels in addressing short electrical events like short circuits, it falls short in facilitating comprehensive studies vital for today's energy landscape, such as frequency control analyses.

The limitations stem from certain assumptions inherent to this model, notably the presumption of constant wind speed leading to a consistent aerodynamic torque. Moreover, crucial elements like error dynamic models and information on available power are lacking, further hindering its suitability for rigorous frequency control studies.

Consequently, the standard Type 4 wind turbine models outlined in this thesis fail to accurately depict real-world wind power plants or adequately address the demands of frequency control essential for future power system services. The incorporation of features necessary for inertia control and synchronizing power, vital for power system stability and reliability, exceeds the scope of this research. The modular structure that shows the working of a IEC generic WT models is shown in Figure 2.13.

In essence, while Type 4 wind turbines represent a commendable advancement in wind energy technology, their current model limitations underscore the need for further research and development to ensure they fulfill the evolving requirements of modern power systems.

The droop control system emerges as a pivotal solution for ensuring uninterrupted power supply systems, aiming to equip distributed generators with both power system-forming capabilities and the ability to share power effectively. This system operates by regulating both real and reactive power, mirroring the parallel operation traits observed in synchronous generators.

However, the inherent lack of inertia support in distributed generators equipped with group control necessitates the development of an innovative control approach known as the virtual synchronous generator (VSG) or virtual synchronous machine. This novel method is tailored not only to emulate the steady-state behavior of synchronous generators but also their transient characteristics, achieved through the application of swing equations to enhance system inertia. The integration of virtual inertia into the system plays a crucial role in mitigating the maximum frequency excursion during short-time faults and smoothing out frequency fluctuations during transitions in load, particularly when secondary frequency control measures are implemented.[35]

In essence, while droop control systems offer significant advancements in power supply reliability, the introduction of virtual synchronous generators represents a groundbreaking development, ensuring not only stable power system operation but also enhancing system resilience and response capabilities during transient events.

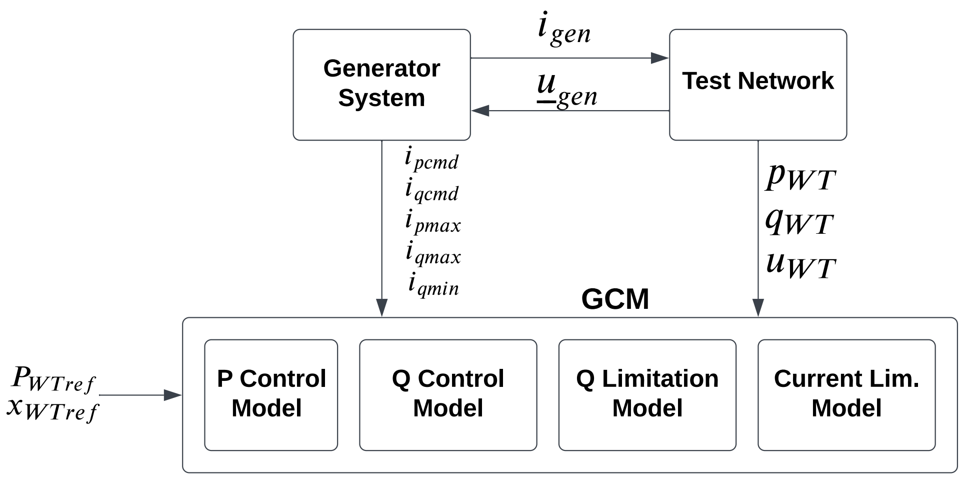



**Figure 2.13:** Modular structure of the IEC generic WT models [36]

**Table 2.8:** Description of signals that are mentioned in Figure 2.13

| Signal | Description |
|---|---|
| $i_{gen}$ | Active Reactive currents injected to power system |
| $u_{gen}$ | Voltage at generator |
| $I_{pcmd}$ | Active current command signal |
| $I_{qcmd}$ | Reactive current command signal |
| $I_{pmax}$ | Active current limit |
| $I_{qmax}$ | Reactive current maximum limit |
| $I_{qmin}$ | Reactive current minimum. limit |
| $p_{WT}$ | Active power measured at WTT |
| $q_{WT}$ | Reactive power measured at WTT |
| $u_{WT}$ | Voltage measured at WTT |
| $P_{WTref}$ | Active power reference |
| $x_{WTref}$ | Reactive Power reference |

**Table 2.9:** Descriptions of each control models used in IEC Type 4B[36] [37]

| Control Model | Function |
|---|---|
| **Generator Set Type 4** | • Including a current limiter, it is designed via a static generator component.<br>• Static generator component is attached to the full converter that helps in determining the power system side response.<br>• Both the current source and voltage source can be supported. But the current source is used. |
| **P control Type 4B** | • Both P and Q control models are used to control the active and reactive power injection at the Wind Turbine Terminals (WTT).<br>• During faults, the generator speed is used as input to account for the electro-mechanical oscillations.<br>• Part of the Generator Control Model (GCM). Outputs $i_{pcmd}$ and $p_{aero}$ calculated to rectify the error between measured and set point signals. |
| **Q Control** | • Q control is able to operate under various control modes: Voltage control, reactive power control, open-loop reactive power control, power factor control, and open-loop power factor control.<br>• Detects voltage dips and sets three operating stages.<br>1. Normal operation<br>2. Operation during faults<br>3. Operation during post-fault periods<br>• Able to control the injection of reactive power at the WTT. |
| **Q Limitation - QP and QU** | Estimates the maximum and minimum reactive power at the wind turbine terminal, with values provided by the Q control model. |
| **Current Limitation** | • Establishes the maximum and minimum limit values of active current.<br>• Active and reactive powers are calculated along with voltages and are given as inputs to different controls. |
| **Two Mass mechanical** | • Emphasis on the drive train of the dynamic structure that contributes to the interaction with the power system.<br>• Significant in frequency control studies as it can disclose the possibility of the wind turbine providing active power during any frequency event.<br>• Represented through a 2-mass model that reflects the torsional shaft oscillations whenever there is sudden torque imbalance.<br>• Aerodynamic and air gap power are inputs calculated at the static generator equal to the electric power injected into the power system. |

# 3

# Implementation in Power Factory

In the following chapter the procedure adopted to implement the Dutch power system in PowerFactory 2023 is presented. The methodology involving simulations for 2030 is also discussed. Firstly, by giving an introduction to the creation and implementation of DSL models for each type of generators, a step by step instruction of execution of RMS simulation that involves PowerFactory, Python, Excel and MATLAB are given. Finally, a detailed analysis of the operating conditions for each scenario that is developed is discussed.

## 3.1. Introduction

A hierarchical approach is followed In PowerFactory, while creating DSL Models. The four key elements of DSL—Composite Frame, Composite Model, Model Definition (also called Block Definition), and Common Model—are crucial for creating dynamic models, Figure 3.1 illustrates how these DSL components connect. Composite Frames and Model Definitions serve as the fundamental structural templates for every power system component and device. Using these templates, Composite Models and Common Models for individual power system elements are generated, enabling customization of parameters.

Now that an understanding of the DSL composition has been established, the following sections will discuss the implementation of DSL models for various types of generators and the connection of each DSL model with their respective composite models.

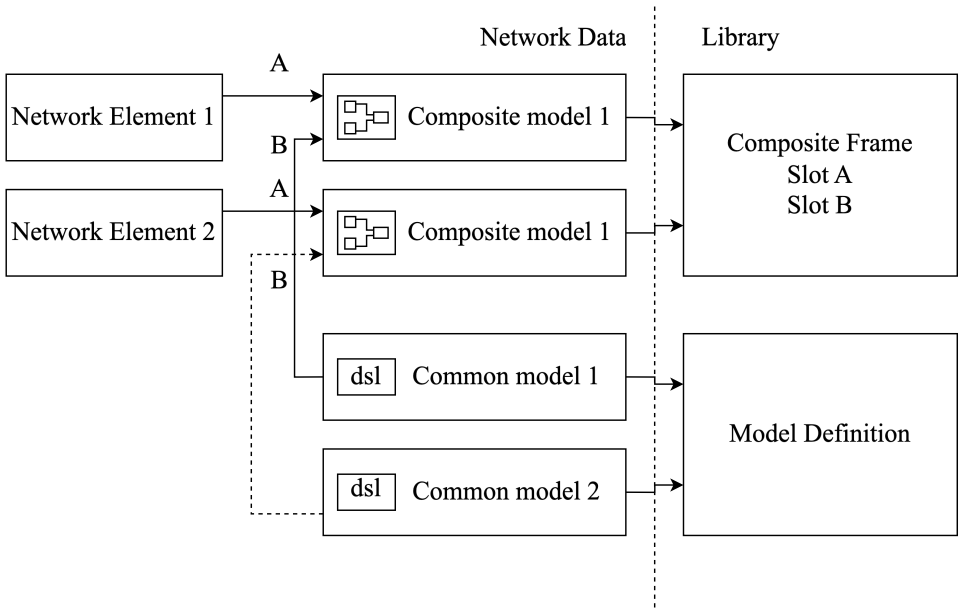



**Figure 3.1:** Hierarchy of the DSL modelling approach in PowerFactory

### 3.1.1. Synchronous Generators

IEEE Frame Synchronous Machine is recommended for implementation of Synchronous Machine composite model.It has 15 block slots consisting of Generator, Governor, Exciter, OEL, UEL etc. The composite model as shown in Figure 3.2, is created which forms the connection between the synchronous machine and the rest of the control systems that will be added. A model definition is added which contains the transfer function of the dynamic model as mentioned in Chapter 2 and Figure 2.6. A composite model is created to link the composite frame to the actual power system elements. A common model combines the DSL model type with the desired parametric values.

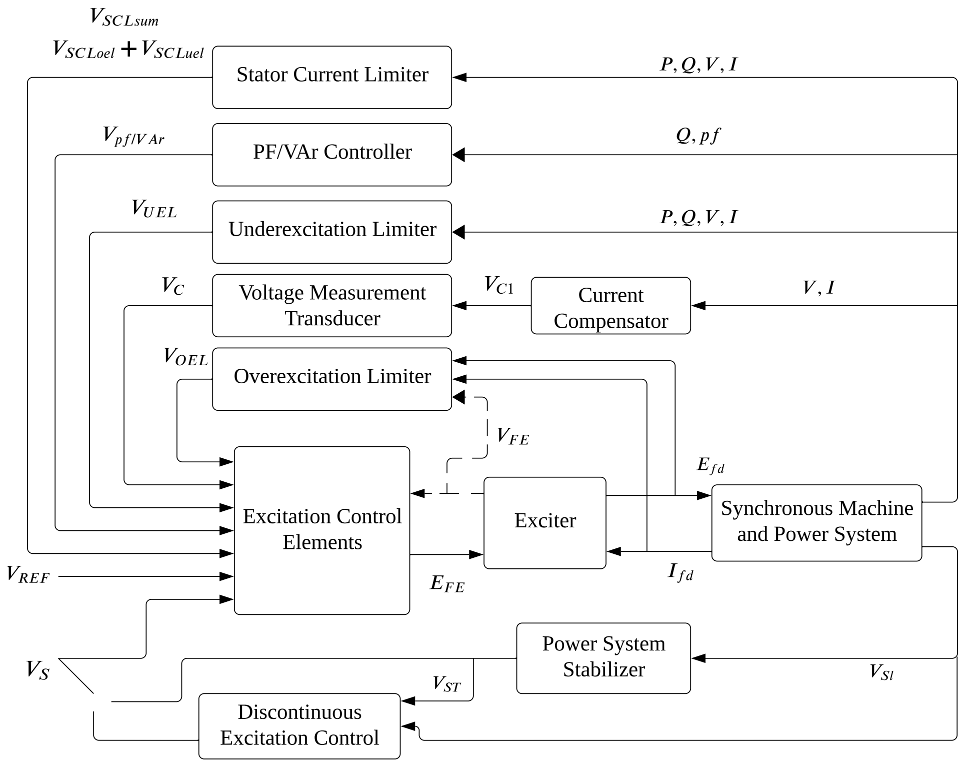



**Figure 3.2:** Composite Frame of Synchronous Machine [27]

**Table 3.1:** Implementation of DSL models in the Composite Model for Generator DG_GAS_NH15

| **Slot** | **power system Element** |
|---|---|
| Generator | DG_GAS_NH15 |
| Governor/ Turbine/ Engine | IEEEG1 |
| V Transducer/ I Compensation | IEEE Voltage Transducer and Current Comp |
| Voltage Regulator/ Exciter | IEEE AC1A |
| Power System Stabiliser | IEEE PSS1A |

Table 3.1 outlines the implementation of DSL models for each Block Slot of the Generator DG_GAS_NH15, as detailed in Chapter 2. Specific parameters for each block are further discussed in Appendix A. While Governor, Exciter, V Transducer, Exciter, and PSS are included, UEL and OEL are excluded due to their complexity and the current system's stability within admissible limits. However, UEL and OEL can be added later if voltage profiles change, available from the DIgSILENT library. The DSL model parameters are tuned based on ideal generator behavior and adjusted from voltage stability test systems like the Nordic Test Systems to fit current system requirements.

### 3.1.2. Photovoltaic Systems

Frame WECC Large-scale PV plant is the generic composite frame used for the implementation of the Composite frame for the Large-scale PV systems. The frame is shown in Figure 3.3. The composite frame follows the same concept discussed in Figure 2.9, that depicts the connections between all the modules of a PV control module. The DSL models that are discussed in Chapter 2 are added to the Block slots of the composite model. While the WECC Large-scale PV Plant template for 50Hz already comes with added DSL models types to the composite model frame, any change in the type of controller used can be implemented using this procedure. While there are 8 slots in the frame, only 7 are added with power system elements out of which 2 are measurement devices. While adding PQ Measurement device, it is crucial to select the correct node at which the PV plant is connected in the power system for correct calculation. Similarly, the correct terminal should be selected while adding the Voltage Measurement device. The addition of correct model sin the correct slots is shown in Table 3.2.

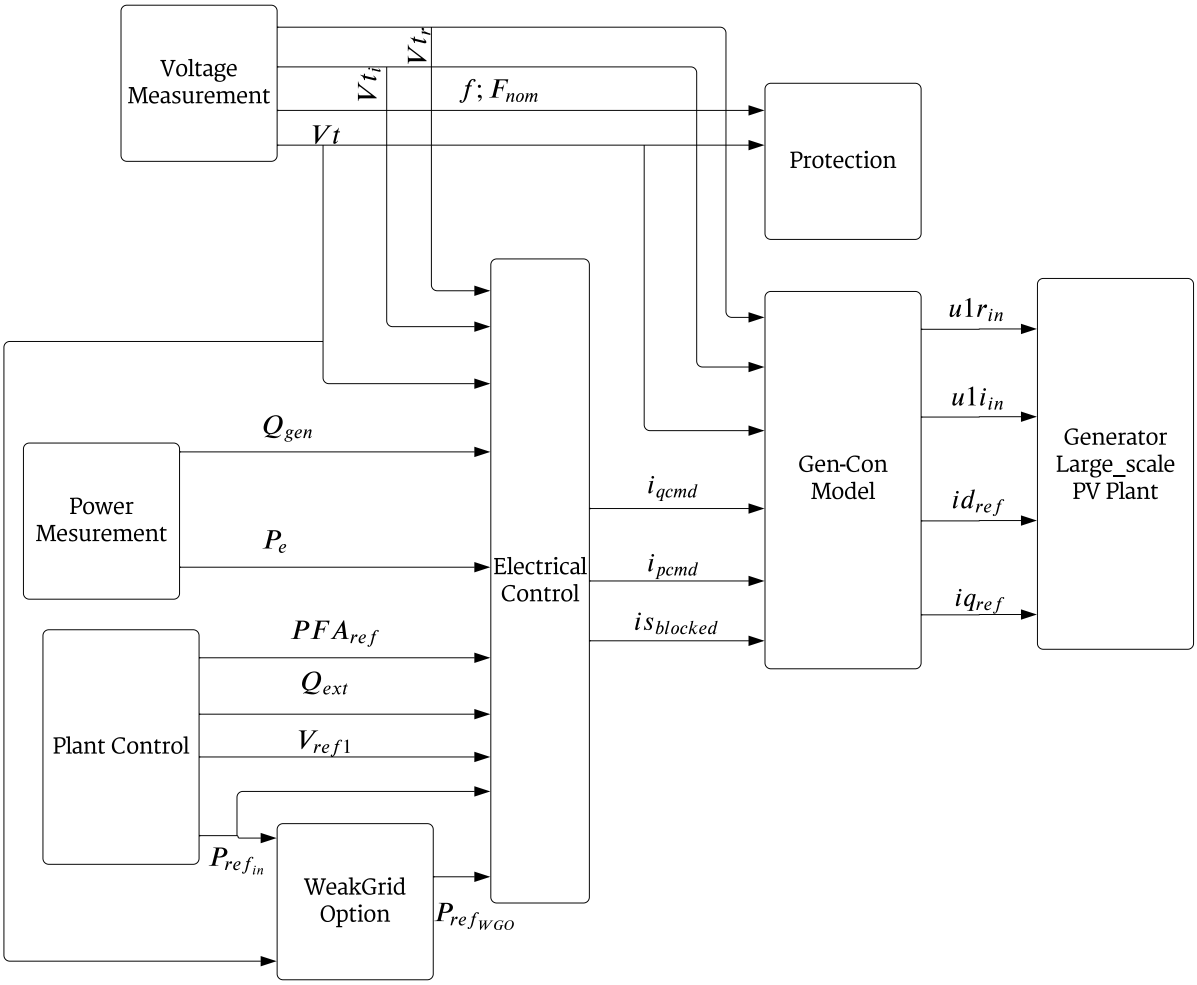



**Figure 3.3:** Composite frame Model of WECC Large-scale PV systems [31]

**Table 3.2:** Implementation of DSL models of the PV systems with generator L_PV_NH150

| Block Slot | Grid Element |
|---|---|
| Generator | L_PV_NH150 |
| Electrical Control | REEC_D Electrical Control Model |
| Gen-Con Model | REGC_B Generator-Convertor Model |
| Power Measurement | PQ Measurement |
| Voltage Measurement | Voltage Measurement |
| Protection | Protection |
| WeakGridOption | WTGWGO_A Weak grid Option Model |

### 3.1.3. Wind Systems

Ever since there has been an increase in the penetration of Wind Energy in today's power system, it has become mandatory for the TSO's and DSO's to develop Dynamic Models for wind systems. These models are designed by the turbine manufacturers to imitate the machine's behaviour with heavy detail. IEC Wind Type 4B is the model type implemented in this section. The *Frame IEC Type 4B* is the recommended composite frame used for this implementation. This can be seen in Figure 3.4. The implementation of different DSL models with various controls that are discussed in Section 2.5.3 are shown in Table 3.3. As mentioned before, the measurement devices should be assigned with the correction measurement point while addition of the template to the power system.

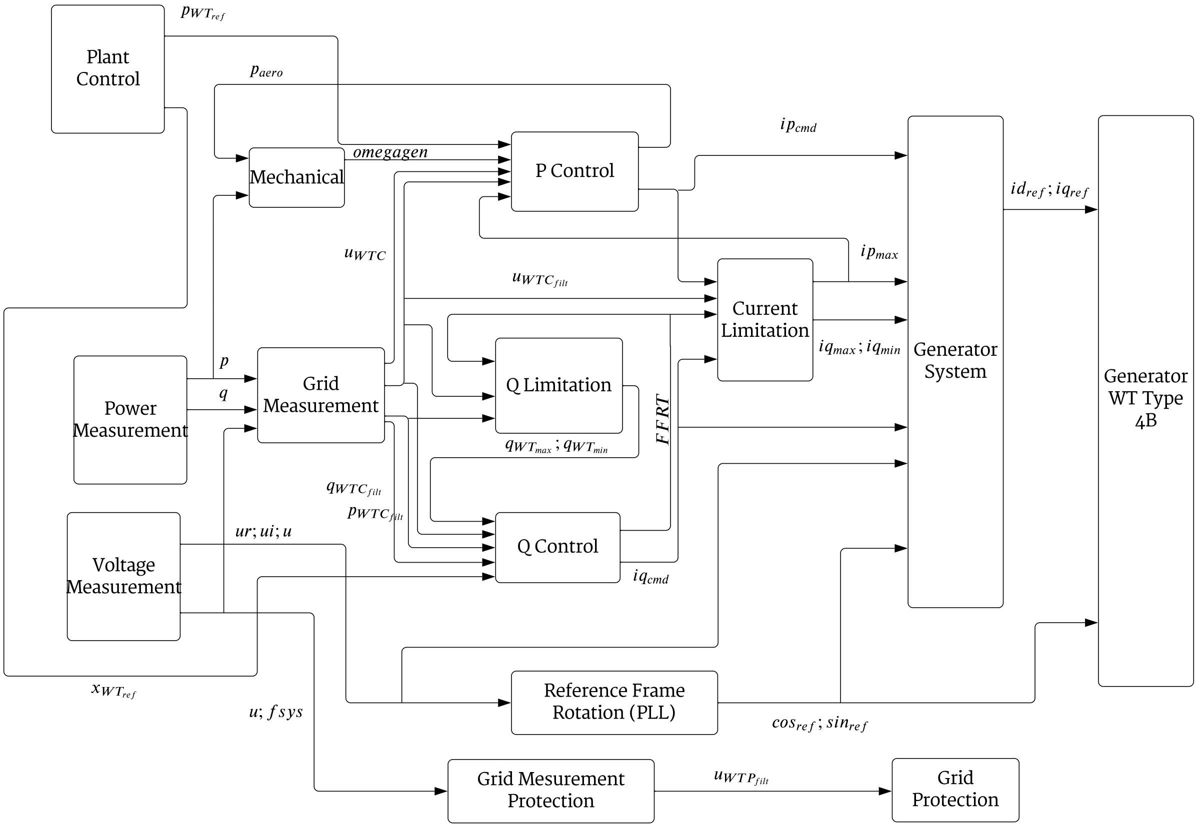



**Figure 3.4:** Composite frame model of Wind Turbine Type 4B [37]

**Table 3.3:** Implementation of DSL models of the Wind Turbine system with static generator W_WOL_NH150

| **Block Slot** | **power system Element** |
|---|---|
| Generator | W_WOL_NH150 |
| Generator System | Generator Set Type 4 |
| Mechanical | Two Masses |
| P Control (Type 4B) | P Control Type 4B |
| Current Limitation | Current Limitation |
| Q Control | Q Control |
| Q Limitation | QP and QU Limitation |
| Grid Measurement Control | Grid Measurement Control |
| Grid Measurement Protection | Grid Measurement Protection |
| PLL | Reference Frame Rotation |
| Power Measurement | Power Measurement |
| Voltage Measurement | Voltage Measurement |

## 3.2. Upgrades for 2030 Model

In this section, different developments that lead to a change in power system topology of the base model are mentioned. The base model is based on the single line diagram from 2019 with the corresponding power system data. Upgrades involve repetition of the existing system components that mimic a similar behaviour but comes with additional attachments involving dynamic simulations. Upgrades do not involve Battery Energy Storage Systems that are currently being proposed in the Dutch power system [38].

### 3.2.1. WECC Photovoltaic systems

**Figure 3.5:** power system of the Large-scale PV system

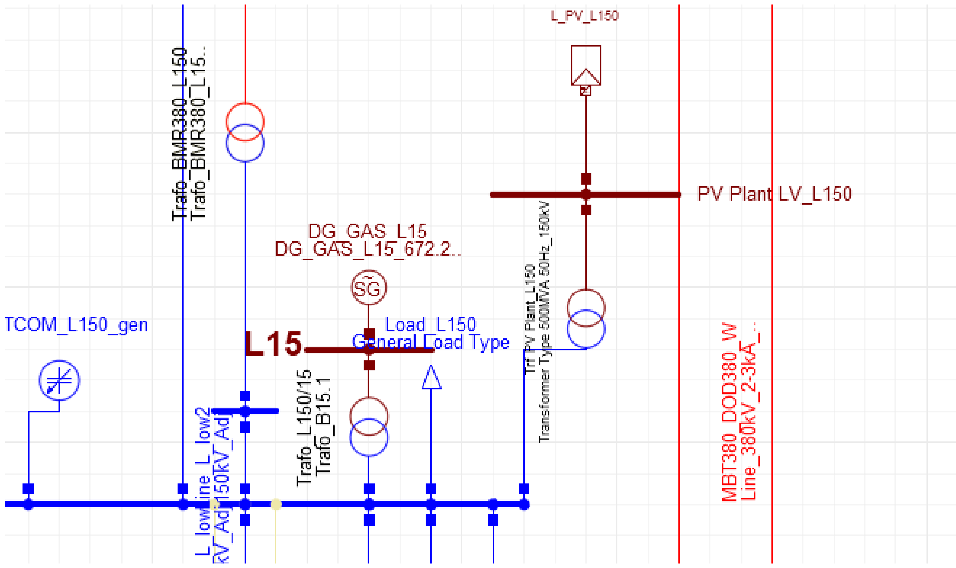



**Figure 3.6:** Implementation of the PV system in the power system

Few upgrades have been established in the 2030 scenarios study cases for the photovoltaic systems and wind systems. According to the WECC templates, the large-scale power systems for PV parks is added as static generators to the power system the simulations are run with the old static generators out of service and the new static generators in service as shown in Figure 3.6. The PV system is attached with the composite model of the WECC control system. According to WECC, the large-scale PV plant model has a nominal frequency of 50 Hertz and a reactive power of 110 MVA. This template has an ElmPvsys class of Photovoltaic systems as opposed to the ElmGenstat class of the static generator with a Photovoltaic plant category. The rated apparent power of each of these photovoltaic systems is assigned with the same apparent power that is dispatched in specific study cases.

### 3.2.2. Wind Systems

The static generators of both on-shore and off-shore wind generators are replaced with the wind turbine model of Type 4B according to IEC 61400271. A bus bar terminal of 15kV and a transformer with rating of 500MVA are added as shown in Figure 3.7. The Wind system is attached to the composite model of the IEC Wind Type 4B control system. According to IEC, the Wind Turbine type 4B has a nominal frequency of 50Hz and a reactive power of 110MVA which is later changed according to the region. The bus terminals line-line voltage is changed to 15kV before integration in the external power system. The dispatches of different scenarios are set using the Python code. The reactive power control mode is also selected to most of the wind systems as Constant Q while selected offshore wind to Constant V. The parameters of the step-up transformer are mentioned in Table 3.4. The power system of the Wind turbine Type 4B is shown in Figure 3.8, where in clear differentiation of terminal voltage levels can be seen.

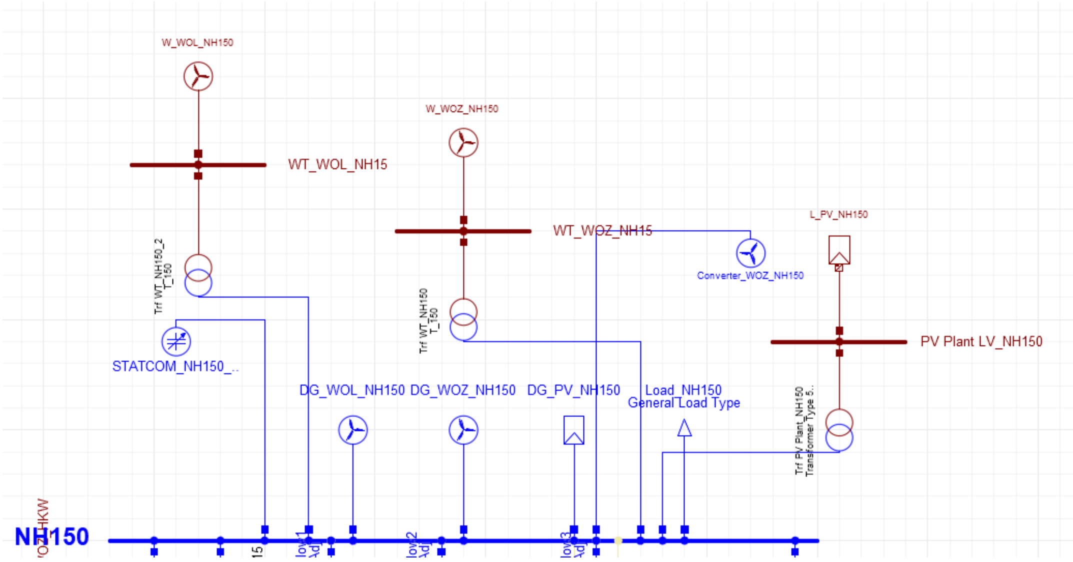



**Figure 3.7:** Implementation of the Wind system power system in PowerFactory

**Figure 3.8:** power system of the Wind turbine Type 4

**Table 3.4:** Parameters of the Step-up transformers

| **Name** | $S_rated$ **(MVA)** | $U_HV$ **(kV)** | $U_LV$ **(kV)** | **uk (%)** | **P_copper (kW)** | **Ratio X/R** | $xl$ **(p.u.)** | $rl$ **(p.u.)** |
|---|---|---|---|---|---|---|---|---|
| T_380 | 500 | 380 | 15 | 15 | 765 | 50 | 0,15 | 0,003 |
| T_150 | 500 | 150 | 15 | 15 | 765 | 50 | 0,15 | 0,003 |
| T_110 | 500 | 110 | 15 | 15 | 765 | 50 | 0,15 | 0,003 |

## 3.3. Description of Scenarios

Any transmission power system is subject to wide range of operational conditions and disturbances. Different scenarios are compared to replicate real-world situations and observe how the power system responds to these changes. This provides a more accurate and comprehensive understanding of the power system's dynamic behavior. The base model is used to simulate scenarios for 2017-2019. The generation capacity and demand are modelled according to KCD2017 for 2018 [39]. The model is further adjusted to include all generators that are currently listed by the ENTSO-e transparency platform to perform simulations.

