Small-Signal Stability Studies under Converter-Based Generator Replacement

Modal Analysis of VSC Integration in Hydro-Dominated Benchmark Grids

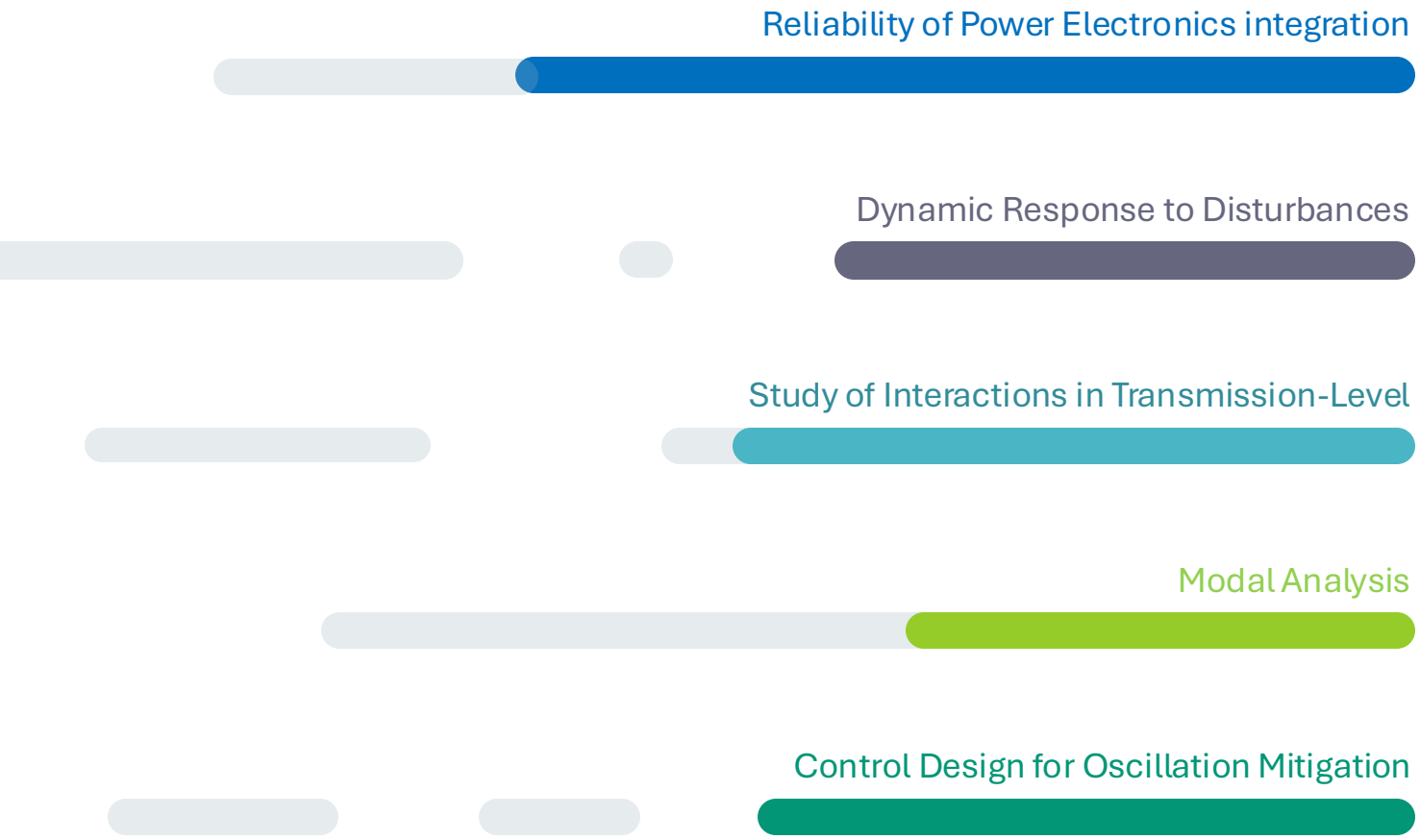
Matta, Stephanie.

ETSEIB PROJECT | Jun 25th 2025. Barcelona, Spain.

DREAM European Master

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH
Escola Tècnica Superior d'Enginyeria Industrial de Barcelona
ETSEIB

Project Aim and Scope



Industry's Need for Stability

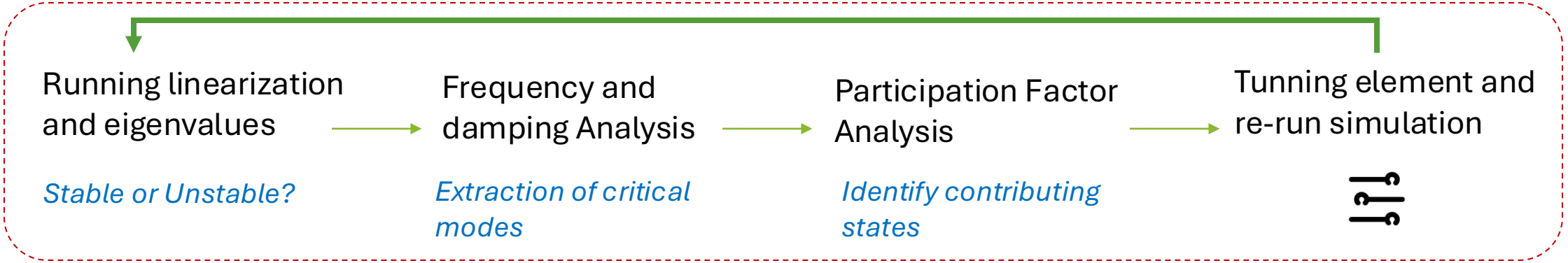
Small-signal stability analysis is vital for transmission systems with increasing renewable energy and power electronics integration. The STAMP tool uses **state-space models** to analyze system dynamics and stability indicators.

This project aims to **enhance** the STAMP tool for better **frequency domain analysis** in transmission systems and **explores the addition of IBR networks** in future stages.

Small Signal Stability

Refers to the ***ability of a power system to maintain synchronism*** when subjected to ***small perturbations***, such as minor load changes or routine switching events. [1]

WORKFLOW:



$$\dot{x} = Ax + Bu$$

Eigenvalues $\lambda = \sigma \pm j\omega$
- $\sigma < 0 \Rightarrow$ stable mode
- $\omega \Rightarrow$ oscillation frequency (rad/s or Hz)

Inter-area modes: 0.5–1 Hz
High-frequency modes: ω > 500 Hz

- $\zeta > 0.05$ $\zeta > 0.05$: well-damped
- $\zeta < 0.05$ $\zeta < 0.05$: poorly damped (risk of instability)

Mode shape: identifies how state variables swing together.

Participation factor: ranks which generators/states drive each mode → guides controller placement.

1 Kundur, P. (1996). Power System Stability.

STAMP Tool Interface

The tool is developed in a MATLAB environment and was chosen for its matrix-oriented programming, robust plotting capabilites, and graphical environment (Simulink).

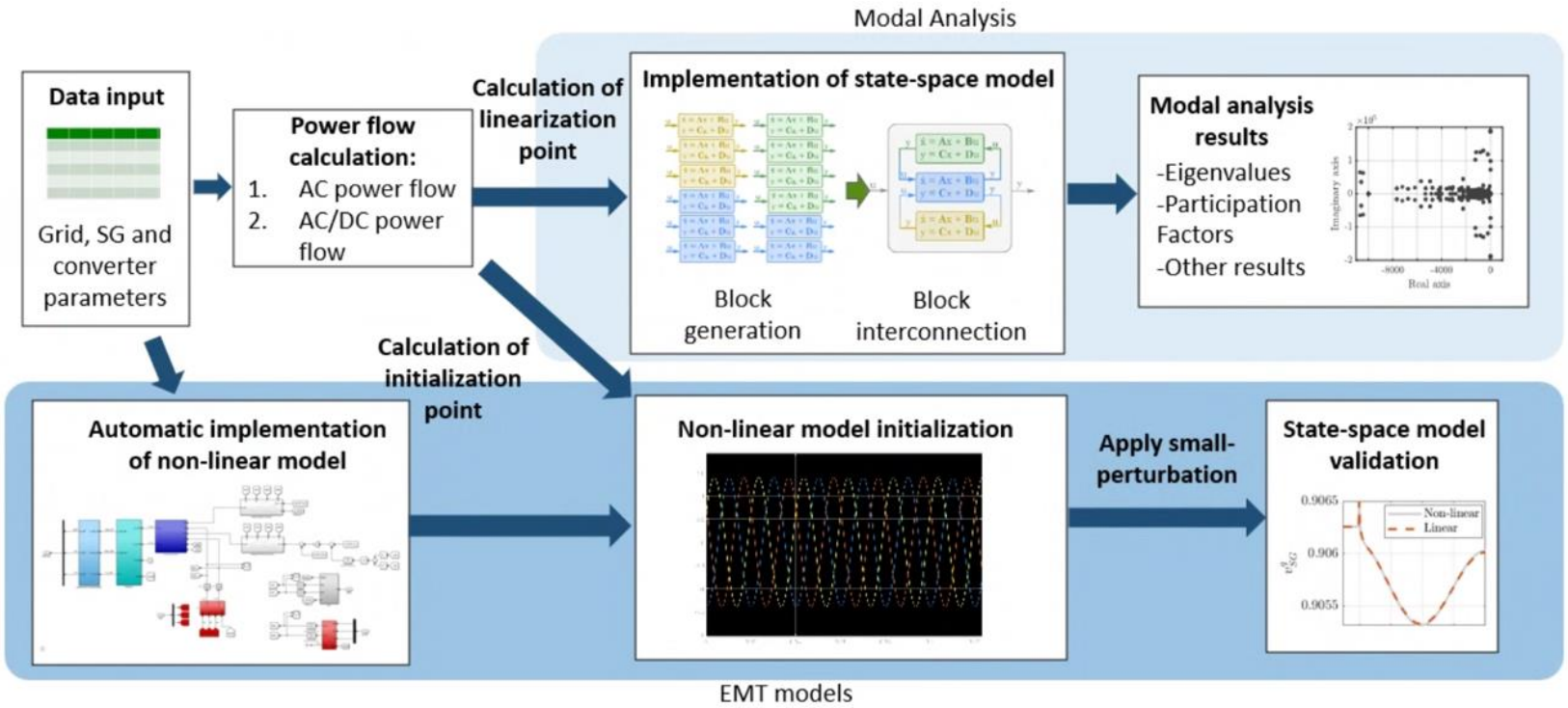
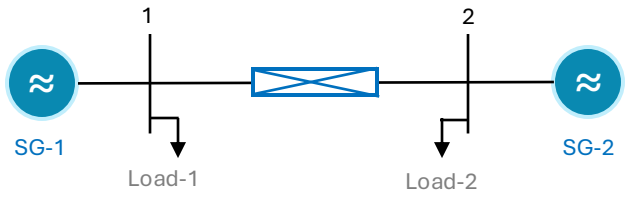


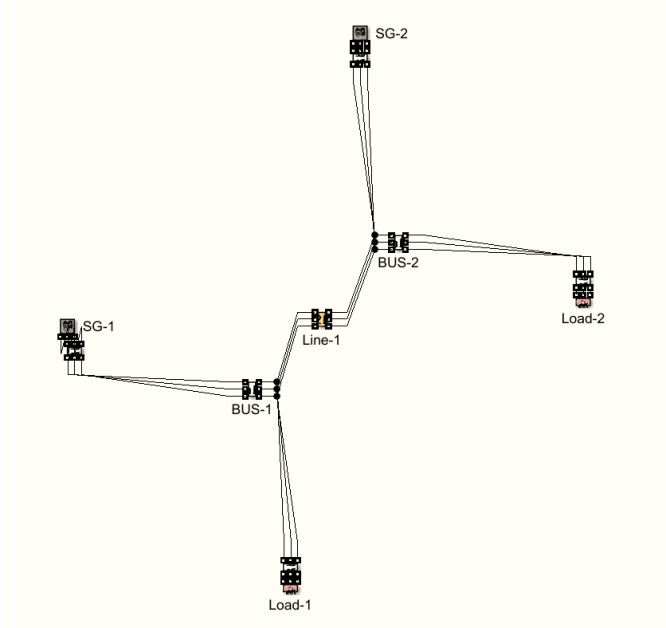
Figure 1. STAMP Tool Documentation, CITCEA UPC.

