



Advanced network operation and management demonstration

Deliverable No: D6.6

Work package: WP6

Official delivery date: 30.06.2026

Actual delivery date: 30.06.2026 (v1), 09.10.2026 (v2)

Dissemination level: Public



Co-funded by
the European Union

Project: 101136119 | HORIZON-CL5-2023-D3-01 | www.twineu.net

Disclaimer

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Document Authors
Gregor Omahen (ELES)
Jernej Lasnik (ELES)
Herman Leopold (UNL)
Urban Rudež (UNL)
Matjaž Škrlec (UNL)
Nermin Suljanović (EIMV)

Version	Date	Notes
0.1	07.02.2025.	First version
0.2	29.05.2025.	Second version, internal review
0.3	30.06.2026	Third version, not reviewed internally yet

Responsible Partner	ELES
Checked by WP leader	Daniele Porcu (ENEL), 30.06.2026 (v1), 08.10.2026 (v2)
Verified by the appointed Reviewers	Nikolaos Koltsaklis (UPRC), 24.08.2026 Kata Fehér (HUPX), 07.10.2026
Approved by Project Coordinator	Padraic McKeever (Fraunhofer), 30.06.2026 (v1), 09.10.2026 (v2)

Table of Contents

Executive Summary	10
1 Introduction	12
1.1 Slovenian demo	12
1.2 Objectives of the Work Reported in this Deliverable	12
1.3 Outline of the Deliverable	13
1.4 How to Read this Document.....	14
2 Current state analysis	15
2.1 Overview of Slovenian power grid	15
2.2 Digital twin in Slovenian power network	16
2.3 Challenges.....	17
3 Methodology and implementation pathway.....	20
3.1 Digital twins in Slovenian demonstration.....	20
3.2 Transmission digital twin	21
3.3 Distribution digital twin	23
3.3.1 Equivalent distribution grid model in CIM	25
3.3.2 Distribution grid model parameterization	29
3.3.3 Parameterization of the static component of the load model	39
3.3.4 Modelling of loads in the distribution grid in PowerFactory	67
3.4 Dynamic security assessment tool	79
3.4.1 Extent of the conducted work.....	79
3.4.2 Dynamic security assessment concept	85
3.4.3 Fully automatized static validation and confirmational test run	86
3.4.4 Acceleration processes.....	88
3.4.5 Visualization and graphical-user interface	92
3.5 Use cases	97
3.5.1 Use Case 1: Upgraded Dynamic RMS Analysis (SLO-BUC-1)	97
3.5.2 Use Case 2: Real-time Dynamic RMS Analysis with Transmission System Model improved with the dynamic parameters of generators and control models of the neighbouring TSOs.....	99
3.5.3 Use Case 3: SCADA/EMS Data Integration for Operational Simulation (SLO-SUC-1)....	102
3.6 Study cases	103
3.6.1 Study case #1, night-time operation	103
3.6.2 Study case #2, day-time operation	110
3.6.3 Study case #3, detected operational issue.....	117
4 Conclusions.....	121
References	123

List of Figures

Figure 2.1: Extent of the observability area model.....	18
Figure 3.1: Task flow of the model creation procedure	20
Figure 3.2: The extent of the Digital twin for DSA purposes	21
Figure 3.3: Comparison of real measurements and model calculations	22
Figure 3.4: Transition from existing distribution grid models to advanced ones	24
Figure 3.5: Methodology of distribution digital twin.....	24
Figure 3.6: Dependencies between the profiles belonging to CGMES [1].....	25
Figure 3.7: Dynamic data of synchronous generator in CIM CGMES	26
Figure 3.8: PowerElectronics package in CGMES [1]	26
Figure 3.9: An example serialisation of static PV model in CGMES.....	26
Figure 3.10: Dynamic modelling of load in CGMES [1]	27
Figure 3.11: An exemplary ZIP load model in CIM.....	28
Figure 3.12: The process of automatic extending transmission network model with distribution equivalent	28
Figure 3.13: Exemplary XML file for difference CIM model.....	29
Figure 3.14: Methodology Overview: Load Model Parameterization.	30
Figure 3.15: Scheduled OLTC Switching Intervals and Transformer Tap Position Changes.....	32
Figure 3.16: Voltage and power profiles for TP Labore, Dinos, Prebačev, and Staretova.....	33
Figure 3.17: Event Identification Flowchart.....	35
Figure 3.18: R^2 and σ analysis for filtered events in Labore	36
Figure 3.19: R^2 and σ analysis for filtered events in Prebačev.....	36
Figure 3.20: R^2 and σ analysis for filtered events in Dinos	36
Figure 3.21: R^2 and σ analysis for filtered events in Staretova	36
Figure 3.22: R^2 and σ analysis for filtered events in RTP Labore TR2	38
Figure 3.23: R^2 and σ analysis for filtered events in RTP Labore TR3	38
Figure 3.24: R^2 and σ analysis for filtered events in RTP Primskovo TR1	38
Figure 3.25: R^2 and σ analysis for filtered events in RTP Primskovo TR2	38
Figure 3.26: Histogram of model parameters Labore – First set of measurements.....	41
Figure 3.27: Model fitting to measured data in Labore – First set of measurements.....	41
Figure 3.28: P(U) graph for selected events in Labore – First set of measurements	42
Figure 3.29: Histogram of the P(U) model parameters Labore TR2 – Second set of measurements...	43
Figure 3.30: Histogram of the Q(U) model parameters Labore TR2 – Second set of measurements..	44

Figure 3.31: Distribution of the exponential factor K_p RTP Labore TR2 – Second set of measurements	44
Figure 3.32: Distribution of the exponential factor K_q RTP Labore TR2 – Second set of measurements	45
Figure 3.33: Model $P(U)$ fitting to measured data in Labore TR2 – Second set of measurements	46
Figure 3.34: Model $Q(U)$ fitting to measured data in Labore TR2 – Second set of measurements	47
Figure 3.35: $P(U)$ graph for selected events in Labore TR2 – Second set of measurements.....	48
Figure 3.36: $Q(U)$ graph for selected events in Labore TR2 – Second set of measurements	49
Figure 3.37: Histogram of the $P(U)$ model parameters Labore TR3 – Second set of measurements...	49
Figure 3.38: Histogram of the $Q(U)$ model parameters Labore TR3 – Second set of measurements ..	50
Figure 3.39: Distribution of the exponential factor K_p RTP Labore TR3 – Second set of measurements	51
Figure 3.40: Distribution of the exponential factor K_q RTP Labore TR3 – Second set of measurements	51
Figure 3.41: Model $P(U)$ fitting to measured data in Labore TR3 – Second set of measurements	52
Figure 3.42: Model $Q(U)$ fitting to measured data in Labore TR3 – Second set of measurements	53
Figure 3.43: $P(U)$ graph for selected events in Labore TR3 – Second set of measurements.....	54
Figure 3.44: $Q(U)$ graph for selected events in Labore TR3 – Second set of measurements	55
Figure 3.45: Histogram of the $P(U)$ model parameters Primskovo TR1 – Second set of measurements	56
Figure 3.46: Histogram of the $Q(U)$ model parameters Primskovo TR1 – Second set of measurements	56
Figure 3.47: Distribution of the exponential factor K_p RTP Primskovo TR1 – Second set of measurements	57
Figure 3.48: Distribution of the exponential factor K_q RTP Primskovo TR1 – Second set of measurements	58
Figure 3.49: Model $P(U)$ fitting to measured data in Primskovo TR1 – Second set of measurements	58
Figure 3.50: Model $Q(U)$ fitting to measured data in Primskovo TR1 – Second set of measurements	59
Figure 3.51: $P(U)$ graph for selected events in Primskovo TR1 – Second set of measurements.....	60
Figure 3.52: $Q(U)$ graph for selected events in Primskovo TR1 – Second set of measurements	61
Figure 3.53: Histogram of the $P(U)$ model parameters Primskovo TR2 – Second set of measurements	61
Figure 3.54: Histogram of the $Q(U)$ model parameters Primskovo TR2 – Second set of measurements	62
Figure 3.55: Distribution of the exponential factor K_p RTP Primskovo TR2 – Second set of measurements	63

Figure 3.56: Distribution of the exponential factor K_q RTP Primskovo TR2 – Second set of measurements	63
Figure 3.57: Model $P(U)$ fitting to measured data (selected measurements) in Primskovo TR2 – Second set of measurements	64
Figure 3.58: Model $Q(U)$ fitting to measured data (selected measurements) in Primskovo TR2 – Second set of measurements	65
Figure 3.59: $P(U)$ graph for selected events in Primskovo TR2 – Second set of measurements	66
Figure 3.60: $Q(U)$ graph for selected events in Primskovo TR2 – Second set of measurements	67
Figure 3.61: Attributes of a dynamical non-linear load in Power Factory	68
Figure 3.62: A model of the analyzed grid in Power Factory	69
Figure 3.63: Input voltage attribute in the AC voltage source	70
Figure 3.64: TS Kleče	71
Figure 3.65: TS Okroglo	71
Figure 3.66: Voltage on the 220 kV and 400 kV side during the instantaneous input voltage change	72
Figure 3.67: Voltage on the 110 kV side of two during the instantaneous voltage change	72
Figure 3.68: Voltage on the 110 kV side of TS Bohinj and TS Labore during the instantaneous voltage change	73
Figure 3.69: Voltage on the 110 kV side of TS Tržič and TS Radovljica during the instantaneous voltage change	73
Figure 3.70: The sum of active and reactive power of all loads in the region	74
Figure 3.71: The impact of the delay parameter on the sum of active and reactive power for residential loads	74
Figure 3.72: Location of the 3-phase short-circuit fault on a 110 kV busbar in TS Bohinj	75
Figure 3.73: The sum of active and reactive power of all loads in the 3-phase short-circuit analysis	76
Figure 3.74: The behaviour of the active and reactive power of a load in Bohinj during a 3-phase short circuit analysis	76
Figure 3.75: Voltage in Bohinj and Radovljica during a 3-phase short-circuit analysis	77
Figure 3.76: Voltage in Labore and Tržič during a 3-phase short-circuit analysis	77
Figure 3.77: Voltage on the 110 kV side in Kleče and Okroglo during a 3-phase short-circuit analysis	78
Figure 3.78 Conceptual Illustration of the Transition from a Steady-State Equivalent to a Dynamic Network Representation	83
Figure 3.79 Stability Phenomena and Associated Stability Indices Implemented in the DSA Tool	84
Figure 3.80 Traffic-light color-coding visualization for stability assessment	85
Figure 3.81 The Dynamic Security Assessment (DSA) concept	85
Figure 3.82 Parallelization of the Time-Domain Simulation Process Across Multiple Processor Cores	88

Figure 3.83 Time-domain calculations without AI support.....	89
Figure 3.84 Comparison of TSA Indices Obtained from Conventional Simulations and a Pre-Trained AI Model.....	90
Figure 3.85 Time-domain calculations with AI support	91
Figure 3.86 Comparison of Total DSA Execution Times With and Without AI Support for analysed 96 Operating States	91
Figure 3.87 Main Input Window of the Dynamic Security Assessment Tool.....	92
Figure 3.88 TSA Dashboard Displaying Critical Clearing Time Results for the Analysed Generating Units	94
Figure 3.89 Frequency Stability Dashboard Displaying RoCoF and System Inertia Indicators	95
Figure 3.90 Small-Signal Stability Dashboard Displaying Electromechanical Oscillation Modes and Associated Stability Indicators.....	97
Figure 3.91 Study case #1 - static validation results (transmission line active power)	104
Figure 3.92 Study case #1 - static validation results (transmission line reactive power)	105
Figure 3.93 Study case #1 - static validation results (bus voltage deviation).....	106
Figure 3.94 Study case #1 - TSA results.....	107
Figure 3.95 Study case #1 – FSA results (map chart)	108
Figure 3.96 Study case #1 – FSA results (bar chart).....	108
Figure 3.97 Study case #1 - SSSA results (polar chart).....	109
Figure 3.98 Study case #1 - SSSA results (grid chart).....	110
Figure 3.99 Study case #1 - SSSA results (mode details).....	110
Figure 3.100 Study case #2 - static validation results (transmission line active power)	111
Figure 3.101 Study case #2 - static validation results (transmission line reactive power)	112
Figure 3.102 Study case #2 - static validation results (bus voltage deviation).....	113
Figure 3.103 Study case #2 - TSA results	113
Figure 3.104 Study case #2 – FSA results (map chart)	114
Figure 3.105 Study case #2 – FSA results (bar chart).....	115
Figure 3.106 Study case #2 - SSSA results (polar chart).....	116
Figure 3.107 Study case #2 - SSSA results (grid chart).....	117
Figure 3.108 Study case #3 - evolution of the corresponding critical clearing time together with the active and reactive power output of GEN ₅₄	118
Figure 3.109 Study case #3 - The critical clearing times for the fault on line44 for different setpoints of reactive power of generator GEN ₅₄	119
Figure 3.110 Study case #3 - Graphical representation of power system transient stability for 29 November at 23:15.	120

List of Tables

Table 1: Event Filtering Criteria..... 34

Table 2: Parameters of dynamical loads; residential, commercial, industrial IM and VFD 68

Table 3: KPI evaluation for SLO-BUC-1..... 98

Table 4: KPI evaluation for SLO-BUC-2..... 100

Table 5: KPI evaluation for SLO-SUC-1 103

List of Abbreviations and Acronyms

Acronym	Meaning
ADMS	Advanced Distribution Management System
API	Application Programming Interface
AR/VR	Augmented Reality/ Virtual Reality
BESS	Battery Energy Storage System
CGMES	Common Grid Model Exchange Standard
CCT	Critical Clearing Time
CIM	Common Information Model
DER	Distribute Energy Resource
DSA	Dynamic Security Assessment
DSO	Distribution System Operator
EMS	Energy Management System
FACTS	Flexible AC Transmission System
GIS	Geographic Information System
GUI	Graphical User Interface
HV	High Voltage
LSM	Least Squares Method
LV	Low Voltage
MV	Medium Voltage
OLTC	On-Load Tap Changer
PGM	Power Generating Module
RoCoF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator

Executive Summary

The rapid evolution of power systems, driven by the increasing integration of renewable energy sources, distributed energy resources, power-electronic interfaced generation, and the growing need for real-time security assessment, has fundamentally changed the operational challenges faced by transmission system operators. The TwinEU project addresses these challenges through the development of advanced digital twin technologies capable of supporting operational decision-making by combining detailed power system models, real-time operational data, and dynamic security assessment (DSA) methodologies.

This deliverable presents the Slovenian TwinEU demonstrator, describing the development, implementation, and validation of a comprehensive digital twin of the Slovenian power system together with a real-time DSA framework. The developed solution integrates a detailed dynamic transmission network model with an extended observability-area model and equivalent representations of the distribution network. Particular attention is devoted to the modelling of voltage- and frequency-dependent loads, aggregation of distributed energy resources, automated model preparation and validation, and incorporation of dynamic information originating from neighbouring transmission system operators through the TwinEU federated data exchange concept.

Building upon the developed digital twin, a fully automated DSA framework was implemented. The framework periodically imports operating snapshots from the SCADA/EMS environment, automatically generates and validates the corresponding digital twin, performs transient, frequency, and small-signal stability analyses, and visualizes the resulting stability indices through an operator-oriented graphical interface. To achieve computational performance suitable for operational environments, the framework combines parallel execution of time-domain simulations with AI-assisted stability screening, significantly reducing computational effort while maintaining the reliability of simulation-based assessments.

Key outcomes of the Slovenian demonstrator include:

- A comprehensive digital twin of the Slovenian transmission system integrated with an extended observability-area model, enabling realistic representation of cross-border dynamic interactions.
- Development of equivalent distribution network models incorporating voltage- and frequency-dependent load behaviour together with aggregated distributed generation.
- Automated procedures for digital twin generation, model merging, parametrization, correction, validation, and periodic execution using real-time SCADA/EMS data.
- A dynamic security assessment framework capable of evaluating transient stability, frequency stability, and small-signal stability under actual operating conditions.
- AI-assisted acceleration techniques and parallel simulation workflows enabling near real-time execution of computationally intensive dynamic analyses.
- An intuitive visualization environment that transforms complex simulation results into actionable stability information suitable for transmission system operators.
- Successful implementation and validation of the Slovenian TwinEU use cases, including the demonstration of federated exchange of dynamic generator information and interoperability with neighbouring TSOs.

The developed framework was successfully validated using extensive sets of real operating data from the Slovenian transmission system, demonstrating accurate reconstruction of operating

conditions and reliable assessment of dynamic stability margins under different operating scenarios. The presented methodology confirms that digital twin technology can provide tangible operational value by transforming detailed dynamic simulations into automated decision-support tools suitable for future transmission system operation.

Overall, the Slovenian TwinEU demonstrator establishes a scalable and modular foundation for the future deployment of digital twin technologies within European transmission systems, contributing to more secure, resilient, and data-driven operation of increasingly dynamic interconnected power systems.

1 Introduction

Electrical power system is facing challenges in recent years how to efficiently integrate large quantities of distributed renewable sources on one hand and new relatively large loads such as heat pumps and e-mobility on another. Gradual phase out of traditional fossil fuel power plants and large share of renewables is impacting the grid operation and requires new tools and approaches in the control centre. In these demonstrations we will present how developing and enabling such tools will allow continuous efficient, safe and reliable operation of the power system.

1.1 Slovenian demo

The Slovenian demo is serving as a live testbed to showcase the application of digital twin technology in dynamic security assessment. Slovenia's power system, with its unique blend of high-voltage transmission lines and a rapidly evolving distribution network, presents an ideal environment for testing innovative grid management solutions. The demonstrator integrates detailed models of the Slovenian transmission system (with its interconnections to neighbouring European networks, whose details for exact modelling are less available) with advanced representations of distributed generation and voltage-sensitive loads in the distribution system.

The choice of Slovenia is driven by several factors:

- **High Renewable Penetration:** The Slovenian grid has seen a significant rise in renewable installations—particularly (roof-top) photovoltaic—which introduce variability and require more agile stability assessment tools.
- **Interconnected Network:** Slovenia's grid forms an integral part of the Continental European (CE) interconnection. The dynamic interactions between the domestic grid and neighbouring systems provide a realistic setting to evaluate the influence of disturbances on local stability.
- **Operational Complexity:** With an increasing share of decentralized generation and dynamic load profiles, the Slovenian grid exhibits complex behaviour that traditional static models cannot fully capture. This calls for a comprehensive digital twin approach that models both steady-state conditions and dynamic responses to disturbances in real time.
- **Pilot Environment:** The demonstrator is deployed within the infrastructure of ELES, the national system operator, where real-time data are collected via SCADA/EMS systems. This live environment facilitates the testing and validation of dynamic simulations against actual operating conditions.

Through the Slovenian demo, TwinEU aims to validate a digital twin framework that can be scaled and adapted to other European systems, ensuring that the lessons learned in Slovenia benefit broader grid modernization efforts.

1.2 Objectives of the Work Reported in this Deliverable

This deliverable is built around several core objectives that address both the technical and operational challenges of modern grid management:

- **Integration of Dynamic Models:**
Develop a unified model that merges a detailed dynamic simulation model of the Slovenian transmission system (supplied by ELES) with a simplified steady-state model of the observability area, supplemented with dynamic data. This integration is essential to capture

both the network's dynamic responses to events within Slovenia alongside the influences from the interconnected European network.

- **Development of the Digital Twin Framework:**
Create a comprehensive digital twin for the distribution network that accurately represents the voltage- and frequency-dependent behaviour of aggregated loads and distributed generation. This twin will replace traditional constant load representations with a dynamic model that better reflects the real-world operating conditions.
- **Real-Time Dynamic Security Assessment:**
Design and implement a dynamic security assessment tool that processes live operational data from SCADA/EMS systems. The tool must calculate key stability indices—such as critical clearing time (CCT), frequency nadirs, and damping ratios—to provide an early warning system for grid instability.
- **Data Integration and Interoperability:**
Ensure seamless data exchange between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) by adopting standardized data models (e.g., Common Information Model, CIM) and protocols (IEC 61970/61968). This objective is critical for the accurate and timely incorporation of operational data into the digital twin framework.
- **Validation and Use Case Demonstration:**
Validate the integrated dynamic model using historical data, field measurements, and real-time snapshots, ensuring that simulation outputs closely align with observed grid behaviour. In addition, the deliverable includes several use cases that demonstrate the practical application of the digital twin approach in dynamic security assessments.
- **Enhanced Visualization for Decision-Making:**
Develop an intuitive graphical user interface (GUI) that aggregates simulation results into easily interpretable visual outputs. While emerging immersive technologies such as AR/VR (Augmented Reality/ Virtual Reality) were considered, the focus remains on clear, conventional visualization techniques that reduce cognitive load and support rapid operator response.

1.3 Outline of the Deliverable

This deliverable is structured into four main chapters, which together describe the development, implementation, and validation of the Slovenian TwinEU demonstrator:

- **Chapter 2** presents the current state analysis of the Slovenian power system. It introduces the characteristics of the Slovenian transmission network and the main challenges associated with dynamic modelling of a highly interconnected power system with an increasing share of renewable energy sources and distributed energy resources.
- **Chapter 3** describes the methodology and implementation pathway of the Slovenian demonstrator. It first presents the overall digital twin concept, followed by the implementation of both the transmission and distribution digital twins. The chapter further describes the development of equivalent distribution network models, their parameterization, and the implementation of voltage- and frequency-dependent load models. The second part of the chapter focuses on the Dynamic Security Assessment (DSA) framework, including the developed workflows, automated model preparation and validation, computational acceleration techniques, graphical user interface, implementation of the

project use cases, and demonstration of the developed solution through representative study cases based on real operating conditions of the Slovenian power system.

- **Chapter 4** summarizes the main achievements of the work, evaluates the overall outcomes of the Slovenian demonstrator, and outlines the most important directions for future development of digital twin technologies and dynamic security assessment tools.

1.4 How to Read this Document

This deliverable is one of several deliverables focusing on individual demonstrations. Our work is deriving from work packages 2, 3 and 4 and will be later outlined in work packages 8 and 9.

2 Current state analysis

This chapter presents a detailed examination of the current state of the Slovenian power grid, providing both a macro- and micro-level understanding of its structure, digital twin implementations, and the operational challenges that necessitate a dynamic security assessment approach.

2.1 Overview of Slovenian power grid

The Slovenian power system integrates high-voltage transmission networks with medium and low voltage distribution systems. At the transmission level, the network operates primarily with 400, 220, and 110 kV lines, which facilitate long-distance power transport and interconnection with neighbouring European systems. The grid is managed by ELES, which provides detailed models that simulate both steady-state conditions and dynamic events.

Key aspects of the Slovenian power system include:

- **Interconnection and Border Dynamics:**
Slovenia's transmission system is tightly interconnected with the Continental European (CE) network. This means that the system's dynamics is influenced not only by domestic power-system elements (e.g. generation and load) but also by those connected externally, outside national borders. Tie-lines and border nodes play a critical role in these interactions, serving as points for data and power exchange and consequently integration of external grid models.
- **High Renewable Penetration:**
In recent years, Slovenia has experienced significant growth in renewable energy installations, particularly in photovoltaic (PV) and wind power. These renewable sources contribute to a variable generation profile that challenges knowledge on stability properties of grids supplied by conventional generation. The fluctuating nature of renewables necessitates appropriate dynamic modelling techniques to capture the rapid transitions in generation and load.
- **Diverse Load Profiles:**
The grid serves a mix of industrial, commercial, and residential loads. These loads exhibit different voltage/frequency sensitivities and consequently individual dynamic responses. Industrial loads tend to be more stable and predictable, whereas residential loads can be highly stochastic and influenced by consumer behaviour and environmental factors.
- **Infrastructure Upgrades:**
Recent investments in the network modernization have focused on enhancing monitoring and control capabilities. The deployment of advanced SCADA/EMS systems has improved the real-time visibility of network conditions, while new technologies in digital metering and communication have facilitated the collection of high-resolution operational data.
- **Dynamic Model Fidelity:**
The dynamic models used by ELES incorporate detailed representations of generators, FACTS (Flexible AC Transmission System) devices, and network compensation systems. These models are critical for simulating transient events such as faults, sudden load changes, or generator outages. However, the accuracy of these models is continually challenged by the evolving grid conditions and the increasing integration of DERs.

Overall, the Slovenian power system represents a complex, dynamic environment where traditional analysis methods must be augmented by digital twin technologies and real-time data

integration. The insights gained from this detailed overview form the basis for developing a dynamic security assessment tool that can respond to the rapid changes in grid conditions.

2.2 Digital twin in Slovenian power network

The concept of a digital twin in the context of the Slovenian power network involves creating a virtual replica of the physical network that mirrors its dynamic behaviour in real time. This virtual model integrates detailed dynamic representation of the transmission system with aggregated models of the distribution network. The digital twin framework serves several critical functions:

- **Real-Time Simulation and Monitoring:**
The digital twin continuously receives data from the SCADA/EMS systems, updating its state to reflect the current operational conditions. This real-time feedback loop enables the model to replicate real conditions when simulating a series of probable events, providing operators with up-to-date insights into system stability.
- **Integration of Multi-Level Models:**
A key innovation in the TwinEU approach is the merging of the detailed dynamic model of the Slovenian transmission network with a steady-state model of the surrounding observability area, supplemented with available dynamic data. This hybrid model allows for a comprehensive simulation of local phenomena (e.g., voltage sags or electromechanical oscillations) being impacted by the broader impacts of cross-border interactions.
- **Incorporation of Distributed Generation and Load Dynamics:**
Unlike traditional models that represent distribution networks as static PQ loads, the digital twin incorporates dynamic representations of DERs and voltage-dependent load models. The advanced modelling techniques enable the twin to simulate the rapid fluctuations and non-linear behaviours observed in low-voltage networks.
- **Data-Driven Parameterisation:**
The digital twin is not a static model but is continuously refined using data from extensive measurement campaigns. Parameters such as load sensitivity, generation variability, and network impedance are regularly updated based on high-resolution data, ensuring that the model remains accurate under varying operating conditions. Furthermore, the TwinEU project introduced a pan-European demonstration scenario aimed at validating the feasibility of dynamic data exchange between neighbouring transmission system operators. The scenario highlighted the potential benefits of sharing dynamic network representations, enabling more accurate modelling of cross-border interactions and improving the reliability of dynamic security assessments in interconnected power systems.
- **Operational Decision Support:**
The digital twin generates key stability indices (including critical clearing time, rate-of-change-of-frequency RoCoF values, and damping ratios) which are presented via an intuitive graphical interface. These indices provide actionable insights for grid operators, enabling them to identify and mitigate potential stability issues before they arise and escalate.

By appropriately replicating the complex dynamics of the Slovenian power network, the digital twin forms the backbone of the dynamic security assessment tool. Its ability to integrate real-time data with advanced simulation capabilities ensures that the virtual model always remains a true representation of the physical grid.

The high share of renewables and decentralized generation connected to the distribution grid is changing the traditional approach of the dynamic analysis of power systems. In addition to the impact of bulk power generation on system stability, the dynamic analysis of the power system should also include the power generation connected to the distribution grid. Nowadays, the total PV generation in Slovenia, mainly connected to the distribution grid, reaches 1.3 GW and its influence cannot be neglected.

Due to the requirements posed by complex analysis at the transmission grid level, the distribution network should be presented with an appropriate equivalent.

2.3 Challenges

Despite the advancements in digital twin technology and dynamic modelling, several challenges persist in accurately representing and managing the Slovenian power grid:

- **Variability of Renewable Generation:**

The intermittent nature of renewable sources introduces significant uncertainty into the dynamic model. Rapid fluctuations in generation can lead to instability, making it essential to accurately capture these variations within the digital twin. The challenge is compounded by the need to integrate real-time weather data and other environmental factors that affect the power output of renewables.

- **Complex Interconnections and External Influences:**

Slovenia's grid is strongly interconnected with neighbouring systems. Disturbances originating from neighbouring countries can propagate into the Slovenian network, complicating the assessment of local stability. The digital twin must therefore incorporate external network models to account for their non-negligible impact, despite limitations in data availability and model resolution. Figure below shows the area that is relevant for digital twin of Slovenia. It is evident that the extent of the so-called observability area significantly exceeds the geographical footprint of the Slovenian 220 kV and 400 kV transmission network. This highlights a distinctive characteristic of the Slovenian power system, where the dynamic behaviour of the national grid is strongly influenced by neighbouring systems. The relatively small size of the Slovenian transmission network, combined with its high degree of interconnection with surrounding countries, results in pronounced cross-border dynamic interactions that must be adequately represented within the digital twin and dynamic security assessment framework.

- **Aggregation of Distributed Generation:**

Aggregating numerous small-scale DERs into a single, representative model poses significant methodological challenges. Each DER type (synchronous or asynchronous) exhibits distinct dynamic characteristics. The aggregation process must preserve these differences to ensure that the equivalent model accurately reflects the impact of distributed generation on grid stability.

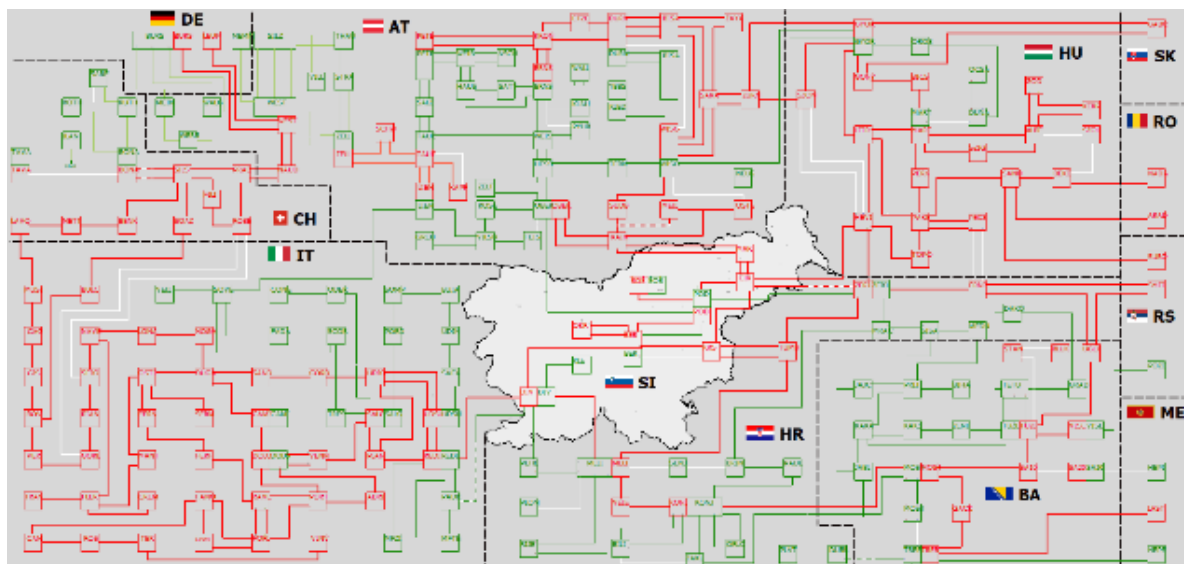


Figure 2.1: Extent of the observability area model

- **Voltage- and Frequency-Dependent Load Models:**

Traditional load models often assume constant power consumption or constant impedance; however, real-world loads are highly dependent on voltage and frequency conditions. Developing accurate load models requires high-resolution measurement data and sophisticated parameter estimation techniques. The challenge lies in filtering out noise and isolating the true load response from other transient events such as OLTC switching operations.

- **Data Quality and Real-Time Integration:**

The effectiveness of the digital twin depends on the quality of data fed into it. Inconsistencies, delays, or inaccuracies in data acquisition from SCADA/EMS systems can lead to discrepancies between the simulated and actual grid states. Moreover, the process of standardizing data formats (using CIM and related protocols) for seamless integration presents technical challenges, especially when dealing with heterogeneous data sources.

- **Computational Efficiency vs. Model Detail:**

A detailed dynamic model that incorporates every nuance of grid behaviour can be computationally intensive, which is problematic for real-time applications. Balancing the trade-off between model accuracy and computational efficiency was addressed within the project through a combination of two complementary technological approaches. First, extensive parallelization of computationally demanding time-domain simulations enables multiple contingency scenarios to be evaluated simultaneously, significantly reducing overall assessment time. Second, artificial intelligence models were trained to provide rapid preliminary estimates of key stability indices. These estimates are subsequently verified using detailed time-domain simulations, ensuring a high level of confidence in the final results while substantially accelerating the overall assessment process. This hybrid approach enabled near real-time performance without compromising the reliability expected by transmission system operators. Furthermore, it represents an important step towards the gradual integration of AI-based decision-support tools into operational power-system processes, where transparency, explainability, and trust remain essential prerequisites for practical adoption.

- **Interoperability and Standardization:**

The digital twin must operate within a broader ecosystem that includes tools from multiple vendors and different technological platforms. Ensuring interoperability through standardized data models and APIs is crucial, but the diversity of existing systems means that achieving full standardization is an ongoing process.

In summary, while the current state of the Slovenian power grid and its digital twin representation shows great promise, addressing these challenges is critical to the success of the dynamic security assessment tool. Overcoming these issues will lead to a more robust, responsive, and scalable solution capable of enhancing grid stability across diverse operating conditions.

3 Methodology and implementation pathway

This chapter describes the comprehensive methodology and implementation pathway for developing and deploying the dynamic security assessment tool within the TwinEU Slovenian demonstrator. The approach integrates advanced dynamic modelling, real-time data processing, and a modular digital twin framework to deliver actionable insights into grid stability.

3.1 Digital twins in Slovenian demonstration

The digital twin concept is central to the TwinEU approach. In the Slovenian demonstration, digital twins are constructed for both the transmission and distribution segments of the power system. These virtual replicas are continuously updated (with a 15-minute resolution) using real-time data from SCADA/EMS systems, ensuring that they accurately reflect the current state of the physical grid. Figure 3.1 shows task flow of the model creation procedure.

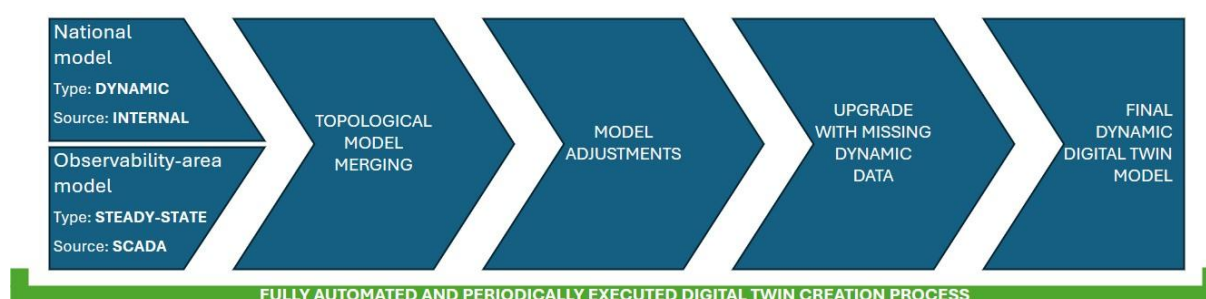


Figure 3.1: Task flow of the model creation procedure

The process of creating the digital twins involves several key steps:

- **Model Acquisition and Preprocessing:**

The starting point is the acquisition of detailed dynamic models of the Slovenian transmission network provided by ELES. These models, developed in DigSILENT PowerFactory, incorporate generator dynamics, FACTS devices, and compensation devices. In parallel, a steady-state model of the observability area is obtained from EMS (energy management system) data and converted to a compatible format.
- **Model Merging:**

The first step in creating the digital twin is topologically merging the detailed dynamic model of the national network with the steady-state representation of the external network, including the outer perimeter equivalents of the remaining continental interconnection. This merging process uses fully automated Python scripts to identify common tie-lines and replace constant load nodes with dynamic equivalents. The resulting model integrates both local and external influences, providing a holistic representation of the network – see Figure below.
- **Data-Driven Parameterization:**

High-resolution measurement data are used to fine-tune load models and update dynamic parameters. This includes calibrating voltage–frequency dependencies and aggregating the behaviours of distributed generation. The calibration process employs regression techniques and least squares methods to ensure that the digital twin accurately replicates observed system responses.

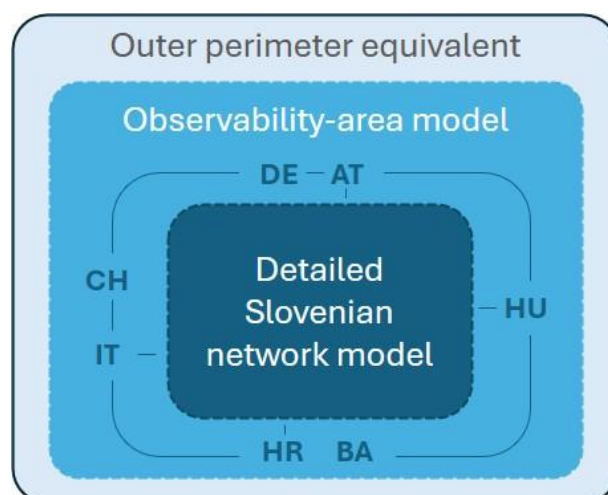


Figure 3.2: The extent of the Digital twin for DSA purposes

The digital twin serves as the backbone for all subsequent dynamic analyses, enabling the integration of complex phenomena such as renewable variability, DER aggregation, and transient events into a single, unified model.

3.2 Transmission digital twin

The transmission digital twin focuses on modelling the high-voltage network that forms the backbone of the Slovenian power system. Key aspects of this twin include:

- Detailed Generator Models:**
 Each synchronous generator in the transmission system is represented with dynamic models that include governor and excitation controller parameters. Where specific data are unavailable, generic models based on industry recommendations are applied. This ensures that the dynamic behaviour of generators—particularly their response to transient disturbances—is accurately captured.
- Network Topology and Interconnections:**
 The twin includes a detailed representation of the transmission network topology, including key tie-lines that connect Slovenia to its neighbouring countries. This detailed mapping is crucial for simulating the propagation of disturbances and understanding the interdependencies between domestic and external grids.
- Dynamic Simulation of Faults and Contingencies:**
 The transmission digital twin is used to simulate a range of contingency scenarios, such as line faults, generator outages, and load shedding events. Time-domain simulations are performed to evaluate transient responses and calculate stability indices such as the critical clearing time (CCT) and frequency nadirs.

The transmission digital twin is thus a detailed and dynamic representation of the high-voltage network, enabling the simulation of complex dynamic phenomena and providing a reliable foundation for overall grid stability assessment.

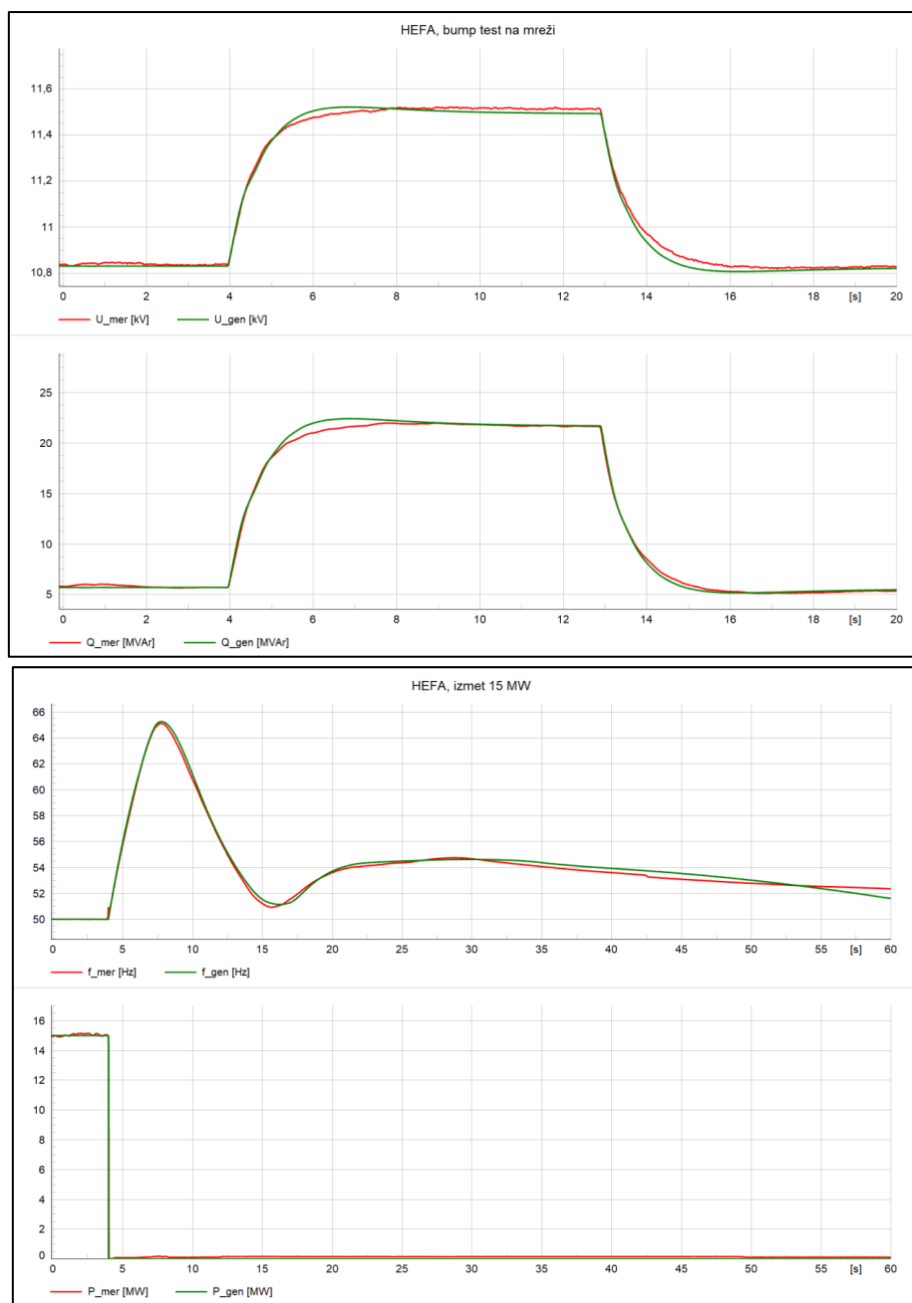


Figure 3.3: Comparison of real measurements and model calculations

The main work was focused on transition from NEPLAN to DigSILENT Power Factory environment. Most of the tasks are already finished and we are finalizing troubleshooting and refinement of Slovenian model. The following tasks were already concluded:

- Development of individual PGM/BESS/FACTS dynamic models,
- Validation of individual models based on field measurements, and
- Integration of individual models into the Slovenian transmission grid dynamic model.

The model was tested against real situations and is showing high level of accuracy as shown in Figure 3.3.

3.3 Distribution digital twin

The distribution digital twin addresses the unique challenges associated with the modelling lower-voltage grids, where distributed generation and voltage-dependent loads are predominant. Its development involves several innovative steps:

- **Aggregation of Distributed Generation:**
The digital twin aggregates numerous small-scale DERs—including PV installations, small wind turbines, and combined heat and power units—into an equivalent model that captures their collective impact on the grid. This aggregation process involves grouping units by type and calibrating the equivalent model using field measurements and statistical analysis.
- **Voltage–Frequency Dependent Load Models:**
Unlike traditional models that assume constant power consumption or constant-impedance behaviour, the distribution digital twin incorporates load models that are sensitive to voltage and frequency variations. Data from measurement campaigns are used to parameterize these models, ensuring that the dynamic response of both residential and industrial loads is accurately represented.
- **Integration with the Transmission Model:**
Once developed, the distribution digital twin is integrated with the transmission twin to form a comprehensive, multi-layered digital replica of the entire grid. This integration is critical for capturing the interactions between high-voltage transmission and lower-voltage distribution networks, particularly under dynamic conditions.
- **Validation through OLTC Event Analysis:**
The twin leverages data from On-Load Tap Changer (OLTC) switching events to refine its parameters. These events provide clear instances of voltage variation and load response, which are used to validate the dynamic models of the distribution network.

The distribution digital twin not only enhances the overall accuracy of the grid simulation but also enables the digital twin framework to capture the nuanced behaviours of modern, DER-rich distribution networks.

Currently, the distribution grid model in Slovenia is modelled as a constant PQ load in all analyses, thus constantly consuming energy from the transmission grid. This can be seen in the schematic representation of a HV/MV substation in Figure 3.4, where the MV level on feeders LOAD1 and LOAD2 is not modelled, but instead the consumption of both feeders is modelled as a constant load, connected to the HV busbars. In such a model, no generation is included, although it is present in the MV grid. This type of modelling is suitable for stationary analyses but can no longer be considered valid for dynamic analyses in the future. Therefore, there is a need for the development of dynamic models of distributed energy sources for the dynamic analyses of the power system. This study does not focus on developing models for a specific type of power generation, but on aggregation and development of equivalent models that represent many DERs with acceptable accuracy. The dynamic DER models of an individual technology (PV, hydro, loads etc) already available in the dynamic simulation tools (Power Factory) are used.

The proposed equivalent model is intended to represent the aggregated dynamic behaviour of many small distributed inverter-based generators (e.g. rooftop PV), asynchronous (e.g. small hydro) and synchronous (e.g. diesel) generators connected to the distribution grid. Aggregation can take place at different levels of the grid hierarchy, leading to a higher or lower complexity of the model. On

the other hand, it is important to emphasize that the use of equivalents and the simplification of the model must not jeopardize the accuracy of the simulations.

Focus was to develop a more accurate distribution grid equivalent models for system studies, that take into account a more detailed approximation of loads and generators on distribution nodes as shown in Figure below.

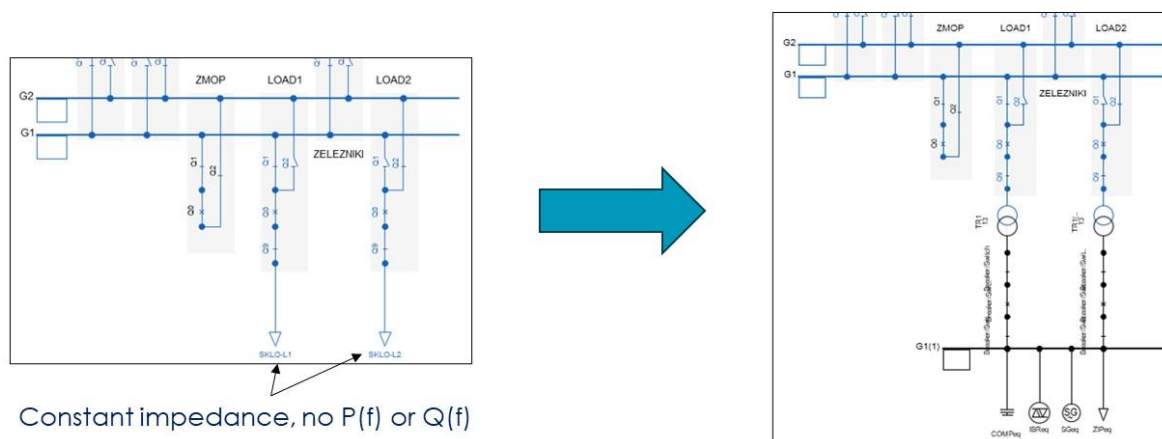


Figure 3.4: Transition from existing distribution grid models to advanced ones

The steps for development of dynamic model of the distribution system, for the purpose of the overall power system stability analysis is presented in Figure 3.5.

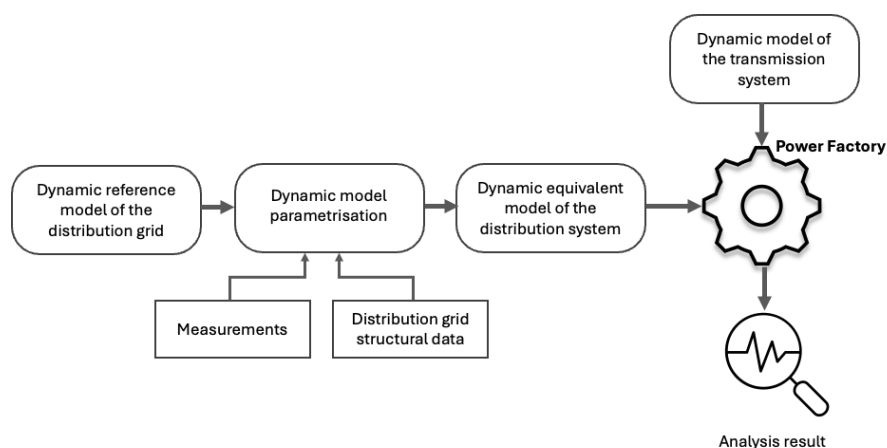


Figure 3.5: Methodology of distribution digital twin

The first step in this process is to develop dynamic reference model of the distribution grid that is appropriate for dynamic analysis of power system at the transmission level. This reference model is determined to be as straightforward as possible with satisfactory accuracy. This dynamic reference model is further parametrized using measurements and structure data. In the next step, dynamic transmission and distribution model are assembled in the Power Factory software for the stability analysis. In the final step, the dynamic equivalent is modelled in CIM so that it can be merged with the transmission network model. This step is important for the automatic process of collecting distribution network data from ADMS and GIS and automatically merging the distribution equivalent with the transmission grid model.

3.3.1 Equivalent distribution grid model in CIM

CIM enables semantic and syntactic interoperability between systems and applications, when exchange power system data. For the transmission network modelling, ENTSO-E developed CGMES (Common Grid Model Exchange Specification) profile. Given that transmission grids are already modelled using CGMES, it is logical and beneficial to adopt the same approach for modelling medium-voltage (MV) distribution networks, ensuring consistency and interoperability across grid domains.

Equivalent distribution grid model incorporates aggregated distributed generation and variable load, as presented in Figure 3.4. The aggregated generation includes at least:

- Roof-top PV plants (inverter-based generators),
- Asynchronous (e.g. small hydro) and
- Synchronous (e.g. diesel) generators.

Dynamic models in CIM are defined by standard IEC 61970-457 and are included in CGMES (Figure 3.6).