In Table 3.5, the Total amount of Generation and Demand that was used in both base model and the upgraded model for 2030 is given. The generation is differentiated between Conventional, Renewable Generation (Solar and Wind). For case which has Electrolysers, the demand is specified in P6. The loads demand in P4. The reason to distinguish the total from conventional generation is because the static or renewable generation in the base model is either Solar PV or Wind which is not controllable.

**Table 3.5:** Installed capacities of different generation types in each scenario

| Scenario | Generation (GW) | Conv. Generation P1 | Renewable Generation | | Loads P4 | IC P5 | Electrolysers P6 | Generation-Demand P1+P2+P3-(P4+P5+P6) |
|---|---|---|---|---|---|---|---|---|
| | | | Solar P2 | Wind P3 | | | | |
| 2017-2019 | Conv. & Wind | 15386.39 | 0 | 889 | 19041 | -1057 | 0 | -1708.23 |
| 2030 | Only Wind | 0 | 0 | 16164.6 | 16000 | 0 | 0 | 164.60 |
| | Only Solar | 0 | 16211.25 | 0 | 16000 | 0 | 0 | 164.6 |
| | Mix Wind & Solar | 0 | 4455 | 16722 | 16000 | 0 | 0 | 211.25 |
| | Elec & Wind | 0 | 0 | 18580 | 12000 | 0 | 6500 | 80 |
| | Elec & Solar | 0 | 18562.5 | 0 | 12000 | 0 | 6500 | 62.5 |
| | Elec, Solar & Wind | 0 | 12870 | 18580 | 21000 | 0 | 10000 | 450 |

## 3.4. Methodology

The initial approach was to choose the most basic and obvious cases in the initial model to provide varied insights of the addition of VRES and their consequences. The generation and demand of each type of supplies change between the operational scenarios. For each case, 3 cases are chosen for base models and one case each for further variations. The further variations include addition of electrolysers. The Electrolyser addition cases that are chosen are the best cases as concluded in the previous thesis [12].

The initial model is developed majorly for the Initial Power Flows, Optimal Power Flow and Contingency Analysis. The Simulation RMS parameters should be defined for each synchronous generator. These are initially input using the Test systems for Voltage Stability Analysis and Security Assessment [11]. The Nordic Test system discussed in the guide contains various types of Conventional Generation including Hydro, Thermal, Biomass and Coal. The parameters that are tuned are mentioned in the Appendix A Table A.2. The MVA rating of the existing generators are rounded and the values closest to the MVA rating of the current system are chosen from the test systems.

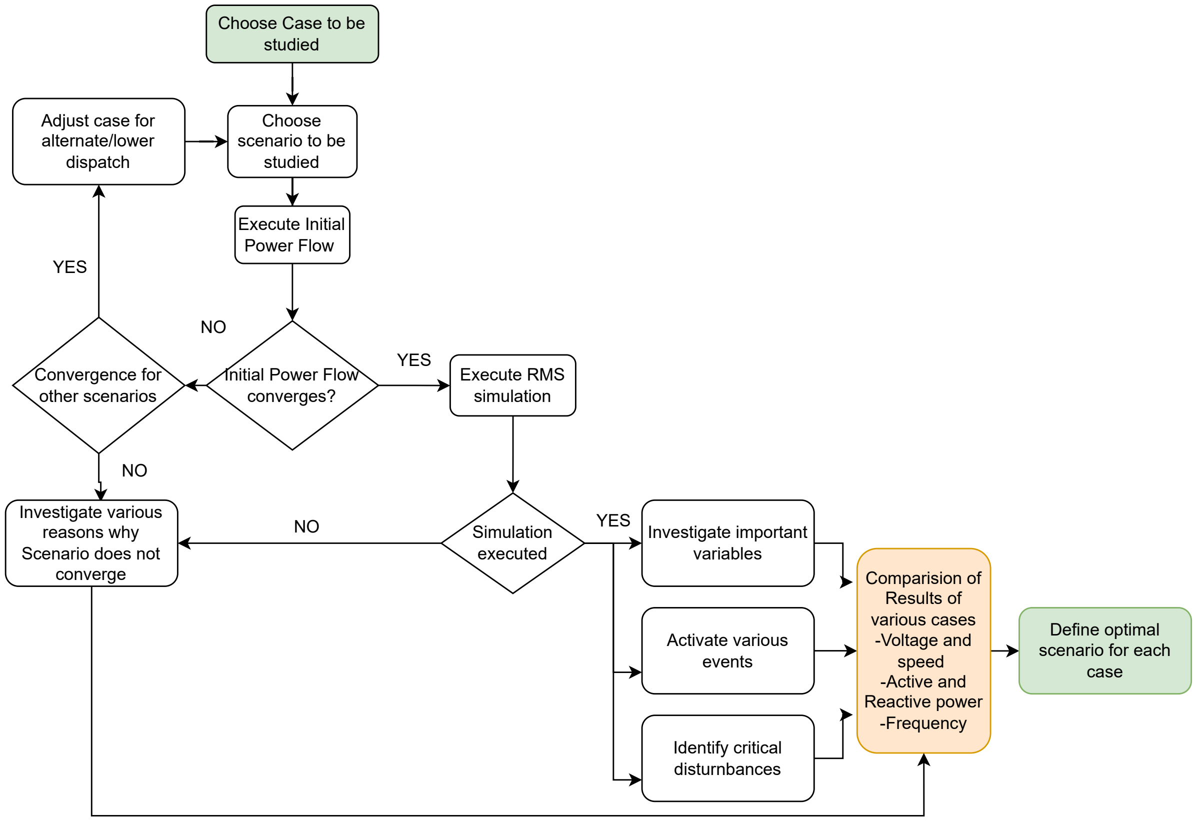



**Figure 3.9:** Approach for simulations of case study

After the addition of DSL models for all types of generators and parameter tuning, RMS simulations are run with various disturbances. The location and duration of each fault is varied according to the convergence of model. Since the model is previously tested for different dispatches and scenarios, load flow issues should not appear. It is majorly convergence issues that are dealt. Critical disturbances for each scenarios are identified and discussed in the Section 4.5. Addition of these critical disturbances in all the locations around the power system, dynamic security is further assessed in Section 4.7.

## 3.5. Integration with Python

Python scripts are developed to avoid manual errors in inputting parameters and easy adjustments of component values. It is possible to execute these scripts from with in the PowerFactory model. Any results of the scripts are printed in the Output window in PowerFactory. The flowchart that discusses the steps off-screen is given below in 3.10.

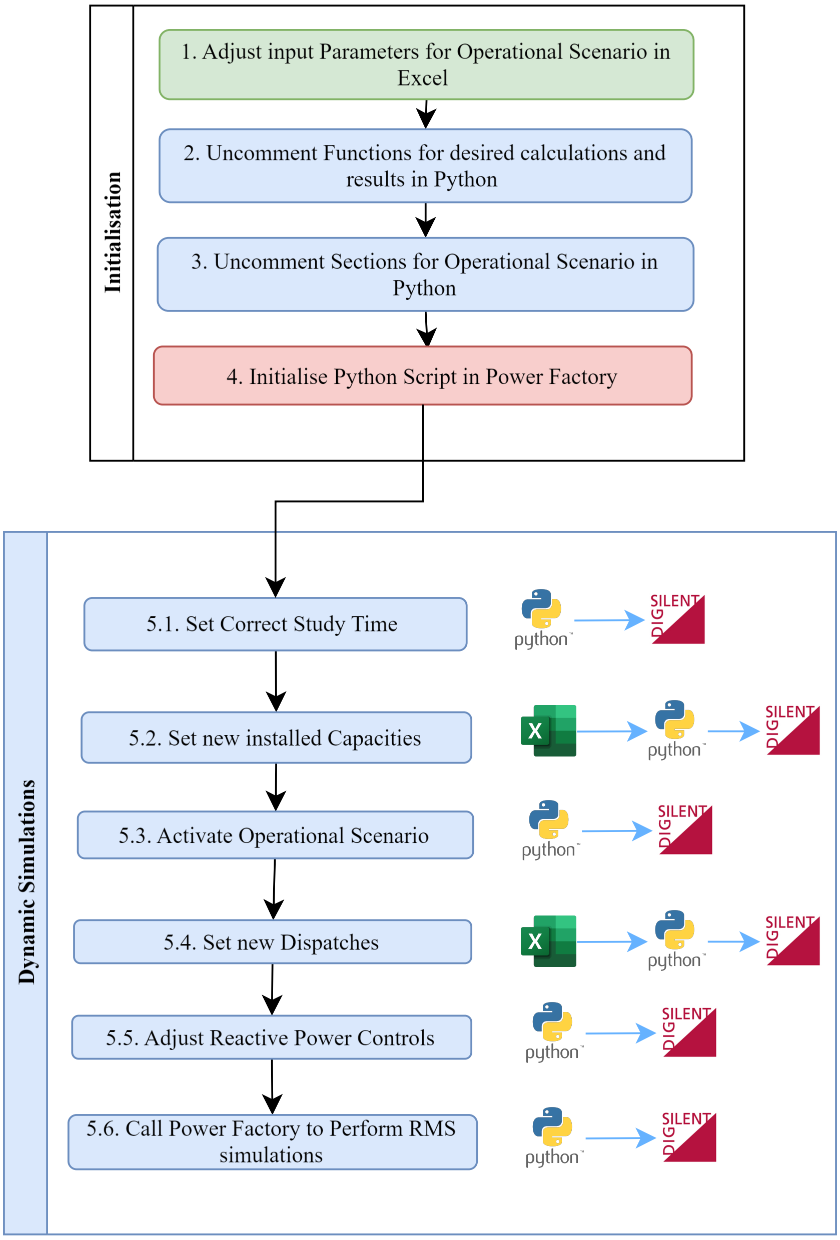



**Figure 3.10:** Flowchart of how the model is executed and automated. The Programs used for every step are mentioned in the right-hand side.

The transmission model power system is in PowerFactory. The python script calls PowerFactory and reads and writes values from Excel. The python scripts allows to perform Load flow simulations and RMS simulations. The guidelines on how to use and change the script for different applications mentioned in Appendix.

**Step 1: Adjusting Parameters for Operational Scenarios in Excel**

Input parameters for the dispatches can be adjusted as well as parameters for installed capacities in Excel. These are not changed throughout the course of this research. For further research these can be changed according to the requirement.

**Step 2: Uncommenting functions for Desired Scenarios**
Two different scripts are developed for two scenarios. In each script the functions for each study case can be uncommented to perform the RMS simulations in each of these cases. The desired testing permutations for each study case can also be selected and executed in the scripts.

**Step 3: Running the Python script**
The external directory of PowerFactory should be adjusted according to the python files location of the User. Desired script should be opened in the model library library>scripts and Executed.

**Step 4: Task Automation in Python Script**
In the Python scripts that are created, the script includes input excel files and output folders. This is activated within PowerFactory. Different functions that are defined in the script and their importance is discussed:

**Scenario 2017-2019**

- *Capacities_BM()*: The specific sheets in Excel are taken and the installed capacities are adjusted to their corresponding system components.
- *Dispatches()*: Dispatches are set for each operational scenario for the system components as given in the Excel sheets.
- *Adjust Reactive Power Control()*: Settings for Reactive Power are set depending on the scenario. Based on the scenario, different sources of Reactive power control can be investigated.
- *RMS_simulation()*: Execute RMS simulation and export the result variable file or assign it to the file of desired name.
- *RMS_testing_dsl()*: Performs iterative simulations of different cases in presence and absence of different control functions.
- *addShortCircuitEvent()*: Adding short circuit event for the required time and at desired location.
- *addLoadEvent()*: Adding load event for the required time and at desired location.
- *addOutageEvent()*: Adding generator outage event for the required time and at desired location.
- *RMS_testing_faults()*: Performs iterative simulations with different faults in service and exports result files to specific location.
- *addRecordedResult()*: Adds relevant result variables to be monitored, to the Result variables file.
- *RMS_results()*: Exports results for any simulation performed in the previous functions.

Actual commands are given in the end of the python script for execution. These steps will be discussed <>. The operational scenarios are activated using if condition loop and then desired simulations are performed.

**Step 5: Reading Results and visualisation**
After choosing the Study case that needs to be analysed, the rest of the actions are performed automatically in the Python scripts. One script performs all the simulations for the Scenario 2017-2019 and the other for Scenario 2030. The script that performs voltage stability performance assessment and exports results is discussed in C. The python scripts that are names RMS_plots.py is used to generate all the plots and results discussed in this paper.

## 3.6. Analysis of Operating Conditions

Three scenarios are developed to test the dynamic stability performance of the Dutch power system. The choice of scenarios is dependant on the objective of the research to draw meaningful conclusions based on the findings. The criteria according to which each of these scenarios are chosen is explained in detail.

### 3.6.1. Base Case Scenario

Base Case scenario represents the operation of the power system under normal operating conditions. This means steady load demand, stable conditions, conventional generation, and no unusual events. The results from this scenario can be used as a reference to the next scenarios for comparison.

The Base Model is used to simulate Scenarios for 2017-2019. The generation capacity and the demand of the loads are modeled according to the recorded dispatches for 2017, 2018, and 2019. The generators that are designed and modelled are the ones mentioned in the ENTSO-e transparency platform to perform simulations. Necessary details and requirements about modeling the generators, and the capacities of each generator installed, and the distribution between conventional and static generators among different regions are discussed. Also, the amount of generation is not evenly distributed among the different HV and EHV regions.

| Region | Symbol |
|---|---|
| Friesland | F |
| Groningen en Drenthe | GD |
| Overijssel en Noordoostpolder | ON |
| Gelderland, Flevoland en Utrecht | GFU |
| Zeeland | Z |
| Noord-Brabant | B |
| Limburg | L |
| Noord-Holland | NH |
| Zuid-Holland | ZH |

**Table 3.6:** Base Model: Total amount of generation and demand

| | Unit | **F** | **GD** | **ON** | **GFU** | **Z** | **B** | **L** | **NH** | **ZH** | **Totals** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 220/380kV Gen Cap | MW | 144 | 5519 | 0 | 426 | 1622 | 0 | 1304 | 435 | 3071 | 12521 |
| 110/150kV Gen Cap | MW | 630 | 1220 | 940 | 2838 | 1741 | 2905 | 963 | 3686 | 4282 | 19205 |
| **Total Gen Cap** | **MW** | **774** | **6739** | **940** | **3264** | **3363** | **2905** | **2267** | **4121** | **7353** | **31726** |

**Table 3.7:** Base Model: Demand modelling according to Distribution of Peak Demand for each region

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Synchr. Gen. Cap.** | MW | 214 | 5239 | 200 | 1929 | 2054 | 2189 | 1909 | 3343 | 6456 | 23533 |
| **Peak Demand** | MW | 590 | 1460 | 1258 | 3251 | 625 | 3550 | 1650 | 3333 | 4355 | 20072 |
| **Total Gen. Cap./D** | | 1,31 | 4,62 | 0,75 | 1,00 | 5,38 | 0,82 | 1,37 | 1,24 | 1,69 | |
| **Sync. Gen. Cap./D** | | 0,36 | 3,59 | 0,16 | 0,59 | 3,29 | 0,62 | 1,16 | 1,00 | 1,48 | |

It is apparent from Table 3.6 that Groningen and Drenthe (GD) has an excess of capacity to meet its own demand, while other regions such as Brabant (B), Overijssel en Noordoostpolder (ON), Gelderland, Flevoland and Utrecht (GFU) show deficits. The demand is modelled according to the distribution of the peak demand.

### 3.6.2. High Renewable Energy Integration

The total amount of conventional generation in the 2030 model gradually decreases as years progress. After the addition of RES, the impact of this integration is evaluated in the 2nd scenario. The stability can be compared to the previous scenario and various stability metrics are extracted to analyze.

**Table 3.8:** 2030 Model: Total amount of generation and demand for each region

| | Unit | **F** | **GD** | **ON** | **GFU** | **Z** | **B** | **L** | **NH** | **ZH** | **Totals** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 220/380kV Gen Cap | MW | 85 | 3350 | 0 | 252 | 4226 | 0 | 770 | 2483 | 4354 | 15520 |
| 110/150kV Gen Cap | MW | 2370 | 6650 | 3280 | 9150 | 2874 | 3820 | 2010 | 4780 | 6700 | 41634 |
| **Total Gen Cap** | **MW** | **2455** | **10000** | **3280** | **9402** | **7100** | **3820** | **2780** | **7263** | **11054** | **57154** |

**Table 3.9:** Peak Demand and share of total national assumed for each region for 2030

| | **unit** | **F** | **GD** | **ON** | **GFU** | **Z** | **B** | **L** | **NH** | **ZH** | **Totals** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Peak Demand** | MW | 750 | 1600 | 1700 | 4300 | 1180 | 3900 | 2200 | 5500 | 5300 | |
| **Distribution** | % | 2,84 | 6,05 | 6.43 | 16,27 | 4,46 | 14,76 | 8,32 | 20,81 | 20,05 | 0 |

# 4
# Case Study

## 4.1. Introduction

The case study is divided into different cases under each scenario. As discussed in Section 3.6, the operating conditions and the dynamic models introduced in each scenario are different. The 2017-2019 scenario is tested for two cases. The addition of different control modules to the system is tested in the first case. In the 2nd case, the system response to three event types is analyzed. For the 2030 scenario, three cases of dominated solar source, wind and a mix of solar and wind each is also tested with three event types, which can be seen from Figure 4.1. The wind systems (cases with dominated wind generation) specifically are tested for three different control types.

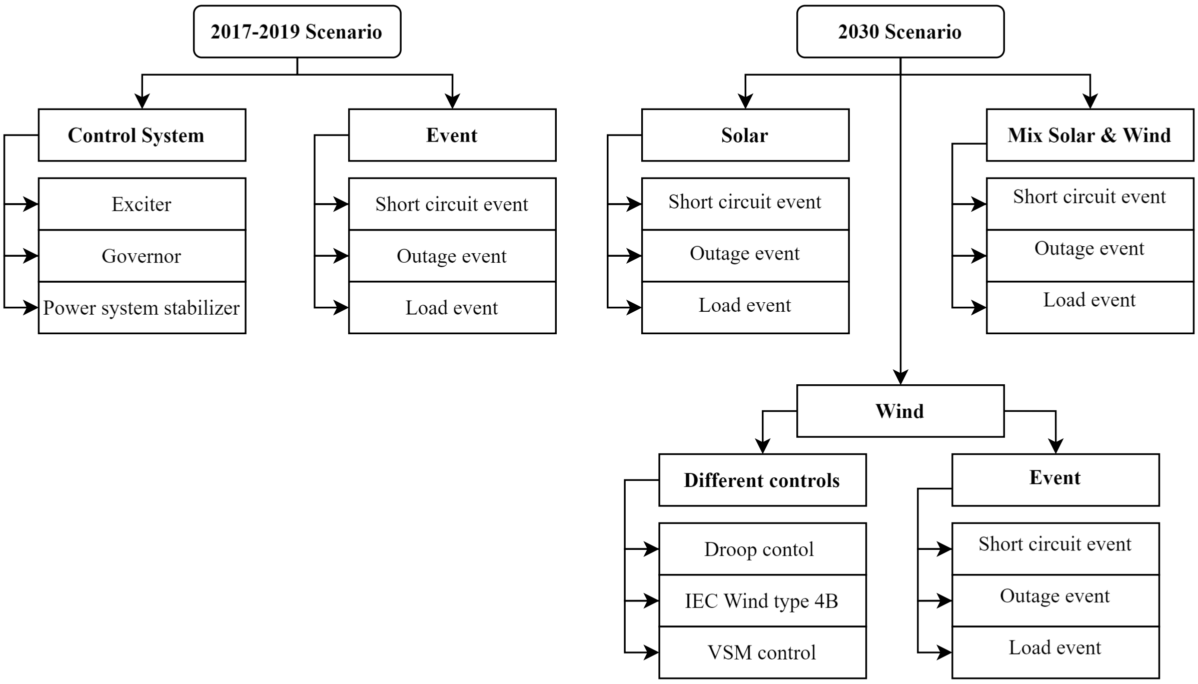



**Figure 4.1:** Case distribution of each scenario in the case study that is implemented

## 4.2. Initial Simulations for the Base Model

Initial simulations simulated a Power Flow using data from historical dispatches during peak demands of 2017 and 2018. This is done primarily in the original thesis to check whether the results of these historical dispatches will mimic the power flows in the actual Dutch power system. The peak demand power distributed in each region is according to the information found according to public sources. Synchronous generators are used to model gas, wkk, nuclear, and coal generation. Static generators are used for wind and solar generation.

The cases that are tested follow the depiction in Figure 4.1. The analyses discussed and the events introduced are as follows:

- **Exciter**: short circuit at terminal ZH150
- **Governor**: short circuit at terminal ZH150
- **Power system stabiliser**: short circuit at terminal ZH150

### 4.2.1. Peak Demand 2017

Initial load flow analysis is performed and the power system summary is studied. The system operates on a balanced condition for the given loading. Different events are introduced to the power system for initial simulations and the system response is recorded. Variables like Terminal voltage, speed, Active power, and Reactive power were examined. The events include the Short circuit event, Load event, and Generator outage event.

In order to test different control systems, a short circuit is introduced at t=4s to t=4.15s at the terminal ZH150. There are various types of generations attached to this terminal therefore a short circuit at this bus would be drastic and help in knowing its effect.

**Exciter**

Without the presence of an exciter, the exciter does not have a role in the event as there is no voltage drop.

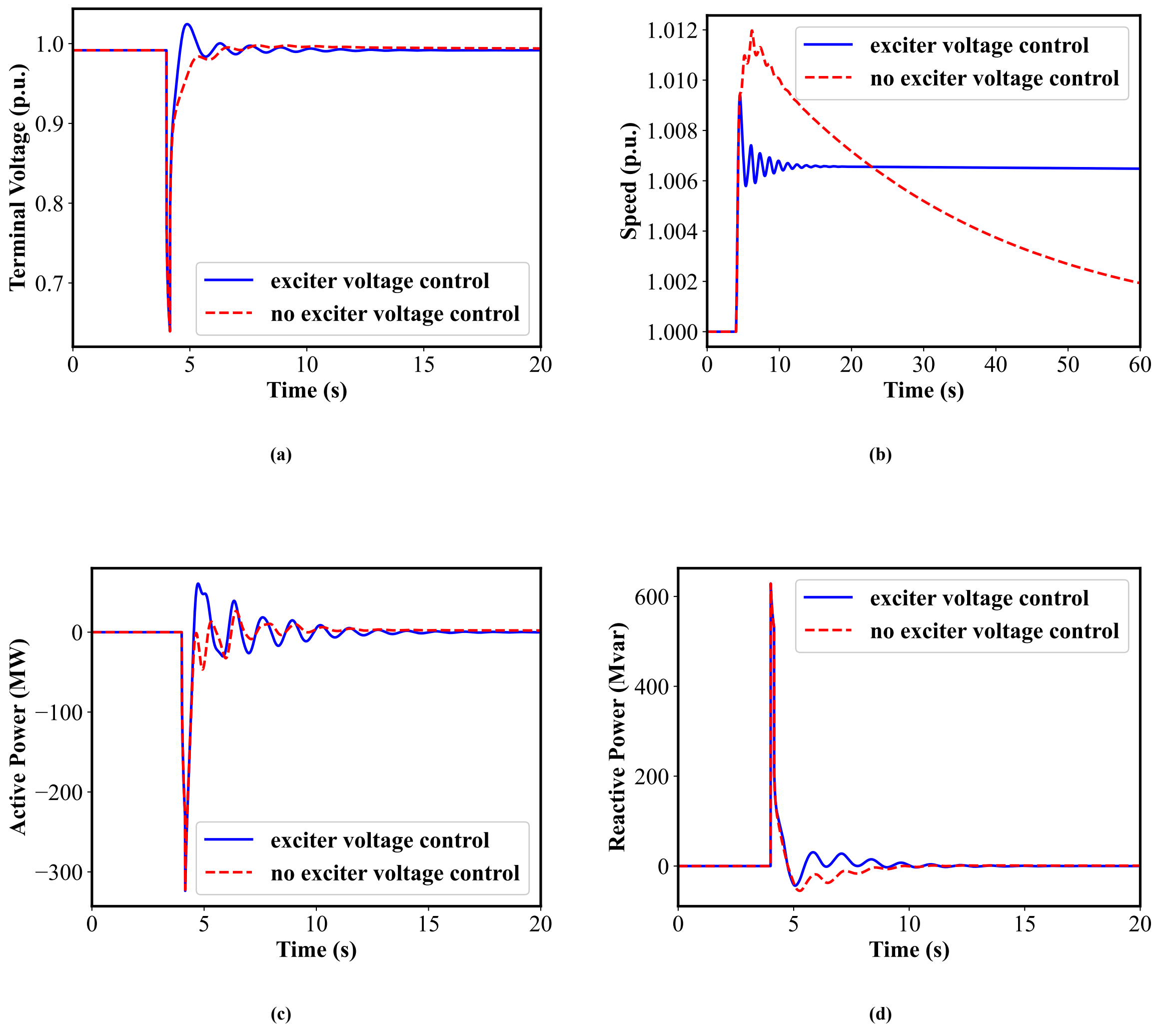



**Figure 4.2:** Different variable responses of synchronous generators with and without the Exciter

Immediately after the disturbance, the voltage comes back to the operating voltage after 0.15s. This can be observed in Figure 4.2a. It can also be seen, in Figure 4.2b, that due to the increase in voltage, speed also increases. When the current flow increases, the voltage drops. The system's exciter detects this voltage decrease and strengthens the magnetic field to restore the voltage to its desired level. However, without a speed governor, the speed decreases, as illustrated. From Figure 4.2c, it can be seen that there is a reduction in active power. When the active power reduces, the flow of excessive current through the faulted section can be avoided.

**Governor**

The governor provides primary speed control and therefore active power and frequency. Since frequency is a common entity throughout the system it is an important factor to control. A similar event as discussed before is introduced. There is no effect on the terminal voltage as can be seen in Figure 4.3a except for a reduction in oscillations. The speed regulation of the system decreases exponentially due to frequency deviation, can be seen in Figure 4.3b. However, in the presence of a governor, it controls the turbine speed and ensures that the generator maintains system frequency despite changes in terminal voltages that are otherwise dissipated.

The governor does not seem to have a significant effect on the active power. The curve shows a larger deviation than the case with a governor and similar to Reactive Power. During the absence of a governor, the generator lacks immediate response mechanisms to changes in system frequency caused by short circuits. However the system inertia that is inherent through the simulation allows them to maintain relatively stable active and reactive power outputs momentarily. Therefore the significant change is observed in the speed plot only.

