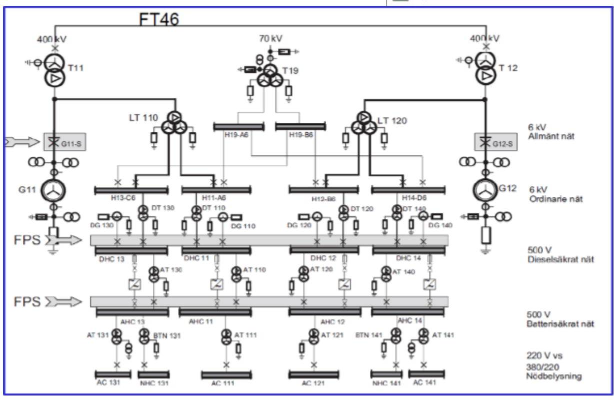
RESEARCH REPORT



SINARP -The Safe Interaction of Nuclear with a Renewable Rich Power System

D2.3.1 Report on co-simulations

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Confidentiality: Public

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beyond the obvious

1. Introduction

The COSI platform [1] [2] [3] developed in MATLAB, provides a co-simulation environment for nuclear power plants (NPPs) and their connection to on-site and off-site electricity grids. It integrates thermodynamical simulation (Apros) with electricity grid modelling (Simulink/Simscape), addressing the limitations of traditional "black-box" approaches that oversimplify NPPs and grids in integration studies and vice versa. NPPs are essential for stable baseload power and integrating intermittent resources, but their safety must be ensured, especially in light of potential grid faults caused by climate conditions and reduced grid inertia due to increased penetration of renewable energy resources. The previous work focused on co-simulating fault events in the on-site and off-site electrical systems of a nuclear power plant [4] [5]. This year, the scope was expanded with the introduction of new scenarios and enhancements to the transmission grid model [6] [7].

The SINARP project builds on COSI by enhancing the transmission system model and preserving electrical co-simulation in Simulink (excluding PowerFactory [1]). The co-simulation of both NPP generators represents a shift from earlier methods. Challenges with data logging and resolution were addressed through data decimation, resolution adjustments, and result capture within the Apros environment.

The report is organized as follows: Section 2 discusses the improvements made to the co-simulation approach. Section 3 outlines the scenarios under consideration. Section 4 presents the co-simulation results, and Section 5 provides a discussion and summary of the findings.

2. COSI platform improvements

The co-simulation approach required addressing three key aspects: doubling of the generators, frequency measurement, and initialization files.

The developed NPP model in Apros includes two generators. However, in order to co-simulate both Loviisa generation blocks with a single NPP model representing both blocks in the transmission system, a workaround was necessary.The Loviisa node consists of two generation blocks, referred to as *Loviisa_1* and *Loviisa_2*, which are modeled exclusively in Simulink. The NPP generators, each rated at 280 MVA, are denoted as *SP10G and SP50G*. The transmission system model expects a total generation of 2x507 MW at the Loviisa node. To maintain stability in the co-simulation, a separate control loop for Loviisa_2 was not feasible, as it caused instability when interacting with the grid stabilizers. Consequently, a workaround was implemented to match the required power levels.

Figure 1 illustrates an excerpt from *Loviisa_1* block. *St.SP10G_Pmech* represents the mechanical power calculated in Apros. After each simulation step, this value is transferred to Simulink and serves as the input for both generators. Both generators have independent control loops, where the stator voltage, rotor speed deviation, and stator voltage are measured and used for excitation voltage control. This control process continues until the next timestep in Apros. Similarly, *St.SP50G* was implemented in *Loviisa_2* block.

Note: The addition of reading the voltage from Apros *(St.SP10G_V)* in the previous year, as shown in Figure 1, did not result in any significant deviation from simply setting the reference value to 1.

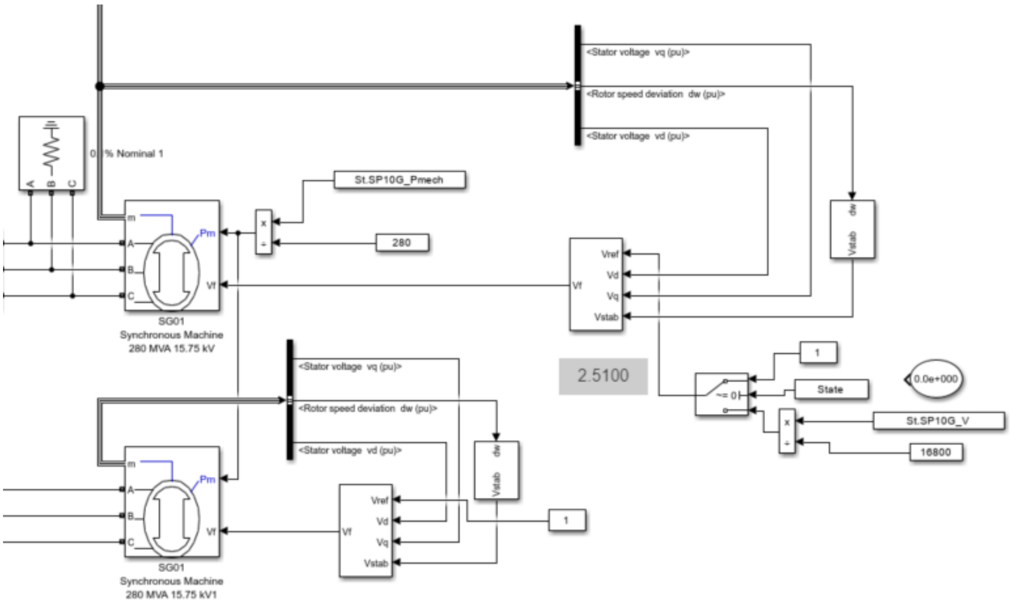

Figure 1: Generator control loop.

Upon review of the grid model, it was confirmed that the network and generators are operating correctly, with no issues in their functionality. However, it was identified that the method used to measure the system frequency was introducing discrepancies (Figure 2). The Phase-Locked Loop (PLL) method, while commonly used, caused transient dynamics, particularly during startup or switching events, as the PLL adjusted to lock onto the grid voltage phase. These dynamics resulted in overshoots, undershoots, or lag in the frequency estimation. To address this, the generator shaft speed was used directly to measure the system frequency, providing a more accurate and stable representation, particularly for analyzing frequency dynamics such as Rate of Change of Frequency (RoCoF) and nadir points. This modification eliminated the additional dynamics introduced by the PLL, ensuring a more precise frequency measurement for system analysis.

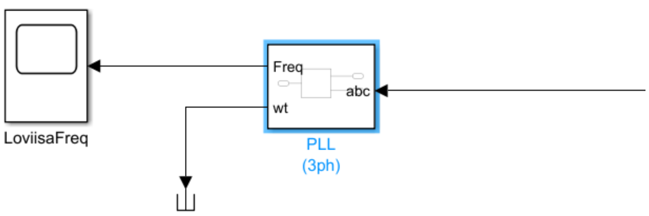

Figure 2: Faulty PLL frequency measurement method.

The implementation of *ScenarioChooser.m* and *ParameterSetting.m*, along with the previous initialization files, was integrated into the main script. This update simplified the co-simulation procedure and streamlined the workflow. In this iteration, the co-simulation focused exclusively on the generators. While the entire NPP plant was simulated in APROS, previous years' co-simulations included both generators and several pumps. However, last year's co-simulation of the pumps did not yield significant results, and improvements to the on-site electric grid on the Simulink side were not achieved. Given these factors, the decision was made to focus solely on the co-simulation of generators. This means that signal exchange was limited to generator measurements and parameters, which were exchanged between APROS and Simulink at every co-simulation step (0.01s)

3. Grid scenario list

Three scenarios were used for co-simulations – 11, 12, and 13. Scenario 11 (Table 1) was carried out with an incomplete transmission system model with injected harmonics – 5th, 7th, 11th, and 13th. A separate simulation was carried out on subharmonics together with the 5th harmonic.

Scenarios 12 and 13 were carried out with a complete model and include a variety of measurements. Scenario 12 corresponds to high wind generation with summer loading conditions. Scenario 13 is a high-wind winter scenario, which includes higher generation and consumption, as seen in *Table 2*.

More details on the grid scenarios are provided in other deliverables (D1.1.2, D2.1.2)

Table 1: Harmonic per unit factors used in the scenario 11

Harmonic factor	Scenario Choice
	11
	Harmonics
FifthHarmonicPerUnit	0.035
SeventhHarmonicPerUnit	0.02
EleventhHarmonicPerUnit	0.0151
ThirteenthHarmonicPerUnit	0.015
LowestFreqSSHFAmplitudePerUnit (5.5 Hz)	0.0005
MiddleFreqSSHFAmplitudePerUnit (27 Hz)	0.0005

Table 2. Scale factors used in the scenarios 12 and 13

Scale factor	Scenario Choice	
	12	13
	High-wind summer	High-wind winter
windScaleFactor	0.65	0.9
synchScaleFactor	0.1	0.2
industrialSynchScaleFactor	0.1	0.8
urbanCHPscaleFactor	0.01	0.8
loadScaleFactor	0.5	1.0

More details on the grid scenarios are provided in other deliverables, but Scenario 12 is high wind in the summer, but with lots of wind curtailed, even assuming the HVDC is exporting power to Sweden. Scenario 13 is high wind in the winter. The contingency that both Scenarios 12 and 13 consider is Olkiluoto 3 tripping.

Table 3. Co-simulation parameters.

Parameter	Description	t [s]
CoSim.Ta	Apros timestep	0.01
CoSim.Ts	Simulink timestep	0.0005
CoSim.SteadyTime	Steady state pre-simulation duration	30
CoSim.Tend	Co-simulation end time	30

4. Co-simulation Results

4.1 Scenario 11

Scenario 11 co-simulations consist of two parts: harmonics and subharmonics. In the first part, a significant number of harmonics were injected into the grid. The second part of the co-simulation focused on the subharmonics, selected based on the natural oscillation frequencies of the turbine and the 5th harmonic.