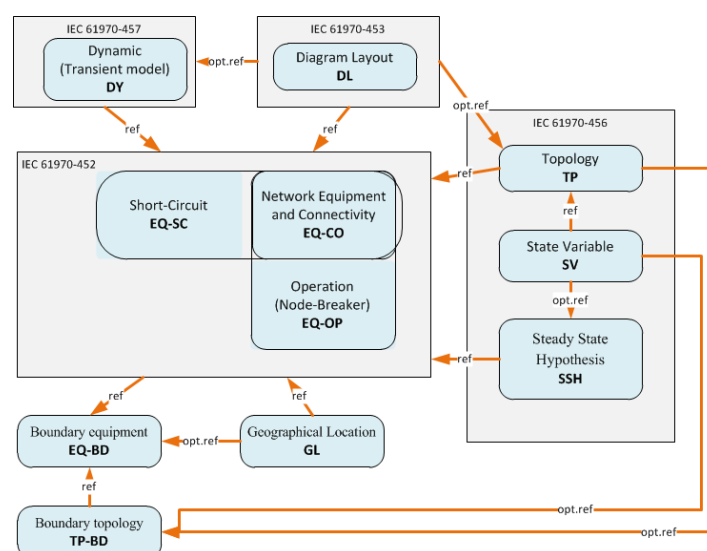


Figure 3.6: Dependencies between the profiles belonging to CGMES [1]

Since all analyses are conducted using the numerical simulation tool PowerFactory, it is essential to validate its interoperability with the CGMES standard. PowerFactory generally supports both the export and import of network models in CGMES 3.0 format. However, a consistent and verifiable mapping must be established between PowerFactory's internal data structures and network models serialized in CGMES 3.0 RDF/XML files. Furthermore, the CGMES Dynamic package provides support for the representation of dynamic models of rotating machines, such as synchronous and asynchronous generators, as well as the dynamic behaviour of loads. While CGMES EQ file contains a topological, static representation of the equipment and connectivity in the power system, dynamic data are stored in the CGMES DY file. An example how dynamic data of synchronous generator are written in DY file is presented in Figure 3.7.

```

<cim:SynchronousMachineTimeConstantReactance rdf:ID="68c60f87-103d-d7a5-c02b-9b3f069fe425">
  <cim:DynamicsFunctionBlock.enabled>true</cim:DynamicsFunctionBlock.enabled>
  <cim:IdentifiedObject.name>Synchronous Machine</cim:IdentifiedObject.name>
  <cim:RotatingMachineDynamics.damping>0</cim:RotatingMachineDynamics.damping>
  <cim:RotatingMachineDynamics.inertia>3.48149</cim:RotatingMachineDynamics.inertia>
  <cim:RotatingMachineDynamics.saturationFactor>0</cim:RotatingMachineDynamics.saturationFactor>
  <cim:RotatingMachineDynamics.saturationFactor120>0</cim:RotatingMachineDynamics.saturationFactor120>
  <cim:RotatingMachineDynamics.statorLeakageReactance>0.1</cim:RotatingMachineDynamics.statorLeakageReactance>
  <cim:RotatingMachineDynamics.statorResistance>0.0021</cim:RotatingMachineDynamics.statorResistance>
  <cim:SynchronousMachineDetailed.eFdBaseRatio>1</cim:SynchronousMachineDetailed.eFdBaseRatio>
  <cim:SynchronousMachineDetailed.ifdBaseType rdf:resource="http://iec.ch/TC57/2013/CIM-schema-cim16#IfdBaseKind.ifag" />
  <cim:SynchronousMachineDynamics.SynchronousMachine rdf:resource="#_559f34ce-a946-48f3-886b-314a6c2ec760" />
  <cim:SynchronousMachineTimeConstantReactance.ks>0</cim:SynchronousMachineTimeConstantReactance.ks>
  <cim:SynchronousMachineTimeConstantReactance.modeType rdf:resource="http://iec.ch/TC57/2013/CIM-schema-cim16#SynchronousMachineModelKind.subtransient" />
  <cim:SynchronousMachineTimeConstantReactance.rotorType rdf:resource="http://iec.ch/TC57/2013/CIM-schema-cim16#RotorKind.roundRotor" />
  <cim:SynchronousMachineTimeConstantReactance.tc>0</cim:SynchronousMachineTimeConstantReactance.tc>
  <cim:SynchronousMachineTimeConstantReactance.tpdo>6.85907</cim:SynchronousMachineTimeConstantReactance.tpdo>
  <cim:SynchronousMachineTimeConstantReactance.tppdo>0.0284918</cim:SynchronousMachineTimeConstantReactance.tppdo>
  <cim:SynchronousMachineTimeConstantReactance.tppqo>0.0451518</cim:SynchronousMachineTimeConstantReactance.tppqo>
  <cim:SynchronousMachineTimeConstantReactance.tpqo>3.77143</cim:SynchronousMachineTimeConstantReactance.tpqo>
  <cim:SynchronousMachineTimeConstantReactance.xDirectSubtrans>0.183</cim:SynchronousMachineTimeConstantReactance.xDirectSubtrans>
  <cim:SynchronousMachineTimeConstantReactance.xDirectSync>2.54</cim:SynchronousMachineTimeConstantReactance.xDirectSync>
  <cim:SynchronousMachineTimeConstantReactance.xDirectTrans>0.237</cim:SynchronousMachineTimeConstantReactance.xDirectTrans>
  <cim:SynchronousMachineTimeConstantReactance.xQuadSubtrans>0.191</cim:SynchronousMachineTimeConstantReactance.xQuadSubtrans>
  <cim:SynchronousMachineTimeConstantReactance.xQuadSync>2.31</cim:SynchronousMachineTimeConstantReactance.xQuadSync>
  <cim:SynchronousMachineTimeConstantReactance.xQuadTrans>0.392</cim:SynchronousMachineTimeConstantReactance.xQuadTrans>
</cim:SynchronousMachineTimeConstantReactance>

```

Figure 3.7: Dynamic data of synchronous generator in CIM CGMES

The CGMES PowerElectronics package, used for modelling PV units in the EQ profile, is illustrated in Figure 3.8. The class PhotovoltaicUnit represents the PV generator, while PowerElectronicsConnection models the inverter interface with the grid. It is important to emphasize that this configuration represents only the static behaviour of the PV system; dynamic behaviour must be modelled separately using the CGMES Dynamics profile.

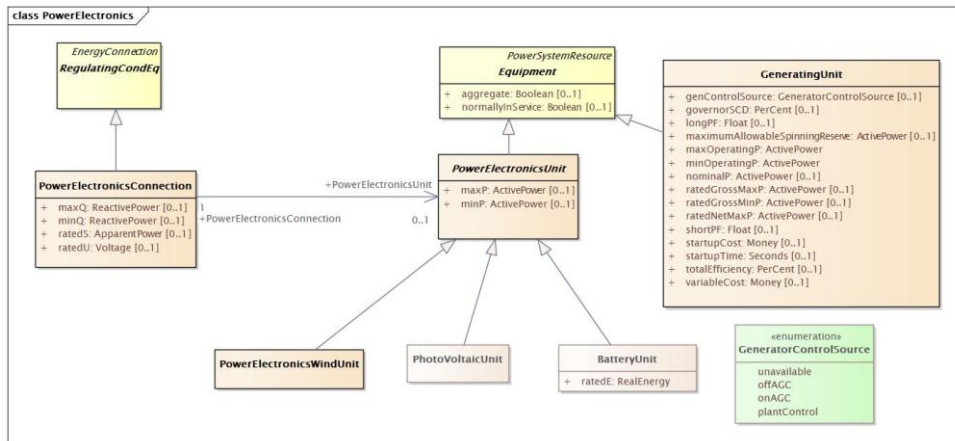


Figure 3.8: PowerElectronics package in CGMES [1]

An example of PV model data serialised in EQ file is given in Figure 3.9.

```

<cim:PowerElectronicsConnection rdf:about="urn:uuid:2021c5e6-099b-420b-80d6-13d72c187d0b">
  <rdf:type rdf:resource="http://iec.ch/TC57/CIM100#PowerElectronicsConnection"/>
  <cim:IdentifiedObject.name>INV_PV_001</cim:IdentifiedObject.name>
  <cim:ConductingEquipment.BaseVoltage rdf:resource="urn:uuid:67a2c33e-2f83-4df4-bc7a-8fba2f00cf3b"/>
</cim:PowerElectronicsConnection>

<cim:PhotovoltaicUnit rdf:about="urn:uuid:7fcb3f61-e8e5-4b7a-b804-e6f93bb902e1">
  <rdf:type rdf:resource="http://iec.ch/TC57/CIM100#PhotovoltaicUnit"/>
  <cim:IdentifiedObject.name>PV_Plant_New</cim:IdentifiedObject.name>
  <cim:GeneratingUnit.maxOperatingP>100</cim:GeneratingUnit.maxOperatingP>
  <cim:GeneratingUnit.highControlLimit>100</cim:GeneratingUnit.highControlLimit>
  <cim:GeneratingUnit.lowControlLimit>0</cim:GeneratingUnit.lowControlLimit>
  <cim:PowerGeneratingUnit.genUnit rdf:resource="urn:uuid:2021c5e6-099b-420b-80d6-13d72c187d0b"/>
</cim:PhotovoltaicUnit>

```

Figure 3.9: An example serialisation of static PV model in CGMES

However, the CGMES Dynamics profile does not provide native support for modelling inverter-based dynamics of PV plants. As a result, PV units are typically included only in the EQ profile, while all dynamic parameters associated with inverter behaviour must be defined directly within the Power Factory environment. Although the abstract class `DynamicsFunctionBlock` could be used to reference a PV unit from the EQ profile, any dynamic representation of PV behaviour would require CIM extensions not defined in the standard CGMES schema. Consequently, automatic import and interpretation of such models into Power Factory is not supported.

The dynamic behaviour of loads is supported in CGMES through the `LoadDynamics` package, as illustrated in Figure 3.10. For modelling aggregated loads in an equivalent distribution grid, the `LoadStatic` class is typically used. This class represents the conventional ZIP load model, allowing the definition of constant impedance, constant current, and constant power components. An example of the corresponding RDF/XML serialization is shown in Figure 3.11.

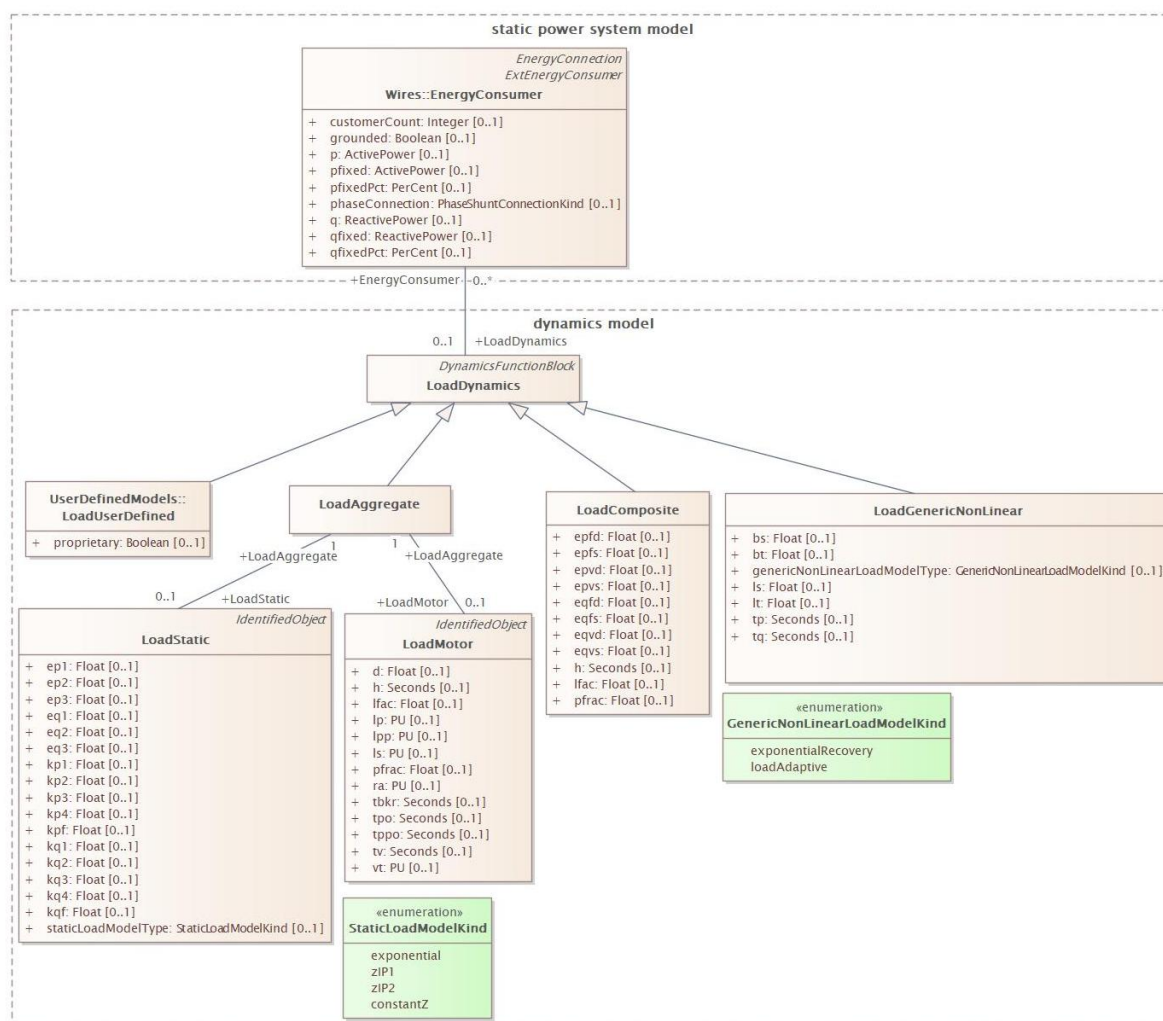


Figure 3.10: Dynamic modelling of load in CGMES [1]

```

<cim:LoadStatic rdf:about="urn:uuid:123e4567-e89b-12d3-a456-426614174000">
  <rdf:type rdf:resource="http://iec.ch/TC57/61970-302#LoadStatic"/>

  <!-- Reference to EnergyConsumer this load dynamics is applied to -->
  <cim:PowerSystemResource.PowerSystemResources rdf:resource="urn:uuid:ec3b92df-3e0d-47e5-9206-a90dc163f11f"/>

  <!-- ZIP Coefficients for Active Power -->
  <cim:LoadStatic.pConstantImpedance>0.2</cim:LoadStatic.pConstantImpedance>
  <cim:LoadStatic.pConstantCurrent>0.3</cim:LoadStatic.pConstantCurrent>
  <cim:LoadStatic.pConstantPower>0.5</cim:LoadStatic.pConstantPower>

  <!-- ZIP Coefficients for Reactive Power -->
  <cim:LoadStatic.qConstantImpedance>0.3</cim:LoadStatic.qConstantImpedance>
  <cim:LoadStatic.qConstantCurrent>0.3</cim:LoadStatic.qConstantCurrent>
  <cim:LoadStatic.qConstantPower>0.4</cim:LoadStatic.qConstantPower>

  <!-- Additional parameters (optional) -->
  <cim:LoadStatic.exponentModel>false</cim:LoadStatic.exponentModel>
  <cim:LoadStatic.vmin>0.7</cim:LoadStatic.vmin>
  <cim:LoadStatic.vmax>1.3</cim:LoadStatic.vmax>
</cim:LoadStatic>

```

Figure 3.11: An exemplary ZIP load model in CIM

The concept of modelling both transmission and distribution networks in CIM is aimed at automating the integration of an equivalent distribution network model into the transmission system model. The equivalent model of the distribution grid typically includes aggregated generation by type and a static load representation. To support this, the necessary model parameters are extracted through the processing of a detailed distribution network model, provided in CIM format. This process is schematically illustrated in Figure 3.12. In this process is important to keep in mind to model distribution equivalent in a standard way with CGMES 3.0 profile without extensions, in order to maintain interoperability with PowerFactory.

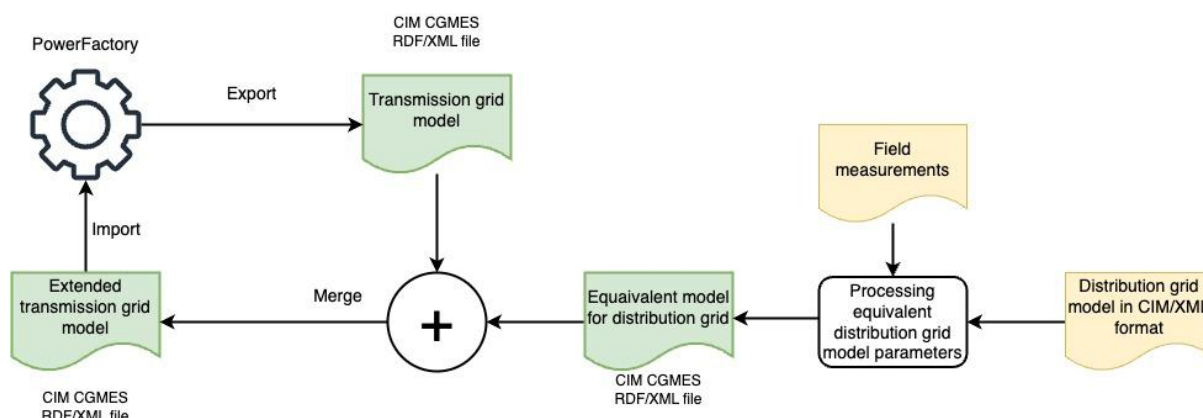


Figure 3.12: The process of automatic extending transmission network model with distribution equivalent

One approach in CGMES to extend transmission network model with distribution grid equivalent is to use incremental updates and difference model, that is difference CIM file. Usage of CIM difference models are defined in standard IEC 61970-552 [2]. This approach is an elegant way to extend network model with new network elements or to update network element attributes. Exemplary XML file for difference model for the distribution grid equivalent is given in Figure 3.13.

```

<?xml version="1.0" encoding="UTF-8"?>
<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:cim="http://iec.ch/TC57/CIM100#">

  <!-- Connectivity Node -->
  <cim:ConnectivityNode rdf:ID="Node_PV_Connect">
    <rdf:type rdf:resource="http://iec.ch/TC57/CIM100#ConnectivityNode"/>
    <cim:IdentifiedObject.name>PV_Connection_Node</cim:IdentifiedObject.name>
    <cim:ConnectivityNode.ConnectivityNodeContainer rdf:resource="#VoltageLevel_1"/>
  </cim:ConnectivityNode>

  <!-- Terminal for Inverter -->
  <cim:Terminal rdf:ID="Terminal_PV_Inverter">
    <rdf:type rdf:resource="http://iec.ch/TC57/CIM100#Terminal"/>
    <cim:IdentifiedObject.name>PV Terminal</cim:IdentifiedObject.name>
    <cim:Terminal.ConnectivityNode rdf:resource="#Node_PV_Connect"/>
    <cim:Terminal.ConductingEquipment rdf:resource="#Inverter_PV_001"/>
  </cim:Terminal>

  <!-- Inverter (PowerElectronicsConnection) -->
  <cim:PowerElectronicsConnection rdf:ID="Inverter_PV_001">
    <rdf:type rdf:resource="http://iec.ch/TC57/CIM100#PowerElectronicsConnection"/>
    <cim:IdentifiedObject.name>PV Inverter</cim:IdentifiedObject.name>
    <cim:ConductingEquipment.BaseVoltage rdf:resource="#BaseVoltage_20kV"/>
  </cim:PowerElectronicsConnection>

  <!-- PV Plant -->
  <cim:PhotovoltaicUnit rdf:ID="PV_Unit_001">
    <rdf:type rdf:resource="http://iec.ch/TC57/CIM100#PhotovoltaicUnit"/>
    <cim:IdentifiedObject.name>New PV Plant</cim:IdentifiedObject.name>
    <cim:GeneratingUnit.maxOperatingP>800</cim:GeneratingUnit.maxOperatingP>
    <cim:GeneratingUnit.highControlLimit>800</cim:GeneratingUnit.highControlLimit>
    <cim:GeneratingUnit.lowControlLimit>0</cim:GeneratingUnit.lowControlLimit>
    <cim:PowerGeneratingUnit.genUnit rdf:resource="#Inverter_PV_001"/>
  </cim:PhotovoltaicUnit>

</rdf:RDF>

```

Figure 3.13: Exemplary XML file for difference CIM model

3.3.2 Distribution grid model parameterization

The main objective of this chapter is to analyse the measurements of the medium voltage (MV) and low voltage (LV) grid, conducted as part of the TwinEU, T6.7 task. The purpose of these measurements was to determine the parameters of an aggregated load model of the distribution grid, which will be used to enhance the dynamic model of the transmission network. The focus of this study is to establish the voltage dependence of power demand.

This chapter specifically aims to:

- Determine the impact of voltage variations on electricity consumption at different locations and for different types of consumers (industrial and residential loads).
- Analyse the response of power demand to OLTC (On-Load Tap Changer) transformer operations and identify relevant events for modelling.
- Process measurement data and filter events to ensure a high-quality dataset for further analysis and modelling.
- Parameterize the static component of the load model based on measurement analysis and estimate its parameters using the least squares method (LSM).

The outcome of this study is a statically parameterized model of the distribution grid, which will serve as the foundation for the enhanced dynamic model. The dynamic component of the model will be determined in a later phase based on literature data and additional simulations.

3.3.2.1 Methodology

The data processing methodology was designed to parameterize the static component of the dynamic model of the distribution grid, which will be used to enhance the dynamic model of the transmission network.

The data processing was carried out in the following phases (Figure 3.14):

- **Data preparation** – Measurements from different locations were aggregated, synchronized, and checked for quality and consistency of time stamps.
- **Measurement filtering** – Anomalies such as sudden jumps, missing values, and signal disturbances were identified and removed to ensure the accuracy of the analysis.
- **Identification of relevant events** – Voltage and load variations caused by OLTC (On-Load Tap Changer) operations or other influencing factors were analysed to capture meaningful load responses.
- **Calculation of static model parameters** – The static load model was derived based on selected events using the least squares method (LSM). The parameters of the exponential model were estimated to represent the aggregated load behaviour of the distribution network.
- **Validation of results** – The static model was verified against measured data using R^2 and RMSE criteria to assess the model's accuracy.

The final outcome of this analysis is a parameterized static model of the distribution network, which will serve as the basis for the further enhancement of the dynamic model.

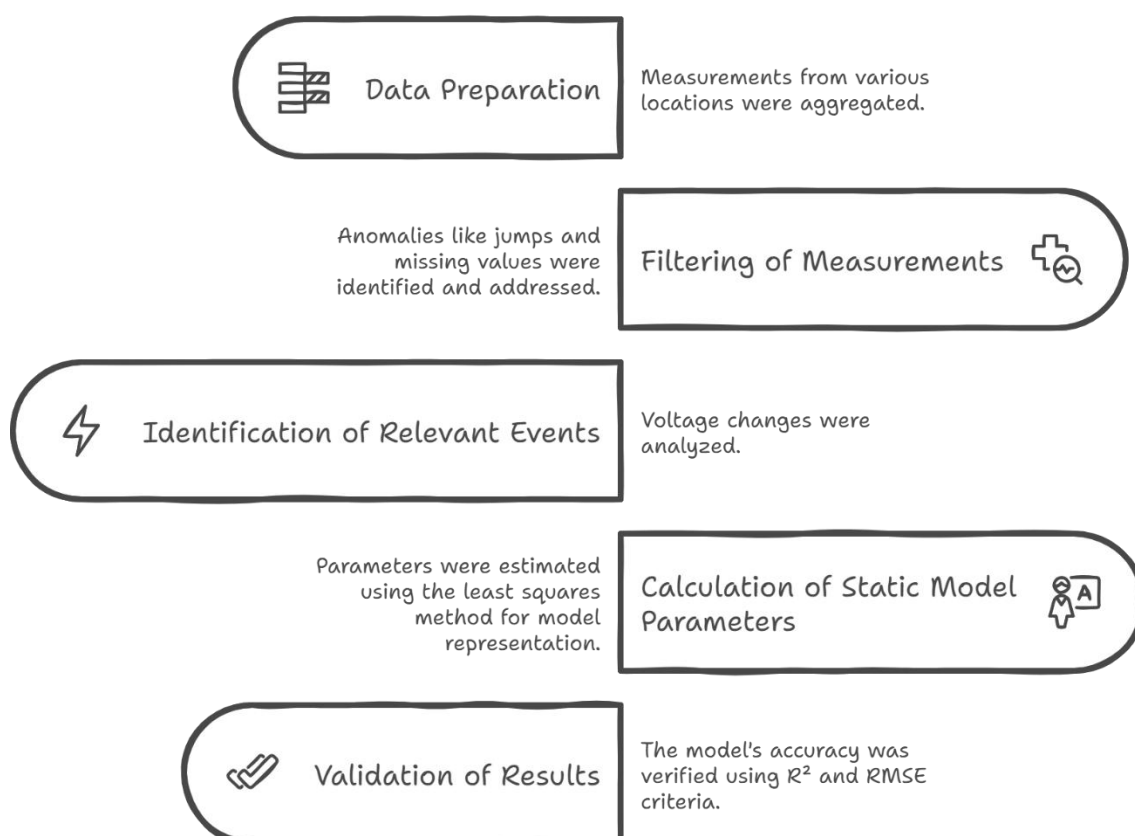


Figure 3.14: Methodology Overview: Load Model Parameterization.

3.3.2.2 Measurement analysis

This chapter presents the analysis of the first and second measurements sets. As the results of the first campaign were not satisfactory, a second campaign was carried out to obtain more reliable data.

3.3.2.2.1 First measurement set

This chapter presents the analysis of the first measurement set performed over a limited period. Since the data collection covered only a few working days (Thursday and Friday), the weekend, and part of Monday, the analysis is based on a single aggregated diagram that represents the entire measurement period.

3.3.2.2.1.1 Description of Locations and Data

The measurements included medium voltage (MV) and low voltage (LV) networks, focusing on analysing the impact of voltage variations on power demand. Measurements were conducted at various locations, covering both **industrial and residential loads**, providing an insight into the response of different consumer types to voltage changes.

The measurements were conducted from **December 11, 2024, at 10:51:54 to December 16, 2024, at 21:31:54**. During this period, both normal operating conditions and targeted OLTC transformer switching operations were recorded, enabling an analysis of both natural and induced voltage variations.

The resolution of the measurements was set to allow an accurate analysis of the dynamic response of loads. The minimum data recording interval was **1 second**, which allows for precise monitoring of OLTC switching events and voltage fluctuations. Measurements were performed continuously for at least 17 hours, covering both **working days and weekends**, enabling a comparison of different consumption patterns.

The following locations were included:

- **RTP Labore (MV busbars)** – Measurements at the MV busbars of RTP Labore were conducted to monitor voltage variations and their effect on power demand across a broader area.
- **TP Gradis Dinos (LV side of the transformer – industrial load)** – This location represents an industrial consumer, where load stability is expected to be higher, and the impact of voltage variations lower compared to residential loads.
- **TP Prebačevo spodnje (LV side of the transformer – residential load, further from TS)** – This site represents a residential consumer located farther from the RTP, making it more susceptible to voltage fluctuations.
- **TP Staretova Čirče (LV side of the transformer – residential load, closer to TS)** – This residential consumer is located closer to the RTP, allowing for a comparative analysis of load responses based on distance from the MV source.

The measurements captured voltage (L1-N, L2-N, L3-N) and current (L1, L2, L3) at all locations. Additionally, neutral current (N) was recorded at LV network sites (TP Gradis Dinos, TP Prebačevo spodnje, TP Staretova Čirče).

The measurement resolution was 1 second.

The OLTC switching operations were planned based on network conditions and were carried out during the following time intervals:

- **Weekdays (Thursday-Monday):** Between 09:00 and 10:00, 17:00 and 18:00, and 01:00 and 02:00, depending on network conditions.

- **Sunday:** OLTC switching was performed between 09:00 and 10:00, 17:00 and 18:00, and 01:00 and 02:00, depending on network conditions.

These scheduled switching events were designed to assess the impact of voltage regulation on power demand and to capture relevant data for modeling the distribution network response.

The schedule of OLTC switching operations is illustrated in Figure 3.15. The upper part of the figure presents the time intervals during which OLTC switching was performed. The lower part of the figure provides a detailed representation of how OLTC tap position changes were executed within each scheduled interval.

The visualization distinguishes the exact sequence of OLTC switching events, showing the progression of tap changes and their duration within each time window. This structured execution ensured that voltage variations were systematically introduced, enabling a controlled assessment of their impact on power demand.

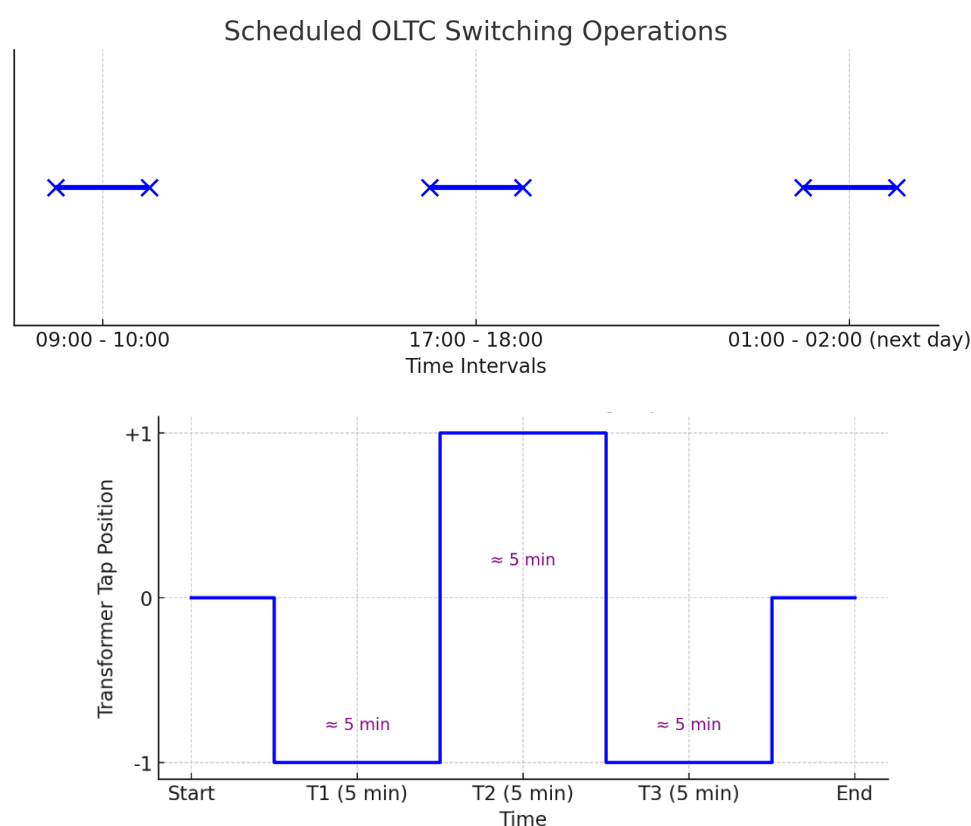


Figure 3.15: Scheduled OLTC Switching Intervals and Transformer Tap Position Changes

3.3.2.2.1.2 Full Measurement Period Diagram

A time diagram has been generated in Figure 3.16 to visualize the voltage and power variations over the entire measurement period. The diagram presents measured voltage (p.u.) and active power (kW) for four transformer stations: TP Labore, TP Dinos, TP Prebačev, and TP Staretova.

Each subplot represents one location. The blue curve shows the average voltage across three phases, normalized to per unit (p.u.) values. The voltage axis is fixed between 0.9 and 1.1 p.u.. The orange curve represents active power (kW) over the same period. The dual-axis format allows direct comparison between voltage variations and power demand across different parts of the distribution

network. The Labore station (20 kV) is shown at the top, while the three 0.4 kV stations are displayed below.

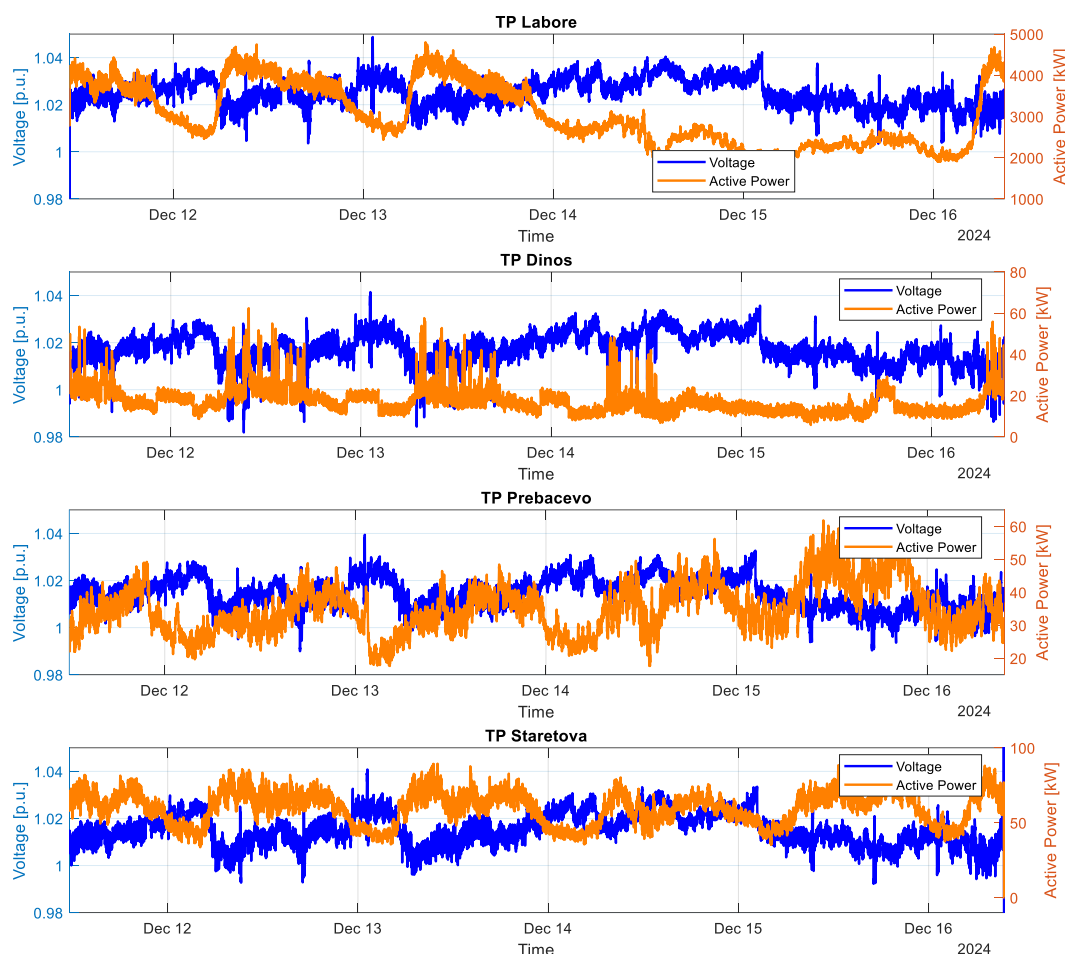


Figure 3.16: Voltage and power profiles for TP Labore, Dinos, Prebačev, and Staretova

From the figures, the exact moments of OLTC tap changes are clearly visible on the blue voltage curve, where sudden voltage shifts correspond to the scheduled OLTC switching operations. Additionally, the power response varies significantly across different locations. At Labore (20 kV), the power variation is more gradual, indicating a more continuous and stable load response at the medium voltage level. However, in Prebačev and Dinos (0.4 kV), the power exhibits more pronounced fluctuations, characterized by step-like changes and higher stochasticity. These sudden variations suggest a stronger influence of load switching or random consumer behaviour, making the low-voltage networks more susceptible to rapid power changes. This variability in power demand could pose a challenge in the subsequent analysis, particularly in the identification of suitable events for model parameterization. The high degree of load fluctuations observed in low-voltage networks (Prebačev and Dinos) increases the difficulty of isolating voltage-dependent power changes from other influences, such as consumer-driven load switching.

For OLTC-caused voltage variations to be useful for parameter estimation, it is essential that during each voltage change, the power demand profile remains relatively constant. If a simultaneous change in load profile occurs, the effect of the voltage variation on power consumption cannot be reliably isolated, leading to inaccurate model parameters.

Therefore, in the next steps of the analysis, careful event selection and filtering will be necessary to ensure that only events where voltage variations are the dominant influencing factor are considered for load model parameterization.

3.3.2.2.1.3 Identification of Relevant Events for Modeling

For distribution network modelling, it is necessary to detect voltage change events that enable reliable estimation of load model parameters. The detection process identifies sudden voltage variations exceeding a predefined threshold ($\Delta U = 0.01 \text{ p.u.}$), while ensuring a consistent trend across all three phases. These variations can result from OLTC operations, load fluctuations, network switching, or other system disturbances, ensuring that all relevant events—regardless of their origin—are included in the analysis.

The algorithm detects events by:

- Comparing consecutive voltage samples, marking significant changes exceeding delta.
- Ensuring trend consistency (same sign across all phases).
- Recording time indices of detected events for further analysis.

For each detected event, key load model parameters are estimated, which will be described in the next chapter. A time window of 4 samples before and 4 samples after the event ensures the analysis captures both pre-event and post-event conditions, improving parameter accuracy.

To ensure data reliability, detected events are filtered using the following quality metrics:

- Regression fit quality ($R^2 \geq 0.85$) – removes events where the regression model does not sufficiently describe the data.
- Standard deviation ($\sigma \leq 1\%$) – excludes events with high noise or instability.

Only events meeting these quality criteria are retained for final model calibration and validation.

Table 1: Event Filtering Criteria

Parameter	Description	Threshold Value
ΔU (delta)	Voltage change threshold for OLTC event detection	0.01 p.u.
R^2	Model fit quality	> 0.85
σ	Relative standard error of the model	< 1%

Figure 3.17 below illustrates the flowchart of the process for identifying relevant events for modeling.

In Figure 3.18 – Figure 3.21 the R^2 and σ analysis for filtered events at four different locations are presented.

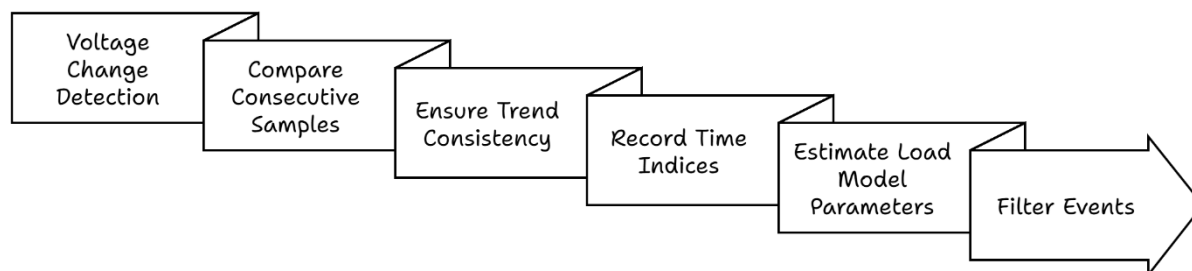


Figure 3.17: Event Identification Flowchart

The top subplot in each Figure represents the R^2 analysis, where the R^2 value (coefficient of determination) indicates how well the load model fits the measured data for each detected event. Blue stars represent all detected events, while red circles highlight filtered events that meet the R^2 threshold. The red dashed line marks the predefined minimum R^2 limit, below which events are excluded from further analysis. Observing the trends in R^2 values over the measurement period provides insights into the reliability of the voltage-to-power relationship.

The bottom subplot represents the σ (standard error) analysis, which measures the deviation between the modelled and actual power values. Blue stars represent all detected events, while red circles indicate filtered events that meet the σ threshold. The red dashed line represents the maximum acceptable σ limit. Higher σ values indicate noisier or less reliable events, which are excluded to improve model accuracy.

Key observations across locations

1. **At Labore** (Figure 3.18), the results show **a mix of high and low R^2 values**, with a significant number of events falling below the threshold. The σ values remain relatively low, though a few exceed the set limit. This indicates that while not all detected events meet the filtering criteria, a portion of the dataset still provides useful information for load model estimation. The moderate-to-high R^2 values suggest a relatively stable correlation between voltage and power, while the generally low σ values indicate that the noise level in the data is not excessively high. These results imply that **Labore has a more reliable dataset for model parameterization compared to other locations**, where instability and high error values are more prevalent.
2. **At Prebačevo** (Figure 3.19), **none of the detected events satisfy both filtering criteria**. All events have R^2 values below the predefined limit, and σ values exceed the maximum allowed threshold, making them unsuitable for further analysis. This indicates that **the voltage-to-power relationship in this dataset is highly unstable or influenced by external disturbances**.
3. **At Dinos** (Figure 3.20), some events meet the R^2 threshold, consistently staying above the lower limit. However, none of the events satisfy the σ criterion, as all exhibit high standard error values. The **excessively high σ values suggest significant measurement noise or rapid fluctuations in power consumption that prevent a reliable load model estimation**.
4. **At Staretova** (Figure 3.21), **only one detected event meets both filtering criteria**, with R^2 exceeding the threshold and σ remaining within acceptable limits. This means that, out of the entire measurement period, only a single event is suitable for parameter estimation. All other events exhibit relatively high σ values, indicating unstable conditions or data inconsistencies in the observed voltage-power dependency.

These figures confirm that the filtering process effectively removes unreliable events and that, for some locations, no events meet the required quality criteria. This highlights the challenges in modeling voltage-dependent load behaviour, emphasizing the need for a more comprehensive dataset to improve parameter estimation accuracy. The results also suggest that the measurement period was relatively short, covering only a few working days and a single Sunday. To obtain a more robust dataset, longer measurement campaigns should be conducted, capturing a wider range of operating conditions.

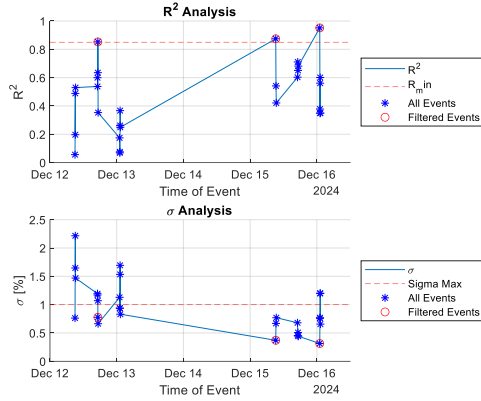


Figure 3.18: R^2 and σ analysis for filtered events in Labore

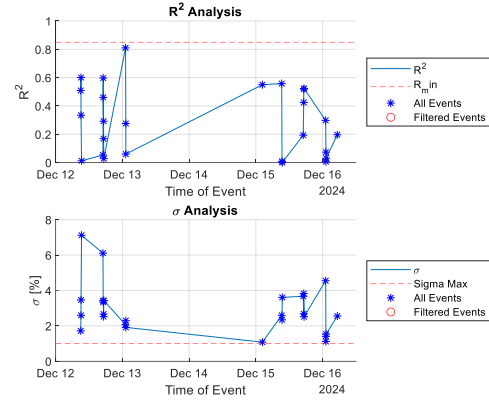


Figure 3.19: R^2 and σ analysis for filtered events in Prebačev

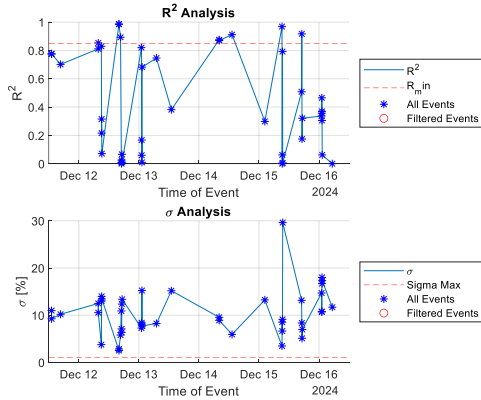


Figure 3.20: R^2 and σ analysis for filtered events in Dinos

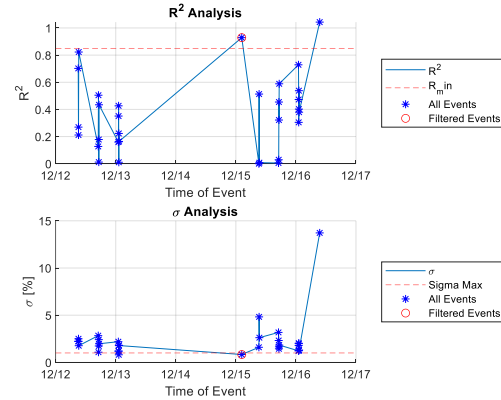


Figure 3.21: R^2 and σ analysis for filtered events in Staretova

3.3.2.2.2 Second measurement set

This chapter presents the analysis of the second measurement set, performed between April 18 and June 6, 2025.

3.3.2.2.2.1 Description of Locations and Data

As mentioned, the measurements included only MV networks. Measurements were conducted at various locations, covering both **industrial and mixed loads**.

The measurements were conducted from **April 18 to June 6, 2025**. During this period, both normal operating conditions and targeted OLTC transformer switching operations were recorded, enabling an analysis of both natural and induced voltage variations.

The resolution of the measurements was set to allow an accurate analysis of the dynamic response of loads. The minimum data recording interval was **10 seconds**.

The following locations were included:

- **RTP Labore (MV busbars)** – Measurements on TR2 (mixed loads) and TR3 (industrial loads).
- **RTP Primskovo** - Measurements on TR1 (mixed loads) and TR2 (mixed loads, TR1 was switched off).

The measurements captured voltage (L1-N, L2-N, L3-N) and current (L1, L2, L3) at all locations. The measurement resolution was 10 second.

3.3.2.2.2 Identification of Relevant Events for Modeling

All other aspects of the methodology remain the same, and the measurements were conducted based on the same principle. Specifically, voltage change events were detected to allow a reliable estimation of load model parameters. The detection procedure identifies sudden voltage variations exceeding a predefined threshold ($\Delta U = 0.01 \text{ p.u.}$) while maintaining a consistent trend across all three phases. Such variations can result from OLTC operations, load changes, network switching, or other disturbances, ensuring that all relevant events are consistently captured for analysis.

All other procedures remain unchanged, and the measurements follow the same detection and filtering approach. The algorithm identifies events by comparing consecutive voltage samples and marking significant changes exceeding the defined delta, while ensuring the same trend direction across all three phases. The time indicated indices of these detected events are then recorded for further analysis.

For each event, key load model parameters are estimated using a time window of four samples before and after the event, allowing the analysis to capture both pre-event and post-event behaviour and thus improve parameter accuracy.

To ensure data reliability, the detected events are filtered using the same quality metrics: a regression fit quality of $R^2 \geq 0.8$ (in the first set of measurements it was 0.85) to remove poorly fitted cases, and a standard deviation threshold of $\sigma \leq 1\%$ to exclude noisy or unstable events. Only events that meet these criteria are retained for the final model calibration and validation.

All other descriptions and visualization principles remain the same, and the figures are interpreted accordingly. The top subplot shows the R^2 analysis, indicating how well the load model fits the measured data. Blue stars mark all detected events, red circles highlight those meeting the R^2 threshold, and the red dashed line represents the minimum acceptable R^2 . Tracking these values over time shows the reliability of the voltage–power relationship.

The bottom subplot presents the σ (standard error) analysis, showing the deviation between modelled and measured power. Blue stars represent all events, red circles the accepted ones, and the red dashed line marks the maximum allowable σ . Events with higher σ are considered too noisy and are excluded to improve model accuracy.

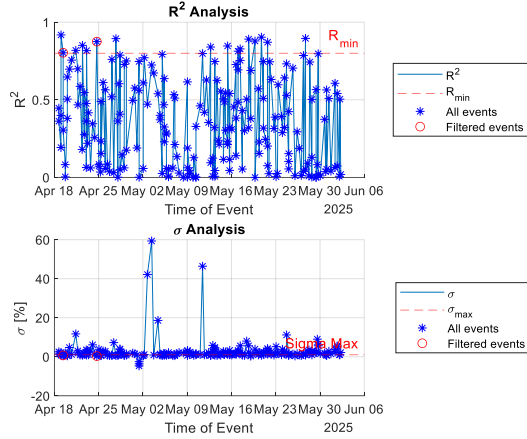


Figure 3.22: R^2 and σ analysis for filtered events in RTP Labore TR2

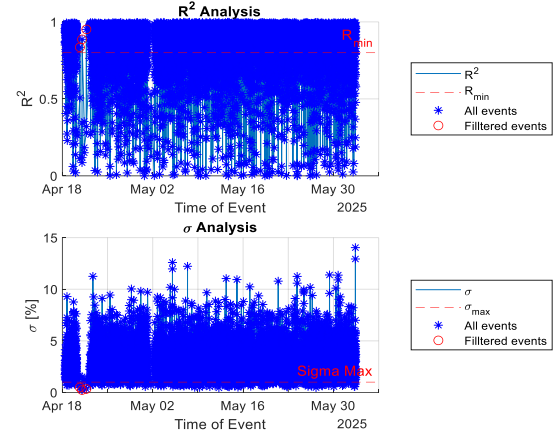


Figure 3.23: R^2 and σ analysis for filtered events in RTP Labore TR3

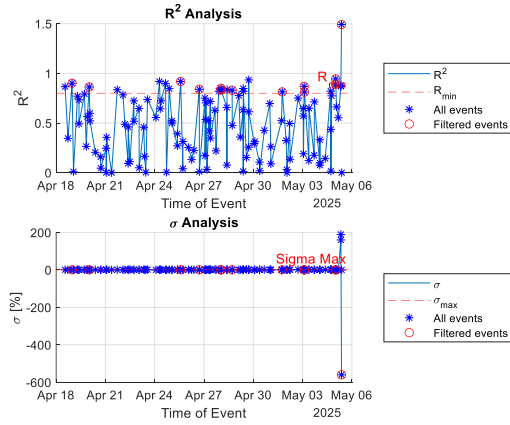


Figure 3.24: R^2 and σ analysis for filtered events in RTP Primskovo TR1

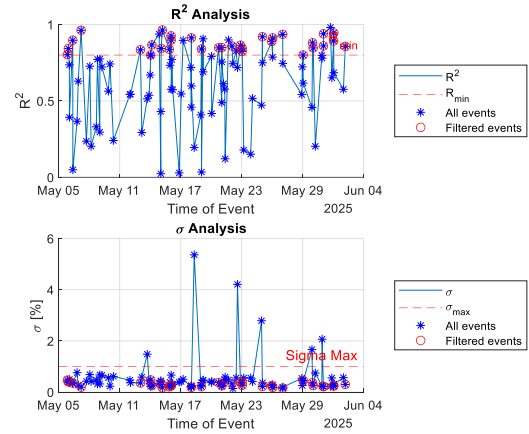


Figure 3.25: R^2 and σ analysis for filtered events in RTP Primskovo TR2

Key observations across locations

1. **At Labore TR2** (Figure 3.22), most detected events show relatively high R^2 values, with the majority lying close to or above the minimum threshold. This indicates a generally strong correlation between voltage and power. However, a few isolated points fall below the limit, suggesting occasional instability or weak event detection. The σ values remain low throughout most of the period, with only one noticeable spike exceeding the maximum limit. Overall, this dataset contains several high-quality events suitable for reliable load model estimation.
2. **At Labore TR3** (Figure 3.23), the R^2 distribution appears denser, with many detected events covering the entire range from 0 to 1. While some reach high R^2 values, many remain below the 0.8 threshold, indicating a weaker overall correlation between voltage and power compared to TR2. The σ analysis shows that most events remain within acceptable noise levels, though a few exceed the σ limit, pointing to short periods of data instability. Despite the broader spread of R^2 , the dataset still provides several valid filtered events for analysis.
3. **At Primskovo TR1** (Figure 3.24), the R^2 values remain consistently above the 0.8 threshold across almost the entire measurement period, indicating a stable and well-behaved voltage-power relationship. The σ values are low and uniform, staying far below the maximum limit,

which confirms the low noise level and high measurement reliability. This location thus provides one of the most consistent and high-quality datasets, suitable for accurate model parameterization.

4. **At Primskovo TR2** (Figure 3.25), the R^2 results show mostly high correlation values, with a majority of events exceeding the 0.8 limit and only a few minor deviations below it. The σ values remain low except for one distinct spike, which is likely caused by a short transient or switching event. In general, the data set demonstrates stable system conditions and a clear voltage-power relationship, making it well-suited for load model calibration.

These results confirm that the second measurement campaign, conducted from 18 April to 6 June 2025, provided usable events in all four analysed datasets. Labore TR2 contained several high-quality events, Labore TR3 provided several valid filtered events, and both Primskovo TR1 and Primskovo TR2 exhibited stable voltage–power relationships with low standard errors. The longer campaign therefore yielded a substantially more comprehensive and reliable basis for load-model calibration than the first measurement set. Additional measurements under a wider range of operating conditions could further improve the robustness of the estimated parameters.