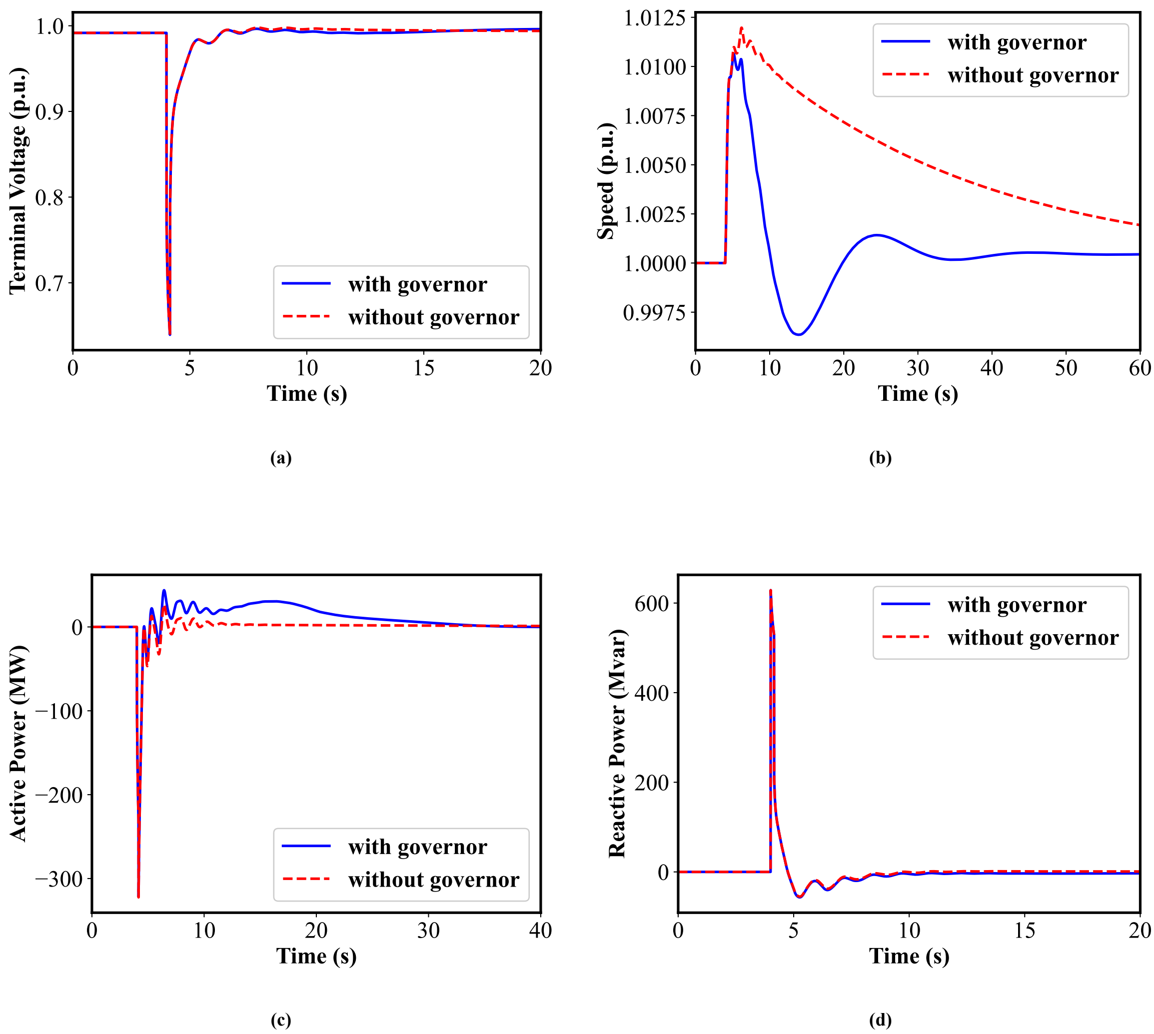



**Figure 4.3:** Different variable responses of synchronous generators with and without the governor

After the testing of addition of different control modules, three different event types are tested:

- **Short circuit**: A 3-phase short circuit at terminal ZH150

- **Generator outage:** An outage event at generator DG_GAS_NH15
- **Load event:** load event at load ZH150

**Short Circuit**
The plant in the captions refers to the Composite Model (Control systems) of the Synchronous Generator. The plots in Figure 4.4 show the responses in the presence of the full plant i.e., Exciter, Power system stabilizer, and governor.

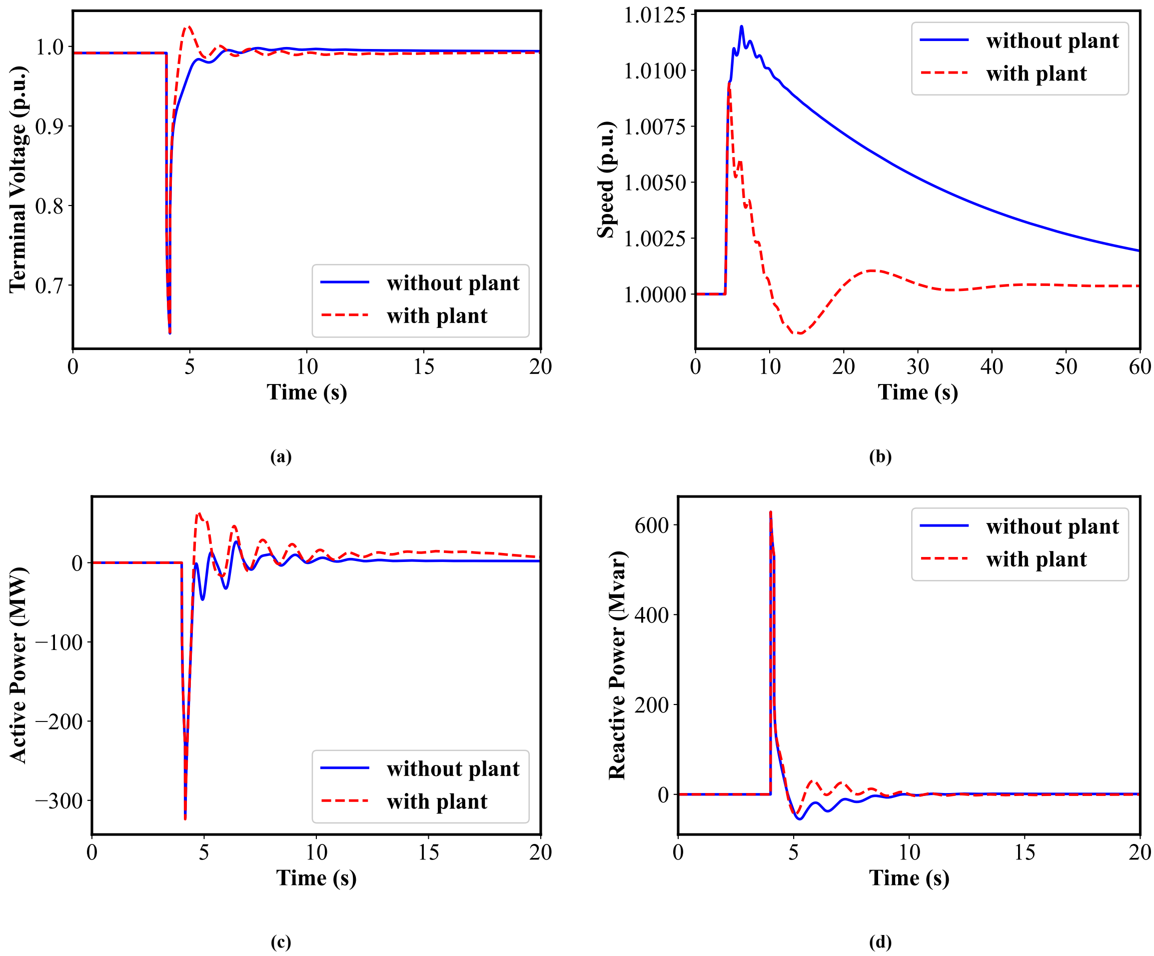



**Figure 4.4:** Different Variable responses of a Synchronous generator DG_BIOM/Coal_B15_2 with and without plant during a Short Circuit event from t=4s to t=4.15s.

Since a Short circuit event causes rapid frequency fluctuations, the system will be rendered unstable due to delayed responses. These can be seen in Figure 4.4b. With the composite model plant containing an exciter, governor, and PSS, the generator will attain enhanced control capabilities. Immediate adjustment of the field voltage results in stabilizing the terminal voltage. This is demonstrated in plots Figure 4.4a. The governor in the plant will regulate the turbine's mechanical power input avoids the exponential increase in speed and stabilize the oscillations much quickly. The speed response discussed can be seen in Figure 4.4b

**Generator Outage**
A generator outage event is introduced in at generator DG_GAS_NH15 at t=4s. In the Peak Demand 2017 scenario, the generator DG_GAS_NH15 dispatches an active power of 2256 MW and reactive power of 658 Mvar with a power factor of 0.96. Due to its significant contribution towards both dispatches, it is chosen to study the effects of the outage of this generator. The results are plotted in Figure 4.5.

As can be seen in Figure 4.5, the system is out of convergence after approximately t=50s. Due to the presence of a large number of nodes and routes, the effect of the outage event takes time to reach all relevant components resulting in the non-convergence at t=50s. Since the system is vast, it takes time for the fault information to propagate through the system. With the addition of the composite plant and controls, the mechanism in place detects and responds to the outage effectively. Since the controls have rapid fault detection, the response comes to a stable operating point immediately after the event.

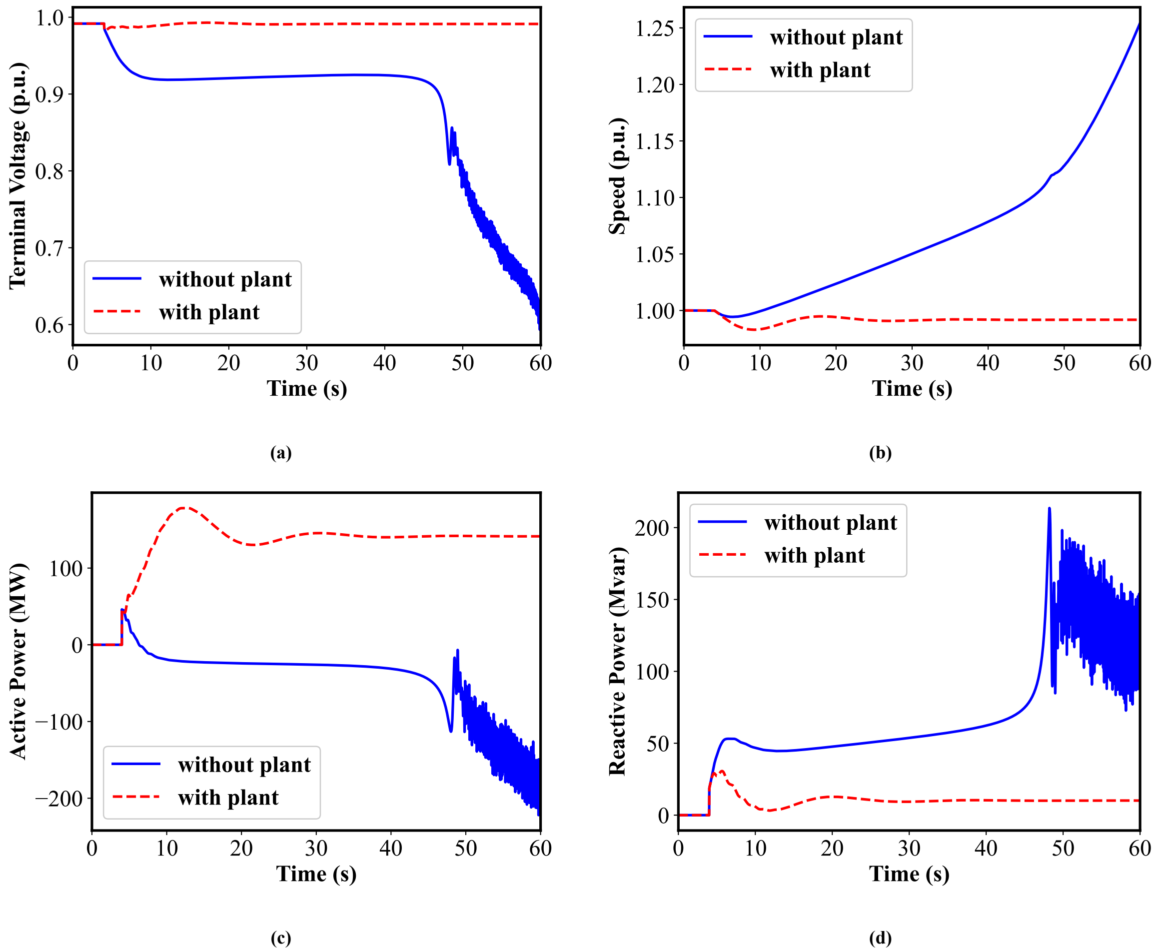



**Figure 4.5:** Different Variable responses of a Synchronous generator DG_BIOM/Coal_B15_2 with and without plant during a Generator Outage event at t=4s.

The plots are scaled according to the relevance of the time shown. If the power system reaches stability at an earlier transient, it is zoomed in to less time to see the variation. Similarly, the full-time period of 60s is shown when the power system takes longer to attain stable operation.

**Load Event**

At the terminal ZH150, a load event is introduced at load ZH150 for an active power increase of ±15. The load Load_ZH150 has an active power demand of 4131,3 MW. There is a sudden collapse in terminal voltage due to high load. But in the presence of a plant, the exciter maintains terminal voltage and ensures stability during load variations. The governor adjusts the turbine output to match load changes and maintain system frequency.

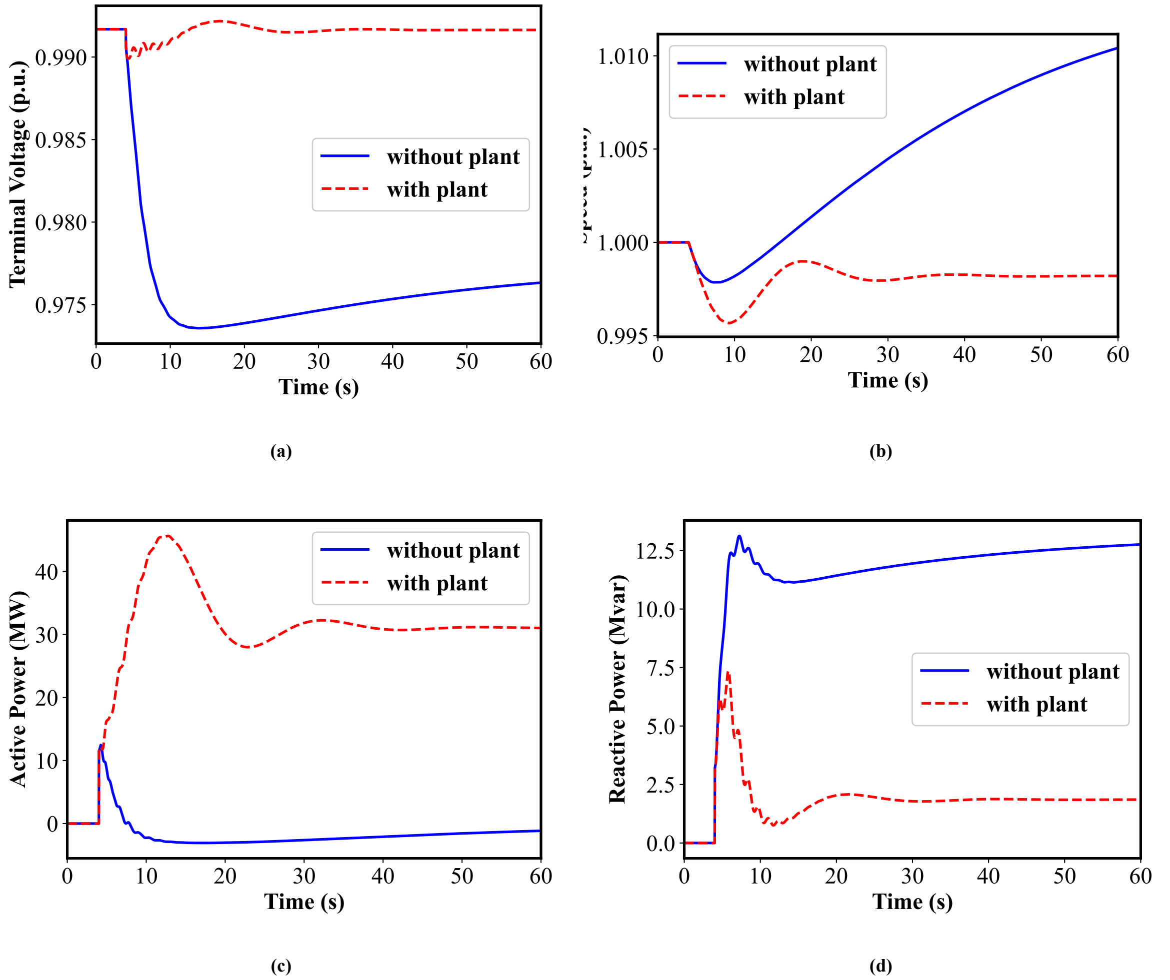



**Figure 4.6:** Different Variable responses of a Synchronous generator DG_BIOM/Coal_B15_2 with and without plant during a load event

**Table 4.1:** Comparison of control system responses to different events

| Event | Conclusion from Plot |
|---|---|
| Short Circuit | Exciter restores and regulates system voltage. The governor responds to the frequency changes and restores frequency within limits. But no significant deviation from when Dynamic modes are in and out of service |
| Load Event | The exciter's voltage control regulates the system voltage. Governor control adjusts the generator's output to match the transient changes in active power demand caused by load event |
| Outage Event | The sudden loss of generation or load caused by an outage event leads to voltage and frequency deviations. The exciter and governor respond to stabilize voltage and frequency. |

Testing includes Peak demand 2018 and Low demand 2019 cases, but results are similar to Peak demand 2017, so they're not discussed separately. Despite differences in peak demand and regional dispatch among the cases, dynamic response remains unaffected due to:

- **System Robustness:** The Dutch power system's robust design handles dispatch and demand changes well, ensuring consistent responses.
- **Control Mechanisms:** Advanced control mechanisms mitigate demand changes, enhancing system performance.
- **Parameter Insensitivity:** Certain model parameters are insensitive to peak demands and dispatches.

## 4.3. Description of Cases

A range of scenarios involving combinations of VRES generation, demand, and electrolyser distribution are considered for operational analysis. Table 2.1 outlines the optimal possibilities. It's important to note that the market should have access to 70% of the primary transmission power system's transfer capacity. Examples of selected cases for investigation include:

1. Case A: Wind as the only source of electricity generation for high demand
2. Case B: Solar as the only source of electricity generation for a high demand
3. Case C: A mix of high wind and some solar generation during peak demand

Three base cases were developed, in which the national system's generation and demand are balanced and there are no electrolysers. A0 represents solely wind generation, B0 represents solely solar generation, and C0 represents a combination of solar and wind generation. Interconnections are blocked since it is believed that the Dutch power system can function independently.

The cases are designed to evaluate various VRES penetration levels. A case includes variations of generation, demand, and imports or exports. Base cases include the participation of conventional generation, wind, and solar in different combinations. Additional cases include the introduction of electrolysers also in different combinations based on their locations.

## 4.4. Results of Case Study

In this section, different cases under the 2030 scenario are discussed. For each case, relevant iterative testing results are demonstrated with potential explanations of these plots. Only significant results are discussed, although all results can be generated using the Python code RMS_plots.py to test different scenarios.

### 4.4.1. Case A: Only Wind Generation

With the introduction of only Wind generation both on-shore and off-shore, three different control systems are tested. The responses of the Droop control system, Virtual synchronous machine, and IEC Wind Type 4B control systems are tested for different faults. A load event at Load_ZH150 is introduced with an active power load step of 15%. While the systems behave as predicted there are critical disturbances that the IEC type 4B control system is unable to handle.

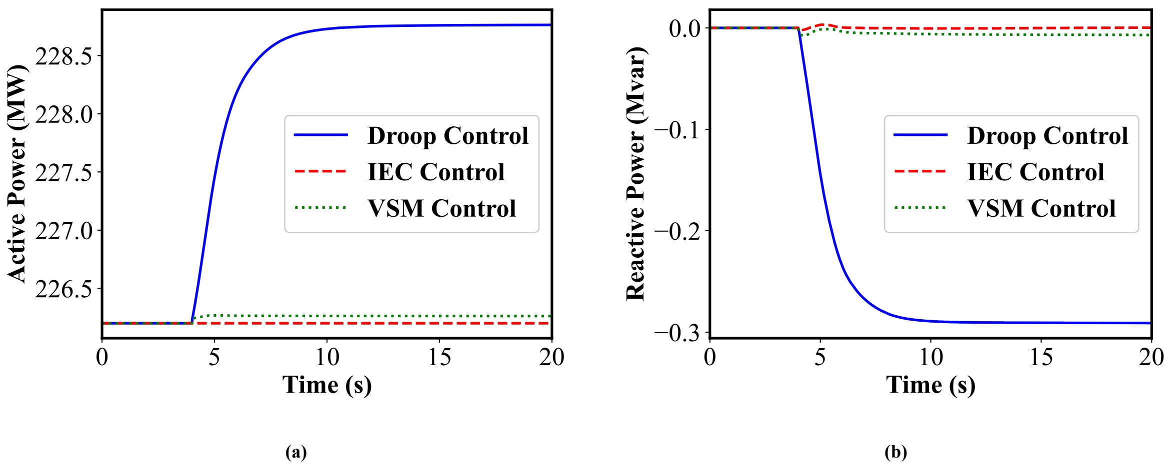



**Figure 4.7:** Plots demonstrating the active and reactive power response To different control systems in only wind case

**Table 4.2:** Description of case A. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = National generation minus Regional demand. The active power surplus is used to balance the power system losses. All values are for Active Power (P) in (GW).

| Case Type | Solar | Wind | Conv. Gen. (GW) | Regional Demand (GW) | P2x. Dem. (GW) | Import(-)/ Export(+)(GW) | Gen - Dem. (GW) | Active Power Surplus (GW) |
|---|---|---|---|---|---|---|---|---|
| **A0** | 0,0 | 16,2 | 0,0 | 16,0 | 0,0 | 0,0 | 0,2 | 0,2 |
| **A4** | 0,0 | 18,6 | 0,0 | 12,0 | 6,5 | 0,0 | 6,6 | 0,1 |

| Type of controller | VSM | Droop Controller | IEC WT Type 4B |
|---|---|---|---|
| **Theory** | Imitates the behavior of a Synchronous Generator | Imitates a Governor in SG, Maintains frequency and voltage stability by adjusting the output power | Ensures optimal power generation while adhering to power system code requirements and stability criteria |
| **Control** | A synchro-converter topology controls the inverter to generate an output voltage via embedding the mathematical model of SG into the controller of the inverter. | Generators respond to frequency or voltage deviations by adjusting their power output in proportion to the deviation | Combines active and reactive power control to achieve power system integration and stability |
| **Function** | Inertial Response Primary Frequency Controls | System frequency regulation both steady-state and transient | specifically for WT, stable power system integration |

### 4.4.2. Case B: Only Solar Generation

The base scenario B0 is without electrolysers where as B6 scenario is only solar generation with 10 GW electrolyser demand. B6 is chosen since among all the scenarios introduced, B6 is the most favorable scenario with electrolyser at MVL380 and EEM380 with a demand of 6,5 GW.

**Table 4.3:** Description of case B. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = National generation minus Regional demand. The active power surplus is used to balance the power system losses. All values are for Active Power (P) in (GW).

| Case Type | Solar | Wind | Conv. Gen. (GW) | Regional Demand (GW) | P2x. Dem. (GW) | Import(-)/ Export(+)(GW) | Gen - Dem. (GW) | Active Power Surplus (GW) |
|---|---|---|---|---|---|---|---|---|
| **B0** | 16,2 | 0,0 | 0,0 | 16,0 | 0,0 | 0,0 | 0,0 | 0,2 |
| **B6*** | 18,6 | 0,0 | 0,0 | 12,0 | 6,5 | 0,0 | 6,6 | 0,1 |

**Case B0: Short circuit Event**

B0, base case scenario with only solar generation is tested with a short circuit event at terminal GFU150 at t=4s to t=4.15s.

Solar power plants typically lack inertia therefore during a short-circuit due to the sudden voltage drop, the active power reduces rapidly. Also the absence of dispatch by synchronous generators, which usually contribute inertia and fault current support helps stabilize the power system during a short circuit event.

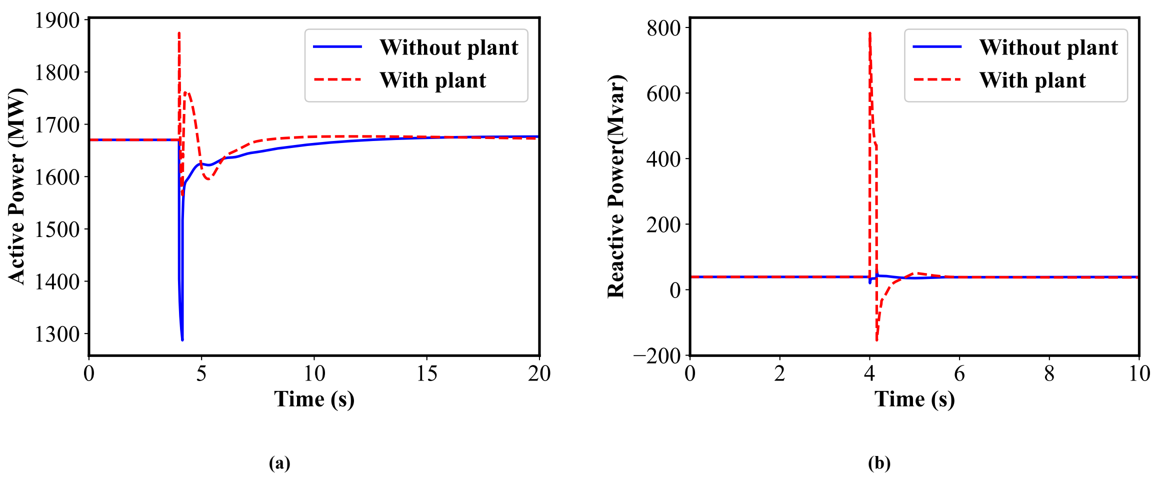
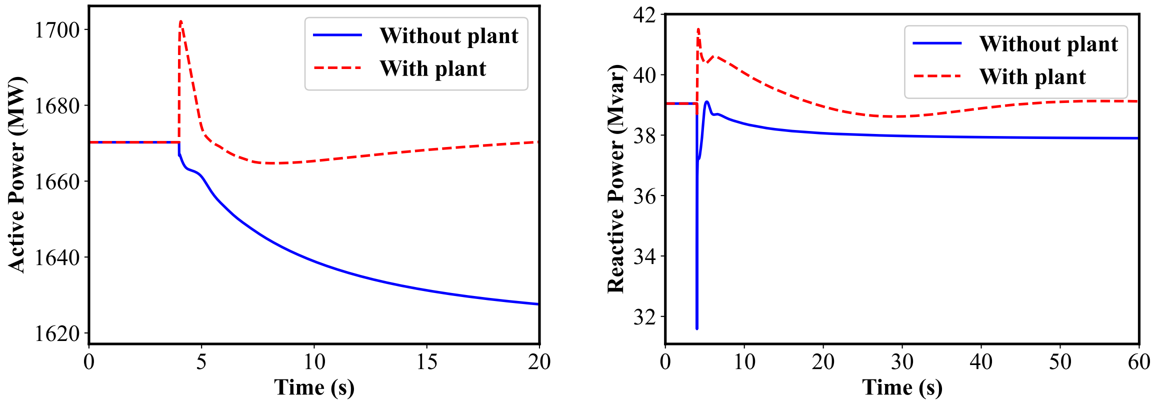



**Figure 4.8:** Active and Reactive power response of L_PV_B150 to Short circuit event at GFU150

However, Solar power plants are assigned local controllers to be a Constant V, which prioritizes voltage stability, and regulates the generator's voltage output to remain constant. This means that "local control" allows voltage regulation autonomously by the generator itself without the involvement of external commands from the power system operator or central control system. The almost straight response of reactive power is due to this reason. In the presence of a plant, the generator's excitation system (REEC_B) enhances voltage stability leading to a rapid increase in reactive power output.