The first part of co-simulations were compared with simulations conducted using Simulink-only and simulations without harmonics, as shown in Figure 3.

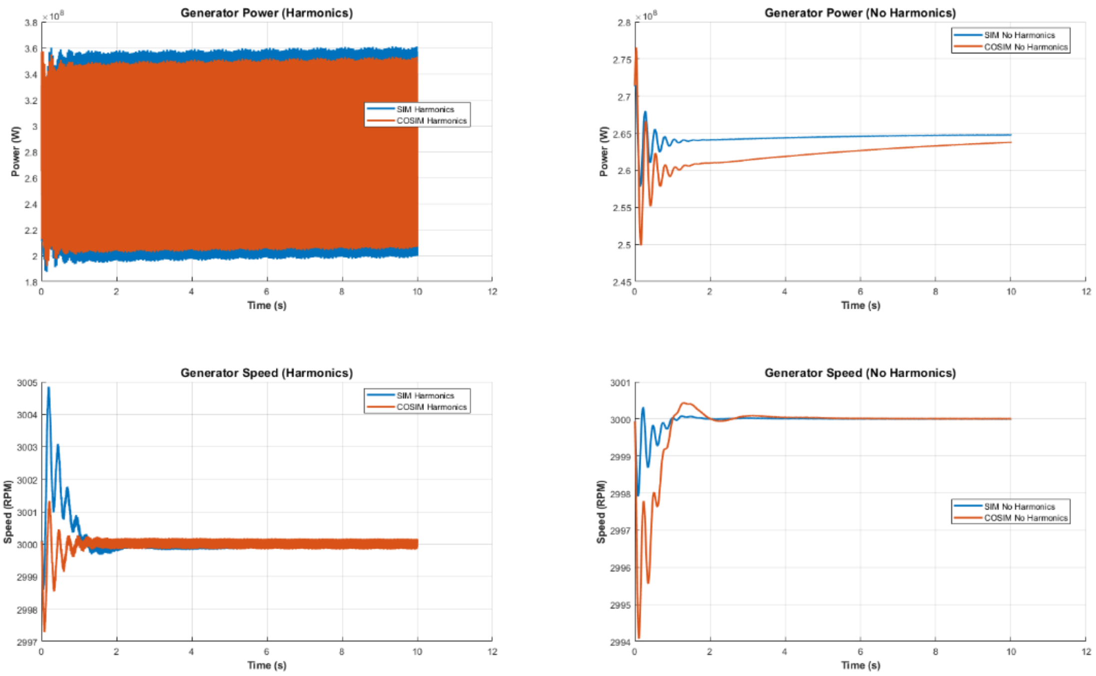

Figure 3: harmonics co-simulation results

Generator power and speed measurements are shown in the figure in the top left. The generator power oscillates significantly, which could lead to serious issues in the Nuclear Power Plant (NPP). The total harmonic distortion (THD) for this case is calculated as follows:

$$THD = \sqrt{V_5^2 + V_7^2 + V_{11}^2 + V_{13}^2} = \sqrt{0.035^2 + 0.02^2 + 0.015^2 + 0.015^2} = 0.0455 = 4.55\% \qquad \{1\}$$

This value exceeds the maximum allowable THD of 3%, as specified by Fingrid (*Table 4*)

Table 4: Power quality in the transmission network [8].

Not multiples of 3		Multiples of 3		Even harmonics	
n	%	n	%	n	%
5	3.0	3	3	2	1.0
7	2.5	9	1.3	4	0.7
11	1.7	15	0.5	6	0.5
13	1.7	21	0.5	>6	0.3
17	1.5	>21	0.3		
19	1.5				
23	0.8				
25	0.8				
>25	0.5				
Total harmonic distortion of voltage				< 3 %	

The results from the two generators are presented below. It appears that the first generator experiences a power drop approximately 2 seconds into the simulation, while the second generator remains unaffected. Both generators, however, exhibit a similar level of oscillation, which is less than 1 percent.