Overview datalog, state space, linear and non linear. + Stability tools (EIG, PFM)

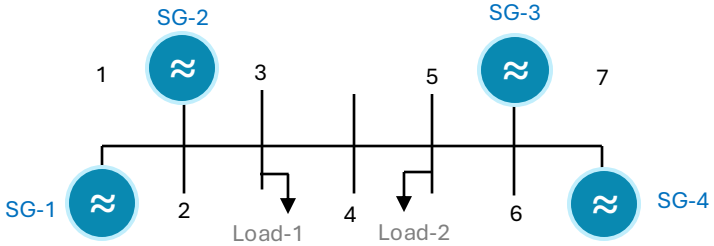
Exploration: 3 preliminary cases

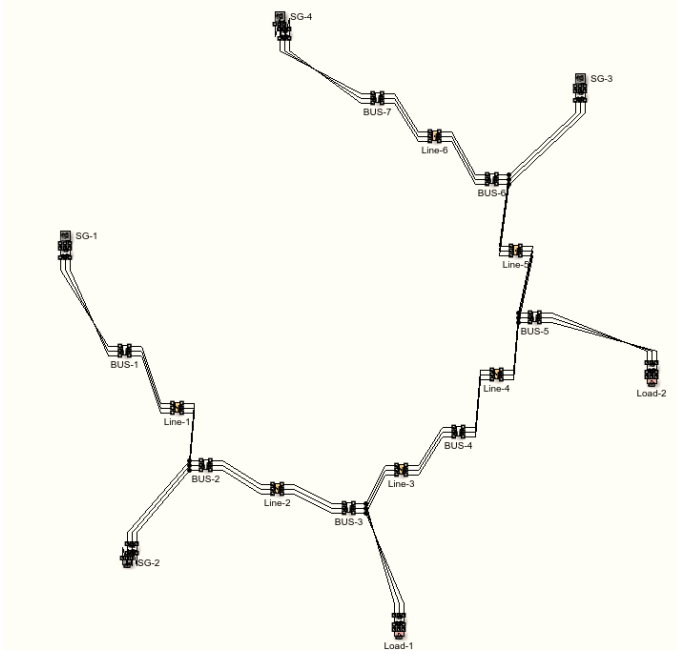
2-Bus System



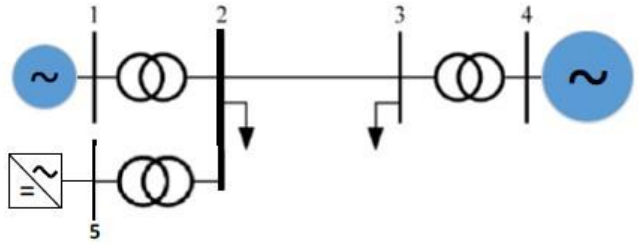


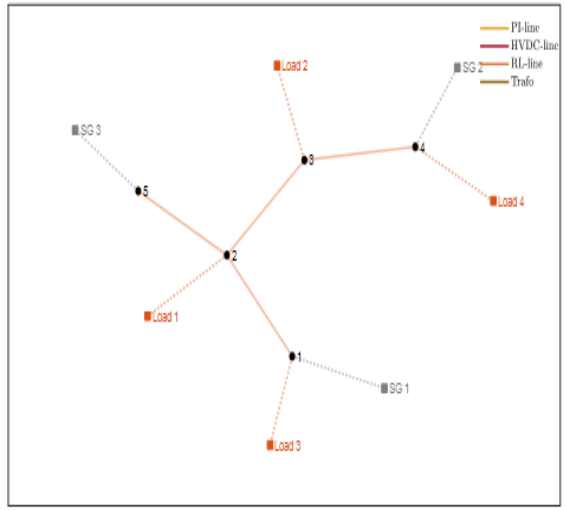
Kundur 2-Area System





NTS (TSO/DSO Model)





Kundur, R. (1996). Power System Stability.

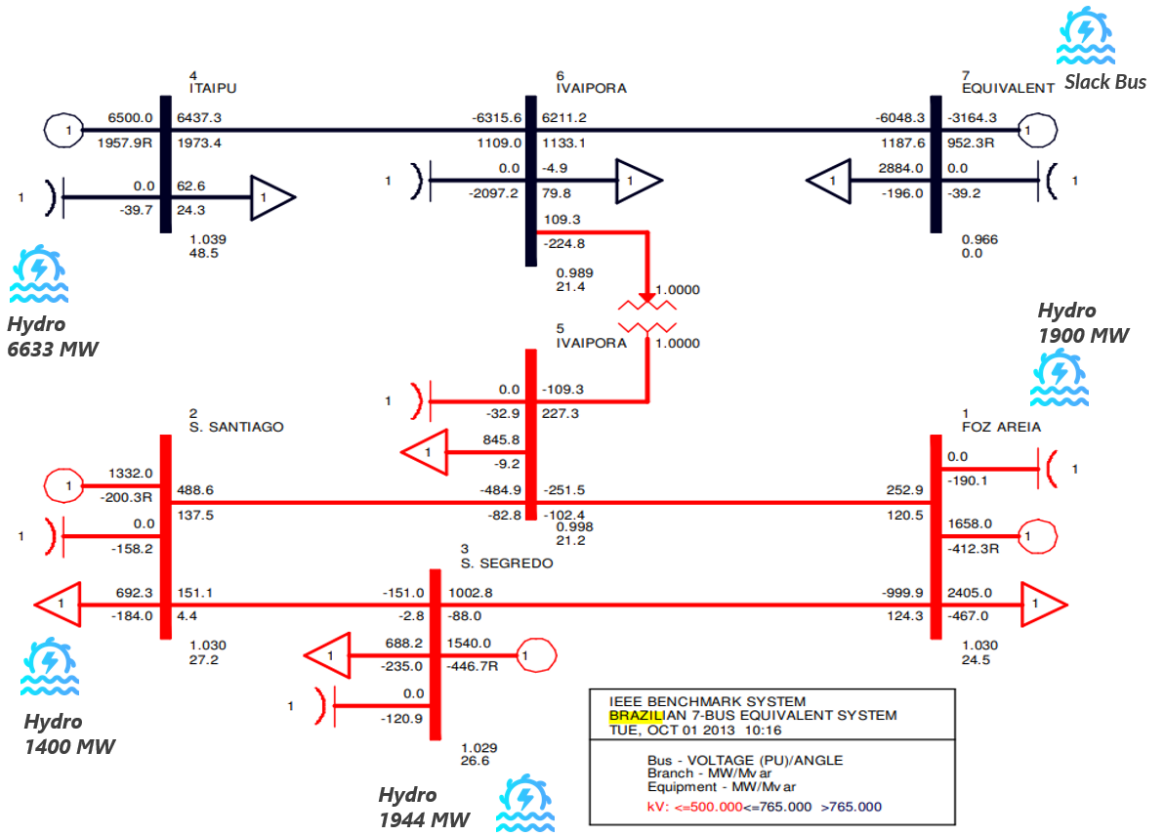
Oscillation Type	Frequency Range	Typical Cause	Involved Elements
Interarea at very low frequency	0.1-0.3 Hz (Global Stability)	Generators swinging against	All generators of the system, split in 2 areas
Interarea at higher frequency	0.4 – 0.7 Hz		Subgroups of generators
Control Modes	0.7 – 1 Hz	Control of equipment (inadequate tuning of the control systems)	SG excitation systems, HVDC converters, static var compensators.
Interplant / intermachine	0.7 – 2 Hz	Rotors of generations close to each other	Two or more generator in same area/ other areas
Torsional Mode	10 – 60 Hz	Control Systems interaction with the turbine shaft.	

Oscillation Type	Frequency Range	Typical Cause	Involved Elements
Harmonic Modes	≥ 100 Hz – 500 kHz	Resonance, converters, filters, PLL dynamics	Power electronics, filters, network RLC path
Switching Dynamics of the Converter	10 – 50 Hz	Shaft torsional resonance	Turbine–generator shaft system

Building some intuition of the dynamics!

Brazilian 7-bus IEEE Benchmark Motivation and Overview

Big hydroelectric capacity and long transmission distance. Inherent marginal stability by topology's nature.



- 5 Synchronous Generators,
- 2 Voltage Level Areas (500 and 765 kV), separated by a transformer substation.

Replacing SG with **VSC-based IBRs** alters:

- The eigenvalue spectrum (less inertia, different control dynamics)
- The system's **natural damping**, sometimes reducing it

This can lead to **new unstable modes**, hence the need to assess participation and damping when VSCs are introduced.

Figure 2. IEEE Benchmark System Study Case

BASE CASE BENCHMARK – NO VSC

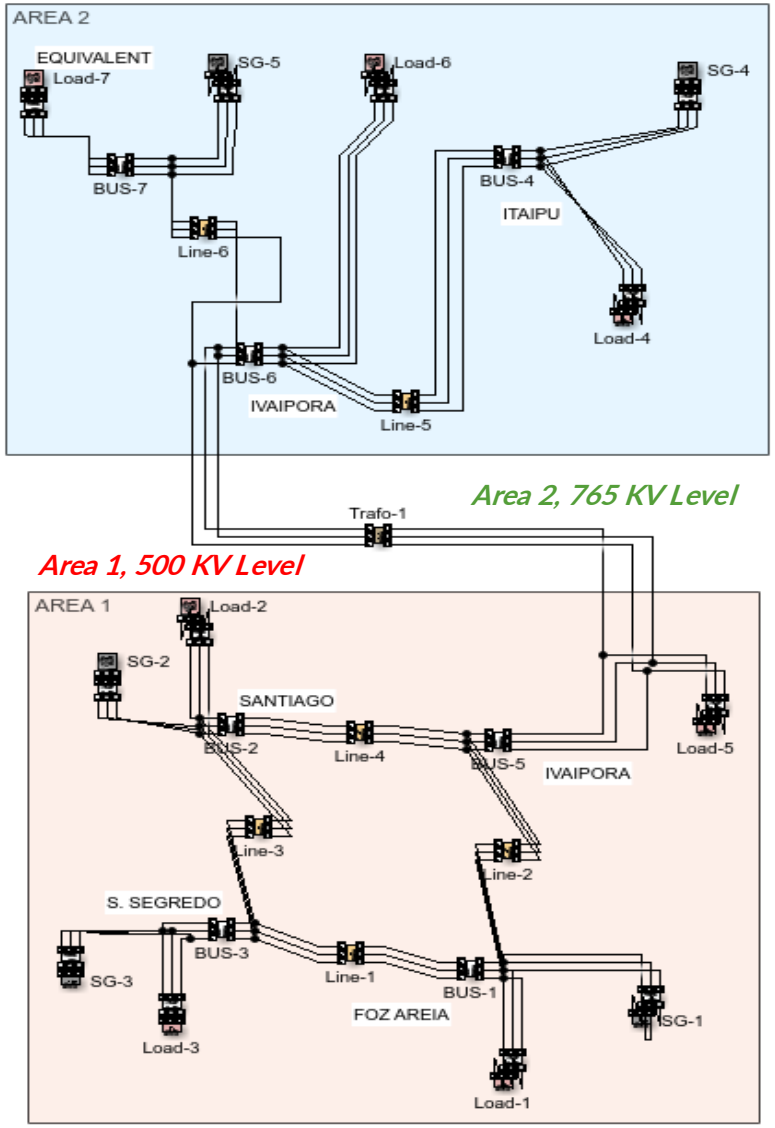


Figure 3. Non-linear Model Topology

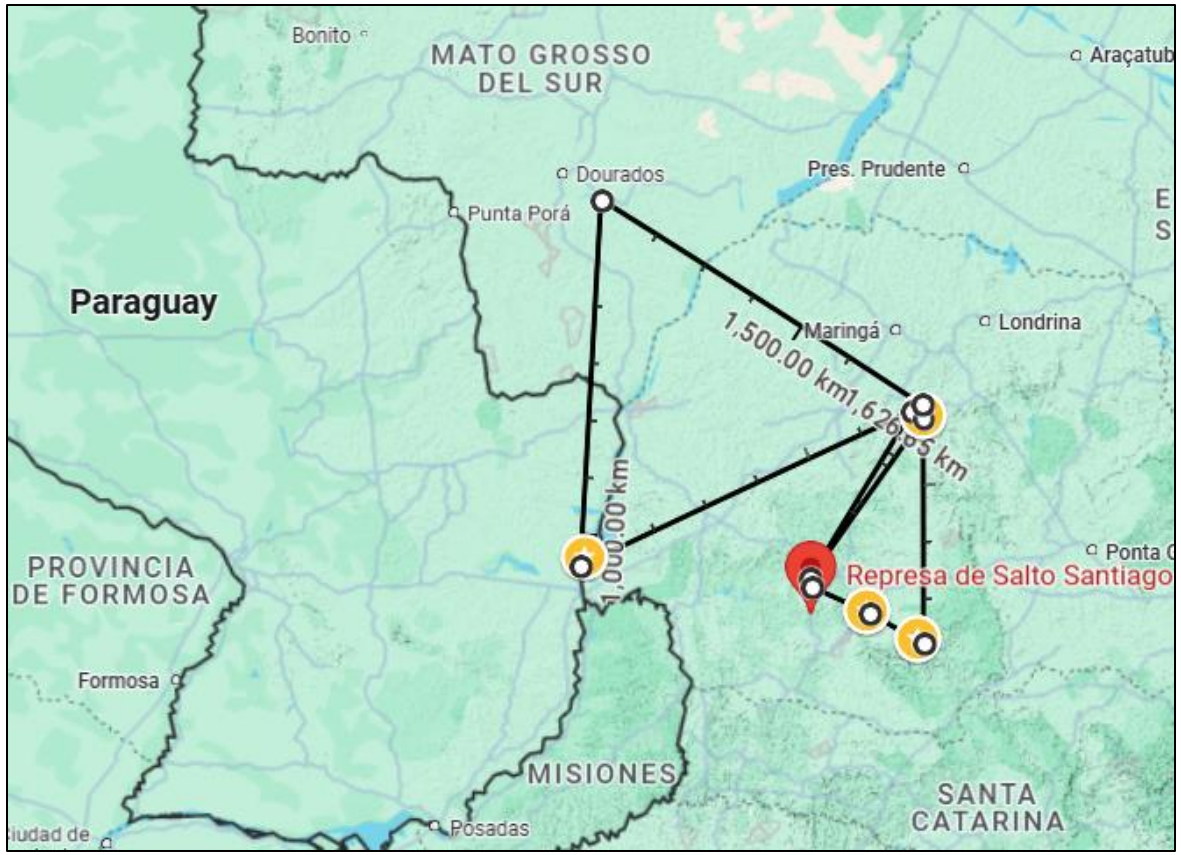


Figure 4. Real Topology of Brazilian Benchmark Network

BASE CASE DYNAMICS – NO VSC

Damping and Frequency Analysis

i.e. Poor Damped + Low and High Frequency Modes FilteE

Nominal frequency excluded

Mode	Real	Imaginary	Frequer	Dampin
1	0.195314522	0	0	-100%
13	-0.397541089	4.942051305	0.786552	8%
14	-0.397541089	-4.94205131	0.786552	8%
51	-7.662950493	376.824746	59.97352	2%
52	-7.662950493	-376.824746	59.97352	2%
61	-9.706702522	376.8215356	59.97301	3%
62	-9.706702522	-376.821536	59.97301	3%
74	-12.74209665	376.9725535	59.99705	3%
75	-12.74209665	-376.972554	59.99705	3%
77	-16.23913093	376.9048339	59.98627	4%
78	-16.23913093	-376.904834	59.98627	4%
87	-27.27893905	376.9890989	59.99968	7%
88	-27.27893905	-376.989099	59.99968	7%
98	-456.8432021	5420.476869	862.6957	8%
99	-456.8432021	-5420.47687	862.6957	8%
100	-456.9243339	4666.505901	742.6975	10%
101	-456.9243339	-4666.5059	742.6975	10%
110	-1135.986844	20559.44184	3272.137	6%
111	-1135.986844	-20559.4418	3272.137	6%
112	-1136.026849	19805.46538	3152.138	6%
113	-1136.026849	-19805.4654	3152.138	6%