3.3.3 Parameterization of the static component of the load model

The parameterization of the static component of the load model is based on the analysis of measurements and identified relevant events, presented in previous chapter. The static part of the model describes the relationship between voltage and active power consumption.

To determine the model parameters, three different approaches are considered: the linear model, the ZIP model, and the exponential model. The model parameters are estimated using the least squares method (LSM).

3.3.3.1 Load Model Selection and Parameterization

The table below presents the fundamental characteristics and mathematical formulations of the most commonly used load models for describing the relationship between voltage and active power.

Model	Equation	Description
Linear model	$P = P_0 \cdot \left(\alpha_P \cdot \frac{U}{U_0} + \beta_P \right)$	The simplest model, assuming a linear relationship between voltage and power.
ZIP model	$P = P_0 \cdot \left(Z_P \cdot \left(\frac{U}{U_0} \right)^2 + I_P \cdot \frac{U}{U_0} + P_P \right)$	A hybrid model that combines different load types: impedance (Z), current (I), and constant power (P) components.
Exponential model	$P = P_0 \cdot \left(\frac{U}{U_0} \right)^{K_P}$	A model with an adjustable exponential factor that allows for a nonlinear dependency of power on voltage.

All models use normalized quantities, where U_0 is the reference voltage and P_0 is the base power.

In previous studies [3] [4] it was demonstrated that the linear model does not provide sufficient accuracy for modeling voltage-dependent load behaviour, making it unsuitable for precise parameter estimation. Consequently, the ZIP model and the exponential model were selected as the primary modeling approaches. However, analysis has shown that the ZIP model can produce unrealistic extrapolated values if the measured voltage data is poorly distributed or if the voltage remains within

a narrow range during measurements. In such cases, the ZIP model tends to assign extreme values to voltages outside the observed range, leading to poor generalization of voltage-power dependency.

In contrast, the exponential model has shown better performance in cases where voltage variations during the measurement period were limited to a narrow band. This model provides a more stable and physically meaningful representation of voltage-dependent power consumption, ensuring that parameter estimation remains robust even with restricted voltage variation in the dataset.

3.3.3.2 Least Squares Method for Parameter Estimation – First set of measurements

The **Least Squares Method** is used to determine model parameters by minimizing the error between measured and modelled power values.

The parameter estimation process consists of the following steps:

- Data preparation – Selection of relevant events and normalization of variables.
- Equation system solving –for the exponential model, a logarithmic transformation is performed to linearize the equation.
- Optimal parameter computation – The best model fit is determined by minimizing the sum of squared errors.

The LSM approach minimizes the difference between the measured power P_i and the estimated power $\hat{P}_i$, which is expressed through the optimization function:

$$\min \sum_{i=1}^n (P_i - \hat{P}_i)^2 \quad (3.1)$$

where:

- P_i is the measured power,
- $\hat{P}_i$ is the estimated power,
- n is the number of measurements.

For the exponential model, the linearized form of the equation is solved as follows:

$$\ln(P) = K_p \cdot \ln\left(\frac{U_n}{U_0}\right) + \ln(P_0) \quad (3.2)$$

This transformation allows the use of linear regression to determine the parameters K_p and P_0 .

To validate the results, the following graphs were generated:

- Histogram of model parameters – distribution of estimated values for K_p and P_0 .
- Model fitting to measured data – evaluation of how well each model represents the voltage-to-power dependency.
- $P(U)$ for selected events – visualization of both measured and modelled power values as a function of voltage.

Figure 3.26 presents a histogram of model parameters for the Labore substation (first set of measurements). The figure consists of two bar charts:

The top chart displays the initial power P_0 values in megawatts (MW) for three filtered events in Labore location (indices 8, 16, and 23). The highest estimated initial power is observed for event 8, while events 16 and 23 exhibit lower but comparable values.

The bottom chart represents the exponential factor K_p values for the same filtered events. The highest value corresponds to event 23, while events 8 and 16 have nearly identical lower values.

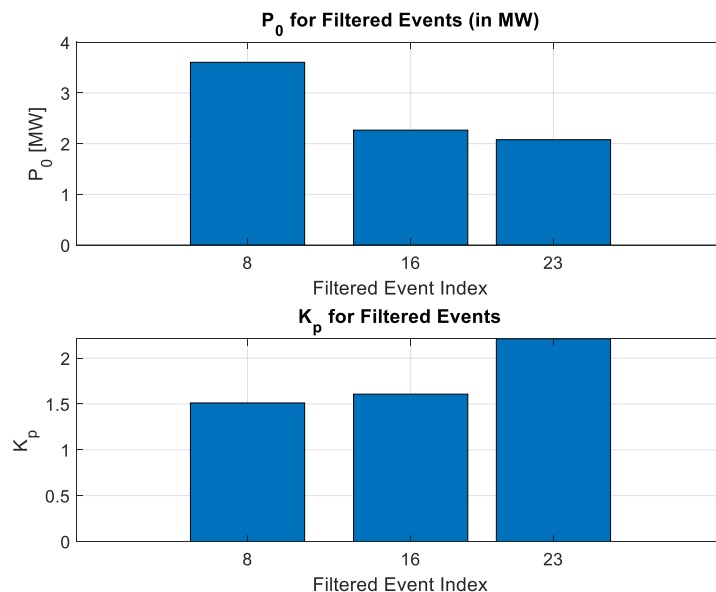


Figure 3.26: Histogram of model parameters Labore – First set of measurements

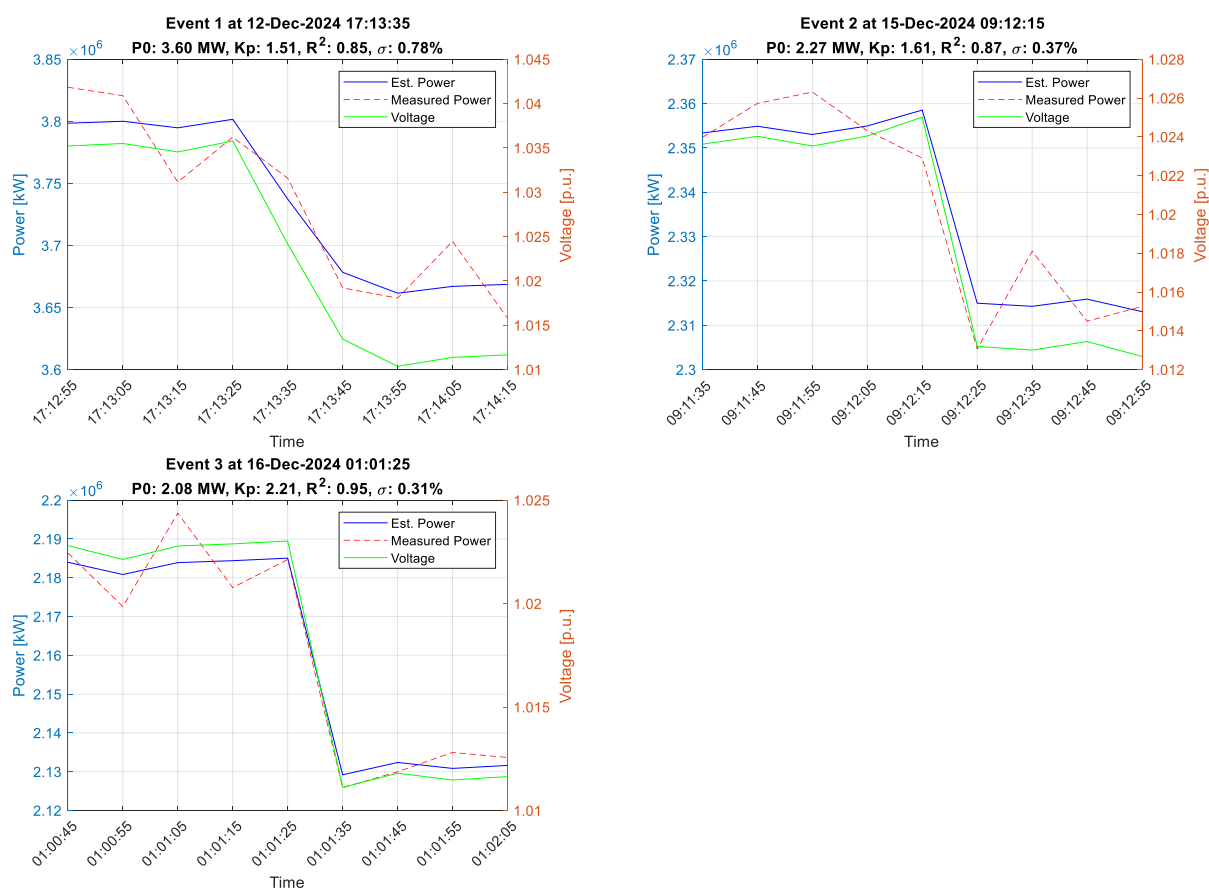


Figure 3.27: Model fitting to measured data in Labore – First set of measurements

Figure 3.27 presents the model fitting to measured data at the Labore substation (first set of measurements). The figure consists of three time-series plots, each illustrating the relationship between estimated power, measured power, and voltage for different OLTC switching events.

- Blue line: estimated power from the model.
- Red dashed line: measured power from actual observations.
- Green line: voltage in per unit (p.u.).

Each plot shows a distinct OLTC switching event, where a noticeable voltage drop corresponds to a change in power consumption. The estimated power closely follows the trend of the measured power, indicating a good fit of the applied model. However, minor deviations suggest possible dynamic effects or transient behaviour not captured by the static model.

Figure 3.28 shows $P(U)$ graph for selected events at the Labore substation (first set of measurements). The figure consists of three scatter plots, each showing the relationship between U (in per unit) and active P (in megawatts) for different OLTC switching events.

- Blue line: the estimated
- Red horizontal line: the reference power level
- Orange circles: measured data points for the selected events.

Each plot demonstrates how power changes as a function of voltage. The estimated model follows a clear trend, so the static model effectively captures the dependency of power on voltage. However, minor deviations in measured points suggest possible external influences or dynamic effects that are not fully represented by the static approach.

This visualization confirms the validity of the statically parameterized model and highlights its applicability for representing load behaviour in response to voltage variations in the Labore dataset.

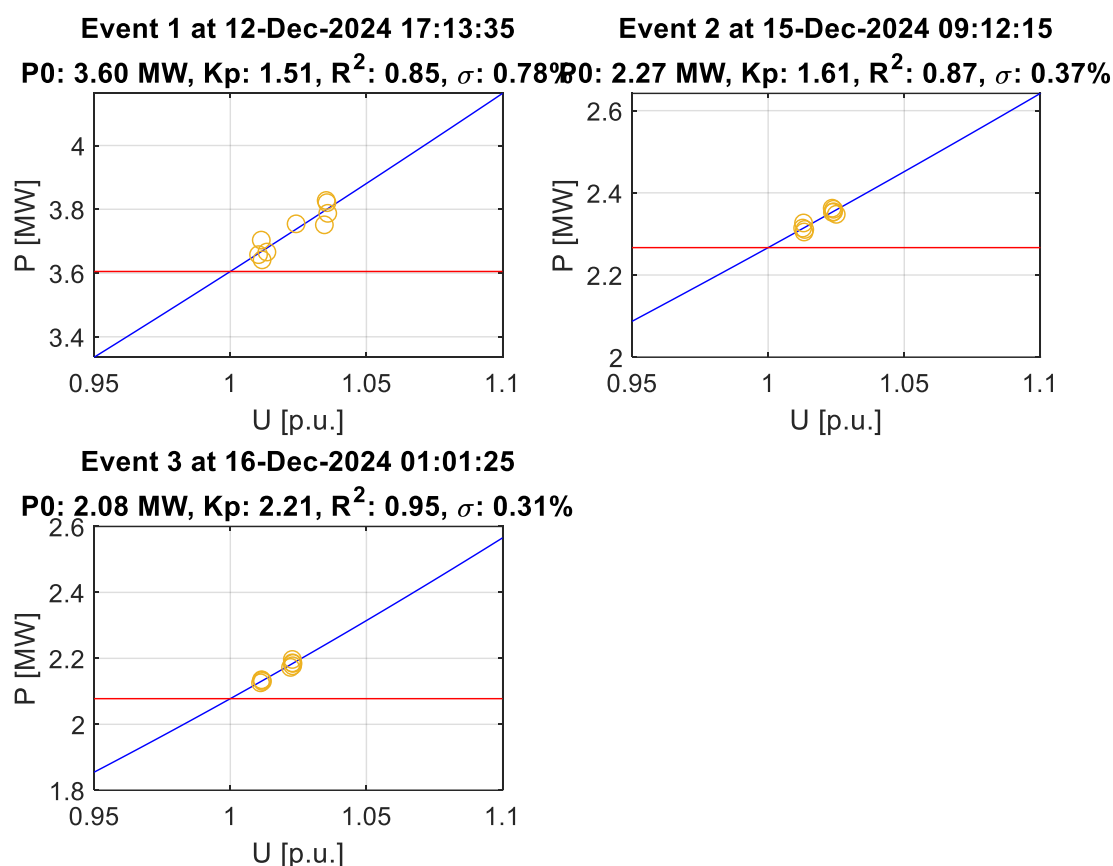


Figure 3.28: $P(U)$ graph for selected events in Labore – First set of measurements

3.3.3.3 Least Squares Method for Parameter Estimation – Second set of measurements

Figure 3.29 presents a histogram of the $P(U)$ model parameters for RTP Labore TR2 (second set of measurements). The figure consists of two bar charts:

The top chart displays the initial power P_0 values in megawatts (MW) for two filtered events at the TR2 transformer in RTP Labore (mixed loads). Event index 32 shows the highest estimated initial power of approximately 3 MW, while event 6 exhibits a lower value of around 1.4 MW. This indicates a noticeable variation in the initial load conditions between the two detected events.

The bottom chart represents the exponential factor K_p values for the same filtered events. Here, event 6 shows a significantly higher K_p value (around 2.2) compared to event 32 (approximately 1.3). The difference in K_p suggests varying dynamic load sensitivities to voltage changes across the two detected events, reflecting different underlying load compositions or operating conditions.

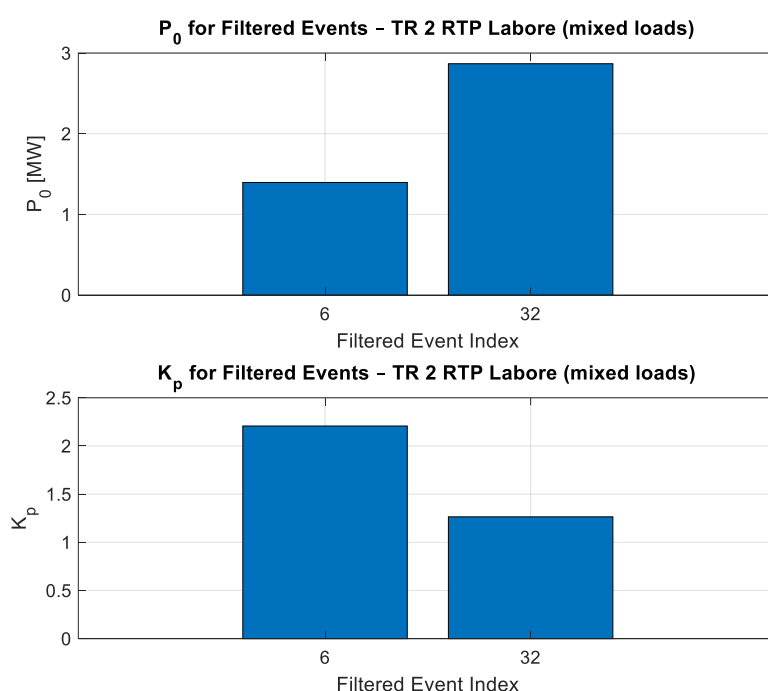


Figure 3.29: Histogram of the $P(U)$ model parameters Labore TR2 – Second set of measurements

Figure 3.30 presents a histogram of the $Q(U)$ model parameters for RTP Labore TR2 (second set of measurements). The figure consists of two bar charts:

The top chart shows the initial reactive power values Q_0 in megavolt-amperes reactive (MVar) for all filtered events at the TR2 transformer (mixed loads). The estimated Q_0 values range roughly between 0.6 and 1.0 MVar, with moderate variation among events but no extreme outliers. This indicates relatively consistent reactive power levels at the beginning of the voltage disturbances.

The bottom chart displays the exponential sensitivity factors K_q for the same filtered events. In this case, the resulting K_q values vary widely and include several large negative values, some approaching -10 . Such values have no physical meaning within the expected $Q(U)$ load model behaviour. The strong negative swings indicate that the parameter estimation procedure did not yield a valid or interpretable K_q parameter for these events, which are likely due to measurement noise, weak reactive power response, or insufficient voltage variation during the events.

Because of this, a meaningful or reliable K_q cannot be determined from the available data. To maintain model consistency and avoid unrealistic behaviour, it is therefore reasonable to assign a default value of $K_q = 1$ for further simulations or aggregated load modeling in all cases. For reliable K_q we would need to have the $Q(U)$ of every photovoltaic generation unit.

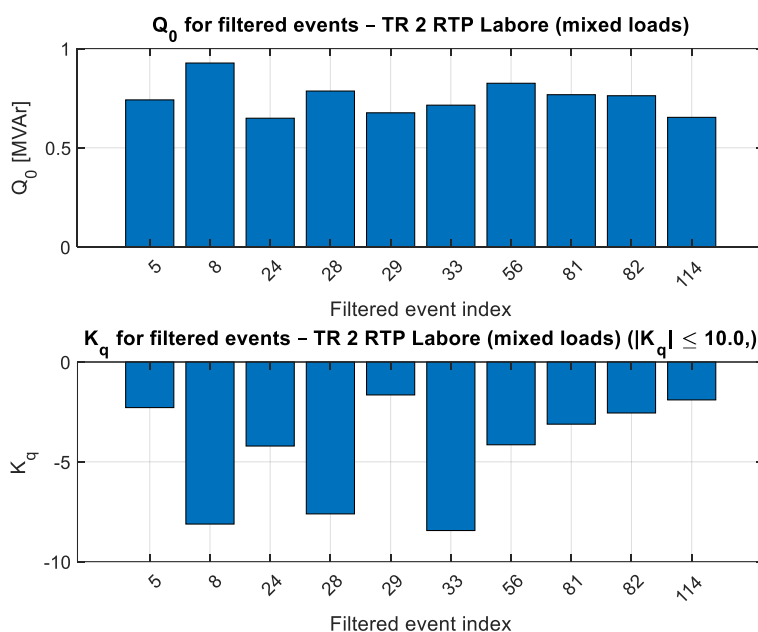


Figure 3.30: Histogram of the $Q(U)$ model parameters Labore TR2 – Second set of measurements

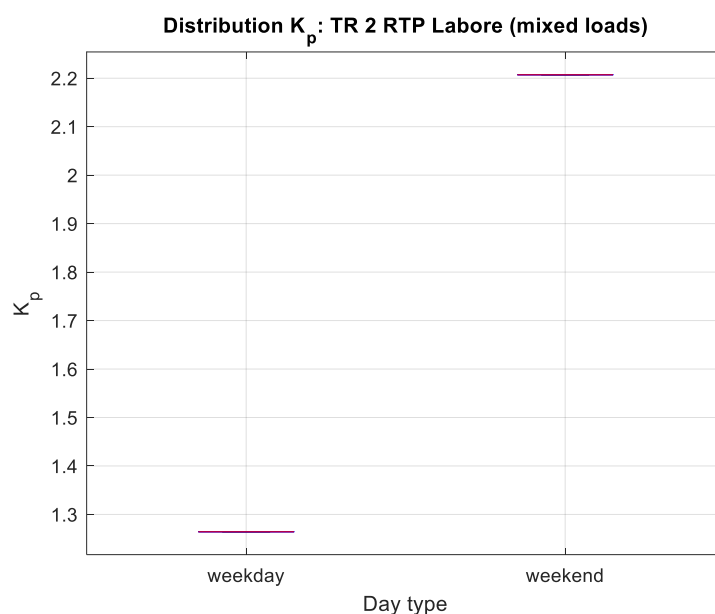


Figure 3.31: Distribution of the exponential factor K_p RTP Labore TR2 – Second set of measurements

Figure 3.31 presents the distribution of the exponential factor K_p for the TR2 transformer at the RTP Labore substation (mixed loads), categorized by day type (weekday vs. weekend). Although the figure shows slightly higher K_p values during the weekend compared to weekdays, the dataset contains only two detected events in total. Consequently, the sample size is too small to draw any meaningful

statistical conclusions about the influence of day type on load voltage sensitivity. Additional measurements would be required to confirm whether such a trend actually exists.

Figure 3.32 presents the distribution of the exponential factor K_q for the TR2 transformer at the RTP Labore substation (mixed loads), categorized by day type (weekday vs. weekend). The boxplot indicates a substantial spread of K_q values for both categories. During weekdays, the estimated K_q values cluster between approximately -2 and -4 , with a lower whisker extending to around -8 . Weekend values, however, exhibit even larger variability, ranging from about -2 down to nearly -10 . The median weekend value appears significantly lower than the weekday median, pointing to stronger negative reactive power sensitivity estimates.

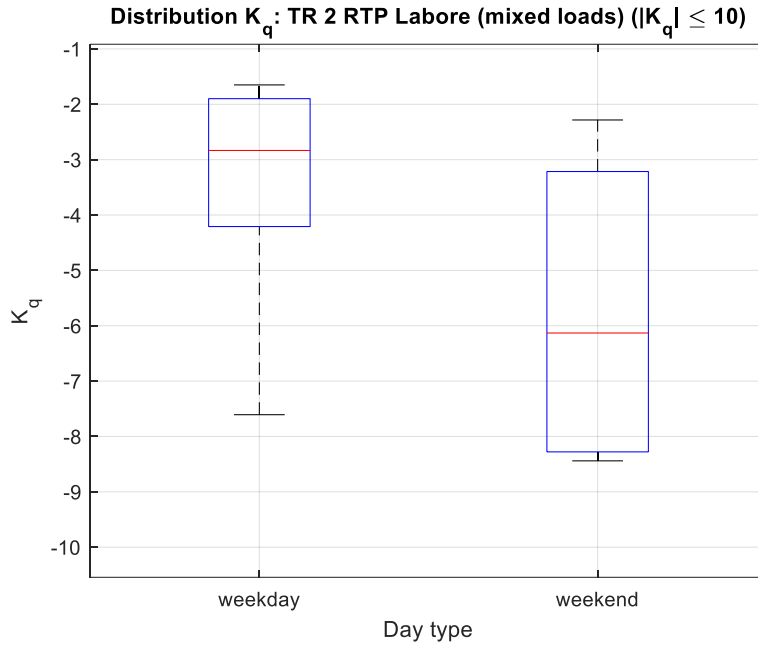


Figure 3.32: Distribution of the exponential factor K_q RTP Labore TR2 – Second set of measurements

Figure 3.33 presents the model fitting results for two filtered events at the TR2 transformer in the RTP Labore substation (mixed loads). Each subplot illustrates the relationship between estimated power (blue), measured power (red dashed), and voltage in per unit (green) during the corresponding OLTC switching event.

In **Event 1 (19-Apr-2025, 09:24:20)**, the initial power P_0 is approximately 1.40 MW, with an exponential factor $K_p = 2.21$, $R^2 = 0.80$, and standard deviation $\sigma = 0.67\%$. A distinct voltage step is followed by a corresponding increase in power, and the model estimation captures the trend of the measured data reasonably well, though slight deviations are visible immediately after the voltage change.

In **Event 2 (24-Apr-2025, 17:08:20)**, the initial power is higher at 2.87 MW, with $K_p = 1.26$, $R^2 = 0.87$, and $\sigma = 0.33\%$. The voltage rise produces a clear and proportional increase in power, and the model shows an excellent match with the measured signal. The higher R^2 and lower σ indicate a more stable event with less noise and better model conformity.

Overall, both events demonstrate that the exponential load model effectively captures the steady-state voltage–power dependency, with minor transient discrepancies likely caused by dynamic load behaviour during OLTC switching.

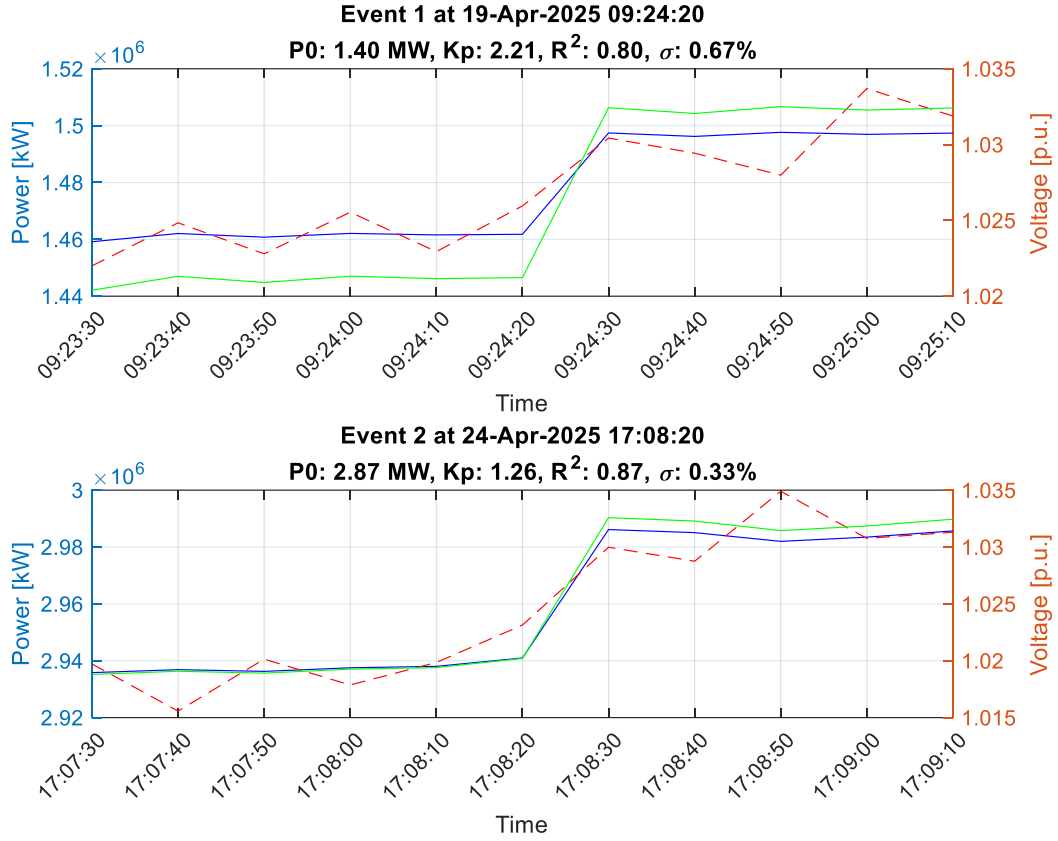


Figure 3.33: Model $P(U)$ fitting to measured data in Labore TR2 – Second set of measurements

Figure 3.34 presents the $Q(U)$ model fitting results for three filtered events at the TR2 transformer in the RTP Labore substation (mixed loads). Each subplot shows the estimated reactive power (blue), measured reactive power (red dashed), and the corresponding per-unit voltage (green) during the OLTC tap-changing events.

In **Event 1 (03-May-2025, 17:01:10)**, the initial reactive power is $Q_0 = 0.71$ MVar, with an exponential factor of $K_q = -8.44$, $R^2 = 0.99$, and a standard deviation $\sigma = 0.64\%$. A clear voltage drop is observed, followed by a rapid change in reactive power. While the estimated $Q(U)$ curve closely matches the measured data (indicated by the high R^2), the strongly negative K_q value is non-physical within the expected reactive power–voltage dependency, indicating instability or over-sensitivity in the parameter estimation.

In **Event 2 (11-May-2025, 01:16:20)**, the initial reactive power is $Q_0 = 0.83$ MVar, with $K_q = -4.15$, $R^2 = 0.87$, and $\sigma = 0.95\%$. The voltage step results in a moderate reactive power response. Although the fit generally follows the measured trend, the negative K_q again suggests that the extracted sensitivity parameter may not accurately represent the underlying load behaviour. The estimation aligns reasonably with measurements but exhibits visible deviations around the switching moment.

In **Event 3 (02-May-2025, 01:07:20)**, the initial reactive power is $Q_0 = 0.68$ MVar, with $K_q = -1.65$, $R^2 = 0.88$, and $\sigma = 0.40\%$. The voltage increase produces a smooth and clearly measurable change in Q , and the model tracks the measured data well. Although the magnitude of

K_q is smaller compared with the first two events, the parameter remains negative and therefore physically questionable.

Overall, the Q(U) model captures the general shape of the reactive power response to OLTC voltage steps, but the fitted exponential factors K_q are consistently negative—contrary to the expected behaviour of typical inductive or mixed loads.

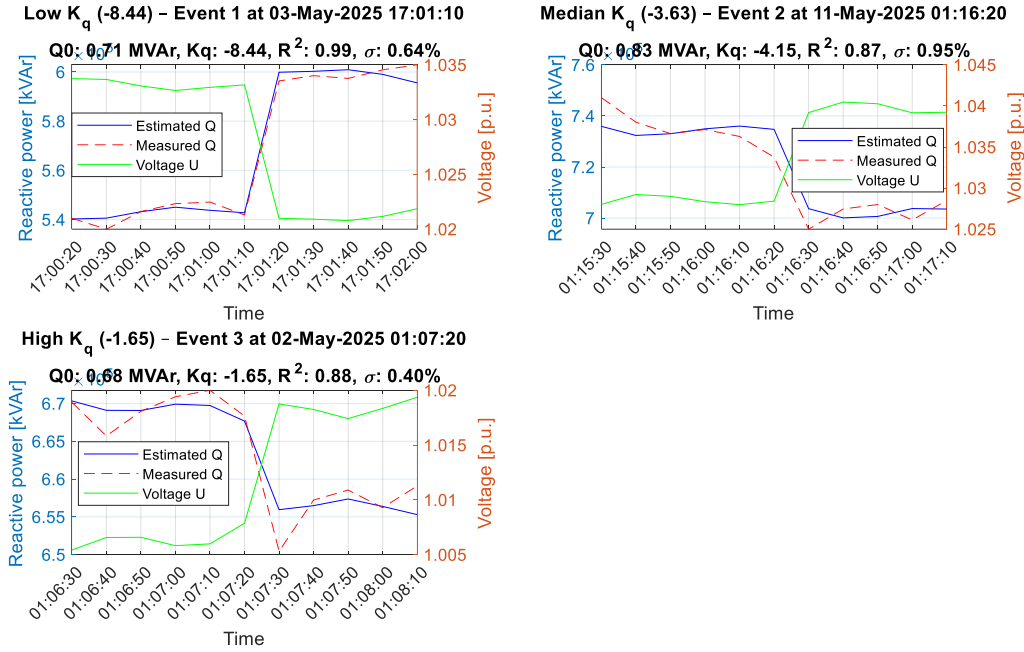


Figure 3.34: Model Q(U) fitting to measured data in Labore TR2 – Second set of measurements

Figure 3.35 presents the P(U) graphs for two selected events at the TR2 transformer in the RTP Labore substation (second set of measurements). Each plot shows the relationship between active power P (in MW) and voltage U (in p.u.) for a specific OLTC switching event. The blue line represents the estimated power–voltage characteristic obtained from the exponential model, the red horizontal line indicates the reference power level P_0 , and the orange circles correspond to the measured data points.

In **Event 1 (19-Apr-2025, 09:24:20)**, the measured data follow the modelled trend with a moderate fit ($R^2 = 0.80$), showing a clear positive slope ($K_p = 2.21$) that reflects increasing power with voltage. The small deviation between the model and data points suggests minor dynamic effects or measurement noise.

In **Event 2 (24-Apr-2025, 17:08:20)**, the correlation improves ($R^2 = 0.87$), and the slope ($K_p = 1.26$) indicates a milder voltage sensitivity. The measured points align closely with the model, confirming stable and consistent load behaviour.

Overall, both cases demonstrate that the static exponential model accurately represents the dependency between active power and voltage, validating its suitability for load modeling in the Labore TR2 dataset.

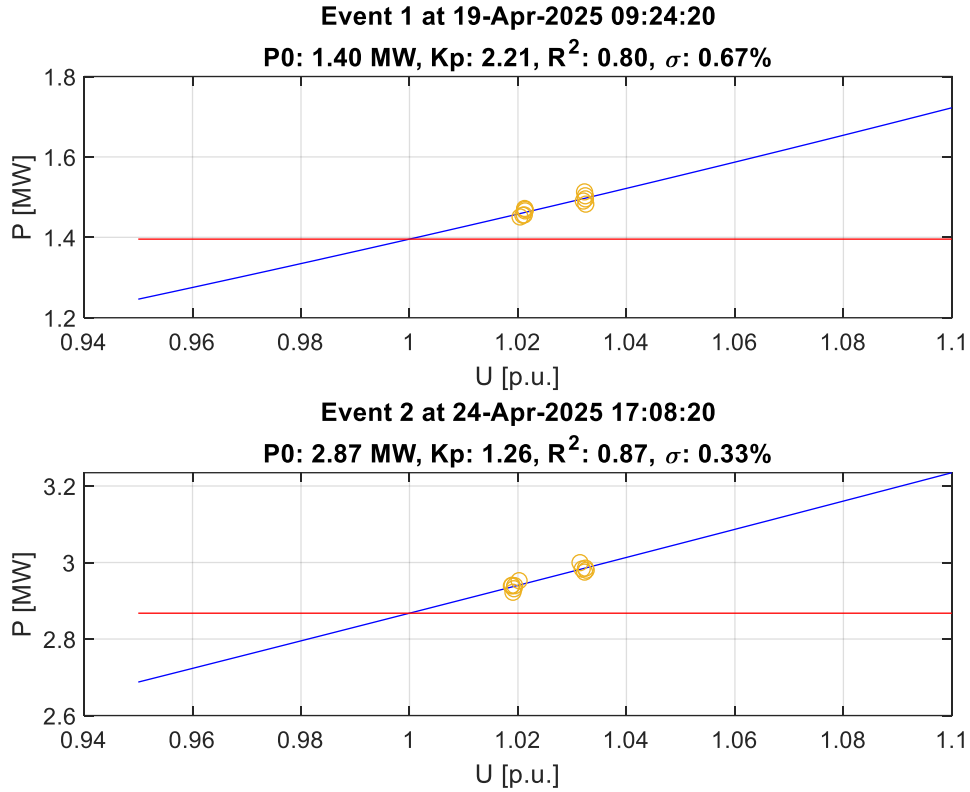


Figure 3.35: $P(U)$ graph for selected events in Labore TR2 – Second set of measurements

Figure 3.36 presents the $Q(U)$ graphs for three selected events at the TR2 transformer in the RTP Labore substation (second set of measurements).

In **Event 1 (03-May-2025, 17:01:10)**, the measured points follow the fitted curve very closely, resulting in a high correlation ($R^2 = 0.99$). The estimated exponential factor is strongly negative ($K_q = -8.44$), causing the model to exhibit a steep downward trend of reactive power with increasing voltage. Although the statistical fit is good, the large negative slope indicates that the extracted parameter is not physically meaningful for typical mixed loads.

In **Event 2 (11-May-2025, 01:16:20)**, the fitted characteristic shows a milder but still distinctly negative slope, with $K_q = -4.15$ and $R^2 = 0.87$. The measured data points align reasonably well with the model, confirming the numerical consistency of the fitting procedure. However, the negative value of K_q again suggests that the event does not yield a physically interpretable reactive-power sensitivity.

In **Event 3 (02-May-2025, 01:07:20)**, the estimated exponential factor is $K_q = -1.65$, and the model achieves a good fit ($R^2 = 0.88$, $\sigma = 0.40\%$). The reactive-power decrease with increasing voltage is less pronounced compared with the other cases, yet the negative trend persists. This further supports the conclusion that the $Q(U)$ parameter cannot be reliably identified from the available OLTC events.

Overall, although the fitted curves exhibit good agreement with the measured points in all three events, the consistently negative values of K_q indicate that the resulting parameters lack physical validity.

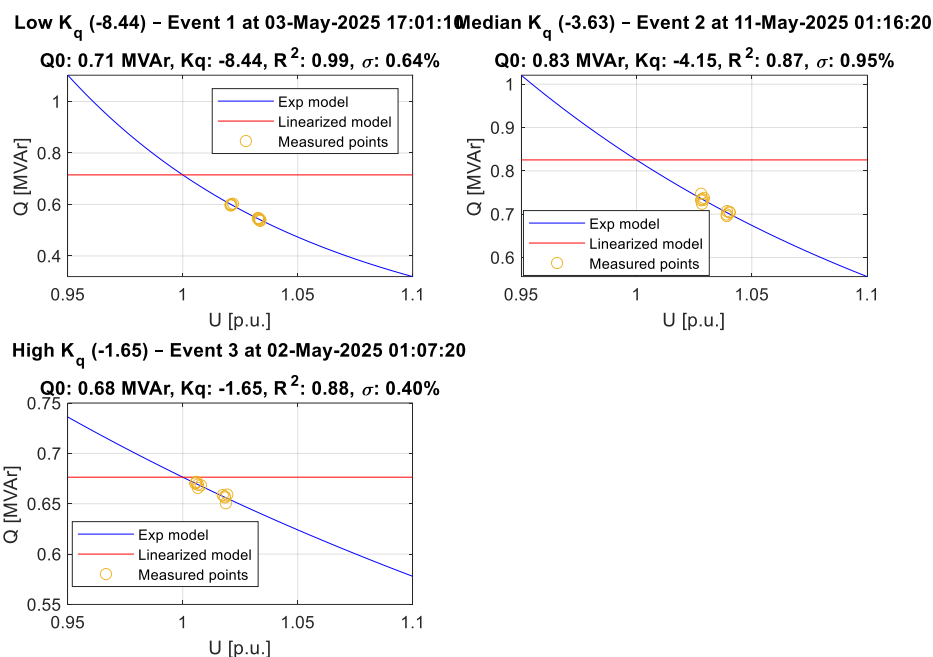


Figure 3.36: $Q(U)$ graph for selected events in Labore TR2 – Second set of measurements

Figure 3.37 presents a histogram of the active power model parameters for RTP Labore TR3 (second set of measurements). The figure consists of two bar charts.

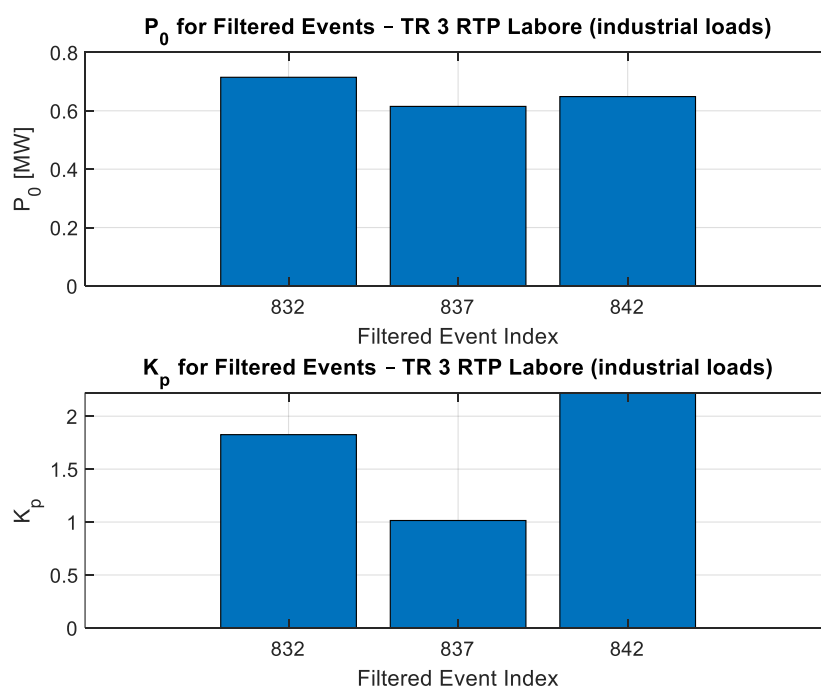


Figure 3.37: Histogram of the $P(U)$ model parameters Labore TR3 – Second set of measurements

The top chart displays the initial power P_0 values in megawatts (MW) for three filtered events at the TR3 transformer in RTP Labore (industrial loads). The estimated initial power ranges from approximately 0.6 MW to 0.7 MW, with only minor variation between the events, indicating relatively stable load conditions during the detected voltage changes.

The bottom chart presents the exponential factor K_p for the same filtered events. Here, greater variation is observed: event 842 exhibits the highest K_p value (around 2.1), event 832 follows with a moderate value (around 1.8), while event 837 shows the lowest voltage sensitivity ($K_p \approx 1.0$). This spread in K_p values suggests that, despite similar base power levels, the industrial loads connected to TR3 respond differently to voltage variations, reflecting distinct operating characteristics or compositions of connected equipment.

Figure 3.38 presents a histogram of the Q(U) model parameters for the TR3 transformer at the RTP Labore substation (industrial loads), based on the second set of measurements. The figure consists of two bar charts:

The top chart shows the initial reactive power values Q_0 in megavolt-amperes reactive (MVar) for all filtered events. The estimated Q_0 values lie in a relatively narrow range between approximately 1 and 1.2 MVar, indicating stable and consistent reactive-power levels across the industrial load events. Compared with mixed-load cases, the variation here is smaller, which aligns with the typically more uniform characteristics of industrial consumers.

The bottom chart displays the exponential sensitivity factor K_q for the same events. The estimated K_q values show mixed behaviour: two events yield slightly negative values, one event produces a considerably more negative result, while another exhibits a positive K_q . This inconsistency suggests that the extracted reactive-power sensitivity is not reliable, even in a more homogeneous industrial-load environment. As in previous analyses, the negative values are physically questionable and indicate that the Q(U) parameter estimation is unstable for these particular OLTC disturbances.

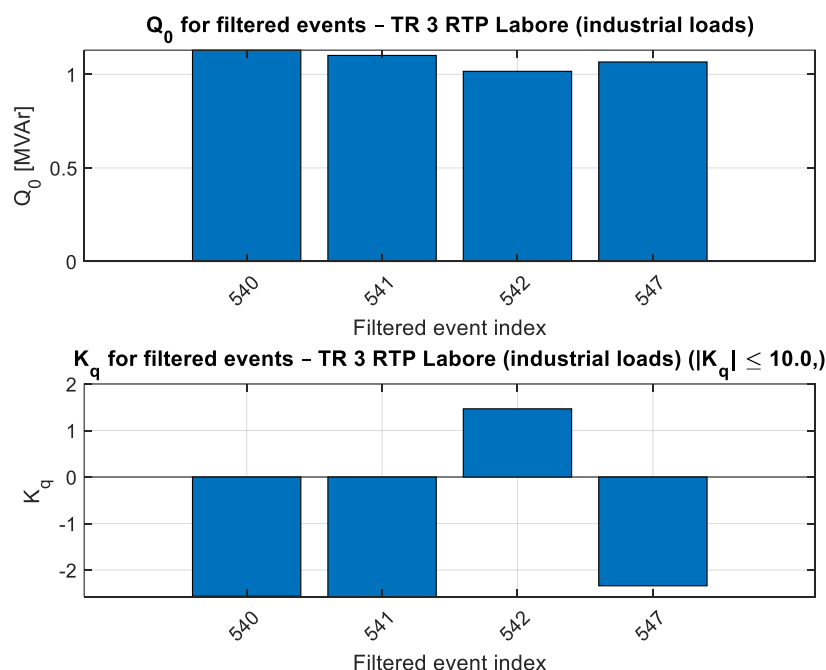


Figure 3.38: Histogram of the Q(U) model parameters Labore TR3 – Second set of measurements

Figure 3.39 presents the distribution of the exponential factor K_p for the TR3 transformer at the RTP Labore substation (industrial loads), categorized by day type. The weekday group shows a moderate spread of K_p values, ranging roughly from 1.0 to 2.2, while the weekend group includes only a single event with K_p around 1.8. This limited number of detected events, especially during the weekend, prevents any statistically meaningful comparison between weekday and weekend

behaviour. Nevertheless, the results suggest that load sensitivity remains within a consistent range, as expected for predominantly industrial consumers.

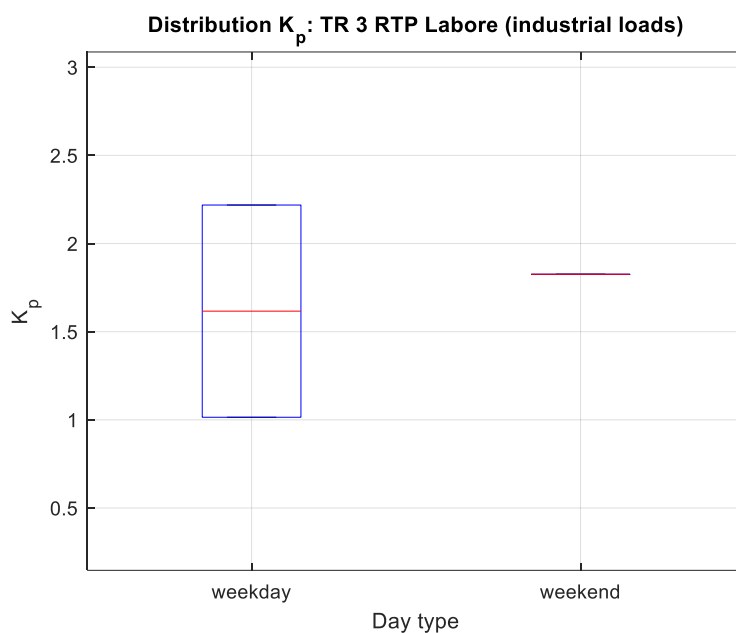


Figure 3.39: Distribution of the exponential factor K_p RTP Labore TR3 – Second set of measurements

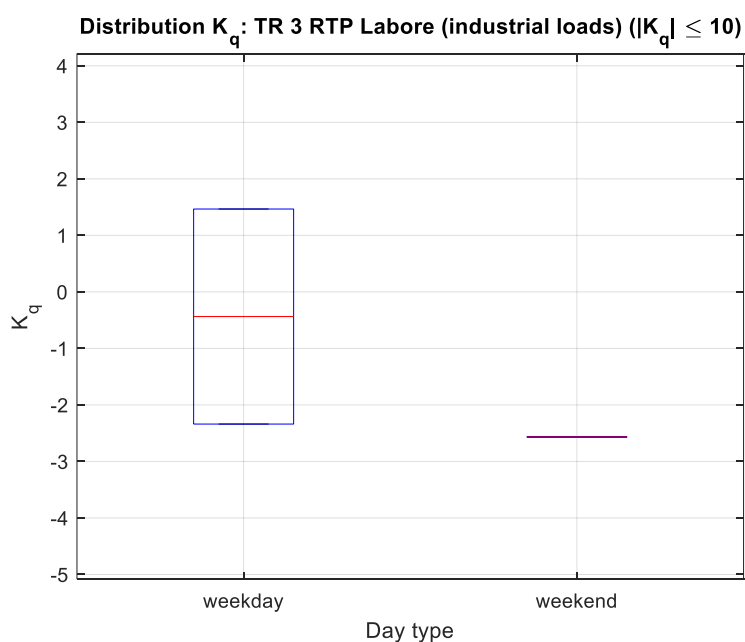


Figure 3.40: Distribution of the exponential factor K_q RTP Labore TR3 – Second set of measurements

Figure 3.40 presents the distribution of the exponential factor K_q for the TR3 transformer at the RTP Labore substation (industrial loads), categorized by day type. The weekday group shows a broad spread of K_q values, ranging from moderately positive to negative, while the weekend group contains only a single event with K_q around -2.5 . Due to the very limited number of events—especially during the weekend—no meaningful comparison between weekday and weekend behaviour can be made.

The mixed signs and variability further confirm that the $Q(U)$ parameter cannot be reliably identified from these events.

Figure 3.41 presents the model fitting results for three filtered events at the TR3 transformer in the RTP Labore substation (industrial loads). Each subplot compares the estimated power (blue line), measured power (red dashed line), and voltage in per unit (green line) during OLTC switching events.

In **Event 1 (20-Apr-2025, 17:12:20)**, the initial power P_0 is 0.71 MW with an exponential factor $K_p = 1.83$, $R^2 = 0.83$, and $\sigma = 0.49\%$. A clear voltage increase corresponds to a proportional power rise, and the model follows the measured data closely, confirming a stable correlation between voltage and active power.

In **Event 2 (21-Apr-2025, 01:14:50)**, $P_0 = 0.62$ MW, $K_p = 1.01$, $R^2 = 0.89$, and $\sigma = 0.23\%$. Here, a voltage decrease leads to a drop in power, and the model reproduces this trend with excellent agreement. The low standard deviation indicates minimal noise and high measurement consistency.

In **Event 3 (21-Apr-2025, 17:14:20)**, $P_0 = 0.65$ MW, $K_p = 2.22$, $R^2 = 0.95$, and $\sigma = 0.33\%$. The event shows a distinct voltage step followed by a strong and well-captured power response. The high R^2 value confirms the excellent fit quality.

Overall, all three events display a clear and consistent voltage–power relationship. The model accurately represents both increasing and decreasing power trends, demonstrating its robustness in characterizing industrial load behaviour under voltage variations.

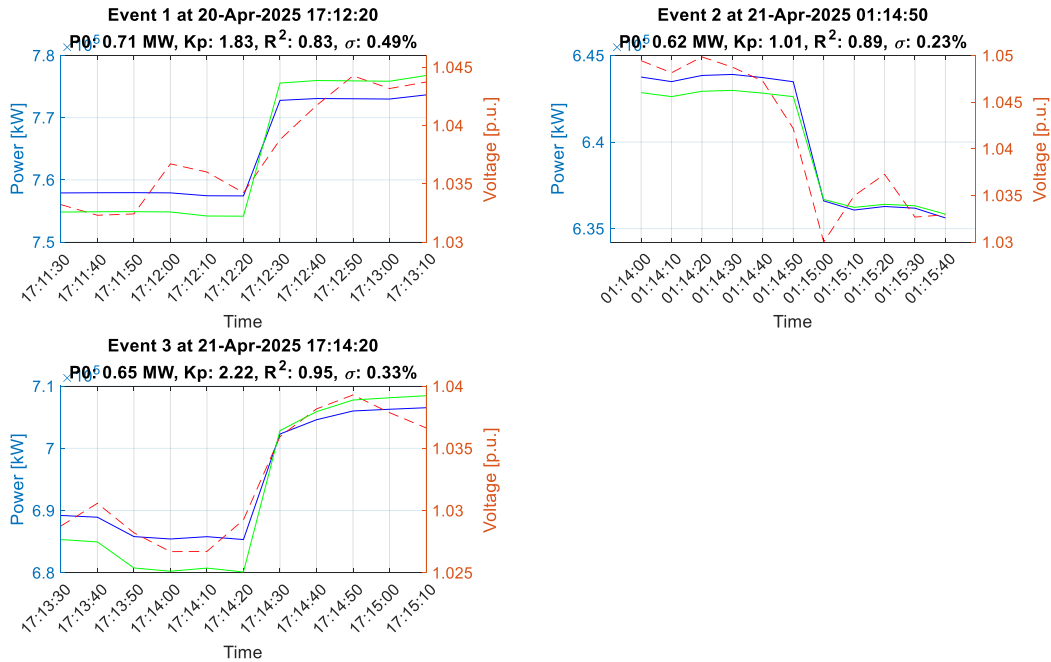


Figure 3.41: Model $P(U)$ fitting to measured data in Labore TR3 – Second set of measurements

Figure 3.42 presents the $Q(U)$ model fitting results for three filtered events at the TR3 transformer in the RTP Labore substation (industrial loads). Each subplot shows the estimated reactive power (blue), measured reactive power (red dashed), and voltage in per unit (green) during the corresponding OLTC switching event.