**Case B0: Outage Event**

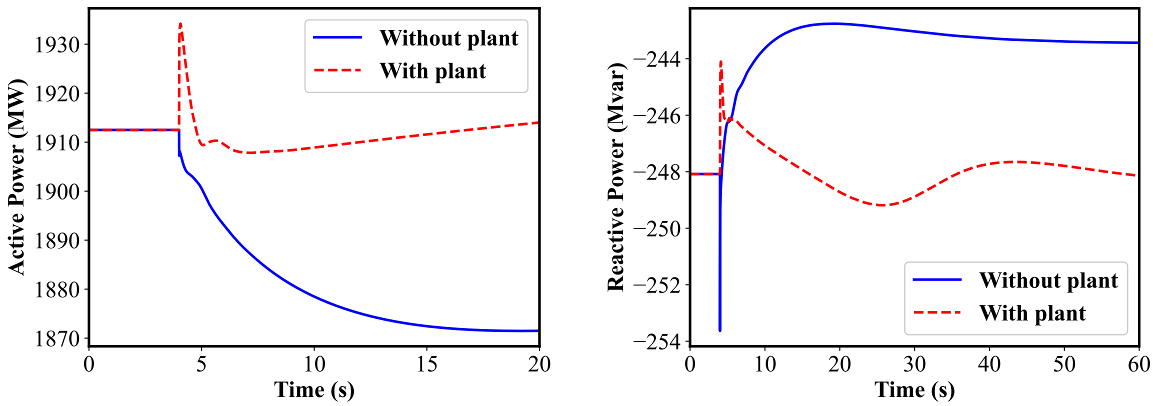



(a) (b)

**Figure 4.9:** Active and Reactive response of L_PV_B150 to Outage event

The Reactive power drop in Figure 4.9b decreases in the presence of a PV plant. But it takes more time to stabilize when compared to active power. During a Generator outage, the focus is more on frequency and active power, as can be seen in Figure 4.9a, the exponential decrease in active power is stabilized in the presence of a plant.

**Case B6: Outage event**




(a) (b)

**Figure 4.10:** Active and reactive power response of L_PV_B150 to Short circuit event

When compared to Case B0, due to the addition of electrolyser demand and PV plants, Case B6 has better power system-support features designed to stabilize active power during generator outages. The magnitude of the impact on reactive power is relatively low during a generator outage than that on active power.

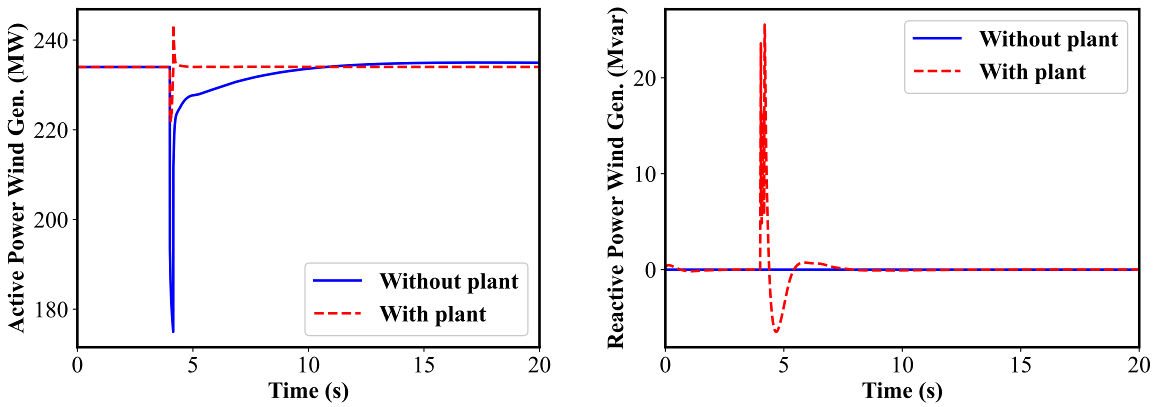
### 4.4.3. Case C: Mix of Solar and Wind

The Case C0 is simulated with a mix of solar and wind dispatches with 4,5 GW and 16,7 GW respectively. The reactive power setting for this scenario is Constant V for all solar plants, Constant Q for all wind plants, and Constant V for selected offshore wind farms. The ideal location of the Electrolyser is either in Eemshaven and Borssele (case C5) or in Maasvlakte and Eemshaven (case C6) according to initial power flows. Because only in these two cases there is no overloading of components. The electrolyser demand considered in this case is 10 GW whereas in the general demand was set to 21 GW. Solar generation is decreased in places where an electrolyser is introduced.

**Table 4.4:** Description of case C. Conv.Gen: Conventional Generation, Import/Export: Interconnections, P2x Dem. = Electrolyser Demand. Gen. - Dem = National generation minus Regional demand. The active power surplus is used to balance the power system losses. All values are for Active Power (P) in (GW).

| Case Type | Solar | Wind | Conv. Gen. (GW) | Regional Demand (GW) | P2x. Dem. (GW) | Import(-)/ Export(+)(GW) | Gen - Dem. (GW) | Active Power Surplus (GW) |
|---|---|---|---|---|---|---|---|---|
| **C0** | 4,5 | 16,7 | 0,0 | 21,0 | 0,0 | 0,0 | 0,2 | 0,2 |
| **C5** | 12,9 | 18,6 | 0,0 | 21,0 | 10,0 | 0,0 | 10,5 | 0,5 |

**Case C0: Short circuit event**




s

**Figure 4.11:** Active and reactive power responses of W_WOL_B150 to short circuit event

In case of a short circuit event at terminal GFU150, at approximately t=4.015s the system loses convergence after reaching a maximum number of outer-loop iterations for the power system model equations. The non-convergence lasts until t=4.162s event after the short-circuit is cleared.

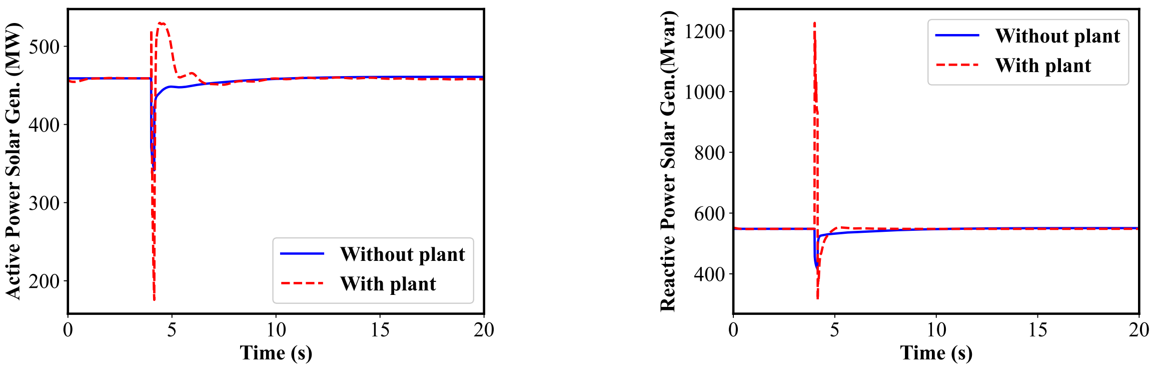
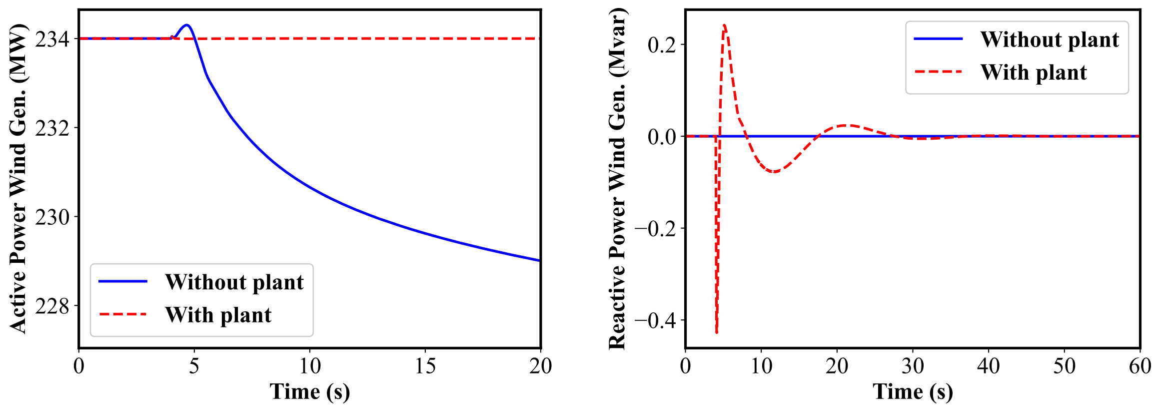



**Figure 4.12:** Active and Reactive power responses of L_PV_B150 to Short circuit event

**Case C0: Outage Event**

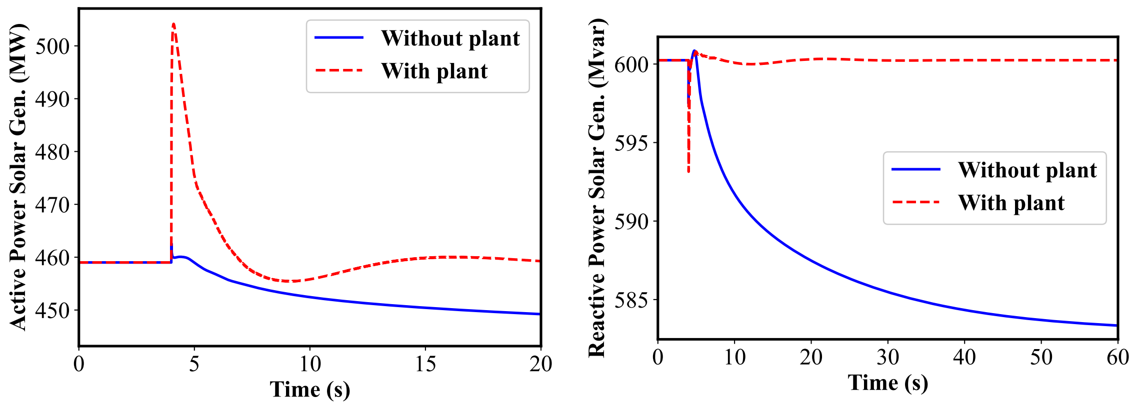
Outage event of a synchronous generator DG_GAS_NH15 is applied at t=4s. In Figure 4.13a, It can be seen that the plot with plant for wind systems is stable after the outage event as opposed to an exponential decrease in the active power in case of the absence of a control system. From Table 4.4, it can be seen that the synchronous generator does not contribute to the generation capacity. Therefore, the outage of a synchronous generator does not directly impact the available power supply. However, in a high VRES penetration system, sudden changes in renewable energy output can still cause frequency fluctuations. Without the stabilizing influence of the synchronous generator, the frequency may exhibit greater volatility, potentially leading to frequency excursions outside acceptable limits. As the generator is not actively generating power, it provides reactive power support to maintain voltage levels within acceptable limits.

When Figure 4.13b, and Figure 4.14b are compared, it can be seen that the outage event has more impact the Solar Generation since static wind generator operates in a constant Q control mode. When the plant for a solar system is active, after a drop, the reactive power stabilizes to its starting value.




(a) (b)

**Figure 4.13:** Active and reactive power responses of W_WOL_B150 to short circuit event

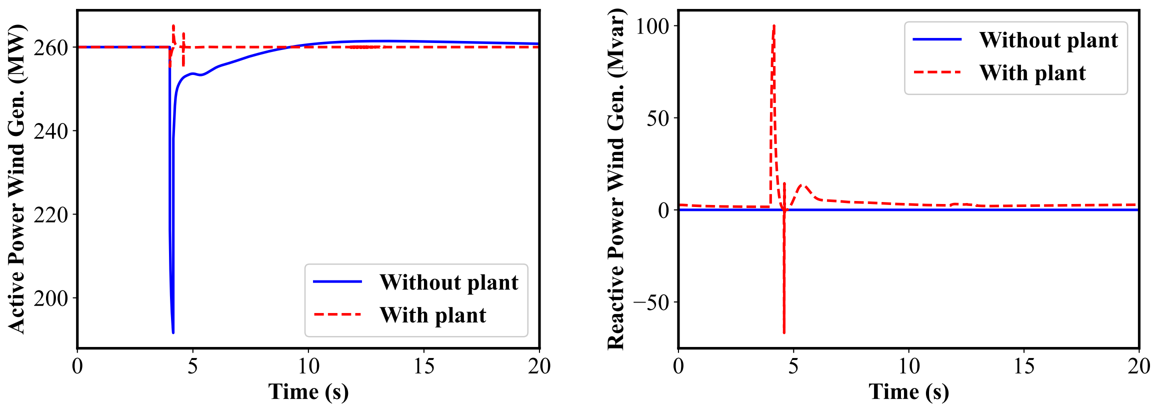



(a) (b)

**Figure 4.14:** Active and Reactive power responses of L_PV_B150 to Outage event

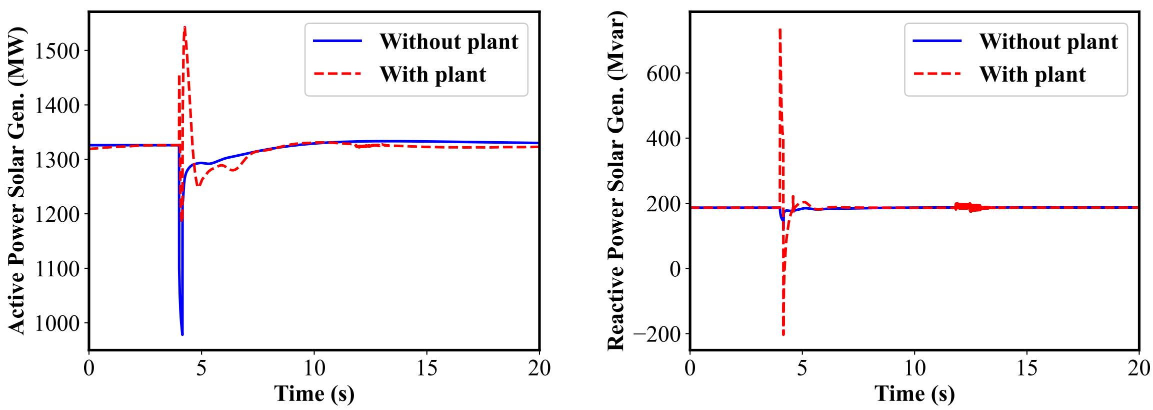
**Case C5: Short circuit event**

The system goes out of convergence similar to C0 case. During a transient event like a short-circuit, a heavy electrolyser demand of 10 GW is a heavy load on the power system. This heavy demand can lead to voltage and frequency fluctuations. The system is struggling to maintain convergence due to added electrolyser operation. The dynamic response of solar and wind systems is not as fast as synchronous generation. Following a short-circuit event, renewable energy sources are not responding quickly enough to restore system stability.




(a) (b)

**Figure 4.15:** Active and reactive power responses of W_WOL_B150 to short circuit event




(a) (b)

**Figure 4.16:** Active and Reactive power responses of L_PV_B150 to short circuit event

Graphs are shown on a smaller scale to have a clear indication on the sensitivity of the fault on the plant. The same goes for outage event. If the short circuit event lasts longer than 3 seconds, the system goes out of synchronism. the static generators get turned off.

## 4.5. Analysis of Critical Disturbances

**B6: Outage Event**

A significant amount of active power is consumed by the electrolyser demand of about 6.5 GW. The decreasing active power is a response to a continuous decrease in active power and the constant demand from electrolysers. Due to the lack of reactive power support (absence of wind generator dispatch), the PV system tries to maintain the voltage response within acceptable limits.

**C0: Outage Event**

The outage event serves as a stress test for the power system's resilience to sudden changes in generation. It highlights the system's ability to maintain stability and reliability in the absence of traditional synchronous generation sources, relying instead on renewable energy and other power system resources. With the synchronous generator offline, the ower system becomes more reliant on VRES sources such as solar and wind energy. Energy storage systems, such as batteries or pumped hydro storage, play a crucial role in stabilizing the power system by providing balancing services and smoothing out fluctuations in renewable energy output. Power system operators face challenges in managing the system during the outage event, ensuring that supply and demand remain balanced and that voltage and frequency remain within acceptable limits. Effective power system management strategies, including real-time monitoring, forecasting, and dispatch of VRES and storage resources, are essential to maintain system stability.

**C5: Short-circuit event**
To address the challenges associated with heavy electrolyzed demand and variable renewable generation, enhanced control and coordination strategies are required. This may involve the implementation of advanced power system control algorithms, energy storage systems, demand response programs, and flexible generation resources to mitigate the impact of disturbances and improve system convergence. The combination of heavy electrolyzed demand and mixed renewable generation can exacerbate the challenges of restoring system convergence after a short circuit event, highlighting the importance of robust power system management and control measures in high-renewable scenarios.

### 4.5.1. Frequency Stability

For Scenario 2030, frequency stability is discussed separately since the major integration of High Renewable Energy Sources has the majority impact on frequency. The Control techniques that are used address the frequency stability of converter-based sources.

**Rate of Change of Frequency (RoCoF)**
RoCoF is the rate of change of frequency. It is the frequency gradient after any event of active power generation or load demand. As shown in Equation 4.2, RoCoF is defined as the rate of change of frequency. It can be calculated in two ways: using Equation 4.2 and computing the slope of frequency decrease in a fixed time window like 0,5s after a disturbance.

$$RoCoF = \frac{df}{dt} \tag{4.1}$$

$$\text{RoCoF} = \frac{f \times \Delta P}{2\left(K_{\text{sys}} - K_{\text{lost}}\right)} \tag{4.2}$$

The frequency for cases A0 and A4 are represented with and without their corresponding plants in service. The numerical texts represented are their respective frequency NADIR values. As mentioned in Section 4.5.1, none of the frequency values are below the mentioned limits. However, for the A4 case due to the inclusion of electrolysers and wind, the initial stability before the event itself is lost.

**Frequency NADIR**
Frequency NADIR is the lowest frequency value obtained after a power imbalance. While implementing frequency control procedures, this metric is highly relevant to indicate when the system violates security thresholds which allows to avoid any consequences like blackouts. The lower limit of maximum admissible frequency deviation for Continental Europe is -800mHz which corresponds to a NADIR of 49,2Hz [40]. Frequency stability is satisfied when:

$$f_{NADIR} \geq f_{\text{min}} \tag{4.3}$$

The range of maximum admissible frequency deviation according to [41] is 47,5 Hz to 51.5 Hz.

The frequency for Case B0 and B6 is given in Figure 4.17. When compared to the wind-dominated case, which had very minute frequency deviations, the solar case shows significant deviations due to an outage event. Since each of the generators has a large dispatch considering that only 9 generators are installed throughout the power system an outage at a single terminal has a huge impact. However, the deviation still falls under the admissible maximum deviation limits. The case without plants does not reach a higher frequency limit. With the presence of plants, the control will automatically take over to match the generation with demand to match the reduced generation with the increased demand which explains the sudden surge in frequency.

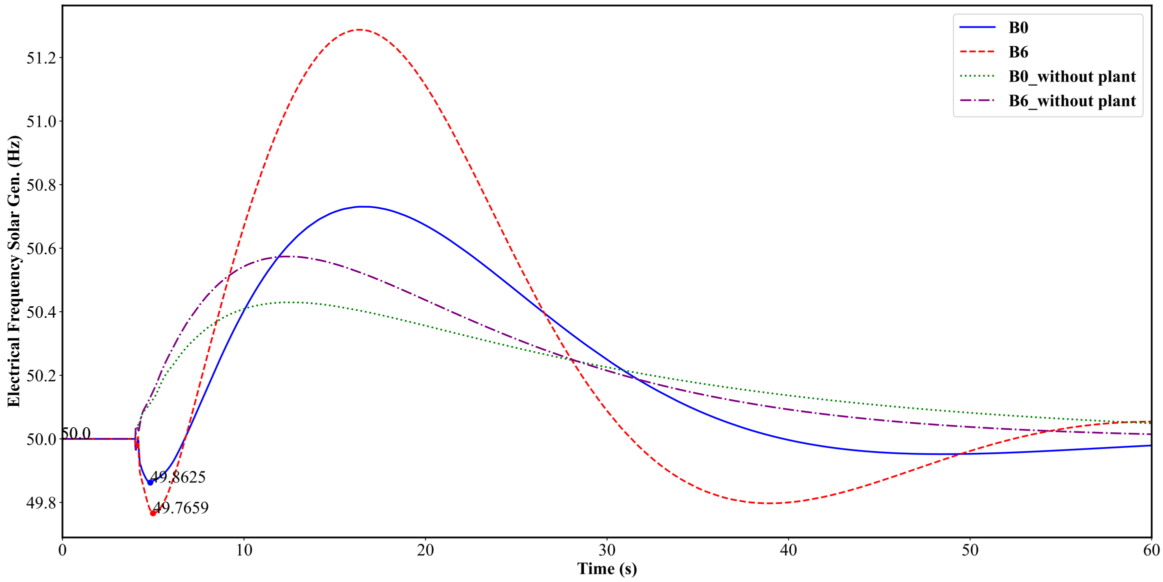



**Figure 4.17:** Variation of frequency for case B0 and B6 with NADIR indication in each case

Only the frequency output of the wind generator is given for the C) and C5 cases which seemed to show peculiar results. In the presence of plants in both cases, the frequency seems to be increasing rapidly and will probably keep increasing. The case has a mixed generation of both solar and wind with and without electrolysers.

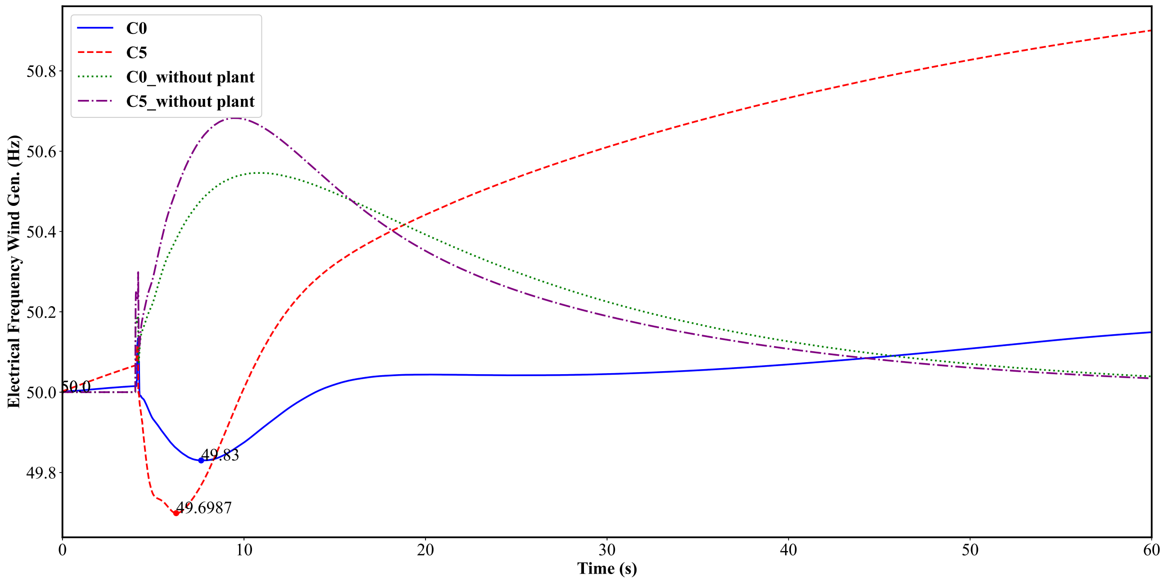



**Figure 4.18:** Variation of frequency for case C0 and C5 with NADIR indication in each case for wind generator

## 4.6. Assessment of Voltage Stability Performance

Rapid changes in the European electricity sector led to a rise in uncertainty and unreliability of the power exchange and flow. DSA is an important tool that helps in Real-time monitoring and enhancing stability.

Assessment of Voltage Stability Performance evaluates the ability of the power system to maintain acceptable voltage levels under normal operating conditions and during disturbances, ensuring the system's reliability and security by identifying potential vulnerabilities and implementing necessary corrective actions. Since synthetic models could offer real-time data acquisition, DSA became a major application and sought-after research topic.

Transmissions have heavily increased in today's bulk power system. Therefore, there is a critical need to determine transient security either in an offline or online environment. Fundamentally, each TSO monitors the dynamic stability of the transmission system and sends relevant data to other TSOs.

Initially, the methodology was developed under the assumption that some level of human interaction is necessary during computations [42]. Even in the presence of very advanced computers, certain simulation methods are deemed too slow to send stability margins and sensitivity details to determine power transfer and mitigation.

Artificial intelligence and machine learning techniques have emerged ever since and are used to analyze huge amounts of data to identify patterns and propose preventative measures [43]. Mostly used online security analyses alerts the dispatcher/operator to conditions that pose a significant risk to system security and provide parameters to determine a decision [44]. This will help to provide reliable power supply to the user which is the priority next to maintaining system security. The key is taking right action at the right time to keep the power system in safe operation.

### 4.6.1. Methodology

In the current thesis, most of the analysis of critical cases and disturbances is done visually using Time-domain simulations. The behavior or the system according to the variable responses compared to the presence and absence of dynamic control systems is done. The numerical analysis allows to establish the behavior of the system precisely using performance indicators.

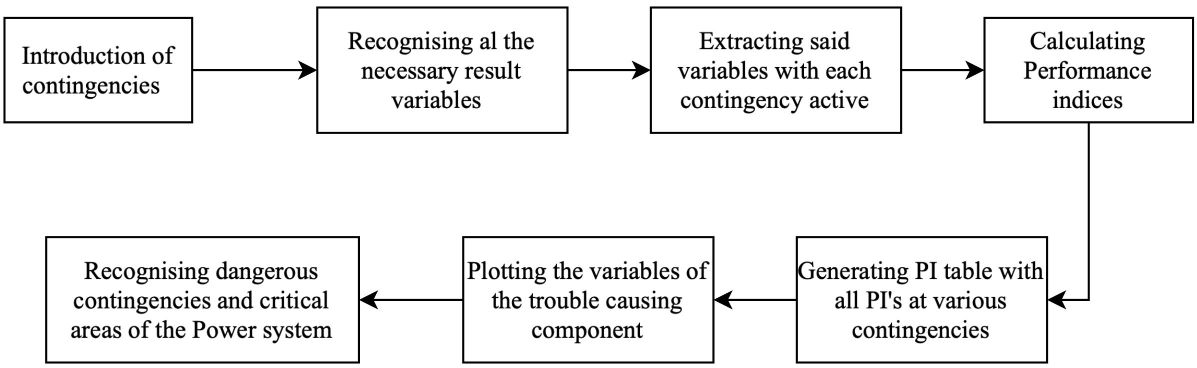



**Figure 4.19:** Methodology used for Voltage Stability performance tests

In Figure 4.19, the methodology used to perform the Voltage Stability Performance tests is discussed. Initially, contingencies that are prevailing in the current Dutch power system are chosen and introduced in the power system. The necessary variables that are important to calculate the performance indices are recognized. The Section 4.6.3 discussed the performance indices. These variables are extracted using the Python script after introducing each contingency. The exported results are used to calculate performance indices in MATLAB. A .csv file is generated in MATLAB that exports all Performance indices at various contingencies. The Index of each event is studied to find the components that are causing instability. The variables at these trouble-causing components are plotted to finally show the behavior of said component in case of an event. Finally, this allows us to recognize critical contingencies and vulnerable areas of the transmission system and suggestions to mitigate it.

