NASPI Work Group Meeting, Oct 7, 2021

GE’s Solution –
2021 IEEE-NASPI Oscillation Source Location Contes

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Agenda

About the Contest

- Contest Challenges
- WECC 240-bus Test System
- Evaluation Criteria

GE's Results

- Results Summary
- Strategies

Case Study

- Case # 9, 6, 10

2021 IEEE-NASPI Oscillation Source Location (OSL) Contest

Tied for 1st Place: Team Woodpecker – from General Electric

Contest Objective:

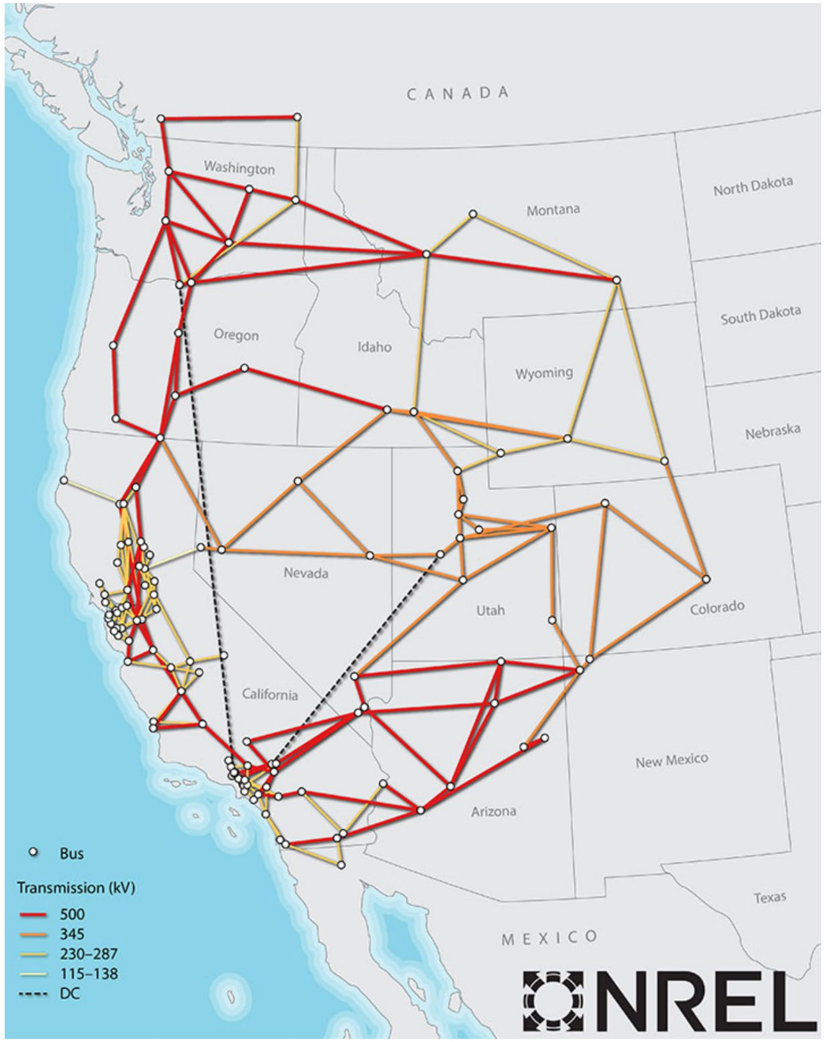
- **Oscillations** are a significant concern for reliable power system operation.
- **Locating the "sources"** is the first step to **mitigate** them
- **Evaluate** constants' OSL methods and highlight the robust methods

Contest Challenges:

- **White noise** is added to the load to mimic **random load fluctuations**
- **Data quality problems** present in the provided PMU data
- **A mix of P Class** (2-cycle window) **and M Class** (6-cycle window) **PMUs**
- Sustained oscillations may be **forced** or due to a poorly damped **natural** mode
- A forced oscillation may **resonate** with a natural mode
- Source(s): **synchronous machine, load, HVDC, or any combination**
- **Frequency and amplitude** of a forced oscillation may be **time-varying**
- **Source(s)** of an oscillation, **may not be monitored** by or close to a PMU
- A **short-circuit fault and/or a line tripping event** may initiate the oscillation(s)

13 cases reflect **real-world challenges**

Contest main website: https://www.naspi.org/node/890



The 240-bus Western Electricity Coordinating Council (WECC) model

Case Summary[1] :

243 AC Buses

146 Generators at 56 power plants

- 109 Conventional model set with GOV, EXC, PSS etc.
- 37 Renewable model set

139 Loads

329 Lines and 122 Transformers

Four areas: NORTH, SOUTH, CALIFORNIA, and MEXICO

HVDC terminals at CELILO and SYLMARLA

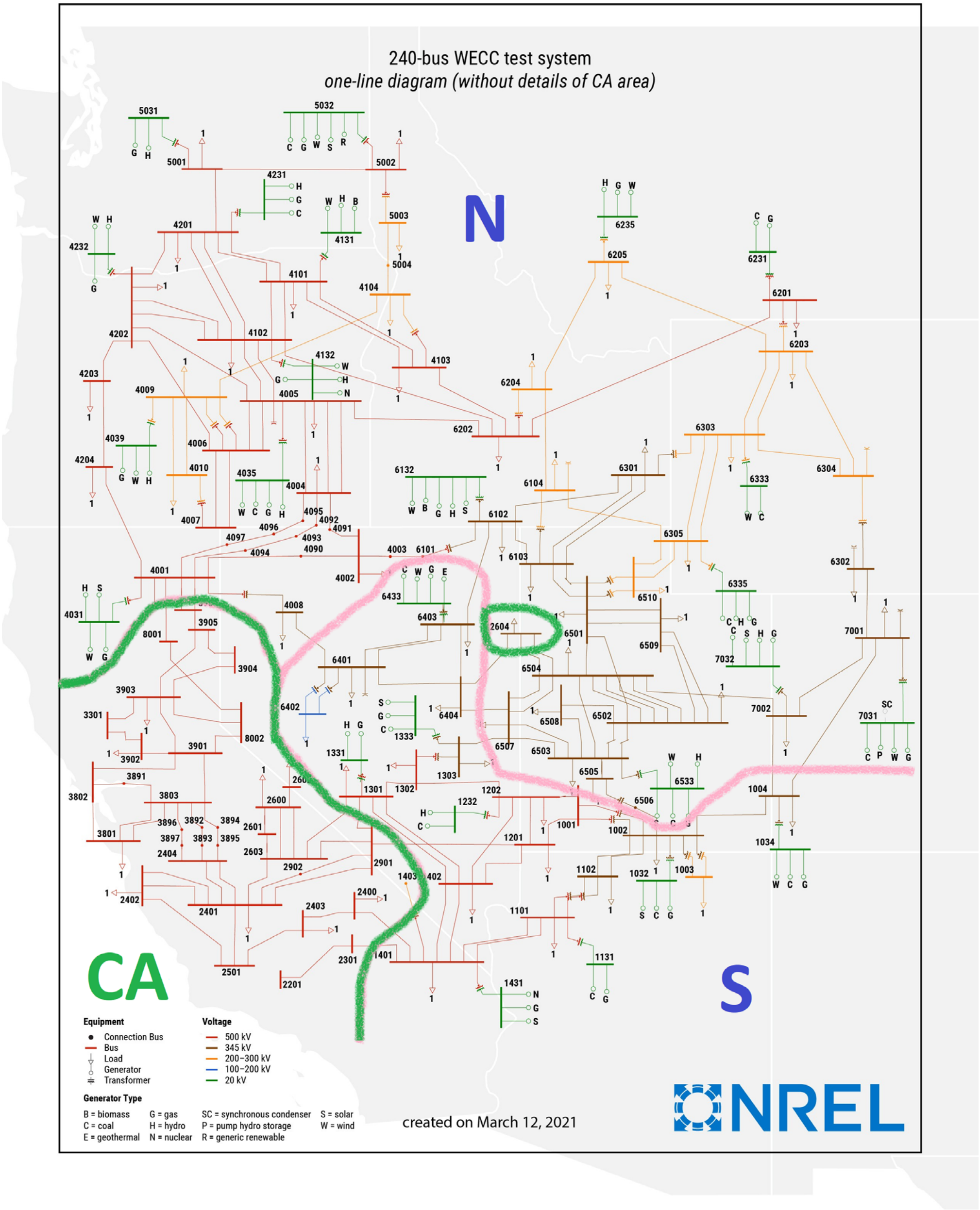
PMU Coverage in the Contest Dataset:

PMUs voltage phasors coverage:

- 58 of 243 buses are monitored

PMUs current phasors coverage:

- 23 of 56 power plants are monitored
- 23 tie-lines between areas
- Total current phasors: 49, 50, 68, or 89



[1] H. Yuan, R. S. Biswas, J. Tan and Y. Zhang, "Developing a Reduced 240-Bus WECC Dynamic Model for Frequency Response Study of High Renewable Integration," 2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), 2020, pp. 1-5, doi: 10.1109/TD39804.2020.9299666.

Contest Evaluation Criteria

Scoring Criteria from contest committee:

1. Total score of for each field is listed on the solution template.

2. Evidence/explanation

Case #	Frequency (Hz)	Area Name	Bus #	Asset Type	Controller
N/A	N/A	3 pt.	+3 pt. – correct +1 pt. – within 1 bus +0 pt. – other	+1 pt. – correct +0 pt. – N/A -1 pt. – wrong	+1 pt. – correct +0 pt. – N/A -1 pt. – wrong

1. Total case **score = 0 if Area is wrong**
2. Asset Type: choose from **Generator, Load, HVDC or N/A** if not sure or not specific.
3. Controller: choose from **Exciter, Governor, Other or N/A** if not sure or not specific.