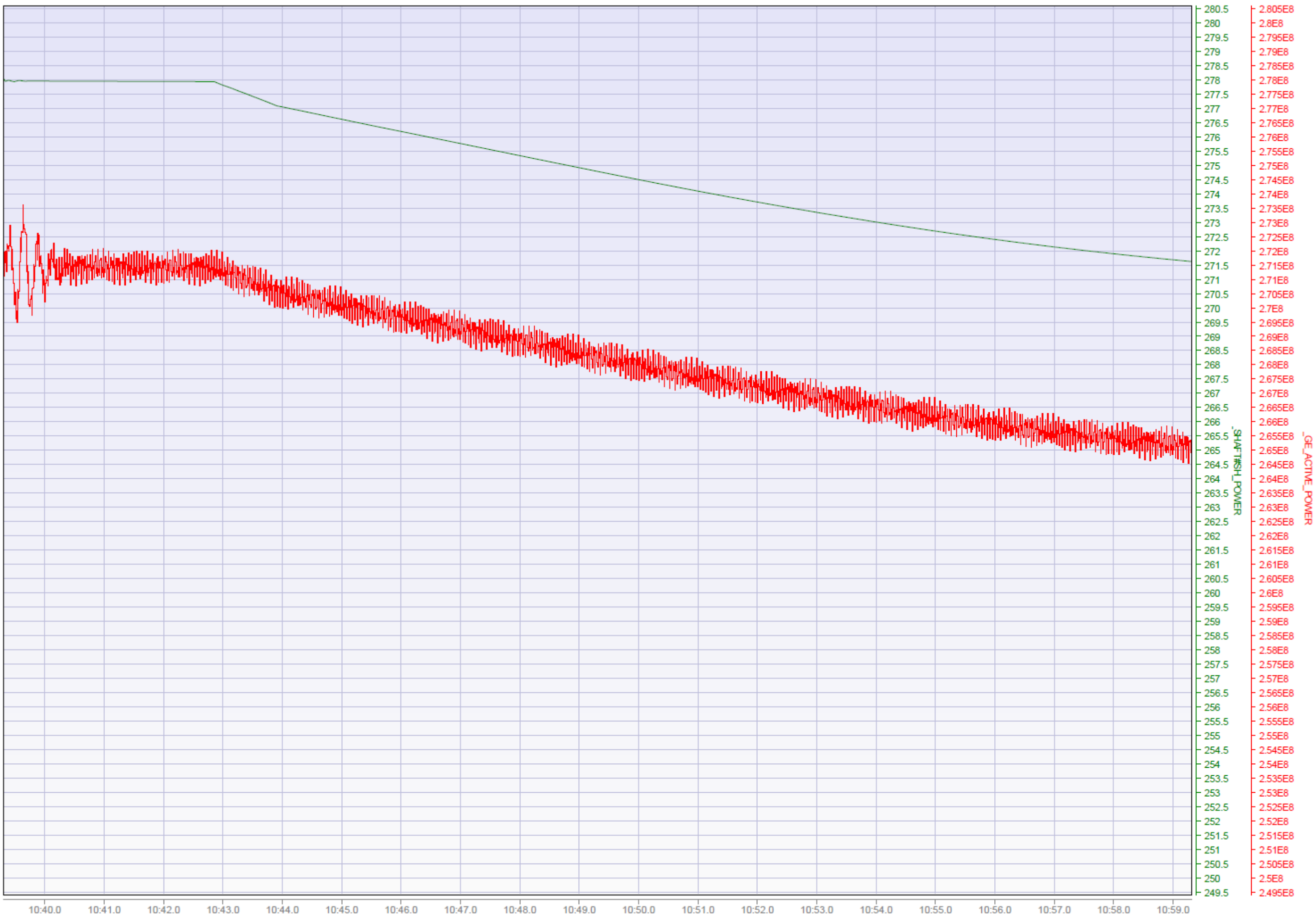

Figure 4: Scenario 11. Generator 1 shaft power and active power

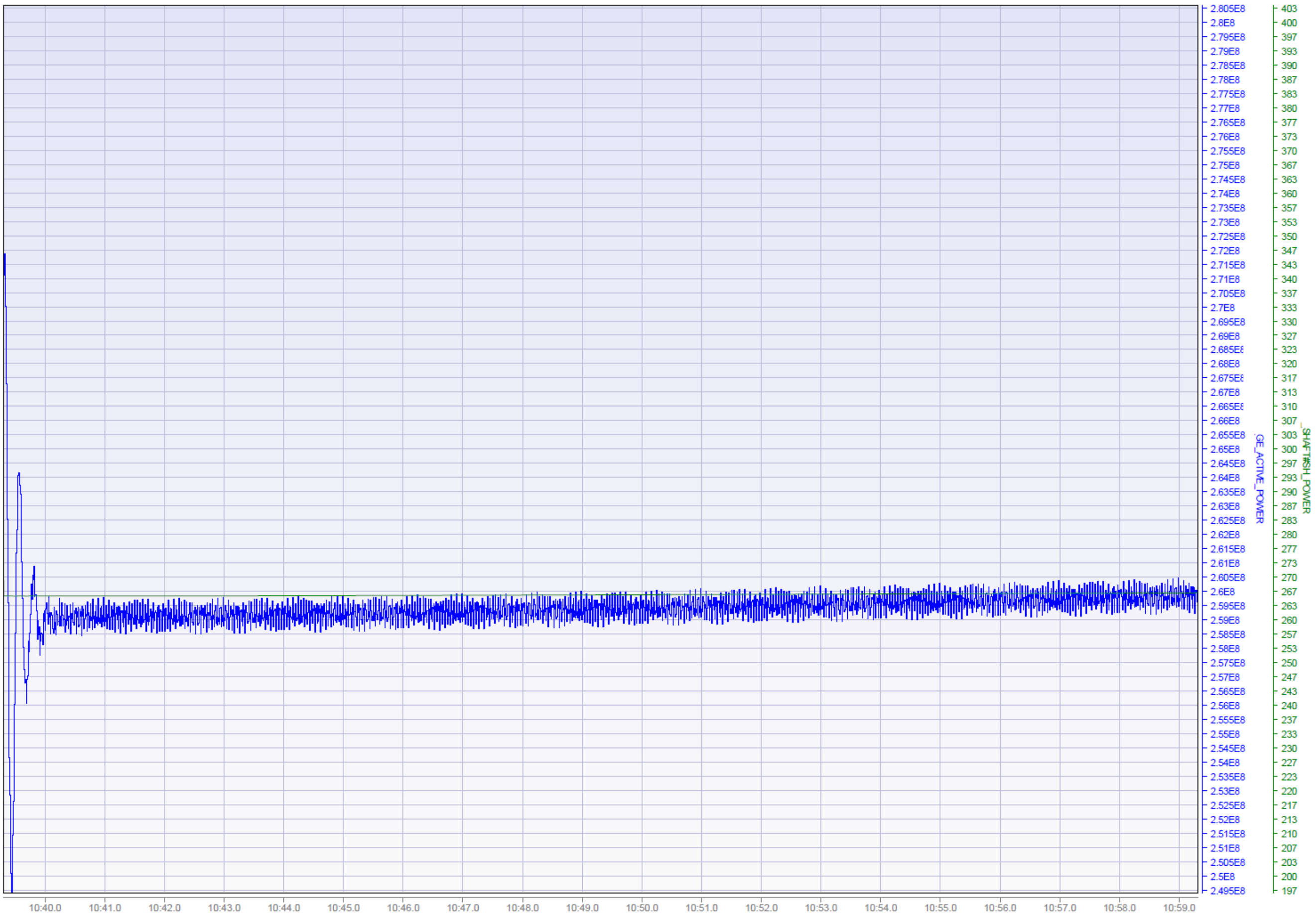

Figure 5: Scenario 11. Generator 2 shaft power and active power

The main process parameters are presented in Figure 6. For confidentiality reasons, the codes for pumps and other devices have been removed from the Y-axis, as they cannot be publicly disclosed. No specific conclusions are drawn from this dataset, as all values remain within expected operational limits, with no anomalies observed. Generic parameter names have been assigned while ensuring confidentiality. A thorough assessment of this relationship would require a more detailed understanding of nuclear power plant (NPP) behaviour.

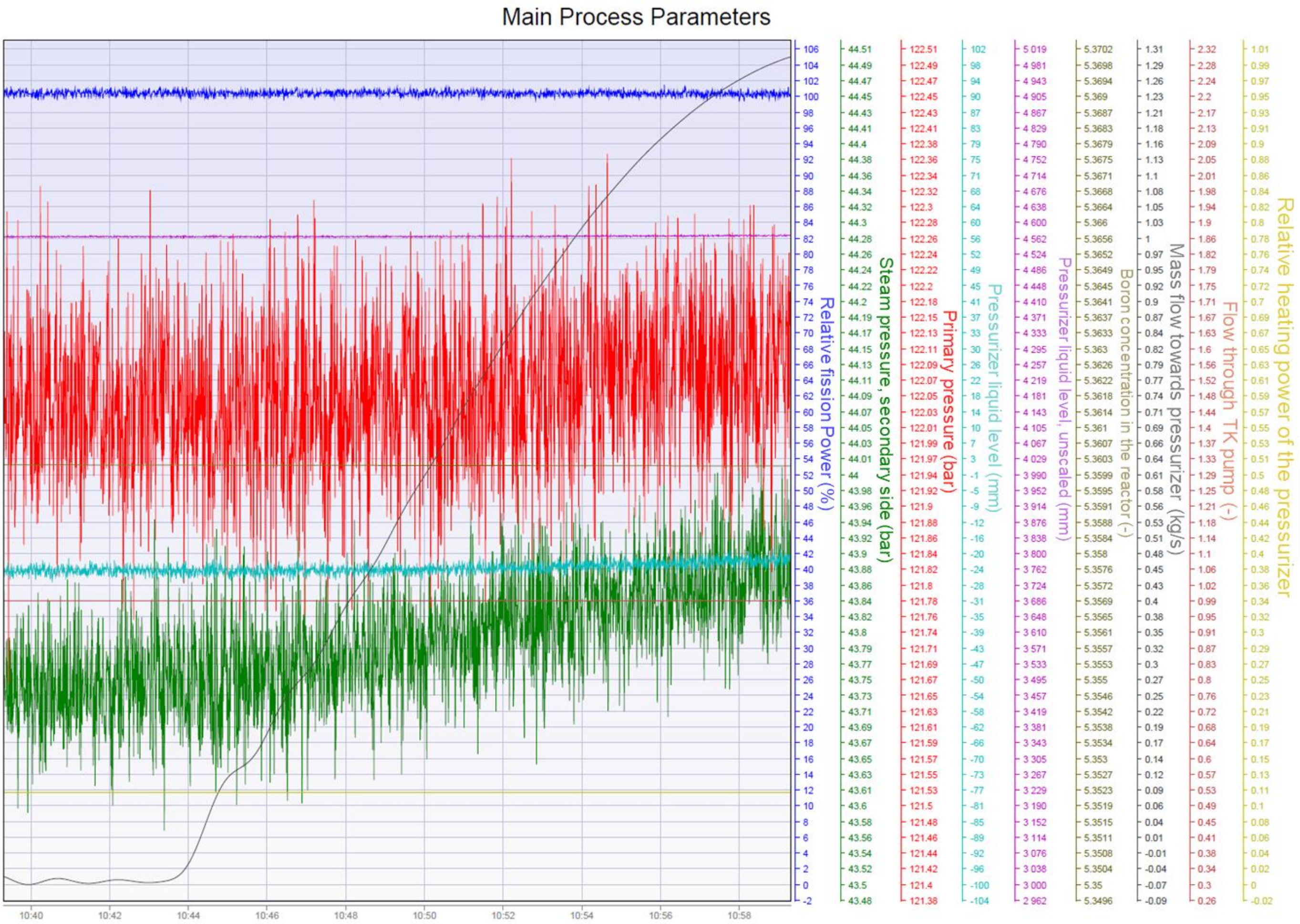

Figure 6: Scenario 11. Main parameters of NPP process.

4.2 Scenario 12

Below are all relevant measurements for Scenario 12. All co-simulations (COSIM) are compared with Simulink-only (SIM) simulation.

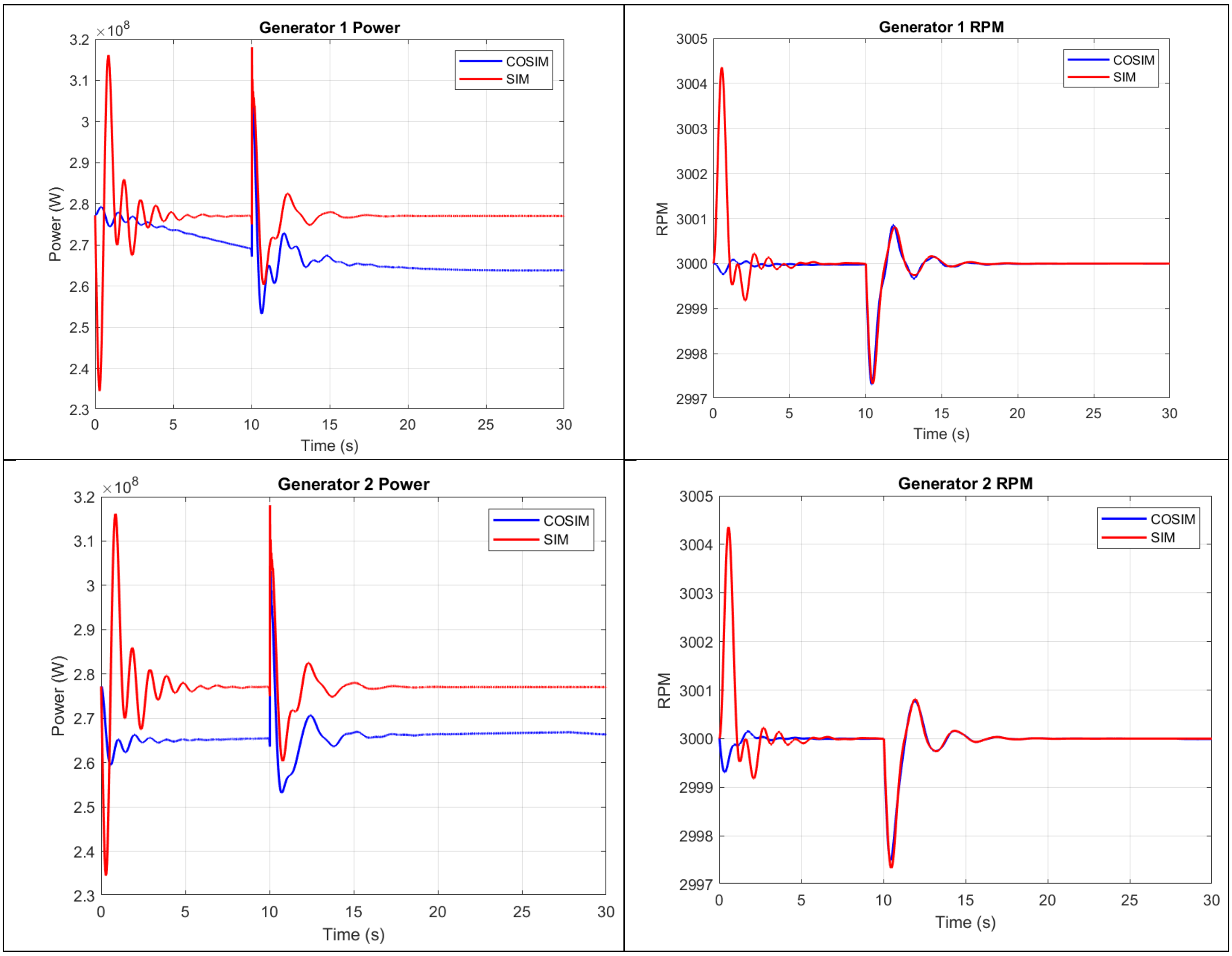

Figure 7: Scenario 12. RPMs and power of Generators

The initial power surge observed in Generators 1 and 2 during the Simulink-only simulation is noteworthy, despite the inclusion of a 30-second pre-simulation period intended to establish steady-state conditions. A possible explanation for this behaviour could be the difference between modelling approaches in both simulators, incorrect saving of initial conditions or an issue with the grid controller or stabilizer. Nevertheless, the transient behaviour subsides within approximately 5 seconds, and the power stabilizes by the time the trip occurs in Olkiluoto. Generator 1, however, takes longer to reach steady-state conditions. In contrast, the co-simulation does not exhibit this pronounced initial spike; however, its steady-state power output is lower than that of the Simulink-only simulation. The response to the disturbance is relatively similar in both cases.