Nominal frequency excluded

For Low Frequencies: < 1 Hz

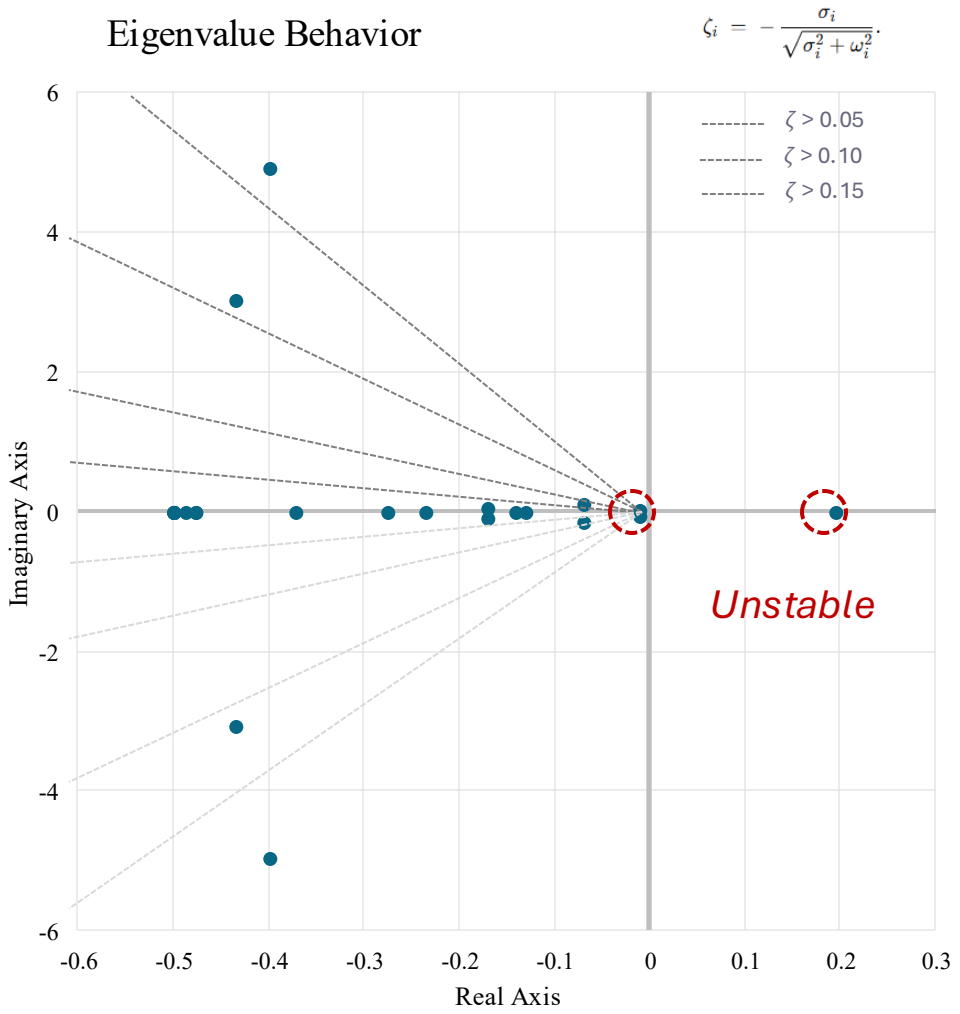
- < 0.5 Hz Slow Controllers (i.e. governor)
- < 1.0 Hz Electromechanical oscillations (Rotor related SG)
- Possible Inter Area Ranges

For High Frequencies: > 500 Hz

- High Frequency – Possible inductance capacitance of the cables
- Very High Frequencies – Switching dynamics of the converter.

Extraction of critical modes table

Conjugate Pairs:	λ 1	λ 13-14	λ 98-99	λ 100-101	λ 110-111	λ 112-113
Real	0.1953	-0.3975	-456.8432	-456.9243	-1135.9868	-1136.0268
Imaginary	0	4.9421	5420.4769	4666.5059	20559.4418	19805.4654
Frequency	0	0.7866	862.6957	742.6975	3272.1368	3152.1377
Damping	-100%	8%	8%	10%	6%	6%



BASE CASE – STABILIZATION EFFORT

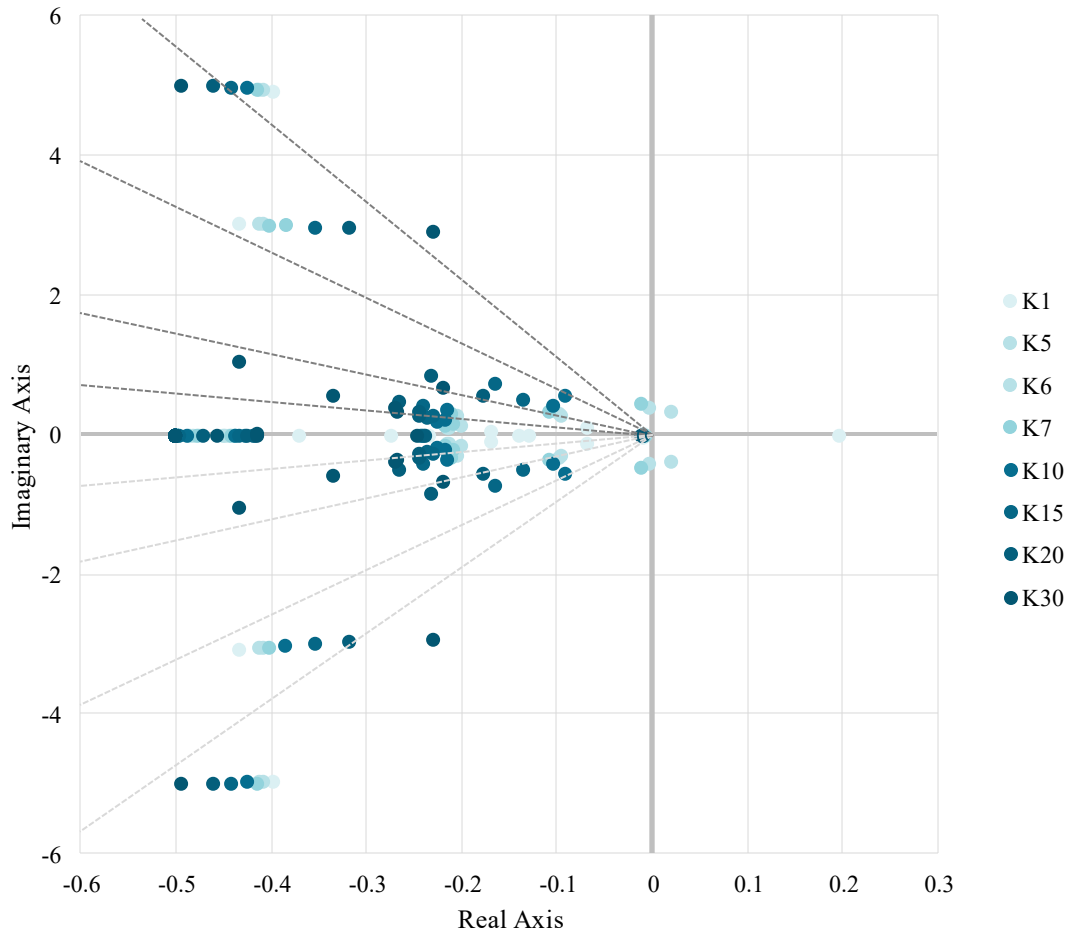
Low damped, inter-area & high-frequency modes

Conjugate Pairs:	λ 1	λ 13-14	λ 98-99	λ 100-101	λ 110-111	λ 112-113
Real	0.1953	-0.3975	-456.8432	-456.9243	-1135.9868	-1136.0268
Imaginary	0.0000	4.9421	5420.4769	4666.5059	20559.4418	19805.4654
Frequency	0.0000	0.7866	862.6957	742.6975	3272.1368	3152.1377
Damping	-100%	8%	8%	10%	6%	6%

NET.iq13	0.00	0.00	0.79	0.79	0.00	0.00
NET.id13	0.00	0.00	0.79	0.79	0.00	0.00
NET.iq23	0.00	0.00	0.41	0.41	0.00	0.00
NET.id23	0.00	0.00	0.41	0.41	0.00	0.00
NET.iq46	0.00	0.01	0.00	0.00	0.41	0.41
NET.id46	0.00	0.00	0.00	0.00	0.41	0.41
Load3.voq	0.00	0.00	1.00	1.00	0.00	0.00
Load3.vod	0.00	0.00	1.00	1.00	0.00	0.00
Load4.voq	0.00	0.00	0.00	0.00	1.00	1.00
Load4.vod	0.00	0.00	0.00	0.00	1.00	1.00
SG1.is_d	0.08	0.61	0.01	0.01	0.00	0.00
SG1.if_d	0.05	0.58	0.00	0.00	0.00	0.00
SG1.w_pu	0.00	0.63	0.00	0.00	0.00	0.00
SG1.e_th	0.00	0.90	0.00	0.00	0.00	0.00
SG2.is_d	0.02	0.37	0.01	0.01	0.00	0.00
SG2.if_d	0.01	0.34	0.00	0.00	0.00	0.00
SG2.w_pu	0.00	0.41	0.00	0.00	0.00	0.00
SG2.e_th	0.00	0.59	0.00	0.00	0.00	0.00
SG3.is_d	0.07	0.65	0.09	0.05	0.00	0.00
SG3.if_d	0.04	0.60	0.00	0.01	0.00	0.00
SG3.w_pu	0.00	0.71	0.00	0.00	0.00	0.00
SG3.e_th	0.00	1.00	0.00	0.00	0.00	0.00
SG4.is_q	0.00	0.00	0.00	0.00	0.43	0.40
SG4.is_d	1.00	0.16	0.00	0.00	0.44	0.39
SG4.if_d	0.70	0.14	0.00	0.00	0.01	0.01
SG4.e_th	0.01	0.72	0.00	0.00	0.00	0.00
SG5.is_d	0.65	0.03	0.00	0.00	0.00	0.00
SG5.if_d	0.45	0.03	0.00	0.00	0.00	0.00

Conjugate Pairs:	λ 1	λ 13-14	λ 98-99	λ 100-101	λ 110-111	λ 112-113
Interactions	SG4, SG5	SG1,2,3,4	Network 1-3, Load 3	Network 1-3, Load 3	SG4, Network 4-6, Load 4	SG4, Network 4-6, Load 4
Frequency Range	Instability	Control Mode	> 800 Hz LC	> 700 Hz Grid LC	> 3000 Hz Grid LC	> 3000 Hz Grid LC
Damping component	PSS	Exciter Tuning	Grid LC	Grid LC	Grid LC	Grid LC
Inter-area oscillation	No	Possible	No	No	No	No

Exciter Gain Iteration $\zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}$



Inter-area oscillation candidate mode
Eigenvectors intra/inter-area oscillations

$$\Phi_i = \begin{bmatrix} \phi_{1i} \\ \phi_{2i} \\ \vdots \\ \phi_{ni} \end{bmatrix}$$

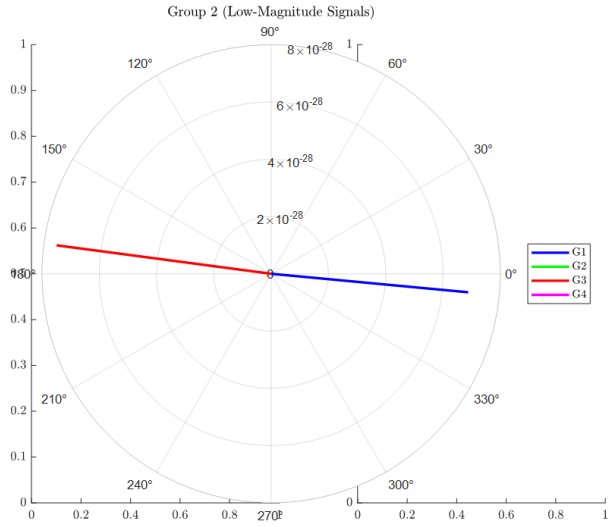
$\lambda = \sigma + j\omega$:

Area 1: 500 V
Area 2: 765 V

SG1 Row 13, Col 65: 7.841811568912547e-05 + 0.000000000000000e+00i — I
SG2 Row 13, Col 88:-0.00124986982031296 - 0.0020738481133687 1i — III
SG3 Row 13, Col 111:-0.0073825399510948 7 + 0.0029766799816266 0i — II
SG4 Row 13, Col 134:-0.0018699217509458 6 + 0 — I

Area 1: 500 V
Area 2: 765 V

SG1 Row 67, Col 13: 6.87658159170693e-28 - 6.46256487014726e-29i — IV
SG2 Row 88, Col 13:-5.34814332487602e-33 + 1.71431555516261e-34i — II
SG3 Row 111, Col 13:-7.48903431948719e-28 + 9.94764783271771e-29i — II
SG4 Row 134, Col 13:-2.58247862139749e-45 + 2.42531579975053e-53i — I



Although **SG4 appears 180°** out of phase **with SG1**, the extremely low magnitude of its eigenvector component in both studied modes **indicates negligible dynamic participation.**

Therefore, no meaningful inter-area oscillation involving SG4 can be confirmed. The system's inter-area dynamics are likely driven by interactions among SG1, SG2, and SG3.