Woodpecker's Results Summary

Unsure the Asset Type

Missed the OSL bus

Missed the Controller

Blue: OSL's flow is not monitored
Purple: Load, not Gen
Orange: HVDC, not Gen
Green: OSL's flow is monitored

Overlooked OSC Freq @1.22 Hz

Case	Frequency	Area	Bus	Asset Type	Controller	Bus/Brn monitored
1	✓	✓	✓	✓	✓	58/89
2	✓	✓	✓	✓	✓	58/89
3	✓	✓	✓	×	×	58/89
4	✓	✓	×	✓	×	58/89
5	✓	✓	✓	✓	×	58/89
6	✓	✓	✓	✓	✓	58/50
7	✓	✓	✓	✓	✓	58/89
8	✓	✓	✓	✓	✓	58/49
9	✓	✓	✓	✓	✓	58/89
	✓	✓	✓	✓	✓	
10	✓	✓	✓	✓	✓	58/68
	×					
11	✓	✓	✓	✓	✓	58/89
12	✓	✓	✓	✓	✓	58/89
13	✓	✓	✓	✓	✓	58/89
	✓	✓	✓	✓	✓	58/89

Strategies used in this contest

Challenges	Countermeasures	Tools/Data	Impact
White noise is added to the load to mimic **random load fluctuations**	Oscillation detection	FFT	low
Data quality problems present in the provided PMU data	Data preprocessor	Bad data detection; Data gap filling	medium
A mix of P Class(2-cycle window) **and M Class** (6-cycle window) **PMUs**	Be mindful	Simple load flow estimation	high
Sustained oscillations may be **forced** or due to a poorly damped **natural** mode A forced oscillation may **resonate** with a natural mode	Select proper time window; DEF method; OSL verifications	Equipment models; Playback simulations	low
Frequency and amplitude of a forced oscillation may be **time -varying**	Target on one frequency	FFT, DEF	low
Source(s): **synchronous machine, load, HVDC, or any combination**	OSL verifications	Equipment models; Playback simulations	low
Source(s) of an oscillation, **may not be monitored** by or close to a PMU	Machine learning	System models; Simulations	high
A **short -circuit fault and/or a line tripping event** may initiate the oscillation(s)	Select proper time window	Oscillation time-window estimation	medium

Dissipating Energy Flow (DEF)

The **oscillation energy** [1] is flowing <u>from</u> the source <u>to</u> the devices, where the energy is **dissipated** .

Energy flow is composed of two components:

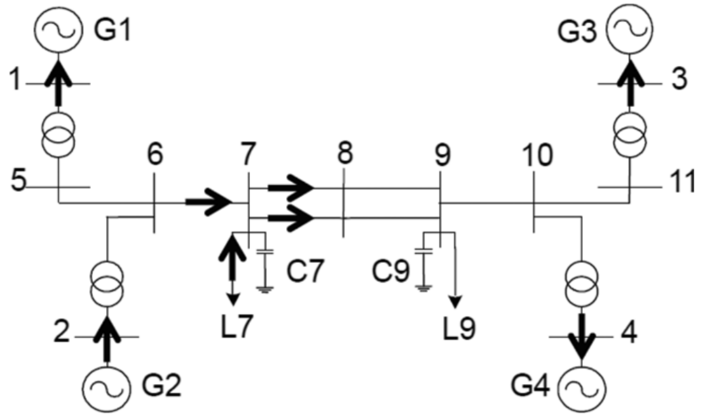
- transient energy
- energy dissipated

$$\int \mathrm{Im}(-\boldsymbol{I}_{\boldsymbol{Gi}}^{*}\mathrm{d}\boldsymbol{U}_{\boldsymbol{i}}) = \left(\frac{1}{2}T_{Ji}\omega_0\omega_i^2 - P_{mi}\delta_i\right) + \int D_i\omega_0\omega_i^2\mathrm{d}t.$$

The equation of the energy flow:

$$W_{ij} = \int (P_{ij,s}\mathrm{d}\Delta\theta_i + Q_{ij,s}\mathrm{d}(\Delta\ln U_i)) + \int (\Delta P_{ij}\mathrm{d}\Delta\theta_i + \Delta Q_{ij}\mathrm{d}(\Delta\ln U_i)).$$

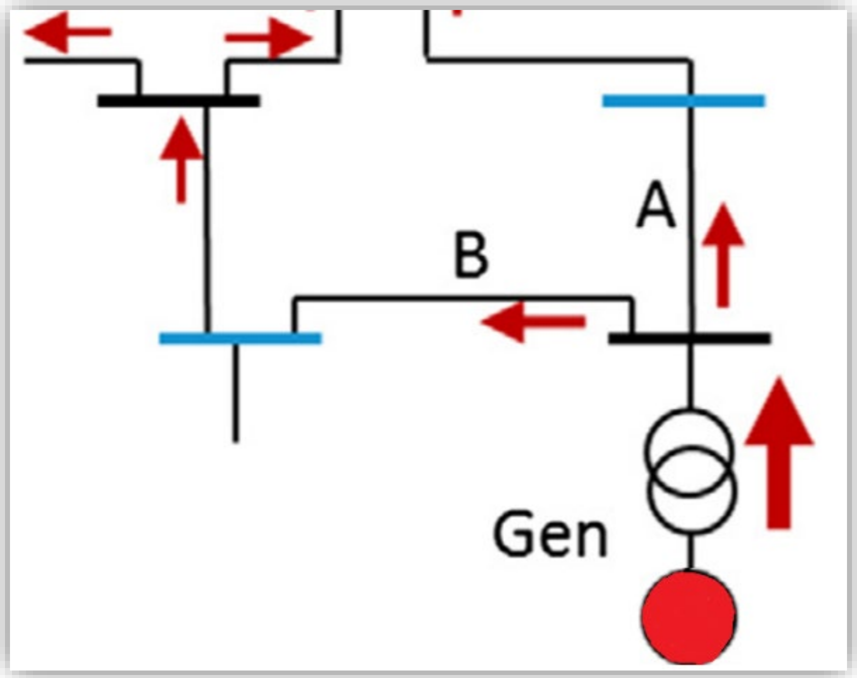
ISONE [2] implemented DEF method for online OSL.

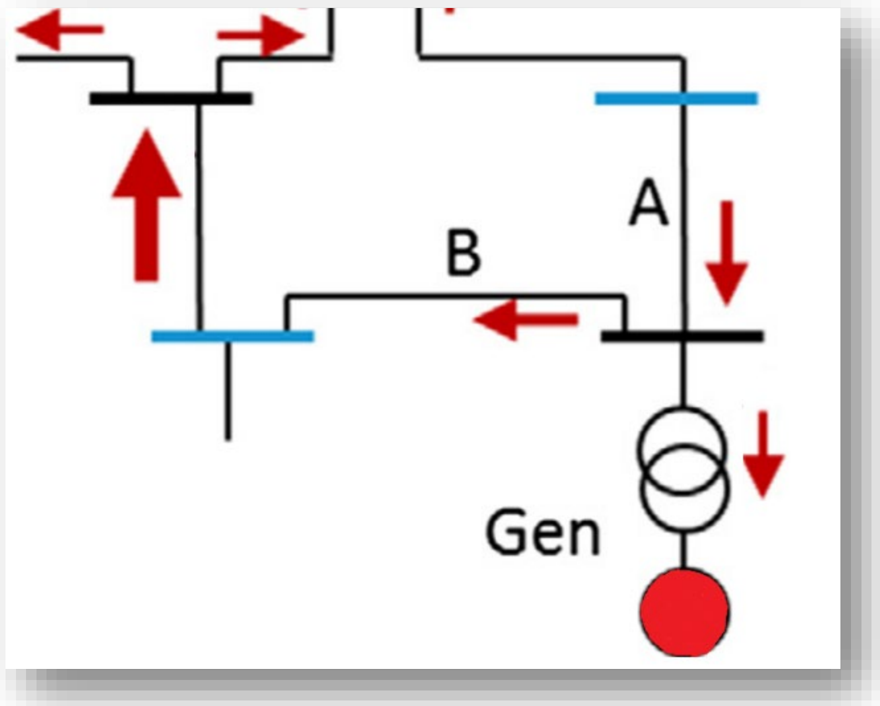


[1] L. Chen, Y. Min and W. Hu, "An energy-based method for location of power system oscillation source," in IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 828-836, May 2013.
[2] S. Maslennikov and E. Litvinov, "ISO New England Experience in Locating the Source of Oscillations Online," in IEEE Transactions on Power Systems, vol. 36, no. 1, pp. 495-503, Jan. 2021.

Dissipating Energy Flow (DEF) - continued

- Impact to the DEF values [2] : resistances, load model, and etc.
- The pattern of DEF values may reveal the disguised OSL.





[1] L. Chen, Y. Min and W. Hu, "An energy-based method for location of power system oscillation source," in IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 828-836, May 2013.
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Dissipating Energy Flow (DEF) - continued

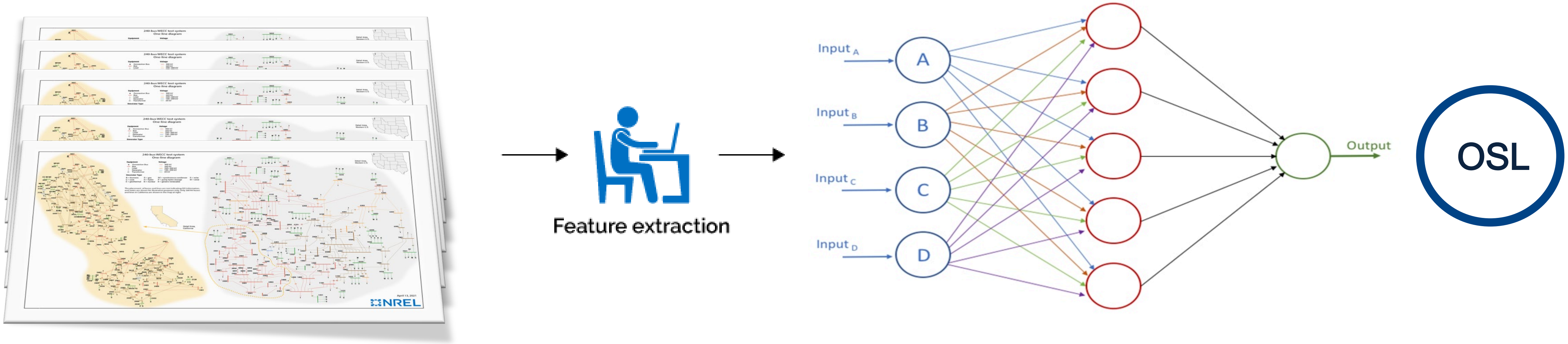
- A simulated case EXC FO at 7031 with varying the load composition

75% MVA + 25% Z Load

74% MVA + 26% Z Load

73% MVA + 27% Z Load

Machine learning pattern recognition (ML-PR) using DEF values as Input



Various oscillatory scenarios and factors, such as:

- generator/load location,
- controller type,
- ambient noise level,
- oscillatory frequency and magnitude,
- load model composition, etc.