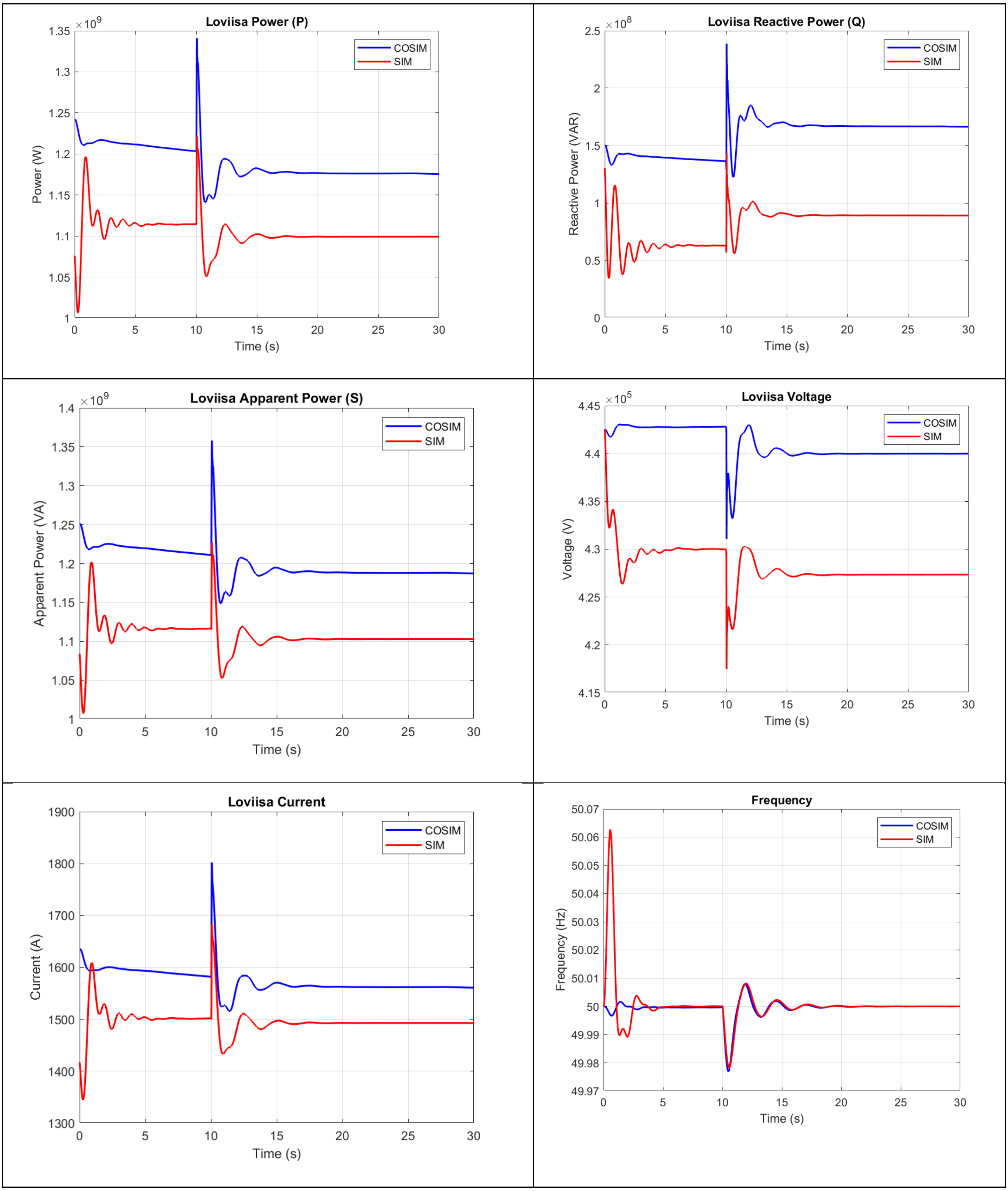

Figure 8: Scenario 12. Power, current and voltage measurements at Loviisa node. Frequency measurement

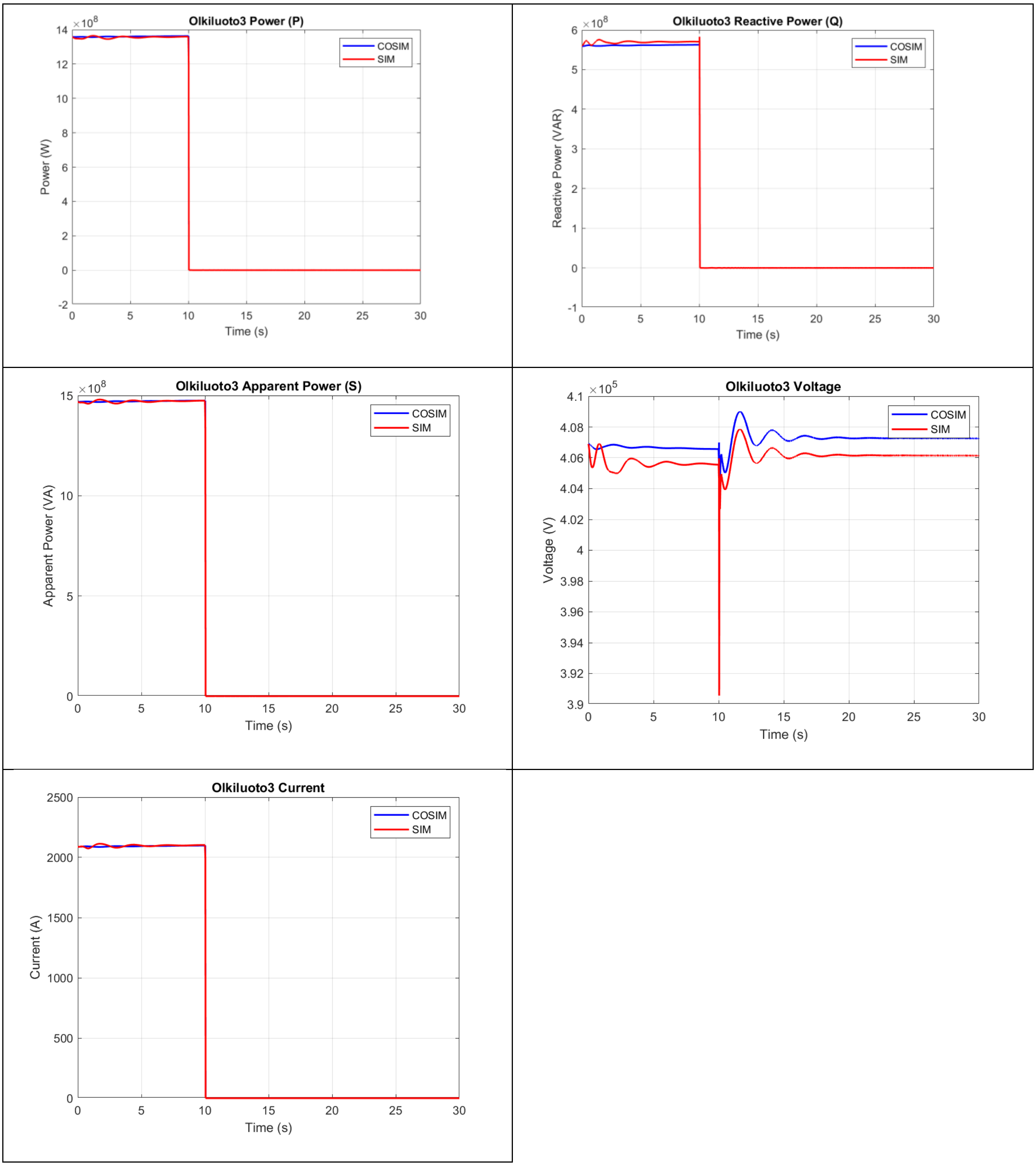

Figure 9: Scenario 12. Power, current and voltage measurements at Olkiluoto node.