In Figure 4.20, the interaction between different programs that are involved while performing the assessment is given. The events are added using the Python script in PowerFactory immediately after the Python file is executed in the PowerFactory. the dynamic simulations are performed for each event at every component. The .csv files are exported from PowerFactory and stored in File Explorer with specific file names. Then MATLAB should be launched by the user and the script should be executed. This script reads all the .csv files from the file

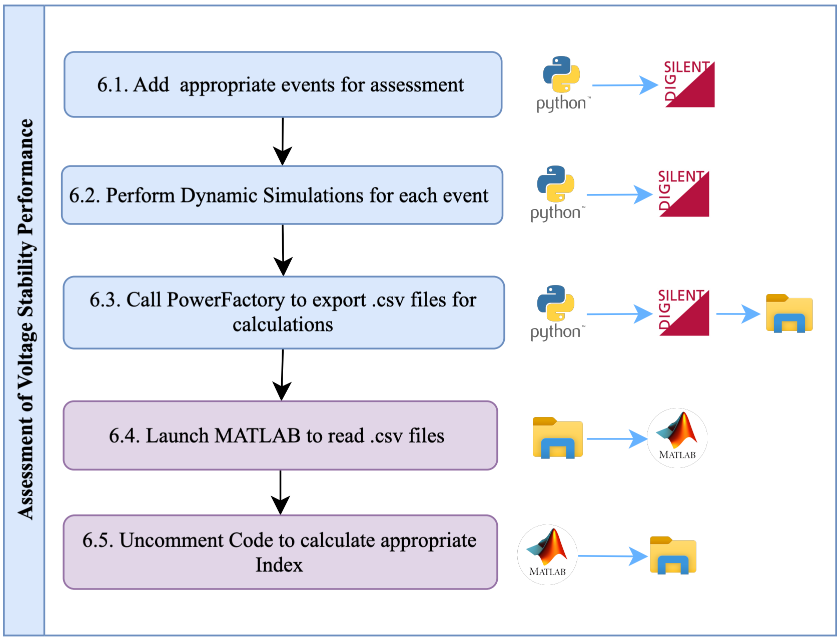



**Figure 4.20:** The interaction between different programs while executing the python script for voltage stability

explorer and calculates Performance indices. Then the Python script plots can be run in Python to plot necessary variables relevant for discussion.

**Table 4.5:** Minimum and Maximum admissible voltage limits in the power system [45]

| kV level | v_min (p.u.) | v_max (p.u.) | Delta_v_min(%) | Delta_v_max(%) |
|---|---|---|---|---|
| **380kV** | 0,9 | 1,05 | -10 | 5 |
| **220kV** | 0,9 | 1,1 | -10 | 10 |
| **150kV** | 0,9 | 1,18 | -10 | 11,8 |
| **110kV** | 0,9 | 1,18 | -10 | 11,8 |
| **15kV** | 0,9 | 1,1 | -10 | 10 |

### 4.6.2. Introduction of Contingencies

and also changing loads if necessary and if not discussed in previous sections.

Various events are introduced in the power system. Ranging from Short circuit events to generator outages, they vary in location and duration of the event. The type of events varies for the Conventional Generation scenario and High Renewable Energy Sources Integration scenario. To test the Dynamic Security of the power system, each event is introduced on every edge element. This helps to find the element, zone, and area of the power system that is vulnerable to voltage instability and subsequently power system collapse.

- Short Circuit event at Terminals
- Short Circuit event at Lines
- Outage Event at Synchronous Generators
- Load event at the Loads

To obtain the results that can be predicted for future demand profiles, there have to be additional energy storage solutions like Battery Energy Storage Systems to accommodate the hourly change in load. But the additional modelling involved for implementing this is out of the scope of this research. Therefore, the voltage stability performance analysis discusses the 2017 scenario majorly which is not VRES dominant.

In the current thesis, the results discussed are the Short Circuit event at terminals as significant changes were observed in this contingency. Any event that is tested at lines would give a stable indication as the system is very robust. A short-circuit event at the lines would not have an effect due to parallel flows unless both the transmission lines fall out of commission which would be a very unlikely scenario. While the code is equipped to perform the voltage stability test for any event in any power system, only the most significant results will be discussed in Section 4.7.

### 4.6.3. Performance Indices

Performance indicators are calculated by analyzing the transient behavior of the system parameters. In a given operating state, the amount of effect on parameters is quantified during a contingency. If the system remains stable or will ”survive” following a disturbance, the power system is secure. Also, the system should be able to not cause another outage during an event that could lead to a complete blackout [46]. These indices are designed using the following criteria:

- Unsatisfactory system performance is associated with significant fluctuations in system parameters, notably voltages and frequency.
- After a disturbance, the system trajectory will ultimately stabilize at an acceptable steady-state condition.

**Angle Index**

Typically generators are equipped with protections that will avoid asynchronous operation. This protection adjusts itself so that the load angle of the generator does not exceed the maximum admissible angle as per the relay. This is taken as $120^\circ$ . The angle index is calculated as the minimum of 1 and the ratio of the maximum deviation of the load angle of generator $i$th during the simulation time to the maximum admissible load angle given by the protection relay [46].

$$AI = \min\left\{1, \max_{i=1\ldots NG}\left(\frac{\delta_{ci,\max}}{\delta_{c,\max,\text{adm}}}\right)\right\} \tag{4.4}$$

**Maximum frequency deviation index**

It clearly represents the dynamic effect produced by the contingency analyzed on the system. The more the maximum frequency deviation, the higher disturbing effect that is produced by the event. The MFDI is calculated as the maximum frequency deviation relative to the maximum admissible frequency deviation. Ranging from 0 to 1, this index informs when there is no frequency deviation it is 0, and 1 means that it has reached the maximum frequency deviation [46].

$$MFDI = \min\left\{1, \max_{i=1\ldots NG}\left[\frac{|\Delta f_{i,\max}|}{\Delta f_{\max,\text{adm}}}\right]\right\} \tag{4.5}$$

**Total Frequency Deviation Index (TFDI)**

This index focuses on the time during which the frequency remained out of its rated value. It is calculated as the quotient between the area of frequency deviation and the maximum admissible area of frequency. Similar to MFDI, the range of variation of this index is 0 to 1, where 0 means no variation in frequency and 1 means that the frequency remained at its maximum admissible value during the simulation time [46].

$$TFDI = \min\left\{1, \max_{i=1\ldots NG}\left[\frac{\int_0^{ts}|\Delta f_i(t)|\,dt}{\Delta f_{\max\,.\,\text{adm}} ts}\right]\right\} \tag{4.6}$$

**Dynamic Voltage Index (DVI)**

For voltage transient, at no point during an RMS simulation except for during a fault should the voltage level remain less than a certain limit. These limits are mentioned in Table 4.5. Except during a short-circuit analysis, during which the voltage drops below the admissible levels and triggers the index [46].

$$DVI = \min\left\{1, \max_{i=1\ldots N}\left[\frac{V_n - v_{i,\min}}{V_n - v_{i,\ \min,\text{adm}}}\right]\right\} \tag{4.7}$$

**Quasi-Stationary Voltage Index (QSVI)**

QSVI takes into account the voltage recovery and control of the node voltage at the end of the transient period following a contingency. It is the index that is mostly discussed in the following sections due to its quantification of the node voltage control following a disturbance. It is calculated as the quotient between voltage deviation at the end of the transient period and the maximum voltage deviation limit [46].

$$bQSVI = \min\left\{1, \max_{i=1\ldots N}\left[\frac{|\Delta v_{i,\text{aft}}|}{|\Delta v_{i,\text{lim}}|}\right]\right\} \tag{4.8}$$

**Power Flow Index (PFI)**
This index finds if there is an excess of power flow through the lines during a contingency. Due to thermal limits, the power flow through the transmission lines can be limited. The value of PFI is 1 when at least one line of the power system the power flows reaches its maximum value. This will trigger the protection in the line and cause an outage [46].

$$\begin{aligned} PFI &= \frac{1}{\text{NL}} \sum_{i=1}^{\text{NL}} w_i \left( \frac{P_{i,\text{aft}}}{P_{i,\text{lim}}} \right)^n, \quad \text{if } P_{i,\text{aft}} < P_{i,\text{lim}} \quad \forall i \\ PFI &= 1, \text{ if } \quad \exists \quad P_{i,\text{aft}} \geq P_{i,\text{lim}} \end{aligned} \tag{4.9}$$

**Load Shedding Index (LSI)**
In order to compensate for lost generation during an unexpected generator outage or loss of generation or unexpected line outage, the load is disconnected. Depending on the magnitude of unbalance the amount of load is disconnected. The is calculated as a quotient between the total disconnected load and the total demand of the system [46].

$$LSI = \frac{P_{\text{shed}}}{P_{\text{total}}} \tag{4.10}$$

**Table 4.6:** Parameters to be extracted from the model to calculate performance indices

| Parameters | Definitions |
|---|---|
| $\delta_{ci,\text{max}}$ | Maximum deviation of the load angle of generator $i$ during the simulation time |
| $\delta_{c,\text{max,adm}}$ | Maximum admissible load angle given by protection relay |
| $NG$ | Number of generators operating in the system |
| $\Delta f_{i,\text{max}}$ | Maximum frequency deviation |
| $\Delta f_{\text{max , adm}}$ | Maximum admissible frequency deviation |
| $\Delta f_i(t)$ | Temporal deviation of frequency |
| $V_n$ | Rated voltage |
| $v_i$, min | Minimum instantaneous voltage $i$th during the transient |
| $v_{i,\text{min,adm}}$ | Minimum admissible voltage value |
| $\Delta v_{i,\text{aft}}$ | Post-contingency voltage deviation on node $i$th |
| $\Delta v_{i,\text{lim}}$ | Maximum voltage deviation limit |
| $P_{i,\text{aft}}$ | Power flow through the line $i$th at the end of the transient period following the contingency |
| $P_{i,\text{lim}}$ | Power-flow limit taking into account the strictest restriction (thermal limit, voltage limit or stability limit) |
| $n$ | Norm, which is used to reduce the contribution to the PFI index of lines that have not reached their limits |
| $P_{\text{shed}}$ | Total disconnected load |
| $P_{\text{total}}$ | Total demand of the system |

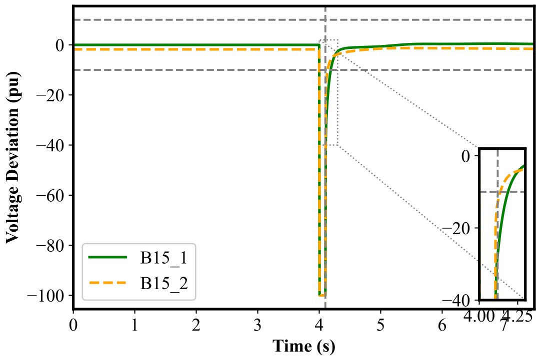
The MATLAB script designed allows to calculate all the indices mentioned in above. However, due to the restrictions around these indices regarding the usage during short-circuit events where the voltage needs to remain under certain limits [46], only $QSVI$ is used to analyse vulnerable buses of the model.

## 4.7. Voltage Stability Performance Results

The Quasi-Stationary Voltage Index (QSVI) is calculated as the minimum of 1 and maximum ratio of post-contingency voltage deviation to the maximum admissible voltage deviation limits. After taking the upper and lower limits of each terminal as inputs, the maximum ratio is calculated for each event. If the minimum value out of 1 and the maximum ratio is 1, the voltage levels seem to exceed the normal deviation values. In a MATLAB script whenever the bus is responsible for the cause of instability, it triggers a flag and the index of this bus is recorded. The behavior of this cause bus during an event at the affected bus is plotted in Figure 4.21.

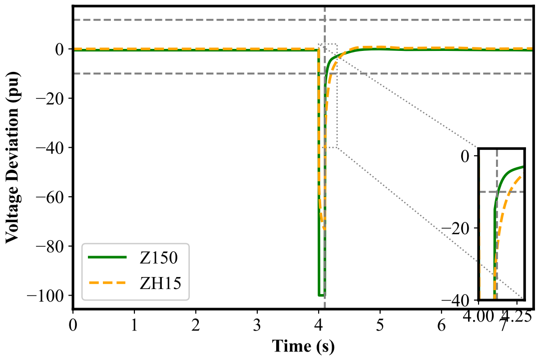
In each plot, the behavior of voltage deviation of two terminals at different voltage levels are shown. In the plots, the upper and lower limits of voltage deviation for each voltage level are plotted. With a vertical line at t=t_contingency_clear. The goal of these plots is to show the terminals that cannot bounce back to the admissible voltage deviations and are cause of the instability of the power system when there is an event at the event bus.

**Peak Demand 2017**



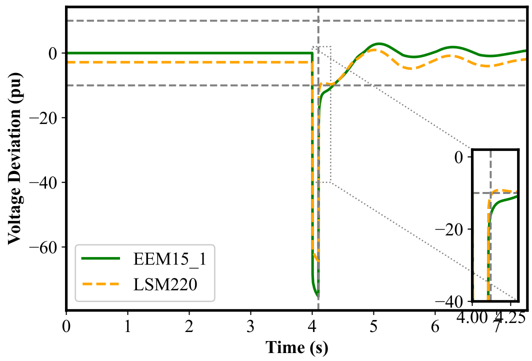

**(a)** 2017 STATCOM 15kV Scenario

| Event Bus | Cause Bus | QSVI |
|---|---|---|
| B15_1 | B15_1 | 1.000000 |
| B15_2 | B15_2 | 0.726141 |



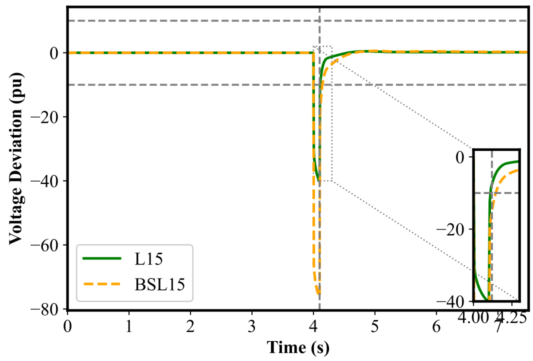

**(b)** 2017 STATCOM 150kV Scenario

| Event Bus | Cause Bus | QSVI |
|---|---|---|
| Z150 | Z150 | 0.851279 |
| ZH150 | ZH15 | 1.000000 |




**(c)** 2017 STATCOM 220kV

| Event Bus | Cause Bus | QSVI |
|---|---|---|
| EHA220 | EEM15_1 | 1.000000 |
| ENS220 | LSM220 | 0.755295 |

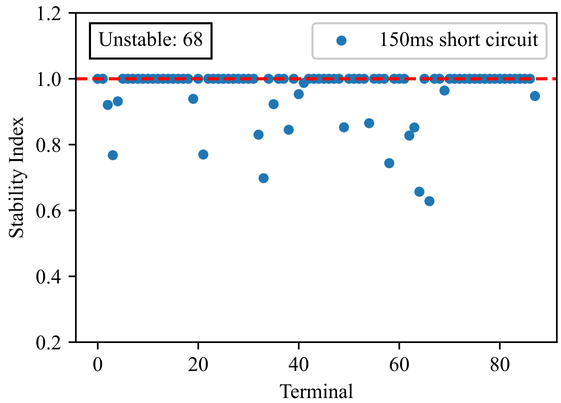



**(d)** 2017 STATCOM 380kV

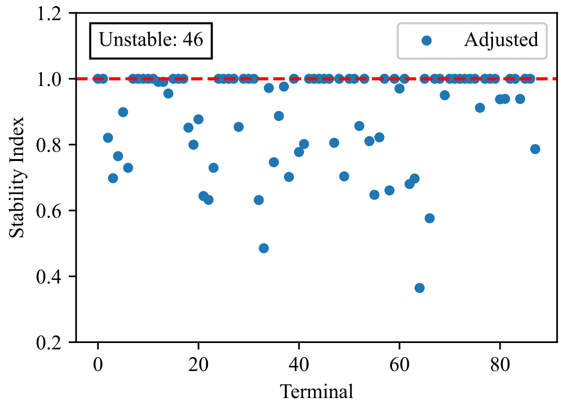
| Event Bus | Cause Bus | QSVI |
|---|---|---|
| BMR380 | L15 | 0.577486 |
| BSL380 | BSL15 | 1.000000 |

**Figure 4.21:** Comparison of Voltage deviation behavior between a stable and unstable bus of different voltage levels 2017 scenario

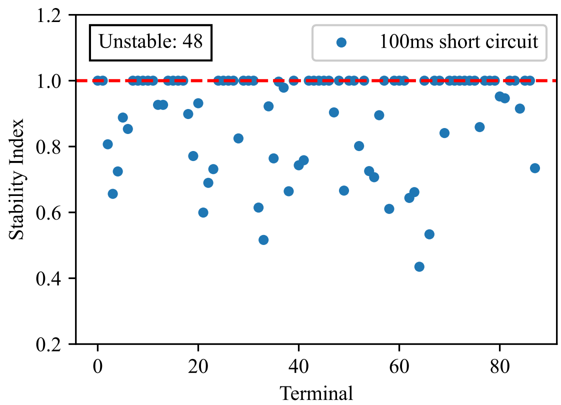
While in most cases the result of a Short-circuit event is an unstable power system, the areas most vulnerable to this are filtered. For a regular dispatch with Peak Demand in 2017, There are 68 unstable busses out of a total of 88 busses. From the 1st plot in Figure 4.22a, it can be seen that most of the busses are prone to causing instability in the power system. The number of buses that are at QSVI < 1 is very limited. Therefore the duration of the short circuit is decreased from 0.15s to 0.10s. As can be seen in the 2nd scatter plot in 4.22a, the number of unstable busses is 48. The major reason for this huge number of unstable buses is because of the insufficient Reactive power dispatch at each terminal. This will cause the terminal voltage to drop beyond the allowed limits in the power system. The reactive power dispatch for each generator is determined by performing a load flow analysis. The maximum reactive power is taken from the installed capacities. Reactive power headroom at each generator is calculated from Q_max and Q_real. The new values of adjusted reactive power are arbitrarily dispatched with values within Q_headroom.



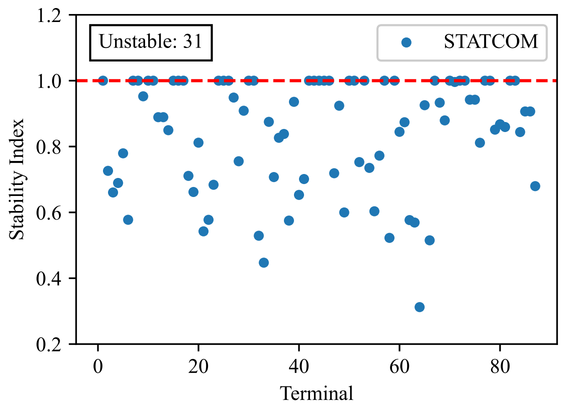

**(a)** Original Peak Demand 2017 dispatches




**(b)** Reduced time duration of event




**(c)** Adjusted 2017 dispatches



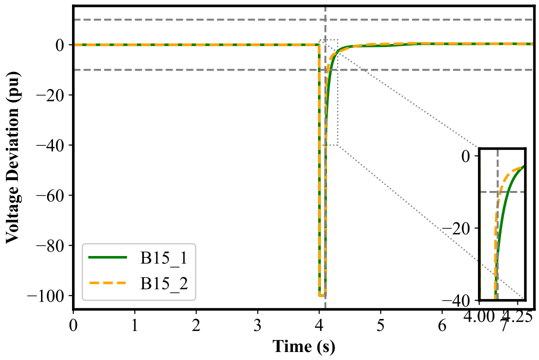

**(d)** After the addition of STATCOMs

**Figure 4.22:** Depiction of number of Unstable busses for 2017 scenario in different situations. The Blue dots represent the buses that resulted in an unstable terminal when the event is added with mentioned conditions.

QSVI is calculated as the ratio of maximum post-contingency voltage deviation at every terminal to the permissible voltage deviation at that kV level. These values are mentioned in Table 4.5. STATCOMs are known for their ability to provide fast and flexible voltage support. By injecting or absorbing reactive power as needed, STATCOMs can help regulate bus voltages and mitigate voltage instability issues, thereby reducing the likelihood of bus instability. Therefore they are added at locations B150, BSL380, DIM380, EOS380, L150, and NH150. They are chosen as the most voltage instability-prone terminals after multiple iterations of security assessment. 46 still is a very high number of unstable busses, STATCOMs are added to stabilize the busses with low voltage response.

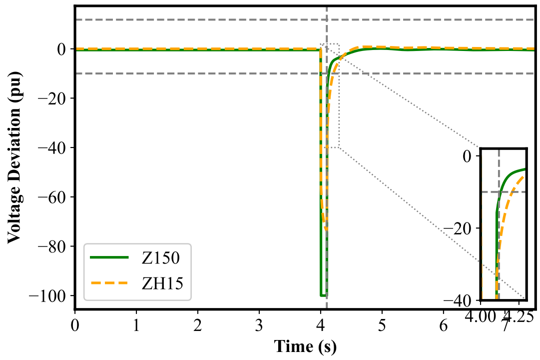
**2018 and 2019 Scenario**

While events like Transformer outages and Generator outages are unpredictable, short-circuit events at each terminal is examined more closely and for different dispatches.



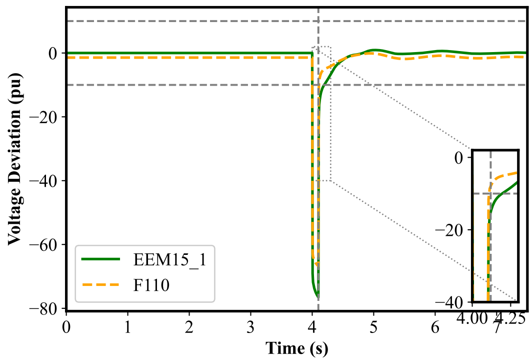

**(a)** 2018 STATCOM 15kV

| Event Bus | Cause Bus | QSVI |
|---|---|---|
| B15_1 | B15_1 | 1.000000 |
| B15_2 | B15_2 | 0.773792 |



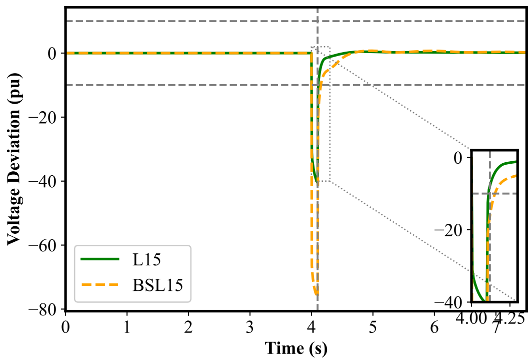

**(b)** 2018 STATCOM 150kV

| Event Bus | Cause Bus | QSVI |
|---|---|---|
| Z150 | Z150 | 0.902042 |
| ZH150 | ZH15 | 1.000000 |




**(c)** 2018 STATCOM 220kV

| Event Bus | Cause Bus | QSVI |
|---|---|---|
| EHA220 | EEM15_1 | 1.000000 |
| ENS220 | LSM220 | 0.576268 |

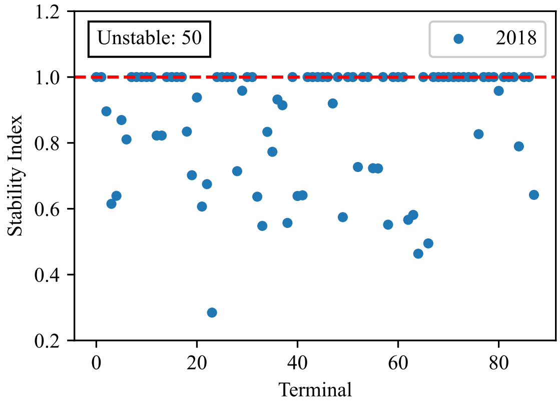



**(d)** 2018 STATCOM 380kV

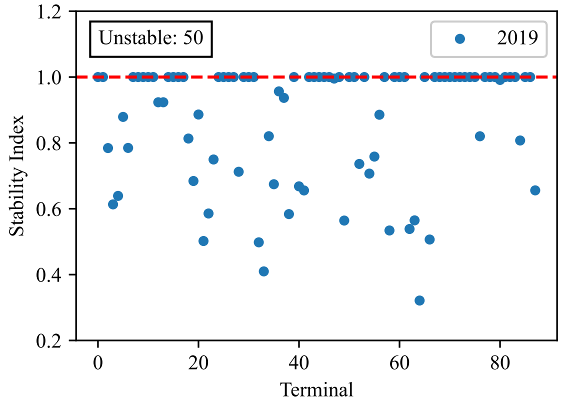
| Event Bus | Cause Bus | QSVI |
|---|---|---|
| BMR380 | L15 | 0.594484 |
| BSL380 | BSL15 | 1.000000 |

**Figure 4.23:** Comparison of Voltage deviation behavior between a stable and unstable bus of different voltage levels 2018-2019 scenario

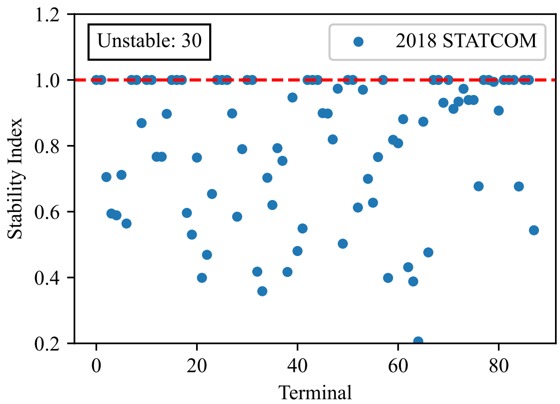
Since the dispatches vary within Peak Demand 2017, Peak Demand 2018, and Low Demand 2019, assessment is done for all scenarios. As evident from Figure 4.24b, the number of unstable busses from Figure 4.24a is much higher for the Peak demand 2018 scenario.



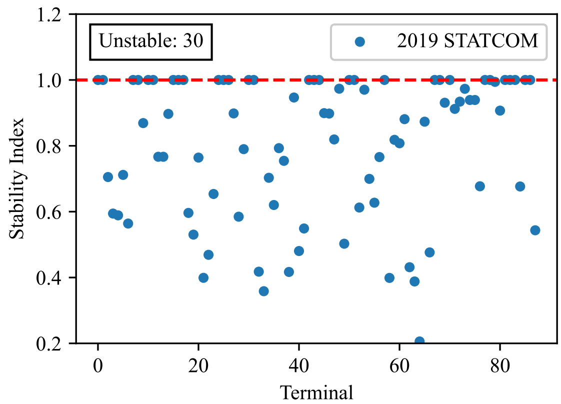

**(a)** Peak Demand 2018




**(b)** After the addition of STATCOM




**(c)** Unstable busses for Low Demand 2019




**(d)** After the addition of STATCOMs

**Figure 4.24:** Depiction of number of Unstable busses for 2018 and 2019 scenario in different situations. The Blue dots represent the buses that resulted in an unstable terminal when the event is added with mentioned conditions.

The buses that are unstable due to Short circuit events remain almost the same for both the 2018 and 2019 scenarios. In the Peak Demand 2017 scenario more buses are unstable is because of overloading transformers in the South as Power Flows from North to South due to the way the power is dispatched. Coming to the Peak Demand 2018 scenario, the reactive power losses are less than in the other scenarios which means that more reactive power is dispatched to the under-voltage terminals to regulate during an event. While the Low Demand 2019 scenario seems very favorable it does not replicate a real-time scenario very aptly. The demand can not be that low despite the addition of storage systems not discussed in the current thesis.

The QSVI index primarily assesses quasi-steady-state conditions and may not fully capture the dynamic characteristics and fast-acting nature of renewable energy sources, leading to an overestimation of instability. This is the reason the results obtained for the same analysis for 2030 scenario show high voltage instability and are therefore not discussed in this thesis.

**Table 4.7:** Conclusions obtained from the stability assessment of three cases of the base case scenario

| **Scenario** | **Stability** | **Result** |
|---|---|---|
| Peak Demand 2017 | 31 unstable buses | More number of buses are unstable. Overloading of transformers in the south as power flows from North to South |
| Peak Demand 2018 | 30 unstable buses | Least number of unstable buses. Reactive power losses are less than the other scenarios and more is dispatched to Undervoltage terminals |
| Low Demand 2019 | 30 unstable buses | Smaller number of overloaded power system elements. But cannot replicate a real-time scenario. |

Depending on the significance of each terminal, an event at the specific location will result in the power system instability. The different busses that resulted in 1 QSVI after simulations are indicated in Figure 4.25 in red ellipses. As can be seen from the figure most of the busses are located in Groningen en Drenthe and Zuid-Holland. There is a significant amount of generation located in Groningen en Drenthe. Zuid-holland has the majority number of Extra High Voltage buses (380kV), which makes the system vulnerable during faults. The busses are sorted into different categories to determine the cause of instability in Table 4.8.