DEF values of monitored branches

Neural Network

Predicted OSL Bus

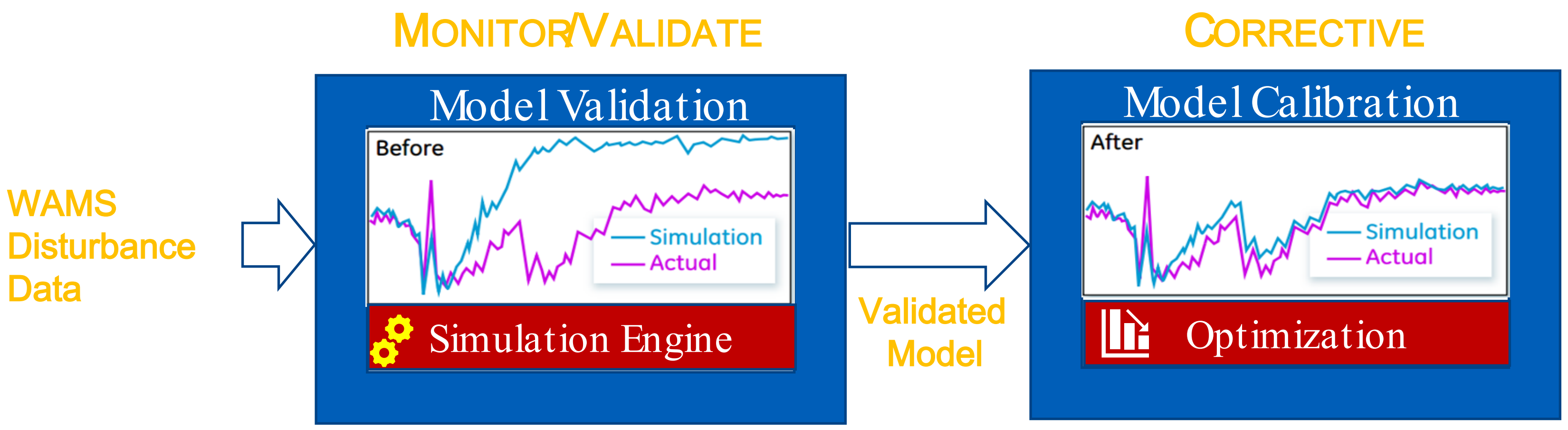
INFO:

- Over 20,000 cases were simulated
- The DEF values of monitored locations from simulated cases were used in ML-PR as the training dataset.
- The output of ML-PR (trained neural network) gives the bus number as the estimated OSL
- ML-PR was used to batch process all given cases and provide the initial estimation.
- When process the case, ML-PR used the same DEF values calculated through the DEF method
  - ML-PR generated its independent result.
- ML-PR showed good tolerance when the number of measurement points were changed.

OSL verifications

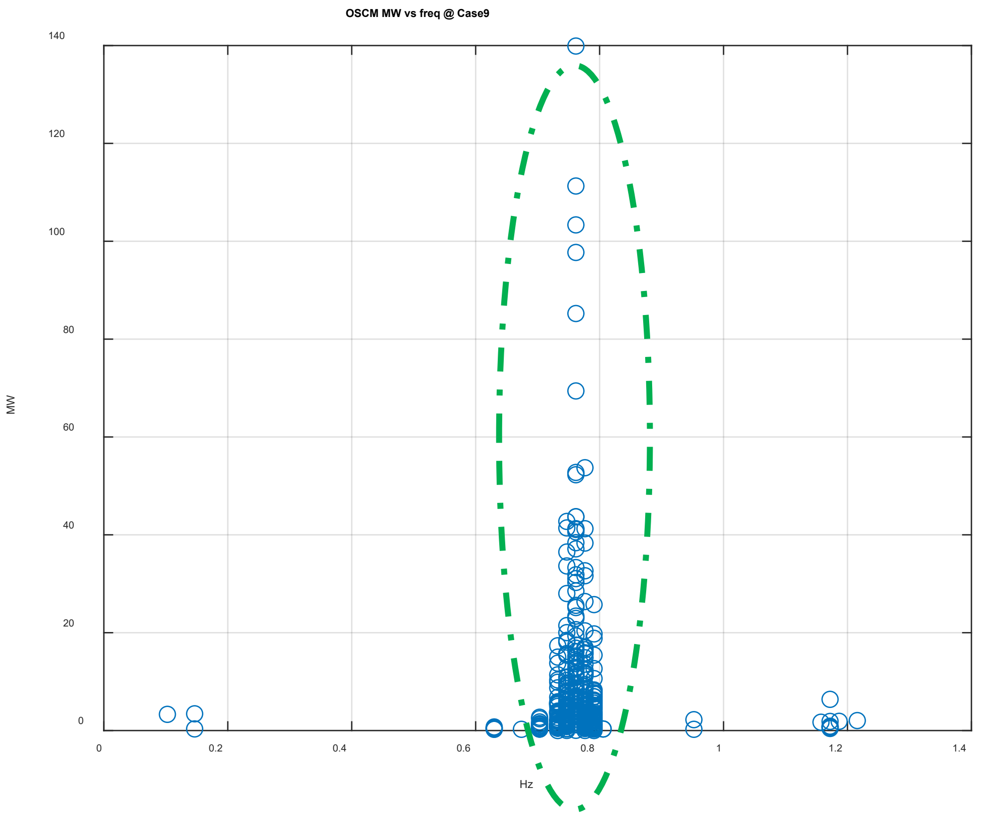
- Playback simulation (Model Validation type of simulation) at power plant level.
  - Pinpoint and verify the OSL bus and the faulty controller once potential OSL candidates were selected.
  - Residuals are mismatches between the simulated P/Q response and the actual response.
  - Residuals are used to determine if any significant deviation in the generators' dynamic performance.

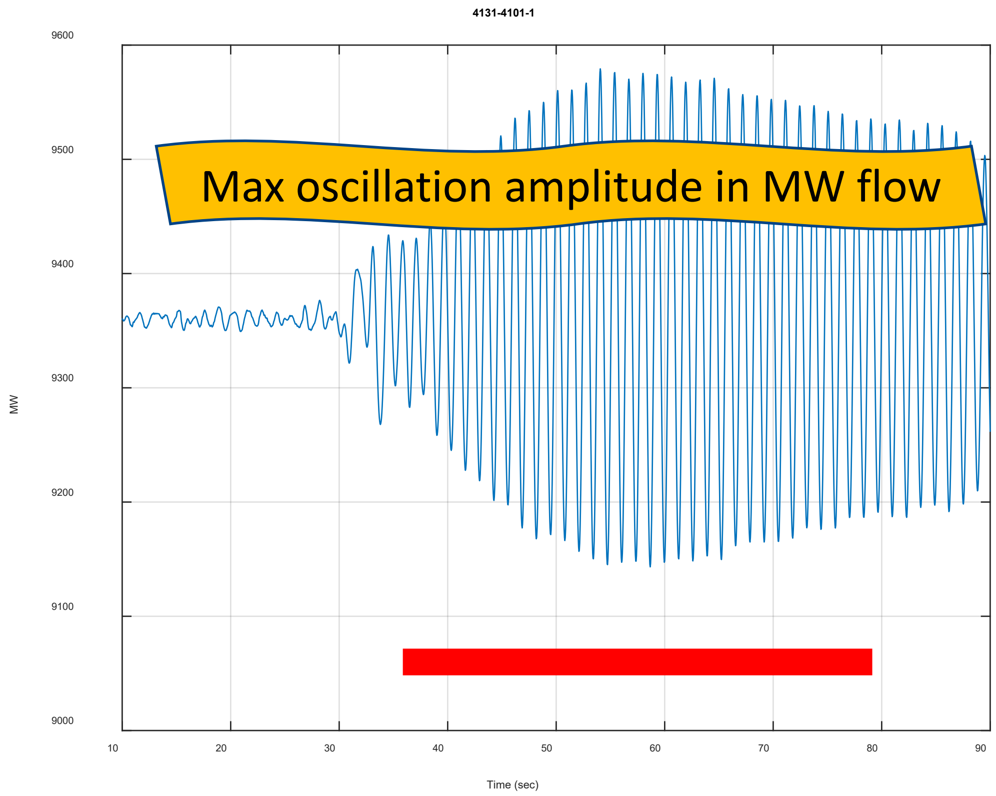
- Controller parameter identification (Model Calibration type of simulation) at individual generator level.
  - Uses optimization method to estimate the possible type of faulty controller.