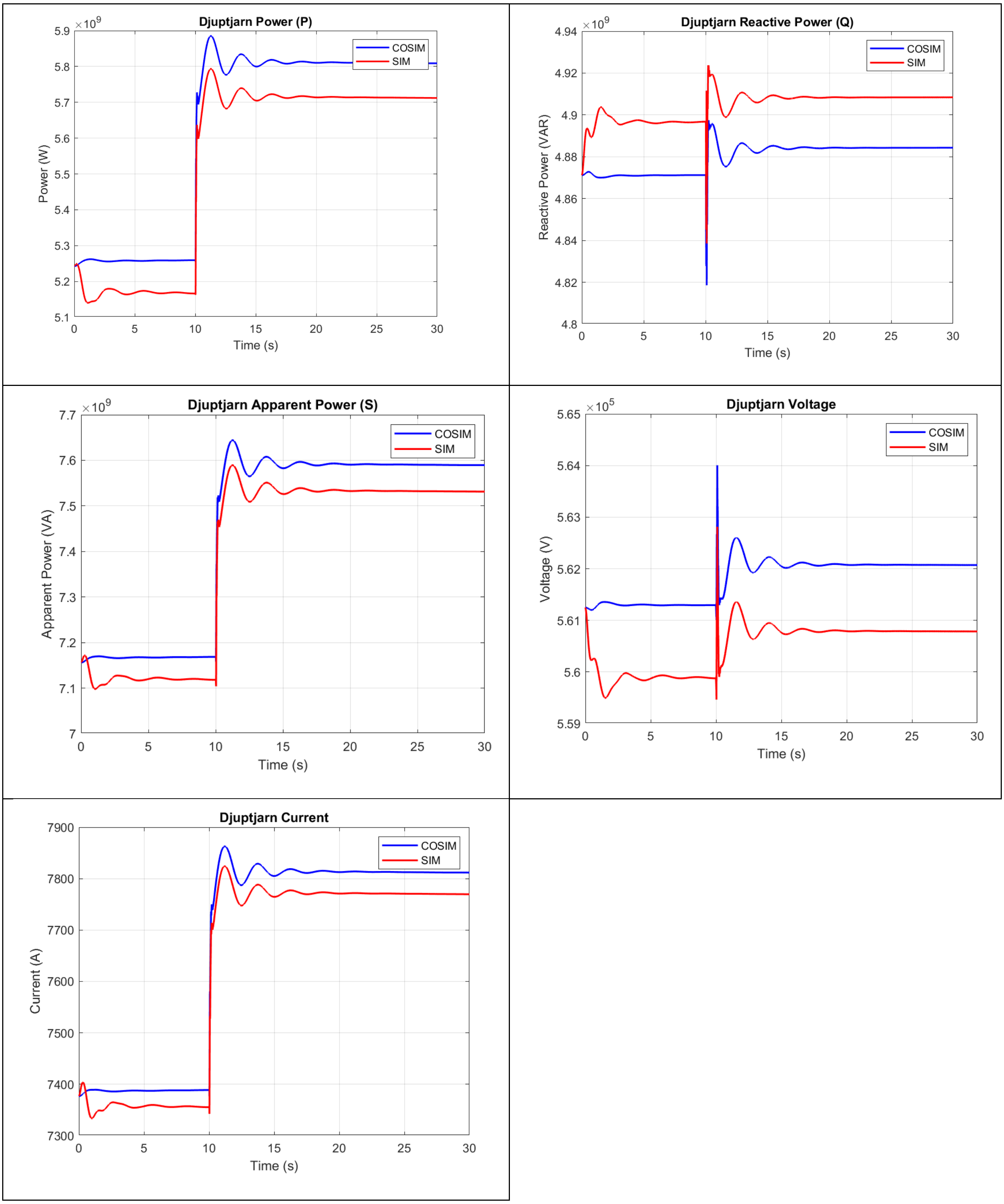

Figure 10: Scenario 12. Power, current and voltage measurements at Djuptjärn node

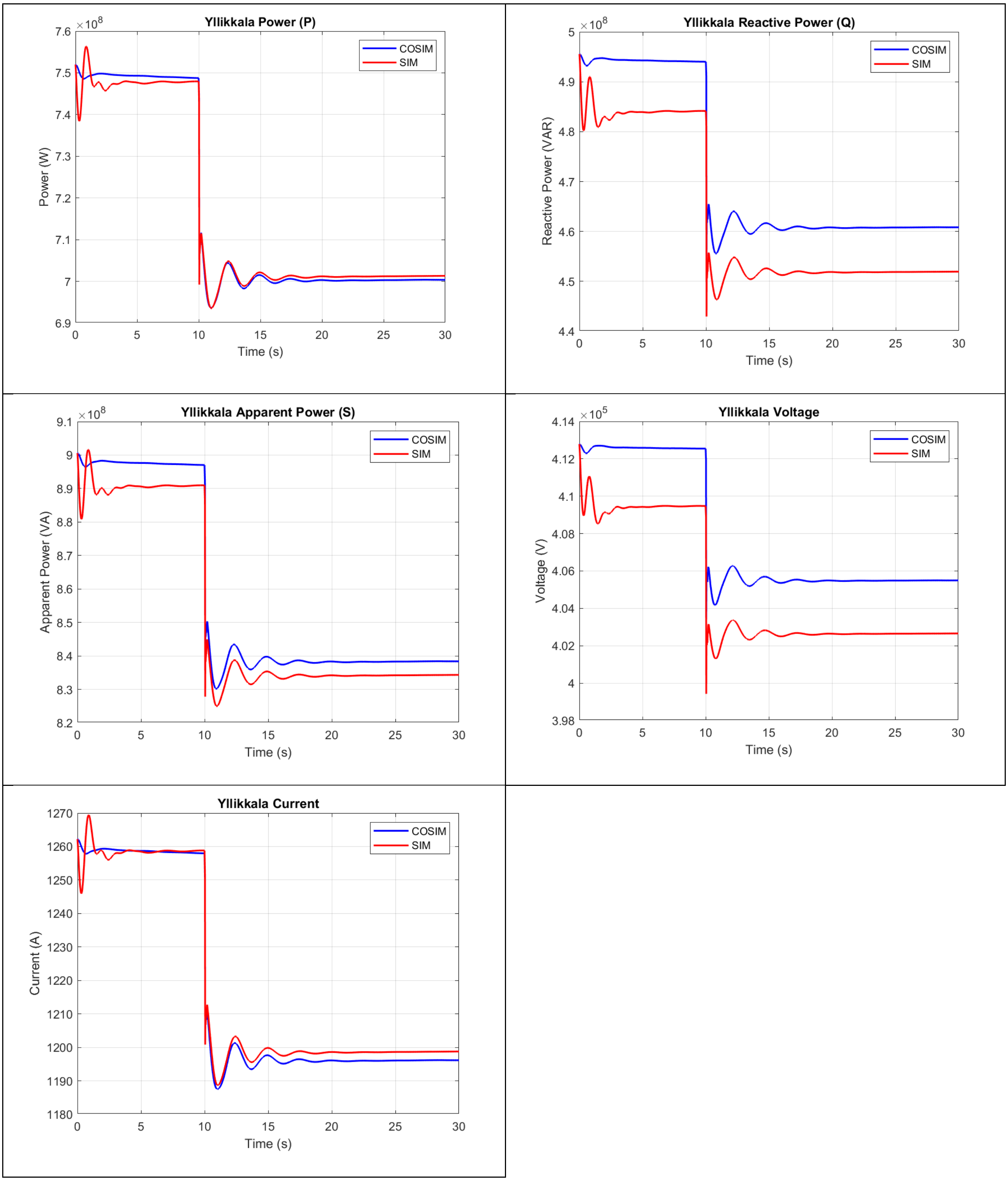

Figure 11: Scenario 12. Power, current and voltage measurements at Yllikkälä node

The power measurement discrepancies between the Simulink-only simulations and the co-simulations appear to stem from differences in the power output representation of the Loviisa NPP in each model. Until this year, the Apros model, coupled with the internal NPP electrical grid and generator models, was significantly underrated, leading to anomalous results in previous years' reports. To address this issue, the model was updated to closely align with Loviisa NPP's current rated output of 2 × 507 MW. These updates included the addition of two generators, as detailed in Section 2. However, the updated model still does not perfectly match the combined output of 1014 MW used in the standalone grid model for Loviisa. Moreover, the actual power output and connection point voltage during the co-simulations—critical parameters for accurate system behaviour—differ slightly from the 2 × 507 MW and 415 kV assumed in the grid-only model. These small discrepancies in one part of the grid or its model can propagate and have measurable impacts across the entire system.

The discrepancies are further exacerbated by differences in the actual power output and connection point voltage observed during co-simulations. The standalone grid model assumes a power output of 2 × 507 MW and a connection point voltage of 415 kV, but the co-simulations revealed the following values at the Loviisa node:

- Higher Voltage: 440 kV and 427 kV, compared to the assumed 415 kV.
- Higher Active Power: 1180 MW and 1100 MW, compared to the assumed 1014 MW.
- Reactive Power Differences: 170 MVar and 95 MVar, with no specific reactive power adjustments accounted for in the grid model.

These deviations may stem from the compensation block in the grid model, which was not adjusted for different scenarios during the co-simulations. Discrepancies in one part of the grid can propagate through the system, leading to measurable impacts on network behaviour. A detailed analysis of the compensation block's settings and its effect on reactive power output is needed to address these issues. Furthermore, while the updates to the Apros model improved alignment with Loviisa's rated values, further clarification of the specific adjustments made—particularly regarding generator parameters and assumptions—would help in resolving the remaining differences. Compared to swing bus (Djuptjärn) measurements from last year, however, the difference in power flow is minor, indicating progress in overall model alignment.