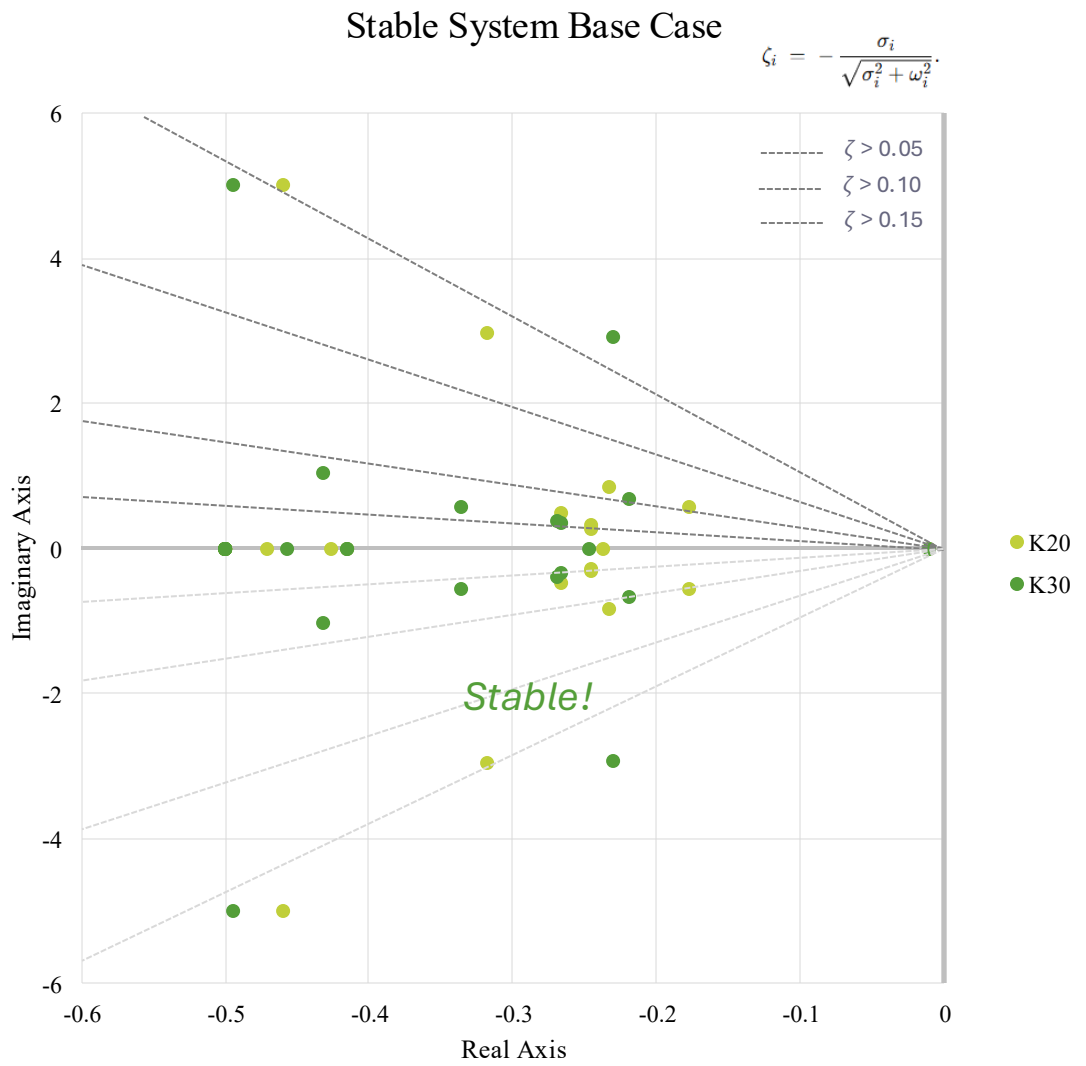
BASE CASE – STABLE SYSTEM K=30

Low damped, inter-area & high-frequency modes

Conjugate Pairs:	λ 1	λ 13-14	λ 98-99	λ 100-101	λ 110-111	λ 112-113
Real	-0.22947	-0.49326	-456.882	-456.934	-1135.98	-1136.02
Imaginary	2.920307	4.99891	5420.463	4666.496	20559.45	19805.5
Frequency	0.464781	0.7956	862.6934	742.696	3272.137	3152.14
Damping	8%	10%	8%	10%	6%	6%

NET.iq23	0.00	0.00	0.70	0.70	0.00	0.00
NET.id23	0.00	0.00	0.70	0.70	0.00	0.00
NET.iq25	0.00	0.00	0.23	0.23	0.00	0.13
NET.id25	0.00	0.00	0.23	0.23	0.00	0.13
NET.iq67	0.00	0.00	0.00	0.00	1.00	0.00
NET.id67	0.00	0.00	0.00	0.00	1.00	0.00
Trafo1.iq	0.00	0.00	0.01	0.01	0.00	0.76
Trafo1.id	0.00	0.00	0.01	0.01	0.00	0.76
Load1.vcq	0.00	0.00	0.41	0.41	0.00	0.00
Load1.vcd	0.00	0.00	0.41	0.41	0.00	0.00
Load2.vcq	0.00	0.00	1.00	1.00	0.00	0.00
Load2.vcd	0.00	0.00	1.00	1.00	0.00	0.00
Load5.vcq	0.00	0.00	0.00	0.00	0.00	1.00
Load5.vcd	0.00	0.00	0.00	0.00	0.00	1.00
Load6.vcq	0.00	0.00	0.00	0.00	0.14	0.01
Load6.vcd	0.00	0.00	0.00	0.00	0.14	0.01
Load7.vcq	0.00	0.00	0.00	0.00	0.86	0.00
Load7.vcd	0.00	0.00	0.00	0.00	0.86	0.00
SG2.pss1.1	0.00	0.78	0.00	0.00	0.00	0.00
SG2.pss1^{x}2	0.00	0.78	0.00	0.00	0.00	0.00
SG2.pss2^{x}1	0.00	0.57	0.00	0.00	0.00	0.00
SG2.pss2^{x}2	0.00	0.57	0.00	0.00	0.00	0.00
SG3.pss1^{x}1	0.00	1.00	0.00	0.00	0.00	0.00
SG3.pss1^{x}2	0.00	1.00	0.00	0.00	0.00	0.00
SG3.pss2^{x}1	0.00	0.32	0.00	0.00	0.00	0.00
SG3.pss2^{x}2	0.00	0.32	0.00	0.00	0.00	0.00
SG4.ig$_d^{x}$	0.81	0.00	0.00	0.00	0.00	0.00
SG4.ig$_q^{x}$	1.00	0.00	0.00	0.00	0.00	0.00

Conjugate Pairs:	λ 4-5	λ 18-19	λ 98-99	λ 100-101	λ 110-111	λ 112-113
Interactions	SG4	All PSS in Area 1	Load 1-2, Network	Load 1-2, Network	Load 6-7, Network Slack	V Load 5, Transformer
Frequency Range	Slow Controller	Electromechanical Rotor	High Frequency (Cables)	High Frequency (Cables)	Very High Frequency (Cables)	Very High Frequency (Cables)
Damping component	Governor Action	PSS	Grid LC (passive)	Grid LC (passive)	Grid LC (passive)	Grid LC (passive)
Inter-area oscillation	No	No	No	No	No	No



STUDY CASE: GENERATOR REPLACEMENT – 1 VSC

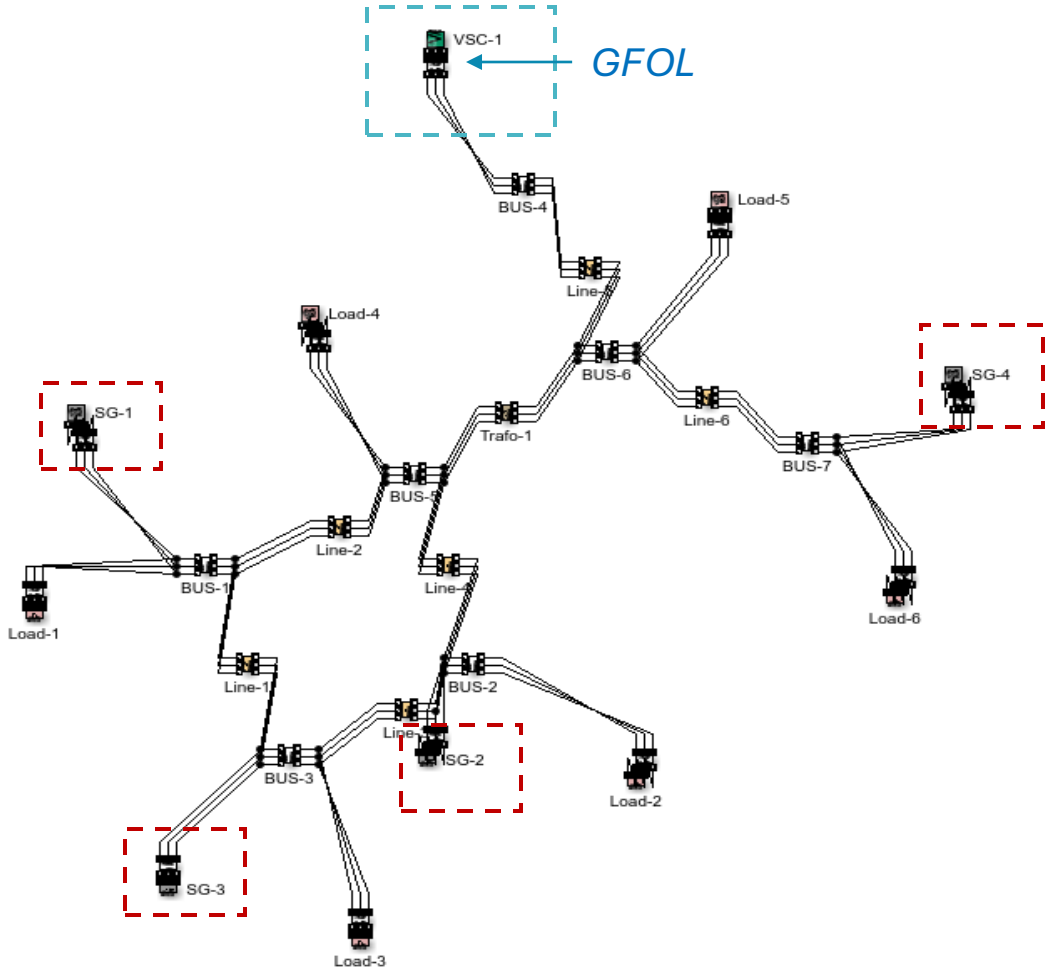
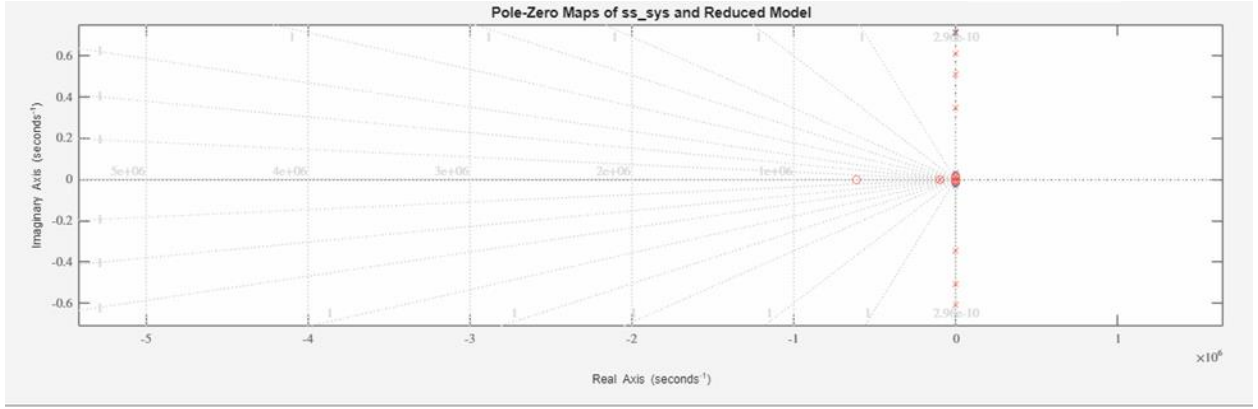