Case 9

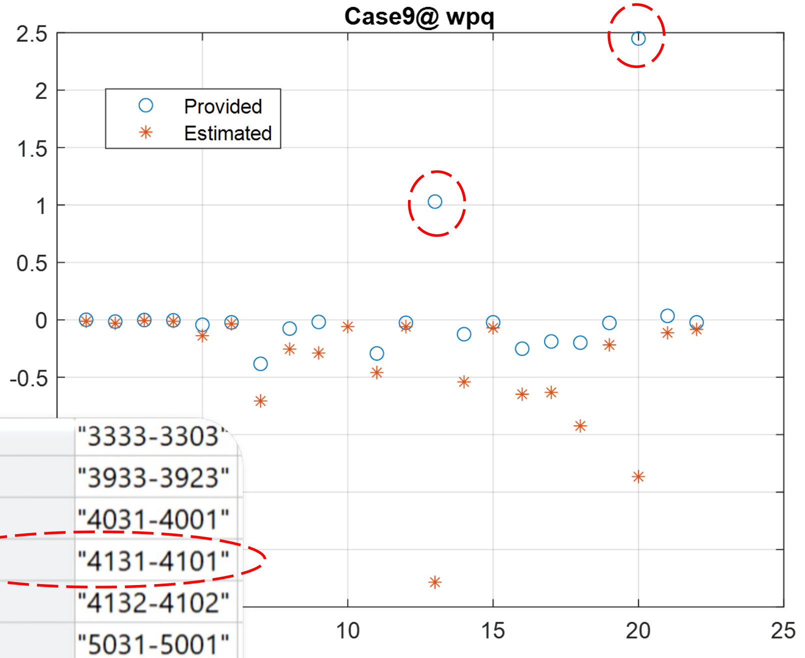
Case	Frequency	Area	Bus	Asset Type	Controller	Comment
9	0.762	NORTH	6533	Generator	Governor	▪ Resonate with a natural mode ▪ Fault at bus 1131 at t=30s ▪ Max oscillation amplitude in MW flow is not at the source
	0.762	NORTH	4131	Generator	Exciter	



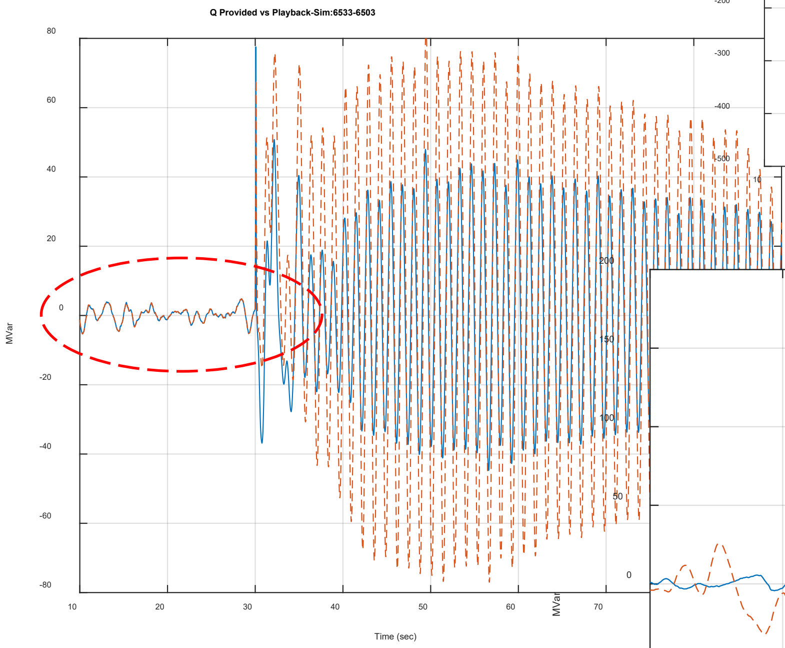


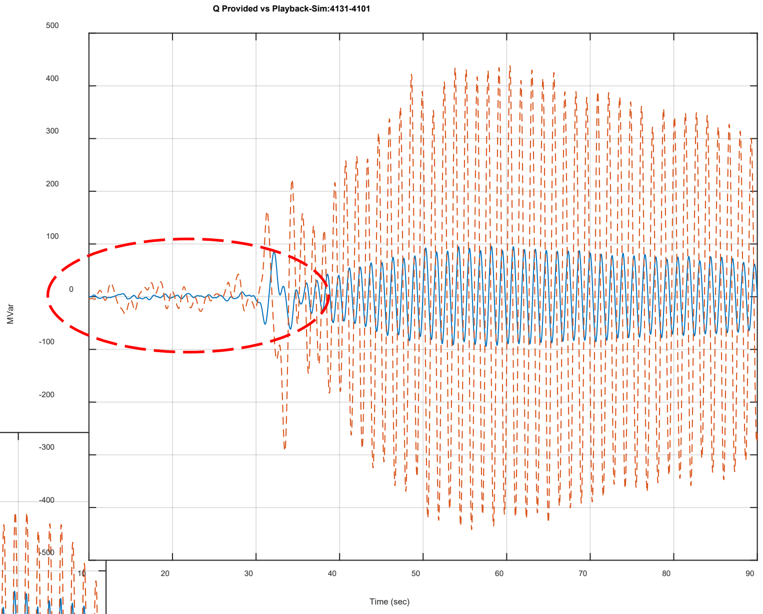
Case 9- continued

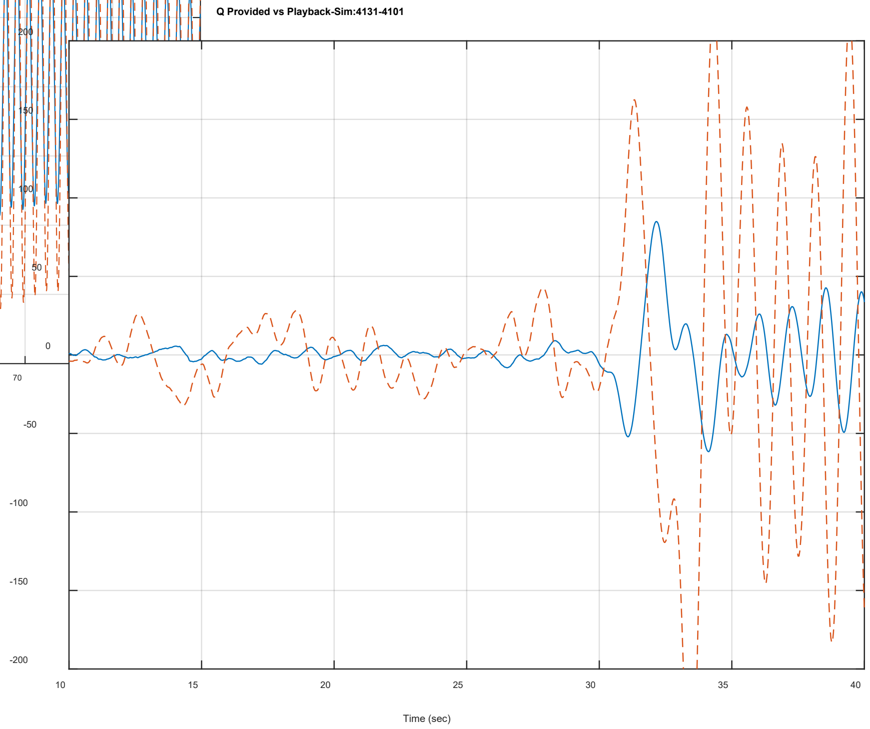
1. Generators at Bus 4131 and 6533 are monitored (voltage and flow)
2. Verify the suspected OSL (Bus 4131 and Bus 6533)
3. Determine Controller Type: GOV or EXC?



10	"3333-3303"
11	"3933-3923"
12	"4031-4001"
13	"4131-4101"
14	"4132-4102"
15	"5031-5001"
16	"5032-5002"
17	"6333-6303"
18	"6335-6305"
19	"6433-6403"
20	"6533-6503"
21	"7031-7001"