**Table 4.8:** Sorting of terminals depending on their nature to determine the cause of instability

| Generator Buses | EHV buses (380kV) | EHV Buses (380kV) | Other Buses |
|---|---|---|---|
| B15_1 | BSL380 | MBT380 | EEM220 |
| BSL15 | BWK380 | MVL380 | EHA220 |
| DKG15 | CST380 | SMH380 | IC_Cobra |
| EOS15 | DIM380 | VVL380 | IC_StattNet |
| L15 | DKG380 | WL380 | L150 |
| MBT15 | EEM380 | WTR380 | RBB220 |
| NH15 | EOS380 | | VVL220 |
| ZH15 | KIJ380 | | ZH150 |

**Generator Buses**
The 15 kV buses that connect the synchronous generators to the main power system are the generator buses mentioned in Table 4.8. An event at the generator bus will disconnect the potential generator for the 0.1s which is creating an imbalance between supply and demand in the power system. In the 2017 case, there are no storage systems or reserves to tend to the lack of generation. Due to this excessive demand, the voltage levels will drop significantly which may not bounce back post-contingency. This will trigger the index resulting in an unstable indication. Apart from ZH15 and NH15, the rest of the generator buses are connected to generators that do not have a huge contribution in the generation, which means an event at their terminals causing instability indicates that they are inadequately planned or improperly tuned control systems. The MBT15 terminal connects the reference bus which even though does not have an actual dispatch in this scenario plays a very important role. Also the reason MBT380 terminal is out of the EHV buses is in the unstable buses list.

**EHV buses (380kV)**
Terminals KIJ380 and DIM 380 connect big parts of the power system, which, when short-circuited will disconnect multiple generations and significant system components. Along with generators, power system support featured components will be disconnected which leads to instability.

**Other Buses**
All the buses in the category ”other buses” do not have a STATCOM attached which would otherwise help in disturbances during a Voltage collapse. Interconnection IC_StatNett receives major active power dispatch in the form of a negative load into the system in this scenario.

The rest of the cases, 2018 and 2019 are not discussed since 2017 has the most number of unstable buses and covers all the buses that are also unstable in 2018 and 2019 cases.

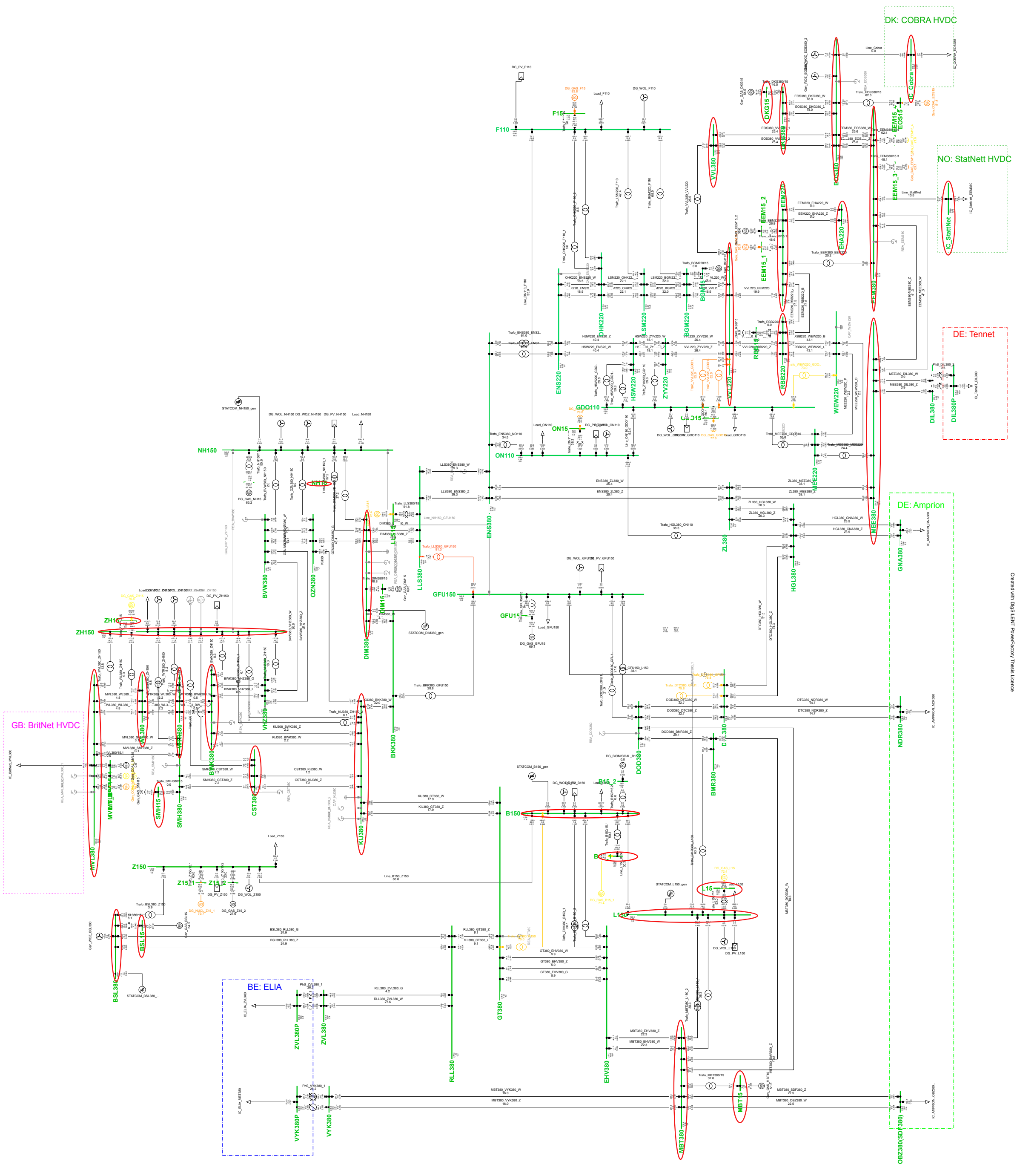



**Figure 4.25:** Indication of "Unstable" buses after Voltage Stability Performance

# 5
# Conclusions

A Synthetic digital model of the Dutch Power System has been developed to perform various studies that pertain to the capability of the power system. Dynamic stability studies were performed on the test model and the influence of different scenarios and events are studied. This was done to test the ability of the system to withstand and recover from disturbances.

## 5.1. Reflections on the Subjective and Associated Results

Conducting comprehensive system studies helped to identify and mitigate potential instability factors. Also, after the implementation of voltage stability performance methods, the instability issues are narrowed to:

- Improving protection schemes
- Enhancing system damping
- Optimizing control system settings
- Ensuring adequate reactive power support

However, for the scenarios discussed in the case study, the inferences are specific to the operating conditions. These are further discussed:

**Scenario 2017-2019**

This scenario provides insight into current system operations and helps validate the test model. As the system is dominated by conventional generation, there are no inherent frequency or voltage issues except during short-circuit events at specific terminals. The addition of STATCOMs mitigates these drawbacks.

**Scenario 2030**

The primary goal of transient studies in the High Renewable Integration scenario of 2030 is to implement control systems for solar and wind generation. Model convergence is achieved through different control strategies and parameter tuning, which is crucial.

Voltage Stability Performance in renewable-dominated power systems is complex, involving fuzzy logic and various online interfaces, which are beyond the scope of this research. Short circuit events were tested using methods designed for synchronous generators. However, because the static generators representing wind and PV systems are connected via separate busbars, an event at these components resulted in a significant loss of generation, and the time taken to achieve steady state post-contingency was much longer compared to synchronous generators. Therefore, these tests need to be modified to specifically address the unique characteristics and challenges of renewable-dominated power systems.

Although the 2030 scenario is not far off, the dynamic stability models developed will pave the way for future scenarios in 2050 and beyond. For 2050, additional controls will be required to execute simulations due to the much higher installed capacities and new technologies. Control systems for electrolysers, which were not addressed in this thesis, will also need to be considered.

### 5.1.1. Conclusions

The various research questions that can be posed which are discussed in 1, are addressed one by one in this section. With possible explanations for various dynamic phenomena observed during the simulations, all the possible mitigation techniques and improvements are discussed.

*How feasible it is to use generic component models and parameters to ensure successful initialisation and correct dynamic simulation?*

While using generic component models and parameters was feasible, several considerations arose. The component models used were from the DIgSILENT library, standardized by IEEE, which typically adhered to industry standards and were broadly compatible with various systems. This adherence allowed the system a basic level of functionality and interoperability, facilitating initial setup. Generic models simplified the modeling process by providing pre-defined components that were readily integrated into the simulation environment. Since there was no need for custom models to be used or implemented, the overall complexity and time required for design were reduced. For preliminary studies and initial feasibility assessments, generic models provided a reasonable approximation of system behavior, proving useful for gaining insights into system dynamics and identifying potential issues early in the design process. Although generic models came with default parameters, they often required tuning to accurately reflect the specific characteristics of the actual system. Therefore, achieving successful initialization depended on adequate parameter tuning. Large-scale implementations of these dynamic models involved multiple components and sub-components, which were made easier with generic models, allowing for the integration of various components without the need for extensive customization.

*What kind of representative operating conditions and disturbance can exhibit instability risks?*

Various operating conditions that the model is tested for are derived from scenarios already evaluated for optimal power flow and contingency analysis. Therefore, load levels (peak and low demands), generation location, and power system configuration can be ruled out as potential instability-causing conditions, leaving disturbances and faults as the primary factors to consider.

In the case of the mixed case of solar and wind, an outage event caused the system to lose convergence after reaching the maximum number of iterations. Although the outage event is at a synchronous generator that does not have a role in power dispatch, it remains online during operations. A synchronous generator with 0 active power dispatch still plays a crucial role in maintaining system stability through its contributions to reactive power support, system inertia, voltage regulation, and power system support functions.

During the outage event, the loss of these stabilizing factors may have caused significant voltage and frequency stability issues, especially in a solar-dominant system where solar inverters provide limited reactive power and dynamic response capabilities. This destabilization led to challenges ultimately caused the system to lose convergence.

The system lost convergence upon adding an electrolyser to both solar-dominant and solar and wind mix cases. The electrolyser's demand for both active and reactive power strained the system's voltage regulation capabilities, while its lack of inertia and frequency regulation further destabilized the system, especially in scenarios dominated by intermittent renewables.

*Up to which extent Voltage Stability Performance metrics from existing literature can provide insights on possible instability phenomena?*

Voltage Stability Performance metrics from existing literature did provide valuable insights into possible instability phenomena to a significant extent. By quantifying system behavior under different operating conditions and disturbances, these metrics can help identify potential stability risks and vulnerabilities.

The indices used measure the post-contingency magnitudes of different variables. While the methods used for Voltage Stability Performance rely on performance indices, focusing on post-contingency magnitudes alone provides an incomplete picture of system stability. These indices focused on the system's state after disturbances have settled, missing critical transient phenomena such as oscillations and damping, which are vital for understanding instability risks. They often overlook the dynamic interactions of control systems, fail to detect transient instabilities and cascading failures, and may not adequately represent the system's nonlinear dynamics. Additionally, these methods are less suitable for real-time monitoring and decision-making, as they do not capture the initial system response to disturbances or account for the continuously evolving nature of power systems.

## 5.2. Recommendations for future research

### 5.2.1. Introduction of BESS

According to Tennet [38], there will be 9 GW of battery capacity in 2030. These battery systems are not added to the power system design. The power system lacks the flexibility to balance supply and demand fluctuations, causing convergence issues without Battery Energy Storage Systems. BESS aids in stabilizing the power system and firms up Renewable Energy Sources. This would help with the convergence issue in the mixed-generation case. The different locations at which the battery energy storage systems are proposed by Tennet are shown in Figure 5.1.

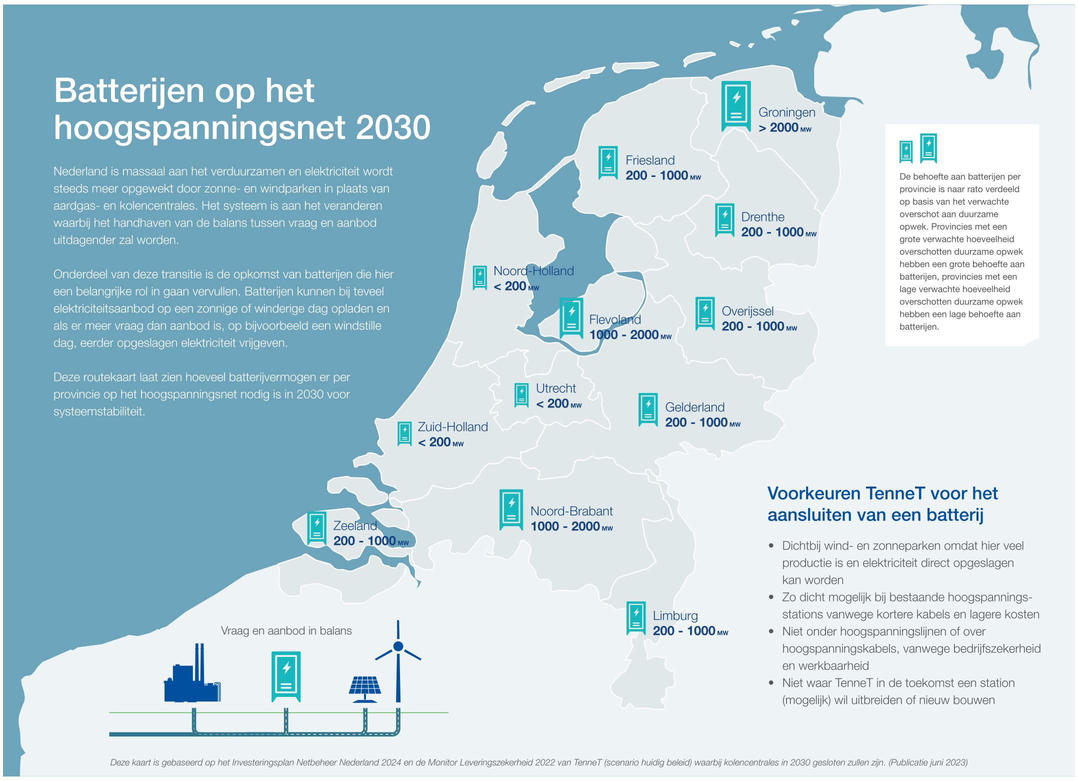



**Figure 5.1:** Locations and capacity of the Battery Energy Storage Systems as proposed by [38]

### 5.2.2. Variable load profile

Different load profiles for different scenarios are taken from the ENTSO-e transparency platform and introduced as a time-characteristic to each load which varies throughout the day. Quarterly variations i.e., every 15-minute change in the loads are given in the transparency platform region-wise. These are changed into hourly changes. With available load profiles of the current year, a day is selected and the hourly variations of the load are extracted. Using today's data, the future scenario is predicted using weighted probability, and the future hourly demand changes are predicted. They implemented the model to test the model's reliability in changing load demand profiles. Due to a lack of storage systems, the system does not have the capability to be converged at all times. However, at loads like Load_F110, Load_GDO110, and Load_Z150, load flows are possible but not at all the loads. These can be re-implemented after the addition of said storage systems and they dynamic stability studies can be furthered by changing load profiles. These load profiles are given in Appendix D for further implementation. As mentioned in Section 5.2.1, the locations of BESS are already proposed, however, implementation will help change load profiles.

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# A

# Parameter Tuning

## A.1. Parameter values

The parameters used in different DSL models are given in this chapter. The Parameters that are relevant to this research are discussed. Other parameters like that of the system components like generators, transformers, transmission lines, terminals, static generators, phase shifters, etc are not discussed.

The Parameters are not changed when compared to the base model but are given in Table A.1. The RMS parameters that are implemented in this thesis are given in Table A.2. They are taken from test systems initially from [10] and [11] but are tuned according to the system response during the simulation like inertia.

**Table A.1:** Detailed synchronous generator parameters

| **General** | **Unit** | **Parameters** |
|---|---|---|
| Nominal Voltage $U_nom$ (kV) | kV | 15 |
| Nominal Power Factor | p.u. | 0,9 |
| Connection | - | YN |
| | | |
| **Load Flow Parameters** | **Unit** | **Parameters** |
| $Qmin$ | p.u. | 1 |
| $Qmax$ | p.u. | 1 |
| $x0$ (zero sequence reactance) | p.u. | 0,1 |
| $r0$ (zero sequence resistance) | p.u. | 0 |
| $x2$ (negative sequence reactance) | p.u. | 0,2 |
| $r2$ (negative sequence resistance) | p.u. | 0 |
| | | |
| **Short Circuit VDE/IEC** | **Unit** | **Paramaters** |
| $xd$”$sat$ (subtransient reactance) | p.u. | 0,2 |
| $rstr$ (stator resistance) | p.u. | 0 |
| $xdsat$ | p.u. | 1,2 |
| Machine Type IEC909/IEC60909 | - | Salient Pole Series 1 |

**Table A.2:** Simulation RMS parameters of the Synchronous Generation

| **Generators (MVA)** | **H (s)** | **xl (p.u.)** | **xd (p.u.)** | **xq (p.u.)** | **xrld (p.u.)** | **xrlq (p.u.)** | **Td0’ (s)** | **Tq0’ (s)** | **xd’ (p.u.)** | **xq’ (p.u.)** | **Td0” (s)** | **Tq0” (s)** | **xd” (p.u.)** | **xq” (p.u.)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 MVA | 3 | 0.119 | 1.676 | 1.586 | 0 | 0 | 5.108 | 0.421 | 0.212 | 0.377 | 0.023 | 0.059 | 0.144 | 0.144 |
| 250 MVA | 2.8 | 0.17 | 2.46 | 2.32 | 0 | 0 | 9.5 | 0.99 | 0.25 | 0.41 | 0.023 | 0.035 | 0.19 | 0.19 |
| 400 MVA | 2.5 | 0.15 | 2.46 | 2.32 | 0 | 0 | 9.5 | 0.99 | 0.252 | 0.41 | 0.023 | 0.035 | 0.25 | 0.25 |
| 600 MVA/800 MVA | 6 | 0.15 | 2.2 | 2 | 0 | 0 | 7 | 1.5 | 0.3 | 0.4 | 0.05 | 0.05 | 0.2 | 0.2 |
| 1300 MVA | 9 | 0.15 | 3 | 2.5 | 0 | 0 | 5 | 0.25 | 0.3 | 0.4 | 0.05 | 0.05 | 0.18 | 0.18 |
| 1500 MVA | 7.5 | 0.2 | 2.46 | 2.32 | 0 | 0 | 6.5 | 0.34 | 0.329 | 0.5 | 0.025 | 0.25 | 0.252 | 0.252 |
| 3000 MVA | 9.5 | 0.15 | 2.6 | 2 | 0 | 0 | 4.5 | 0.2 | 0.3 | 0.4 | 0.05 | 0.05 | 0.15 | 0.15 |

# A.2. Synchronous Generator

## A.2.1. Exciter

As mentioned before the sample parameters for exciter are taken from [27]. They are changed slightly to match the test systems initially [11]. Values like $K_a$ and all the time constant are the parameters that most likely needed tuning. The parameters that are finally implemented in Exciter IC1A is given in A.3.

**Table A.3:** Exciter DSL parameter values

| Description | Symbol | Value | Unit |
|---|---|---|---|
| Regulator output gain | $Ka$ | 400 | [p.u.] |
| regulator output time constant | $Ta$ | 0,02 | [s] |
| Regulator lag time constant | $Tb$ | 0 | [s] |
| Regulator lead time constant | $Tc$ | 0 | [s] |
| Rate dfeedback gain | $Kf$ | 0,03 | [p.u.] |
| rate feedback time constant | $Tf$ | 1 | [s] |
| Exciter field proportional constant | $Ke$ | 1 | [p.u.] |
| Exciter field time constant | $Te$ | 0,8 | [s] |
| Rectifier loading factor | $Kc$ | 0,2 | [p.u.] |
| Demagnetizing factor | $Kd$ | 0,38 | [p.u.] |
| Exciter output voltage for Se(Ve1) | $Ve1$ | 4,18 | [p.u.] |
| Exciter saturation factor at Ve1 | $SeVe1$ | 0,1 | [p.u.] |
| Exciter output voltage for Se(Ve2) | $Ve2$ | 3,14 | [p.u.] |
| Exciter saturation factor at Ve2 | $SeVe2$ | 0,03 | [p.u.] |
| Minimum regulator output | $Va\_min$ | -14,5 | [p.u.] |
| Minimum exciter field voltage | $Vr\_min$ | -5,43 | [p.u.] |
| Maximum regulator output | $Va\_max$ | 14,5 | [p.u.] |
| Maximum exciter field voltage | $Vr\_max$ | 6,03 | [p.u.] |

## A.2.2. Governor

The parameters used to implement the Governor DSL model are given in Table A.4. Parameters like Governor gain $K$, $P_{min}$ and $P_{max}$ are likely to be having an influence in the system response. These are the parameters that are mostly tuned.

**Table A.4:** The Governor parameters implemented in the final model

| Description | Symbol | Value | Unit |
|---|---|---|---|
| Turbine rated power, 1st shaft | $Trate1$ | 0 | [MW] |
| Turbine rated power, 2nd shaft | $Trate2$ | 0 | [MW] |
| Governor gain (1/droop) | $K$ | 25 | [p.u.] |
| Governor lag time constant | $T1$ | 0 | [s] |
| Governor lead time constant | $T2$ | 0 | [s] |
| Valve positioner time constant | $T3$ | 0,1 | [s] |
| Inlet piping/steam bowl time constant | $T4$ | 0,3 | [s] |
| Fraction of 1st shaft power first boiler pass | $K1$ | 0,2 | [p.u.] |
| Fraction of 2nd shaft power first boiler pass | $K2$ | 0 | [p.u.] |
| Second boiler pass time constant | $T5$ | 5 | [s] |
| Fraction of 1st shaft power second boiler pass | $K3$ | 0,3 | [p.u.] |
| Fraction of 2nd shaft power second boiler pass | $K4$ | 0 | [p.u.] |
| Third boiler pass time constant | $T64$ | 0,5 | [s] |
| Fraction of 1st shaft power third boiler pass | $K5$ | 0,5 | [p.u.] |
| Fraction of 2nd shaft power third boiler pass | $K6$ | 0 | [p.u.] |
| Fourth boiler pass time constant | $T7$ | 0 | [s] |
| Fraction of 1st shaft power fourth boiler pass | $K7$ | 0 | [p.u.] |
| Fraction of 2nd shaft power fourth boiler pass | $K8$ | 0 | [p.u.] |
| Speed deviation deadband | $db$ | 0 | [p.u.] |
| Maximum valve closing rate | $Uc$ | -0,25 | [p.u./s] |
| Minimum valve opening | $Pmin$ | 0 | [p.u.] |
| Maximum valve opening rate | $Uo$ | 0,25 | [p.u./s] |
| Maximum valve opening | $Pmax$ | 1 | [p.u.] |

### A.2.3. PSS

**Table A.5:** The Power System Stabilizer parameters implemented in the final model

| Description | Symbol | Value | Unit |
|---|---|---|---|
| Input type selector (see diagram) | Vsi_in | 1 | [0/1/2/3/4] |
| PSS gain | Ks | 0,5 | [p.u.] |
| Notch filter (2nd order block) constant | A1 | 0 | [s] |
| Notch filter (2nd order block) constant | A2 | 0 | [s*s] |
| Lead compensating time constant 1 | T1 | 0,2 | [s] |
| Lag compensating time constant 1 | T2 | 0,005 | [s] |
| Lead compensating time constant 2 | T3 | 0,2 | [s] |
| Lag compensating time constant 2 | T4 | 0,005 | [s] |
| Washout time constant | T5 | 4,5 | [s] |
| Transducer time constant | T6 | 0 | [s] |
| Minimum PSS output | Vst_min | -0,05 | [p.u.] |
| Maximum PSS output | Vst_max | 0,05 | [p.u.] |

## A.3. Photovoltaic

Among all the controls corresponding to the Photovoltaic systems, REEC_D requires the most tuning. It is important to set the flag parameters to the correct ones as mentioned in Table A.6. The flags are set to Q control in most cases considering reactive power droop or control a priority.

### A.3.1. REEC_D

**Table A.6:** Parameters of REEC_D

| **Description** | **Symbol** | **Value** | **Unit** |
|---|---|---|---|
| Power factor flag: 1 = pf control, 0 = Q control | PfFlag | 0 | |
| Voltage control flag: 1 = Q ctrl., 0 = voltage control | VFlag | 1 | |
| Filter time constant for power measurement | Tp | 0.05 | [s] |
| Proportional gain | Kqp | 1 | [p.u.] |
| Integral gain | Kqi | 0.7 | [p.u.] |
| Q control flag: 1 = voltage/Q, 0 = const. pf or Q ctrl. | QFlag | 0 | |
| Proportional gain | Kvp | 1 | [p.u.] |
| Integral gain | Kvi | 0.7 | [p.u.] |
| Filter time constant for voltage measurements | Trv | 0.01 | [s] |
| Voltage deadband for overvoltage iq injection | dbd1 | -0.05 | [p.u.] |
| Voltage deadband for undervoltage iq injection | dbd2 | 0.05 | [p.u.] |
| Gain for reactive current injection during fault | Kqv | 2 | [p.u.] |
| Undervoltage condition trigger voltage | Vdip | 0.9 | [p.u.] |
| Overvoltage condition trigger voltage | Vup | 1.1 | [p.u.] |
| Time constant on lag delay | Tiq | 0.01 | [s] |
| Time constant | Tpord | 0.01 | [s] |
| Priority flag on current limit: 1 = P, 0 = Q priority | PqFlag | 0 | |
| Maximum converter current limit | Imax | 1.3 | [p.u.] |
| Ipcmd_max delay after fault | Thld2 | 0 | [s] |
| Ipmin scaling factor | Ke | 0 | |
| Power control flag: 0 = P reference, 1 = Speed ref. | PFlag | 1 | |
| Reference voltage, enter 0 for terminal voltage | Vref0 | 0 | [p.u.] |
| User-defined ref./bias on inner-loop voltage ctrl. | Vref1 | 0 | [p.u.] |
| Current-compensation resistance | Rc | 0 | [p.u.] |
| Current-compensation reactance | Xc | 0.01 | [p.u.] |
| 0 = reactive droop, 1 = current compensation | VcmpFlag | 0 | |
| Reactive-current compensation gain | Kc | 0.02 | |
| Filter time constant for voltage measurement | Tr1 | 0.02 | [s] |
| Voltage below which the converter is blocked | vblkl | 0.1 | [p.u.] |
| Voltage above which the converter is blocked | vblkh | 1.2 | [p.u.] |
| Time for which the converter will remain blocked | Tblk_delay | 0.1 | [s] |
| Reactive current injection delay after voltage dip | Thld | 0 | [s] |
| Value at which injection is held after voltage dip | Iq_frz | 0 | [p.u.] |
| Reactive power limit minimum | qvmin | -1 | [p.u.] |
| Voltage control minimum | Vmin | 0.9 | [p.u.] |
| Minimum limit of reactive current injection | Iql1 | -1.44 | [p.u.] |
| Ramp rate on power reference | dPmin | -2 | [p.u./s] |
| Minimum power reference | Pmin | 0 | [p.u.] |
| Reactive power limit maximum | qvmax | 1 | [p.u.] |
| Voltage control maximum | Vmax | 1.1 | [p.u.] |
| Maximum limit of reactive current injection | Iqh1 | 1.44 | [p.u.] |
| Ramp rate on power reference | dPmax | 2 | [p.u./s] |
| Maximum power reference | Pmax | 1 | [p.u.] |
| Set by configuration script, no input needed | WGO_active | 0 | [0/1] |

### A.3.2. REGC_B

The maximum and minimum reactive current rate limits are predetermined. The Iqrmin is the negative reactive current recovery limit which can be to 0 or a positive value to disable and vice versa for Idrmax. The RateFlag is also set to 0 for the active power ramp rate or 1 for the active current ramp rate.

**Table A.7:** Parameters of REGC_B

| Description | Name | Value | Unit |
|---|---|---|---|
| Converter time constant | Tg | 0.02 | [s] |
| Voltage filter time constant | Tfltr | 0.02 | [s] |
| Rate limit: 0=Active power/1=Reactive power | RateFlag | 0 | |
| Source resistance | re | 0 | [p.u.] |
| Source reactance | xe | 0.1 | [p.u.] |
| Emulated delay in converter controls | Te | 0.02 | [s] |
| Min reactive current rate limit | Iqrmin | -999 | [pu/s] |
| Max reactive current rate limit | Iqrmax | 999 | [pu/s] |
| Active current rate limit | rrpwr | 1 | [pu/s] |

### A.3.3. WTGWGO_A Weak Grid Option Model

The weak grid option offers supplemental control whereas WTGWGO is a generic model. This model WTG-WGO_A can only be used with type 4 WTGs and is attached between REPC and REEC. The parameters for the weak grid option are given in **??**.