Figure 3. Non-linear Model Topology

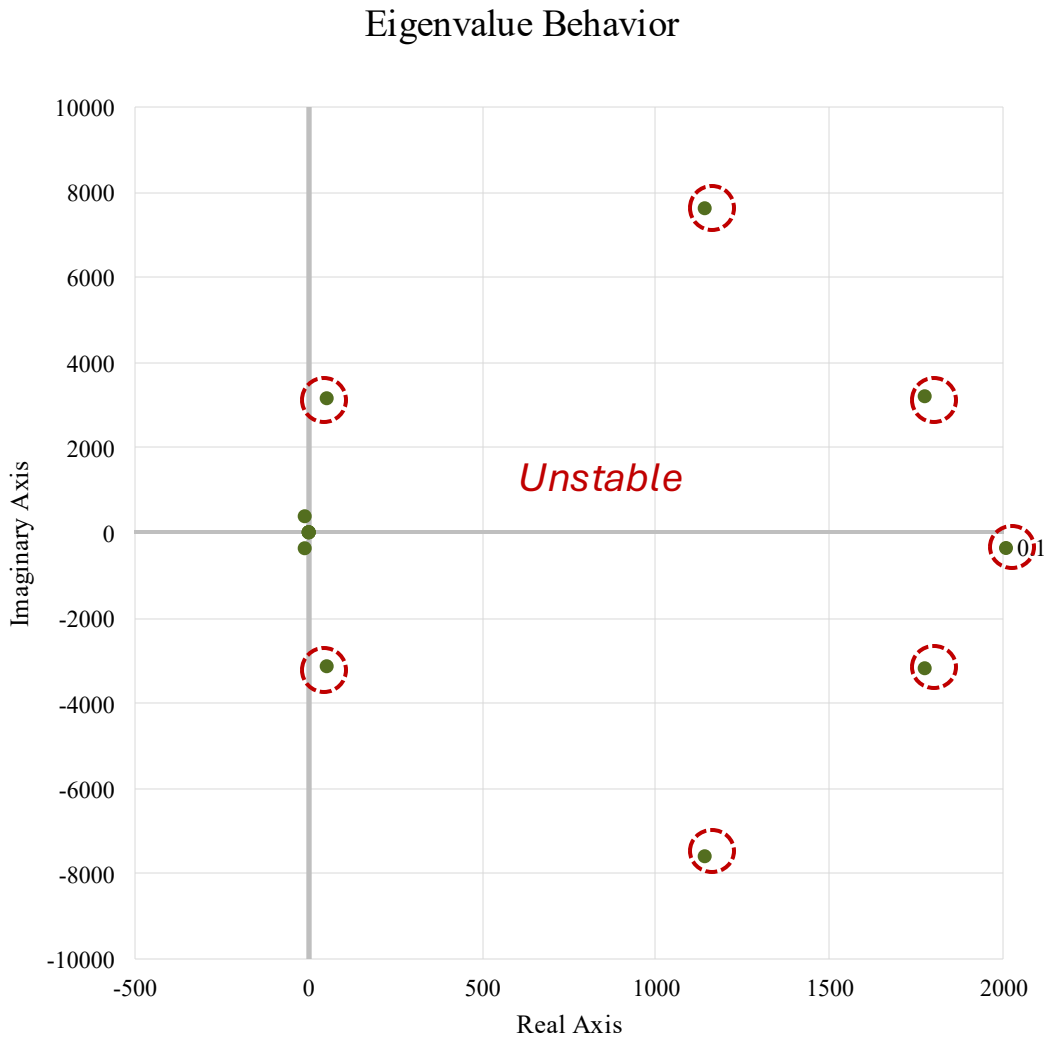
Voltage Source Converter Parameters

Mode	GFoL (Grid-Forllowig)
Rated Power (Sn)	1400 MVA at 500 kV
Power Injection	P = 1.332 pu, Q = -0.2003 pu
Droop Gains	kdroop_f= 0.5, kdroop_u = 2
PLL Damping	τPLL= 20 ms, ξPLL = 0.7



Reduced Model – Damping Curves

GENERATOR REPLACEMENT – 1 VSC GFOL DYNAMICS



Damping and Frequency Analysis

State N	Real	Imaginar	Freque	Dampi	Freque
1	1776.07072	3210.361	510.945	-48%	425.631
2	1776.07072	-3210.361	510.945	-48%	425.631
3	1142.30355	7606.1668	1210.56	-15%	1196.83
4	1142.30355	-7606.167	1210.56	-15%	1196.83
5	52.30648	3166.6716	503.991	-2%	503.923
6	52.30648	-3166.672	503.991	-2%	503.923
10	-0.24937	2.83391	0.45103	9%	0.44928
11	-0.24937	-2.83391	0.45103	9%	0.44928
27	-0.54267	5.39463	0.85858	10%	0.85423
28	-0.54267	-5.39463	0.85858	10%	0.85423
49	-8.09193	376.81791	59.9724	2%	59.9586
50	-8.09193	-376.8179	59.9724	2%	59.9586
59	-12.74053	376.9715	59.9969	3%	59.9626
60	-12.74053	-376.9715	59.9969	3%	59.9626
68	-15.98885	376.89233	59.9843	4%	59.9303
69	-15.98885	-376.8923	59.9843	4%	59.9303
78	-27.27014	376.98834	59.9996	7%	59.8424
79	-27.27014	-376.9883	59.9996	7%	59.8424
88	-421.97853	4678.2539	744.567	9%	741.532
89	-421.97853	-4678.254	744.567	9%	741.532
90	-430.49772	5432.2956	864.577	8%	861.858
91	-430.49772	-5432.296	864.577	8%	861.858
100	-1135.98449	20559.446	3272.14	6%	3267.14
101	-1135.98449	-20559.45	3272.14	6%	3267.14
102	-1136.02485	19805.46	3152.14	6%	3146.95
103	-1136.02485	-19805.46	3152.14	6%	3146.95

Nominal frequency excluded

Extraction of critical modes

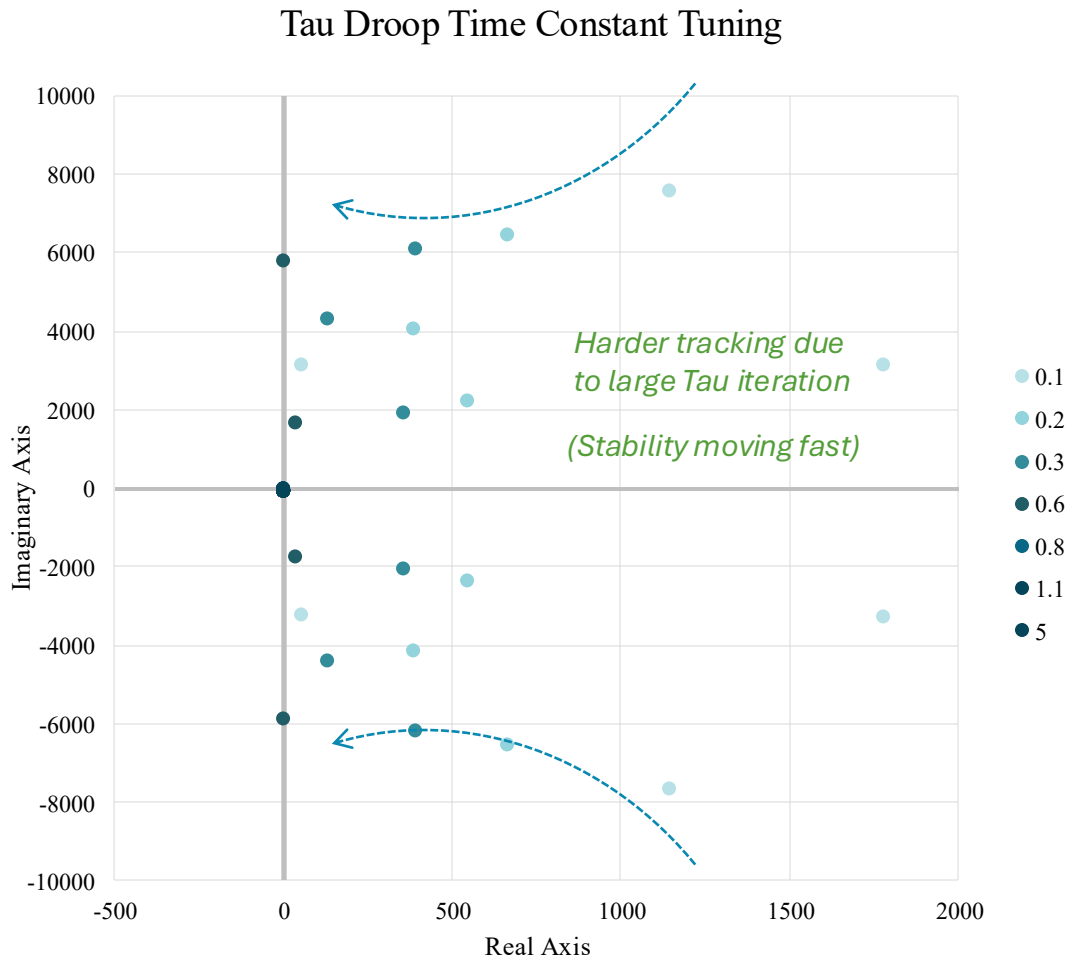
Conjugate Pairs:	λ 1-2	λ 3-4	λ 5-6	λ 10-11	λ 88-89	λ 90-91	λ 100-101	λ 102-103
Real	1776.071	1142.304	52.30648	-0.24937	-421.979	-430.498	-1135.98	-1136.02
Imaginary	3210.361	7606.167	3166.672	2.83391	4678.254	5432.296	20559.45	19805.46
Frequency	510.9448	1210.559	503.9914	0.45103	744.5672	864.5767	3272.137	3152.137
Damping	-48%	-15%	-2%	9%	9%	8%	6%	6%

VSC GFOL – STABILIZATION EFFORT

Low damped, low and high-frequency modes

Conjugate Pairs:	λ 1-2	λ 3-4	λ 5-6	λ 10-11	λ 88-89	λ 90-91	λ 100-101	λ 102-103
Real	1776.071	1142.304	52.30648	-0.24937	-421.979	-430.498	-1135.98	-1136.02
Imaginary	3210.361	7606.167	3166.672	2.83391	4678.254	5432.296	20559.45	19805.46
Frequency	510.9448	1210.559	503.9914	0.45103	744.5672	864.5767	3272.137	3152.137
Damping	-48%	-15%	-2%	9%	9%	8%	6%	6%
NET.iq13	0.02	0.00	0.24	0.00	0.73	0.78	0.00	0.00
NET.id13	0.00	0.00	0.02	0.00	0.79	0.74	0.00	0.00
NET.iq23	0.12	0.00	0.47	0.00	0.43	0.44	0.00	0.00
NET.id23	0.03	0.01	0.14	0.00	0.41	0.39	0.00	0.00
NET.iq46	0.00	0.00	0.00	0.01	0.00	0.00	0.41	0.41
NET.id46	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.41
Load2.vcq	0.35	0.03	1.00	0.00	0.18	0.18	0.00	0.00
Load3.vcq	0.02	0.00	0.11	0.00	0.95	1.00	0.00	0.00
Load3.vcd	0.01	0.00	0.03	0.00	1.00	0.95	0.00	0.00
Load4.vcq	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
Load4.vcd	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
SG3.is_q	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.40
SG3.is_d	0.00	0.00	0.00	1.00	0.00	0.00	0.44	0.39
SG3.if_d	0.00	0.00	0.00	0.96	0.00	0.00	0.01	0.01
SG3.w_pu	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00
SG3.e_th	0.00	0.00	0.00	0.46	0.00	0.00	0.00	0.00
SG4.is_d	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00
SG4.if_d	0.00	0.00	0.00	0.73	0.00	0.00	0.00	0.00
GFOL1.ig_q	1.00	0.19	0.66	0.00	0.07	0.05	0.00	0.00
GFOL1.ig_d	0.30	0.58	0.21	0.00	0.02	0.01	0.00	0.00
GFOL1.is_q	0.48	0.18	0.22	0.00	0.03	0.00	0.00	0.00
GFOL1.is_d	0.13	0.66	0.12	0.00	0.00	0.03	0.00	0.00
GFOL1.ucap_q	0.35	0.31	0.15	0.00	0.01	0.01	0.00	0.00
GFOL1.ucap_d	0.11	1.00	0.05	0.00	0.01	0.01	0.00	0.00
States								

Interactions	VSC currents, Load	Capacitance	VSC currents, Load	SG3, SG4 currents	AC Net, Load	AC Net, Load	SG3, AC Net, Load	SG3, AC Net, Load
Frequency Range	VSC Control	VSC Capacitance	VSC Control	Control Mode	VSC Control	VSC Control	Switching Dynamics	Switching Dynamics
Damping component	VSC Outer Loop	Inner current loop- LC filter	Decoupling	SG Excitation System	Load VC Loop, decoupling	Load VC Loop, decoupling	LCL/AC Filter, inner loop	LCL/AC Filter, inner loop
Inter-area oscillation	No	No	No	No	No	No	No	No