In **Event 1 (20-Apr-2025, 17:12:20)**, the initial reactive power is $Q_0 = 1.10$ MVar, with an exponential factor $K_q = -2.57$, $R^2 = 0.91$, and a standard deviation $\sigma = 0.49\%$. The voltage step produces a corresponding change in reactive power, and the model captures the overall trend of the measured data. Despite the good statistical fit, the negative K_q value again lacks physical interpretation.

In **Event 2 (20-Apr-2025, 09:00:50)**, the fitting parameters are $Q_0 = 1.13$ MVar, $K_q = -2.56$, $R^2 = 0.98$, and $\sigma = 0.29\%$. The measured Q response aligns closely with the model, indicating a stable and low-noise event. However, the resulting K_q remains negative, confirming the recurring issue observed in other TR3 events.

In **Event 3 (21-Apr-2025, 01:05:20)**, the estimated parameters are $Q_0 = 1.02$ MVar, $K_q = 1.47$, $R^2 = 0.85$, and $\sigma = 0.41\%$. This event exhibits a positive K_q , unlike the previous two cases, yet the measured reactive-power variation remains relatively small. The model reproduces the general shape of the Q response, though with slightly weaker conformity than in Event 2.

As in earlier analyses, using a representative fixed value of K_q is recommended to ensure physically meaningful load modeling.

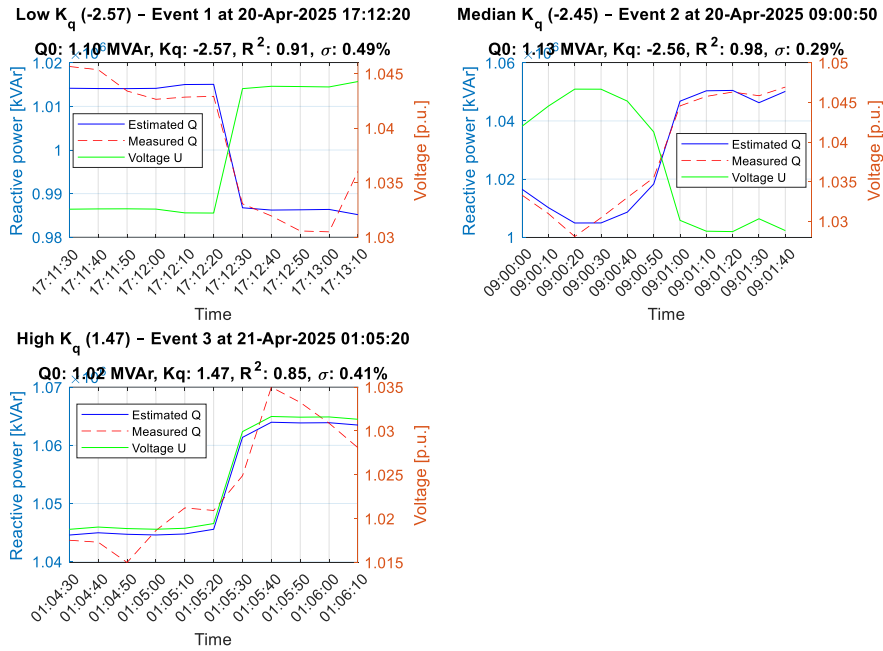


Figure 3.42: Model $Q(U)$ fitting to measured data in Labore TR3 – Second set of measurements

Figure 3.43 presents the $P(U)$ graphs for three filtered events at the TR3 transformer in the RTP Labore substation (industrial loads). Each subplot shows the relationship between active power P (in MW) and voltage U (in p.u.) during individual OLTC switching events.

In **Event 1 (20-Apr-2025, 17:12:20)**, $P_0 = 0.71$ MW, $K_p = 1.83$, $R^2 = 0.83$, and $\sigma = 0.49\%$. The measured points align well with the model, showing a clear positive dependency between voltage and power.

In **Event 2 (21-Apr-2025, 01:14:50)**, $P_0 = 0.62$ MW, $K_p = 1.01$, $R^2 = 0.89$, and $\sigma = 0.23\%$. The measured data tightly follows the modeled trend, indicating a nearly linear response and stable load behaviour.

In **Event 3 (21-Apr-2025, 17:14:20)**, $P_0 = 0.65$ MW, $K_p = 2.22$, $R^2 = 0.95$, and $\sigma = 0.33\%$. This event shows the strongest voltage sensitivity, with the model fitting the measured data exceptionally well.

Overall, all three cases confirm the reliability of the static exponential model for representing industrial load response to voltage variations, with particularly strong agreement in events characterized by higher R^2 and moderate K_p values.

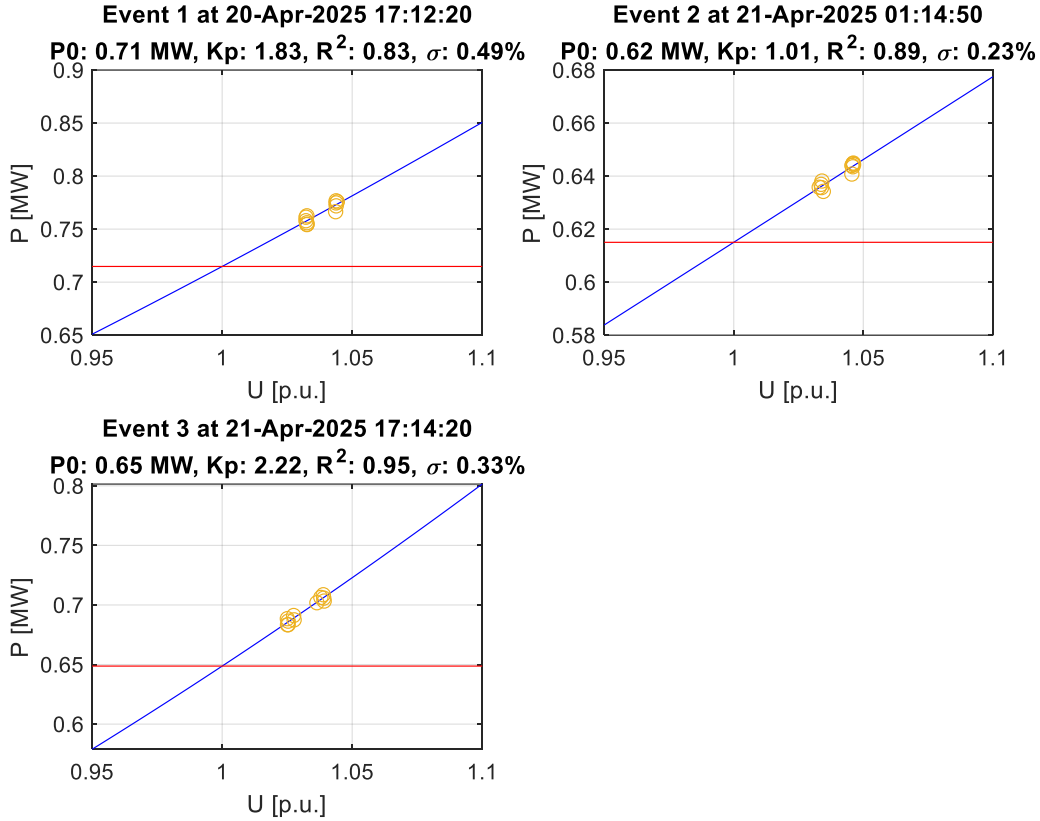


Figure 3.43: $P(U)$ graph for selected events in Labore TR3 – Second set of measurements

Figure 3.44 presents the $Q(U)$ graphs for three selected events at the TR3 transformer in the RTP Labore substation (second set of measurements).

In **Event 1 (20-Apr-2025, 17:12:20)**, the measured points align well with the model trend, yielding $R^2 = 0.91$. The negative slope ($K_q = -2.57$) indicates a decreasing reactive-power response with increasing voltage, a behaviour that is mathematically consistent within the fitting procedure but physically questionable for industrial loads.

In **Event 2 (20-Apr-2025, 09:00:50)**, the fit improves ($R^2 = 0.98$), and the slope remains negative ($K_q = -2.56$). The measured points follow the model closely, confirming stable numerical convergence. As in the previous event, however, the negative sensitivity suggests that the extracted parameter does not reflect realistic $Q(U)$ characteristics.

In **Event 3 (21-Apr-2025, 01:05:20)**, the estimated slope becomes positive ($K_q = 1.47$), with $R^2 = 0.85$. This event shows a more conventional $Q(U)$ trend, but the reactive-power variation remains small, leading to a weaker parameter identification.

Overall, the three cases illustrate that although the exponential $Q(U)$ model can match the measured points with good statistical accuracy, the fitted K_q values remain inconsistent across events. This variability confirms that the reactive-power sensitivity cannot be reliably extracted from the available TR3 data.

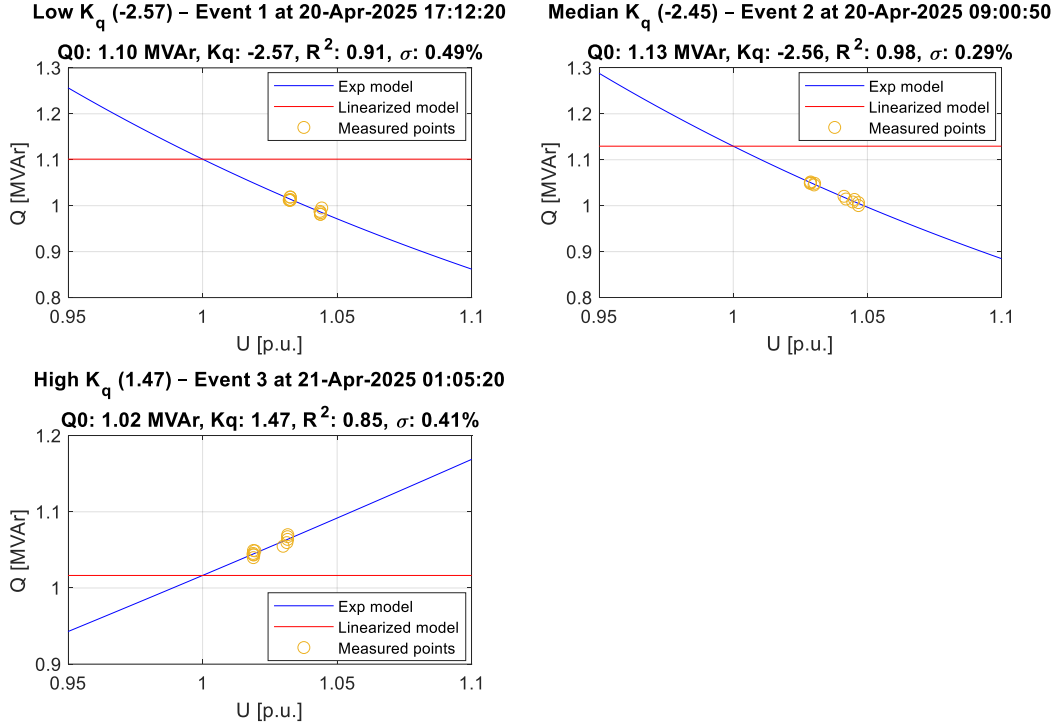


Figure 3.44: $Q(U)$ graph for selected events in Labore TR3 – Second set of measurements

Figure 3.45 presents a histogram of the active power model parameters for RTP Primskovo TR1 (second set of measurements). The figure consists of two bar charts:

The top chart displays the initial power P_0 values in megawatts (MW) for several filtered events at the TR1 in RTP Primskovo (mixed loads). The P_0 values range approximately between 1.2 MW and 2.7 MW, showing noticeable variability across the detected events. This spread suggests that the load conditions at TR1 Primskovo fluctuate significantly during the analyzed periods, reflecting a combination of residential, commercial, and smaller industrial consumers.

The bottom chart presents the exponential factor K_p for the same events. Most K_p values fall between 1.0 and 2.2, indicating moderate to strong sensitivity of active power to voltage variations. A few events exhibit higher K_p , implying more responsive or dynamic load components.

Overall, the dataset reveals a diverse load composition at Primskovo, where both P_0 and K_p vary considerably among events. This variability highlights the mixed-load nature of the network, confirming that the static exponential model must account for a wide range of operating behaviours to accurately represent voltage–power dependency.

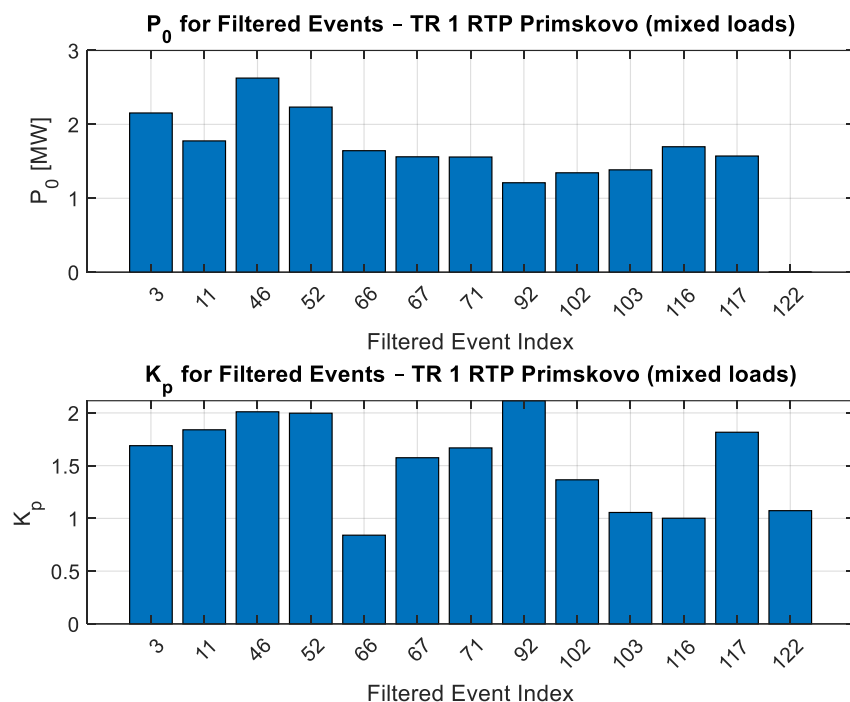


Figure 3.45: Histogram of the $P(U)$ model parameters Primskovo TR1 – Second set of measurements

Figure 3.46 presents a histogram of the $Q(U)$ model parameters for the TR1 transformer at the RTP Primskovo substation (mixed loads). The top chart shows the initial reactive-power values Q_0 , which range between approximately 0.6 and around 0.8 MVar. The variation across events is moderate, indicating relatively stable reactive-power levels at the beginning of the OLTC switching disturbances.

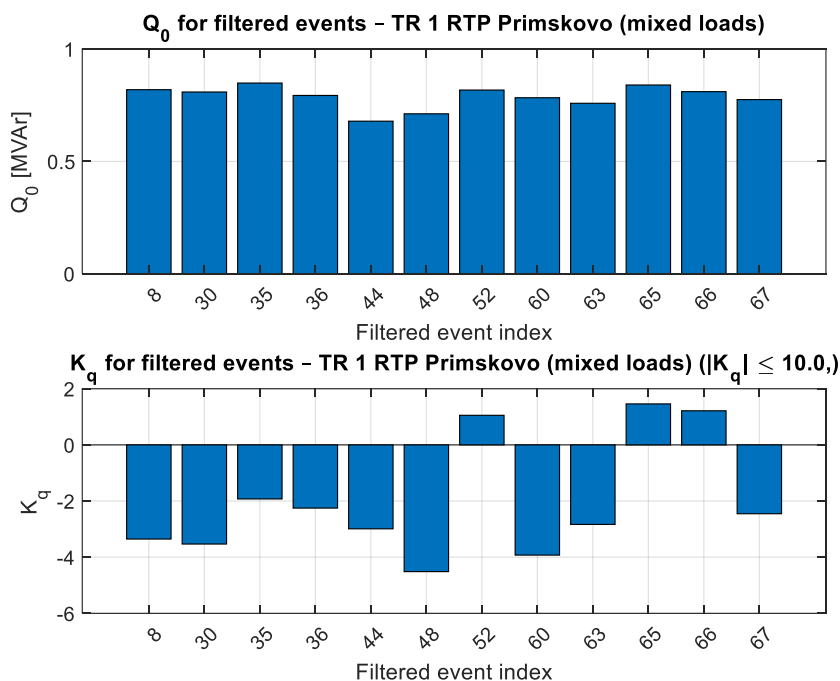


Figure 3.46: Histogram of the $Q(U)$ model parameters Primskovo TR1 – Second set of measurements

The bottom chart displays the exponential factor K_q for the same filtered events. The values cover a wide range, from small positive values up to several strongly negative ones, with many events yielding negative K_q . This inconsistency reflects the difficulty of reliably identifying reactive-power sensitivity from the available measurements, as the resulting parameters do not follow a clear pattern and often lack physical meaning.

Figure 3.47 shows the distribution of the exponential factor K_p for the TR1 transformer at the RTP Primskovo substation (mixed loads), categorized by day type. The weekday data exhibit slightly higher median K_p values (around 1.7) and a narrower interquartile range compared to the weekend data, which have a lower median (around 1.38) and wider spread. This suggests that load voltage sensitivity tends to be more stable during weekdays and slightly more variable during weekends. However, while the dataset contains a larger number of events compared to previous locations, the difference between weekday and weekend K_p distributions is still not pronounced enough to indicate a clear pattern. The observed variations are within the expected range for mixed-load areas where both residential and commercial activities influence load dynamics.

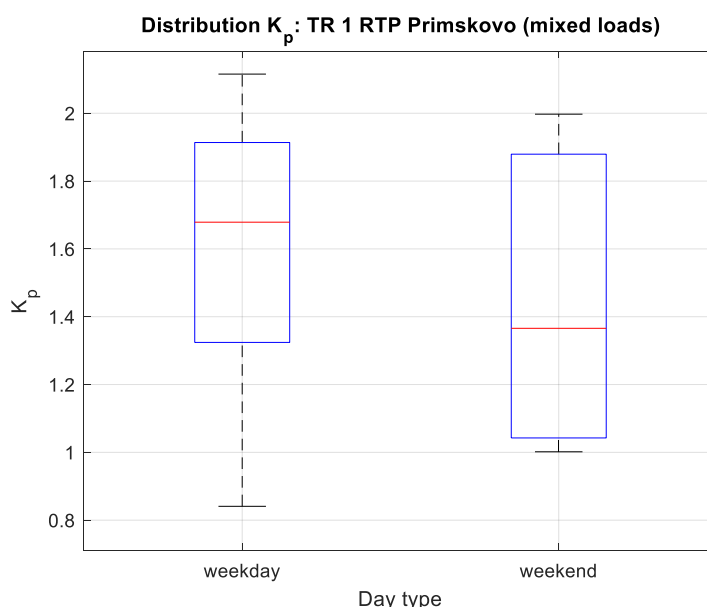


Figure 3.47: Distribution of the exponential factor K_p RTP Primskovo TR1 – Second set of measurements

Figure 3.48 presents the distribution of the exponential factor K_q for the TR1 transformer at the RTP Primskovo substation (mixed loads). The weekday values show a wide spread, ranging from mildly positive down to approximately -4.5 , with a median -3 . The weekend group displays a narrower distribution but remains centered around negative values as well. Despite the larger sample size compared with other transformers, the results do not reveal any clear difference between weekday and weekend behaviour. The consistently negative and highly variable K_q values confirm that the Q(U) sensitivity cannot be reliably determined from these events.

Figure 3.49 presents the P(U) model fitting results for three selected events at the TR1 transformer in the RTP Primskovo substation (second set of measurements). Each subplot shows the estimated active power (blue), measured power (red dashed), and the per-unit voltage (green) during the OLTC switching event.

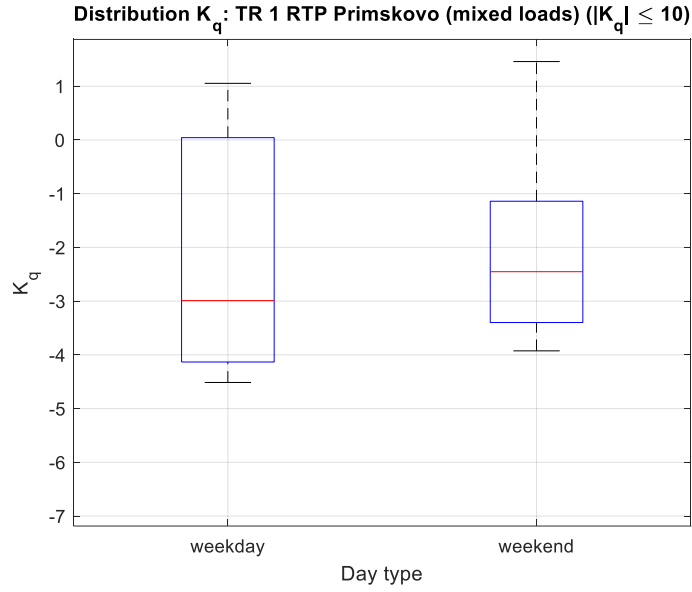


Figure 3.48: Distribution of the exponential factor K_q RTP Primskovo TR1 – Second set of measurements

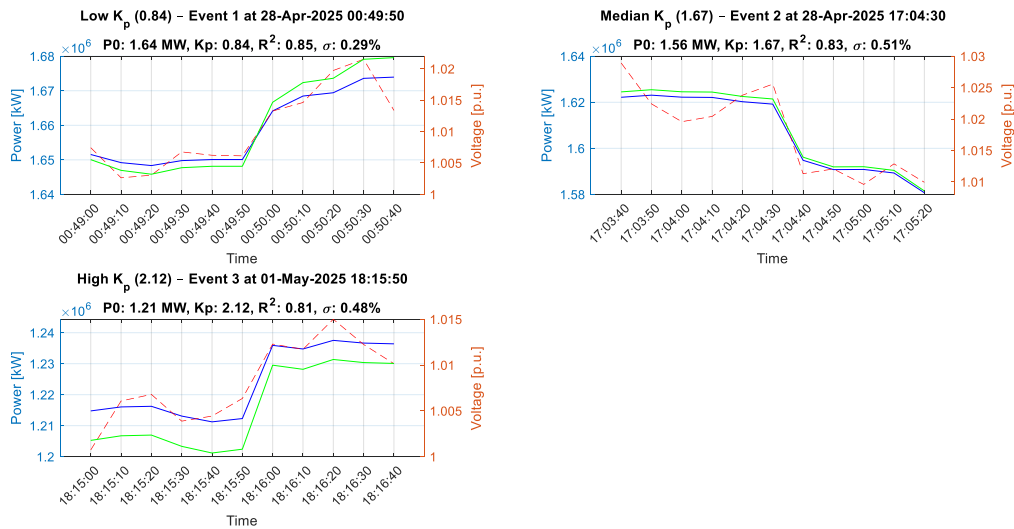


Figure 3.49: Model $P(U)$ fitting to measured data in Primskovo TR1 – Second set of measurements

In **Event 1 (28-Apr-2025, 00:49:50)**, the initial active power is $P_0 = 1.64$ MW, with $K_p = 0.84$, $R^2 = 0.85$, and $\sigma = 0.29\%$. A clear voltage increase produces a corresponding rise in active power, and the fitted exponential model follows the measured trend reasonably well, with minor deviations during the transient.

In **Event 2 (28-Apr-2025, 17:04:30)**, the parameters are $P_0 = 1.56$ MW, $K_p = 1.67$, $R^2 = 0.83$, and $\sigma = 0.51\%$. The measured power exhibits a more pronounced voltage-dependent behaviour, and the model captures the overall shape of the response despite some scatter around the voltage step.

In **Event 3 (01-May-2025, 18:15:50)**, the active-power response is characterized by $P_0 = 1.21$ MW, $K_p = 2.12$, $R^2 = 0.81$, and $\sigma = 0.48\%$. The higher K_p reflects stronger sensitivity of active power to the voltage increase, and the measured points align well with the modeled curve once the new steady-state level is reached.

Overall, the three events demonstrate that the exponential P(U) model provides a consistent approximation of the voltage–power dependency at the TR1 transformer. The quality of fit and parameter values confirm stable active-power behaviour during OLTC tap changes.

Figure 3.50 presents the Q(U) model fitting results for three selected events at the TR1 transformer in the RTP Primskovo substation (mixed loads). Each subplot shows the estimated reactive power (blue), measured reactive power (red dashed), and the per-unit voltage (green) during the OLTC switching event.

In **Event 1 (29-Apr-2025, 17:17:30)**, the initial reactive power is $Q_0 = 0.71$ MVar, with $K_q = -4.51$, $R^2 = 0.90$, and $\sigma = 0.91\%$. The measured reactive-power response follows the general trend of the model, although the strongly negative slope again lacks physical meaning. Despite this, the fit adequately reproduces the steady-state relationship.

In **Event 2 (03-May-2025, 17:11:50)**, the parameters are $Q_0 = 0.76$ MVar, $K_q = -2.83$, $R^2 = 0.82$, and $\sigma = 0.74\%$. The match between the measured signal and the model is reasonable, but the reactive-power variation remains weak, leading to instability in the fitted exponential factor and another negative K_q value.

In **Event 3 (04-May-2025, 01:00:00)**, the model yields $Q_0 = 1.02$ MVar, $K_q = 1.46$, $R^2 = 0.85$, and $\sigma = 0.38\%$. This event exhibits a positive reactive-power sensitivity, and the model aligns well with the measured data. However, the overall variation remains small, limiting the robustness of the parameter identification.

Overall, the three events show that while the exponential model can reproduce the measured Q(U) trend, the resulting K_q values vary significantly in both magnitude and sign. This inconsistency confirms that reliable identification of reactive-power sensitivity is not achievable from the available TR1 OLTC events.

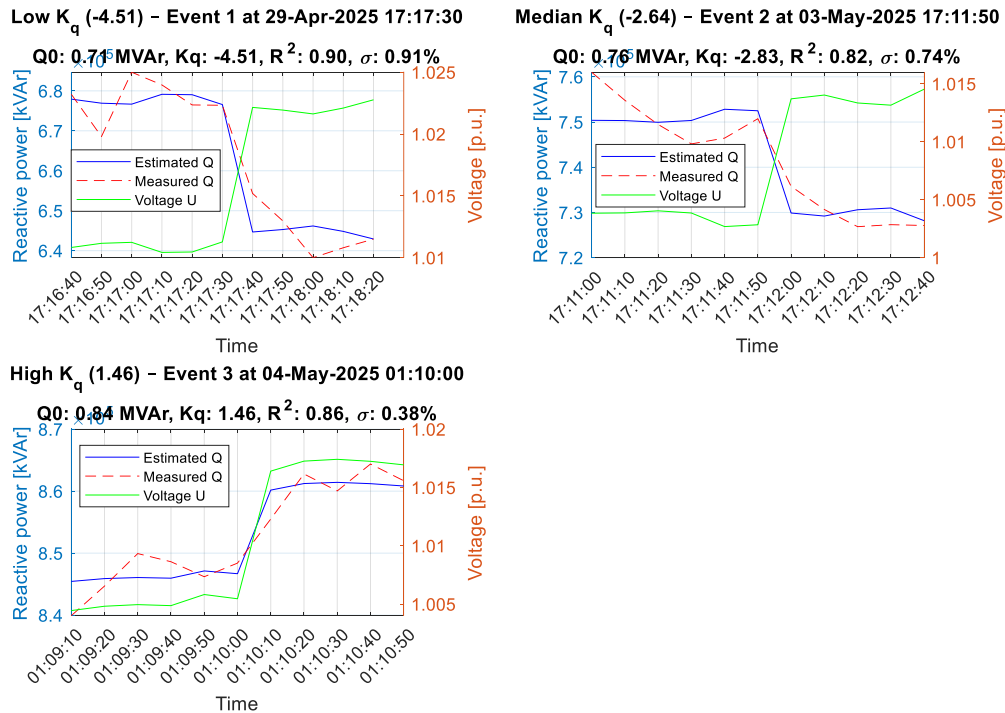


Figure 3.50: Model Q(U) fitting to measured data in Primskovo TR1 – Second set of measurements

Figure 3.51 presents the $P(U)$ graphs for three selected events at the TR1 transformer in the RTP Primskovo substation (second set of measurements).

In **Event 1 (28-Apr-2025, 00:49:50)**, the measured points follow the modelled trend with a good agreement ($R^2 = 0.85$). The positive slope ($K_p = 0.84$) reflects a moderate increase of active power with voltage, and the deviations between the model and measurements remain small.

In **Event 2 (28-Apr-2025, 17:04:30)**, the sensitivity increases ($K_p = 1.67$), and the correlation remains strong ($R^2 = 0.83$). The measured values align closely with the exponential curve, confirming a consistent voltage–power dependency.

In **Event 3 (01-May-2025, 18:15:50)**, the slope becomes steeper ($K_p = 2.12$), indicating a stronger active-power response to voltage changes. Although the scatter of measured points is slightly larger, the model still fits well ($R^2 = 0.81$).

Overall, the three events demonstrate that the exponential $P(U)$ model accurately captures the dependence of active power on voltage for the TR1 transformer under mixed-load conditions.

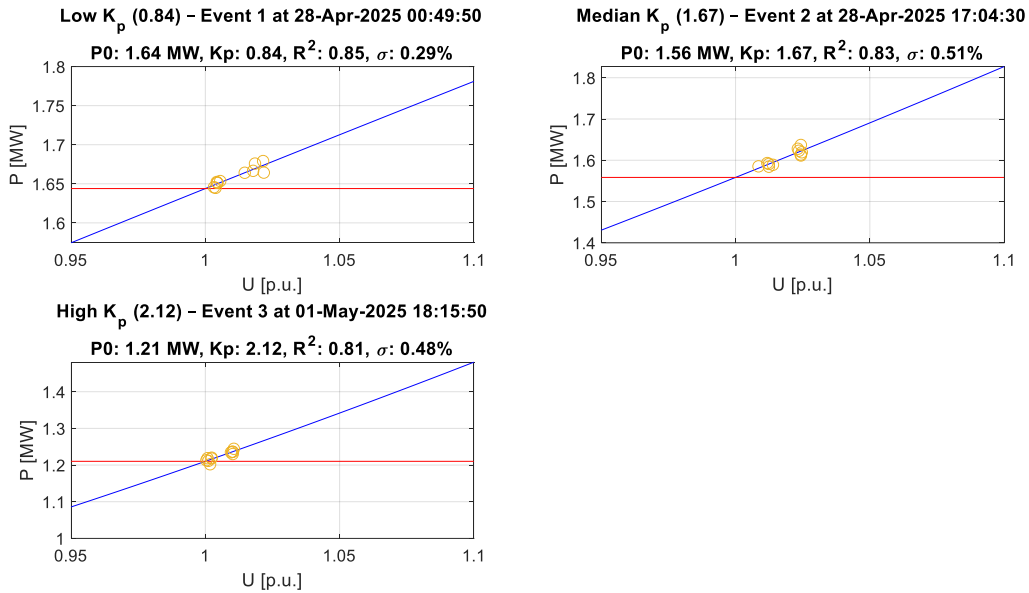


Figure 3.51: $P(U)$ graph for selected events in Primskovo TR1 – Second set of measurements

Figure 3.52 presents the $Q(U)$ graphs for three selected events at the TR1 transformer in the RTP Primskovo substation (second set of measurements).

In **Event 1 (29-Apr-2025, 17:17:30)**, the measured points follow the general trend of the fitted model with a good correlation ($R^2 = 0.90$), showing a clear negative slope ($K_q = -4.51$). The deviation between the modeled and measured values remains small, although the negative voltage sensitivity again appears physically questionable.

In **Event 2 (03-May-2025, 17:11:50)**, the trend is similar, with $K_q = -2.83$ and $R^2 = 0.82$. The measured samples align reasonably well with the exponential curve, but the reactive-power variation is small, which limits the robustness of the parameter estimation.

In **Event 3 (04-May-2025, 01:10:00)**, the slope becomes positive ($K_q = 1.46$), and the model achieves $R^2 = 0.86$. The measured data points follow the fitted curve closely, indicating a stable event, despite the relatively modest reactive-power change.

Overall, the three events demonstrate that the $Q(U)$ model can approximate the measured dependence between reactive power and voltage. However, the large variability and inconsistent sign of K_q confirm that the reactive-power sensitivity cannot be reliably determined from the TR1 dataset.

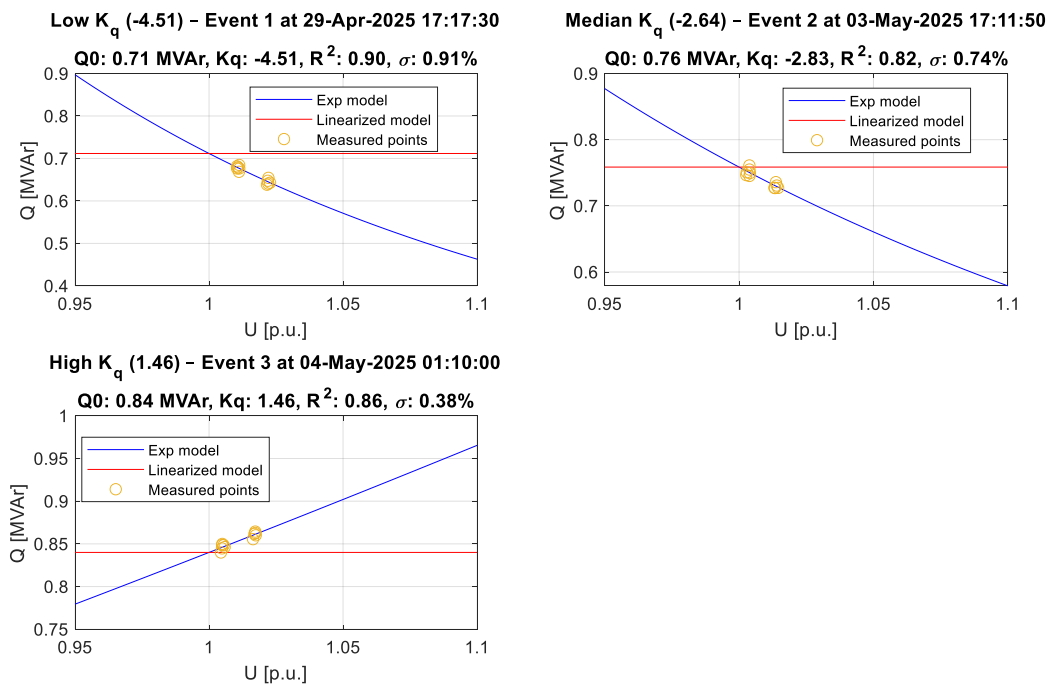


Figure 3.52: $Q(U)$ graph for selected events in Primskovo TR1 – Second set of measurements

Figure 3.53 presents a histogram of model parameters for RTP Primskovo TR2 (second set of measurements). The figure consists of two bar charts:

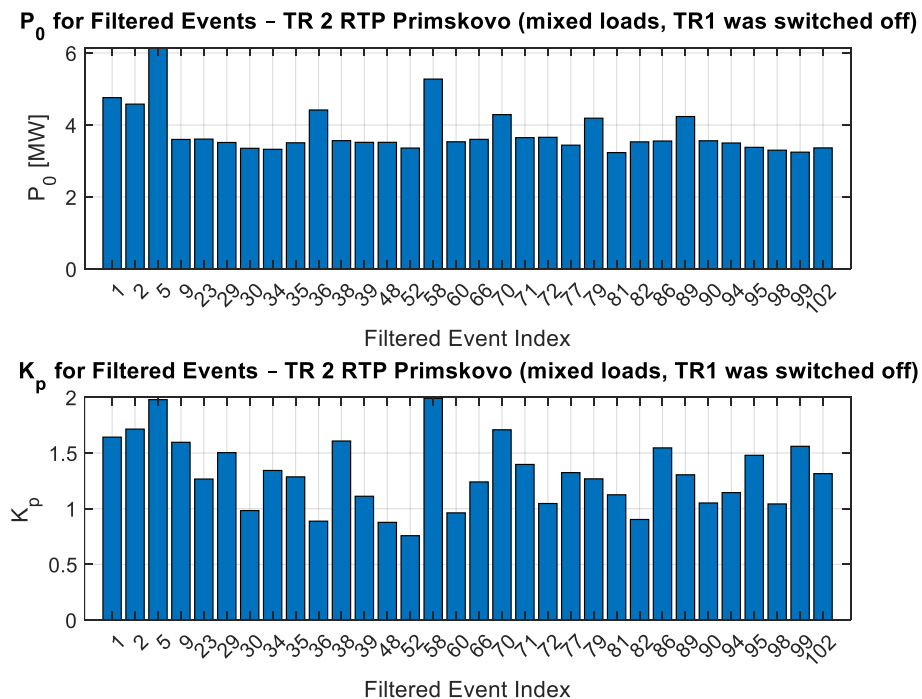


Figure 3.53: Histogram of the $P(U)$ model parameters Primskovo TR2 – Second set of measurements

The top chart displays the initial power P_0 values in megawatts (MW) for all filtered events at the TR2 transformer in RTP Primskovo (mixed loads, TR1 was switched off). The P_0 values range widely from approximately 3 MW to over 6 MW, indicating substantial variation in load levels across the detected events. This variability reflects the dynamic and diverse load composition supplied by TR2 during the period when TR1 was disconnected, likely including both residential and industrial consumers.

The bottom chart shows the exponential factor K_p for the same set of events. Most K_p values lie between 1.0 and 1.8, with occasional peaks close to 2.0. This distribution suggests moderate sensitivity of active power to voltage variations, characteristic of mixed-load behaviour where resistive and motor-driven loads coexist.

Overall, the results indicate that while base load levels (P_0) fluctuate significantly, the voltage sensitivity (K_p) remains within a consistent range. This implies that, despite varying operational conditions, the TR2 transformer exhibits stable load–voltage characteristics, confirming reliable system performance even with TR1 offline.

Figure 3.54 presents a histogram of the Q(U) model parameters for the TR2 transformer at the RTP Primskovo substation (mixed loads, TR1 switched off). The upper chart shows the initial reactive-power values Q_0 , which remain relatively consistent across events around 2.5 MVar.

The lower chart displays the exponential factor K_q . The values vary substantially, spanning from small positive values to distinctly negative ones. Several events exhibit strongly negative K_q , indicating unstable or non-physical reactive-power sensitivity. As in previous cases, the extracted K_q parameters do not form a clear or interpretable pattern, confirming that reliable estimation of Q(U) sensitivity is not achievable from these events.

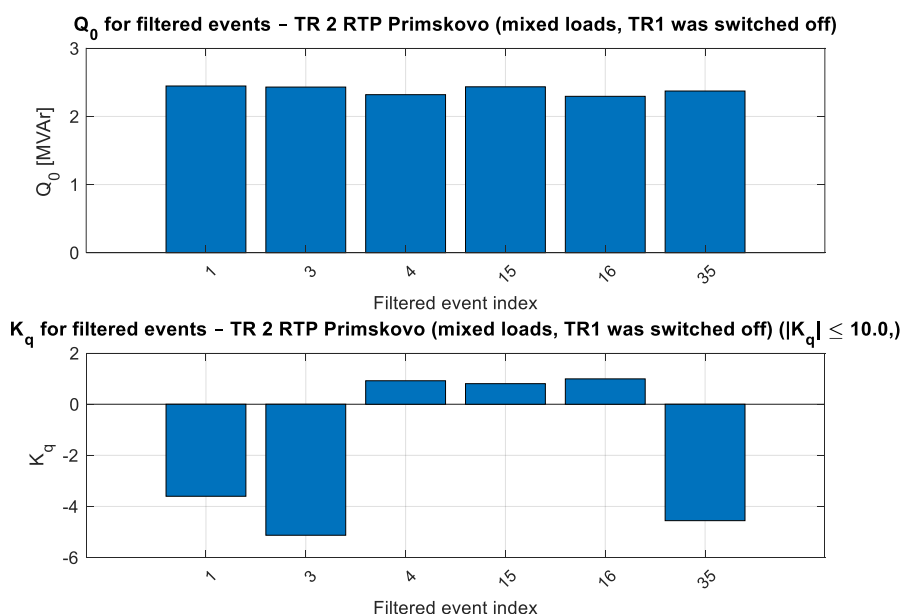


Figure 3.54: Histogram of the Q(U) model parameters Primskovo TR2 – Second set of measurements

Figure 3.55 presents the distribution of the exponential factor K_p for the TR2 transformer at the RTP Primskovo substation (mixed loads, TR1 switched off), categorized by day type. The weekday values show a median K_p of around 1.3 with a wider spread, ranging roughly between 0.8 and 2.0,

while the weekend values exhibit a slightly lower median (1.25) and a narrower range. These results suggest that load voltage sensitivity remains relatively consistent throughout the week, with no clear distinction between weekday and weekend behaviour. The observed variability is small and likely linked to normal fluctuations in mixed-load conditions, rather than systematic operational differences.

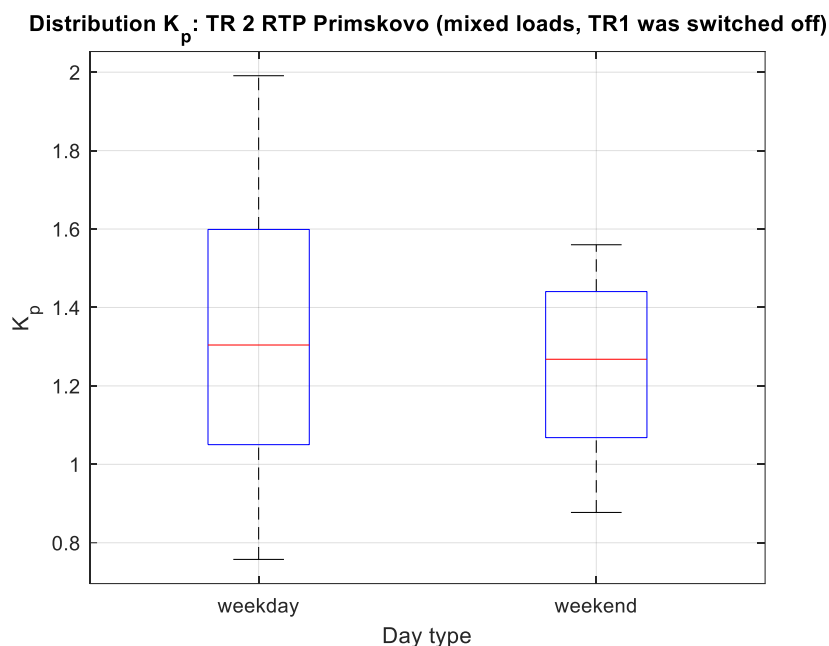


Figure 3.55: Distribution of the exponential factor K_p RTP Primskovo TR2 – Second set of measurements

Figure 3.56 presents the distribution of the exponential factor K_q for the TR2 transformer at the RTP Primskovo substation (mixed loads, TR1 switched off). The weekday group shows a wide spread of K_q values, ranging from approximately 1 down to around -5 , with the median near -1.5 . No weekend events were detected, therefore no comparison between day types is possible. The large variability and predominantly negative values again indicate that the Q(U) sensitivity cannot be reliably determined from the available events.

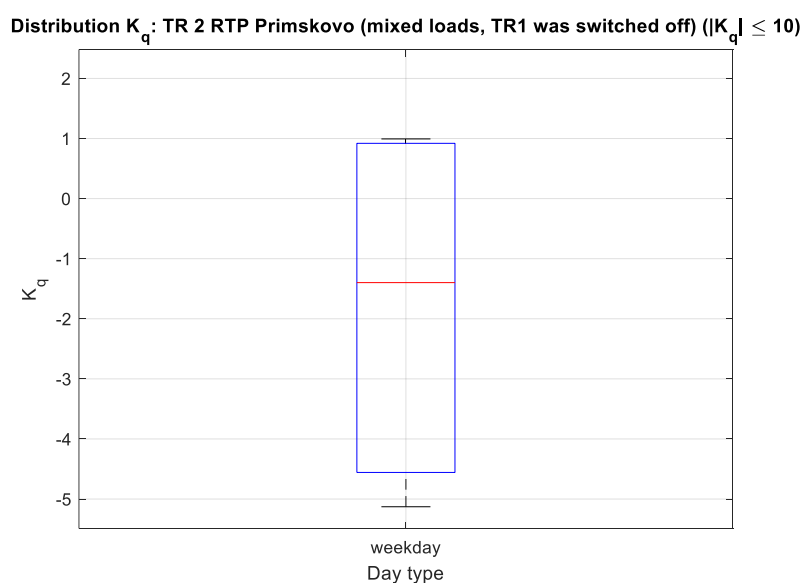


Figure 3.56: Distribution of the exponential factor K_q RTP Primskovo TR2 – Second set of measurements

Figure 3.57 presents the P(U) model fitting results for three selected events at the TR2 transformer in the RTP Primskovo substation (second set of measurements).

In **Event 1 (19-May-2025, 01:06:30)**, the initial active power is $P_0 = 3.36$ MW, with $K_p = 0.76$, $R^2 = 0.84$, and $\sigma = 0.21\%$. The voltage increase results in a clear upward step in active power, and the model captures the steady-state behaviour well, with only small deviations in the transient segment.

In **Event 2 (29-May-2025, 23:27:20)**, the estimated parameters are $P_0 = 4.23$ MW, $K_p = 1.30$, $R^2 = 0.88$, and $\sigma = 0.37\%$. The measured active-power response aligns closely with the exponential model, showing a stronger voltage sensitivity compared with Event 1. The fit remains consistent across the full duration of the voltage change.

In **Event 3 (20-May-2025, 17:35:00)**, the parameters are $P_0 = 5.27$ MW, $K_p = 1.99$, $R^2 = 0.85$, and $\sigma = 0.37\%$. This event shows the steepest slope, indicating the highest sensitivity of active power to voltage variations among the three events. The measured and modeled values match well once the new steady-state is established.

Overall, the three events demonstrate that the exponential P(U) model successfully captures the voltage–power relationship for Primskovo TR2. The increasing values of K_p across the selected events illustrate differing load sensitivities, while consistently high R^2 values confirm reliable model performance.

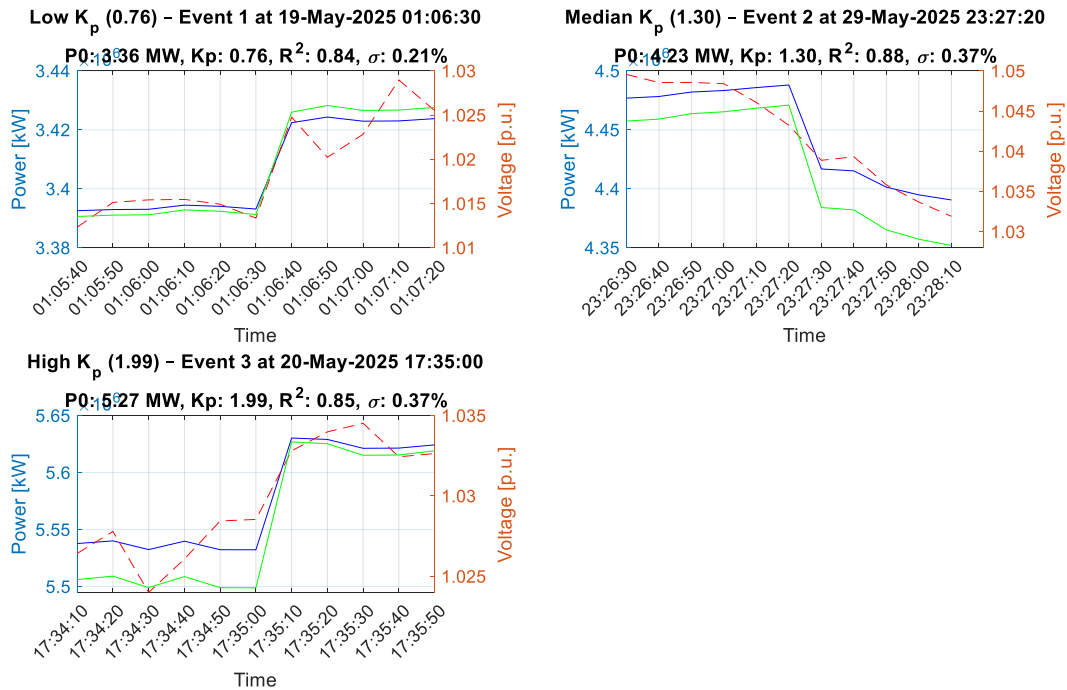


Figure 3.57: Model P(U) fitting to measured data (selected measurements) in Primskovo TR2 – Second set of measurements

Figure 3.58 presents the Q(U) model fitting results for three selected events at the TR2 transformer in the RTP Primskovo substation (second set of measurements). Each plot shows the estimated reactive power (blue), measured reactive power (red dashed), and the corresponding per-unit voltage (green) during the OLTC switching event.

In **Event 1 (06-May-2025, 19:22:20)**, the initial reactive power is $Q_0 = 2.43$ MVar, with $K_q = -5.13$, $R^2 = 0.93$, and $\sigma = 0.69\%$. The measured data follow the model trend reasonably well, but the strongly negative K_q value indicates a non-physical voltage sensitivity, consistent with instability in the parameter estimation.

In **Event 2 (16-May-2025, 03:16:00)**, the parameters are $Q_0 = 2.44$ MVar, $K_q = -1.40$, $R^2 = 0.85$, and $\sigma = 0.21\%$. The reactive-power response is smoother, and the model reproduces the shape of the measured curve well. Despite this, the negative slope again suggests that the extracted sensitivity does not reflect realistic $Q(U)$ behaviour.

In **Event 3 (16-May-2025, 05:12:10)**, the model yields $Q_0 = 2.30$ MVar, $K_q = 0.99$, $R^2 = 0.86$, and $\sigma = 0.24\%$. This event shows a positive sensitivity and a good fit between measured and modeled values, indicating a more stable and interpretable response compared with the first two cases.

Overall, the three events show that the exponential $Q(U)$ model can capture the general shape of the reactive-power response, but the resulting K_q values vary considerably in magnitude and sign. This variability confirms that reliable identification of $Q(U)$ sensitivity is limited, and that a fixed representative parameter remains the most practical choice for TR2 load modeling.