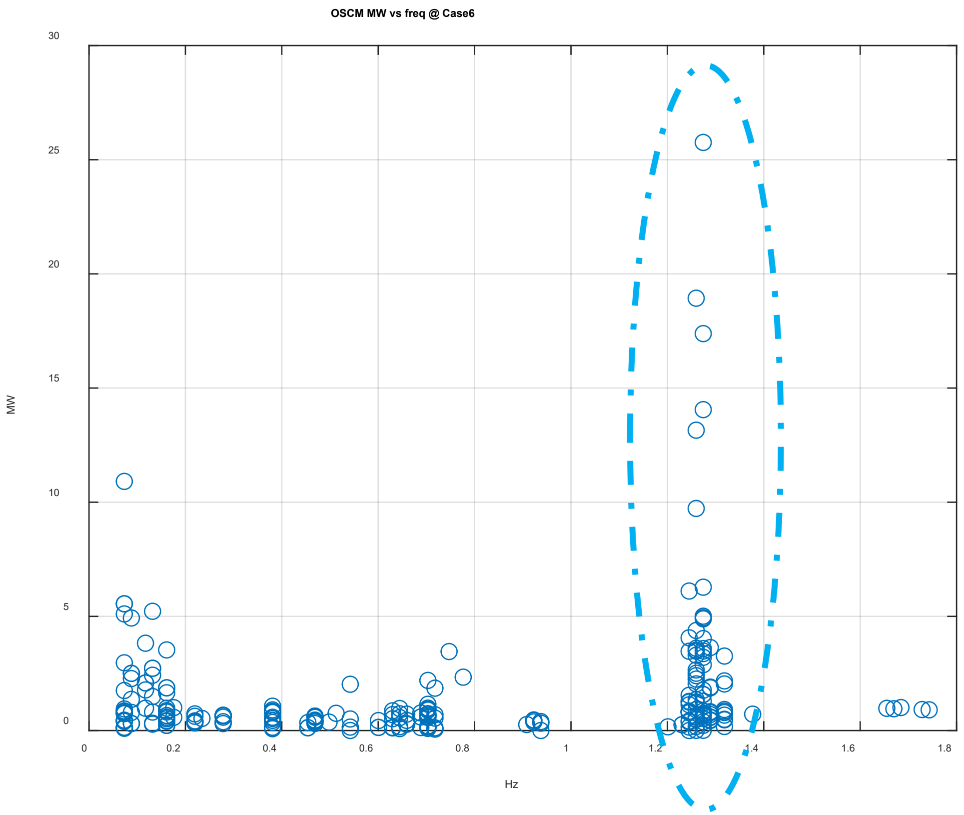


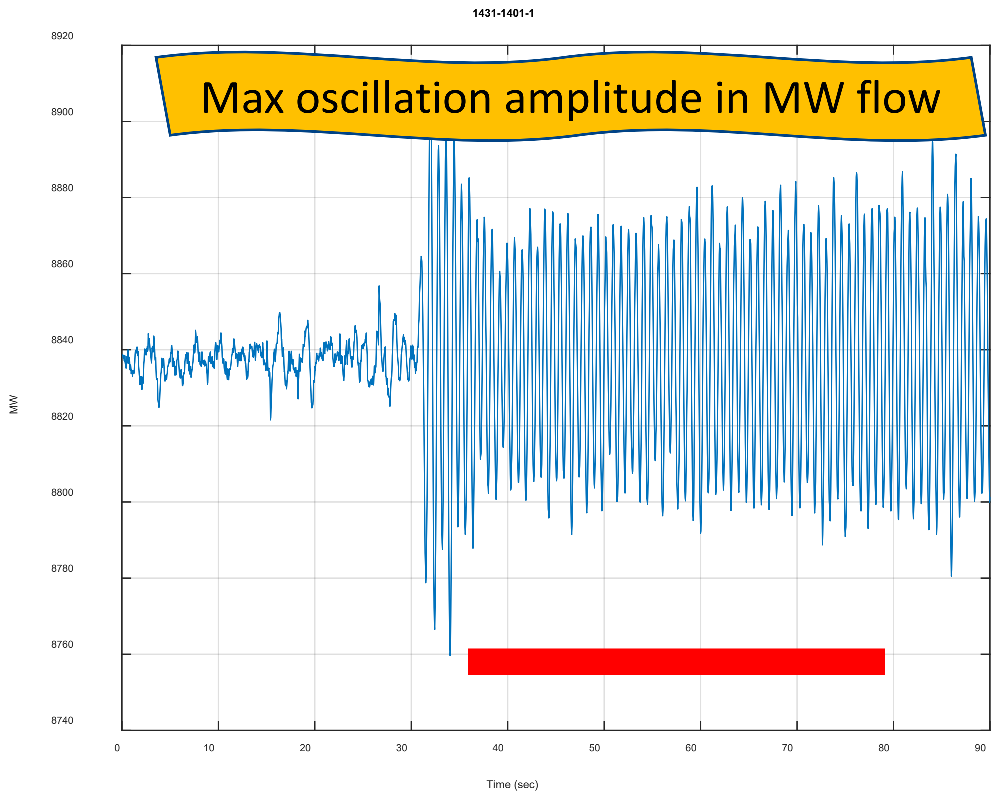




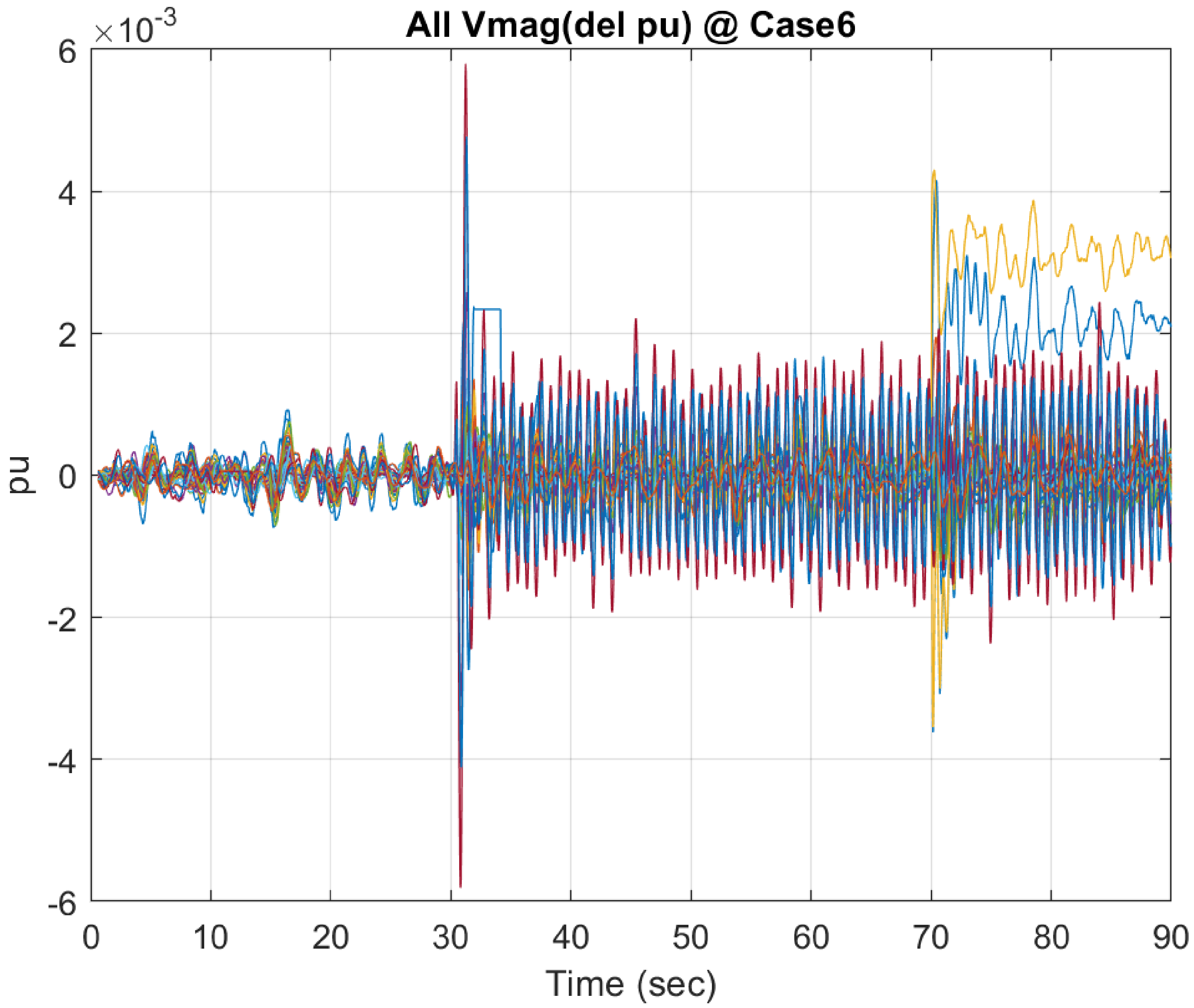
Case 6

Case	Frequency	Area	Bus	Asset Type	Controller	Comment
6	1.27	NORTH	7031	Generator	Governor	▪ Resonate with a natural mode ▪ Line 2604-6404_1 tripped at t=70s ▪ Voltage at bus 7031 is monitored but not current ▪ Only 50 lines are monitored ▪ Max oscillation amplitude in MW flow is not at the source