**Table A.8:** Parameter for the Weak Grid Option Model

| Description | Name | Value | Unit |
|---|---|---|---|
| Voltage measurement time constant | Tfltr | 0.02 | [s] |
| Voltage threshold below with the WGO function is initiated | Vwgo | 0.5 | [p.u.] |
| Power reference held during a fault when WGO is initiated | Pwgo1 | 0.5 | [p.u.] |
| Ramp rate at which power is increased from Pwgo1 to Pwgo2 | rpw1 | 0.2 | [p.u/s] |
| Power reference held for Thold seconds after the fault | Pwgo2 | 0.7 | [p.u.] |
| Ramp rate at which power is increased from Pwgo2 back to normal | rpw2 | 0.2 | [p.u./s] |
| Time for which the power reference is held at Pwgo2 | Thold | 1 | [s] |
| Small hysteresis on voltage recovery to start the first ramp | eps | 0.01 | [p.u.] |

## A.4. Wind Systems

The parameters of the DSL models of different control techniques implemented for wind systems is given in this section.

### A.4.1. Droop Control System

Since the implementation of the Droop control system has been established for a long time, only the parameters that are used for this work are listed.

#### Droop Control

**Table A.9:** Parameters of the Droop control DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Active power droop coefficient | $mp$ | 0.01 | [p.u.] |
| Reactive power droop coefficient | $mq$ | 0.05 | [p.u.] |
| Low-pass filter cut-off frequency | $w_c$ | 60 | [rad/s] |
| Initial speed setting | $f_{setpoint}$ | 1 | [p.u.] |

### Virtual Impedance

**Table A.10:** Parameters for the Virtual Impedance DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Basic virtual resistance | $r$ | 0.006 | [p.u.] |
| Basic virtual reactance | $x$ | 0.006 | [p.u.] |
| Control mode: 0 = const. Z; 1 = Proportional over-current limitation | Mode | 1 | |
| Over-current threshold | $i_lim$ | 1.01 | [p.u.] |
| Proportional factor for additional resistance | $kpr$ | 8 | [p.u.] |
| Proportional factor for additional reactance | $kpx$ | 8 | [p.u.] |
| Time constant of low-pass filter | $T_lpf$ | 0.0001 | [s] |

### Output Voltage Calculation

**Table A.11:** Parameters for the Output Voltage Calculation DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Current limitation: 0 = disabled; 1 = enabled | Mode | 1 | |
| Maximum current | i_max | 1.2 | [p.u.] |
| Series resistance | Rseries | 0 | [%] |
| Series reactance | Xseries | 10 | [%] |

## A.4.2. Virtual Synchronous Machine

The parameters for different DSL models implemented in the Virtual Synchronous machine are listed below.

### Virtual Synchronous Machine

**Table A.12:** Parameters for the Virtual Synchronous Machine DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Acceleration time constant | Ta | 3 | [s] |
| Damping coefficient | Dp | 100 | [p.u.] |
| Damping filter cut-off frequency | w_c | 0 | [rad/s] |
| Voltage setpoint low-pass filter time constant | T_LPF_u | 0.003 | [s] |
| Initial speed setting | f_setpoint | 1 | [p.u.] |

### Virtual Impedance

**Table A.13:** Parameters for Virtual Impedance DSL model for Virtual synchronous machine

| Description | Name | Value | Unit |
|---|---|---|---|
| Basic virtual resistance | r | 0.006 | [p.u.] |
| Basic virtual reactance | x | 0.006 | [p.u.] |
| Control mode: 0 = const. Z; 1 = Proportional over-current limitation | Mode | 1 | |
| Over-current threshold | i_lim | 1.01 | [p.u.] |
| Proportional factor for additional resistance | kpr | 8 | [p.u.] |
| Proportional factor for additional reactance | kpx | 8 | [p.u.] |
| Time constant of low-pass filter | T_lpf | 0.0001 | [s] |

**Proportional Voltage Controller**

**Table A.14:** Parameters for Proportional Voltage Controller DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Measurement filter time constant | Tr | 0.02 | [s] |
| Controller gain | K | 0.5 | |
| Minimum AVR output voltage | u_set_min | -1.5 | [p.u.] |
| Maximum AVR output voltage | u_set_max | 1.5 | [p.u.] |

**Output Voltage Calculation**

**Table A.15:** Parameters for Output Voltage Calculation DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Current limitation: 0 = disabled; 1 = enabled | Mode | 1 | |
| Maximum current | i_max | 1.2 | [p.u.] |
| Series resistance | Rseries | 0 | [%] |
| Series reactance | Xseries | 10 | [%] |

### A.4.3. IEC Wind type 4B System

The implementation parameters used for the IEC wind type 4 turbine are discussed in this section. The initial parameters for Generator set type 4, two mass mechanical models, and the Q control model are taken from [37] while some tweaks are made according to the current model. The parameters for the rest of the model are the sample data given in the template IEC Type 4B wind turbine. After the parameters are tuned, it is also important to set the measurement devices to the current nodes where the wind generators are connected to the power system as mentioned.

**Generator Set Type 4**

**Table A.16:** Parameters for the Generator Set Type 4 DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Time constant | Tg | 0.01 | [s] |
| Minimum reactive current ramp rate | diqmin | -100 | [Ibase/s] |
| Maximum active current ramp rate | dipmax | 1 | [Ibase/s] |
| Maximum reactive current ramp rate | diqmax | 100 | [Ibase/s] |

**Two Masses**

**Table A.17:** Parameters for the Two masses DSL Model

| Description | Name | Value | Unit |
|---|---|---|---|
| Inertia constant of generator | Hgen | 5 | [s] |
| Inertia constant of wind turbine rotor | HWTR | 5 | [s] |
| Drive train stiffness | kdrt | 80 | [Tbase] |
| Drive train damping | cdrt | 1 | [Tb/wb] |

### P Control Type 4B

**Table A.18:** Parameters for the P control type 4B DSL model

| Description | Name | Value | Unit |
|---|---|---|---|
| Time constant in power order lag | Tpordp4B | 0.01 | [s] |
| Time constant in aerodynamic power response | Tpaero | 0.5 | [s] |
| Voltage scaling for power ref during voltage dip (0: no scaling/1: scaling) | MpUscale | 0 | |
| Voltage dip threshold for P control | updip | 0.85 | [Ub] |
| Minimum WT reference power ramp rate | dprefmin4B | -0.5 | [Sb/s] |
| Maximum wind turbine power ramp rate | dpmaxp4B | 1 | [Sb/s] |
| Maximum WT reference power ramp rate | dprefmax4B | 1 | [Sb/s] |

### Current Limitation

**Table A.19:** Parameters for the current limitation dsl model

| Description | Name | Value | Unit |
|---|---|---|---|
| Max. continuous current at WTG terminals | imax | 1 | [Ib] |
| Max. current during voltage dip at WTG terminals | imaxdip | 1.1 | [Ib] |
| Lim of typ3 stator current (0:total, 1: stator cur) | MDFSLim | 1 | |
| Prio of q power during FRT (0:active / 1:reactive power priority) | Mqpri | 1 | |
| WT voltage in the op where zero q current can be delivered | upqumax | 2 | [Ub] |
| Partial derivative of reactive current limit vs. voltage | Kpqu | 2 | [Ib/Ub] |

### Grid Measurement Control

**Table A.20:** Parameters for the grid measurement control dsl model

| Description | Name | Value | Unit |
|---|---|---|---|
| Time constant in voltage measurement filter | Tufilt | 0.005 | [s] |
| Time constant in current measurement filter | Tifilt | 0.005 | [s] |
| Time constant in power measurement filter | Tpfilt | 0.005 | [s] |
| Time constant in reactive power measurement filter | Tqfilt | 0.005 | [s] |
| Time constant in frequency measurement filter | Tffilt | 0.005 | [s] |
| Maximum rate of change of frequency | dPhimax | 5 | [fn/s] |

### Grid Measurement Protection

**Table A.21:** Parameters for the grid measurement dsl model

| Description | Name | Value | Unit |
|---|---|---|---|
| Time constant in voltage measurement filter | Tufilt | 0.005 | [s] |
| Time constant in current measurement filter | Tifilt | 0.005 | [s] |
| Time constant in power measurement filter | Tpfilt | 0.005 | [s] |
| Time constant in reactive power measurement filter | Tqfilt | 0.005 | [s] |
| Time constant in frequency measurement filter | Tffilt | 0.005 | [s] |
| Maximum rate of change of frequency | dPhimax | 5 | [fn/s] |

### Q Control

**Table A.22:** Parameters for the Q control dsl model

| Description | Name | Value | Unit |
|---|---|---|---|
| Q modes 0=u;1=q;2=qol;3=pf;4=openLoop pf | MqG | 1 | |
| Reactive power PI controller proportional gain | KPq | 0 | [Ub/Sb] |
| Post fault reactive current injection | iqpost | 0 | [Ib] |
| Voltage scaling factor for FRT current | Kqv | 2 | [Ib/Ub] |
| FRT Q control modes 0/1/2/3 | MqFRT | 2 | |
| Reactive power PI controller integration gain | KIq | 2 | [Ub/Sb/s] |
| Voltage PI controller proportional gain during FRT | KPuFRT | 0 | [Ib/Ub] |
| Voltage PI controller proportional gain | KPu | 2 | [Ib/Ub] |
| Voltage PI controller integration gain | KIu | 2 | [Ib/Ub/s] |
| Resistive component of voltage drop impedance | rdrop | 0 | [Zb] |
| Inductive component of voltage drop impedance | xdrop | 0 | [Zb] |
| Voltage change dead band lower limit | deltaudb1 | -0.1 | [Ub] |
| Voltage change dead band upper limit | deltaudb2 | 0.1 | [Ub] |
| Time constant of stead state voltage filter | Tuss | 30 | [s] |
| User defined bias in voltage reference | uref0 | 1 | [Ub] |
| Voltage threshold for UVRT detection in Q control | uqdip | 0.9 | [Ub] |
| Length of time period where post fault reactive power is injected | Tpost | 0 | [s] |
| Voltage threshold for OVRT detection in Q control | uqrise | 1.1 | [Ub] |
| Time constant in reactive power order lag | Tqord | 0 | [s] |
| Minimum voltage in voltage PI controller integral term | umin | 0 | [Ub] |
| Minimum reactive current injection | iqmin | -1.05 | [Ib] |
| Maximum voltage in voltage PI controller integral term | umax | 2 | [Ub] |
| Maximum reactive current injection during dip | iqh1 | 1.05 | [Ib] |
| Maximum reactive current injection | iqmax | 1.05 | [Ib] |

### Reference Frame Rotation (PLL)

**Table A.23:** Parameters for the reference frame rotation PLL dsl model

| Description | Name | Value | Unit |
|---|---|---|---|
| Time constant for PLL first order filter model | TPLL | 0.02 | [s] |
| Voltage below which the angle of the voltage is filtered and possibly also frozen | uPLL1 | 0.13 | [Ub] |
| Voltage below which the angle of the voltage is frozen if uPLL2 <= **uPLL1** | uPLL2 | 0.13 | [Ub] |

# B

# Case Study

## B.1. Python Code: Scenario 2017-2019

Different code snippets that depicts the functions used to perform various tasks in and around PowerFactory are given in this section. Small explanations and precautions while implementing the code are also mentioned. The Code in B.1, the components that are selected to add a disturbance during the simulation are taken. The functions addShortCircuitEvent, addLoadEvent and addOutageEvent are given in Codes C.1, C.2 and C.3.

**Listing B.1:** Code snippet used to add different events

```
    schterm = app.GetCalcRelevantObjects(ZH150.ElmTerm)[0]
    ldeload = app.GetCalcRelevantObjects(Load_ZH150.ElmLod)[0]
    oegen = app.GetCalcRelevantObjects(DG_GAS_NH15.ElmSym)[0]
    addShortCircuitEvent(schterm ,4, 0.15)
    addLoadEvents(ldeload, 4, 15)
    addOutageEvents(oegen,4)
```

In Code B.2, *for* loop is used to iterate over all the events that are added to the fault folder. All the plants are put in ”out of service” so that the results can first be exported with no plants. Then all the faults are inactive to iteratively put one fault after another active. The *if* condition checks if the event is a short-circuit event to also put its corresponding short-circuit clear event ”in service”. The functions addRecordedResult_scenario() and rms_results_scenario are discussed in C.4 and C.5.

**Listing B.2:** Code snippet used to iterate between the added events

```
fault_folder = app.GetFromStudyCase('IntEvt')
faults = fault_folder.GetContents()
# Extract unique targets
unique_targets = set(fault.p_target for fault in faults)
for plant in plants:
    plant.outserv = 1
for event_id, target in enumerate(unique_targets):
# Set all faults out of service
    for fault in faults:
        fault.outserv = 1
# Set the faults associated with the current target in service
    for fault in faults:
        if fault.p_target == target:
            sc_event_name = f'{target.loc_name}'
            scc_event_name = f'{target.loc_name}-clear'
            if fault.loc_name == sc_event_name or fault.loc_name ==
                scc_event_name:
                 fault.outserv = 0
```

```
#add the variables you need
    addRecordedResult_scenario()
    simulations()                                          # Perform
        simulations
    rms_results_scenario(study_case, event_id, 'fault')
```

The code B.3, the presence and absence of different DSLs are tested. The DSLs are differentiated into exciters, pss', governors, and vtcs to put the relevant DSL active and export results. The *if* condition is written to check the DSL's list with their corresponding name. The clearelmRes function is used to clear all the old result variables in the results folder before adding the new results. Simularly the same logic is followed for the governor and power system stabilizer.

**Listing B.3:** Code for different DSL testing

```
def rms_testing_dsl(study_case):
# To differentiate dsl's based on their loc_name to put them out and in
    service iteratively
    exciters = []
    psss = []
    governors = []
    vtcs = []
    for dsl in elmdsl:
        if dsl.loc_name == 'IEEE AC1A':
            exciters.append(dsl)
        if dsl.loc_name == 'IEEE PSS1A':
            psss.append(dsl)
        if dsl.loc_name == 'IEEEG1':
            governors.append(dsl)
        if dsl.loc_name == 'IEEE Voltage Transducer and Current Comp':
            vtcs.append(dsl)
    for exciter in exciters:
        exciter.outserv = 0
    for vtc in vtcs:
        vtc.outserv = 0
    clearelmRes(elmRes)
    addRecordedResult_scenario()
    simulations()
    rms_results_scenario(study_case, exc_vtc_fault)
```

## B.2. Python code: Scenario 2030

The Python code that is used to implement the testing of Scenario 2030 is discussed in this section. The same functions that are discussed in Section B.1 are not repeated here.

In Code B.4, similar to B.3, since all the different generators come under one class **ElmGenstat*, they are sorted according to the component names. Unlike the steady-state model, the PV generators are now under the class name **ElmPvsys*. Different static generators are VSM generators, IEC wind generators, old wind generators, and old PV generators(which remain inactive throughout the simulations). Their corresponding plants are also sorted according to their names into droops, IECs, VSMs, plants_sync(plants for synchronous generators), WECCs, and statcoms.

**Listing B.4:** Code snippet to differentiate static generators and their plants

```
    statGens = app.GetCalcRelevantObjects('*.ElmGenstat')
    pvsys = app.GetCalcRelevantObjects('*.ElmPvsys')
    VSM_droop_statgens = []
    IEC_statgens = []
    old_PV_statgens = []
    old_Wind_statgens = []
```

```
    for statGen in statGens:
        if 'Converter' in statGen.loc_name:
            VSM_droop_statgens.append(statGen)
        if 'W_WOL_' in statGen.loc_name or 'W_WOZ_' in statGen.loc_name:
            IEC_statgens.append(statGen)
        if 'DG_PV' in statGen.loc_name:
            old_PV_statgens.append(statGen)
        if 'DG_WOL' in statGen.loc_name or 'DG_WOZ' in statGen.loc_name or 'Gen_WOZ' in statGen.loc_name:
            old_Wind_statgens.append(statGen)
        if 'DG_BATT_ZH150' in statGen.loc_name or 'DG_FuelCell_ZH150' in statGen.loc_name:
            statGen.outserv = 1
    droops = []
    IECs = []
    VSMs = []
    plants_sync = []
    WECCs = []
    statcoms = []
    for plant in plants:
        if 'Droop' in plant.loc_name:
            droops.append(plant)
        if 'IEC' in plant.loc_name:
            IECs.append(plant)
        if 'VSM' in plant.loc_name:
            VSMs.append(plant)
        if 'Plant' in plant.loc_name:
            plants_sync.append(plant)
        if 'WECC' in plant.loc_name:
            WECCs.append(plant)
        if 'STATCOM' in plant.loc_name:
            statcoms.append(plant)
```

In code B.5, the function is used to put appropriate plants and their corresponding static generators ”in service”. The study_case is inputed into the function from where the function is called and then executed. This logic is used multiple times in the code in different situations, in testing different faults, different control techniques in case of wind case A0 and A4. The results are recorded and exported as discussed in B.3.

**Listing B.5:** Code used to put appropriate static generator and their plants in service

```
def rms_2030(study_case):
if study_case == 'A0' or study_case == 'A4':
#only wind generation
        for droop in droops:
         droop.outserv = 1
        for statgen in VSM_droop_statgens:
            statgen.outserv = 1
        for IEC_statgen in IEC_statgens:
            IEC_statgen.outserv = 0
        for IEC in IECs:
            IEC.outserv = 0
        for plant_sync in plants_sync:
            plant_sync.outserv = 0
        for WECC in WECCs:
            WECC.outserv = 1
        for plant in plants:
                if plant.loc_name == Plant_Electrolyser_BSL380 or plant.loc_name == Plant_Electrolyser_EEM380 or plant.loc_name ==
```

```
                    Plant_Electrolyser_MVL380:
                    plant.outserv = 0
if study_case == 'B0' or study_case == 'B6':
#only PV generation
        for gen in pvsys:
            gen.outserv = 0
        for WECC in WECCs:
            WECC.outserv = 0
        for IEC in IECs:
            IEC.outserv = 1
        for VSM in VSMs:
            VSM.outserv = 1
        for IEC_statgen in IEC_statgens:
            IEC_statgen.outserv = 1
        for droop in droops:
            droop.outserv = 1
        for plant in plants:
                if plant.loc_name == Plant_Electrolyser_BSL380 or plant.loc_name == Plant_Electrolyser_EEM380 or plant.loc_name == Plant_Electrolyser_MVL380:
                    plant.outserv = 0
if study_case == 'C0' or study_case == 'C5':
        for statGen in statGens:
            statGen.outserv = 1
        for plant_sync in plants_sync:
            plant_sync.outserv = 0
        for IEC in IECs:
            IEC.outserv = 0
        for IEC_statgen in IEC_statgens:
            IEC_statgen.outserv = 0
        for gen in pvsys:
            gen.outserv = 0
        for WECC in WECCs:
            WECC.outserv = 0
        for plant in plants:
                if plant.loc_name == Plant_Electrolyser_BSL380 or plant.loc_name == Plant_Electrolyser_EEM380 or plant.loc_name == Plant_Electrolyser_MVL380:
                    plant.outserv = 0
```

# C

# Assessment of Voltage Stability Performance

## C.1. STATCOMs

Before the addition of STATCOMs, the generator's reactive power dispatch is altered according to the reactive power headroom left in each generator. Initial power flows (load flow calculation) gives the $Q\_real$ values and the headroom is calculated using the $Q\_max$. Despite change in the dispatches did not change the voltage drops in the terminals (during short-circuit events) which is why STATCOM's are added.

The addition and implementation of STATCOMs is discussed in the Guidelines for Simulations document.

**Table C.1:** Adjusted reactive Power dispatches for the 2017 Peak demand scenario

| Generator | Q_real | Q_max | Q_headroom | Q_adj_dispatch |
|---|---|---|---|---|
| DG_BIOM/COAL_B15_2 | 0 | 765,4 | 765,4 | 0 |
| DG_GAS_B15_1 | 289,6319025 | 1937 | 1536,25 | 402,5 |
| DG_GAS_F15 | 37,33791452 | 86,4 | 67,20833244 | 19,19167 |
| DG_GAS_GDO15 | 74,02813891 | 395,1 | 307,3666702 | 87,73333 |
| DG_GAS_GFU15 | 347,3185031 | 1855,6 | 1485,084161 | 370,4167 |
| DG_GAS_L15 | 104,2389847 | 746,9 | 589,8666595 | 160,4167 |
| DG_GAS_NH15 | 544,4516736 | 3590,1 | 2932,1 | 729,1667 |
| DG_GAS_ON15 | 95,99478651 | 246,9 | 192,0666679 | 54,83333 |
| DG_GAS_Z15_2 | 31,04826895 | 851,9 | 783,3583359 | 72,91666 |
| DG_GAS_ZH15 | 782,4867193 | 4179 | 3318,583313 | 875 |
| DG_NUCL_Z15_1 | 37,29344595 | 609,9 | 468,15 | 141,75 |
| Gen_COAL_EOS15 | 319,8807201 | 975,3 | 515,05 | 230,125 |
| Gen_COAL_MVL15_1 | 0 | 1321 | 1321 | 0 |
| Gen_COAL_MVL15_3 | 207,4233739 | 902,4 | 695,6083282 | 204,1667 |
| Gen_GAS_BGM15 | 0 | 88,9 | 88,9 | 0 |
| Gen_GAS_BSL15 | 68,53905133 | 537,3 | 367,2583282 | 102,0833 |
| Gen_GAS_DIM15 | 122,7212914 | 537 | 429,0833359 | 116,6667 |
| Gen_GAS_DKG15 | 232,8279553 | 580,2 | 305,7416565 | 116,6667 |
| Gen_GAS_EEM15_1 | 71,87314655 | 445,7 | 338,075 | 107,625 |
| Gen_GAS_EEM15_2 | 109,5976948 | 443,2 | 345,4916641 | 52,5 |
| Gen_GAS_EEM15_3 | 90,37722389 | 443,2 | 336,7416641 | 106,4583 |
| Gen_GAS_EEM15_4 | 64,86260531 | 444,4 | 352,2333359 | 102,0833 |
| Gen_GAS_LLS15 | 146,3881371 | 525,9 | 412,4416641 | 113,4583 |
| Gen_GAS_MBT15 | 212,2827191 | 1609,9 | 1609,9 | 0 |
| Gen_GAS_MVL15_2 | 209,2234265 | 521 | 306,3333282 | 116,6667 |
| Gen_GAS_RBB15 | 0 | 161,8 | 161,8 | 0 |
| Gen_GAS_SMH15 | 0 | 525,9 | 525,9 | 0 |

## C.2. Voltage Stability Performance PowerFactory

The steps performed in PowerFactory to perform assessment of voltage stability performance are explained in this section. The script *DSA_python.py* is also explained in this section. *DSA_python.py* is the python script that is used to perform simulation in PowerFactory and export relevant variables while *final_dsa.m* script is used to calculate performance indicators. In Code C.1, all the elements that come under the target names which can be terminals, lines are taken and a short circuit event is created at all the components of the class. If the duration is mentioned in the function call, event the short-circuit clear event is created.

**Listing C.1:** Code snippet to add a short circuit event at target components

```
def addShortCircuitEvent(target_names, time, duration = None):
# getting element where the short circuit will be applied
evt_folder = app.GetFromStudyCase('IntEvt')        # getting the event folder
for target in target_names:        # for each target name
    sc = evt_folder.CreateObject('EvtShc', f'{target.loc_name}')# create a short circuit event
    sc.time = time                 # set the time of the event
    sc.p_target = target           # set the target of the event
    sc.i_shc = 0                # set the short circuit type
    if duration is not None: # if duration is not None
       scc = evt_folder.CreateObject('EvtShc', f'{target.loc_name}-clear')
                   scc.time = time + duration
        scc.p_target = sc.p_target # set the target of the clear event
        scc.i_shc = 4
```

Similar to Code C.1, the code snipped in Code C.2, adds a load event at all the components of the **ElmLod* class. If there are electrolysers active in the scenario, an *if* condition should be inserted in this function to avoid an event at the electrolysers.

**Listing C.2:** Code snippet to add a load event at target loads

```
def addLoadEvents(target_names, time, loadstep):
evt_folder = app.GetFromStudyCase('IntEvt')   # getting the event folder
for i, target in enumerate(target_names):
    le = evt_folder.CreateObject('EvtLod', f'{target.loc_name}')
    le.p_target = target
    le.time = time
    le.iopt_type = 0
    le.dP = loadstep
```

In Code C.3, an outage event is created at the *target_names*, be it generators or transformer. In this work only generators are discussed since a transformer outage in a system such as the Dutch EHV power system is unlikely.

**Listing C.3:** Code snippet used to add an Outage event at target component

```
def addOutageEvents(target_names, time, duration = None):
evt_folder = app.GetFromStudyCase('IntEvt')
for i, target in enumerate(target_names):
    oe = evt_folder.CreateObject(EvtOutage, f'{target.loc_name} ')
    oe.p_target = target
    oe.time = time
    oe.i_what = 3
    if duration is not None:
        oec = evt_folder.CreateObject('EvtOutage', f'{target.loc_name}-clear')
        oec.time = time + duration
        oec.p_target = oe.p_target
        oec.i_what = 2
```

The Code C.4 is used to add relevant variables before every simulation so they can be recorded during the simulation

**Listing C.4:** Code snippet used to add relevant variables

```
def addRecordedResult(elmRes, obj, param):
  if type(obj) is str: # if the object is a string
    for elm in app.GetCalcRelevantObjects(obj): # for each element in the
       object
      elmRes.AddVariable(elm, param)# add the element to the elmRes object
  elif type(obj) is list: # if the object is a list
    for elm in obj:# for each element in the object
      elmRes.AddVariable(elm, param)# add the element to the elmRes object
  else:
    elmRes.AddVariable(obj, param)
```

The variables recorded previously should be exported as results which is executed using ComRes.

**Listing C.5:** Code snippet used to export results as .csv files

```
def export_results(objects, target_type, variable, event_id):
    relevant_objects =
    relevant_variables =
    for object in objects:
        obj_id = object.obj_id
        obj_classname = obj_id.GetClassName()
        if obj_classname == target_type:
            relevant_objects.append(obj_id)
            relevant_variables.extend([variable])
    variable_shortcuts = {
    'c:loading': 'cl',
    'm:u1': 'mu',
    'm:du': 'md',
    'n:dfehz:bus1': 'ndb',
    's:fipol': 'sf',
    'm:Psum:bus1': 'mpb',
    'e:plini': 'ep'}
    shortcut = variable_shortcuts.get(variable, variable)
    fileName = ftarget_type_shortcut_event_id.csv
    filePath = os.path.join(folderPath, fileName)
    comRes = app.GetFromStudyCase(ComRes)
    comRes.pResult = elmRes
    comRes.f_name = filePath
    comRes.iopt_sep = 0
    comRes.col_Sep = ;
    comRes.dec_Sep = .
    comRes.iopt_exp = 6
    comRes.iopt_csel = 1
    comRes.iopt_vars = 0
    comRes.iopt_tsel = 0
    comRes.iopt_rscl = 0
    comRes.iopt_locn = 1
    comRes.ciopt_head = 1
    relevant_objects.insert(0, elmRes)
    relevant_variables.insert(0, 'b:tnow')
    comRes.element = relevant_objects
    comRes.cvariable = relevant_variables
    comRes.Execute()
```

It is very extensive because the *.csv* files exported after each simulation are used either to generate plots in rms simulations or to make indicator calculations in this section. This is majorly to separate all the variables based om their class to make calculations easier and assign shortcuts to all the variables and append the files. While executing ComRes it is important to add the time variable 'b:tnow' which is otherwise added when performing this manually.

In Code C.6, the short-circuit events that are added are simulated, one by one using an *if* condition that checks the loc_name and puts the event and its corresponding 'clear' event in service. Similarly, the outage event and load events are executed. The code is elaborated in the Python file.