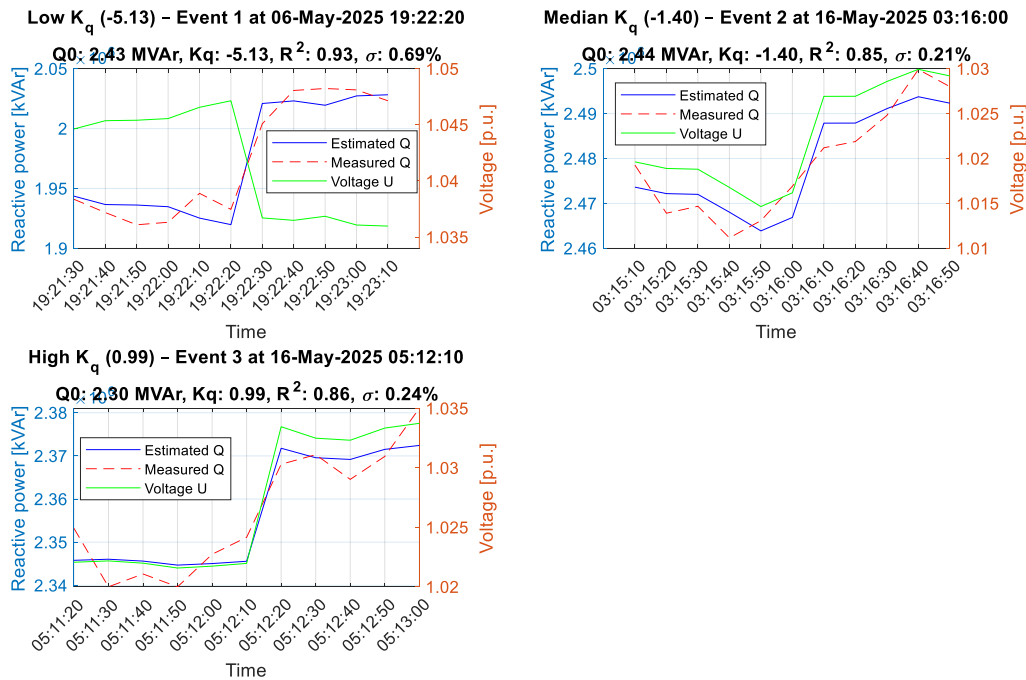


Figure 3.58: Model $Q(U)$ fitting to measured data (selected measurements) in Primskovo TR2 – Second set of measurements

Figure 3.59 presents the $P(U)$ graphs for three selected events at the TR2 transformer in the RTP Primskovo substation (second set of measurements). Each plot shows the relationship between active power P (in MW) and voltage U (in p.u.). The blue line represents the exponential $P(U)$ model, the red horizontal line indicates the initial active-power level P_0 , and the orange circles correspond to the measured data points.

In **Event 1 (19-May-2025, 01:06:30)**, the measured points follow the model closely, with $R^2 = 0.84$. The slope $K_p = 0.76$ indicates a relatively mild active-power sensitivity to voltage changes, and the deviation between the model and data points remains small.

In **Event 2 (29-May-2025, 23:27:20)**, the voltage–power relationship becomes more pronounced. The estimated parameter $K_p = 1.30$ and the strong correlation ($R^2 = 0.88$) show that the measured points are well aligned with the model, confirming a stable response.

In **Event 3 (20-May-2025, 17:35:00)**, the fitted slope increases further to $K_p = 1.99$, reflecting the strongest voltage sensitivity among the three events. Despite slightly higher scatter in the measured samples, the model still provides a consistent approximation with $R^2 = 0.85$.

Overall, the three events demonstrate that the exponential $P(U)$ model effectively captures the dependency between active power and voltage for the TR2 transformer, with the increasing K_p values indicating varying load sensitivities under mixed-load conditions.

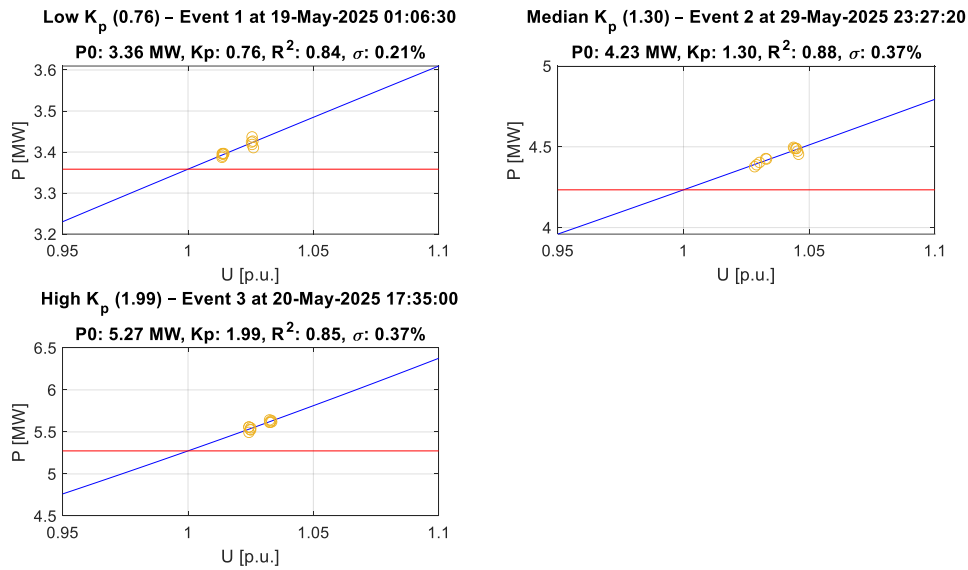


Figure 3.59: $P(U)$ graph for selected events in Primskovo TR2 – Second set of measurements

Figure 3.60 presents the $Q(U)$ graphs for three selected events at the TR2 transformer in the RTP Primskovo substation (second set of measurements). Each plot shows the relationship between reactive power Q (in MVar) and voltage U (in p.u.). The blue line represents the exponential $Q(U)$ model, the red horizontal line indicates the initial reactive-power level Q_0 , and the orange circles correspond to the measured data points. A linearized model is also included.

In **Event 1 (06-May-2025, 19:22:20)**, the measured points align well with the modelled downward trend ($K_q = -5.13$, $R^2 = 0.93$). The steep negative slope indicates strong voltage dependency within the mathematical fit, although such negative sensitivity is not physically meaningful.

In **Event 2 (16-May-2025, 03:16:00)**, the estimated slope remains negative ($K_q = -1.40$), with a good fit to the measured samples ($R^2 = 0.85$). The reactive-power variation is modest, but the model still captures the general trend across the observed voltage range.

In **Event 3 (16-May-2025, 05:12:10)**, the sensitivity becomes positive ($K_q = 0.99$), and the measured points follow the model closely ($R^2 = 0.86$). This event shows a more conventional $Q(U)$ behaviour compared with the previous two.

Overall, the three events show that the exponential $Q(U)$ model can represent the measured data, but the wide variation and inconsistent sign of K_q highlight the challenges in reliably determining reactive-power voltage sensitivity for Primskovo TR2.

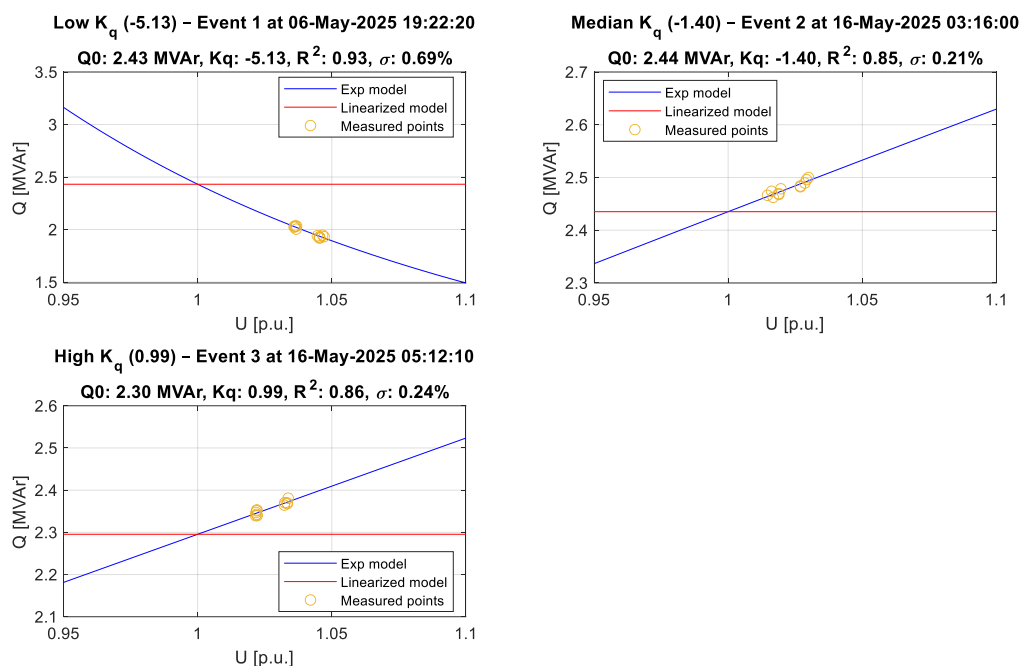


Figure 3.60: $Q(U)$ graph for selected events in Primskovo TR2 – Second set of measurements

3.3.4 Modelling of loads in the distribution grid in PowerFactory

This chapter focuses on finding the best approach for modelling distributed generation and voltage- and frequency-dependent loads connected to the MV distribution grid when performing stationery and dynamic analyses in the power system. This means choosing the correct load model and setting its parameters so that the performance of loads is accurate during RMS simulations. The modeling in this chapter is primarily focused on and performed with PowerFactory software, but the conclusions can be generalized to other similar software tools on the market.

MV-side loads exhibit different responses to voltage and frequency fluctuations depending on the load type – e.g., commercial/residential, industrial IM, and VFD loads. The software also enables the user to input (in %) the static vs. dynamic portions of the load to be modelled.

Entirely static loads have their parameters (resistance, inductance, capacitance) initialized from load-flow results. The active and reactive power consumption of these loads remains largely unchanged except for voltage-dependent variations during load-flow analyses. Simulations with entirely static loads will be included in this chapter mainly as a reference for comparison with other loads with a larger dynamic portion.

Dynamic portion of loads primarily represents the behaviour of motors (especially induction motors) and can be modelled with various time constants, frequency dependence factors, etc., as shown in Figure 3.61. In general, the loads should have both their dynamic and static portions. Only the dynamic part can be controlled by external signals in sense that the dynamic response is influenced by the behaviour of the grid. Therefore, during dynamic simulations, external signals are used to control only the dynamic portion of the load, while the static part remains fixed.

The values and ranges of the parameters for various types of loads are shown in table 2. The values of voltage and frequency dependence factors used for calculations in this chapter are the mean values of the given ranges.

The “Nonlinear voltage, linear frequency” model dependence in Figure 3.61 was selected for simulations, as it suitably represents nonlinear dynamic load behaviour under conditions where frequency deviations remain close to the nominal frequency (as is the case in subsequent simulations).

General Load Type - Grid\odj tip Labore.TypLod

Basic Data

Description

Version

Load Flow

Short-Circuit VDE/IEC

Short-Circuit Complete

Short-Circuit ANSI

Short-Circuit IEC 61363

Short-Circuit DC

Simulation RMS

Simulation EMT

Power Quality/Harmonics

Reliability

Hosting Capacity Analysis

Power Park Energy Analysis

Optimal Power Flow

Percentage

Static (const Z) 40 %

Dynamic 60 %

Model dependence Nonlinear voltage, linear frequency

Time constants

Delay 0,2 s

P frequency dep. 1,5 s

Q frequency dep. 1,5 s

P voltage dep. 0,2 s

Q voltage dep. 0,3 s

Frequency dependence

Coefficient kpf 1,2 %/%

Coefficient kqf -1,8 %/%

Voltage dependence of P

Coefficient aP 0,

Exponent e_aP 0,

Coefficient bP 0,

Exponent e_bP 1,

Coefficient cP 1,

Exponent e_cP 1,6

Voltage dependence of Q

Coefficient aQ 0,

Exponent e_aQ 0,

Coefficient bQ 0,

Exponent e_bQ 1,

Coefficient cQ 1,

Exponent e_cQ 1,

Voltage limits

Lower 0,8 p.u.

Upper 1,2 p.u.

OK

Cancel

Figure 3.61: Attributes of a dynamical non-linear load in Power Factory

Table 2: Parameters of dynamical loads; residential, commercial, industrial IM and VFD

	Residential	Commercial	Industrial IM	Industrial VFD
Dynamic [%]	30	40	60	60
Static [%]	70	60	40	40
Delay t_1 [s]	0,2	0,2	0,2	0,2
P frequency dep. t_{pf} [s]	2,0	1,5	1,0	1,5
Q frequency dep. t_{qf} [s]	2,0	1,5	1,0	1,5
P voltage dep. t_{pu} [s]	0,7	0,45	0,12	0,2
Q voltage dep. t_{qu} [s]	0,7	0,45	0,2	0,3
k_{pf} [%/%]	0,5	0,7	1,2	1,2
k_{qf} [%/%]	-0,5	-0,8	-1,8	-1,8

The "Delay" parameter t_1 in Figure 3.61 can have a significant impact on the dynamic response of loads. In PowerFactory's general load model, load dynamics are represented as the response of the load to voltage and frequency changes at its connection bus. The dynamics represented by this time

constant, as well as by the lead time constants t_{pu} , t_{qu} , etc., are associated with motors and other dynamic components within the load structure. If these constants are set to zero, the load response to voltage and frequency changes becomes instantaneous. As the delay increases, the transient becomes progressively less pronounced (i.e., more damped and smoother). Since precise data for estimating this parameter across different load types are not available, a default value of 0.2 s was adopted for this study.

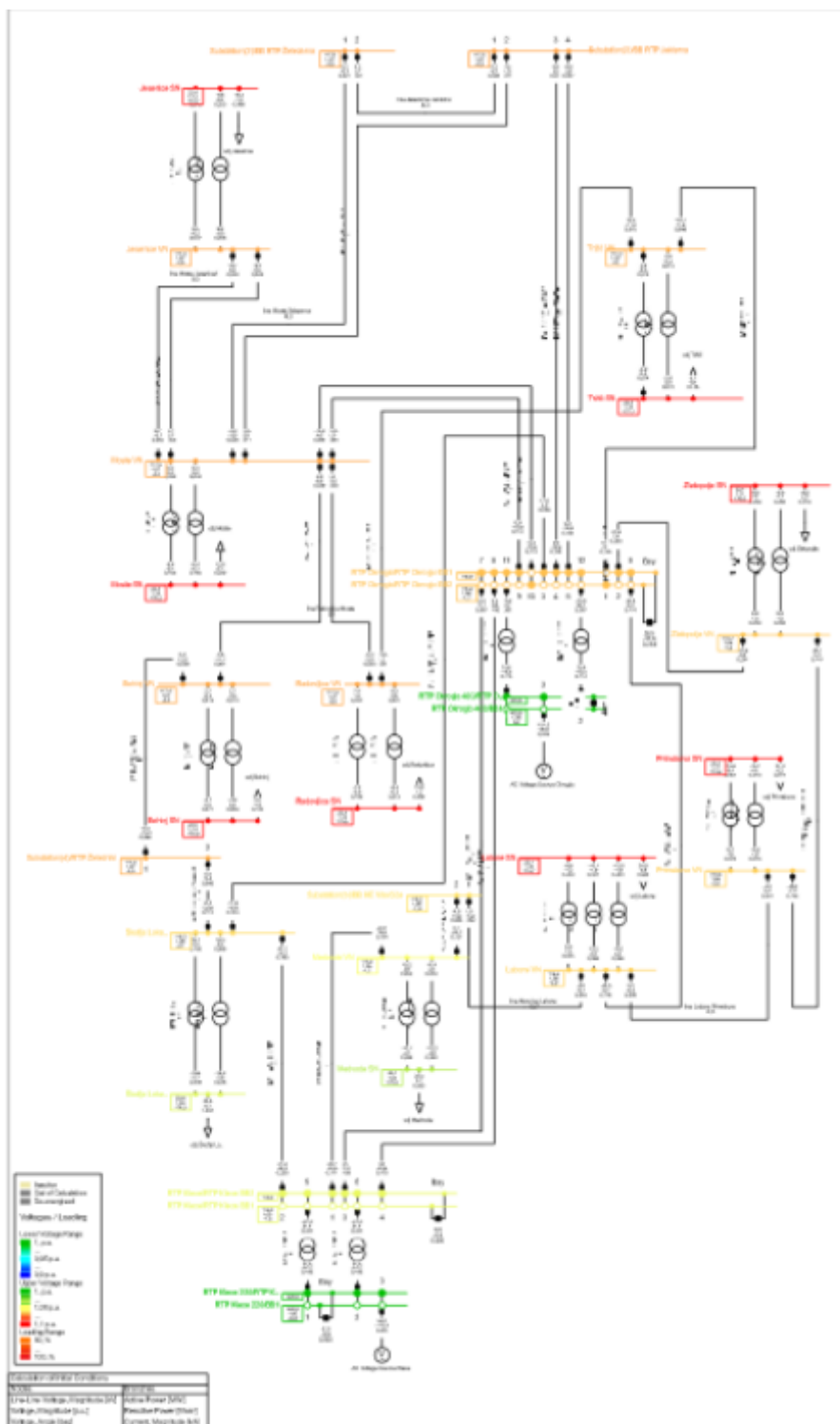


Figure 3.62: A model of the analyzed grid in Power Factory

After defining the relevant load types and their parameters, the load behaviour is further evaluated on the model grid of Gorenjska region. The model, presented in Figure 3.62 includes 14 110/20 kV transformer substations (TS), TS Okroglo 400/110 kV and TS Kleče 220/110 kV. The busbars on the 20 kV sides contain equivalent loads, representing active and reactive power consumption of consumers and active losses in the MV and LV grid. Annual peak demand load values in individual TS are used for simulations, as this results in the most unfavourable dynamic conditions.

A comparison of load behaviour using different parameters will be performed in subsequent simulations. This will provide valuable guidance in identifying the most appropriate parameter settings for dynamic simulations in the network. Two scenarios will be analyzed; a simultaneous change of the voltage in the 110 kV grid and a 3-phase short circuit on the 110 kV busbar on the Bohinj substation.

3.3.4.1 Instantaneous voltage change

During the dynamic analysis, the following quantities will be monitored: the voltage in 2 locations on the 110 kV side and the total active and reactive power of loads in the grid. These RMS simulations are conducted with a focus on observing the behaviour of various types of loads and their modelled parameters.

The voltage change is introduced in PowerFactory by changing the voltage-source parameter “u0 (p.u.)” shown in Figure 3.63. An instantaneous voltage change on the 110 kV grid is produced by applying voltage steps at the 400 kV node in TS Okroglo and the 220 kV node in TS Kleče; these locations are shown in Figure 3.64 and Figure 3.65. The resulting voltage responses on the 400 kV and 220 kV sides are shown in Figure 3.66, while the responses at the selected 110 kV busbars are presented in Figure 3.67-Figure 3.69. Figure 3.70 presents the resulting total active- and reactive-power response of all loads in the region.

As shown in Figure 3.71, the residential and commercial loads exhibit more pronounced transients of their total active and reactive power during voltage changes. This is due to their larger voltage-dependency time constants. A step change voltage on the 110 kV grid induces a temporary spike in power before the system settles to a new steady state. From this, it follows that residential and commercial loads are the most sensitive to network disturbances, involving sudden voltage change.

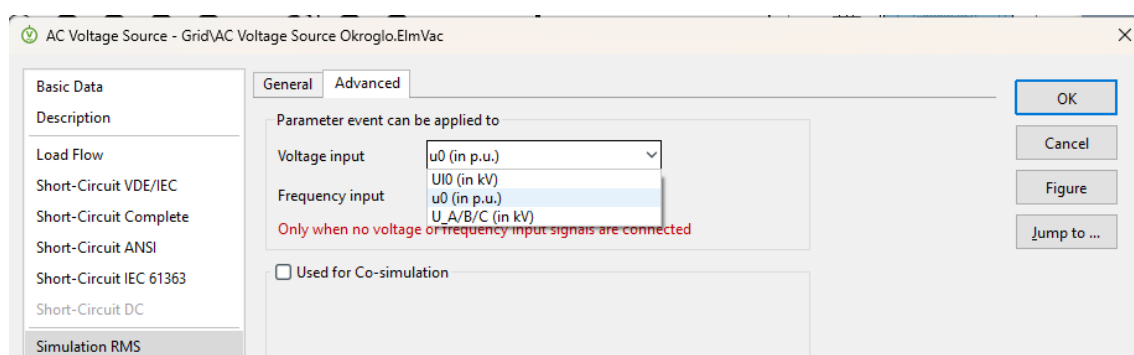


Figure 3.63: Input voltage attribute in the AC voltage source

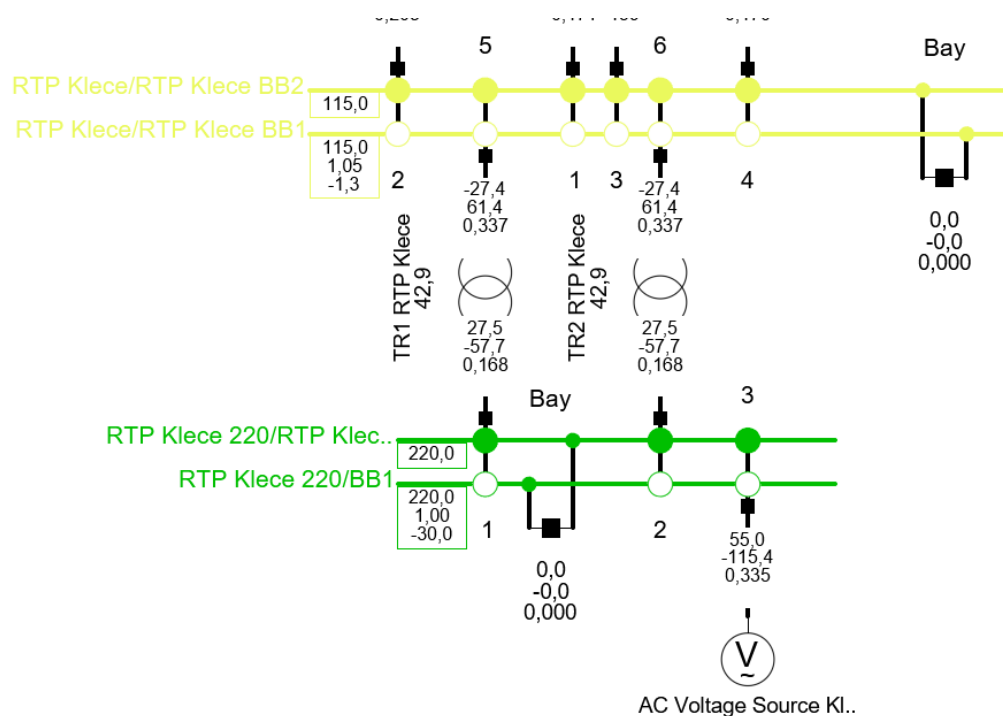


Figure 3.64: TS Kleče

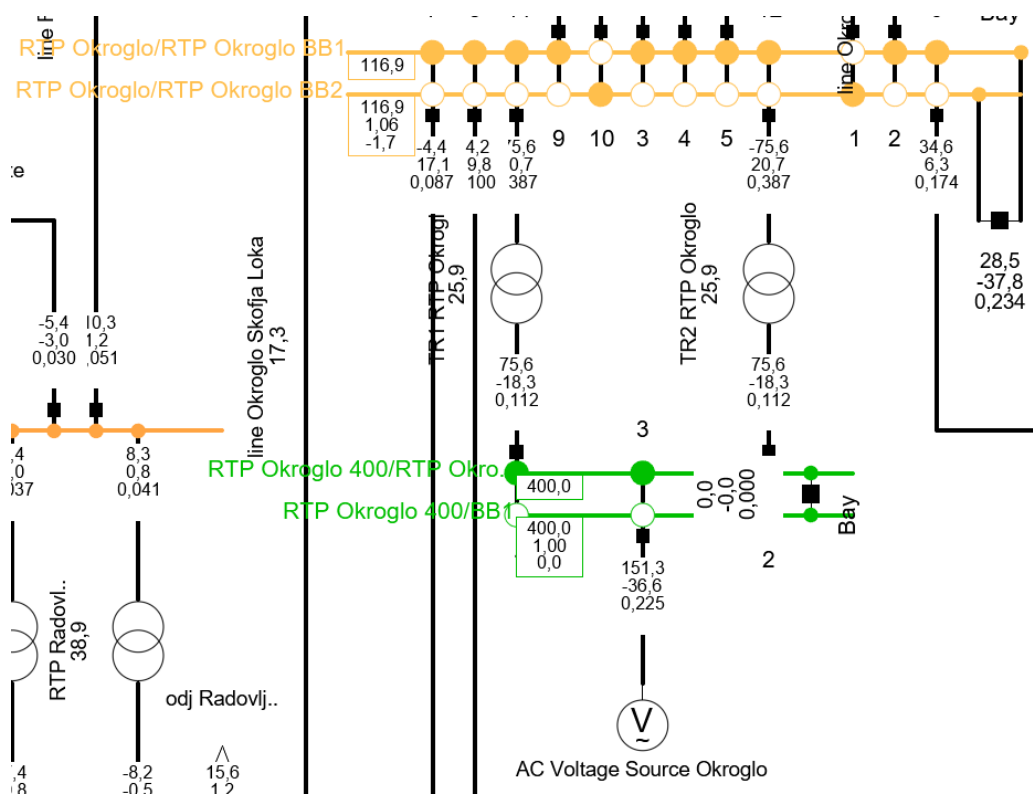


Figure 3.65: TS Okroglo

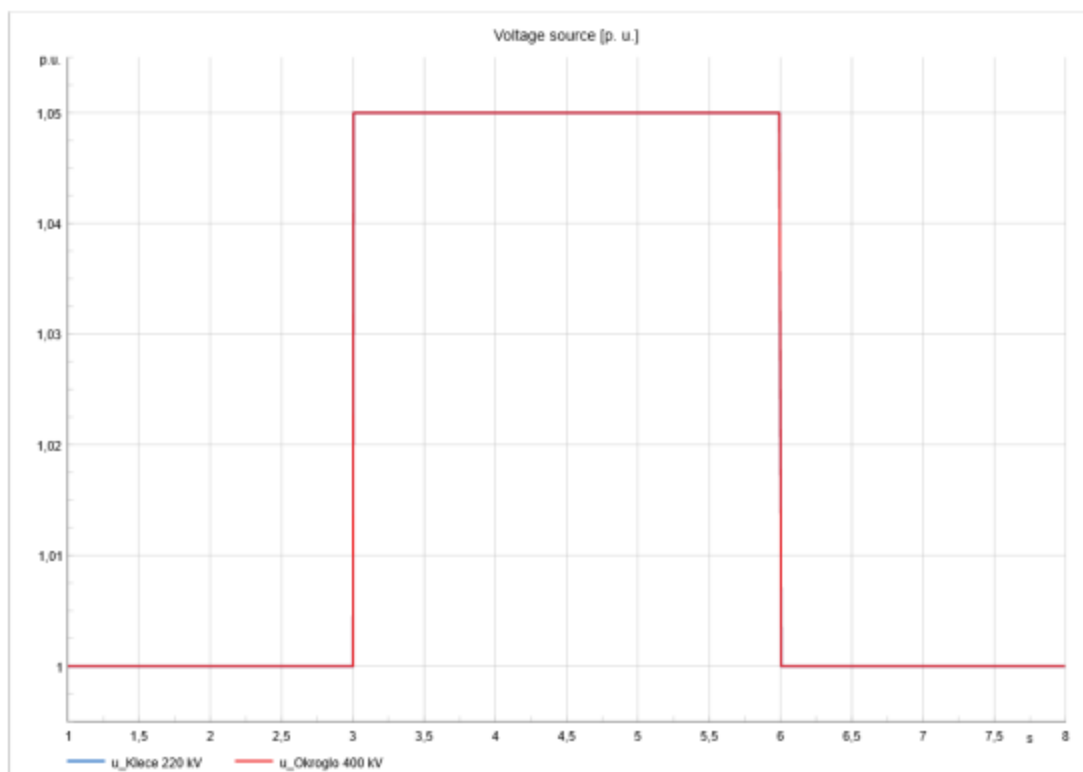


Figure 3.66: Voltage on the 220 kV and 400 kV side during the instantaneous input voltage change

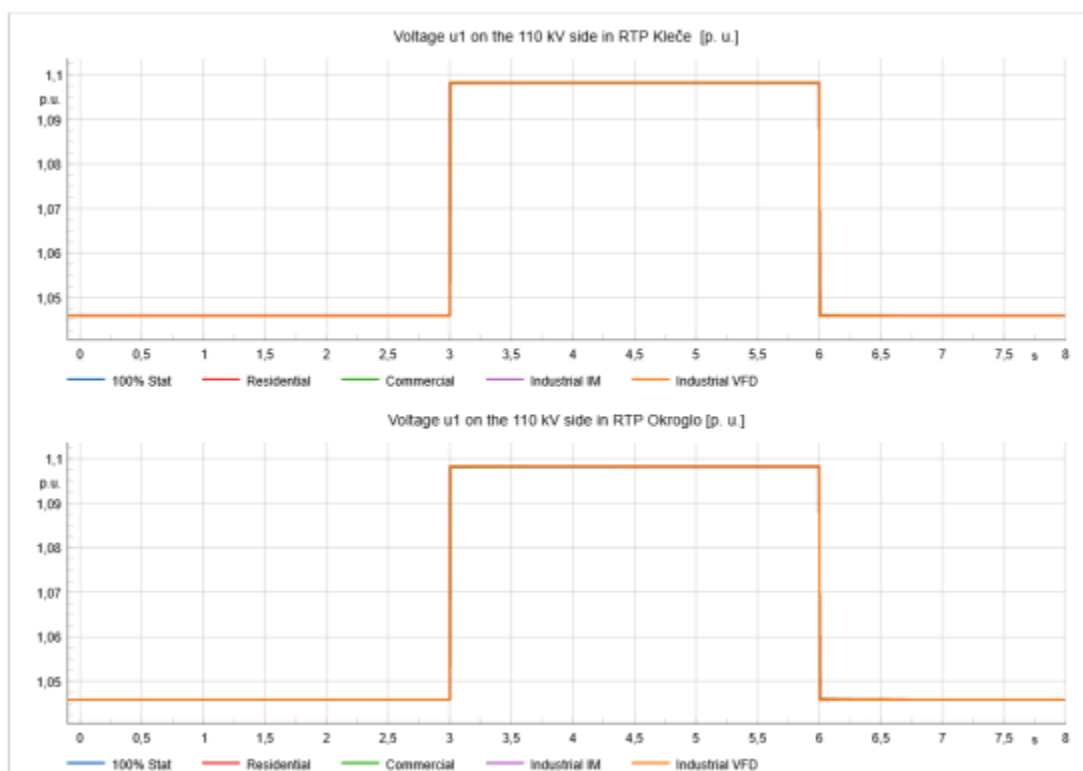


Figure 3.67: Voltage on the 110 kV side of two during the instantaneous voltage change

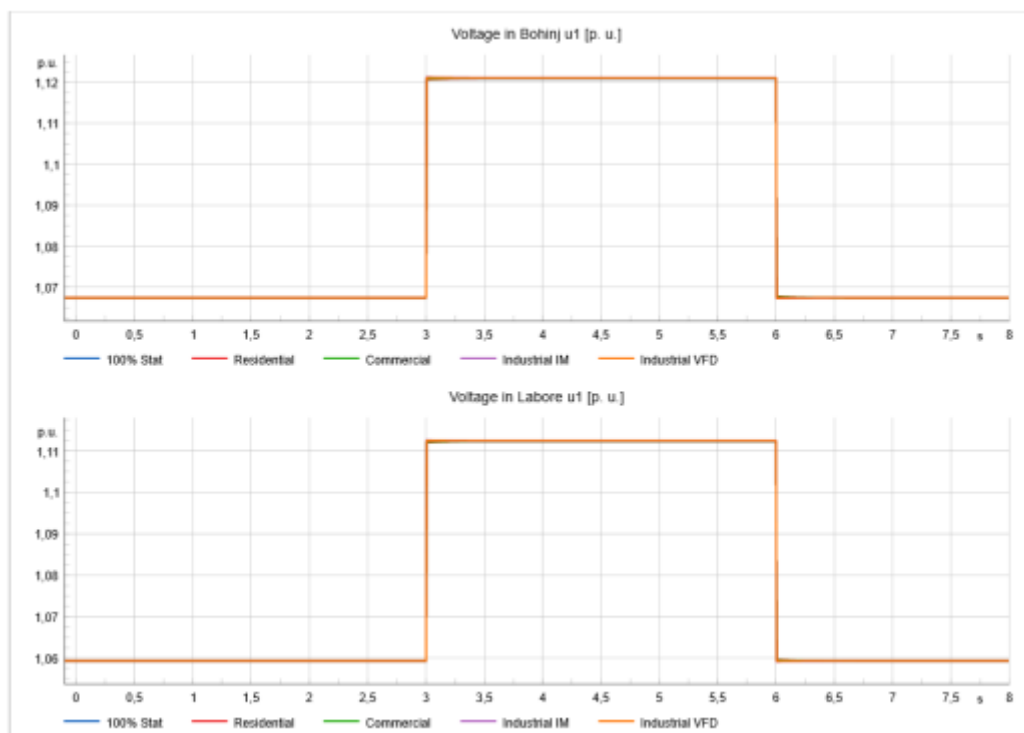


Figure 3.68: Voltage on the 110 kV side of TS Bohinj and TS Labore during the instantaneous voltage change

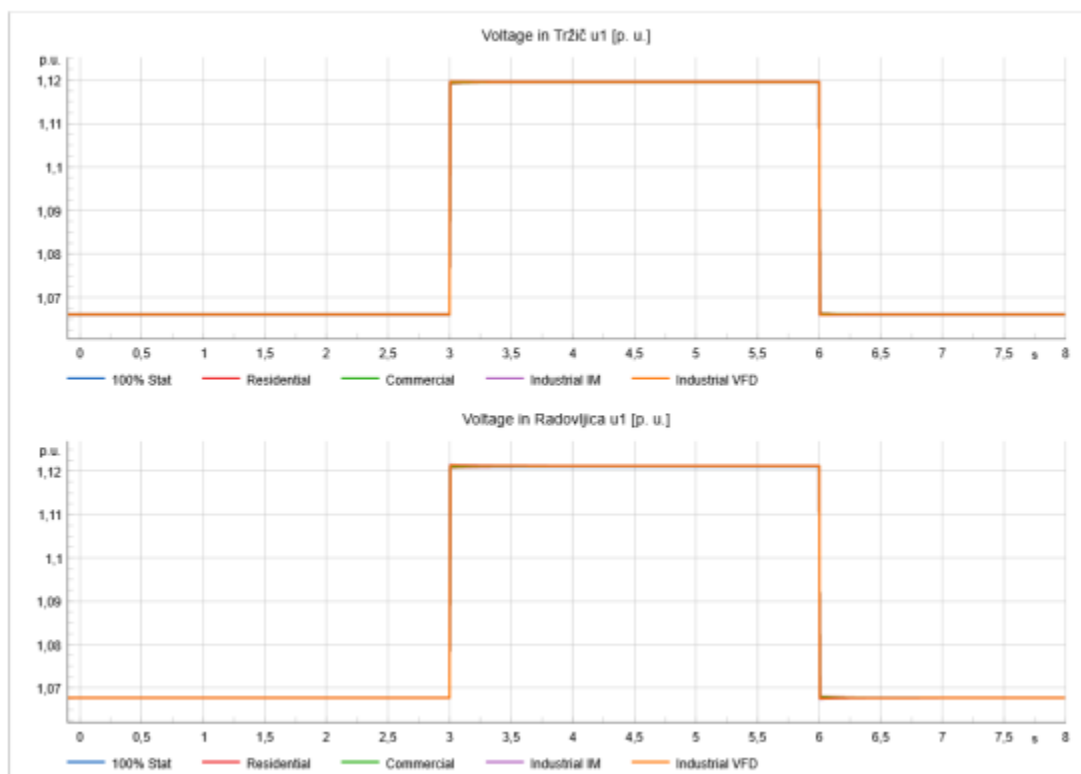


Figure 3.69: Voltage on the 110 kV side of TS Tržič and TS Radovljica during the instantaneous voltage change

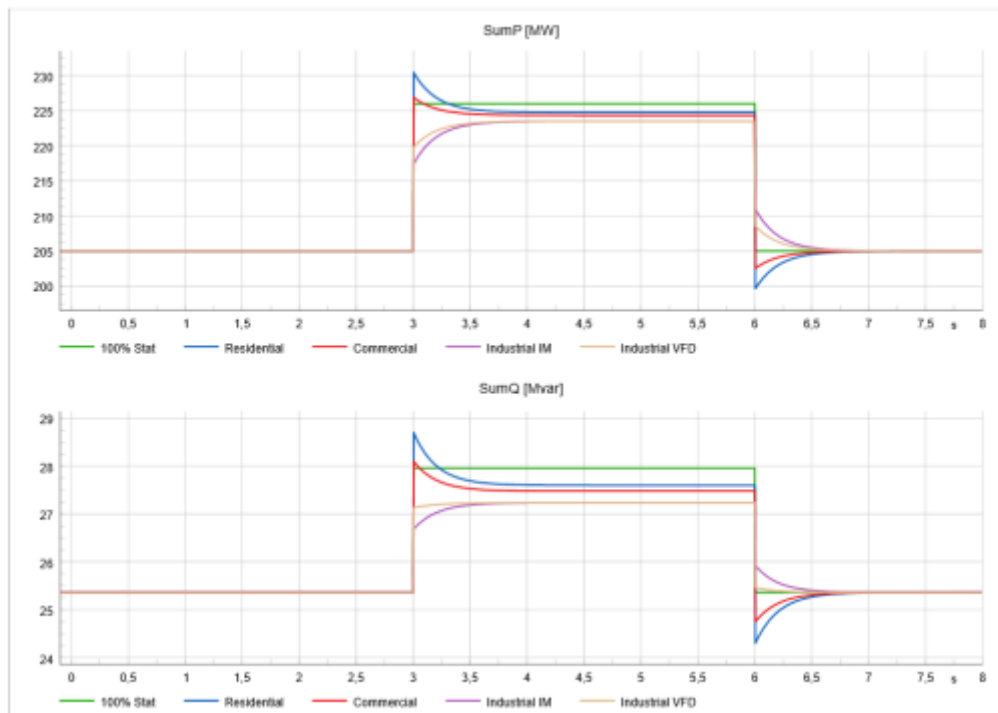


Figure 3.70: The sum of active and reactive power of all loads in the region

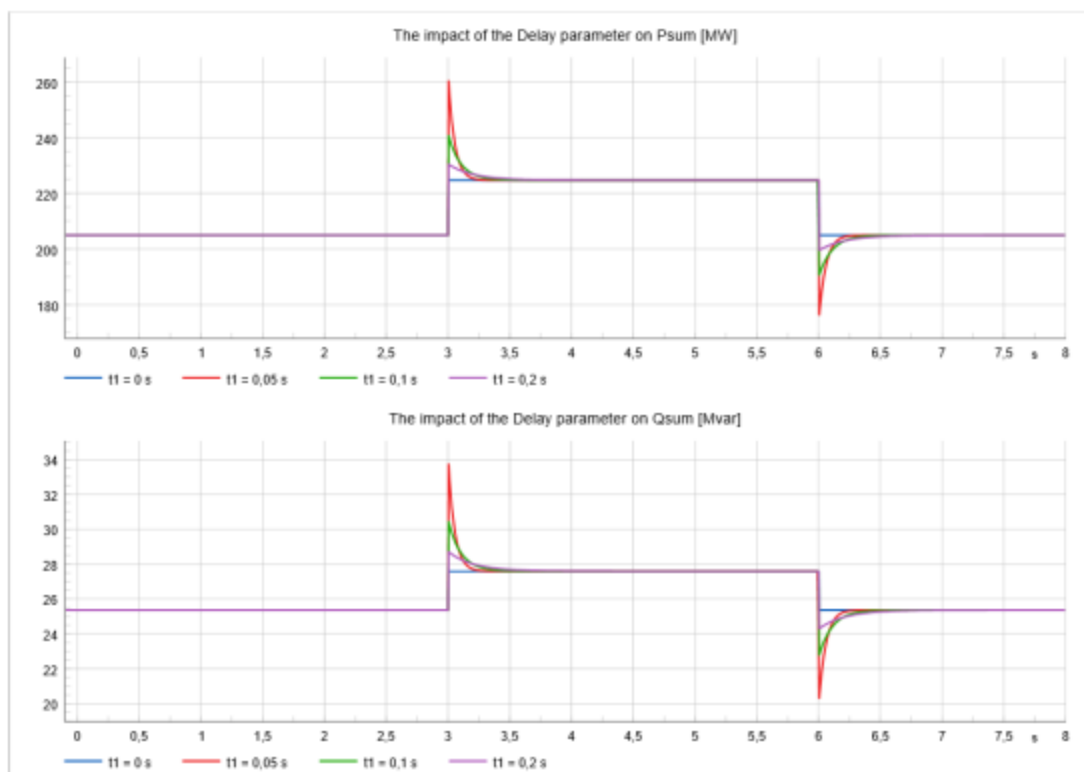


Figure 3.71: The impact of the delay parameter on the sum of active and reactive power for residential loads

3.3.4.2 Three-phase short circuit

The 3-phase short-circuit is simulated on a 110 kV busbar in TS Bohinj (Figure 3.72). This causes a voltage drop throughout the grid in other TSs, as seen in figures below. Figures 3.73 and 3.74 illustrate load responses in active and reactive power during the 3-phase fault. At fault clearing, all load types, especially residential and commercial, exhibit a temporary power increase as shown in total active and reactive power of all loads. This is due to their larger voltage-dependency time constants. Stronger voltage dependence leads to a more pronounced voltage drop, which in turn results in a higher aggregated active and reactive power response. Consequently, during 3-phase fault clearing, these loads also produce more significant transient power spikes. This indicates that residential and commercial loads have higher sensitivity to sudden fault disturbances.

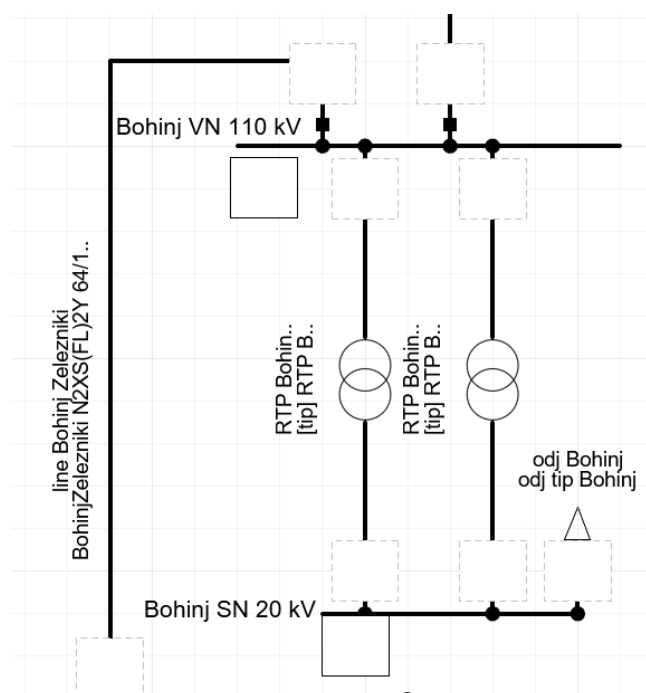


Figure 3.72: Location of the 3-phase short-circuit fault on a 110 kV busbar in TS Bohinj

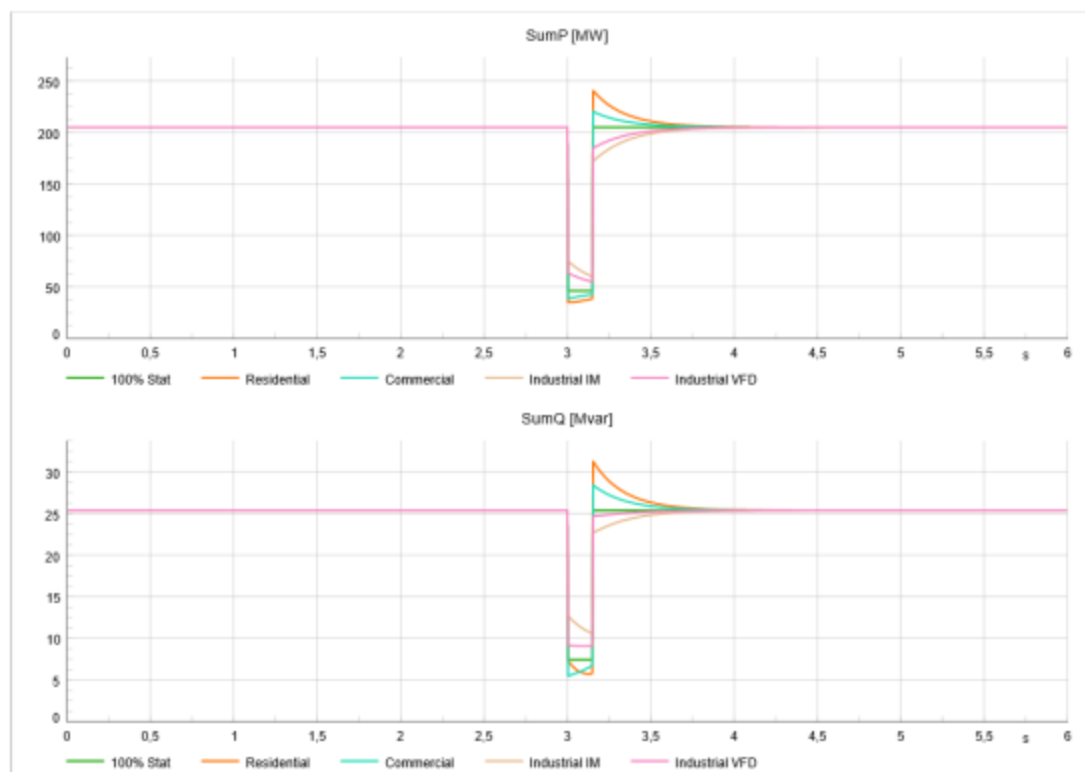


Figure 3.73: The sum of active and reactive power of all loads in the 3-phase short-circuit analysis

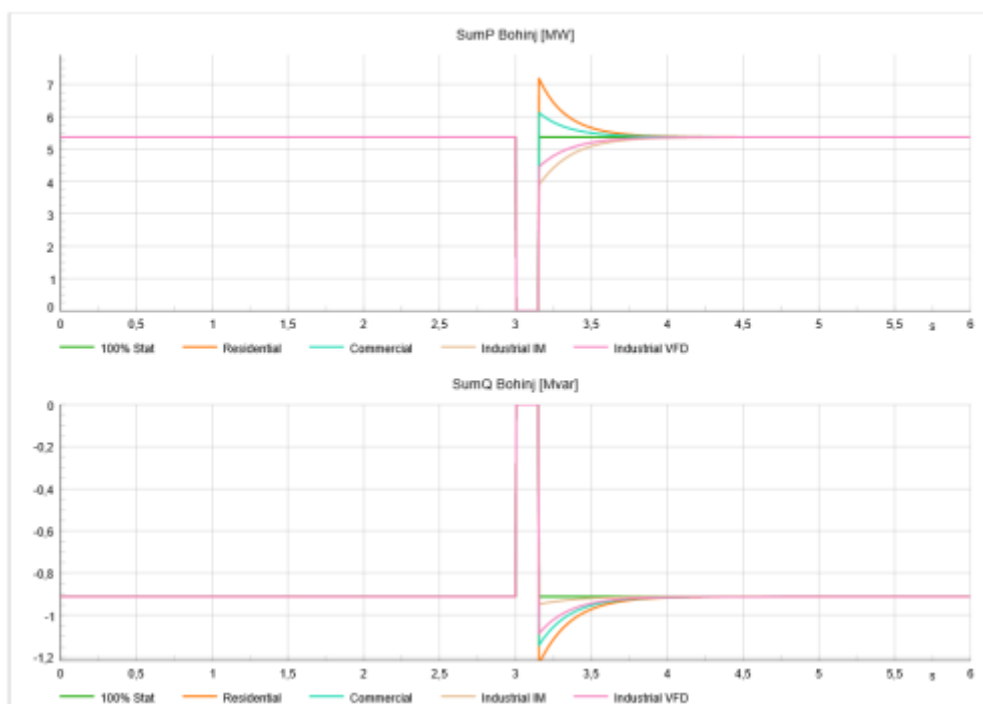


Figure 3.74: The behaviour of the active and reactive power of a load in Bohinj during a 3-phase short circuit analysis

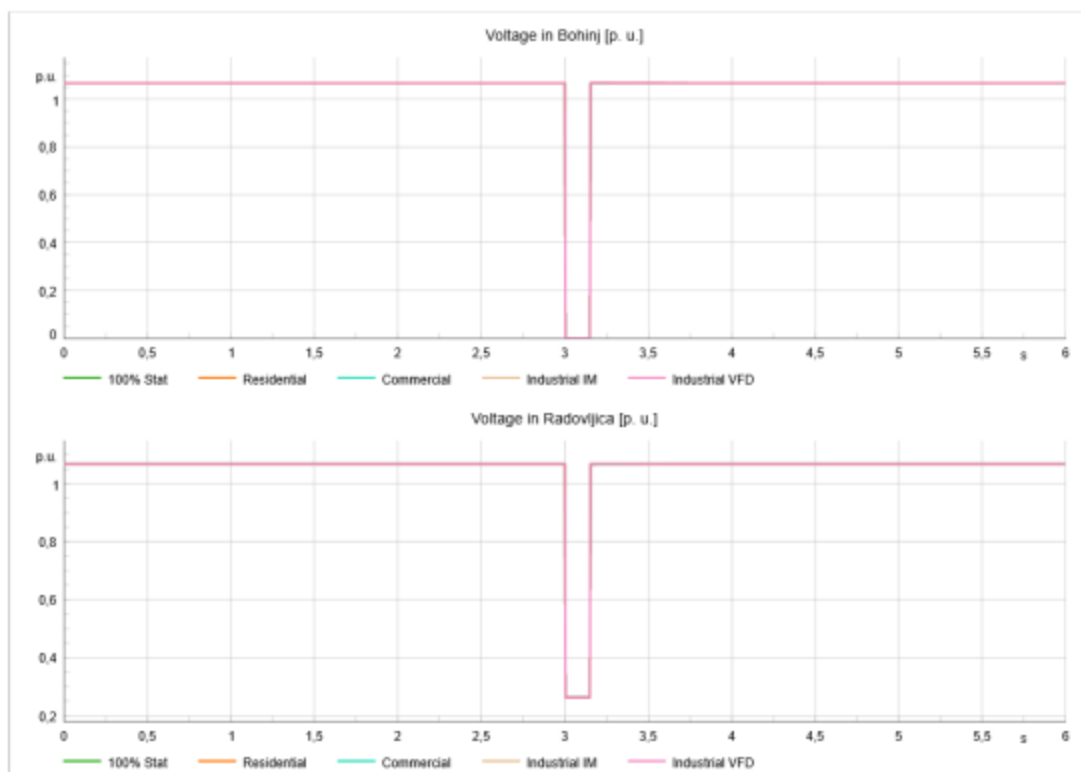


Figure 3.75: Voltage in Bohinj and Radovljica during a 3-phase short-circuit analysis

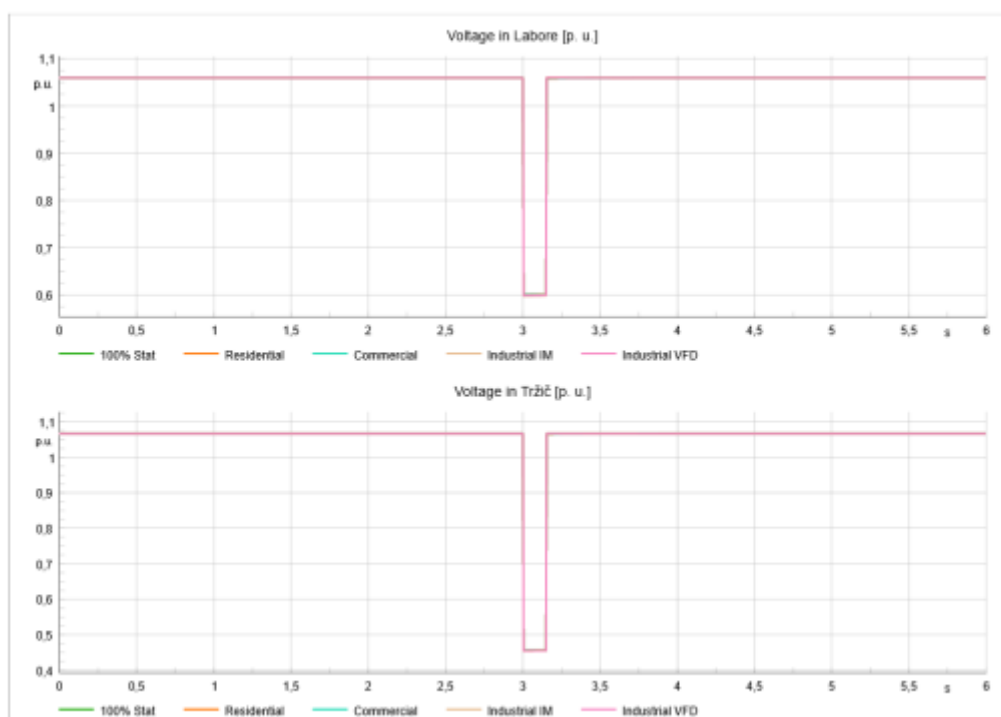


Figure 3.76: Voltage in Labore and Tržič during a 3-phase short-circuit analysis

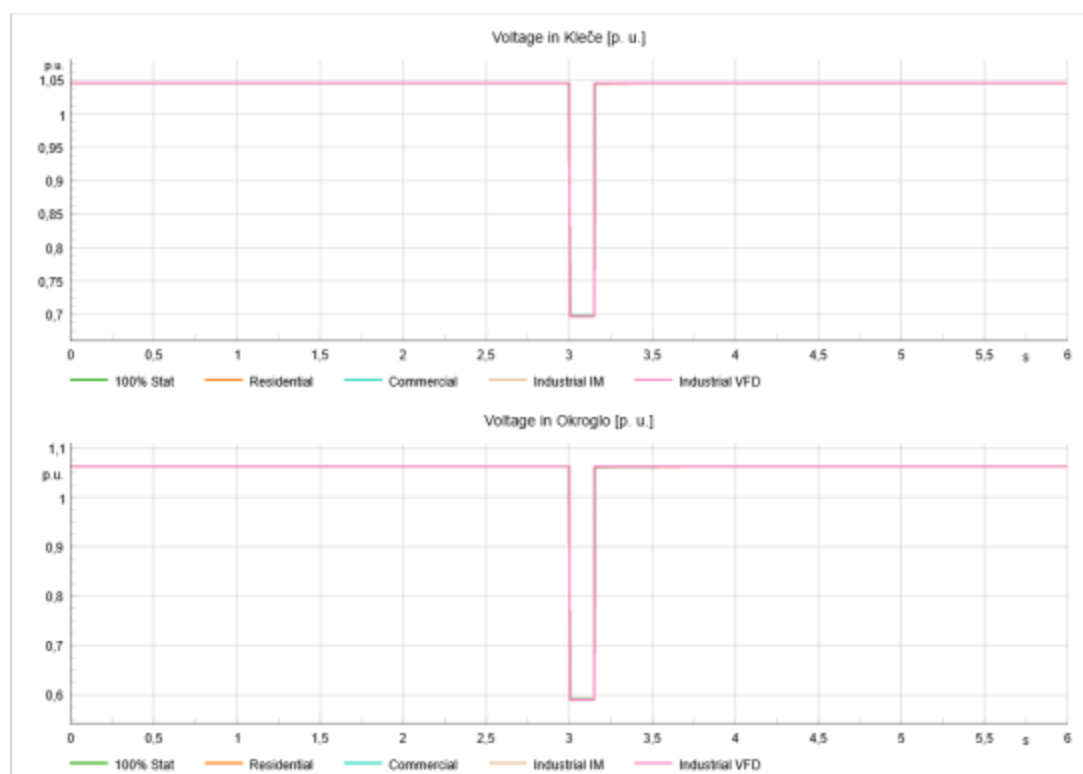


Figure 3.77: Voltage on the 110 kV side in Kleče and Okroglo during a 3-phase short-circuit analysis

3.3.4.3 Conclusions on load modeling

Based on the simulations performed in this chapter we can conclude the following regarding modeling of loads in PowerFactory:

- “General Load Type (.TypLod)” model with its wide selection of parameters enables adequate representation of different type of consumers’ static and dynamic responses and should be used to model loads in the MV and LV grids when performing analyses in the HV grid.
- Loads representing the consumption of MV/LV grids should not be modelled as 100 % static loads but should also have their dynamic part included in the model. The proportion of static/dynamic parts in total load should be obtained through measurements or analysis of the consumers in the MV/LV networks (industrial, commercial, mixed, etc.). Table 2 gives general values of parameters that can be used for modeling.
- Loads with a significant share of motors should have the delay time constant set to relatively conservative value (e.g. 0,2 seconds), as smaller values may cause significant transients and should only be used if they are derived from measurements¹.