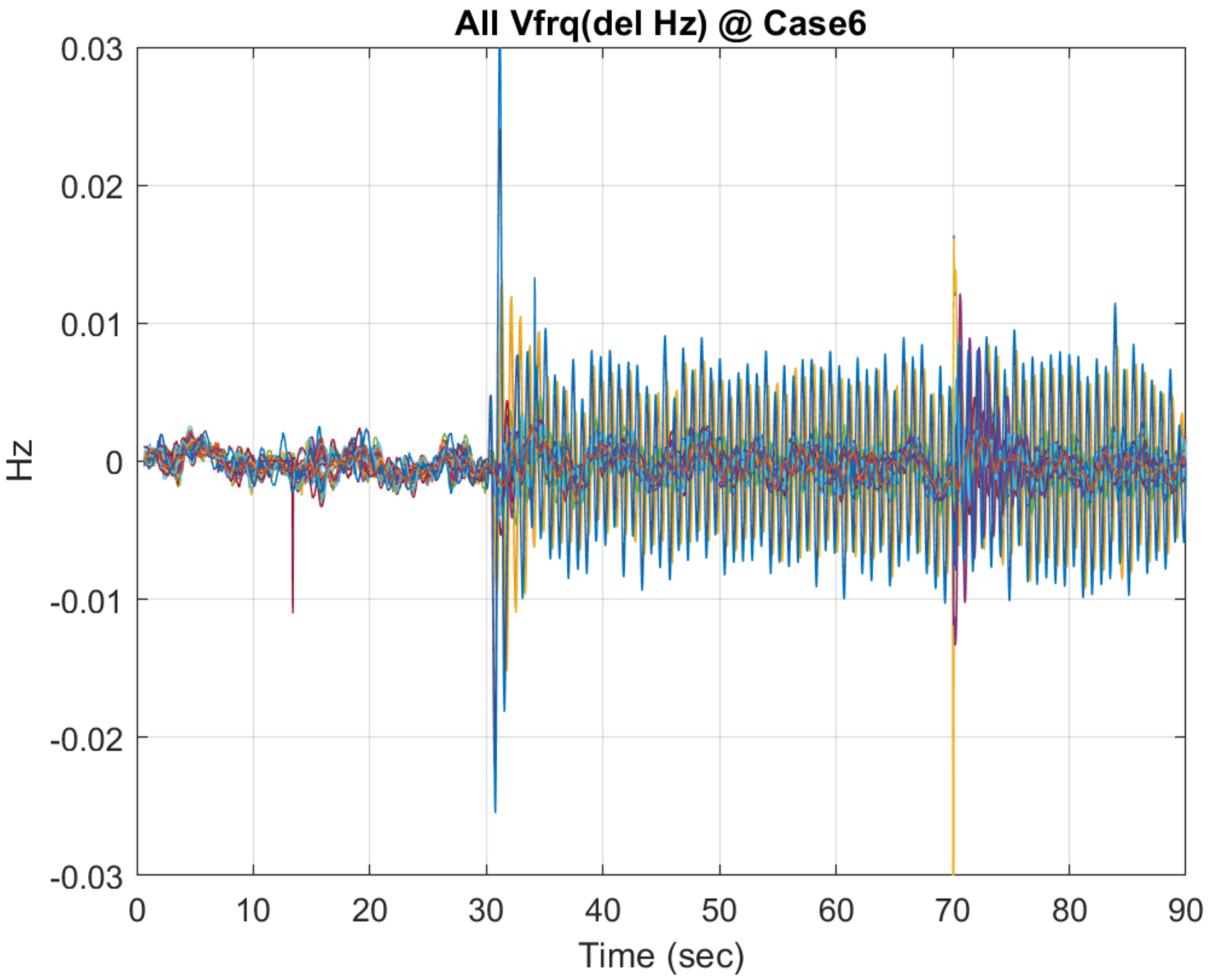




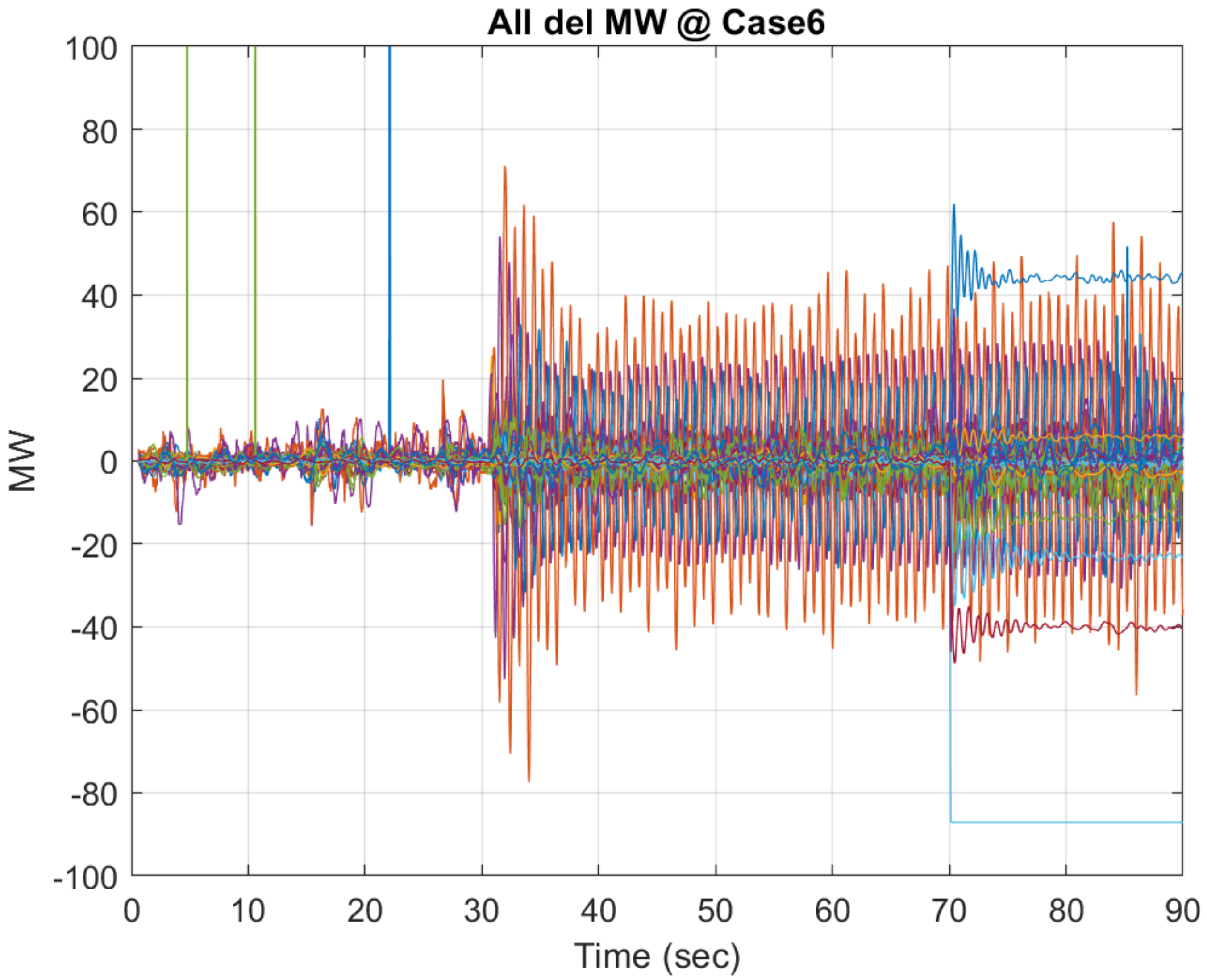
Case 6- Voltage Profile



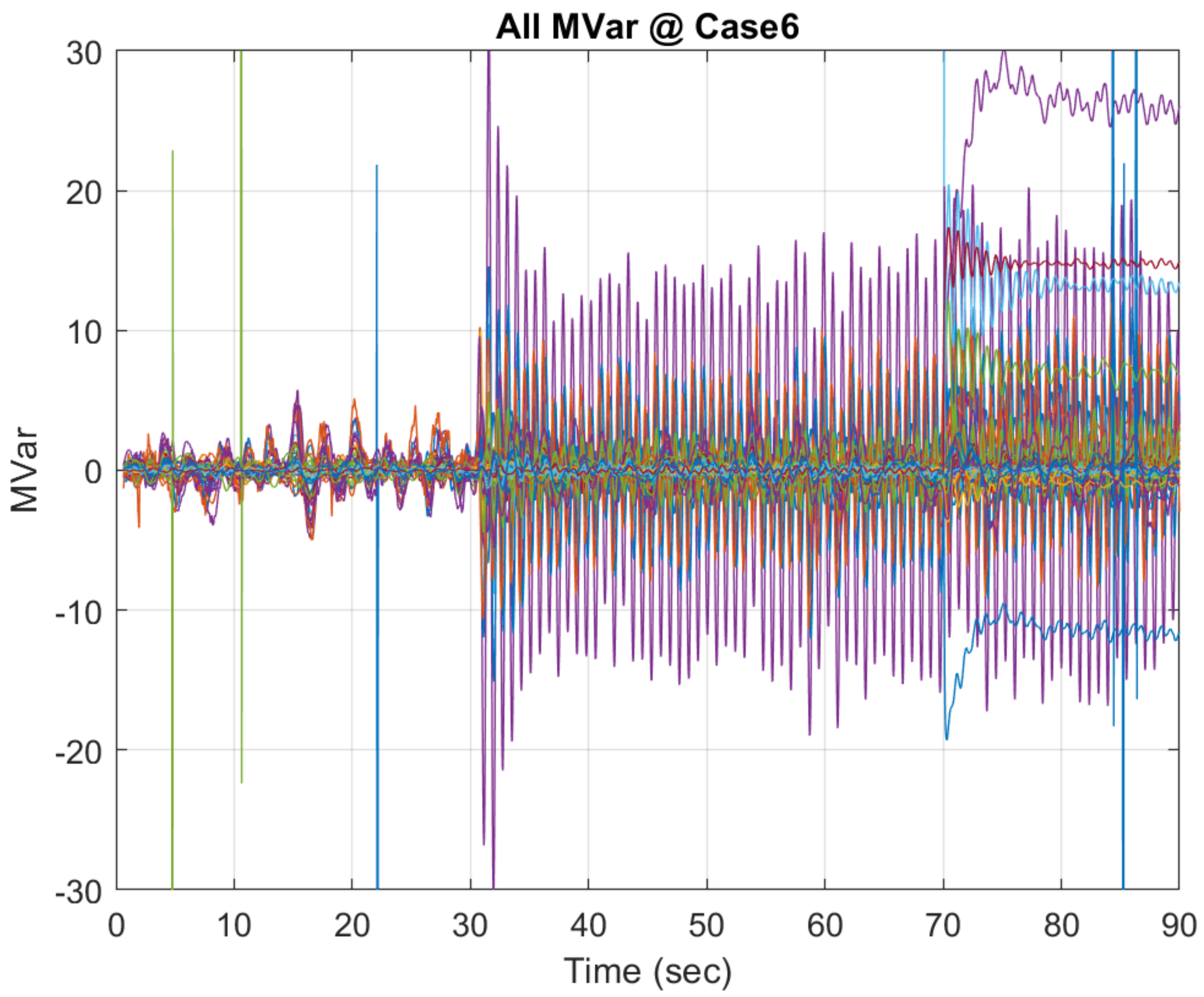
Case 6- Frequency Profile



Case 6- MW Profile



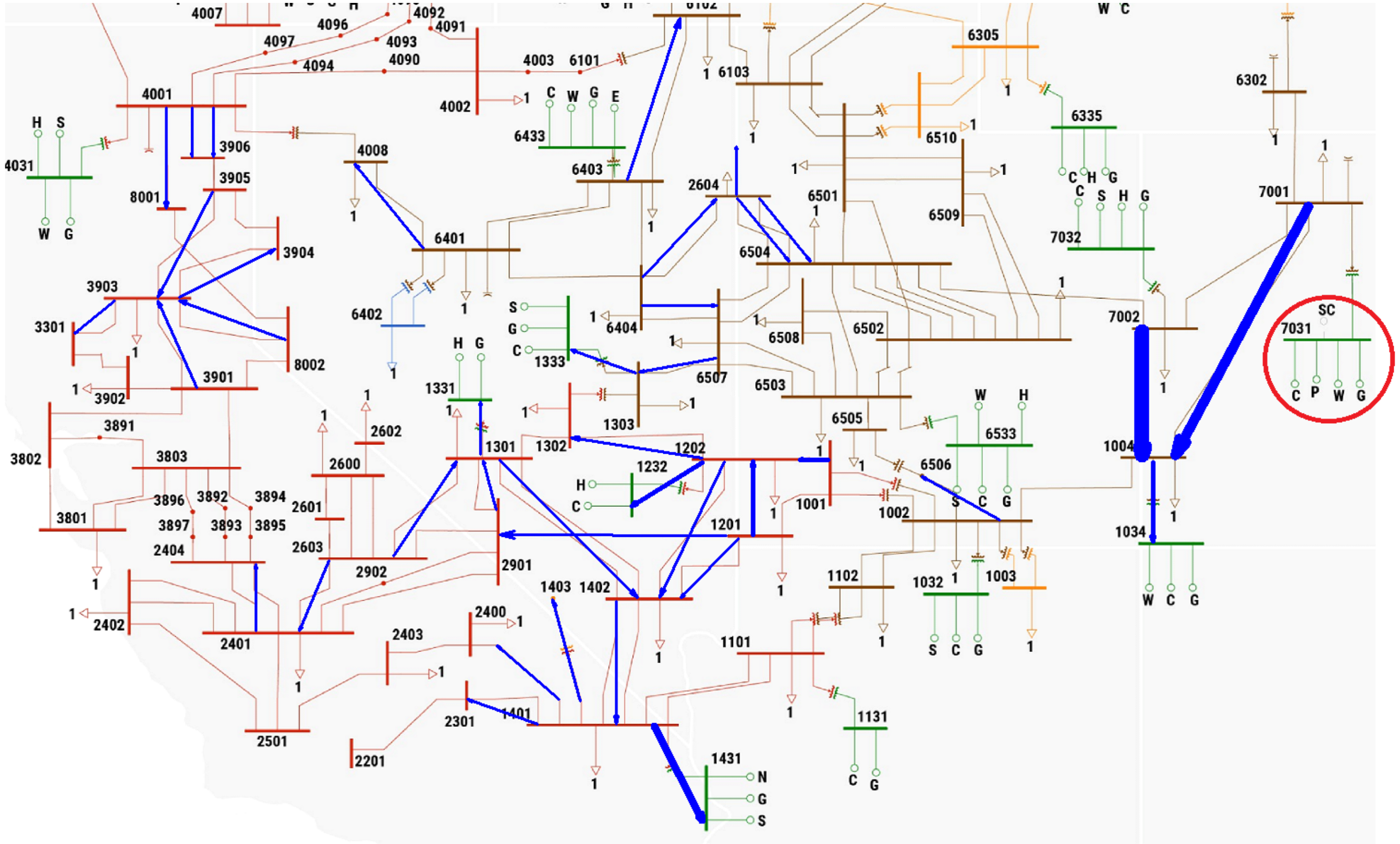
Case 6- MVarProfile



Case 6 - continued

1. Machine learning classifier points to bus 7031
2. DEF flow factors shows oscillation source from bus 7031
3. Flow of power plant at bus 7031 is not monitored

Bus	ML
7031	0.951815
7032	0.040598