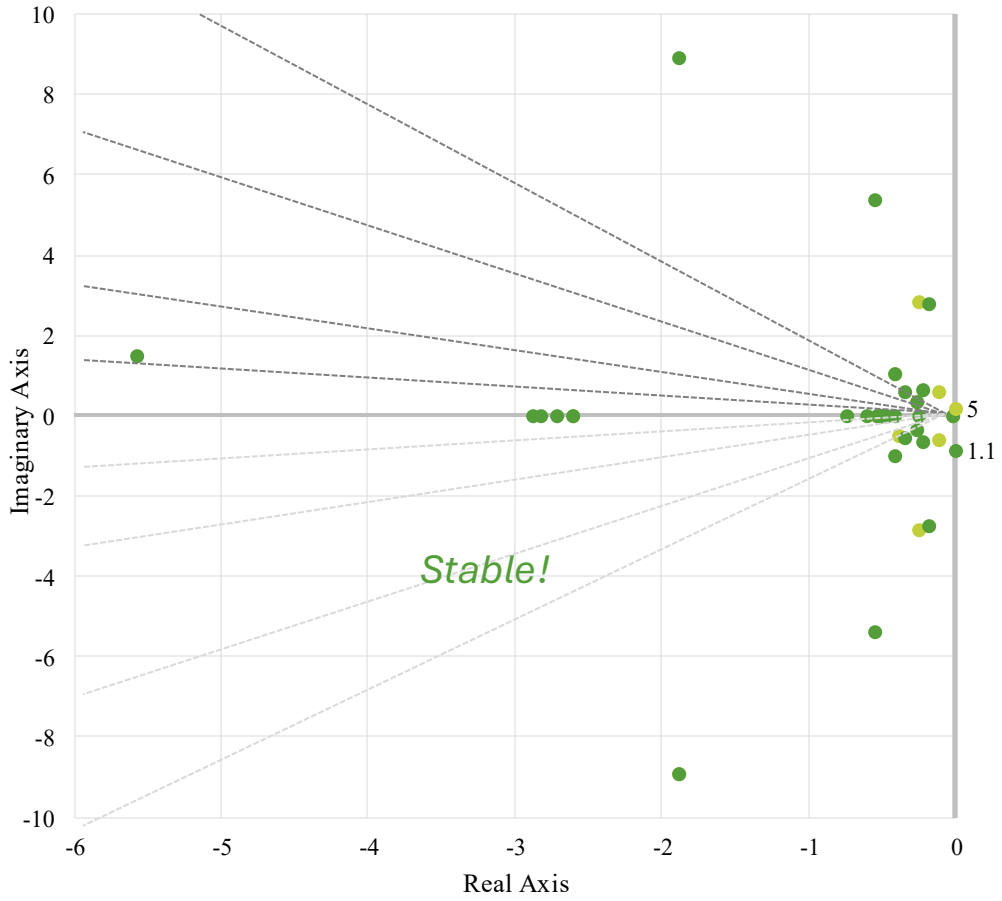


VSC GFOL – STABLE

Conjugate Pairs:	λ 1-2	λ 22-23	λ 81-82	λ 83-84	λ 88-89	λ 90-91	λ 100-101	λ 102-103
Real	-0.17537	-0.54062	-150.062	-181.943	-267.304	-305.591	-1135.98	-1136.02
Imaginary	2.767	5.39446	5789.089	4392.482	4823.042	5288.844	20559.45	19805.46
Frequency	0.44038	0.85856	921.3621	699.0853	767.611	841.7457	3272.137	3152.137
Damping	6%	10%	3%	4%	6%	6%	6%	6%
States								
NET.iq13	0.00	0.00	0.16	0.13	0.07	1.00	0.00	0.00
NET.id13	0.00	0.00	0.07	0.14	0.37	0.69	0.00	0.00
NET.iq23	0.00	0.00	0.47	0.21	0.26	0.14	0.00	0.00
NET.iq25	0.00	0.00	0.51	0.02	0.03	0.02	0.00	0.00
NET.iq46	0.00	0.01	0.18	0.00	0.00	0.00	0.41	0.41
NET.id46	0.00	0.00	0.18	0.00	0.00	0.00	0.41	0.41
Load1.vcq	0.00	0.00	0.21	0.03	0.01	0.33	0.00	0.00
Load1.vcd	0.00	0.00	0.35	0.03	0.10	0.21	0.00	0.00
Load2.vcq	0.00	0.00	0.32	0.36	0.55	0.25	0.00	0.00
Load2.vcd	0.00	0.00	0.09	0.49	0.24	0.08	0.00	0.00
Load3.vcq	0.00	0.00	0.05	0.21	0.17	0.98	0.00	0.00
Load3.vcd	0.00	0.00	0.12	0.24	0.47	0.76	0.00	0.00
Load4.vcq	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
Load4.vcd	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
Load6.vcq	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Load6.vcd	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
SG1.is_d	0.23	0.67	0.03	0.00	0.00	0.01	0.00	0.00
SG1.if_d	0.30	0.62	0.01	0.00	0.00	0.00	0.00	0.00
SG1.w_pu	0.07	0.69	0.00	0.00	0.00	0.00	0.00	0.00
SG1.e_th	0.02	0.90	0.00	0.00	0.00	0.00	0.00	0.00
SG2.is_d	0.23	0.73	0.01	0.02	0.01	0.06	0.00	0.00
SG2.if_d	0.30	0.65	0.00	0.00	0.00	0.01	0.00	0.00
SG2.w_pu	0.07	0.78	0.00	0.00	0.00	0.00	0.00	0.00
SG2.e_th	0.02	1.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.exc_x1	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.pss1_x1	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.pss1_x2	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.is_q	0.00	0.00	0.13	0.00	0.00	0.00	0.43	0.40
SG3.is_d	1.00	0.18	0.14	0.00	0.00	0.00	0.44	0.39
SG3.if_d	0.60	0.16	0.02	0.00	0.00	0.00	0.01	0.01
SG3.e_th	0.08	0.41	0.00	0.00	0.00	0.00	0.00	0.00
SG4.is_d	0.33	0.07	0.24	0.00	0.00	0.00	0.00	0.00
SG4.if_d	0.40	0.07	0.05	0.00	0.00	0.00	0.00	0.00
GFOL1.ig_q	0.00	0.00	0.56	0.65	1.00	0.92	0.00	0.00
GFOL1.ig_d	0.00	0.00	0.16	1.00	0.34	0.49	0.00	0.00
GFOL1.is_q	0.00	0.00	0.89	0.03	0.12	0.18	0.00	0.00
GFOL1.ucap_q	0.00	0.00	0.32	0.41	0.54	0.56	0.00	0.00
GFOL1.ucap_d	0.00	0.00	0.09	0.74	0.18	0.41	0.00	0.00
Interactions	GFOL	GFOL	GFOL	SG2, Load 6	Network	Load 3	Load 4	Load 4
Frequency Range	Mid-High (VSC)	High (VSC)	High (VSC)	Low	High	High	High	High
Damping component	Inner or outer controller	Inner or outer controller	Inner or outer controller	Governor action	Cable/Line	Cable/Line	Electromagnetic + Gov. action	Electromagnetic + Gov. action
Inter-area oscillation	No	No	No	No	No	No	No	No

Stable Case GFOL

$$\zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}$$



2 VSC GFOL (Two SG Replacement)

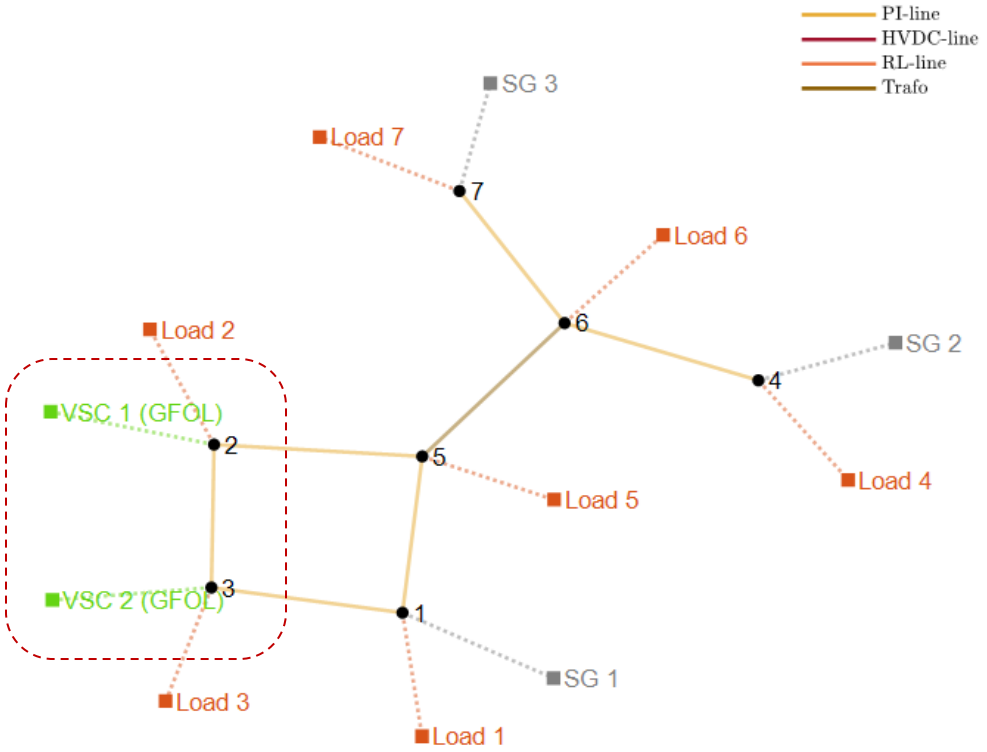
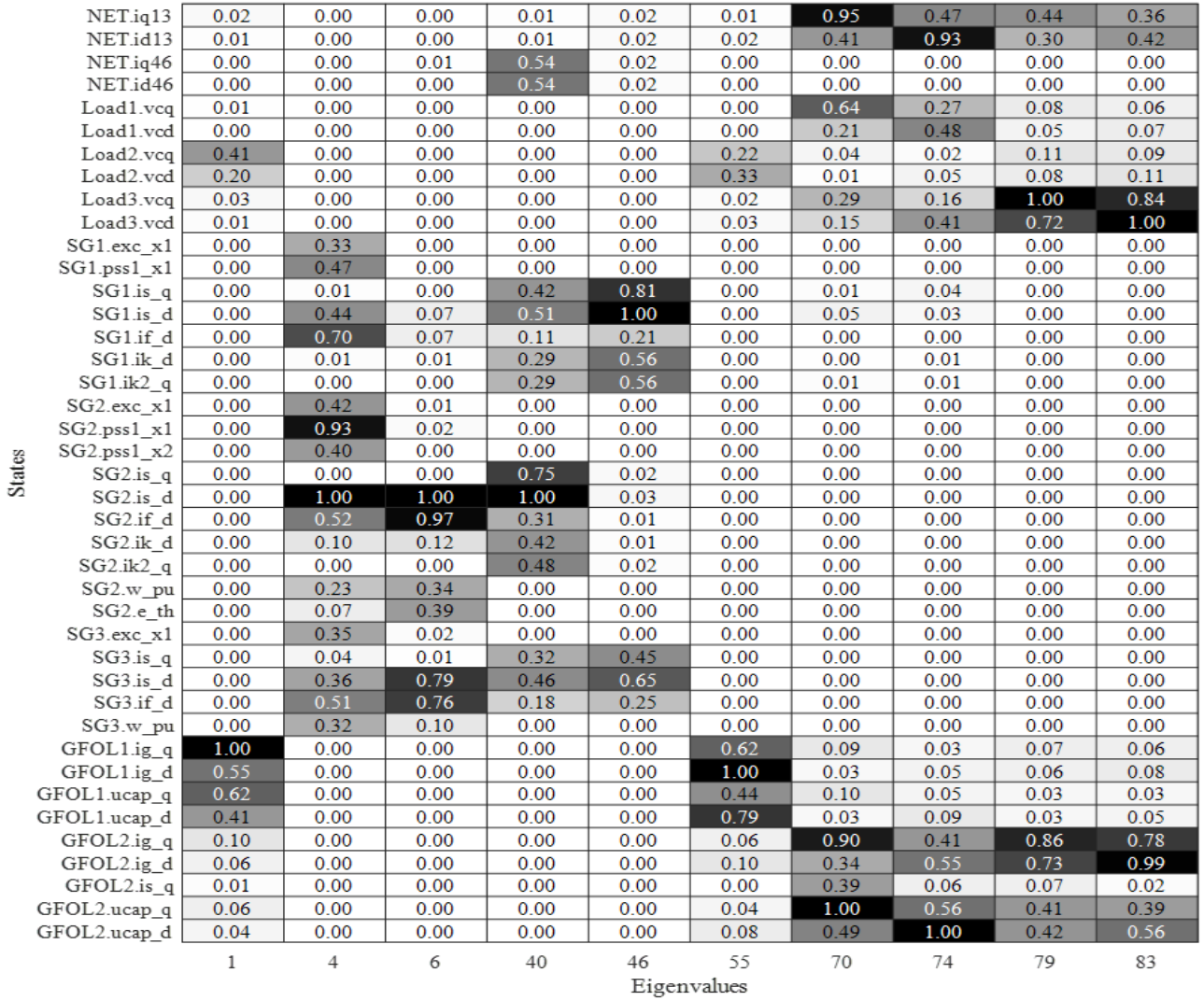
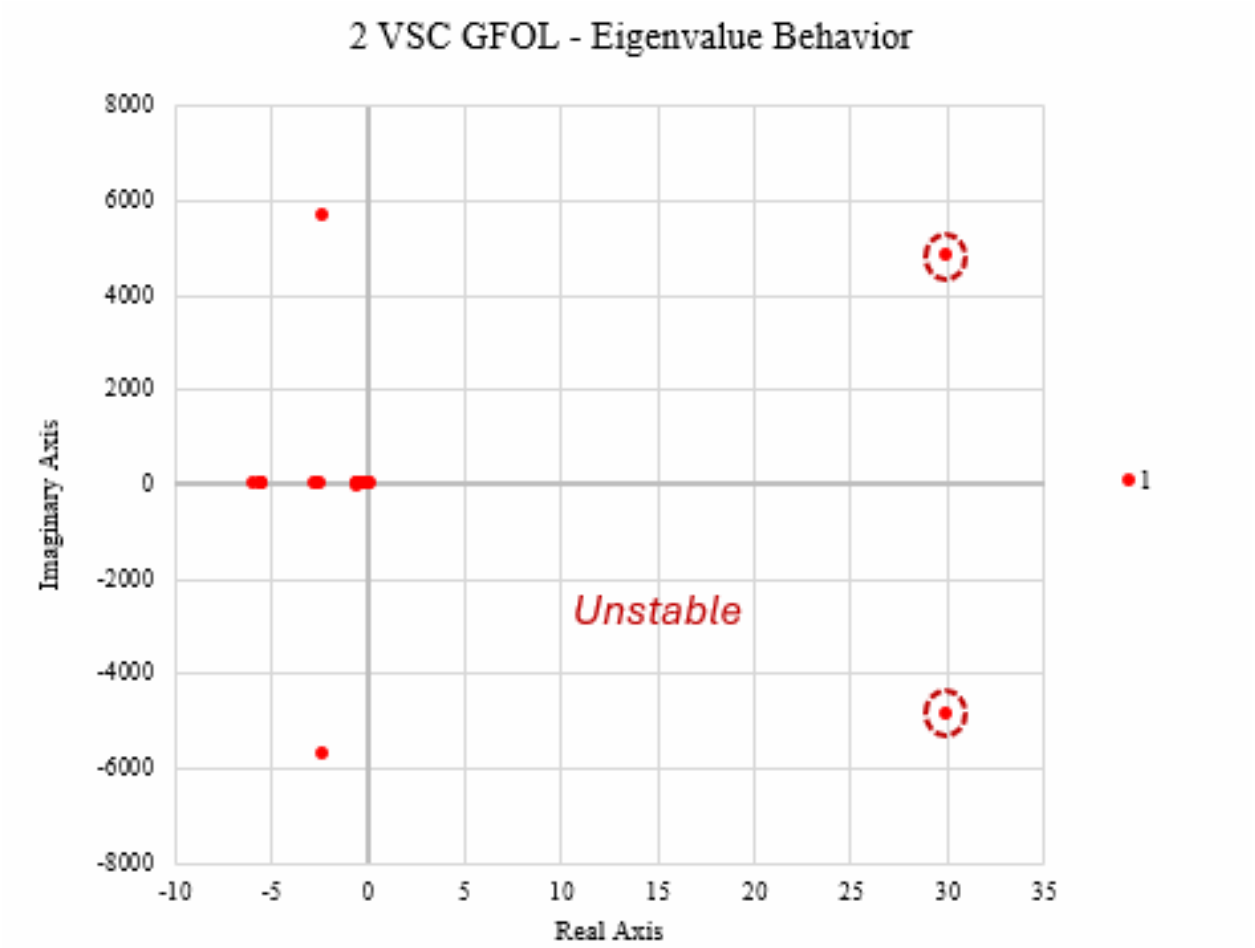