¹ Loads with a higher proportion of motors (e.g. industrial loads) exhibit slower dynamics and damped transient response during events in the grid, compared to residential and commercial loads (as can be observed from Figure 3.70 and Figure 3.74). This can be attributed to their inertia.

3.4 Dynamic security assessment tool

The dynamic security assessment (DSA) tool is the operational component that leverages the digital twin models to provide real-time insights into grid stability. Its main features include:

- **Real-Time Data Integration:**
The tool continuously ingests data from SCADA/EMS systems, ensuring that the digital twin is updated in near real time. This real-time integration enables the DSA tool to simulate the grid's response to current operating conditions and dynamic events.
- **Automated Contingency Analysis:**
Predefined contingency scenarios are automatically triggered based on operational data. These scenarios simulate faults, generator outages, and other disturbances. The tool then calculates key stability indices such as CCT, frequency nadirs, and oscillation damping ratios.
- **Visualization and Dashboard Interface:**
The DSA tool features an intuitive graphical user interface that presents stability indices in aggregated formats. The dashboard is designed to minimize cognitive load, providing clear visual cues that help operators quickly assess grid conditions and make informed decisions.
- **Integration with Operational Workflows:**
By employing standard data exchange protocols (e.g., CIM standards), the DSA tool integrates seamlessly with existing grid management systems. This interoperability ensures that the tool can be deployed in parallel with legacy systems, providing an additional layer of security and operational insight.

In essence, the dynamic security assessment tool transforms the detailed simulations provided by the digital twins into actionable intelligence for grid operators, ensuring that potential instabilities are detected and addressed promptly.

3.4.1 Extent of the conducted work

We have conducted the following tasks:

- **Setup of snapshot export from SCADA/EMS in appropriate formats**

The digital twin utilized by the DSA tool is periodically updated, initialized, and executed in an automated manner. To support this process, it is essential to have access to historical and real-time SCADA/EMS snapshots representing the operating states that are subject to analysis. For this purpose, an automated export mechanism was established to periodically retrieve SCADA/EMS snapshots with a temporal resolution of 15 minutes and store them in a dedicated repository for long-term use.

The archived snapshots serve multiple purposes. Besides enabling retrospective analyses of past operating conditions, they provide a valuable data source for various data analytics tasks, including the development, training, and validation of artificial intelligence (AI) models used within the DSA framework. At the same time, every newly acquired snapshot is automatically processed and used as an input to the DSA tool, enabling continuous assessment of the current state of the electric power system of Slovenia.

The analyses and results presented in this deliverable were performed using operating-state snapshots collected during three representative observation periods: from 27 June 2024 to 26

January 2025 (213 days, corresponding to 20,448 operating states), from 14 October 2025 to 20 October 2025 (6 days, corresponding to 576 operating states), and from 1 April 2026 to 31 May 2026 (60 days, corresponding to 5,760 operating states). Altogether, more than 26,000 operating states were processed and analysed within the project framework.

These periods were carefully selected to ensure that the dataset captures not only the most typical operating conditions of the Slovenian electric power system but also a wide range of characteristic and potentially critical situations. The selected time intervals include seasonal variations, different demand and generation patterns, periods with high renewable energy penetration, and operating conditions characterized by significant cross-border power exchanges. As such, they provide a representative basis for assessing the performance of the digital twin and DSA tool under both normal and potentially challenging system conditions, including those that could lead to dynamic instability phenomena.

- **Development of the procedure for merging the Slovenian dynamic model with the observability area model**

A dedicated Python-based workflow was developed to perform the automated topological merging of different network model types into a single simulation-ready representation suitable for a digital twin application. The procedure combines the detailed dynamic model of the Slovenian transmission system, extending up to the national borders, with the steady-state model of the observability area. While the Slovenian model provides a comprehensive representation of dynamic behaviour within the national transmission system, the observability area model primarily serves to accurately reproduce steady-state operating conditions and power flows across cross-border interconnections (tie-lines).

The model-merging process represents a fundamental building block of the digital twin creation procedure and constitutes the first step in the automated generation of periodically updated digital twins used by the DSA tool. The developed workflow performs the necessary topological modifications, boundary-node identification, network consistency checks, and integration of external network representations in a fully automated manner, ensuring that the resulting model is suitable for the next steps towards an operational DSA.

A key design principle of the solution was the use of operational models that are developed, maintained, and continuously updated by the transmission system operator ELES. The detailed Slovenian dynamic model and the observability area model are both maintained by the respective departments within ELES and represent the official models used in operational and planning studies. By directly utilizing these operational models, which were further enhanced and extended within the project to support DSA-specific functionalities, the project avoided unnecessary duplication of modelling efforts and eliminated the risk of inconsistencies between different model versions.

This approach also ensured full consistency between the network models and the associated initialization data required to establish the correct operating point before executing dynamic simulations. Since the underlying models continue to evolve as part of standard utility processes, the developed merging procedure automatically benefits from all future model improvements, updates, and corrections. As a result, the digital twin remains aligned with the latest available network representations without requiring additional manual maintenance or synchronization activities.

- **Development of the procedure for addition of dynamic characteristics to PGM models outside Slovenia**

Within the observability area model, power generating modules (PGMs) are represented in a simplified manner. This modelling approach is appropriate for steady-state analyses, for which the observability model was originally developed. From a steady-state perspective, multiple generating units and other power-injecting elements can be aggregated into a single equivalent representation without significantly affecting the accuracy of power-flow calculations. As a result, the model can accurately reproduce active and reactive power exchanges while maintaining a manageable level of complexity.

However, such aggregation is generally not suitable for dynamic simulations. Accurate representation of dynamic behaviour requires knowledge of the number of generating units, their technology types, ratings, control systems, and operational limitations. Dynamic phenomena such as frequency response, voltage control, electromechanical oscillations, and fault ride-through capabilities are highly dependent on these characteristics and cannot be adequately represented by overly simplified equivalent models.

To address this challenge, a dedicated methodology was developed to enhance the observability area model with dynamic information derived from publicly available sources. In essence, the procedure performs a reverse process of traditional aggregation and equivalencing. Rather than combining multiple devices into a single equivalent representation, the objective was to identify the likely composition of generating facilities connected to individual network nodes. This included estimating the number of generating units, their installed capacities, technology types, and other relevant characteristics based on publicly available generation databases, power plant registries, network information, and technical documentation.

Once the likely composition of generation assets at individual nodes had been established, generic dynamic characteristics were assigned to the identified units. These characteristics were selected based on the type of generation technology, unit size, and the estimated number of generating units represented at a given location. The assigned models included appropriate dynamic representations and control structures that are commonly used in power-system stability studies. Extensive practical experience gained through numerous dynamic studies has demonstrated that, in situations where detailed manufacturer-specific or operator-provided data are unavailable, the use of carefully selected generic models often provides sufficiently accurate results for system-level stability assessments. This is particularly relevant for external network areas, where detailed dynamic data are typically unavailable due to confidentiality restrictions, differing modelling practices, or limited data exchange mechanisms between transmission system operators.

The developed methodology therefore enabled a substantial improvement in the dynamic representation of the observability area while relying exclusively on publicly accessible information. As a result, the digital twin became capable of capturing cross-border dynamic interactions with a significantly higher level of realism, thereby improving the reliability and credibility of dynamic security assessments performed for the Slovenian power system.

- **Development of the procedure for applying corrections to the merged model**

Following the merging of the Slovenian dynamic model with the observability area model and the enrichment of external generation assets with dynamic characteristics, an additional

validation and correction step was required to ensure that the resulting digital twin remained physically consistent and suitable for dynamic simulations. The primary purpose of the observability area model is the accurate representation of network topology, power flows, and voltage conditions under steady-state operating conditions. As a consequence, certain modelling simplifications that are acceptable for power-flow calculations can lead to unrealistic situations when the same model is used for dynamic studies. In particular, the aggregation of multiple generation units, loads, compensation devices, and other power-injecting elements into a single equivalent representation may conceal the actual composition of equipment connected to a network node. While such simplifications generally have negligible impact on steady-state calculations, they can introduce inconsistencies when dynamic limits and physical capabilities of individual devices must be respected.

During the development process, several types of potentially unrealistic operating conditions were identified. One of the most prominent examples involved excessive reactive power injections assigned to equivalent generating units. In some cases, the reactive power output attributed to a single represented machine exceeded values that would be physically achievable for a generator of the corresponding rated capacity. Although such conditions may still produce acceptable steady-state power-flow solutions, they can lead to incorrect initialization of dynamic simulations and unrealistic dynamic responses.

To address these issues, a dedicated correction procedure was developed and integrated into the digital twin creation workflow. The procedure automatically screens the merged model for potentially unrealistic operating conditions and applies corrective measures where necessary. The implemented algorithms identify violations of physical operating limits, assess their impact on dynamic model initialization, and modify the affected model elements to restore a physically plausible representation of the system.

A key requirement during the development of this procedure was to preserve the original steady-state operating point as much as possible. Therefore, the correction mechanisms were specifically designed to minimize their impact on power-flow results while simultaneously ensuring that all dynamically relevant components operate within realistic technical limits. This balance was particularly important because the resulting model had to remain representative of the actual SCADA/EMS snapshot while also being suitable for large-scale automated dynamic simulations.

The developed validation and correction framework significantly increased the robustness of the digital twin generation process. By automatically detecting and resolving model inconsistencies before the execution of dynamic simulations, the procedure improved simulation reliability, reduced the occurrence of initialization failures, and ensured a consistent quality level across the large number of operating states processed by the DSA tool.

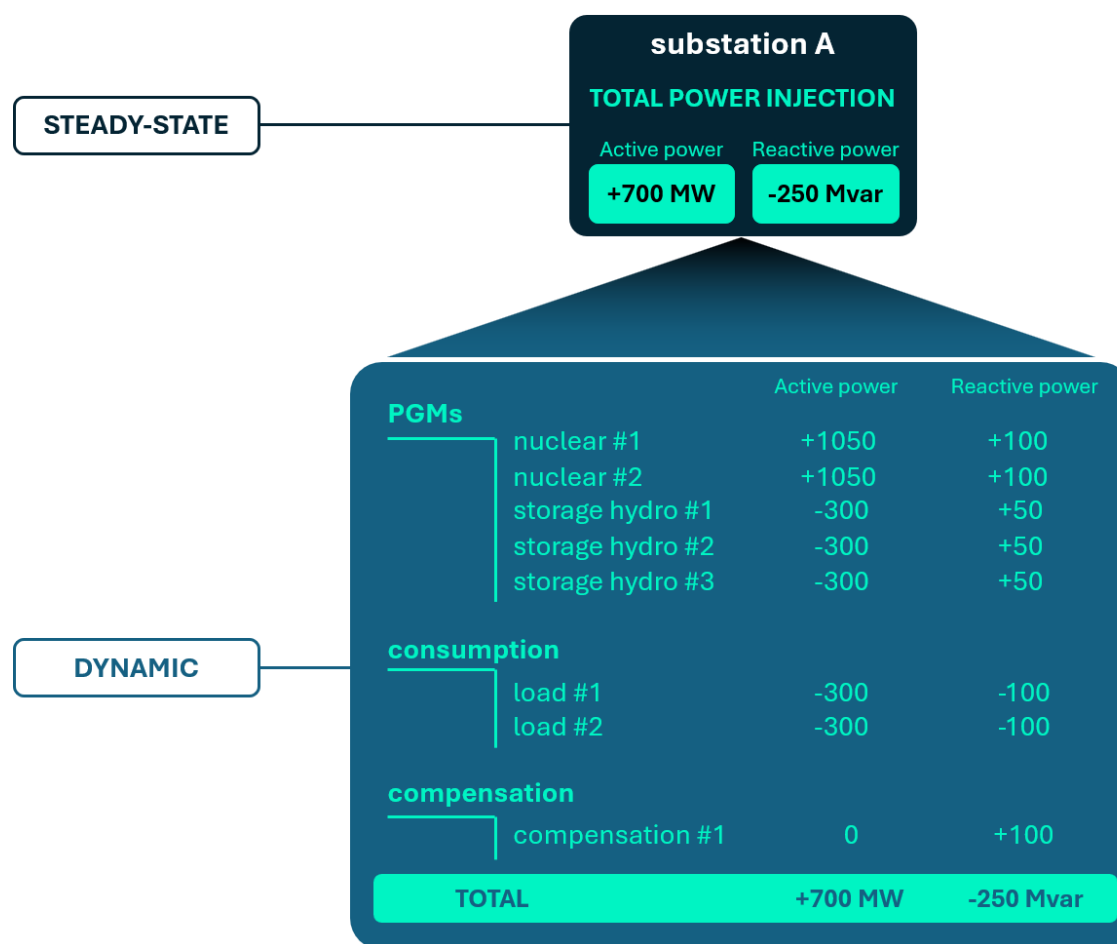


Figure 3.78 Conceptual Illustration of the Transition from a Steady-State Equivalent to a Dynamic Network Representation

- **Determination of stability phenomena to be analysed using the DSA tool**

A dedicated assessment was performed to determine which categories of power-system stability phenomena could be reliably analysed using the developed digital twin and DSA framework. The selection was guided by the available model structure, observability area coverage, and the practical requirements of transmission system operation.

The project focused on electromechanical stability phenomena, including both rotor-angle stability and frequency stability – see Figure 3.79. These phenomena can be accurately represented using the developed digital twin and are particularly relevant for the Slovenian power system due to its strong interconnection with neighbouring networks and the increasing penetration of renewable generation. The implemented analyses evaluate the system response to disturbances such as faults, generation outages, and active-power imbalances, providing key stability indicators for operational decision support.

Other stability categories were not included in the current implementation, as the available digital twin infrastructure does not yet provide the modelling detail required for their reliable assessment. Nevertheless, the DSA platform was intentionally designed as a modular framework that enables the future integration of additional stability analysis modules. This will allow the scope of the tool to be gradually expanded, including the assessment of

converter-driven stability phenomena associated with the increasing deployment of inverter-based resources.

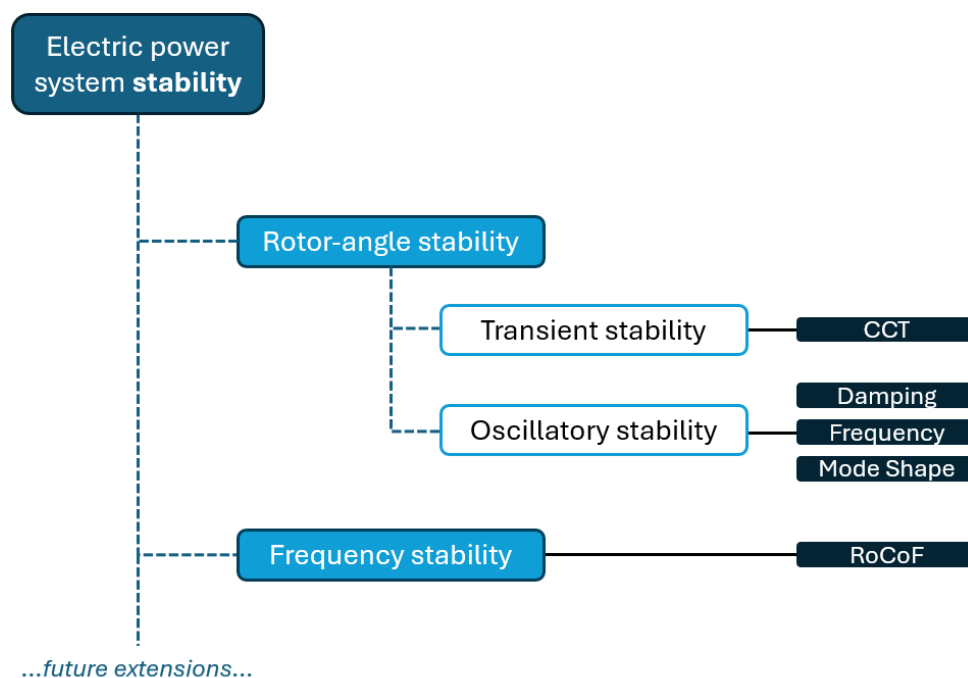


Figure 3.79 Stability Phenomena and Associated Stability Indices Implemented in the DSA Tool

- **Definition of stability indices**

For each selected stability category, appropriate stability indices were defined to quantify the stability margin associated with a particular operating state of the power system. The objective was to identify indicators that are both technically meaningful and suitable for automated large-scale analysis within the DSA framework. For transient stability, which represents one manifestation of rotor-angle stability, the selected indicator was the critical clearing time (CCT). The CCT was determined for individual generating units by applying different fault scenarios at various locations throughout the network and evaluating the maximum fault duration that could be sustained without loss of synchronism. For oscillatory stability, another aspect of rotor-angle stability, the primary indicator was the relative damping of local and regional electromechanical oscillatory modes. In addition, supporting information such as oscillation frequencies and mode shapes was calculated to provide further insight into the nature and location of poorly damped oscillations. Insight into inter-area modes was not possible due to the extent of the observability area.

For frequency stability, the selected indicator was the initial rate of change of frequency (RoCoF) observed at individual generating units following generation outages within the Slovenian power system. While more comprehensive frequency-response analyses could also be performed, this would require a substantially more detailed representation of the external interconnected system. Although such an extension would be technically feasible, it would introduce significant challenges related to model parametrization and initialization, primarily because the underlying SCADA/EMS infrastructure does not provide real-time visibility of the required external network data. This limitation ultimately defines the current scope of the digital twin and DSA framework. Nevertheless, the selected stability indices provide valuable insight into the most relevant electromechanical stability phenomena affecting the Slovenian

power system while remaining compatible with the available data sources and operational requirements.

- **Development of unique and intuitive visualization of stability conditions.**

To support operators in the control centre environment, a dedicated visualization concept was developed for presenting stability indices in a simple and intuitive manner. The interface utilizes a traffic-light colour scheme (see Figure 3.80), enabling rapid assessment of system conditions and quick identification of potentially critical situations. This approach allows operators to efficiently scan large amounts of information while maintaining a clear overview of overall system stability. At the same time, the visualization is not limited to high-level indicators. Additional details, supporting analyses, and underlying simulation results are available on demand, allowing operators to investigate specific situations in greater depth whenever required. This layered approach ensures a balance between simplicity and analytical depth, providing both rapid situational awareness and access to more detailed information when operational decision-making requires it.



Figure 3.80 Traffic-light color-coding visualization for stability assessment

3.4.2 Dynamic security assessment concept

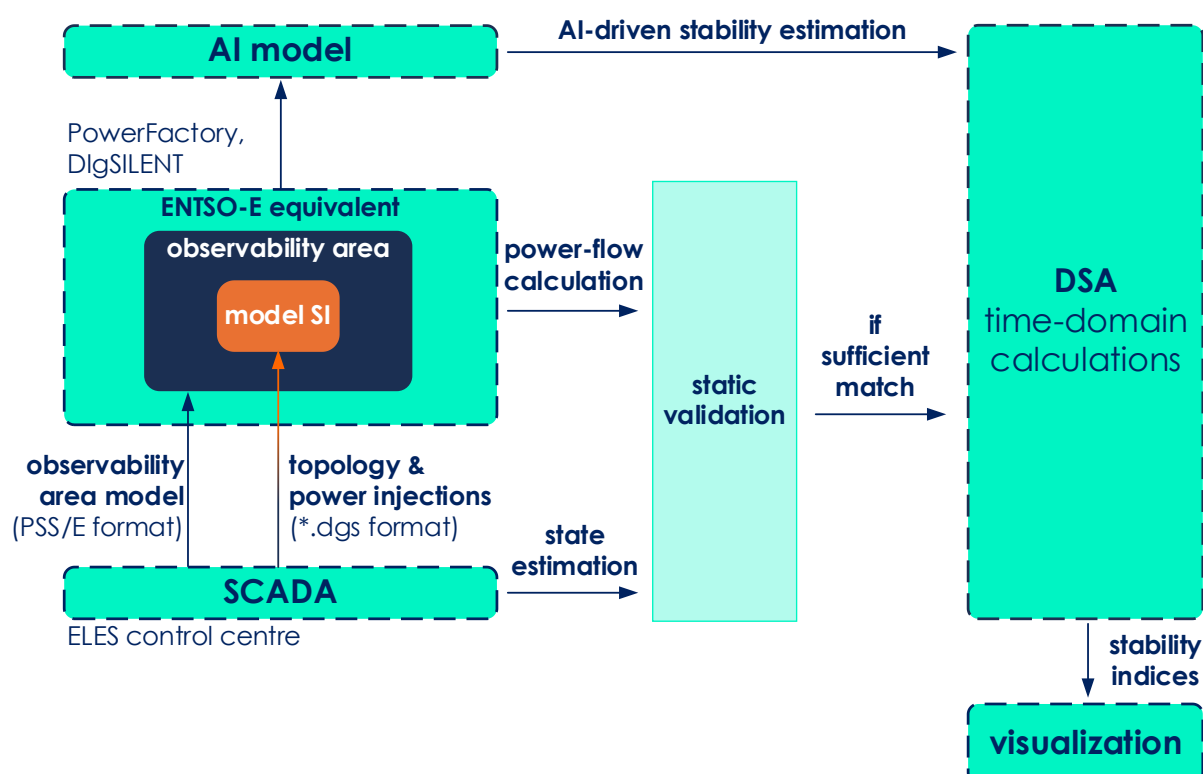


Figure 3.81 The Dynamic Security Assessment (DSA) concept

The developed Dynamic Security Assessment (DSA) framework is built around the concept of a periodically updated digital twin that continuously follows the operating state of the Slovenian power

system – see schematic in Figure 3.81. Every 15 minutes, a new operating-state snapshot is automatically exported from the SCADA/EMS environment and used as the starting point for the assessment process. The exported data consists of two complementary datasets. The first is the observability-area network model in PSS®E format, representing the wider interconnected system surrounding Slovenia. The second contains the actual network topology and power injections obtained from the SCADA/EMS environment and exported in *.dgs format. Together, these datasets provide the information required to construct and initialize a digital twin corresponding to the current operating state.

Following the import of operational data, a model initialization procedure and power-flow calculations are performed. The results are subjected to a static validation process, where calculated power flows and voltage conditions are compared against the operating point obtained from the SCADA/EMS state estimator. Only after sufficient agreement between the model and the actual operating state has been achieved is the model considered suitable for dynamic security assessment. The SCADA/EMS state estimator therefore serves as the reference against which the digital twin is validated.

In parallel with the digital twin initialization process, a pre-trained artificial intelligence model evaluates the current operating state and provides an initial estimate of the selected stability indices. These predictions serve as an indication of the expected stability margins and help identify potentially critical operating conditions. In other words, they provide a rapid screening of the system state, while acknowledging that full operational trust in AI-based assessments has not yet been established. Particular attention was therefore devoted to the requirements and working practices of transmission system operators. In operational environments, confidence in analytical tools is essential, and simulation-based assessments remain the most trusted method for evaluating system stability. For this reason, AI-generated results are not used directly as final stability indicators. Instead, for potentially critical situations (CCTs below 400 ms), they are treated as guidance for the subsequent simulation process. Still, despite providing only guidance, the AI-based estimates significantly reduce the uncertainty associated with the expected stability margins. Consequently, the DSA engine can focus its time-domain simulations on a substantially narrower range of possible outcomes, reducing the number of simulations required to determine the final stability indices. In practice, this dramatically reduces the search space and, consequently, the computational effort required to obtain accurate stability margins. This approach results in a considerable reduction in calculation time while preserving the accuracy and credibility of detailed dynamic simulations.

The final values of the stability indices are obtained through time-domain simulations performed on the validated digital twin and subsequently presented to operators through a dedicated visualization environment. By combining AI-based screening with simulation-based verification, the framework achieves near real-time performance while maintaining the level of reliability, transparency, and operator confidence required for operational decision-making.

3.4.3 Fully automatized static validation and confirmational test run

The **static validation process** evaluates the consistency between the operating point calculated by the digital twin and the operating state obtained from the SCADA/EMS state estimator. The objective is not to achieve a perfect numerical match, which is practically impossible due to modelling simplifications and measurement uncertainties, but rather to ensure that the deviations remain within predefined acceptable limits.

The validation is performed using a representative set of quantities that characterize the steady-state behaviour of the power system. These include busbar voltage magnitudes as well as active and reactive power flows across the most relevant network elements, such as transmission lines, transformers, and cross-border interconnections. Since the importance of individual elements differs considerably throughout the network, the assessment is based on normalized deviations rather than absolute differences. This approach allows quantities associated with different voltage levels, power ratings, and operational significance to be evaluated using a common framework.

To obtain a comprehensive measure of model quality, individual deviations are aggregated into weighted performance indicators. Greater importance is assigned to elements operating at higher voltage levels, as inaccuracies within the 400 kV and 220 kV transmission networks generally have a significantly larger impact on the overall behaviour of the interconnected power system than deviations observed in lower-voltage parts of the network. The resulting indicators therefore provide a balanced assessment of model accuracy while emphasizing those components that are most relevant for dynamic security studies.

The validation procedure is fully automated and executed each time a new digital twin is generated. If any of the aggregated indicators exceed predefined acceptance thresholds, the corresponding operating state is flagged for further investigation, and the dynamic assessment process is temporarily suspended. In addition to overall validation metrics, the framework also identifies individual network elements responsible for the largest deviations, enabling efficient diagnosis of model inconsistencies and supporting continuous improvement of the digital twin generation process.

Successful completion of the static validation stage confirms that the digital twin accurately reproduces the steady-state operating conditions of the real power system and can therefore be used as a reliable basis for subsequent dynamic simulations and stability assessments.

Following successful static validation, an additional **confirmational test run** is performed before proceeding with contingency-based dynamic security assessment. The purpose of this step is to verify that the initialized digital twin exhibits stable dynamic behaviour in the absence of any externally applied disturbances. Although a model may accurately reproduce the steady-state operating point, this alone does not guarantee that the dynamic initialization process has been successful. Small inconsistencies in dynamic parameters, controller settings, or interactions between different control systems can occasionally lead to artificial oscillations or unstable behaviour that are unrelated to the actual power-system operating condition. Such issues must be detected and resolved before the model can be used for stability assessment.

To address this requirement, a time-domain simulation without any intentionally applied disturbance is executed. During this simulation, the dynamic responses of key generators and control systems are monitored. Particular attention is given to rotor-angle trajectories, frequency behaviour, and the response of voltage-control equipment. The objective is to confirm that all observed variables remain close to their initial values and that no growing oscillations or other signs of instability are present. The confirmational test run therefore serves as an important quality-assurance mechanism, ensuring that any instability observed during subsequent contingency simulations is caused by the simulated disturbance itself and not by deficiencies in model initialization.

As with static validation, the confirmational test run is fully automated and forms an integral part of the digital twin generation workflow. Only models that successfully pass both validation stages are accepted for further processing within the DSA framework. This significantly improves the robustness

and reliability of the resulting stability assessments and minimizes the risk of generating misleading operational indicators.

3.4.4 Acceleration processes

As already mentioned, dynamic security assessment based on time-domain simulations is computationally demanding. This challenge is widely recognized within the power-system community, particularly when stability assessments must be performed for large numbers of operating states and contingency scenarios within operational time constraints. Within the project, two complementary acceleration mechanisms were developed and implemented.

Parallel Execution of Time-Domain Simulations

The first acceleration mechanism exploits the parallel-computing capabilities of the simulation environment used within the project. The selected software platform, PowerFactory, supports the simultaneous execution of independent simulation tasks across multiple processor cores. Since contingency analyses typically consist of a large number of mutually independent simulation scenarios, they are particularly well suited for parallel execution. In the developed DSA framework, simulations were distributed across 64 parallel processes. The achievable level of parallelization is primarily limited by the available computational resources and can be further increased when more powerful hardware is employed. Once the digital twin has been successfully created and the set of contingency scenarios has been defined, the required time-domain simulations can be executed simultaneously rather than sequentially. A schematic representation of this approach is shown in Figure 3.82. The practical consequence of this approach is that the total calculation time is no longer determined by the sum of all simulation durations, but rather by the longest-running simulation within the parallel execution group. This significantly reduces the overall time required to evaluate a large number of stability scenarios and enables near real-time operation of the DSA framework.

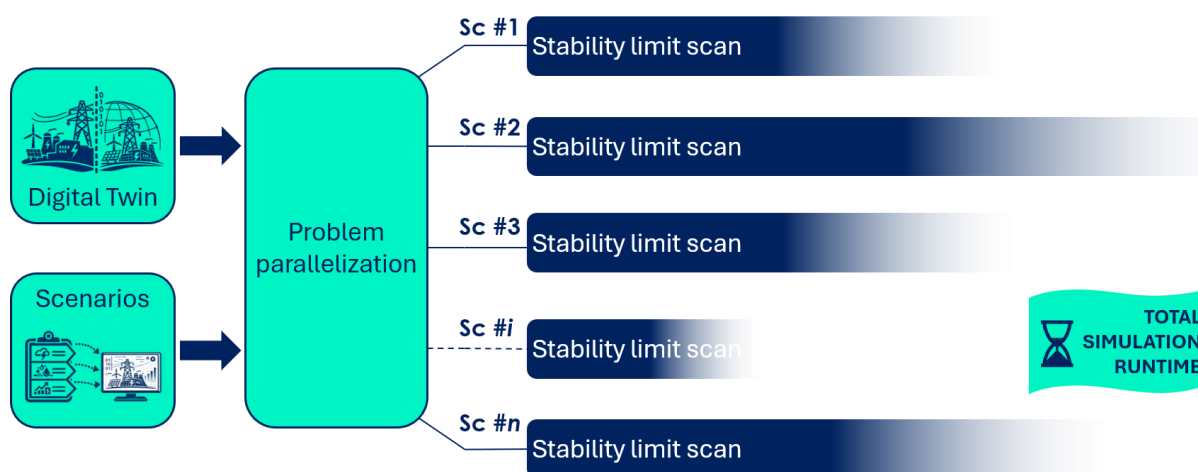


Figure 3.82 Parallelization of the Time-Domain Simulation Process Across Multiple Processor Cores

For transient stability assessment (TSA), the determination of the critical clearing time (CCT) index represents a typical example of an iterative process that benefits from parallel execution. Figure 3.83 illustrates such a procedure. The left-hand side of the figure shows rotor-angle deviations of a selected synchronous generator relative to the centre of angles for different fault durations. Stable cases are indicated in green, while unstable cases resulting in loss of synchronism are shown in red. The

boundary between stable and unstable behaviour defines the critical clearing time, which represents the stability limit to be determined by the DSA process.

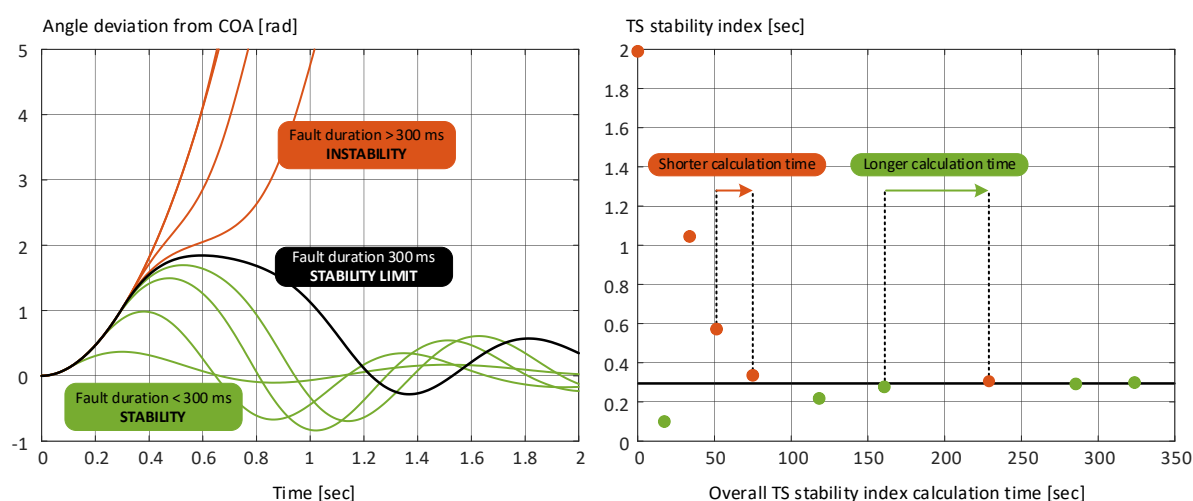


Figure 3.83 Time-domain calculations without AI support

The right-hand side of the figure illustrates the corresponding simulation durations. Since the implemented framework automatically terminates simulations once instability is detected, unstable scenarios often finish considerably earlier than stable ones. In the present implementation, simulations are terminated when rotor-angle deviations exceed 360° (2π radians), which serves as an indication of loss of synchronism. This early-termination mechanism provides an additional reduction in computational effort and further improves the efficiency of the assessment process.

AI-Assisted Reduction of the Search Space

The second acceleration mechanism focuses on reducing the number of simulations required during the iterative search for stability limits. Conventionally, the search process starts from a conservatively selected interval that is identical for all operating states and scenarios. While robust, such an approach often requires a relatively large number of simulations before the actual stability boundary is identified. To overcome this limitation, a pre-trained artificial intelligence model was employed to provide an initial estimate of the expected stability indices. These predictions effectively serve as a screening mechanism, allowing the search interval to be narrowed before detailed simulations are performed. Whenever stability indices are estimated as critical (CCTs below 400 ms), time-domain simulations are performed nonetheless in order to align with the established working practices of transmission system operators and the trust they put in AI-supported tools.

A comparison between conventionally obtained stability indices and AI-based predictions is presented in Figure 3.84. The results demonstrate that the AI model is capable of identifying stability margins with reasonably high accuracy. Although some deviations remain, confirming the need for simulation-based verification, the predictions are sufficiently accurate to substantially reduce the search space explored by the iterative algorithm. The resulting effect is illustrated in Figure 3.85. When AI-based estimates are available, the iterative search starts significantly closer to the final solution than in the conventional approach. Consequently, fewer simulations are required to identify the stability boundary, resulting in a substantial reduction of the overall calculation time. At the same time, the final results remain fully validated through detailed time-domain simulations, ensuring the level of reliability required for operational applications.

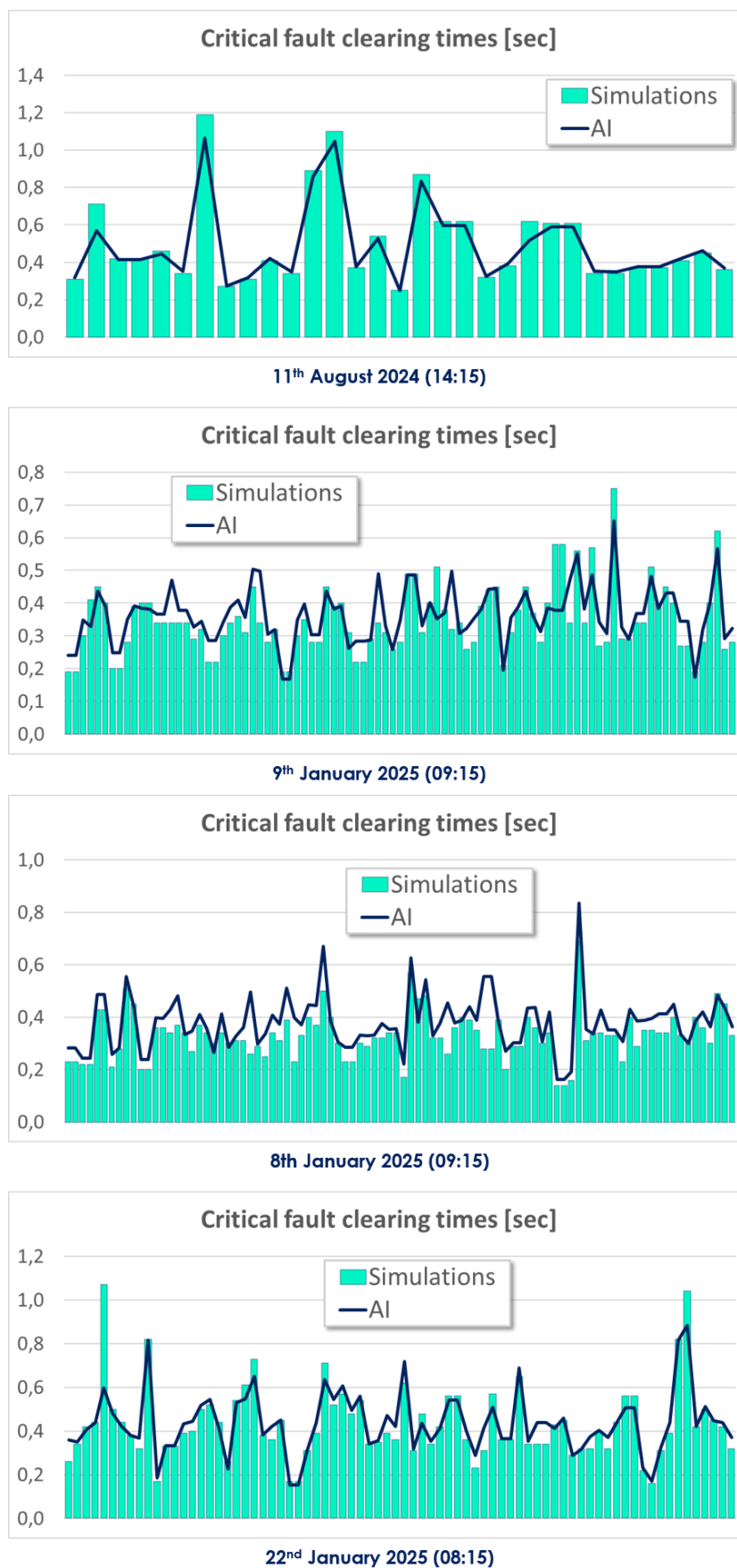


Figure 3.84 Comparison of TSA Indices Obtained from Conventional Simulations and a Pre-Trained AI Model

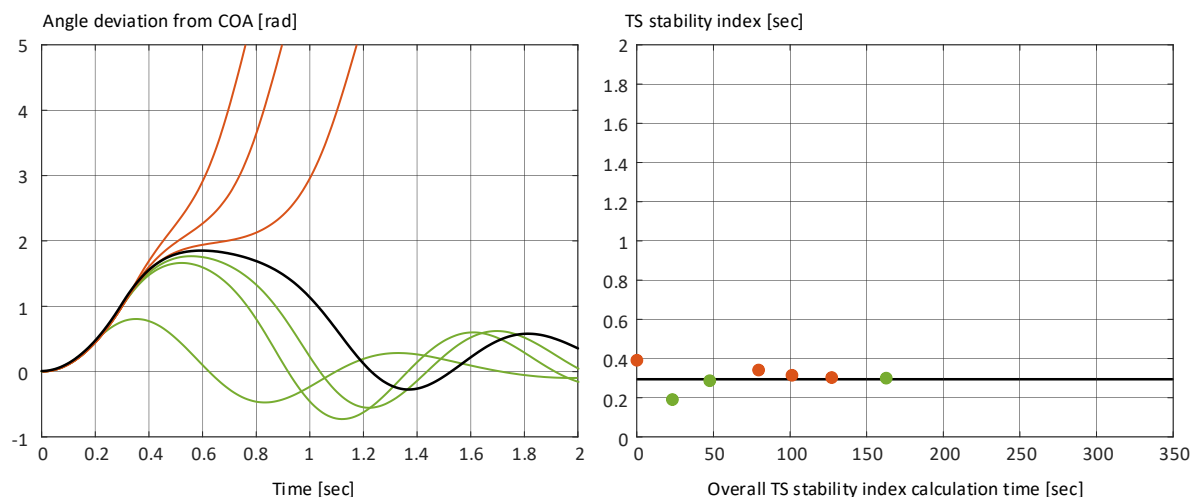


Figure 3.85 Time-domain calculations with AI support

The use of AI-assisted screening within the DSA framework resulted in a significant reduction of the computational effort required to determine the final stability indices and, consequently, a substantial decrease in the overall calculation time. By providing an initial estimate of the expected stability margins, the AI model effectively narrows the search interval used by the iterative simulation procedure, thereby reducing the number of time-domain simulations that must be executed before the final stability boundary is identified.

To quantify this benefit, Figure 3.86 compares the total DSA execution times obtained with (blue line) and without (orange line) AI support for a set of 96 operating conditions spanning the period from 28 June 2024 to 24 January 2025. The operating states shown in the figure are sorted in descending order according to the required calculation time. The comparison demonstrates a clear and consistent reduction in calculation time across the analysed operating states. On average, the use of AI support reduced the total execution time by approximately 37% compared to the conventional simulation-only approach. This represents a significant improvement, particularly considering that the final stability indices are still verified using detailed time-domain simulations and therefore retain the level of confidence required for operational applications.

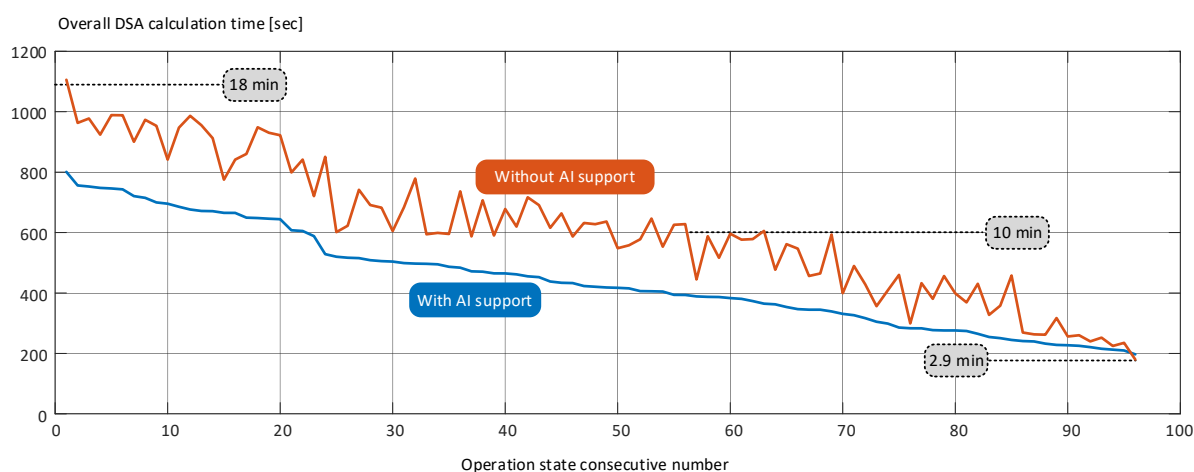


Figure 3.86 Comparison of Total DSA Execution Times With and Without AI Support for analysed 96 Operating States

The achieved reduction confirms that AI-assisted screening can play an important role in accelerating dynamic security assessment without compromising result quality. Furthermore, the obtained results indicate that additional optimization potential still exists. Future improvements in AI model accuracy, search algorithms, simulation scheduling, and computational infrastructure could further reduce the overall execution time and bring the DSA framework even closer to real-time operation. The results therefore demonstrate not only the practical value of the proposed hybrid AI-simulation approach but also its scalability and future development potential.

3.4.5 Visualization and graphical-user interface

As described in the previous sections, the DSA framework consists of a large number of mutually interconnected processes, all of which are executed in a fully automated manner. The only notable exception is the validation against PMU measurements of real system events, which still requires expert supervision. The high degree of automation, combined with the complexity of the underlying workflows, necessitated the development of a dedicated graphical user interface (GUI) that enables intuitive interaction with the framework and provides efficient access to both input and output data.

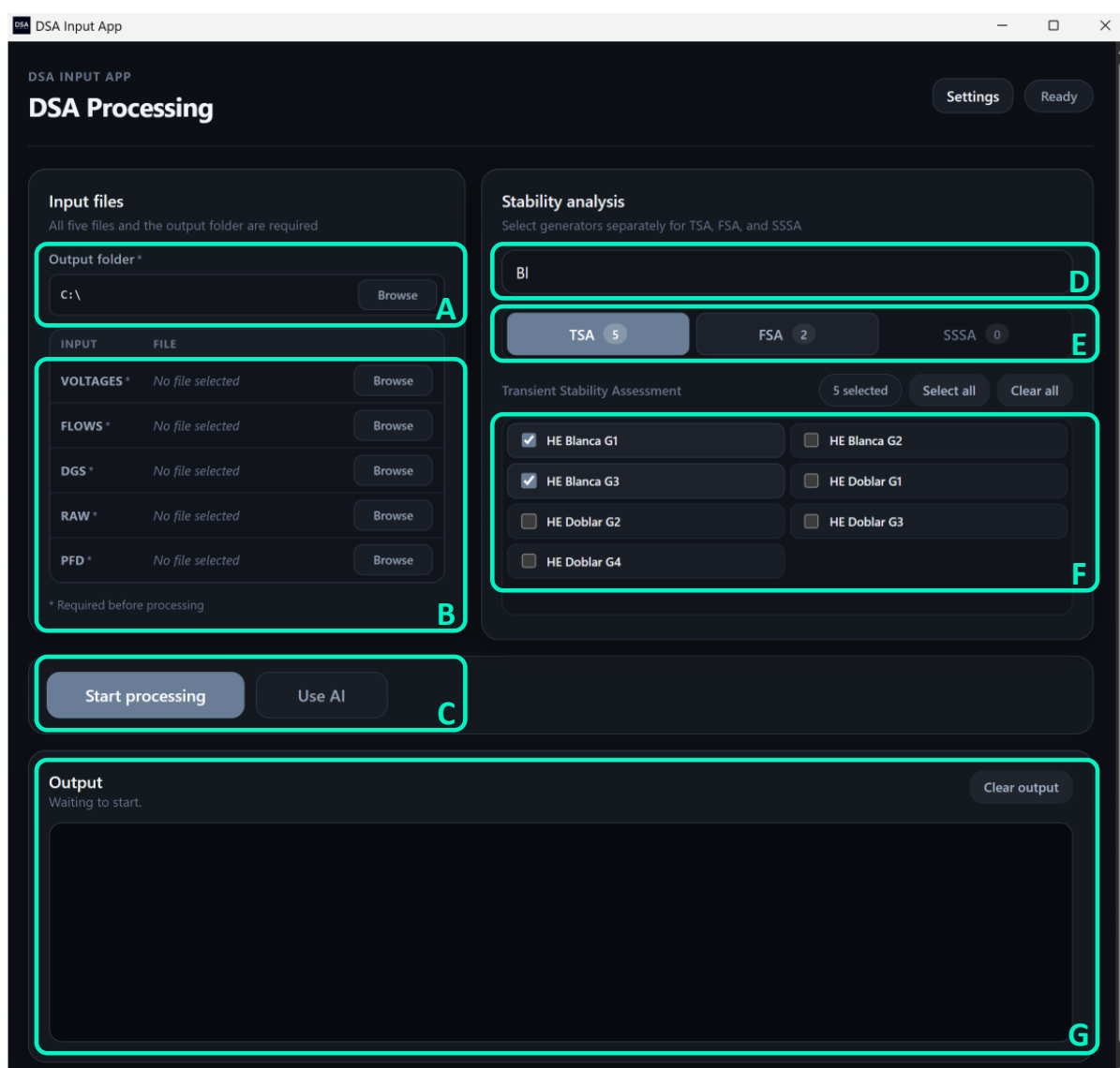


Figure 3.87 Main Input Window of the Dynamic Security Assessment Tool

The GUI was designed with two primary objectives. The first is to simplify the preparation and execution of DSA analyses by providing a clear and structured environment for data input and configuration. The second is to present the status and results of the assessment process in a manner that is understandable and useful for both experts and power-system operators.