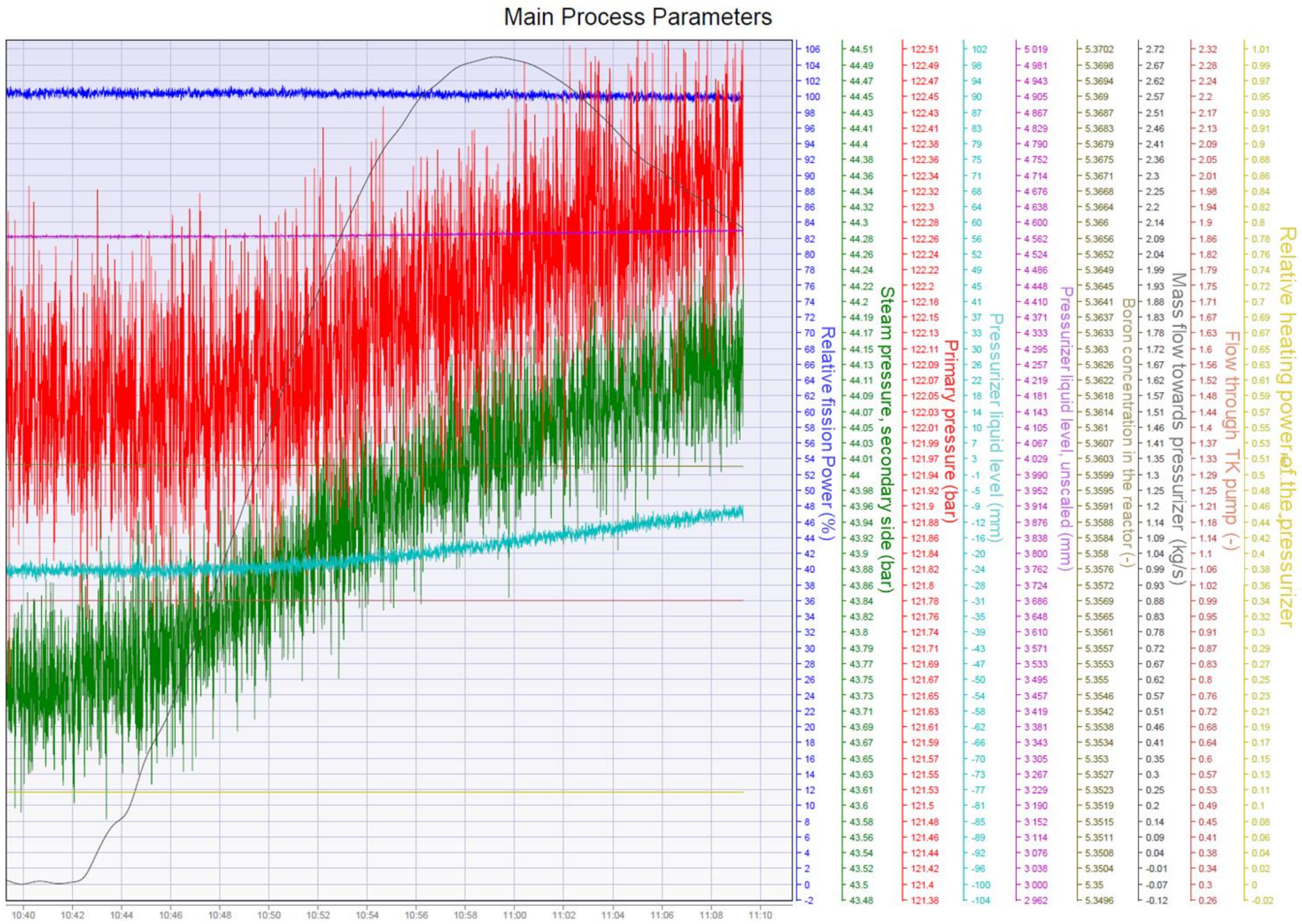

Figure 12: Scenario 12. Main process parameters in NPP.

The main process parameters are presented in Figure 12. For confidentiality purposes, the codes for pumps and other devices have been removed from the Y-axis, and generic names have been assigned to these parameters. No conclusions are drawn from this data, as all values fall within expected operational parameters, with no anomalies identified.

4.3 Scenario 13

Below are all relevant measurements for Scenario 13. All co-simulations are compared with Simulink-only simulation.

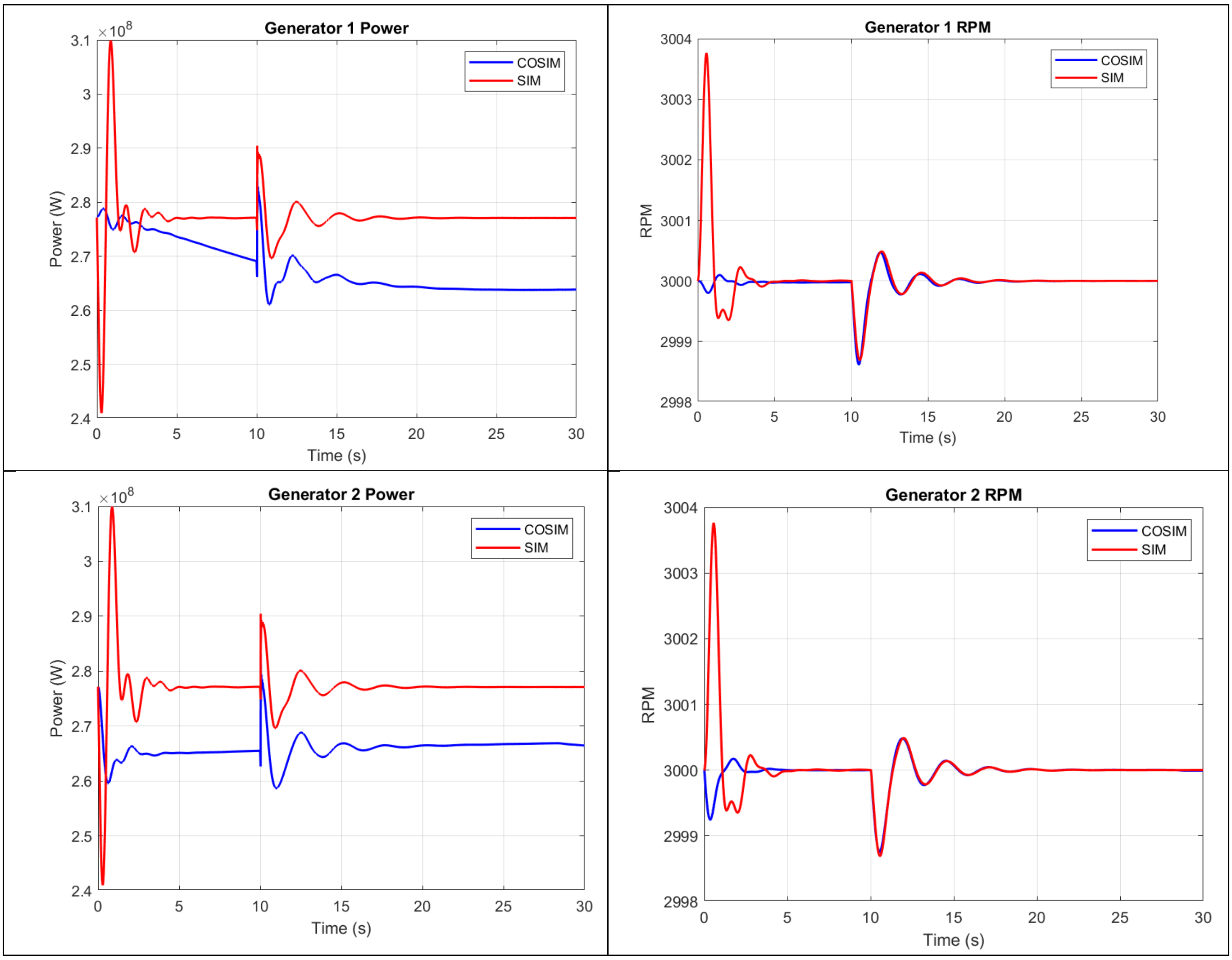

Figure 13: Scenario 13. RPMs and power of Generators

Figure 13 shows same behaviour that was observed in Scenario 12. A similar pattern is evident in Scenario 13, where comparable conclusions can be drawn. The initial power surge in the Simulink-only simulation and its transient behaviour, along with the differences in steady-state power levels and response to disturbances between the co-simulation and Simulink-only cases, exhibit consistent trends across both scenarios.

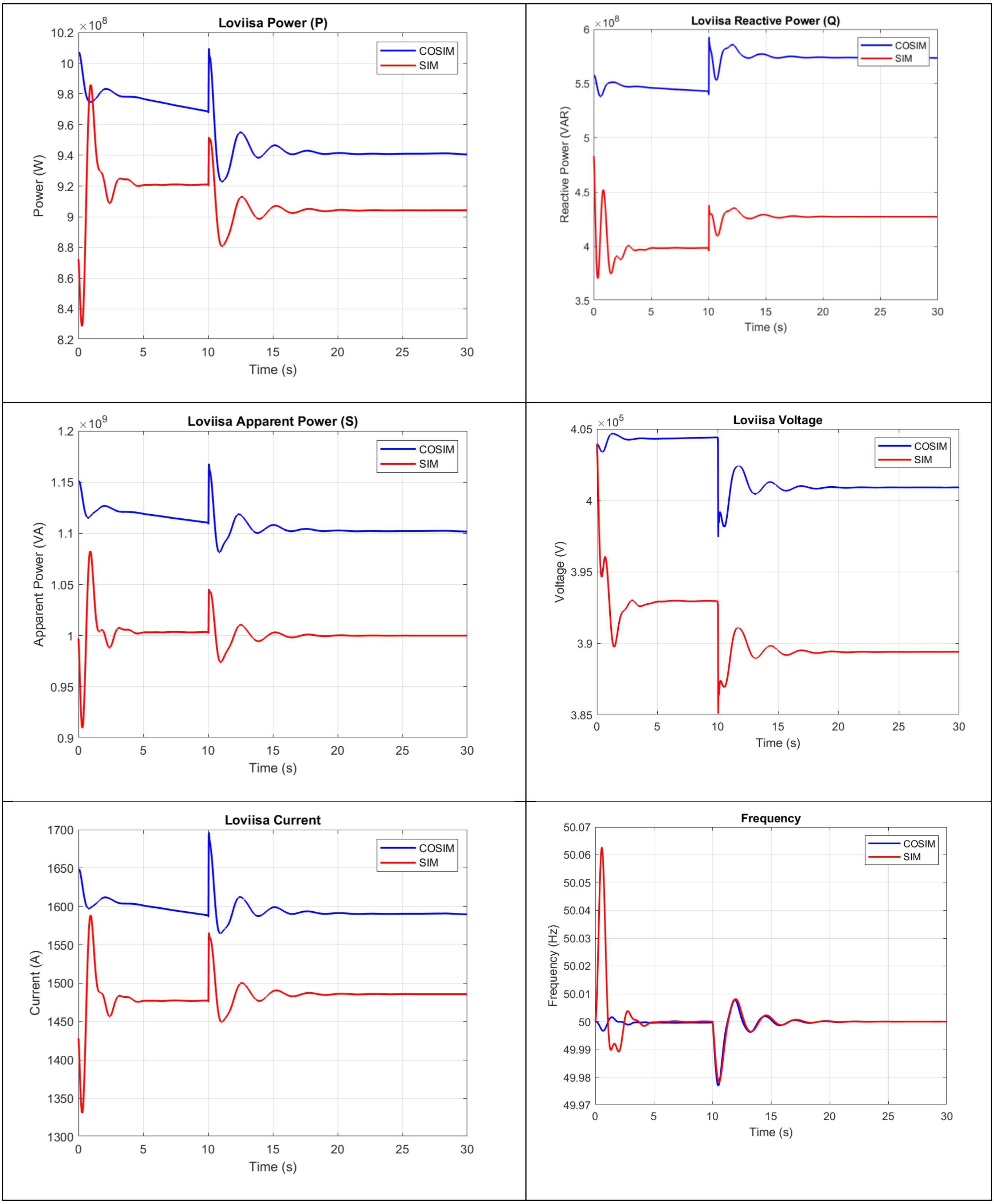

Figure 14: Scenario 13. Power, current and voltage measurements at Loviisa node. Frequency measurement