3234	0.002665
2438	0.002332
4131	0.001459
1034	0.000435
1232	0.000408
1333	9.11E-05



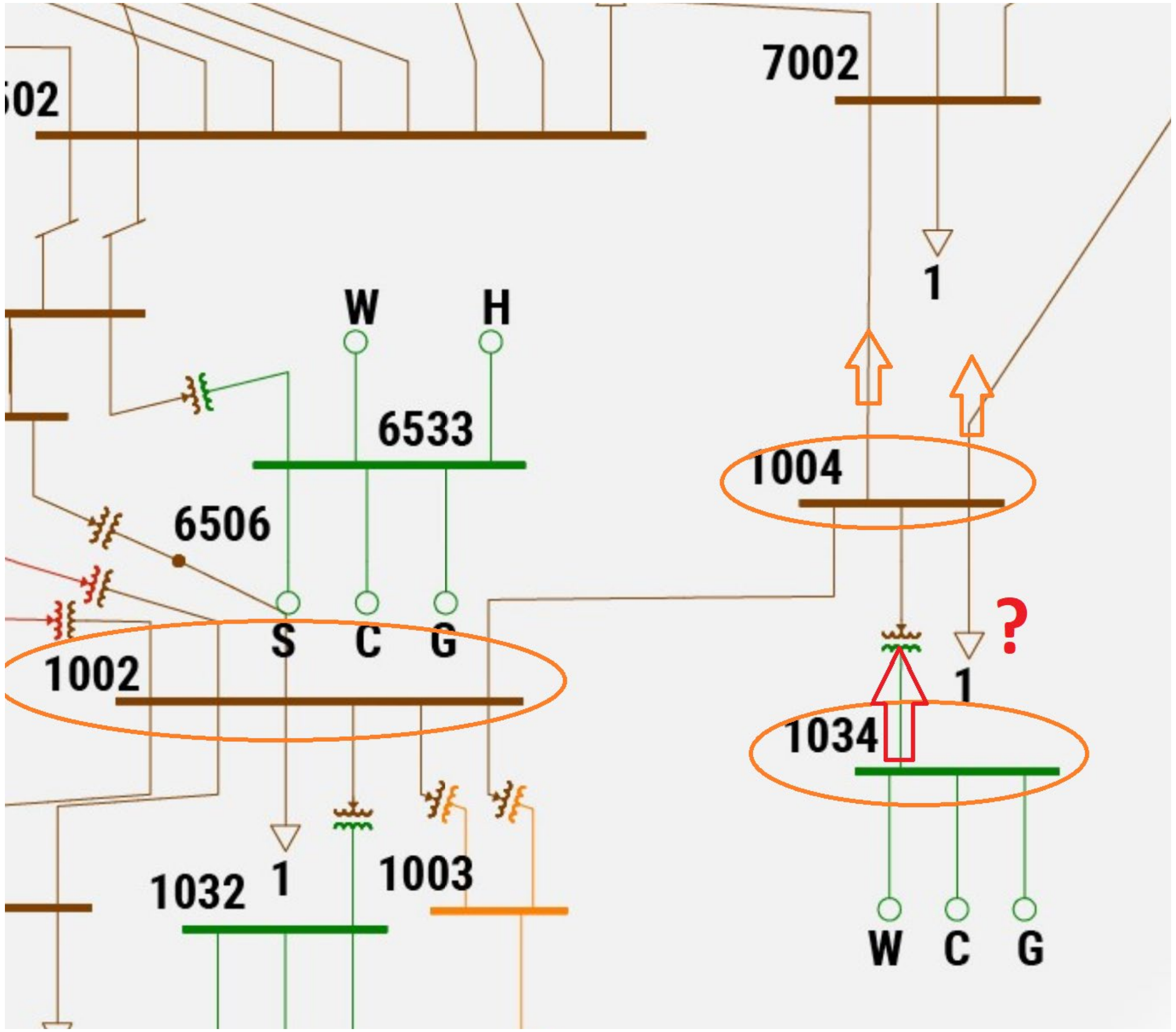
Branch	DEF
"1004-7002-1"	-1
"1004-7001-1"	-0.65
"1431-1401-1"	-0.4
"1232-1202-1"	-0.25
"1034-1004-1"	-0.24
"1202-1201-1"	-0.21
"1202-1001-9"	-0.11
"1202-1302-1"	0.07

Case 6- continued

To estimate the load at Bus 1004

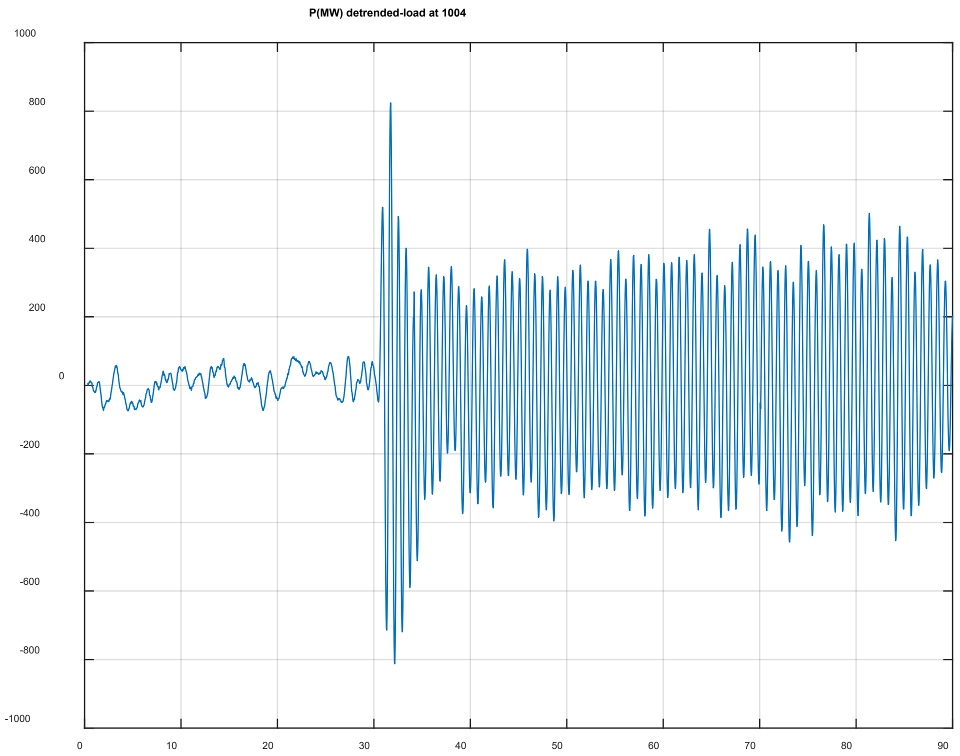
- The given are:
  - Voltage at 1034, 1004, 1002
  - Flow: 1034-1004-1, 1004-7002-1, 1004-7001-1