The framework supports both manual and fully automated operation. Manual execution is primarily intended for development, testing, and analysis purposes, as demonstrated throughout this deliverable. In operational deployments, however, the required input data can be supplied automatically, enabling periodic or near real-time execution of the entire DSA workflow. [Figure 3.87](#) presents the main input window of the application. The required input datasets are clearly grouped and displayed in [section B](#). These include the *.dgs files containing SCADA/EMS snapshots of the operating state (topology, injections, other settings), the *.pfd file representing the Slovenian dynamic model up to national boundaries, the *.raw file containing the observability area network model. Additional data exported from the state estimator include busbar voltage measurements and power-flow information that are required for the static validation process. The destination directory for all generated outputs can be specified in [section A](#).

Prior to executing the DSA process, users can configure a number of analysis-specific settings. Separate configuration options are available for transient stability assessment (TSA), frequency stability assessment (FSA), and small-signal stability assessment (SSSA), as indicated in [section E](#). Furthermore, a dedicated search and filtering mechanism ([section D](#)) allows users to identify and prioritize specific generating units. The selected units are displayed and managed through the list shown in [section F](#), enabling focused analysis of assets considered particularly important from an operational perspective.

The GUI also provides the option to enable or disable AI-assisted acceleration mechanisms independently from the remaining workflow components. This functionality is accessible through [section C](#) and allows users to evaluate both conventional and AI-supported execution modes. During execution, the current status of the DSA process is continuously reported to the user through the progress and logging window shown in [section G](#). This functionality provides transparency regarding the current stage of the workflow, including model preparation, validation, simulation execution, AI evaluation, and result processing. As a result, users are able to monitor the progress of the assessment and quickly identify any issues that may arise during execution.

The results of the dynamic security assessment are presented through a dedicated DSA dashboard ([Figure 3.88](#) - [Figure 3.90](#)). The dashboard is organized into separate tabs corresponding to the individual stability categories considered within the framework, namely transient stability assessment (TSA), frequency stability assessment (FSA), and small-signal stability assessment (SSSA), as indicated by [section A](#) in [Figure 3.88](#).

Transient stability results

An example of the TSA results is presented in [Figure 3.88](#). The largest portion of the dashboard is dedicated to the visualization of the selected TSA stability index, namely the critical clearing time (CCT). The displayed results are obtained from a predefined set of contingency scenarios, each representing a fault at a specific network location followed by fault clearing after a given time interval. Depending on the scenario, the fault-clearing process may also include topology changes resulting from the operation of protection systems and associated circuit breakers.

The main graph shown in [section B](#) displays the calculated CCT values for all generating units represented within the Slovenian power system. The horizontal axis lists the individual generating

units, while the vertical axis represents the corresponding clearing times. For each generator, the displayed value corresponds to the most critical contingency, i.e., the scenario resulting in the lowest critical clearing time. In general, faults electrically close to a particular generator are those most likely to cause loss of synchronism of that unit. The presence of multiple low-CCT values associated with a particular generator therefore indicates increased sensitivity to disturbances occurring within a broader electrical neighbourhood.

To facilitate operational interpretation, the calculated CCT values are compared against two predefined threshold levels represented by horizontal reference lines. The orange line corresponds to a clearing time of 600 ms, while the red line represents a clearing time of 150 ms. These thresholds were selected based on typical protection-system operation times. The 150 ms threshold corresponds approximately to the operation of the (instant) first zone of distance protection, while the 600 ms threshold represents a typical clearing time associated with the (delayed) second protection zone. Based on the position of the calculated CCT values relative to these thresholds, operating conditions can be classified into three categories. Values above the orange threshold indicate secure operating conditions with substantial transient-stability margins. Values located between the two thresholds indicate reduced but still acceptable stability margins. Finally, values below the red threshold indicate potentially critical operating conditions, where loss of synchronism may occur before the fault can be cleared by conventional protection schemes. Such situations require particular attention from system operators, as they may indicate insufficient transient-stability reserves under the current operating conditions.

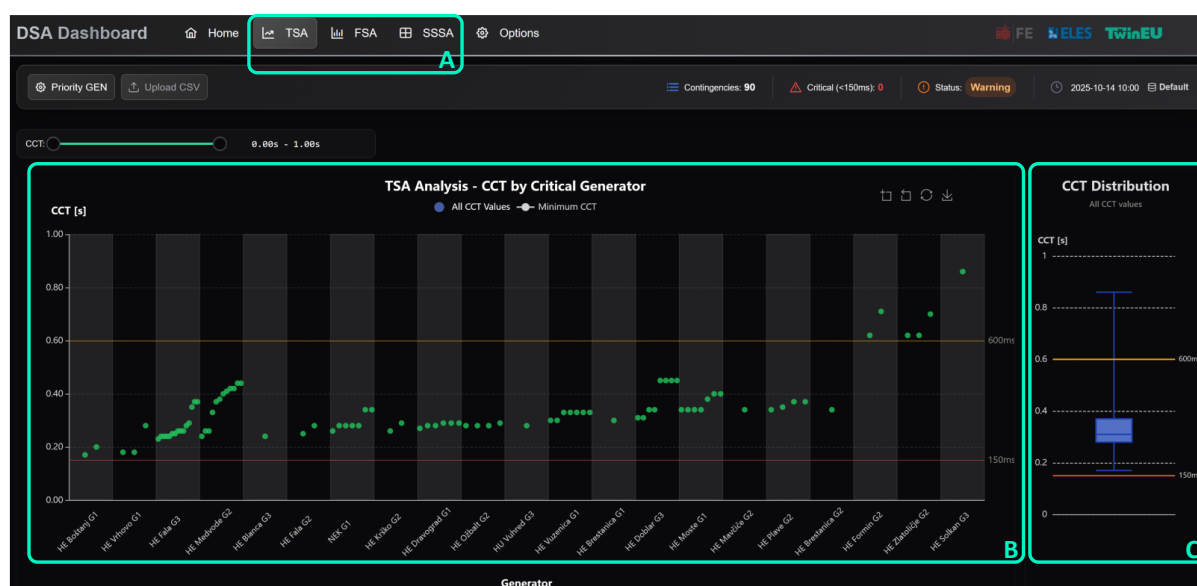


Figure 3.88 TSA Dashboard Displaying Critical Clearing Time Results for the Analysed Generating Units

It should be noted that the displayed results represent a combination of AI-based predictions and simulation-verified values. In order to accelerate the DSA process, detailed time-domain simulations are performed only for scenarios that the AI model identifies as potentially critical, specifically those for which the predicted critical clearing time falls below 400 ms. Consequently, all results displayed below the 400 ms threshold have been verified and finalized using detailed time-domain simulations performed on the digital twin. For operating conditions where the AI model predicts critical clearing times above 400 ms, no additional time-domain verification is performed, and the displayed values correspond directly to the AI estimates. This approach significantly reduces the computational burden

while maintaining a high level of confidence in the results that are most relevant from an operational perspective. Since the potentially critical scenarios are always verified through detailed simulations, the acceleration benefits of AI can be exploited without compromising the reliability of stability assessments in regions close to the actual stability boundary.

Section C presents a statistical summary of the calculated CCT values in the form of a whisker plot. This representation provides operators with a compact overview of the overall transient-stability robustness of the system by illustrating the distribution, variability, and spread of stability margins across all analysed contingency scenarios. As such, it complements the detailed generator-level results shown in the main graph and provides an immediate indication of the general resilience of the power system to severe disturbances.

Frequency stability results

The results of the frequency stability assessment are presented in **Figure 3.89**. Frequency stability phenomenon is strongly influenced by the geographical and electrical distribution of inertia throughout the system. Consequently, the dashboard adopts a spatially oriented visualization approach that enables operators to quickly identify the location and severity of frequency-related stability concerns.

The largest portion of the dashboard is dedicated to the geographical representation of generating units within the Slovenian power system (**section C**). The displayed results are based on contingency scenarios representing the outage of individual generating units, which create active-power imbalances and consequently trigger frequency excursions throughout the modelled network. For each scenario, the frequency response of the remaining generating units is evaluated, with particular focus on the initial rate of change of frequency (RoCoF), which was selected as the primary frequency stability indicator within the DSA framework.

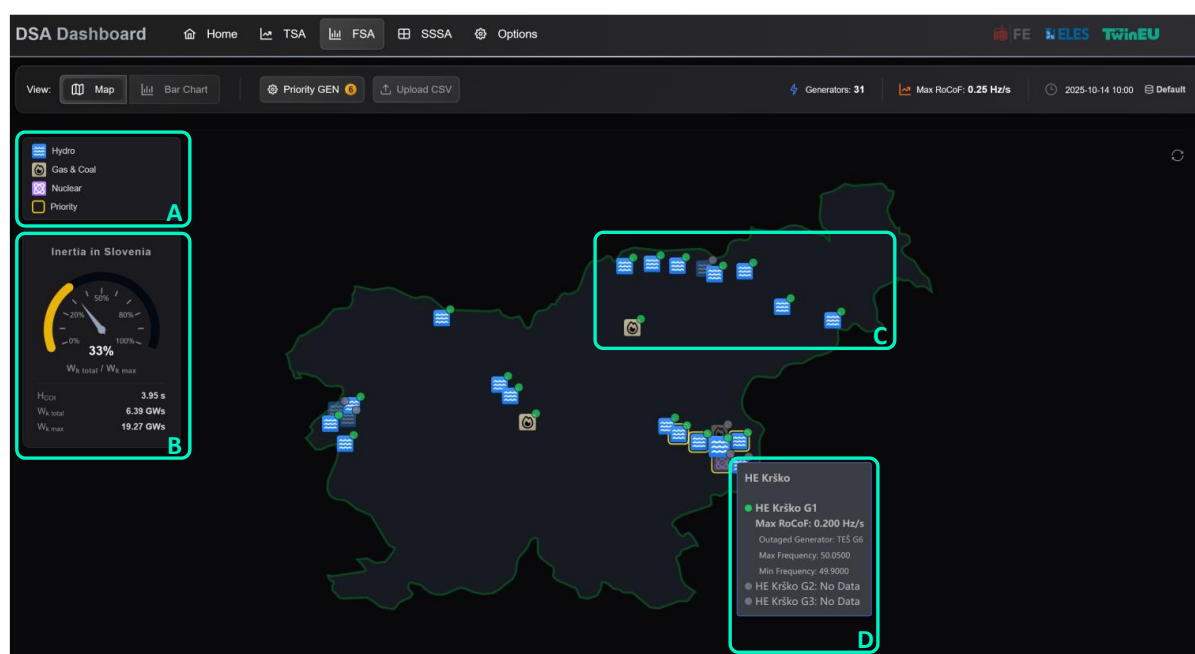


Figure 3.89 Frequency Stability Dashboard Displaying RoCoF and System Inertia Indicators

Each generating unit is represented by a dedicated symbol indicating its generation technology. The corresponding legend is provided in **section A** and enables differentiation between hydro, thermal, nuclear, and other generation technologies. In addition to the technology-specific symbol,

each unit is equipped with a colour-coded stability indicator. Green markers indicate satisfactory frequency stability margins, orange markers indicate increased sensitivity to frequency disturbances, while red markers highlight potentially critical operating conditions characterized by elevated RoCoF values. This visualization enables rapid identification of vulnerable areas and generation assets within the system.

Additional information regarding individual scenarios can be obtained by selecting a specific generating unit on the map. The resulting information panel (**section D**) provides detailed information about the selected generator and the corresponding contingency scenario, allowing operators to investigate the underlying causes of elevated RoCoF values and better understand the dynamic behaviour of the system following generation outages.

Since system inertia plays a fundamental role in limiting frequency excursions immediately following a power imbalance, dedicated inertia-related indicators are also included in the dashboard. **Section B** provides a compact overview of the inertia available within the Slovenian power system for the currently analysed operating state. Several complementary indicators are displayed, including the equivalent centre-of-inertia constant (H_{COI}), the total rotational kinetic energy available in the system (W_{Ktotal}), and the maximum achievable rotational kinetic energy (W_{Kmax}) that could be obtained from the currently installed generation fleet.

The gauge shown in **section B** illustrates the percentage utilization of the available inertia resources. This representation provides operators with an immediate indication of the system's capability to withstand sudden active-power imbalances and complements the RoCoF-based stability assessment presented on the geographical map. Together, these indicators provide a comprehensive overview of the frequency stability condition of the Slovenian power system and its resilience to generation-loss contingencies.

Small-signal stability results

Unlike transient and frequency stability assessments, which require the evaluation of multiple contingency scenarios, small-signal stability assessment is performed for a single operating condition. This is because eigenvalue analysis inherently provides a comprehensive overview of the oscillatory characteristics of the system around the analysed operating point. Consequently, a single analysis is sufficient to identify the dominant electromechanical oscillatory modes, assess their damping, and determine the generating units most strongly involved in the observed oscillations.

The results of the small-signal stability assessment are presented in [Figure 3.90](#). The primary visualization, located on the left-hand side of the dashboard, provides a compact overview of the detected electromechanical oscillatory modes and their associated damping characteristics. The radial labels shown in **section A** identify the generating units participating in the analysed oscillations. The angular position of each bubble represents the relative damping of the corresponding oscillatory mode, ranging from 0% to 12%. To facilitate interpretation, the display is divided into three operational regions. Oscillatory modes with damping ratios below 3% are classified as critical and are displayed within the red region. Modes with damping ratios between 3% and 5% are considered marginally acceptable and are displayed within the orange region. Modes exhibiting damping ratios above 5% are classified as sufficiently damped and are displayed within the green region. This classification enables operators to rapidly assess the overall oscillatory stability condition of the system.

The size of the bubbles shown in **section B** represents the participation of individual generating units in the corresponding oscillatory mode. Larger bubbles indicate stronger participation and

therefore identify the machines that contribute most significantly to the observed oscillation. This visualization allows operators and analysts to quickly determine which generating units are involved in a particular mode.

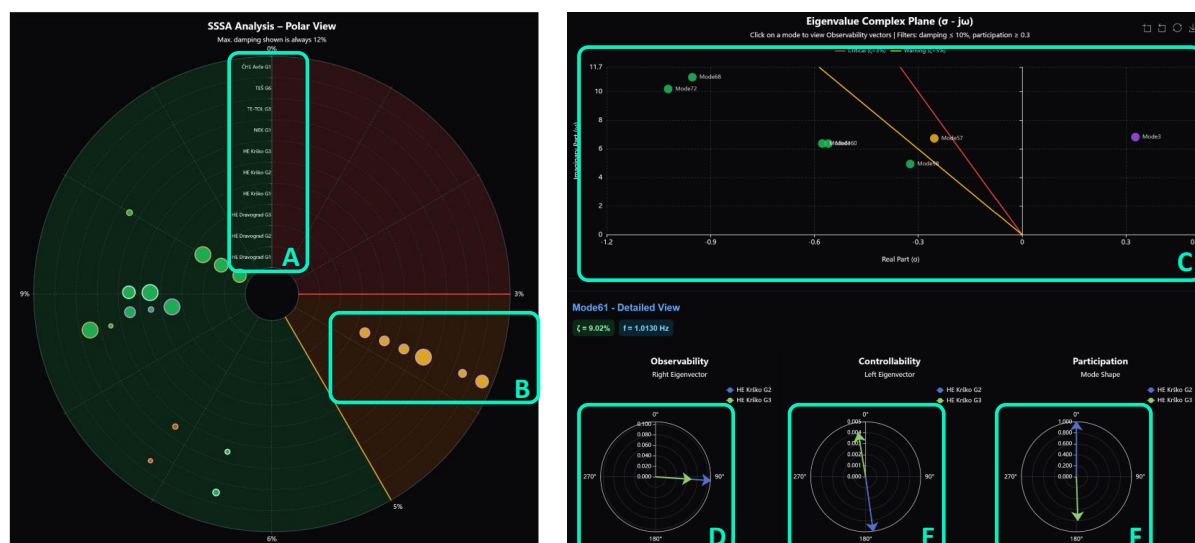


Figure 3.90 Small-Signal Stability Dashboard Displaying Electromechanical Oscillation Modes and Associated Stability Indicators

The right-hand side of the dashboard provides additional information intended primarily for expert users performing detailed modal analysis. **Section C** displays the eigenvalues in the complex plane, providing a classical representation of the detected oscillatory modes and their stability margins. The same oscillatory modes represented in the polar view are therefore also available in their original eigenvalue form. Further diagnostic information is provided through **sections D, E, and F**. These display the mode shapes, left eigenvectors, and participation factors associated with the selected oscillatory mode. Together, these quantities provide detailed insight into the physical nature of the oscillation, its geographical distribution, and the relative contribution of individual generating units. Such information is particularly valuable when investigating poorly damped oscillations and identifying potential corrective actions aimed at improving system damping and overall oscillatory stability.

3.5 Use cases

To illustrate the practical application of the developed methodologies, several use cases have been formulated. These use cases demonstrate how the integrated digital twin and dynamic security assessment framework can enhance grid management in real-world scenarios.

3.5.1 Use Case 1: Upgraded Dynamic RMS Analysis (SLO-BUC-1)

Use Case 1 addresses the upgrade of the transmission-system dynamic model by integrating an equivalent dynamic representation of the distribution grid. The main purpose of the use case is to improve the accuracy of RMS dynamic analyses by replacing the conventional representation of distribution networks as constant PQ loads with a more detailed equivalent model. The equivalent distribution model includes aggregated distributed generation, represented by technology type, and an aggregated load model with voltage- and frequency-dependent behaviour.

The use case was implemented through the development of a distribution digital twin and its integration pathway towards the transmission digital twin. The distribution equivalent was designed to represent aggregated rooftop PV generation, asynchronous generation, synchronous generation and equivalent loads at the distribution level. The modelling approach was implemented in a way that preserves compatibility with the existing transmission system modelling environment and supports standardized data exchange between DSO and TSO through CIM/CGMES based model representation.

The implementation followed the process defined in SLO-BUC-1. First, the equivalent distribution model structure and required parameters were defined. Distributed generation was aggregated by type, while the load model was parameterized using measurement data from the distribution grid. Second, the equivalent model was prepared for integration with the transmission system model. Third, the upgraded model was used in the PowerFactory environment for load flow calculation and RMS dynamic simulations. This enabled the assessment of how the improved distribution grid representation influences the dynamic response of the wider power system.

The use case therefore demonstrates that the distribution grid can be represented by a dynamic equivalent that is suitable for transmission-level dynamic studies. Compared with the previous approach, where distribution grids were represented as static constant power loads, the upgraded model provides a more realistic representation of the impact of distributed generation and load dynamics on power system behaviour.

3.5.1.1 KPI evaluation for SLO-BUC-1

SLO-BUC-1 was successfully demonstrated. The use case confirms that the distribution grid can be represented by an equivalent dynamic model suitable for integration into the transmission system digital twin. It also confirms that the upgraded model can be used in RMS dynamic analyses and that the behaviour of voltage dependent loads can be parameterized and evaluated based on distribution grid measurements. The main added value of the use case is the transition from a simplified static representation of the distribution grid towards a dynamic, interoperable and measurement supported equivalent model that improves the realism of transmission level dynamic security studies.

Table 3: KPI evaluation for SLO-BUC-1

KPI	Definition	Evaluation	Status
KPI 1	Equivalent dynamic network model is successfully merged with the dynamic transmission network model.	The distribution equivalent was defined as a model containing aggregated distributed generation and equivalent load representation. The KPI is fulfilled because the integration concept and model representation required for merging the distribution equivalent with the transmission digital twin were successfully developed and demonstrated.	Achieved
KPI 2	Successful run of dynamic RMS analysis with included equivalent distribution model.	RMS simulations were carried out in PowerFactory using the improved distribution grid load representation. The dynamic behaviour of different load categories was analysed under representative disturbances. The simulations showed that the upgraded model provides meaningful dynamic responses of active and reactive power. The KPI is	Achieved

		fulfilled because the upgraded model was successfully used in RMS dynamic simulations and produced interpretable dynamic responses.	
KPI 3	Voltage and frequency dependency of the load model in the distribution grid.	The voltage and frequency dependency of the aggregated distribution grid load model was addressed through measurement based parameterization and dynamic load modelling in PowerFactory. Voltage change events, mainly originating from OLTC operations and other operational voltage variations, were detected and filtered using the defined quality criteria. The evaluation was based on the coefficient of determination R^2 , which indicates the quality of the model fit, and the relative standard error σ , which indicates the reliability of the analysed event. Based on the selected events, the exponential load model was applied to represent the voltage dependent behaviour of aggregated distribution loads. The resulting parameters were then used as a basis for defining improved dynamic load models in PowerFactory, including both voltage and frequency dependency for different load categories. The upgraded load representation was tested in RMS simulations under representative disturbances, confirming that the improved model provides a more realistic dynamic response than the conventional constant load representation.	Achieved

3.5.2 Use Case 2: Real-time Dynamic RMS Analysis with Transmission System Model improved with the dynamic parameters of generators and control models of the neighbouring TSOs

SLO-BUC-2 addresses one of the key objectives of the TwinEU project: enabling real-time dynamic security assessment (DSA) through the integration of digital-twin technology, operational SCADA/EMS data, and federated exchange of dynamic network model information between neighbouring transmission system operators (TSOs).

The use case focuses on the development and deployment of a framework capable of continuously assessing the dynamic security of the Slovenian power system under actual operating conditions. Unlike traditional offline stability studies, which are typically performed for a limited number of representative scenarios, the proposed solution utilizes periodically updated digital twins that reflect the current state of the network and therefore enable near real-time stability assessments.

The implemented workflow begins with the export of operational snapshots from the SCADA/EMS environment and the creation of a digital twin representing the current operating state of the Slovenian power system with a representative neighbourhood. To ensure that the influence of

neighbouring interconnected systems is adequately represented, the national dynamic model is merged with a model of the observability area. Since dynamic phenomena in the Slovenian power system are strongly affected by interactions with neighbouring transmission systems, the inclusion of external network representations is essential for obtaining realistic dynamic simulation results.

A major innovation introduced through this use case is the incorporation of dynamic information originating from neighbouring TSOs. Through the TwinEU federated data exchange concept, dynamic generator models and associated controller parameters can be exchanged between TSOs and integrated into the observability-area model. This approach significantly improves the realism of dynamic simulations and enables more accurate assessment of transient stability, frequency stability, and oscillatory stability phenomena.

Within the project, a complete workflow for automated digital twin generation, validation, dynamic simulation, stability index calculation, and visualization was developed and demonstrated. Particular attention was devoted to automation, computational efficiency, and operational applicability. The resulting DSA framework combines AI-assisted stability screening with detailed time-domain simulations, enabling near real-time performance while maintaining the level of accuracy and transparency required by transmission system operators.

The following section evaluates the achievement of the key performance indicators defined for SLO-BUC-2 and summarizes the extent to which the objectives of the use case have been fulfilled.

3.5.2.1 KPI evaluation for SLO-BUC-2

The implementation activities carried out within SLO-BUC-2 resulted in the successful achievement of all defined key performance indicators. The developed solution demonstrated the feasibility of integrating operational data, dynamic network models, and federated data exchange into a single framework capable of performing dynamic security assessment in near real time.

The evaluation of individual KPIs is summarized in Table 4.

Table 4: KPI evaluation for SLO-BUC-2

KPI	Definition	Evaluation	Status
KPI 1	Dynamic network models exchange.	A complete workflow enabling the exchange and utilization of dynamic network model information originating from a neighbouring TSO (MAVIR – Hungary) was established. The project successfully demonstrated the capability of integrating externally provided dynamic generator data into the observability-area model through the TwinEU federated data exchange concept. This confirmed the feasibility of dynamic model exchange as a means of improving the quality of dynamic security assessments and supporting future cross-border cooperation between TSOs.	Achieved
KPI 2	Dynamic network model of the transmission grid with	The KPI was achieved through the development of a digital twin consisting of the	Achieved

	observability area is developed.	detailed Slovenian dynamic RMS model merged with the observability-area model. Automated procedures for model merging, dynamic parametrization of external generating units, model correction, initialization, and validation were developed and successfully deployed. The resulting model provides a realistic representation of both the Slovenian transmission system and the surrounding interconnected network, enabling comprehensive dynamic analyses.	
KPI 3	Run dynamic network analysis on the extended network model with operational data retrieved from SCADA.	The developed DSA framework successfully performs dynamic analyses using operational data automatically exported from the SCADA/EMS environment. More than 26,000 operating states were processed during project activities, demonstrating the robustness and scalability of the developed solution. The framework automatically initializes the digital twin, validates the operating state, performs transient, frequency, and small-signal stability assessments, calculates stability indices, and presents the results through a dedicated visualization environment.	Achieved
KPI 4	Number of TSOs for dynamic data exchange.	The project successfully demonstrated dynamic data exchange with a neighbouring transmission system operator (the target was data exchange with at least one neighbouring TSO). Dynamic generator and controller information provided by MAVIR (Hungary) was integrated into the observability-area model and utilized within the DSA framework. Although dynamic data exchange was ultimately realized with one neighbouring TSO, the implemented methodology and federated exchange concept are inherently scalable and can be extended to additional TSOs as soon as the corresponding data become available. The achieved result therefore confirms the practical feasibility of cross-border dynamic data exchange and its positive impact on the accuracy of dynamic security assessments.	Achieved

3.5.3 Use Case 3: SCADA/EMS Data Integration for Operational Simulation (SLO-SUC-1)

SLO-SUC-1 represents the system-level use case supporting the implementation of the real-time dynamic security assessment workflow. While SLO-BUC-2 focuses on the broader business objective of performing dynamic RMS analysis using an extended transmission system model, SLO-SUC-1 defines the technical process by which operational data from the SCADA/EMS environment are made available to the power system analysis tool.

The main objective of this use case is to provide numerical simulation and analysis tools, such as DigSILENT PowerFactory, with operational data from SCADA/EMS. These data are required for the initialization of the digital twin and for further analyses.

The implemented workflow is based on the periodic export of power system snapshots from the SCADA/EMS environment. Each snapshot represents the current operating state of the power system and includes the relevant network and operational information, such as generation and consumption values, voltage measurements, power flows, currents, and the operational states of switching elements. The snapshots are exported in formats suitable for power system analysis, including PSS/E, CIM/CGMES and supporting text-based formats.

After being generated by SCADA/EMS, the snapshots are stored on shared storage that is accessible to the power system analysis environment. The Power System Analysis Tool retrieves the required files from this shared storage and imports them into the simulation environment. In this way, the simulation model can be initialized with the actual operating state of the power system, rather than relying only on predefined or manually prepared study cases.

Within the Slovenian demonstration, this use case was implemented as an essential part of the automated digital twin generation process. Operational snapshots exported from SCADA/EMS are used as input data for the creation of periodically updated digital twins. The imported data enable the model to reproduce actual operating conditions and provide the basis for subsequent validation against the SCADA/EMS state estimator. Once the digital twin is successfully initialized and validated, it can be used for dynamic simulations and stability index calculation within the DSA framework.

The use case therefore demonstrates the operational data integration layer required for dynamic security assessment. It ensures that the developed digital twin and DSA tool are not limited to offline simulations, but can be continuously supplied with real operational data. This is a key prerequisite for applying the developed methodology in an operational environment.

3.5.3.1 KPI evaluation for SLO-SUC-1

SLO-SUC-1 was successfully demonstrated. The use case confirms that operational data from SCADA/EMS can be periodically exported, stored on shared storage, retrieved by the power system analysis tool and imported into the simulation environment. This enables the digital twin to be initialized with actual operating data and provides the foundation for automated operational simulation and dynamic security assessment.

Table 5: KPI evaluation for SLO-SUC-1

KPI	Definition	Evaluation	Status
KPI 1	Operational data are successfully retrieved and imported in the simulation tool.	The SCADA/EMS environment periodically generates operational snapshots of the power system and stores them on shared storage accessible to the power system analysis environment. The snapshots contain the required operational data, including generation, load, voltages, power flows and switching element states, and are provided in formats suitable for further processing, such as PSS/E, CIM/CGMES and supporting text based formats. The Power System Analysis Tool successfully retrieves the exported snapshots and imports them into the simulation environment, where they are used to initialize the digital twin and support load flow calculation, static validation and dynamic security assessment. The KPI is fulfilled because the complete data path from SCADA/EMS export to simulation tool import was established and demonstrated within the Slovenian pilot.	Achieved

3.6 Study cases

For showcasing DSA performance, three situations have been observed and analysed individually:

- a specific night-time operation in spring on 25th April 2026 at 03:00,
- a specific day-time operation in spring on 2nd April 2026 at 19:00 and
- a sequence of operating states between 25th November and 2nd December 2024.

3.6.1 Study case #1, night-time operation

Study Case #1 represents a typical night-time operating condition of the Slovenian power system during the spring season. Such operating conditions are generally characterized by relatively low system loading and elevated voltage levels throughout the transmission network. The higher voltage profile is primarily a consequence of reduced power transfers and lower loading of transmission lines and transformers, resulting in lower voltage drops across the network. The generation portfolio during night-time operation also differs significantly from daytime conditions. A relatively small number of generating units are in operation, while many hydroelectric units remain offline in order to preserve water reserves for periods of higher demand and increased market value of electricity. Furthermore, a considerable number of double-circuit transmission lines operate with only one circuit in service, reflecting the reduced operational requirements during periods of low system demand.

For the analysed operating state, the Slovenian power system was importing approximately 250 MW of active power from neighbouring systems. Domestic generation amounted to approximately

830 MW, while total domestic demand was approximately 1,050 MW. For reference, the latest publicly available operational statistics indicate that the maximum system demand in Slovenia exceeded 2,100 MW during 2024, while minimum demand values were approximately 450 MW. The analysed operating condition therefore represents quite poorly loaded night-time state located closer to the lower end of the annual demand range.

Before performing dynamic security assessment, the quality of the digital twin initialization was thoroughly evaluated. The results of the steady-state validation are presented in Figure 3.91, Figure 3.92 and Figure 3.93. Figure 3.91 compares active power flows obtained from the SCADA/EMS environment with the corresponding values calculated by the initialized digital twin. The comparison includes all transmission lines located within the Slovenian national borders, while power flows in the surrounding observability area are excluded from the analysis. Blue bars represent the measured values obtained from SCADA/EMS, whereas red bars represent the corresponding values calculated by the digital twin.

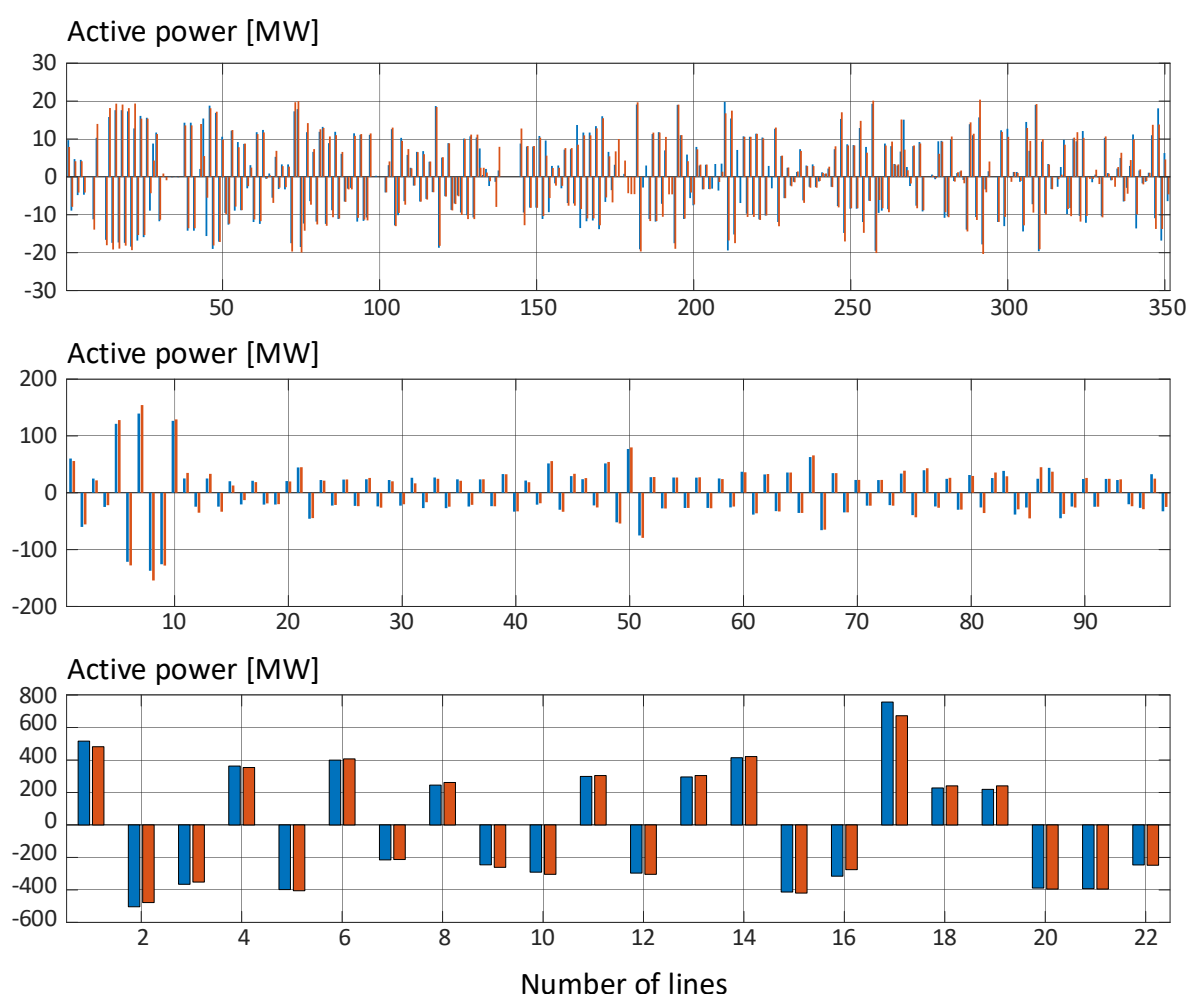


Figure 3.91 Study case #1 - static validation results (transmission line active power)

The results demonstrate excellent agreement between the two datasets, indicating that the initialization process successfully reconstructed the actual operating state of the power system. The average deviation of active power flows amounts to only 1.35% of the rated transmission-line power. The largest deviations are primarily associated with elements connected to the 110 kV network. Although the 110 kV network is formally considered part of the Slovenian transmission system, it

generally does not participate in significant cross-border power exchanges, with only a few historical exceptions involving interconnections with the Croatian network.

A similarly high level of agreement can also be observed for reactive power flows. Figure 3.92 presents the comparison between measured and calculated reactive power values using the same colour-coding convention as Figure 3.91. The average deviation of reactive power flows amounts to only 1.24% of the rated transmission-line power, further confirming the accuracy of the digital twin initialization process.

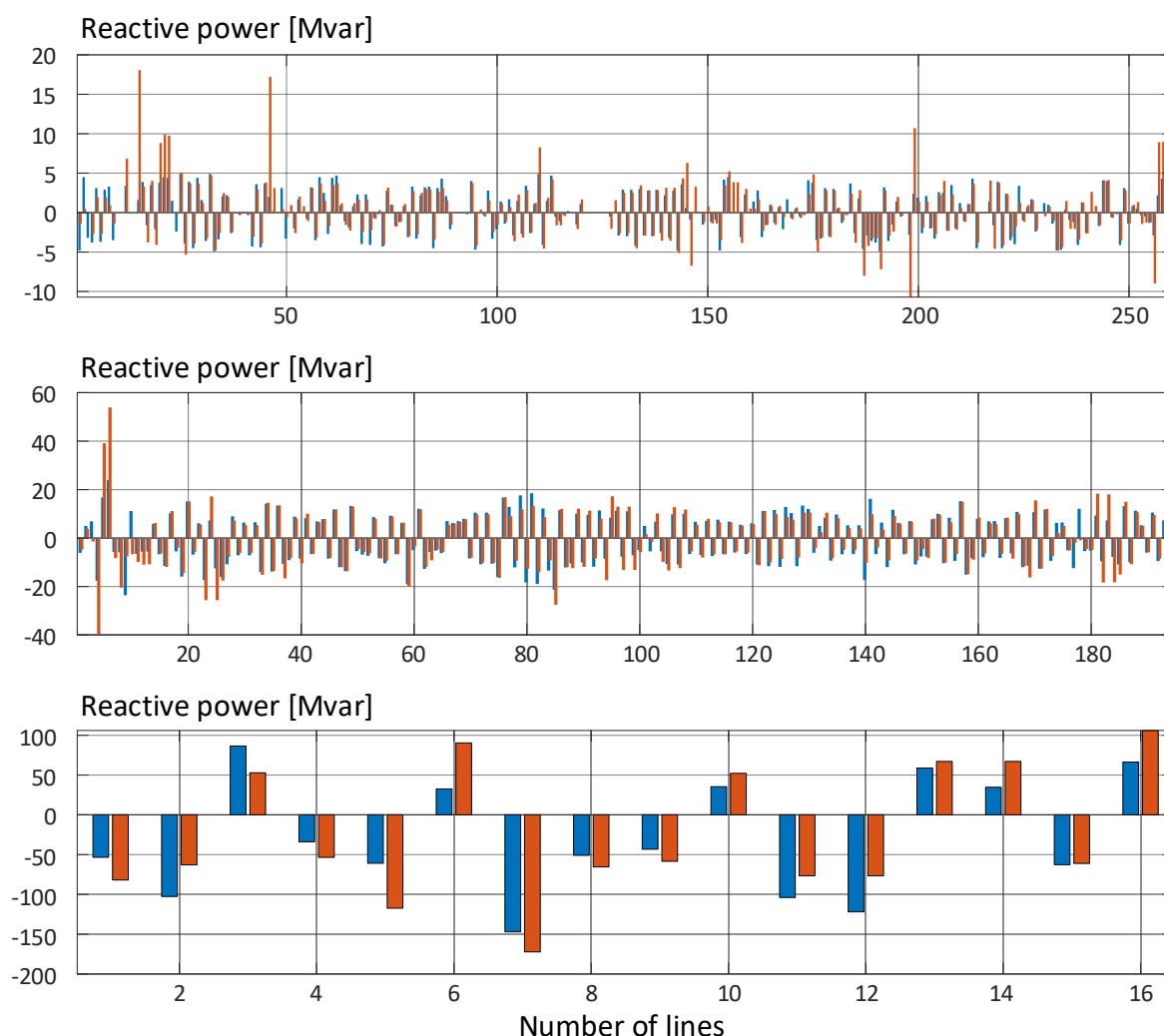


Figure 3.92 Study case #1 - static validation results (transmission line reactive power)

The comparison of voltage profiles shown in Figure 3.93 provides additional confirmation of the quality of the reconstructed operating state. The figure presents the relative voltage deviations across all 400 kV, 220 kV, and 110 kV substations within the Slovenian transmission network. The results indicate excellent agreement between the SCADA/EMS operating state and the digital twin. The maximum observed voltage deviation is approximately 2%, while the majority of substations exhibit substantially smaller differences.

Based on the presented results, it can be concluded that the digital twin accurately reproduces the steady-state operating condition of the Slovenian power system. The achieved level of agreement

confirms that the initialization procedure was successful and that the resulting digital twin provides a reliable basis for the subsequent dynamic security assessment analyses.

Following the successful validation of the digital twin initialization, the calculated stability indices can be analysed in greater detail. Let us first examine the transient stability assessment results.

Due to the low-load night-time operating conditions, the number of generating units connected to the system is relatively limited. It should be noted that the number of generating units displayed in the TSA dashboard (Figure 3.94) does not necessarily correspond to the total number of generators operating within the Slovenian power system. The dashboard lists only those generating units that were identified as critical in at least one of the simulated transient stability scenarios, meaning that they experienced loss of synchronism for sufficiently severe disturbances. For the analysed operating state, this set consists of only eleven generating units, which is consistent with the relatively low generation level characteristic of the considered night-time operating regime.

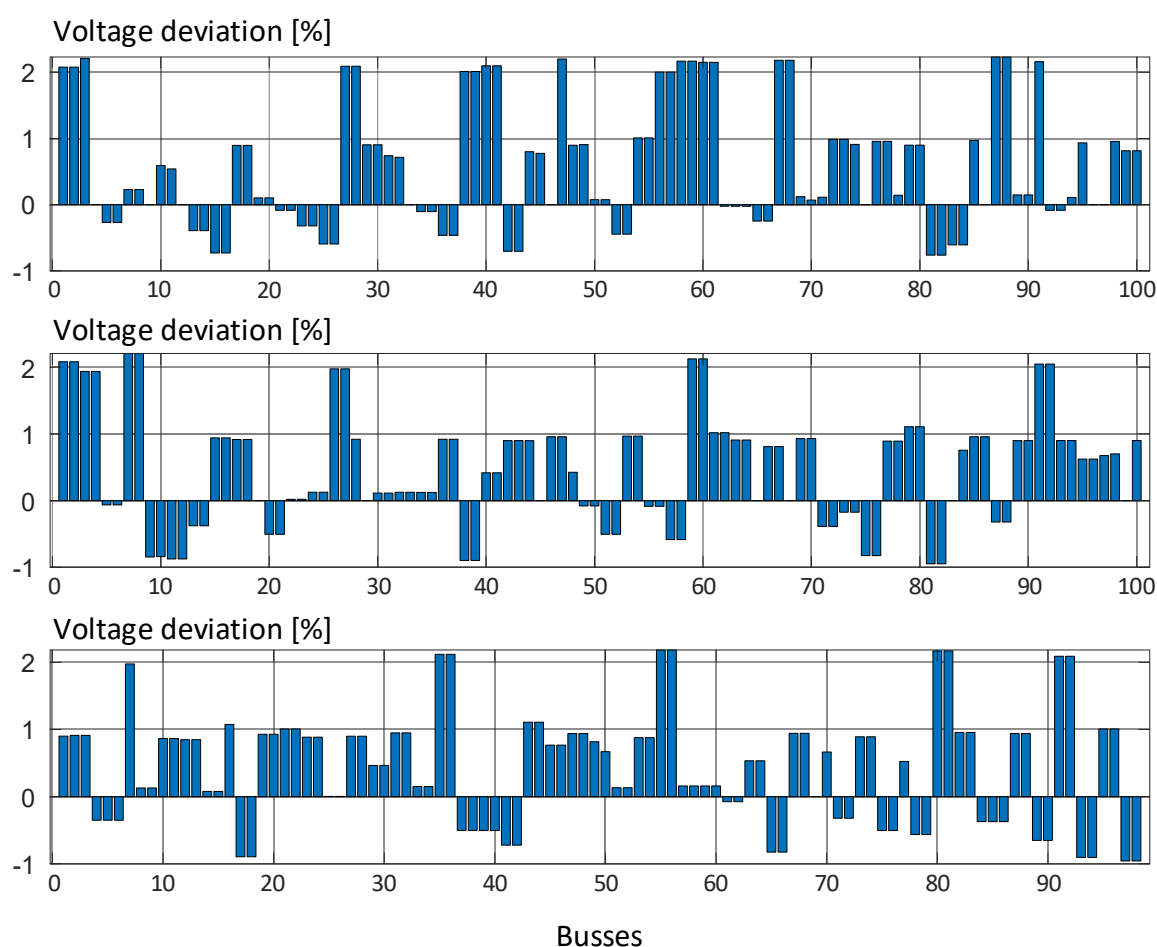


Figure 3.93 Study case #1 - static validation results (bus voltage deviation)

The results clearly demonstrate that the transient stability condition of the system is satisfactory. All calculated critical clearing times remain above the 150 ms threshold associated with the operation of the first zone of distance protection. Furthermore, the overall distribution of the calculated CCT values indicates a comfortable transient stability margin. The average critical clearing time is approximately 500 ms, while the lower quartile lies slightly below 400 ms, indicating that at least 75% of all simulated contingencies result in critical clearing times above this level. The statistical indicators therefore confirm that the system remains securely stable against the analysed disturbances.

The relatively small number of operating generating units has a direct impact on the available system inertia. As shown in Figure 3.95, only approximately 26% of the total installed inertia resources are online in the analysed operating state. This corresponds to an equivalent inertia constant of $H_{COI} = 4.04$ seconds and a total rotational kinetic energy of approximately 4.98 GWs stored in the rotating masses of synchronous generators. At present, the Slovenian power system does not contain any sources of synthetic inertia, while inertia contributions from distribution-connected resources are not yet included in the present assessment framework. Consequently, the available frequency support depends almost entirely on the synchronous generation fleet currently in operation.

The geographical distribution of the operating generating units can also be observed from Figure 3.95. Besides providing information about generator locations, the figure offers insight into the spatial distribution of inertia throughout the system, which directly influences the frequency stability assessment results. While all generating units remain securely stable from the transient stability perspective, the frequency stability indicators reveal the consequences of operating with a relatively small number of online synchronous machines.

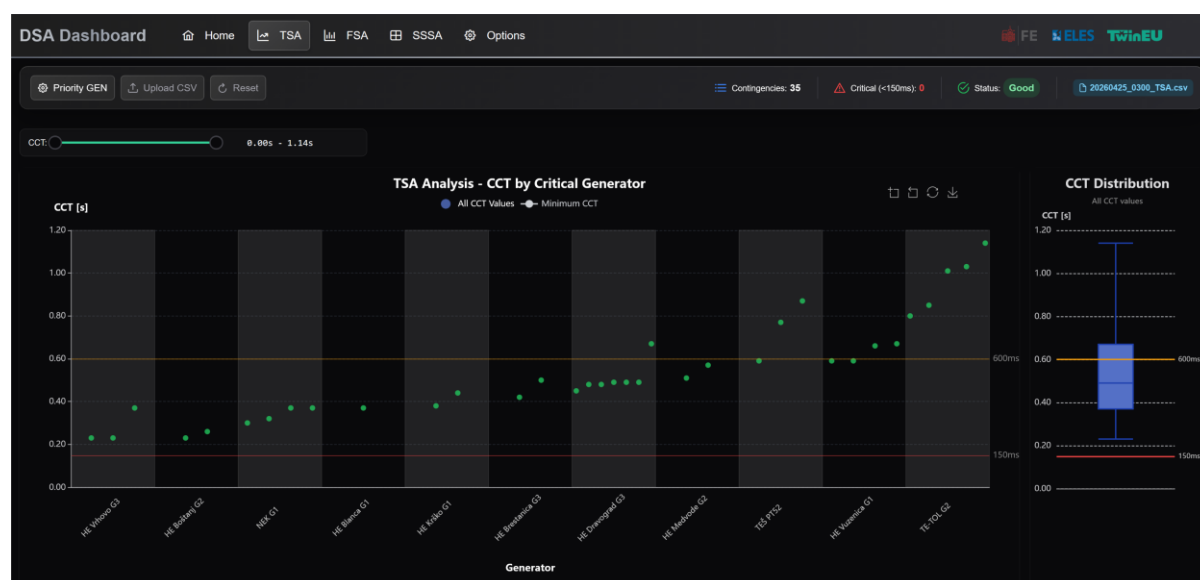


Figure 3.94 Study case #1 - TSA results

The RoCoF results presented in Figure 3.96 show that the remaining generators are required to absorb a larger share of frequency disturbances following generation outages. Average RoCoF values are approximately 0.3 Hz/s, while some units experience values approaching 0.4 Hz/s. The highest RoCoF values are typically observed at generators located electrically close to large generating units, such as the Krško Nuclear Power Plant. Since the outage of such a large generation source represents a significant fraction of total national generation, only a limited number of nearby generators are available to immediately contribute inertial response. As a result, generators within the electrical vicinity of the disturbed unit experience more pronounced frequency excursions and higher RoCoF values. Nevertheless, the strong interconnection of the Slovenian network with the Continental European synchronous area ensures that all observed values remain within acceptable limits.

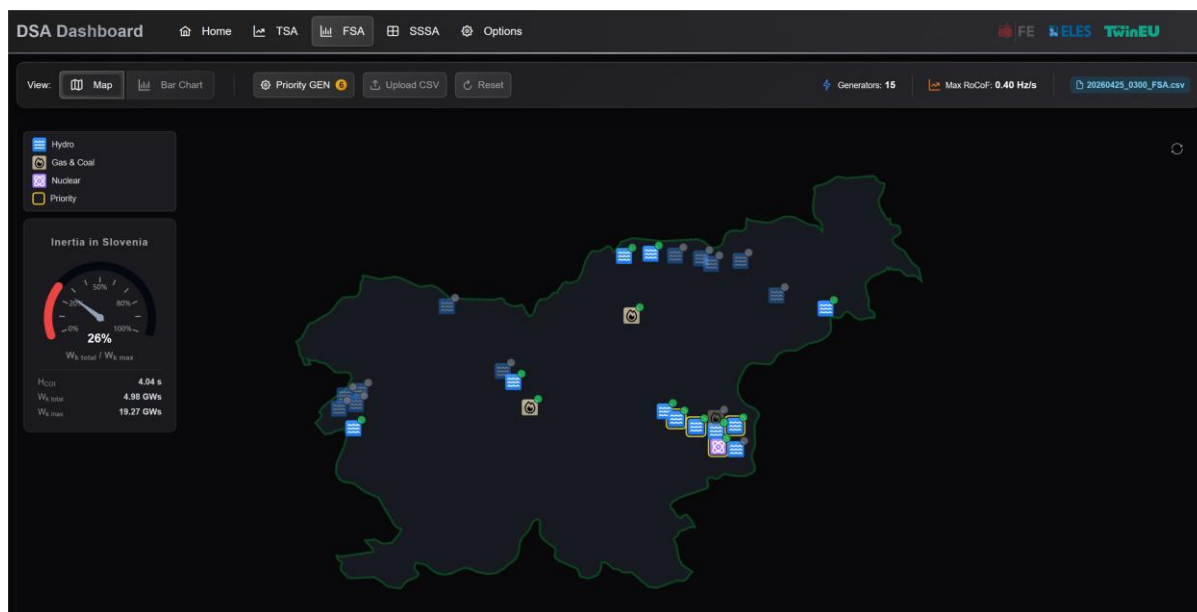


Figure 3.95 Study case #1 – FSA results (map chart)

The small-signal stability assessment results exhibit a similar dependence on the number of operating synchronous machines. A reduced number of active generators generally leads to a reduced number of electromechanical oscillatory modes involving significant participation of Slovenian generating units. The visualization shown in Figure 3.97 allows the user to specify a minimum participation threshold required for a generating unit to be displayed. For a threshold of 30%, only four electromechanical modes satisfy the display criterion under the analysed night-time operating conditions, namely Modes 4, 5, 6, and 7.