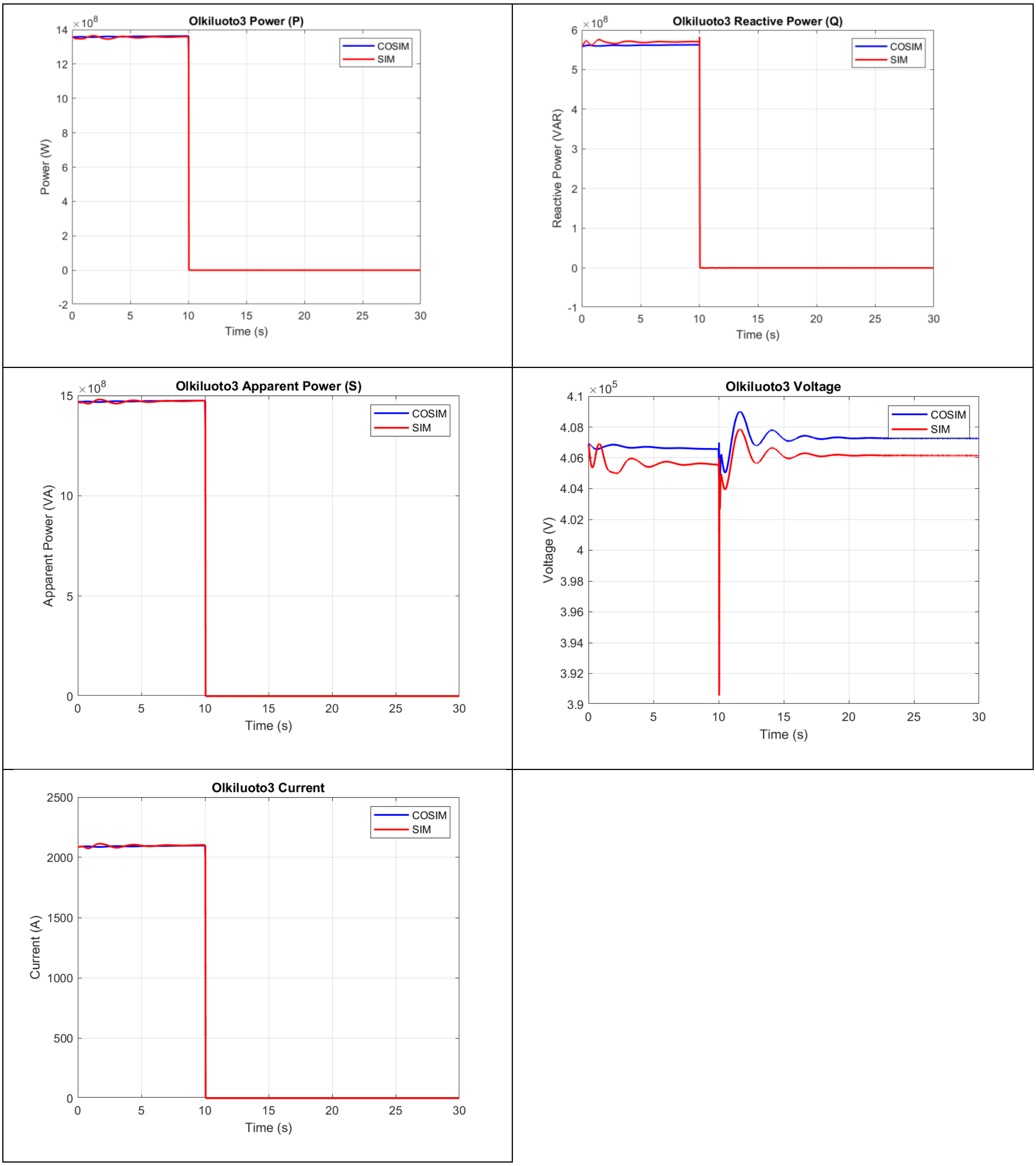

Figure 15: Scenario 13. Power, current and voltage measurements at Olkiluoto node.

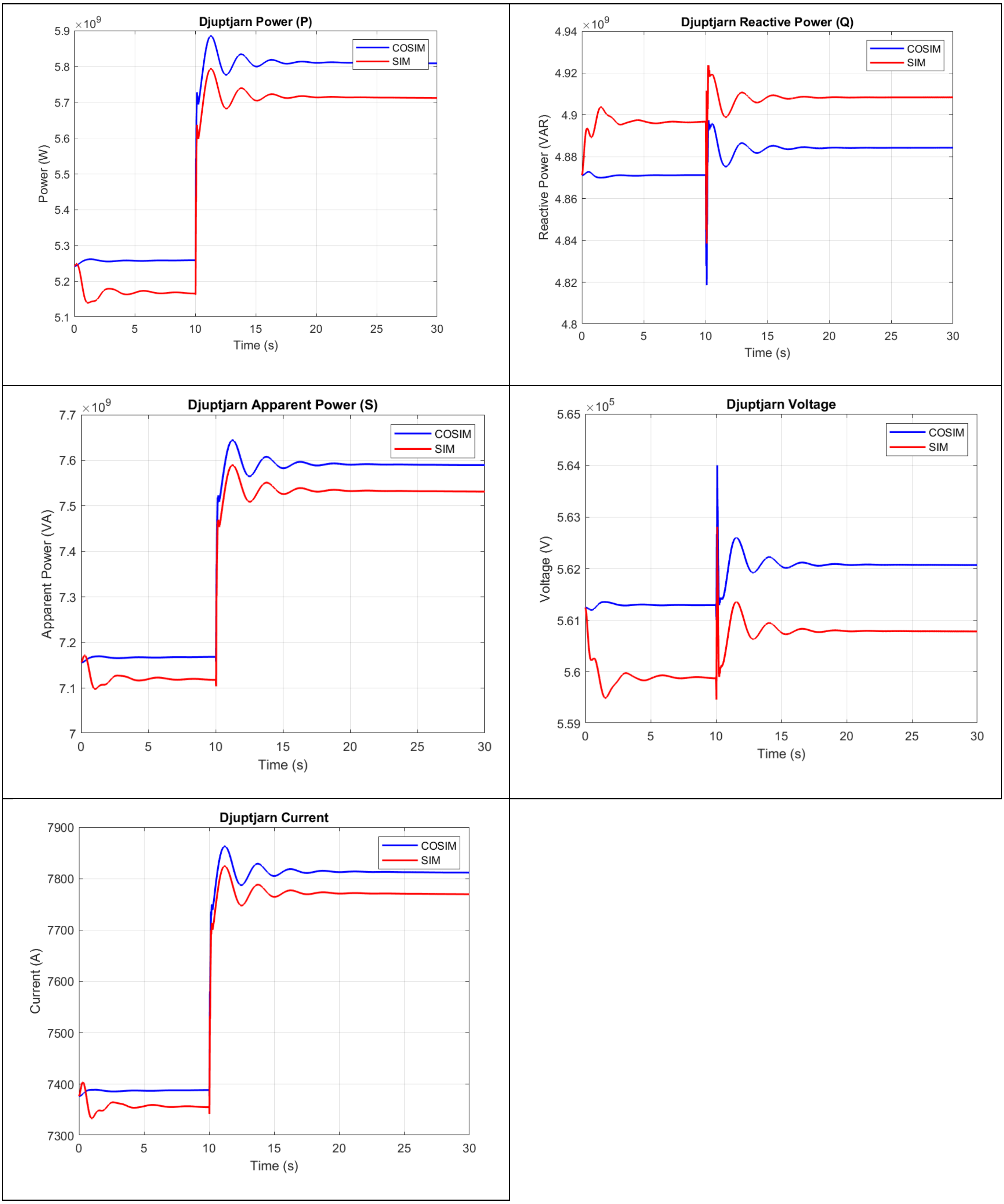

Figure 16: Scenario 13. Power, current and voltage measurements at Djuptjärn node