Figure 4. Non-linear Model Topology, 2 VSC Aggregation



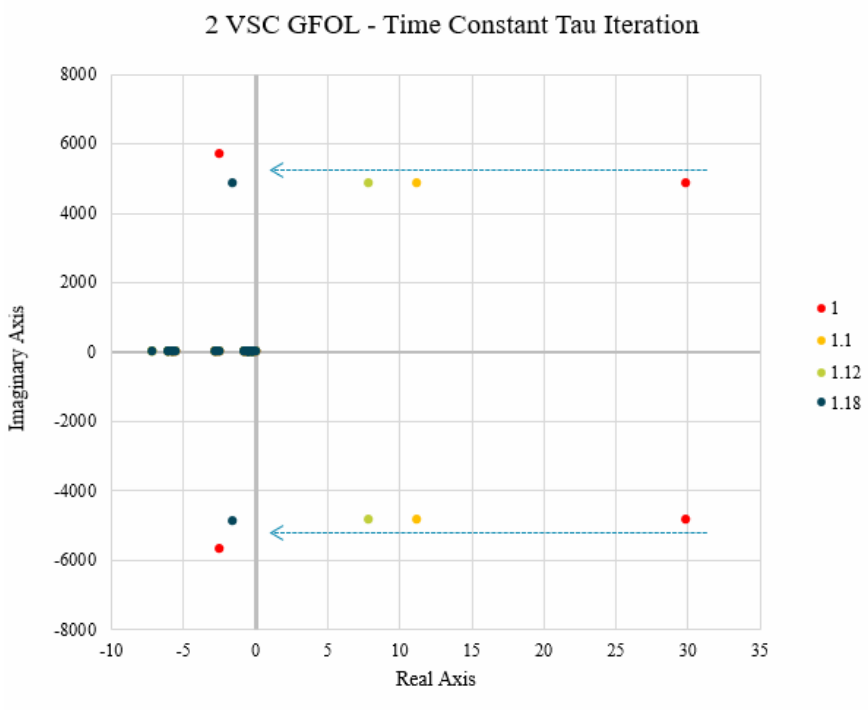


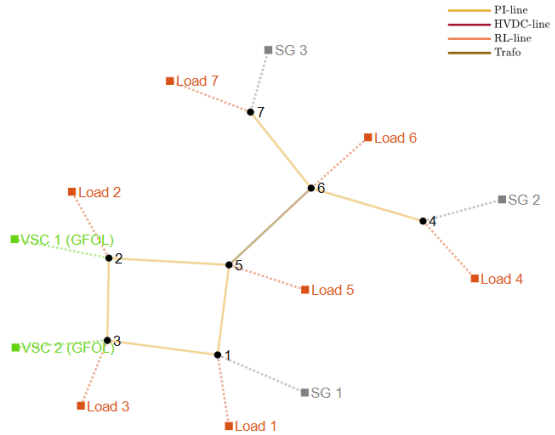
State Mod	Real	Imaginary	Frequency	Damping	Frequency
1	11.19239	4846.0746	771.27673	0%	771.27468
2	11.19239	-4846.0746	771.27673	0%	771.27468
6	-0.16968	2.66994	0.42493	6%	0.42408
7	-0.16968	-2.66994	0.42493	6%	0.42408
40	-12.53894	376.95121	59.99365	3%	59.96045
41	-12.53894	-376.95121	59.99365	3%	59.96045
46	-14.56594	376.89959	59.98543	4%	59.94062
47	-14.56594	-376.89959	59.98543	4%	59.94062
55	-21.37226	5698.7832	906.98952	0%	906.98314
56	-21.37226	-5698.7832	906.98952	0%	906.98314
58	-27.19843	376.99108	59.99999	7%	59.84364
59	-27.19843	-376.99108	59.99999	7%	59.84364
70	-115.76808	3201.0149	509.45735	4%	509.12406
71	-115.76808	-3201.0149	509.45735	4%	509.12406
74	-180.98483	4077.6467	648.97762	4%	648.33807
75	-180.98483	-4077.6467	648.97762	4%	648.33807
79	-225.71536	5780.3907	919.97774	4%	919.27609
80	-225.71536	-5780.3907	919.97774	4%	919.27609
83	-235.99726	6547.9309	1042.1356	4%	1041.4585
84	-235.99726	-6547.9309	1042.1356	4%	1041.4585
94	-1135.9845	20559.446	3272.1375	6%	3267.1388
95	-1135.9845	-20559.446	3272.1375	6%	3267.1388
96	-1136.0248	19805.46	3152.1369	6%	3146.9473
97	-1136.0248	-19805.46	3152.1369	6%	3146.9473

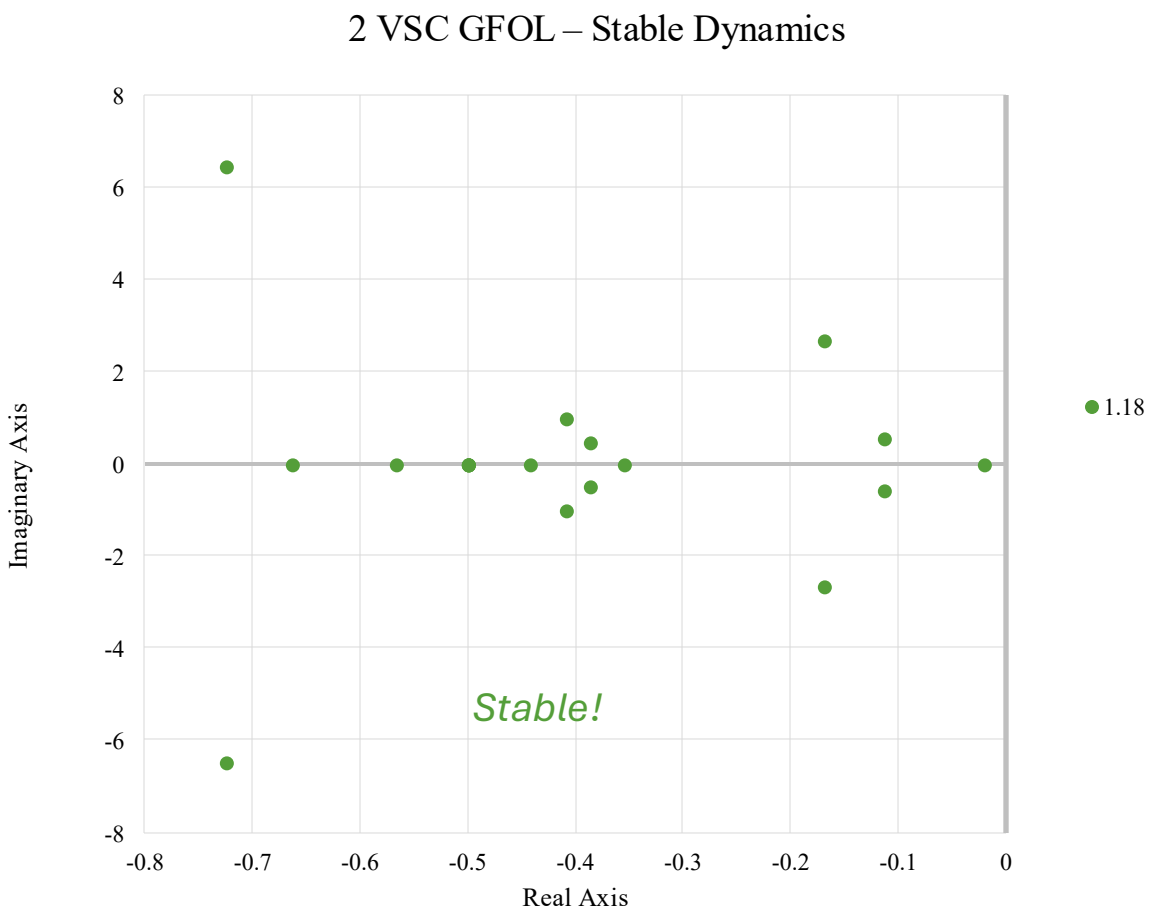
771.28	0.42	906.99	509.46	648.98	919.98	1042.14	3272.14	3152.14
0%	6%	0%	4%	4%	4%	4%	6%	6%
0.02	0.00	0.01	0.95	0.47	0.44	0.36	0.00	0.00
0.01	0.00	0.02	0.41	0.93	0.30	0.42	0.00	0.00
0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.41	0.41
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.41
0.01	0.00	0.00	0.64	0.27	0.08	0.06	0.00	0.00
0.00	0.00	0.00	0.21	0.48	0.05	0.07	0.00	0.00
0.41	0.00	0.22	0.04	0.02	0.11	0.09	0.00	0.00
0.20	0.00	0.33	0.01	0.05	0.08	0.11	0.00	0.00
0.03	0.00	0.02	0.29	0.16	1.00	0.84	0.00	0.00
0.01	0.00	0.03	0.15	0.41	0.72	1.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.40
0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.44	0.39
0.00	0.97	0.00	0.00	0.00	0.00	0.00	0.01	0.01
0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00	0.00	0.62	0.09	0.03	0.07	0.06	0.00	0.00
0.55	0.00	1.00	0.03	0.05	0.06	0.08	0.00	0.00
0.62	0.00	0.44	0.10	0.05	0.03	0.03	0.00	0.00
0.41	0.00	0.79	0.03	0.09	0.03	0.05	0.00	0.00
0.10	0.00	0.06	0.90	0.41	0.86	0.78	0.00	0.00
0.06	0.00	0.10	0.34	0.55	0.73	0.99	0.00	0.00
0.01	0.00	0.00	0.39	0.06	0.07	0.02	0.00	0.00
0.06	0.00	0.04	1.00	0.56	0.41	0.39	0.00	0.00
0.04	0.00	0.08	0.49	1.00	0.42	0.56	0.00	0.00
1	6	55	70	74	79	83	94	96

Eigenvalues

OL 1 ap, ig & Load cq	SG2 is/fd, w, e & SG3 is/fd	GFOL 1 ucap, ig qd, & Load 2 vcd	GFOL 2, AC Net 13 & Load 1vcq	GFOL 2, AC Net 13, Load 1 & 3	Load 3 q voltages & GFOL 2 q currents	Load 3 d voltages & GFOL 2 d currents	Load 4 qd voltages & Network 4-6, SG2	Load 4 qd voltages & Network 4-6, SG2
gh (VSC)	Low	High (VSC)	High (VSC)	High (VSC)	High (VSC)	Very High (VSC)	Very High	Very High
	PSS, AVR,	Inner/outer loop &	Inner/outer loop &	Inner/outer loop &	Inner/outer loop &	Inner/outer loop &	Cable/lines	Cable/lines