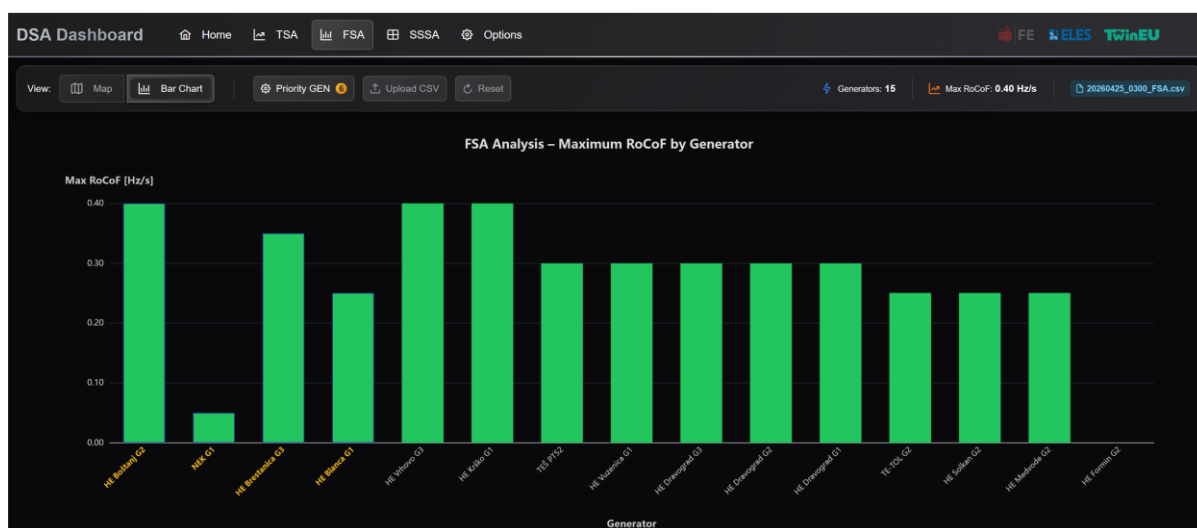


Figure 3.96 Study case #1 – FSA results (bar chart)

The complete modal spectrum is presented in Figure 3.98, while Figure 3.97 provides a more intuitive representation of the same information through the damping-based visualization introduced earlier. The results show that all identified modes exhibit satisfactory damping ratios above the recommended 5% threshold. The least damped mode is associated with significant participation of the Krško Nuclear Power Plant, although its damping remains comfortably within the secure operating region. It should also be noted that some generating units displayed in the visualization originate from

the observability area model. These units are identified by coded names beginning with the prefix “sym” and represent external generation sources that participate in the analysed oscillatory modes.

More detailed modal information can be obtained from Figure 3.99. The figure presents the analysis of Mode 5, which exhibits a damping ratio slightly below 9%. The accompanying table lists only those state variables whose participation exceeds the configured threshold of 30%. Inspection of these dominant state variables clearly indicates that the mode is electromechanical in nature, as the most influential variables correspond to rotor-angle (φ) deviations and speed (ω) deviations of synchronous generators. Both quantities are directly associated with the mechanical dynamics of conventional synchronous machines and therefore represent the classical form of power-system electromechanical oscillations.



Figure 3.97 Study case #1 - SSSA results (polar chart)

Overall, the analysed operating condition can be considered stable from the perspectives of transient, frequency, and small-signal stability. Although the low generation level results in reduced inertia and a relatively small number of participating generators, all evaluated stability indices remain

within acceptable limits and indicate secure operation of the Slovenian power system under the considered night-time conditions.

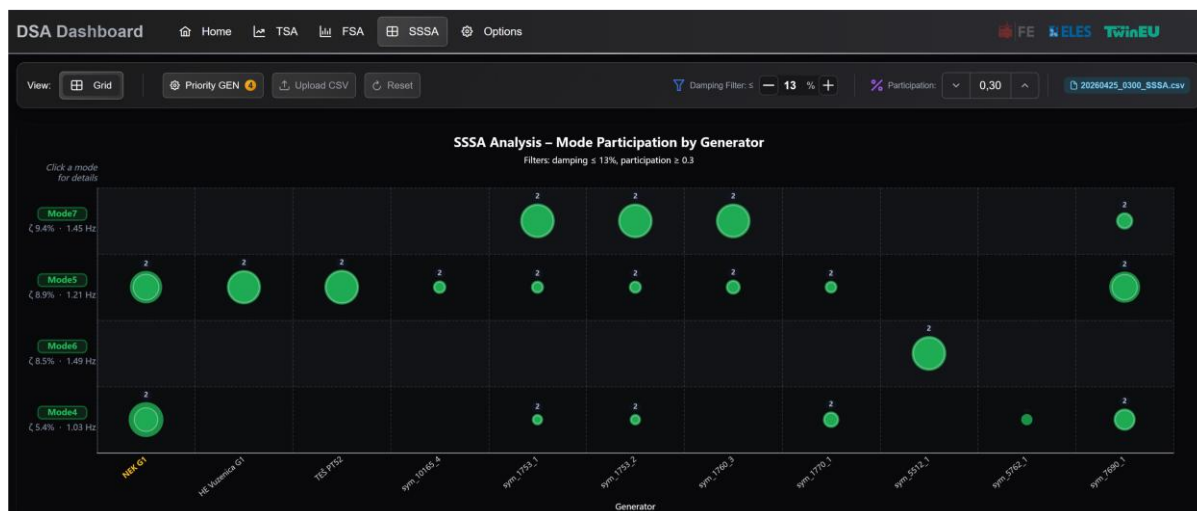


Figure 3.98 Study case #1 - SSSA results (grid chart)

Mode5 state-variable details

Damping: 8.95% Frequency: 1.209 Hz Qualifying generators: 5 Qualifying states: 9

Generator	State variable	Participation		Observability	
		Magnitude	Angle	Magnitude	Angle
HE Vuzenica G1 HVUZ-G1	ω	0.984	5.25°	0.001	-65.68°
	φ	0.963	174.99°	0.024	-160.86°
NEK G1 NEK-G1	ω	0.929	5.47°	0.000	-64.92°
	φ	0.736	167.87°	0.003	-160.28°
sym_1760_3	φ	0.433	172.83°	0.010	2.08°
sym_1760_1	ω	0.722	6.84°	0.000	106.15°
	φ	0.890	174.28°	0.007	11.77°
TEŠ PT52 TSOS-G2	ω	1.000	0.00°	0.000	-66.82°
	φ	0.964	170.26°	0.011	-162.11°

Figure 3.99 Study case #1 - SSSA results (mode details)

3.6.2 Study case #2, day-time operation

While Study Case #1 represented a lightly loaded night-time operating condition, Study Case #2 captures a significantly different operating regime corresponding to daytime operation of the Slovenian power system. Increased electricity demand, higher utilization of generating resources, and more intensive cross-border power exchanges result in a considerably different network configuration and operating environment. For the analysed operating state, domestic generation amounted to approximately 2,046 MW, while total Slovenian demand reached 1,644 MW. As a result, the Slovenian power system operated as a net exporter, supplying approximately 370 MW of active power to neighbouring systems. Compared to the previous case study, both system demand and generation

levels were substantially higher, resulting in increased loading of transmission corridors and a generally more active operating state.

Such operating conditions require a larger number of generating units to remain connected to the network. Consequently, system inertia and available short-circuit power are higher than during night-time operation. In addition, the increased power transfers necessitate the operation of both circuits on many double-circuit transmission lines, resulting in a network topology that differs significantly from that observed in Study Case #1. These factors directly influence the dynamic behaviour of the power system and therefore have an important impact on the stability margins evaluated by the DSA framework.

As with the previous study case, the first step consisted of verifying the quality of the digital twin initialization before proceeding to dynamic analyses. The results of the steady-state validation are presented in Figure 3.100, Figure 3.101 and Figure 3.102, which compare the operating state reconstructed by the digital twin with the corresponding SCADA/EMS data.

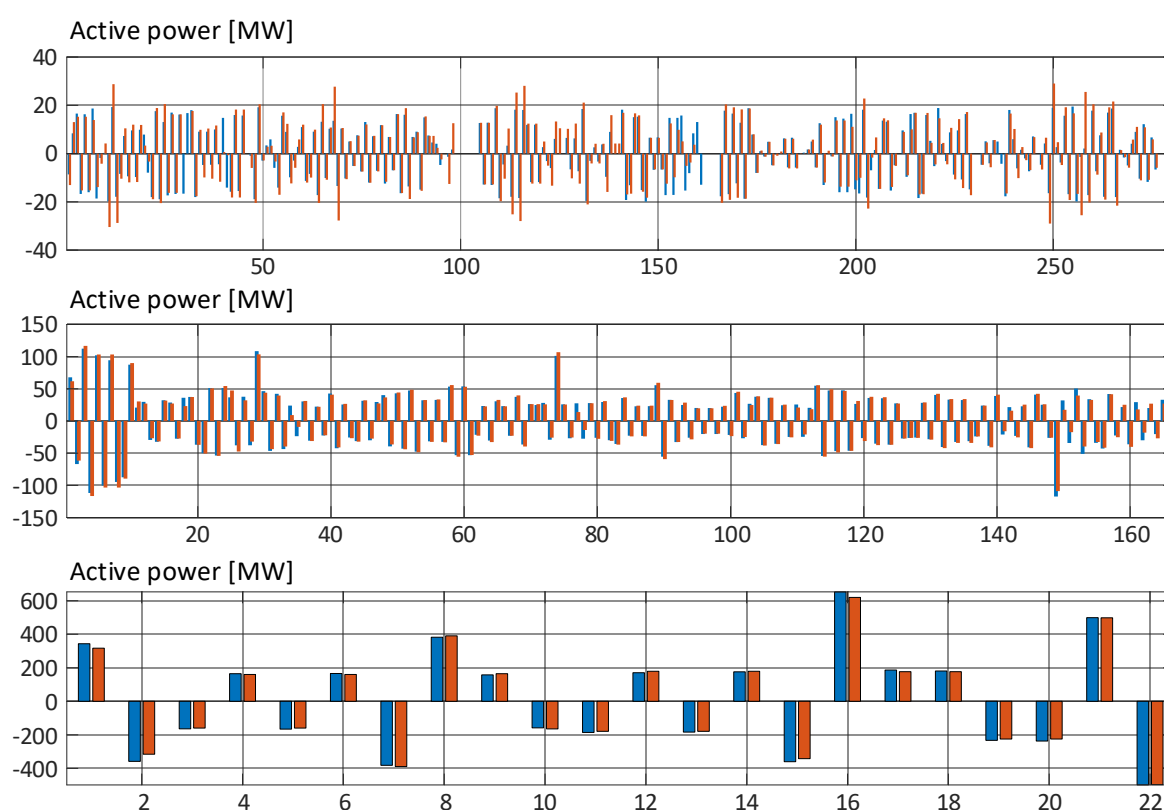


Figure 3.100 Study case #2 - static validation results (transmission line active power)

Figure 3.100 presents the comparison of active power flows across the Slovenian transmission network. The results demonstrate a high degree of consistency between the measured and calculated values, confirming that the initialization procedure successfully reproduced the actual operating condition of the system. The average deviation of active power flows amounts to 2.09% of the rated transmission-line power, which is only slightly higher than in the previously analysed operating state despite the substantially increased network loading and complexity of power exchanges.

A similarly satisfactory level of agreement is observed for reactive power flows. Figure 3.101 shows that the average deviation of reactive power values amounts to 1.79% of the rated transmission-line power. As in the previous case study, the largest discrepancies are predominantly associated with

elements connected to the 110 kV network. These deviations are expected due to the more local nature of the 110 kV system and have only a limited impact on the overall behaviour of the interconnected transmission network.

The comparison of voltage magnitudes shown in Figure 3.102 further confirms the quality of the reconstructed operating state. The observed deviations remain small throughout the network and are fully comparable to those obtained in Study Case #1. No systematic errors or significant mismatches were identified, indicating that the digital twin accurately captures the steady-state conditions present in the SCADA/EMS environment.

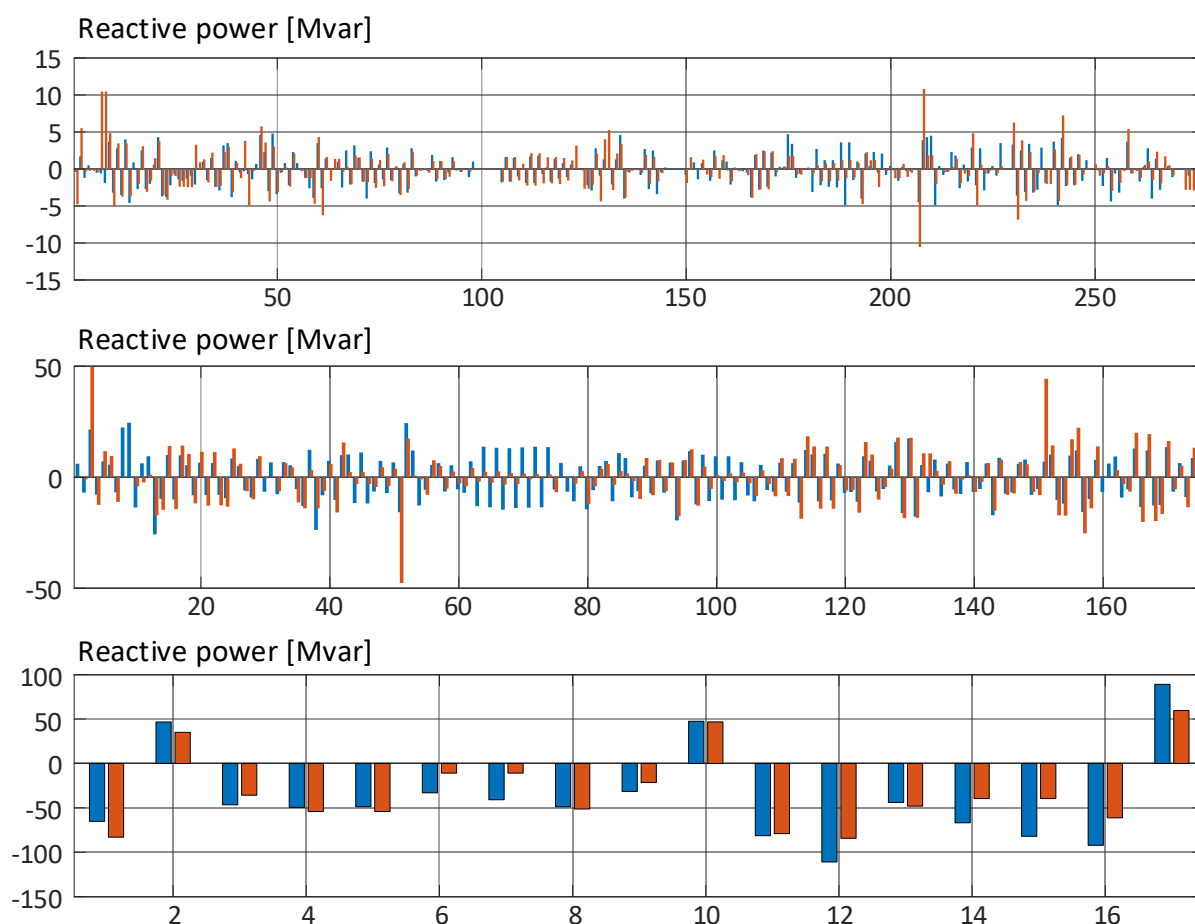


Figure 3.101 Study case #2 - static validation results (transmission line reactive power)

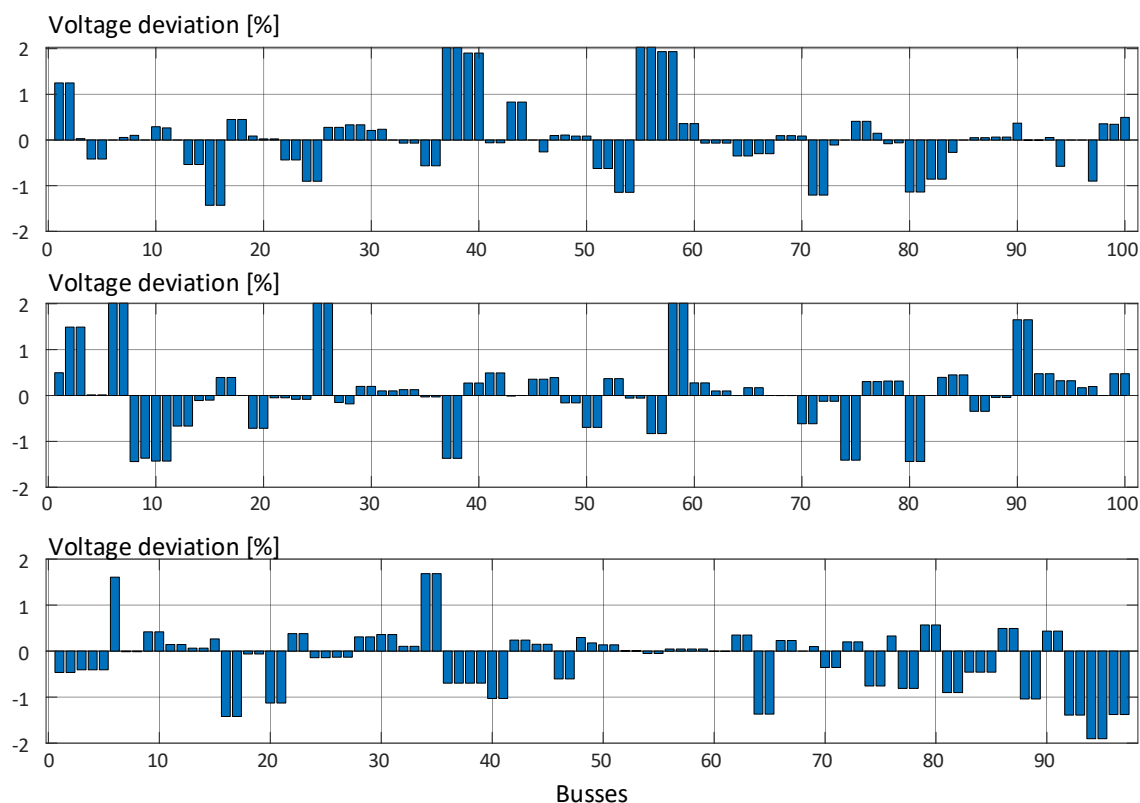


Figure 3.102 Study case #2 - static validation results (bus voltage deviation)

Overall, the validation results demonstrate that the digital twin provides a faithful representation of the actual daytime operating condition of the Slovenian power system. The achieved level of agreement is comparable to that obtained for the night-time operating state and confirms that the automated initialization procedure remains robust across substantially different operating regimes. The model can therefore be considered sufficiently accurate for the subsequent estimation of stability indices and execution of dynamic security assessment analyses.

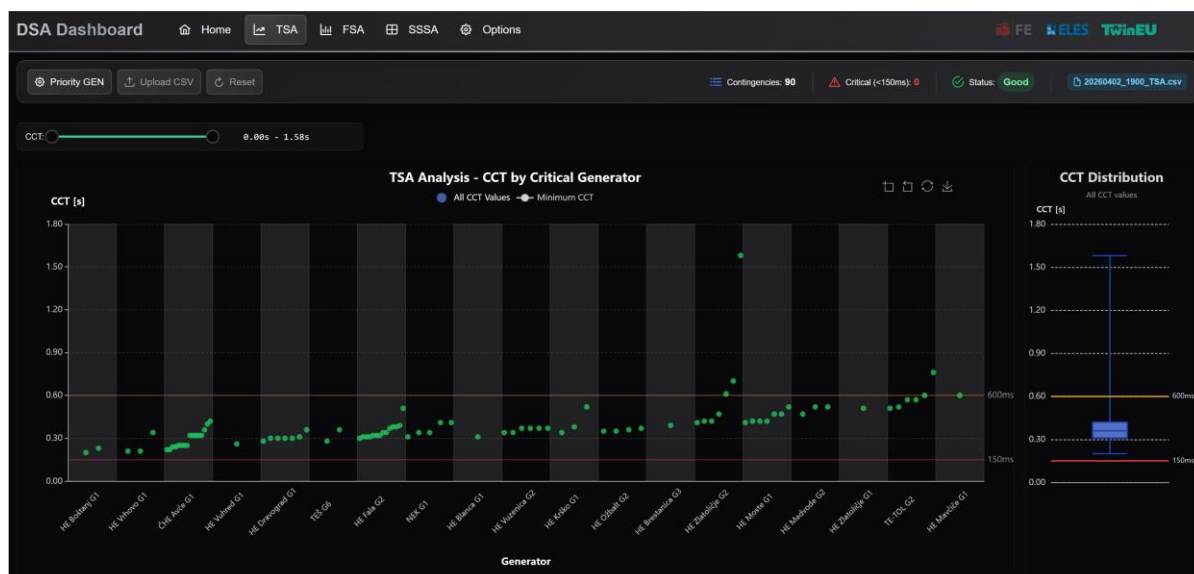


Figure 3.103 Study case #2 - TSA results

Following the static validation of the digital twin, the calculated stability indices can now be examined and compared with those obtained for the night-time operating condition discussed in Section 3.6.1.

One of the most obvious differences between the two operating states is the substantially larger number of generating units in operation during daytime conditions. This is immediately reflected in the TSA results presented in Figure 3.103. As previously explained, the generators shown in the TSA dashboard do not represent all online generating units but only those that become transiently unstable in at least one of the simulated contingency scenarios. While the night-time operating condition resulted in eleven such generators, the daytime operating state exhibits nineteen generators classified as critical in at least one scenario. This increase is consistent with the significantly higher generation level and the more heavily loaded transmission network.

A more important observation, however, is the change in the statistical distribution of critical clearing times. Compared to the previous study case, the average CCT decreases substantially and reaches only slightly above 350 ms. Furthermore, the interquartile range becomes noticeably narrower, indicating a more concentrated distribution of stability margins. From an operational perspective, this means that the system possesses a smaller transient stability reserve than during the night-time operating condition. This result is consistent with established transient stability principles. Higher generation levels generally imply larger rotor-angle deviations between synchronous machines and a more heavily loaded transmission network. Both factors reduce the ability of the system to withstand severe disturbances. In addition, daytime operation is typically associated with lower voltage levels throughout the network, which further reduces transient stability margins.

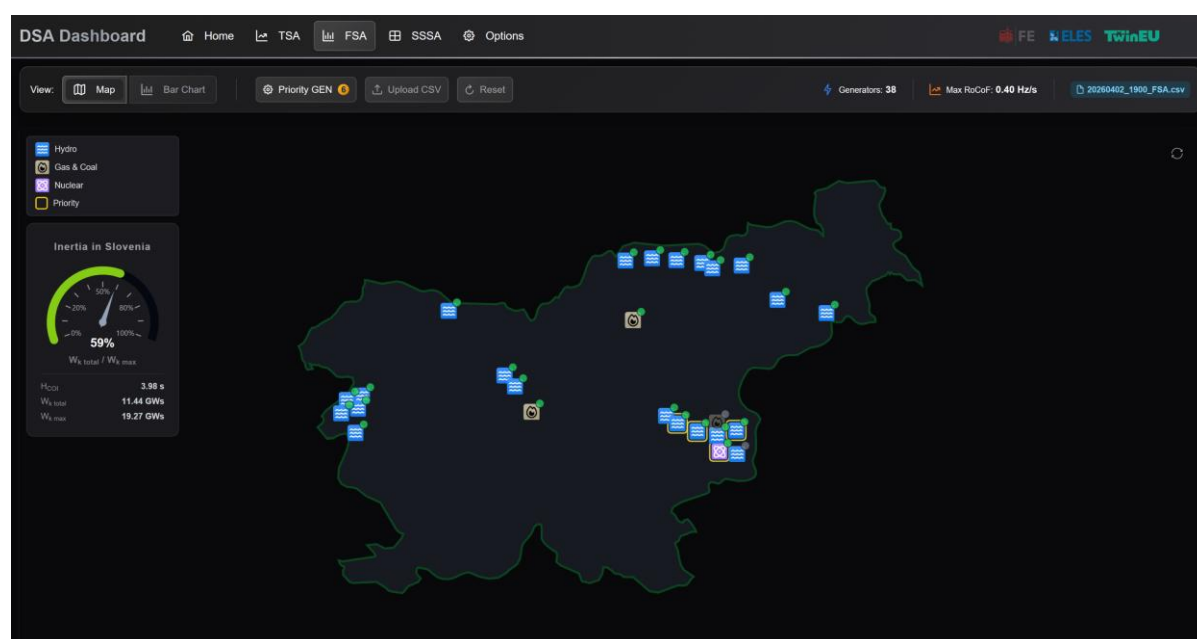


Figure 3.104 Study case #2 – FSA results (map chart)

The majority of the calculated critical clearing times are therefore located in the range between 150 ms and 600 ms. Although none of the evaluated contingencies produce CCT values below the critical 150 ms threshold, the overall picture is noticeably less favourable than in Study Case #1. From a technical perspective, the system remains secure; however, the reduced stability margins justify increased operator awareness. Further increases in generator loading or unfavourable changes in reactive-power operating points could significantly reduce the available transient stability reserve. In

particular, increased reactive-power absorption by individual generators could rapidly decrease critical clearing times and potentially push some contingencies below the 150 ms threshold, triggering operational concern and the need for preventive corrective actions (such a case is extensively shown in Section 3.6.3).

The larger number of online generating units also results in a substantial increase in the total inertia available within the Slovenian power system. As illustrated in Figure 3.104, nearly 60% of the maximum available rotational kinetic energy is present in the system, representing a significant increase compared to the night-time operating condition. At first sight, the equivalent inertia constant H_{COI} may appear lower than in the previous case. This apparent contradiction arises because H_{COI} represents normalized kinetic energy, calculated with respect to the total installed capacity of all generators contributing inertia. Consequently, comparisons of H_{COI} between different operating conditions must be interpreted carefully.

To avoid potential ambiguity, the visualization developed within the DSA framework primarily emphasizes the share of the total available rotational kinetic energy rather than the H_{COI} value itself. Nevertheless, H_{COI} remains an important metric from the perspective of ENTSO-E operational requirements, as future inertia-related requirements are expected to be expressed in terms of equivalent inertia constants at the national level.

The geographical distribution of operating generators shown in Figure 3.104 clearly reflects the increased generation activity across the Slovenian power system. Despite the substantial increase in available inertia, the maximum observed RoCoF values shown in Figure 3.105 do not change significantly compared to the previous operating state. This indicates that the benefits of higher inertia are partially offset by the larger generation outages that must be considered under high-generation operating conditions.

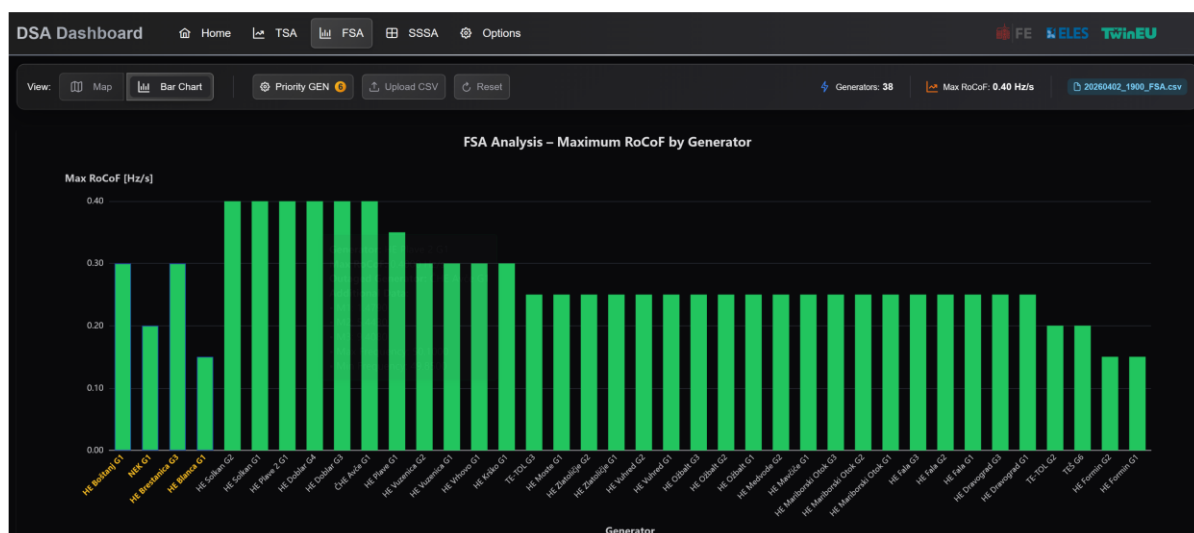


Figure 3.105 Study case #2 – FSA results (bar chart)

The most significant differences between the two operating states become visible in the small-signal stability assessment results (Figure 3.106 and Figure 3.107). The larger number of operating synchronous machines naturally results in a greater number of electromechanical oscillatory modes with meaningful participation of Slovenian generating units. For the selected participation threshold of 40%, fourteen oscillatory modes are identified in the analysed operating state. Most of these modes exhibit satisfactory damping characteristics. However, two modes stand out as potentially

problematic. Mode 2 exhibits a relative damping ratio of approximately 2.1%, while Mode 3 reaches approximately 2.6%. Both values fall below the recommended 3% threshold and therefore warrant additional attention. Based on their corresponding oscillation frequencies, both modes can be classified as local electromechanical oscillations, involving individual power plants or synchronous machines oscillating against the remainder of the interconnected system. The remaining identified modes exhibit significantly higher damping ratios and can therefore be considered adequately damped. Furthermore, Slovenian generating units participate only marginally in most of these oscillations, indicating that the dominant dynamics are associated with broader regional interactions.

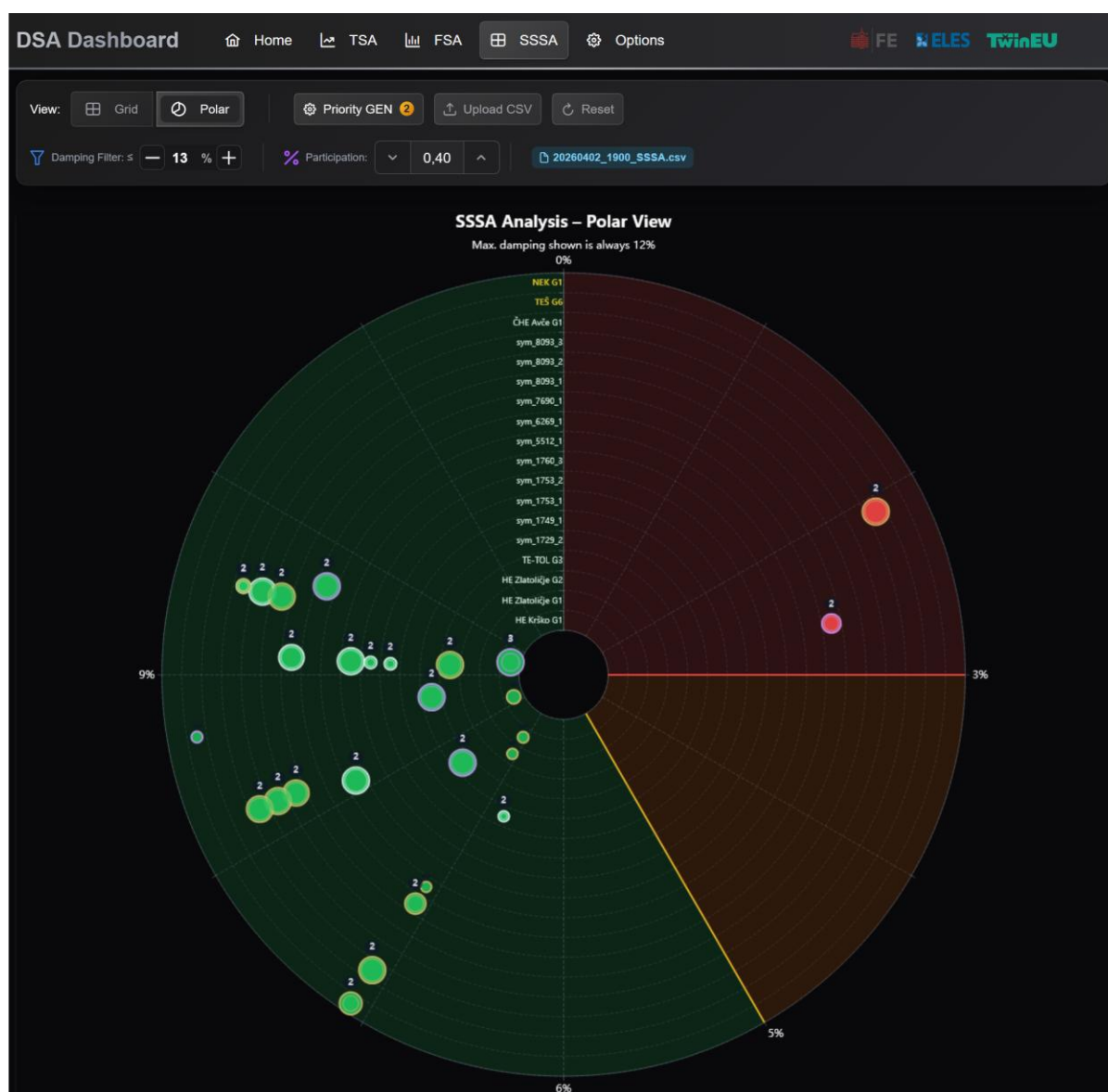


Figure 3.106 Study case #2 - SSSA results (polar chart)

Overall, the analysed daytime operating condition exhibits lower stability margins than the night-time scenario presented in Section 3.6.1. The reduction is most apparent in the transient stability results, where the available critical clearing times are noticeably lower, and in the small-signal stability assessment, where two poorly damped local oscillatory modes have been identified. Although all remaining stability indicators remain within acceptable operational limits, the results suggest that particular attention should be devoted to maintaining adequate reactive-power operating conditions

and to monitoring oscillatory phenomena in the frequency range between approximately 1.1 Hz and 1.7 Hz, where the least damped modes were observed.

3.6.3 Study case #3, detected operational issue

Unlike the first two study cases (presented in sections 3.6.1 and 3.6.2), which focused on the assessment of individual operating states, the third study case demonstrates what can be considered a significant step forward in the practical application of dynamic security assessment. While the calculation of stability indices for a single operating point is valuable in itself, substantially greater operational insight can be obtained by continuously tracking the evolution of those indices over time.

The ability to observe stability margins across a sequence of operating states enables the identification of trends, recurring operating patterns, and gradual deterioration of system security. Such information can reveal operating practices that repeatedly lead to reduced stability margins and can support the development of preventive or corrective remedial actions before critical conditions are reached. For this reason, the third study case focuses on a time series of operating states rather than on a single network snapshot.

Since the quality of the digital twin initialization was extensively demonstrated in the previous study cases (sections 3.6.1 and 3.6.2), the analysis presented in this section focuses exclusively on the dynamic security assessment results. The validity of the steady-state reconstruction is therefore assumed and is not discussed further.

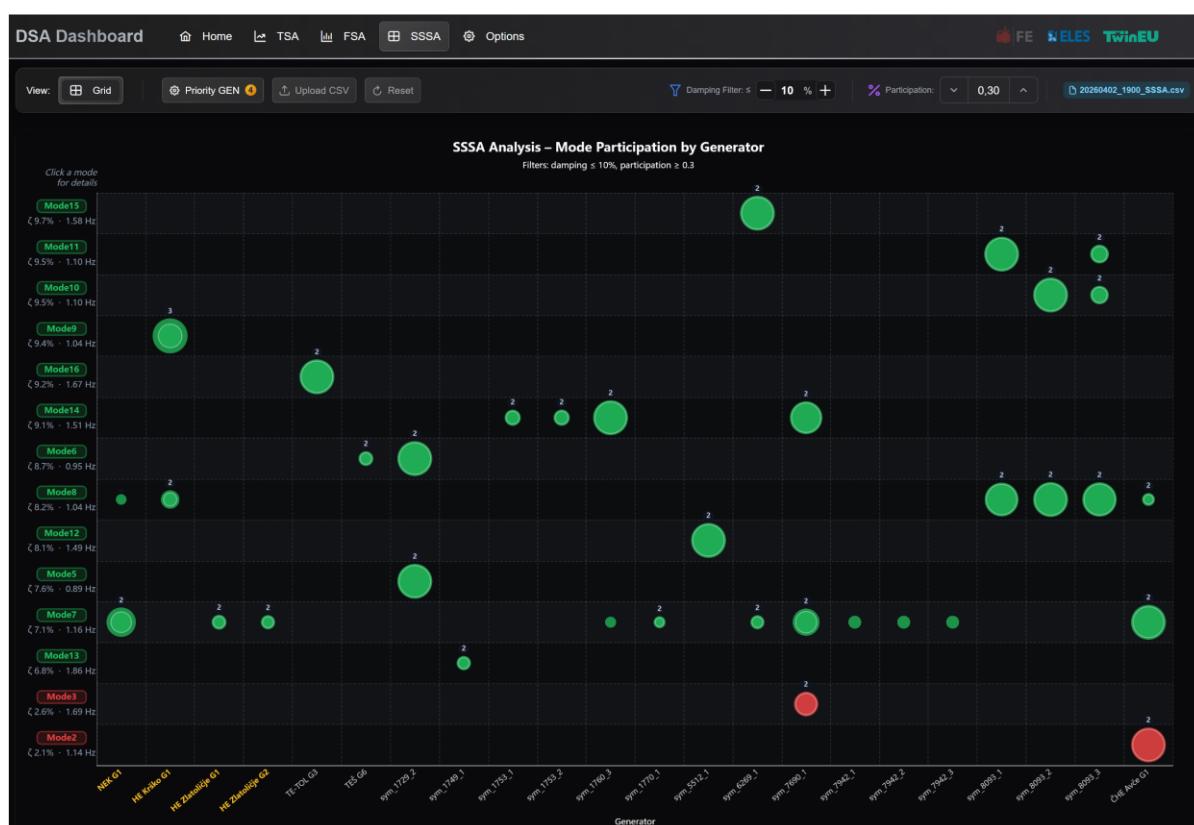


Figure 3.107 Study case #2 - SSSA results (grid chart)

To evaluate the performance and practical usefulness of the DSA framework, a sequence of operating states from the Slovenian power system between 25 November and 2 December 2024 was analysed. The selected dataset covers a representative range of operating conditions and includes

both working-day and weekend operation. The recordings were sampled at one-hour intervals, with the operating state corresponding to 15 minutes after each full hour being selected for analysis. This approach was adopted because major market-driven generation redispatch actions are typically completed by that time, resulting in a more representative and stable operating condition.

For confidentiality and security reasons, all network elements, generating units, transmission lines, and associated operating data presented in the following discussion have been anonymized. This anonymization was intentionally applied due to the critical nature of electric power systems infrastructure. The presented analyses are based on real operating conditions and include information related to system stability margins, critical contingencies, and potential vulnerabilities of the transmission network. Public disclosure of the identities and locations of specific generating units, transmission lines, or substations associated with reduced stability margins could reveal sensitive information about the operation of the national power system. For this reason, all references to network elements have been replaced by generic identifiers. This approach preserves the technical value of the presented results and conclusions while ensuring that potentially sensitive information related to the security and resilience of critical national infrastructure remains protected. The anonymization does not affect the interpretation of the presented analyses, as the objective of the study is to demonstrate the capabilities of the DSA framework rather than to disclose operational details of specific power-system assets.

Among all analysed results, the most interesting observations were associated with generator GEN_{54} and a three-phase fault applied on transmission line 44 in the electrical vicinity of the machine. Figure 3.108 presents the evolution of the corresponding critical clearing time (depicted in blue) together with the active (depicted in green) and reactive (depicted in orange) power output of GEN_{54} . With the red dashed horizontal line a limit of 150 ms is depicted, corresponding to a maximum expected time delay of the fault clearing by first zone of the distance protection. In the light of this, two operating states exhibiting particularly low transient stability margins were identified on 29 November at 23:15 and on 30 November at 06:15. In both cases, the critical clearing time decreased to approximately 150 ms, which is deemed very critical.

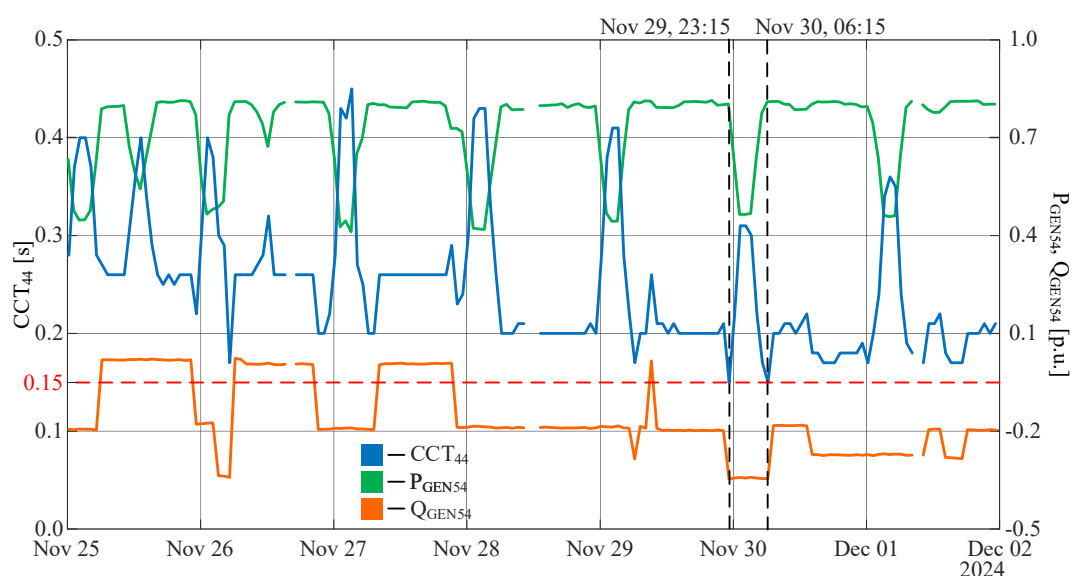


Figure 3.108 Study case #3 - evolution of the corresponding critical clearing time together with the active and reactive power output of GEN_{54}

This 150 ms value is particularly important because it corresponds to the upper limit of the required operating time of the first zone of distance protection, including an appropriate engineering margin. Consequently, any further reduction of the transient stability margin would imply that loss of synchronism could occur before the fault is cleared by the primary protection system.

To better understand the origin of these reduced stability margins, the active and reactive power output of GEN₅₄ were analysed alongside the calculated critical clearing times. A strong correlation between generator operating conditions and transient stability margins can be observed. The results indicate that the lowest CCT values coincide with operating conditions characterized by high active-power production combined with significant reactive-power absorption (under-excited mode of operation in the terminology of synchronous machines).

The operating state recorded on 29 November at 23:15 was investigated in greater detail. At that time, GEN₅₄ was operating at its scheduled maximum active-power output while simultaneously absorbing a considerable amount of reactive power in order to support the local voltage profile. This operating regime corresponds to underexcited operation and was found to significantly reduce the transient stability margin of the machine.

To assess potential corrective actions, a sensitivity study was performed by varying the reactive-power setpoint of GEN₅₄ while maintaining the remaining operating conditions unchanged. The results are presented in Figure 3.109. A clear improvement in the critical clearing time can be observed as the amount of absorbed reactive power is reduced. This demonstrates that generator reactive-power dispatch can have a substantial influence on transient stability and can therefore be used as an effective remedial action.

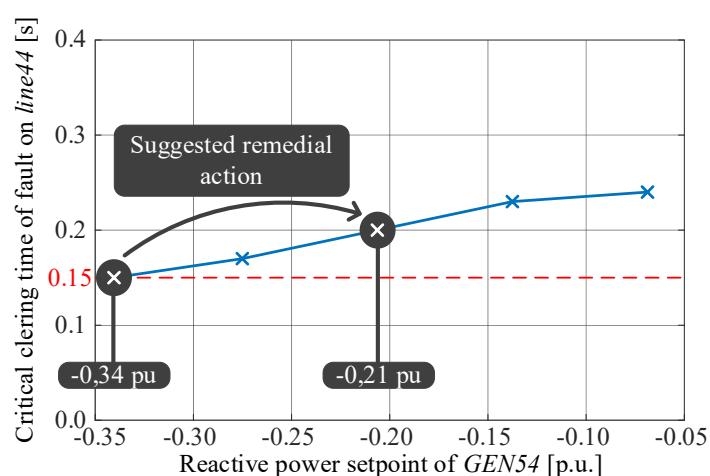


Figure 3.109 Study case #3 - The critical clearing times for the fault on line44 for different setpoints of reactive power of generator GEN₅₄.

The analysis showed that a reactive-power setpoint of approximately 0.21 p.u. represents a suitable compromise. Under this operating condition, the generator continues to contribute to local voltage support while simultaneously providing a significantly improved transient stability margin. It should be noted, however, that reducing reactive-power absorption at GEN₅₄ may require additional voltage-support resources elsewhere in the vicinity in order to maintain acceptable voltage levels.

This example clearly demonstrates one of the main benefits of dynamic security assessment. Rather than merely identifying critical operating conditions, the DSA framework can provide valuable insight into the underlying causes of reduced stability margins and support the identification of

practical corrective actions. In this case, the analysis revealed a direct relationship between generator reactive-power operation and transient stability performance, allowing a specific operational measure to be proposed.

Figure 3.110 presents an example of the operator-oriented visualization used by the DSA dashboard for the critical operating state observed on 29 November at 23:15. The horizontal axis lists generating units that are identified as critical for at least one analysed contingency, while the vertical axis represents the corresponding critical clearing times. Multiple stability margins may be associated with a single generator because different fault locations can affect the same machine in different ways.



Figure 3.110 Study case #3 - Graphical representation of power system transient stability for 29 November at 23:15.

For each generating unit, the most critical contingency is highlighted using the traffic-light colour scheme introduced earlier in this deliverable, while the remaining contingencies are shown using blue markers. By selecting or hovering over a particular result, operators can access detailed information about the corresponding contingency scenario. In the example shown, the dashboard highlights the previously discussed fault on line 44 and clearly indicates that corrective actions related to the operating conditions of GEN₅₄ or equipment in its electrical vicinity could improve overall system security.

The presented results demonstrate that the DSA framework is capable not only of identifying critical operating conditions but also of continuously tracking the evolution of stability margins over time, detecting emerging trends, and supporting operators in the development of targeted remedial actions. This capability represents a significant advancement beyond traditional offline stability studies and illustrates the practical value of dynamic security assessment in future operational environments.

4 Conclusions

This deliverable presented the development and validation of the Slovenian TwinEU demonstrator for real-time dynamic security assessment based on digital twin technology. The work addressed the complete workflow required for operational deployment, including digital twin creation, integration of transmission and distribution network models, automated model initialization and validation, dynamic security assessment, AI-assisted acceleration techniques, and intuitive visualization of stability indicators for transmission system operators.

Particular emphasis was placed on automation and operational applicability. The developed framework demonstrates that complex dynamic security analyses can be performed in a near real-time environment using actual SCADA/EMS operating data while maintaining the level of accuracy and reliability required for operational decision support. The performed study cases further confirmed the capability of the framework to detect changes in system stability margins, identify potentially critical operating conditions, and provide actionable information to control room operators.

The main achievements of the work can be summarized as follows:

- Within the TwinEU Slovenian demonstrator, a comprehensive digital twin of the Slovenian power system was successfully developed, integrating the national transmission network, the observability area, and aggregated dynamic representations of the distribution system.
- The developed methodology demonstrated that distribution networks can no longer be represented solely by constant PQ equivalents when performing dynamic security assessments. The inclusion of voltage- and frequency-dependent load models significantly improves the realism of dynamic simulations.
- A practical methodology for creating CIM/CGMES-compatible dynamic distribution equivalents was developed, enabling automated integration of distribution-system representations into transmission-level studies.
- The developed DSA framework successfully combines real-time SCADA/EMS data, dynamic simulation models, and automated processing procedures into a unified assessment platform capable of continuously evaluating system stability.
- Three complementary stability domains were addressed within a single framework: transient stability, frequency stability, and small-signal stability. This enables operators to assess multiple aspects of system security simultaneously rather than relying on isolated studies.
- Extensive automation was achieved throughout the workflow, including model preparation, topology processing, static validation, contingency generation, dynamic simulations, and visualization of results. This substantially reduces the engineering effort required for routine stability assessments.
- The application of parallel processing techniques and artificial-intelligence-assisted screening significantly reduced overall calculation times while preserving the accuracy required for operational use. The proposed hybrid approach represents an important step toward near real-time dynamic security assessment.
- Validation against real operating conditions demonstrated that the digital twin reproduces actual system behaviour with a high level of accuracy, providing confidence in the calculated stability indices and identified operational risks.

- The developed visualization environment successfully translates complex simulation outputs into intuitive stability indicators suitable for control-room personnel, reducing the gap between advanced dynamic simulations and practical operational decision-making.
- The demonstrator confirmed the operational value of dynamic security assessment by identifying operating conditions with reduced stability margins and by enabling the evaluation of remedial actions before actual system security limits are violated.
- The study cases showed that system stability margins vary significantly between different operating conditions. Night-time operation exhibited lower inertia but favourable transient stability margins, while heavily loaded daytime operation resulted in lower transient stability reserves and increased sensitivity to oscillatory phenomena.
- The time-series analysis of stability indices demonstrated that dynamic security assessment should not be limited to single operating snapshots. Monitoring the evolution of stability indicators over time enables the identification of trends, recurring operational patterns, and emerging risks that would otherwise remain unnoticed.
- The TwinEU federated data exchange concept was successfully demonstrated through the exchange and utilisation of dynamic generator data from neighbouring TSOs, confirming the feasibility and practical value of cross-border dynamic model sharing for interconnected European power systems.

The work presented in this deliverable establishes a solid foundation for the operational deployment of digital twin technologies and dynamic security assessment within transmission system operation. Nevertheless, several research and development directions have been identified during the project that could further improve both the accuracy of the digital twin and the operational value of the developed DSA framework. The most important development directions identified during the project are summarized below:

- Extension of dynamic modelling capabilities for converter-dominated resources and grid-forming technologies.
- Expansion of dynamic data exchange to a larger number of neighbouring TSOs.
- Integration of PMU measurements directly into model calibration and dynamic validation procedures.
- Further development of AI-assisted stability assessment methods with explainable and operator-trustworthy decision support.
- Automated and Dynamic Parametrization of External Network Equivalents.

Overall, the developed Slovenian demonstrator has successfully validated the feasibility of integrating digital twin technology into the operational environment of a transmission system operator. Beyond the individual technical developments presented throughout this deliverable, the project established a modular and extensible framework that can continuously evolve alongside future power-system requirements. The experience gained within TwinEU provides a strong basis for further research, wider deployment across Europe, and the gradual transition towards digital-twin-based operation of future power systems.

References

- [1] IEC 61970-600-1 Energy management system application program interface (EMS-API) - Part 600-1: Common Grid Model Exchange Standard (CGMES) - Structure and rules, 2021.
- [2] Energy management system application program interface (EMS-API) - Part 552: CIMXML Model exchange format, IEC 61970-552, 2016.
- [3] J. Milanović et al., "International Industry Practice on Power System Load Modeling," IEEE Trans. POWER Syst., vol. 28., no. 3., Aug. 2013. DOI: 10.1109/TPWRS.2012.2231969 [Online]. Available: <https://ieeexplore.ieee.org/document/6399552>
- [4] L. M. Korunović, D. P. Stojanović, and J. V. Milanović, 'Identification of static load characteristics based on measurements in medium-voltage distribution network', IET Gener. Transm. Distrib., vol. 2, no. 2, pp. 227–234, Mar. 2008. Online]. Available: <https://doi.org/10.1049/iet-gtd:20070091>