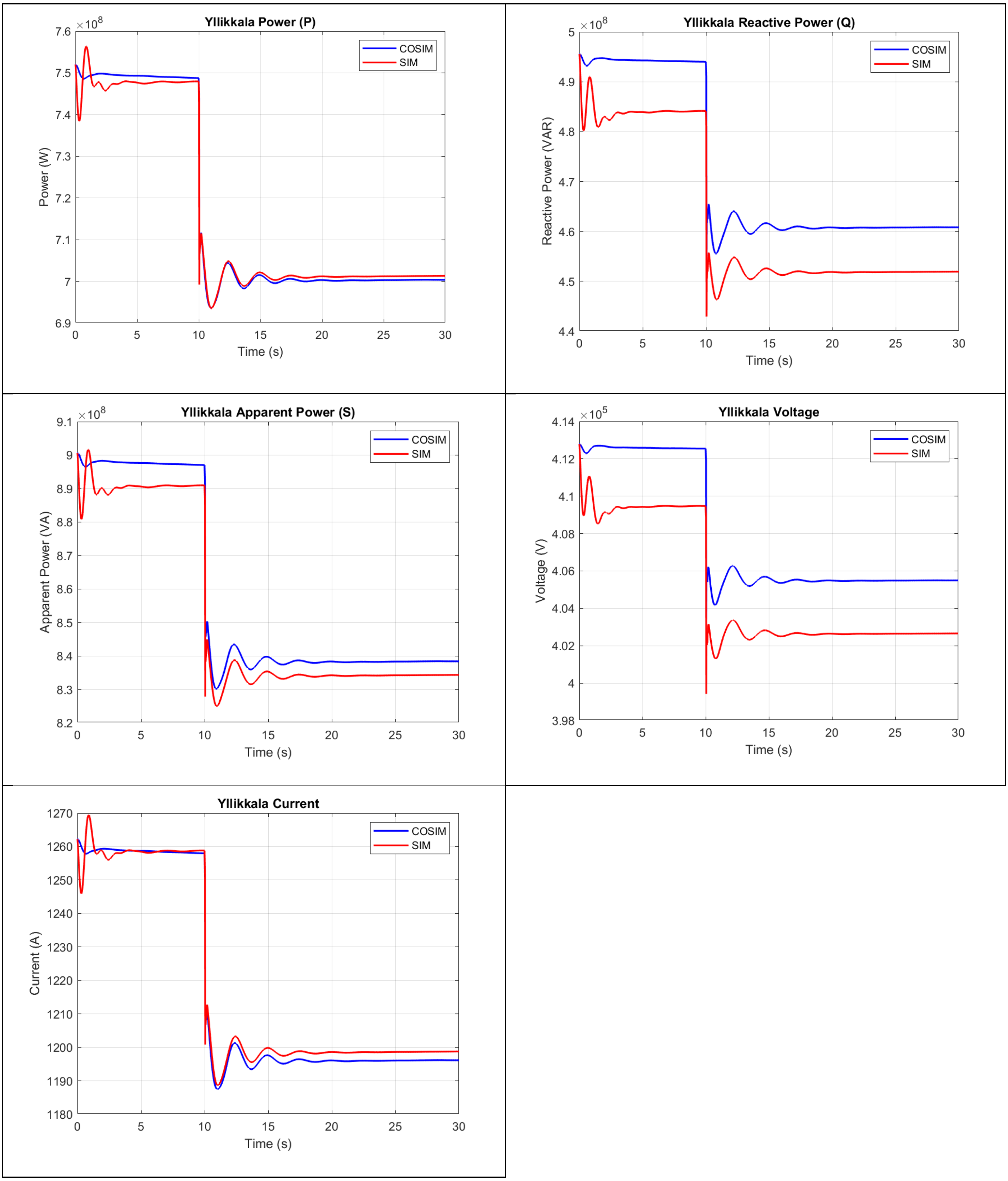

Figure 17: Scenario 13. Power, current and voltage measurements at Yllikkälä node

The power measurement discrepancies in the high-wind scenario, follow similar patterns to the previous observations. Differences in power output representation and grid dynamics between the models contribute to these discrepancies. While the standalone grid model assumes 2 × 507 MW at 415 kV for Loviisa NPP, the actual values during co-simulations differ:

- Lower Voltage: 401 kV and 390 kV (compared to 415 kV).
- Lower Active Power: 940 MW and 902 MW (compared to 1014 MW)
- Higher reactive Power: 575 MVar and 470 MVar

These variations may result from the integration of wind power, which introduces dynamic behaviour into the grid and affects voltage stability and power flows. The compensation block in the grid model, which remains unadjusted for these scenarios, likely contributes to the observed reactive power differences.

The discrepancies highlight the need for refined model adjustments, including recalibrating compensation blocks and incorporating renewable power variability. Further analysis of how these elements interact with the grid and the NPP's contributions is essential to ensure accurate simulations and system stability.

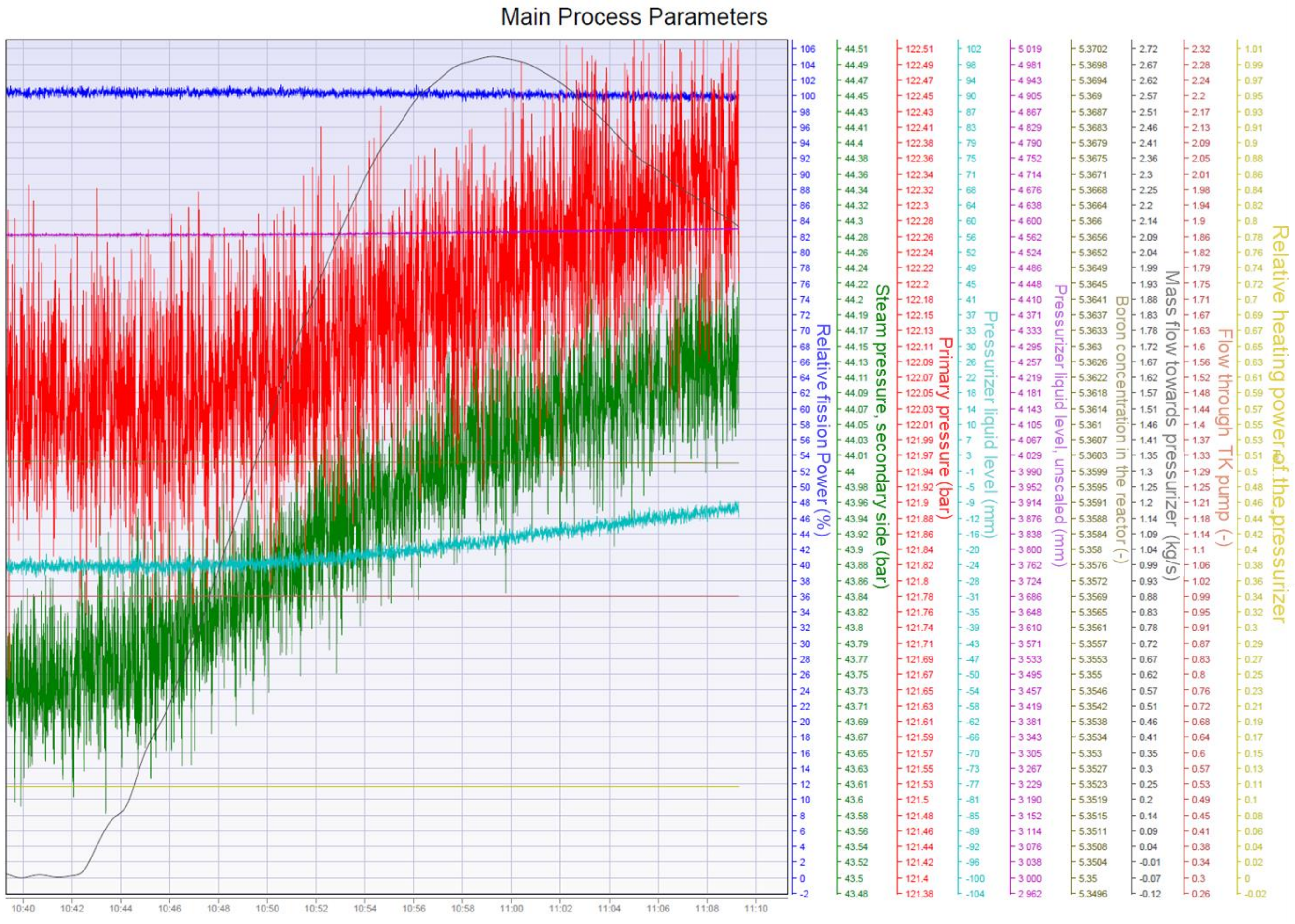

Figure 18: Scenario 13. Main process parameters.

The main process parameters are presented in Figure 12. For confidentiality purposes, the codes for pumps and other devices have been removed from the Y-axis, as they cannot be disclosed publicly. No conclusions are drawn from this data, as all values fall within expected operational parameters, with no anomalies identified.

5. Summary and Discussion

To address discrepancies observed in the co-simulations, we should adjust the grid-only model to better align with the power output and setpoint voltage used in the co-simulations. While key parameters such as harmonics, voltage stability, and reactive power differences remain points of interest, particular attention should be given to harmonics behavior. These may increase as the integration of converter-connected equipment grows but could decrease as grid codes tighten and converter technologies improve.

The coincidence of a potential turbine shaft torsional oscillation mode with one of the subsynchronous frequencies measured in the grid is a significant observation. These harmonics were reproduced only via current sources at wind parks, suggesting a need for further investigation into wind park behavior and its interaction with the system. The stronger oscillations observed in high wind generation scenarios highlight the importance of careful parameterization of the grid stabilizer and wind turbine/converter models to accurately capture both transient and steady-state behavior.

Initial observations from last year's co-simulations—such as the ripple or measurement spike caused by mismatched initial conditions in Simulink and Apros—further underscore the challenges of coupling different simulation tools. Similarly, the steady-state offset between co-simulations and Simulink-only results points to model parameter mismatches that require iterative adjustments and careful investigation.

The swing bus in the transmission system model also remains a critical focus, as its apparent power distribution enforces mismatched active and reactive power across several buses. This discrepancy, combined with the lack of inertia in certain scenarios, impacts frequency stability and transient dynamics, especially in high renewable penetration cases. Addressing these challenges by refining swing bus modeling and enhancing inertia representation in synchronous machines will be essential for future studies.

Despite these challenges, the SAFER-SINARP project concludes with a robust 400 kV grid model and a co-simulation platform successfully linking the grid model, the internal electrical network of Loviisa NPP, and the thermodynamic APROS software. This combination of tools has deepened our understanding of system dynamics and lays the groundwork for further improvements in future projects.

References

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