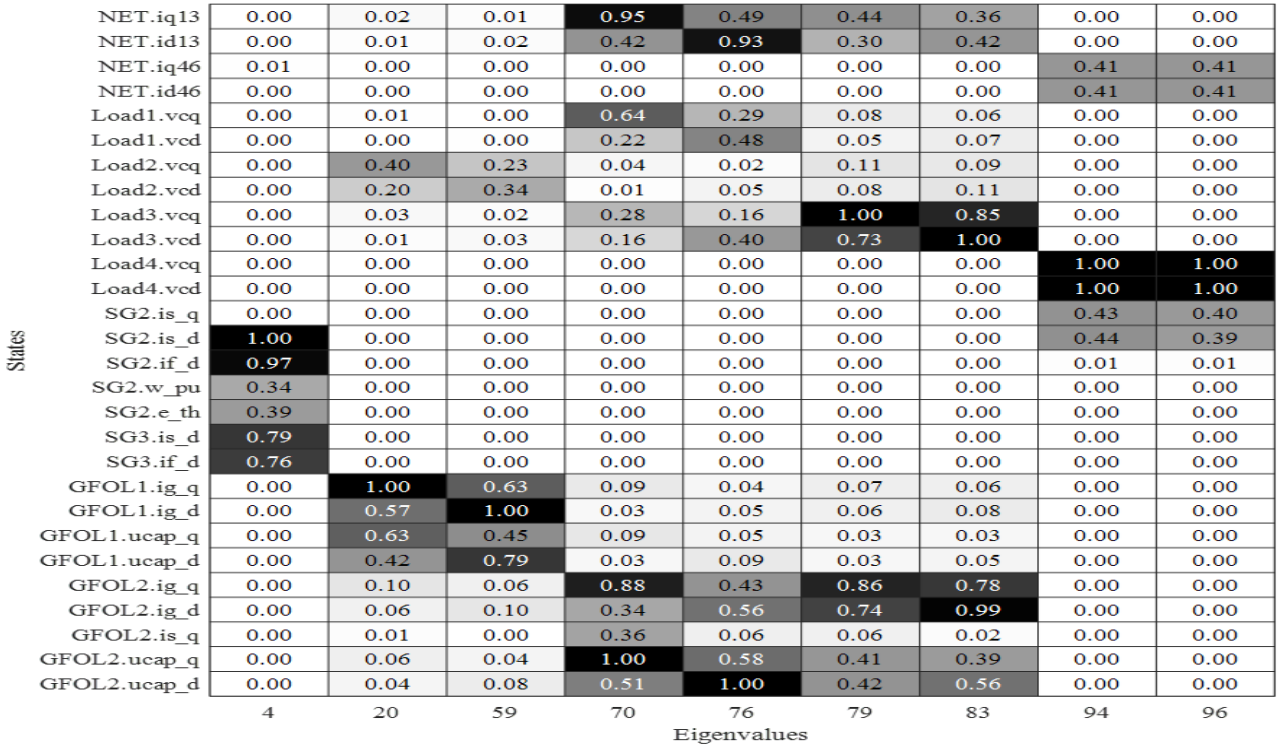


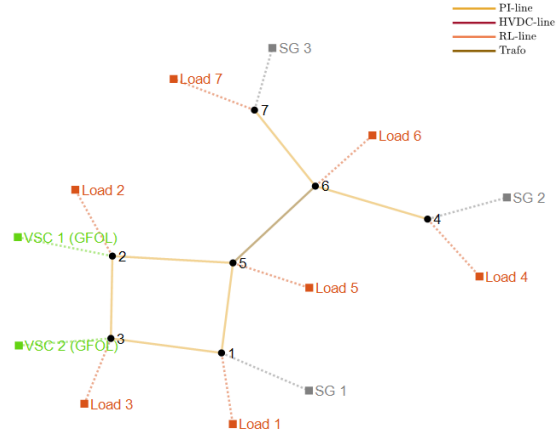




State Mode	Real	Imaginary	Frequency	Damping	Frequency F
4	-0.16974	2.66993	0.42493	6%	0.42407
5	-0.16974	-2.66993	0.42493	6%	0.42407
20	-1.60211	4851.4766	772.13648	0%	772.13644
21	-1.60211	-4851.4766	772.13648	0%	772.13644
40	-12.53919	376.95147	59.99369	3%	59.96049
41	-12.53919	-376.95147	59.99369	3%	59.96049
46	-14.56441	376.9006	59.98559	4%	59.94079
47	-14.56441	-376.9006	59.98559	4%	59.94079
56	-27.19789	376.99138	60.00004	7%	59.84369
57	-27.19789	-376.99138	60.00004	7%	59.84369
59	-34.11813	5693.50209	906.149	1%	906.13273
60	-34.11813	-5693.50209	906.149	1%	906.13273
70	-128.77068	3207.93376	510.55852	4%	510.14701
71	-128.77068	-3207.93376	510.55852	4%	510.14701
76	-189.17665	4070.49974	647.84015	5%	647.14013
77	-189.17665	-4070.49974	647.84015	5%	647.14013
79	-231.68773	5782.00873	920.23527	4%	919.49619
80	-231.68773	-5782.00873	920.23527	4%	919.49619
83	-242.14897	6548.42025	1042.21345	4%	1041.50065
84	-242.14897	-6548.42025	1042.21345	4%	1041.50065
94	-1135.98449	20559.4462	3272.13749	6%	3267.13881
95	-1135.98449	-20559.4462	3272.13749	6%	3267.13881
96	-1136.02484	19805.4604	3152.13692	6%	3146.94726
97	-1136.02484	-19805.4604	3152.13692	6%	3146.94726

Conjugate Pairs:	λ 4-5	λ 20-21	λ 59-60	λ 70-71	λ 76-77	λ 79-80	λ 83-84	λ 94-95	λ 96-97
Real	-0.17	-1.60	-34.12	-128.77	-189.18	-231.69	-242.15	-1135.98	-1136.02
Imaginary	2.67	4851.48	5693.50	3207.93	4070.50	5782.01	6548.42	20559.45	19805.46
Frequency	0.42	772.14	906.15	510.56	647.84	920.24	1042.21	3272.14	3152.14
Damping	6%	0%	1%	4%	5%	4%	4%	6%	6%





Interactions	SG 2 and 3 field currents	GFOL 1 currents and voltages	GFOL 1 currents and voltages	GFOL 2 and Network q-axis	GFOL 2 and Network d-axis	GFOL 2 ig qd & Load 3 qd voltages	GFOL 2 ig qd & Load 3 qd voltages	Load 4 qd voltages & AC net 4-6 ITAIPU	Load 4 qd voltages & AC net 4-6 ITAIPU
Frequency Range	<0.5 Hz	Med-High frequency	High frequency	High frequency	High frequency	Switching frequency	Switching frequency	Very High	Very High
Damping component	PSS, AVR, Gov. Action	Inner/outer loop	Inner/outer loop	LC passive	LC passive	Inner/outer loop	Inner/outer loop	Cable/line filters	Cables/line filters
Inter-area oscillation	Yes	No	No	No	No	No	No	No	No

Comparison on poor damped modes (a) 2 VSC Addition, (b) 1 VSC

States	4	20	59	70	76	79	83	94	96
NET.iq13	0.00	0.02	0.01	0.95	0.49	0.44	0.36	0.00	0.00
NET.id13	0.00	0.01	0.02	0.42	0.93	0.30	0.42	0.00	0.00
NET.iq46	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.41
NET.id46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.41
Load1.vcq	0.00	0.01	0.00	0.64	0.29	0.08	0.06	0.00	0.00
Load1.vcd	0.00	0.00	0.00	0.22	0.48	0.05	0.07	0.00	0.00
Load2.vcq	0.00	0.40	0.23	0.04	0.02	0.11	0.09	0.00	0.00
Load2.vcd	0.00	0.20	0.34	0.01	0.05	0.08	0.11	0.00	0.00
Load3.vcq	0.00	0.03	0.02	0.28	0.16	1.00	0.85	0.00	0.00
Load3.vcd	0.00	0.01	0.03	0.16	0.40	0.73	1.00	0.00	0.00
Load4.vcq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
Load4.vcd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
SG2.is_q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.40
SG2.is_d	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.39
SG2.if_d	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
SG2.w_pu	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG2.e_th	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.is_d	0.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.if_d	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GFOL1.ig_q	0.00	1.00	0.63	0.09	0.04	0.07	0.06	0.00	0.00
GFOL1.ig_d	0.00	0.57	1.00	0.03	0.05	0.06	0.08	0.00	0.00
GFOL1.ucap_q	0.00	0.63	0.45	0.09	0.05	0.03	0.03	0.00	0.00
GFOL1.ucap_d	0.00	0.42	0.79	0.03	0.09	0.03	0.05	0.00	0.00
GFOL2.ig_q	0.00	0.10	0.06	0.88	0.43	0.86	0.78	0.00	0.00
GFOL2.ig_d	0.00	0.06	0.10	0.34	0.56	0.74	0.99	0.00	0.00
GFOL2.is_q	0.00	0.01	0.00	0.36	0.06	0.06	0.02	0.00	0.00
GFOL2.ucap_q	0.00	0.06	0.04	1.00	0.58	0.41	0.39	0.00	0.00
GFOL2.ucap_d	0.00	0.04	0.08	0.51	1.00	0.42	0.56	0.00	0.00

Eigenvalues

States	2	22	81	83	88	90	101	103
NET.iq13	0.00	0.00	0.16	0.13	0.07	1.00	0.00	0.00
NET.id13	0.00	0.00	0.07	0.14	0.37	0.69	0.00	0.00
NET.iq23	0.00	0.00	0.47	0.21	0.26	0.14	0.00	0.00
NET.iq25	0.00	0.00	0.51	0.02	0.03	0.02	0.00	0.00
NET.iq46	0.00	0.01	0.18	0.00	0.00	0.00	0.41	0.41
NET.id46	0.00	0.00	0.18	0.00	0.00	0.00	0.41	0.41
Load1.vcq	0.00	0.00	0.21	0.03	0.01	0.33	0.00	0.00
Load1.vcd	0.00	0.00	0.35	0.03	0.10	0.21	0.00	0.00
Load2.vcq	0.00	0.00	0.32	0.36	0.55	0.25	0.00	0.00
Load2.vcd	0.00	0.00	0.09	0.49	0.24	0.08	0.00	0.00
Load3.vcq	0.00	0.00	0.05	0.21	0.17	0.98	0.00	0.00
Load3.vcd	0.00	0.00	0.12	0.24	0.47	0.76	0.00	0.00
Load4.vcq	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
Load4.vcd	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
Load6.vcq	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Load6.vcd	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
SG1.is_d	0.23	0.67	0.03	0.00	0.00	0.01	0.00	0.00
SG1.if_d	0.30	0.62	0.01	0.00	0.00	0.00	0.00	0.00
SG1.w_pu	0.07	0.69	0.00	0.00	0.00	0.00	0.00	0.00
SG1.e_th	0.02	0.90	0.00	0.00	0.00	0.00	0.00	0.00
SG2.is_d	0.23	0.73	0.01	0.02	0.01	0.06	0.00	0.00
SG2.if_d	0.30	0.65	0.00	0.00	0.00	0.01	0.00	0.00
SG2.w_pu	0.07	0.78	0.00	0.00	0.00	0.00	0.00	0.00
SG2.e_th	0.02	1.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.exc_x1	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.pss1_x1	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.pss1_x2	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SG3.is_q	0.00	0.00	0.13	0.00	0.00	0.00	0.43	0.40
SG3.is_d	1.00	0.18	0.14	0.00	0.00	0.00	0.44	0.39
SG3.if_d	0.60	0.16	0.02	0.00	0.00	0.00	0.01	0.01
SG3.e_th	0.08	0.41	0.00	0.00	0.00	0.00	0.00	0.00
SG4.is_d	0.33	0.07	0.24	0.00	0.00	0.00	0.00	0.00
SG4.if_d	0.40	0.07	0.05	0.00	0.00	0.00	0.00	0.00
GFOL1.ig_q	0.00	0.00	0.56	0.65	1.00	0.92	0.00	0.00
GFOL1.ig_d	0.00	0.00	0.16	1.00	0.34	0.49	0.00	0.00
GFOL1.is_q	0.00	0.00	0.89	0.03	0.12	0.18	0.00	0.00
GFOL1.ucap_q	0.00	0.00	0.32	0.41	0.54	0.56	0.00	0.00
GFOL1.ucap_d	0.00	0.00	0.09	0.74	0.18	0.41	0.00	0.00

Eigenvalues

* No inter-area oscillations observed.

Stability Insights and Conclusions

Weak grid structure:
High line impedance and low short-circuit strength reduce the system's ability to damp oscillations naturally.

Loss of inertia with VSCs:
Replacing SGs with VSCs removes natural inertia and damping; dynamics now rely entirely on control systems.

Poor observability and controllability:
The critical modes are concentrated in Area II (SG4 & SG5), but actuation from control points is limited.

Low natural damping:
Existing synchronous machines already provide minimal damping (<5%), leaving little margin for disturbances.

Modal interaction with control loops:
VSCs introduce control modes (from PLLs and Current/ voltage regulators) that can resonate or interfere with electromechanical modes.

Intra area oscillations emerge:
Frequency modes (0.2–0.7 Hz) indicate inter-area swings between voltage zones, hard to damp without coordinated controls.

Literature Review and References

- [1] Chea, M. (s.f.). CITCEA. Modal analysis tool for large power systems.
- [2] Chea, M. et al (2021). WIREs. Modeling and analysis approaches for small-signal stability assessment of power-electronic-dominated systems.
- [3] Alican, O. et al. (s.f.). CITCEAA-UPC. Small-signal models of power system components for stability analysis
- [4] Power System Dynamic Performance Committee. (2015). Benchmark Systems for Small-Signal Stability Analysis and Control.