**Listing C.6:** Code snippet used to execute simulations with short circuit events

```
def eventSimShortCircuit(target):
    evt_folder = app.GetFromStudyCase('IntEvt')
    events = evt_folder.GetContents()
    target_types = ['lines', 'terminals', 'generators','loads']
    for event_id, target in enumerate(target):
        for event in events:
            event.outserv = 1
# set all the events out of service so each event can be run individually
        for event in events:
            if event.p_target == target:#if the event target is the same
                as the target
                sc_event_name = f'{target.loc_name}'            # set the
                    short circuit event name
                scc_event_name = f'{target.loc_name}-clear'     # set the
                    clear short circuit event name
                if event.loc_name == sc_event_name or event.loc_name ==
                    scc_event_name:
                    event.outserv = 0
        addRecordedResult(elmRes, lines, 'c:loading')
# Run the simulation once after all variables have been added, add
    required variables here
        elmRes_simulation = rmsSimulation(elmRes)  # Run the simulation
            using each elmRes variable
        export_results(objects, 'ElmLne', 'c:loading', event_id)  # Save
            the result for each target type
```

## C.3. Indicator Calculation

The *final_dsa.m* code in MATLAB is used to calculate all the indicators mentioned above. The logic behind how the results from dynamic simulations are extracted from PowerFactory and how the indicators are calculated is discussed in this section.

### File Extraction

The .csv files that are extracted from PowerFactory using the *DSA_python.py* are stored in PC. The directory that shows the location of these files should be mentioned in the code. This is user-defined. Since the files are stored according to the event number and variable, they are sorted into structures according to the event ID. All the variable files that are extracted during a certain event are stored in one "structure". Each structure is then extracted into different cells, which are variables that are necessary for calculation.

### Angle index logic

**Listing C.7:** MATLAB code for calculating Angle index

```
max_adm_phi = 120; %maximum admissible angle as per the synchronism
    protection relay

Delta_phi_max = cell(1,number_events);
```

```
AI = zeros(1,number_events);
for A = 1:number_events
    Delta_phi_max{A} = zeros(1, NG);
    for i = 2:size(firel{1,A},2)
        Delta_phi_max{A}(i-1) = max(firel{1,A}(:,i));
    end
    ratio = Delta_phi_max{A}/max_adm_phi;
    AI(A) = min(1,max(ratio));
end
for A = 1:number_events
    fprintf('AI = %f\n',AI(A));
end
```

**Maximum Frequency Deviation Index logic**

**Listing C.8:** MATLAB code for calculating Maximum Frequency Deviation Index

```
Delta_f_max_adm = 3.5; % Example value for Delta_f_max_adm, the maximum
    admissable frequency deviation

% Calculate Maximum frequency deviation

Delta_f_i_max = cell(1, number_events);
for A = 1:number_events
    Delta_f_i_max{A} = zeros(1, NG);
    for i=2:NG+1
        Delta_f_i_max{A}(i-1) = max(Delta_f_i{1,A}(:,i));
    end
end

% Calculate MFDI
max_values = cell(1, number_events);
for A = 1:number_events
    max_values{A} = zeros(1, NG);
    for i = 1:NG
        max_values{A}(i) = abs(Delta_f_i_max{1,A}(:,i)) / Delta_f_max_adm;
    end
end

MFDI = zeros(1,A);
for A = 1:number_events
    max_MFDI = max(max_values{1,A});
    MFDI(A) = min(1, max_MFDI);
end

% Display the result
fprintf('MFDI = %f\n', MFDI);
```

**Total Frequency Deviation Index logic**

**Listing C.9:** MATLAB code for calculating Total Frequency Deviation Index

```
T_contingency_start = 4; % seconds
T_contingency_end = 4.10; % seconds
% Calculate integral of absolute frequency deviation for each generator

integral = cell(1, number_events); % Initialize integral as a cell array
```

```
TFDI = zeros(1, number_events); % Initialize TFDI as a zeros array
for A = 1: number_events
    %time vector as first column of each Delta_f_i
    time_vector = Delta_f_i{1,A}(:,1);
    % Find the indices corresponding to the contingency time
    contingency_indices = find(time_vector >= T_contingency_start &
        time_vector <= T_contingency_end);

    % Calculate the absolute area of frequency deviation
    integral{A} = trapz(time_vector(contingency_indices), abs(Delta_f_i{1,
        A}(contingency_indices,2)));

    % Calculate the maximum admissible area
    max_admissible_area = Delta_f_max_adm * (T_contingency_end -
        T_contingency_start);

    % Calculate Total Frequency Deviation Index for each event
    ratio = integral{A} / max_admissible_area;
    TFDI(A) = min(1, max(ratio));

    fprintf('TFDI= %f\n',TFDI(A));
end
```

**Dynamic Voltage Index logic**

**Listing C.10:** MATLAB code for calculating Dynamic Voltage Index

```
v_i_min_adm = -0.9*ones(1,NB_B);
v_i_max_adm_B = [];%array of voltages for base case in p.u.
v_i_max_adm_R =  []; %array of voltages for 2030 case in p.u.
%Calculate Minimum instantaneous voltage

v_i_min = cell(1,number_events);
for A = 1:number_events
    v_i_min{A} = zeros(1,NB_B);
    for i = 2:NB_B+1
        v_i_min{A}(i-1)= min(v_i{1,A}(:,i));
    end
end

% Calculate DVI

min_values_DVI = cell(1,number_events);
max_DVI = zeros(1,number_events);
for A = 1:number_events
    min_values_DVI{A} = zeros(1,NB_B);
    for i=1:NB_B
        if NB_B == 88
            min_values_DVI{A}(i) = (v_i_max_adm_B(i) - v_i_min{1,A}(i))/(
                v_i_max_adm_B(i) - abs(v_i_min_adm(i)));
        else
            min_values_DVI{A}(i) = (v_i_max_adm_R(i) - v_i_min{1,A}(i))/(
                v_i_max_adm_R(i) - abs(v_i_min_adm(i)));
        end
    end
    max_DVI(A) = max(min_values_DVI{A});
end
```

```

DVI = min(1, max_DVI);

% Display the result
fprintf('DVI = %f\n', DVI);
```

**Quasi-stationary Voltage index logic**

**Listing C.11:** MATLAB code for calculating Quasi-stationary Voltage index

```
Delta_v_min = -10 * ones(1, NB_B);
Delta_v_max_B = []; %array of voltages for base case in percentages
Delta_v_max_R = [];%array of voltages for 2030 case in percentages
T_contingency = 4; %time at which contingency is active
T_contingency_clear = 4.10; %contingency clear time

vol_i_aft = cell(1, number_events);
max_values_QSVI = cell(1, number_events);
max_QSVI = zeros(1,number_events); % Initialize max_QSVI outside the loop
max_indexes = zeros(1, number_events); % Initialize max_indexes to store
    the indexes

for A = 1:number_events
    Total_time = size(mdu{A},1);
    vol_i_aft{A} = zeros(1,NB_B);
    max_values_QSVI{A} = zeros(1,NB_B);
    for i = 1:Total_time
        if mdu{A}(i,1) == T_contingency_clear
            for j = 1:NB_B
                if i+2 <= Total_time
                    vol_i_aft{A}(1,j) = mdu{A}(i+2,j+1);
                else
                    vol_i_aft{A}(1,j) = mdu{A}(i-2,j+1);
                end
                if NB_B == 88
                    max_values_QSVI{A}(1,j) = vol_i_aft{A}(1,j)/(
                        Delta_v_max_B(j) + abs(Delta_v_min(j))); % Index
                        Delta_v_max with j
                else
                    max_values_QSVI{A}(1,j) = vol_i_aft{A}(1,j)/(
                        Delta_v_max_R(j) + abs(Delta_v_min(j))); % Index
                        Delta_v_max with j
                end
            end
        end
    end
    [max_QSVI(A), max_indexes(A)] = max(abs(max_values_QSVI{A}));
    fprintf('Index at event %d = %d\n', A, max_indexes(A));
end

QSVI = min(1, max_QSVI);

% Display the result
fprintf('QSVI = %f\n', QSVI);
```

**Power Flow Index logic**

**Listing C.12:** MATLAB code for calculating Power Flow Index

```
P_lim = 100; %According to the thermal limit. loading is 100% (strictest
    limit);
P_i_aft = cell(1, number_events);
PFI = zeros(1, number_events);
PFI_NL = cell(1, number_events);

for A = 1:number_events
    Total_time = size(loading{A},1);
    P_i_aft{A} = zeros(1, NL_R);
    for i=1:Total_time
        if loading{A}(i,1) == T_contingency_clear
            for j=2:NL_R+1
                if i+1 <= Total_time
                    P_i_aft{A}(1,j-1) = loading{A}(i+1,j);
                else
                    P_i_aft{A}(1,j-1) = loading{A}(i-1,j);
                end
            end
        end
    end
    PFI_NL{A} = zeros(1,NL_R);
    exceed_flag = false;% flag is to track if any line exceeds P_lim
    for k=1:NL_R
        if P_i_aft{A}(1,k)<P_lim % Changed P_i_lim to P_lim
            PFI_NL{A}(1,k) = P_i_aft{A}(1,k)/P_lim;
        else
            exceed_flag = true;
            PFI(A) = 1;
            break;%
        end
    end
    if ~exceed_flag
       PFI(A) = sum(PFI_NL{A})/NL_R;
    end
end
% Display the result
fprintf('PFI = %f\n', PFI);
```

**Load Shedding Index logic**

**Listing C.13:** MATLAB code for calculating Load Shedding Index

```
% to calculate load shedding index
P_shed = cell(1,number_events);
P_total = cell(1,number_events);
LSI = zeros(1,number_events);
P_shed_final = zeros(1,number_events);

for A = 1:number_events
    time_LSI = size(load_active_power{A},1);
    P_shed{A} = zeros(1,NLoads);
    P_total{A} = zeros(1,NLoads);
    for i = 1:time_LSI
        if load_active_power{A}(i,1) == T_contingency
            for m = 2:NLoads%+1
```

```
                    P_shed{A}(1,m-1) = load_active_power{A}(i+1,m);
                    P_total{A}(1,m-1) = load_power{A}(i+1,m);
                end
            end
        end
end

for A = 1:number_events
    for m = 1:NLoads
        if P_shed{A}(1,m) == 0
            P_shed_final(A) = P_total{A}(1,m);
            break;
        else
            P_shed_final(A) = 0;
        end
    end
end

for A = 1:number_events
    P_sum = 0;
    for m = 1:NLoads
        P_sum = P_sum + P_total{A}(1,m);
        LSI(A) = P_shed_final(A) / P_sum;
    end
end

fprintf('LSI = %f\n',LSI);
```

**Indices files**

**Listing C.14:** MATLAB code for writing Indices .csv file

```
    for A = 1:number_events
    Indices(A,1) = A;
end
Indices(:, 2) = AI;
Indices(:, 3) = MFDI;
Indices(:, 4) = TFDI;
Indices(:, 5) = DVI;
Indices(:, 6) = QSVI;
Indices(:, 7) = PFI;
Indices(:, 8) = LSI;
% Write to CSV
csvwrite('Indices.csv', Indices);
% Open the file with write permission
fid = fopen('Indices.csv', 'w');

% Write the header
fprintf(fid, '%s,%s,%s,%s,%s,%s,%s,%s\n', 'Event_Name','AI','MFDI','TFDI',
    'DVI', 'QSVI', 'PFI','LSI');

% Close the file
fclose(fid);

% Write the data
dlmwrite('Indices.csv', Indices, '-append');
```

# D

# Load Profiles

## D.1. Scenario 2017-2019 Load profiles

**Table D.1:** Hourly Changing load profiles for all loads for 2017-2019 scenarios

| **Hours** | **Load_B150** | **Load_F110** | **Load_GDO110** | **Load_GFU150** | **Load_L150** | **Load_NH150** | **Load_ON110** | **Load_Z150** | **Load_ZH150** |
|---|---|---|---|---|---|---|---|---|---|
| **00:00 - 01:00** | 1950 | 324 | 802 | 1786 | 906,25 | 1831 | 690,75 | 343,25 | 2392 |
| **01:00 - 02:00** | 1909,50 | 317,50 | 785,00 | 1748,25 | 887,25 | 1792,50 | 676,25 | 336,25 | 2341,75 |
| **02:00 - 03:00** | 1825,25 | 303,5 | 750,5 | 1671,5 | 848 | 1713,5 | 646,5 | 321,5 | 2239 |
| **03:00 - 04:00** | 1756,75 | 292 | 722 | 1608,25 | 816,5 | 1649,25 | 622,25 | 309,25 | 2154,25 |
| **04:00 - 05:00** | 1712 | 285 | 704 | 1567,5 | 795,75 | 1607,5 | 606,25 | 301,25 | 2100 |
| **05:00 - 06:00** | 1707 | 283,75 | 701,75 | 1563,25 | 793,25 | 1603 | 604,75 | 300,5 | 2093,75 |
| **06:00 - 07:00** | 1730,5 | 287,5 | 711,75 | 1584,5 | 804,25 | 1625 | 612,75 | 304,5 | 2122,5 |
| **07:00 - 08:00** | 1789,75 | 297,75 | 736 | 1638,75 | 831,5 | 1680,25 | 634 | 315 | 2195 |
| **08:00 - 09:00** | 1850,75 | 307,75 | 761 | 1694,75 | 860 | 1737,5 | 655,5 | 326 | 2270,5 |
| **09:00 - 10:00** | 1919,5 | 319,25 | 789,5 | 1757,75 | 892 | 1802 | 680 | 337,75 | 2354,75 |
| **10:00 - 11:00** | 2043,5 | 340 | 840,5 | 1871,5 | 949,75 | 1918,75 | 724 | 359,5 | 2506,75 |
| **11:00 - 12:00** | 2146,5 | 357 | 882,75 | 1965,75 | 997,5 | 2015,25 | 760,25 | 377,75 | 2632,75 |
| **12:00 - 13:00** | 2215,25 | 368,5 | 911 | 2028,5 | 1029,25 | 2079,75 | 784,75 | 390 | 2717,25 |
| **13:00 - 14:00** | 2238 | 372 | 920,5 | 2049,25 | 1040 | 2101 | 792,75 | 394 | 2745 |
| **14:00 - 15:00** | 2245,25 | 373,5 | 923,25 | 2056 | 1043,25 | 2108 | 795,5 | 395,5 | 2754 |
| **15:00 - 16:00** | 2251,25 | 374,5 | 926 | 2061,25 | 1046,25 | 2113,25 | 797,5 | 396,5 | 2761,5 |
| **16:00 - 17:00** | 2328,25 | 387 | 957,5 | 2132 | 1081,75 | 2186 | 824,75 | 410 | 2855,75 |
| **17:00 - 18:00** | 2495,75 | 414,75 | 1026,5 | 2285,5 | 1159,75 | 2343 | 884 | 439,25 | 3061,25 |
| **18:00 - 19:00** | 2498 | 415,25 | 1027,25 | 2287,5 | 1160,75 | 2345 | 884,75 | 439,75 | 3063,75 |
| **19:00 - 20:00** | 2450,5 | 407,25 | 1008 | 2243,5 | 1138,75 | 2300,75 | 868,25 | 431,25 | 3005,5 |
| **20:00 - 21:00** | 2378,75 | 395,75 | 978,25 | 2178 | 1105,25 | 2233,25 | 842,5 | 418,75 | 2917,75 |
| **21:00 - 22:00** | 2266,5 | 374,4 | 926,2 | 2062,6 | 1046,4 | 2114,6 | 798 | 396,6 | 2762,6 |
| **22:00 - 23:00** | 2145 | 356,75 | 882,25 | 1964,5 | 997 | 2014 | 760 | 377,75 | 2631 |
| **23:00 - 00:00** | 1996,5 | 332,25 | 821 | 1828,25 | 927,75 | 1874,5 | 707,25 | 351,5 | 2448,75 |

# D.2. Scenario 2030 Load Profiles

### Case A0

**Table D.2:** Hourly Changing load profiles for all loads for Case A0 2030 scenario

| Hours | Load_B150 | Load_F110 | Load_GDO110 | Load_GFU150 | Load_L150 | Load_NH150 | Load_ON110 | Load_Z150 | Load_ZH150 |
|---|---|---|---|---|---|---|---|---|---|
| **00:00 - 01:00** | 1367 | 262,75 | 560,75 | 1507,25 | 771,5 | 1927,75 | 595,75 | 413,75 | 1858 |
| **01:00 - 02:00** | 1338,5 | 257,25 | 549,25 | 1475,75 | 755 | 1887,5 | 583,25 | 405 | 1818,75 |
| **02:00 - 03:00** | 1279,25 | 246 | 524,75 | 1410,75 | 722 | 1804,5 | 557,75 | 387,25 | 1739 |
| **03:00 - 04:00** | 1231,25 | 236,75 | 505,25 | 1357,25 | 694,5 | 1736,5 | 536,75 | 372,5 | 1673,25 |
| **04:00 - 05:00** | 1200,25 | 230,75 | 492,75 | 1323,25 | 677 | 1692,5 | 523 | 363,25 | 1631 |
| **05:00 - 06:00** | 1196,5 | 230,25 | 490,75 | 1319,5 | 674,75 | 1688 | 521,5 | 362 | 1626 |
| **06:00 - 07:00** | 1213,25 | 233,25 | 497,5 | 1337,5 | 684,5 | 1710,75 | 528,75 | 367 | 1648,75 |
| **07:00 - 08:00** | 1254,25 | 241,25 | 514,5 | 1383 | 707,75 | 1769,25 | 547 | 379,75 | 1705 |
| **08:00 - 09:00** | 1297,5 | 249,5 | 532,5 | 1430,75 | 732 | 1829,75 | 565,5 | 392,5 | 1763,5 |
| **09:00 - 10:00** | 1345,5 | 258,75 | 552 | 1483,75 | 759,25 | 1898 | 586,5 | 407,25 | 1828,75 |
| **10:00 - 11:00** | 1432,75 | 275,5 | 588 | 1579,75 | 808 | 2020,5 | 624,5 | 433,5 | 1947 |
| **11:00 - 12:00** | 1505 | 289,25 | 617,5 | 1659 | 848,5 | 2122,25 | 655,75 | 455,25 | 2045 |
| **12:00 - 13:00** | 1553 | 298,75 | 637 | 1712 | 876 | 2190 | 676,75 | 470 | 2110,5 |
| **13:00 - 14:00** | 1568,5 | 302 | 643,5 | 1729,75 | 885 | 2212,5 | 683,75 | 474,75 | 2131,75 |
| **14:00 - 15:00** | 1574 | 302,5 | 645,75 | 1735,75 | 887,75 | 2219,75 | 686 | 476,5 | 2139 |
| **15:00 - 16:00** | 1578 | 303,5 | 647,5 | 1739,75 | 890 | 2225,5 | 687,75 | 477,75 | 2144,5 |
| **16:00 - 17:00** | 1632 | 313,75 | 669,5 | 1799,25 | 920,75 | 2301,75 | 711,5 | 494 | 2217,75 |
| **17:00 - 18:00** | 1749,5 | 336,25 | 718 | 1929 | 986,75 | 2467 | 762,75 | 529,25 | 2377,5 |
| **18:00 - 19:00** | 1751,25 | 336,5 | 718,5 | 1930,75 | 987,75 | 2469,25 | 763,25 | 529,75 | 2379,75 |
| **19:00 - 20:00** | 1717,75 | 330,25 | 704,75 | 1893,75 | 969 | 2422,5 | 748,75 | 519,75 | 2334,5 |
| **20:00 - 21:00** | 1667,5 | 320,75 | 684,25 | 1838,5 | 940,75 | 2351,5 | 726,75 | 504,5 | 2266,25 |
| **21:00 - 22:00** | 1588,75 | 305,5 | 652 | 1752,25 | 896,5 | 2240,75 | 692,75 | 480,75 | 2159,25 |
| **22:00 - 23:00** | 1503,75 | 289 | 617 | 1658 | 848,25 | 2120,75 | 655,75 | 455,25 | 2043,5 |
| **23:00 - 00:00** | 1399,75 | 269 | 574,25 | 1543,25 | 789,75 | 1973,75 | 610 | 423,5 | 1901,75 |

### Case B0

**Table D.3:** Hourly Changing load profiles for all loads for Case B0 2030 scenarios

| Hours | Load_B150 | Load_F110 | Load_GDO110 | Load_GFU150 | Load_L150 | Load_NH150 | Load_ON110 | Load_Z150 | Load_ZH150 |
|---|---|---|---|---|---|---|---|---|---|
| **00:00 - 01:00** | 1367 | 262,75 | 560,75 | 1507,25 | 771,5 | 1927,75 | 595,75 | 413,75 | 1858 |
| **01:00 - 02:00** | 1338,5 | 257,25 | 549,25 | 1475,75 | 755 | 1887,5 | 583 | 405 | 1818,75 |
| **02:00 - 03:00** | 1279,25 | 246 | 524,75 | 1410,75 | 722 | 1804,25 | 557,75 | 387,25 | 1739 |
| **03:00 - 04:00** | 1231,25 | 236,75 | 505,25 | 1357,25 | 694,5 | 1736,5 | 536,75 | 372,5 | 1673,25 |
| **04:00 - 05:00** | 1200,25 | 230,75 | 492,75 | 1323,25 | 677 | 1692,5 | 523 | 363 | 1631 |
| **05:00 - 06:00** | 1196,5 | 230,25 | 490,75 | 1319,5 | 674,75 | 1688 | 521,5 | 362 | 1626 |
| **06:00 - 07:00** | 1213,25 | 233,25 | 497,5 | 1337,5 | 684,5 | 1710,75 | 528,75 | 367 | 1648,75 |
| **07:00 - 08:00** | 1254,25 | 241,25 | 514,5 | 1383 | 707,75 | 1769,25 | 546,75 | 379,5 | 1705 |
| **08:00 - 09:00** | 1297,5 | 249,5 | 532,5 | 1430,75 | 732 | 1829,75 | 565,5 | 392,5 | 1763,5 |
| **09:00 - 10:00** | 1345,75 | 258,75 | 552 | 1483,75 | 759,25 | 1897,75 | 586,5 | 407,25 | 1828,75 |
| **10:00 - 11:00** | 1432,75 | 275,5 | 588 | 1579,75 | 808 | 2020,5 | 624,5 | 433,5 | 1947 |
| **11:00 - 12:00** | 1505 | 289,25 | 617,5 | 1659 | 848,5 | 2122,25 | 655,75 | 455,25 | 2045 |
| **12:00 - 13:00** | 1553 | 298,75 | 637 | 1712 | 876 | 2190 | 676,75 | 470 | 2110,5 |
| **13:00 - 14:00** | 1568,5 | 302 | 643,5 | 1729,75 | 885 | 2212,5 | 683,75 | 474,5 | 2131,75 |
| **14:00 - 15:00** | 1574 | 302,5 | 645,75 | 1735,75 | 887,75 | 2219,75 | 686 | 476,5 | 2139 |
| **15:00 - 16:00** | 1578,25 | 303,5 | 647,5 | 1739,75 | 890 | 2225,5 | 687,5 | 477,5 | 2144,5 |
| **16:00 - 17:00** | 1632 | 313,75 | 669,5 | 1799,25 | 920,75 | 2301,75 | 711 | 494 | 2217,75 |
| **17:00 - 18:00** | 1749,5 | 336,25 | 718 | 1929 | 986,75 | 2467 | 762,75 | 529,25 | 2377,5 |
| **18:00 - 19:00** | 1751,25 | 336,5 | 718,5 | 1930,75 | 987,75 | 2469,25 | 763,25 | 529,75 | 2379,75 |
| **19:00 - 20:00** | 1717,75 | 330,25 | 704,75 | 1893,75 | 969 | 2422,5 | 748,75 | 519,75 | 2334,5 |
| **20:00 - 21:00** | 1667,5 | 320,75 | 684,25 | 1838,5 | 940,75 | 2351,5 | 726,75 | 504,5 | 2266,25 |
| **21:00 - 22:00** | 1589 | 305,5 | 652 | 1752,25 | 896,5 | 2240,75 | 692,75 | 480,5 | 2159,25 |
| **22:00 - 23:00** | 1503,75 | 289 | 617 | 1658 | 848,25 | 2120,75 | 655,75 | 455,25 | 2043,5 |
| **23:00 - 00:00** | 1399,75 | 269 | 574,25 | 1543,25 | 789,75 | 1973,75 | 610 | 423,5 | 1901,75 |

## Case C0

**Table D.4:** Hourly Changing load profiles for all loads for Case C0 2030 scenario

| Hours | Load_B150 | Load_F110 | Load_GDO110 | Load_GFU150 | Load_L150 | Load_NH150 | Load_ON110 | Load_Z150 | Load_ZH150 |
|---|---|---|---|---|---|---|---|---|---|
| **00:00 - 01:00** | 1794 | 345 | 736 | 1978,25 | 1012 | 2530,5 | 782,25 | 543 | 2438,5 |
| **01:00 - 02:00** | 1756,75 | 338 | 720,5 | 1936,75 | 991 | 2477,25 | 765,75 | 531,5 | 2387 |
| **02:00 - 03:00** | 1679,25 | 323 | 689 | 1851,75 | 947,5 | 2368,5 | 732 | 508 | 2282,25 |
| **03:00 - 04:00** | 1616 | 310,75 | 663,25 | 1782 | 911,5 | 2279,25 | 704,25 | 489 | 2196 |
| **04:00 - 05:00** | 1575,25 | 303 | 646,25 | 1736,75 | 888,25 | 2221,25 | 686,5 | 476,75 | 2140,75 |
| **05:00 - 06:00** | 1570,75 | 302 | 644,5 | 1732 | 886,25 | 2215 | 684,75 | 475,5 | 2134,75 |
| **06:00 - 07:00** | 1592 | 306,25 | 653,25 | 1755,5 | 898,25 | 2245,5 | 694 | 481,5 | 2163,75 |
| **07:00 - 08:00** | 1646,5 | 316,75 | 675,5 | 1815,5 | 929 | 2321,75 | 717,75 | 498,25 | 2237,5 |
| **08:00 - 09:00** | 1703 | 327,5 | 698,5 | 1877,5 | 960,5 | 2401,75 | 742,25 | 515,25 | 2314,5 |
| **09:00 - 10:00** | 1766,25 | 339,75 | 724,5 | 1947,5 | 996,5 | 2490,75 | 770 | 534,25 | 2400 |
| **10:00 - 11:00** | 1880,5 | 361,5 | 771,5 | 2073,5 | 1061 | 2652 | 819,75 | 569 | 2555,5 |
| **11:00 - 12:00** | 1974,75 | 379,75 | 810 | 2177,75 | 1114,25 | 2785,25 | 860,5 | 597,75 | 2684 |
| **12:00 - 13:00** | 2038,5 | 391,75 | 836 | 2247 | 1149,75 | 2874,5 | 888,5 | 616,75 | 2769,75 |
| **13:00 - 14:00** | 2059 | 396 | 844,75 | 2270 | 1161,5 | 2904 | 897,5 | 623 | 2798 |
| **14:00 - 15:00** | 2066 | 397,5 | 847,5 | 2277,5 | 1165,25 | 2913,25 | 900,5 | 624,75 | 2807,25 |
| **15:00 - 16:00** | 2071,25 | 398,5 | 850 | 2283,75 | 1168,5 | 2921,25 | 903 | 626,5 | 2814,75 |
| **16:00 - 17:00** | 2142,25 | 412 | 879 | 2361,75 | 1208,25 | 3021 | 933,5 | 648,25 | 2911,25 |
| **17:00 - 18:00** | 2296,5 | 441,25 | 942,25 | 2531,75 | 1295,5 | 3238,25 | 1000,75 | 694,5 | 3120,5 |
| **18:00 - 19:00** | 2298 | 442 | 943 | 2534 | 1296,25 | 3241,25 | 1001,75 | 695,5 | 3123,25 |
| **19:00 - 20:00** | 2254,5 | 433,25 | 925 | 2485,75 | 1271,75 | 3179,25 | 982,75 | 682 | 3064 |
| **20:00 - 21:00** | 2188,75 | 420,75 | 898,25 | 2413 | 1234,5 | 3086,5 | 954,25 | 662,25 | 2974,25 |
| **21:00 - 22:00** | 2085,5 | 401 | 855,5 | 2299,5 | 1176,5 | 2941 | 909 | 631 | 2834,25 |
| **22:00 - 23:00** | 1973,75 | 379,5 | 809,75 | 2176 | 1113,25 | 2783,5 | 860,25 | 597,25 | 2682,5 |
| **23:00 - 00:00** | 1837 | 353,25 | 753,75 | 2025,25 | 1036,5 | 2590,5 | 800,75 | 555,5 | 2496,25 |