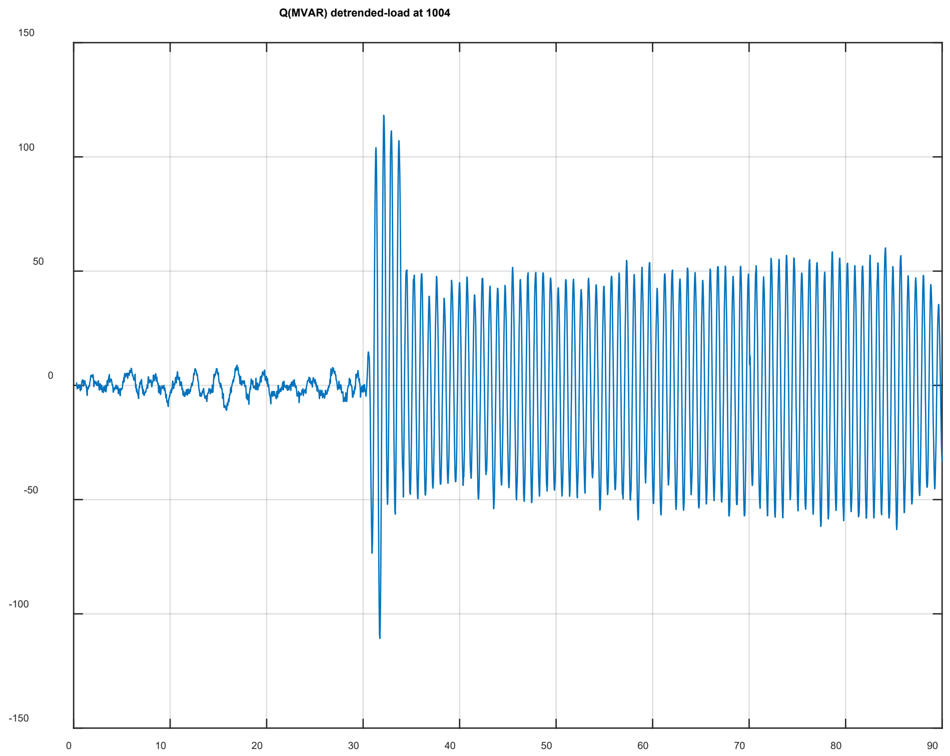
- So, the load intuitively is the sum of the followings:
  - 1004-7002-1 (given)
  - 1004-7001-1 (given)
  - 1004-1002-1 (calculated from voltage 1002 and 1004 using given impedance at line 1002-1004-1)
  - 1004-1034-1 (calculated from voltage 1004 and 1034 using given impedance at trf 1004-1034-1)



Case 6- continued

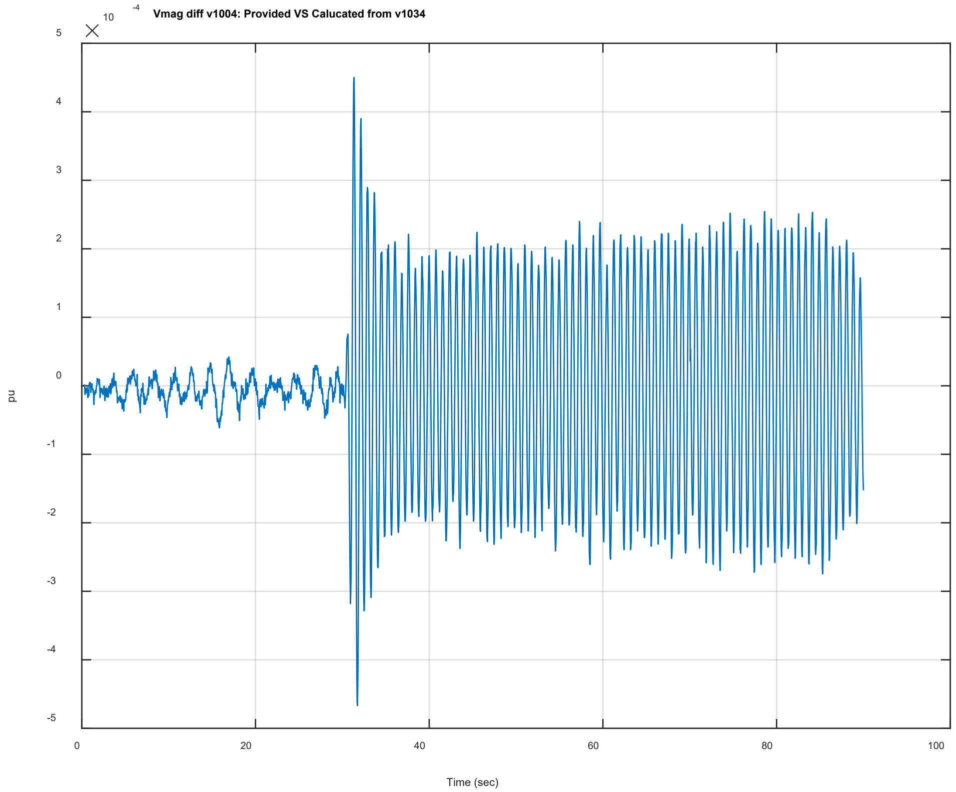
Estimated load shows significant oscillations…200~300 MW, 50 Mvar

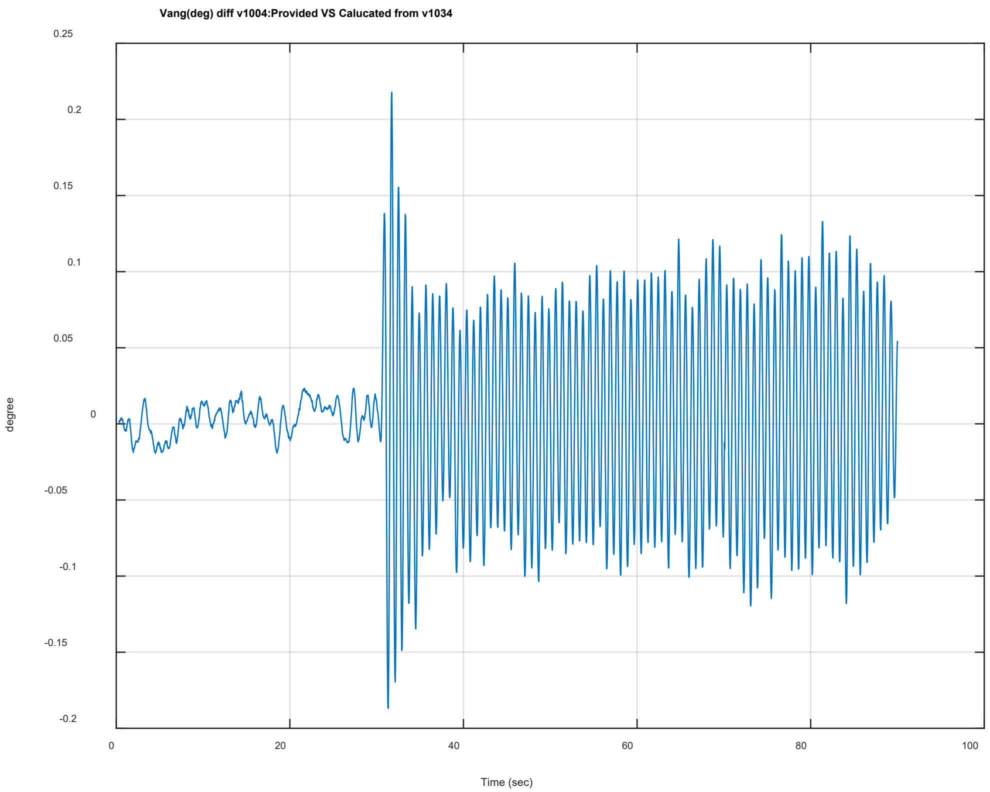




Case 6- continued

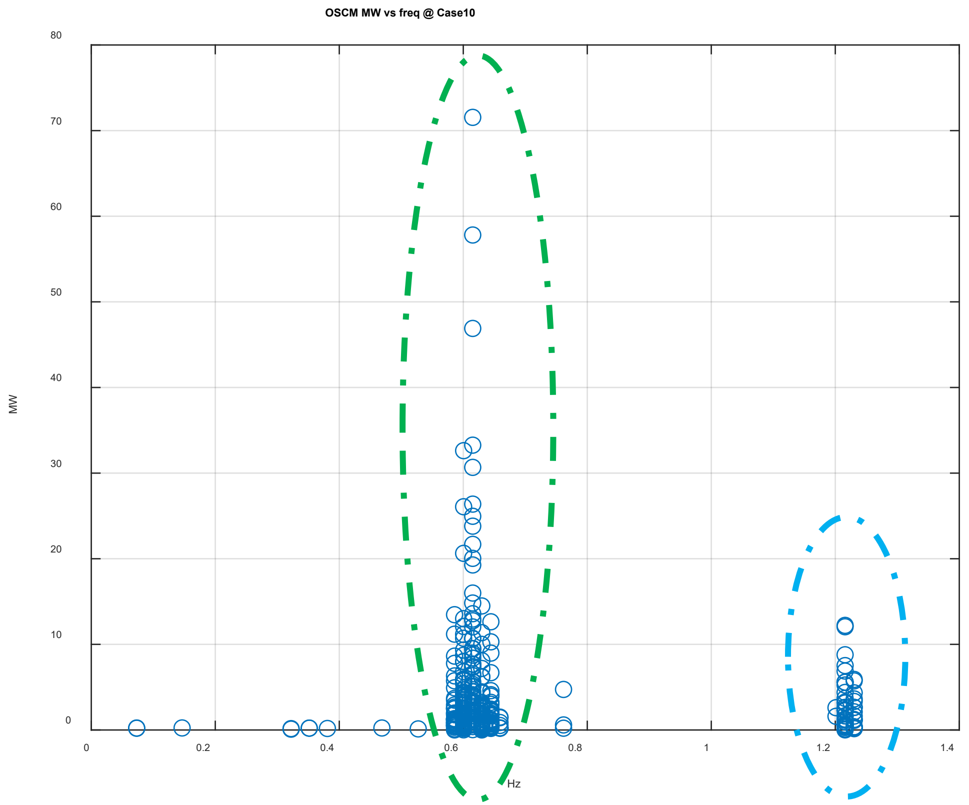
- Voltage at 1004 is not agree with the calculated value using voltage at 1034 and flow 1004-1034-1
  - ➢ Delta angle is as large as 0.1 degree
- Mixture of M class and P class PMUs could contribute to that…

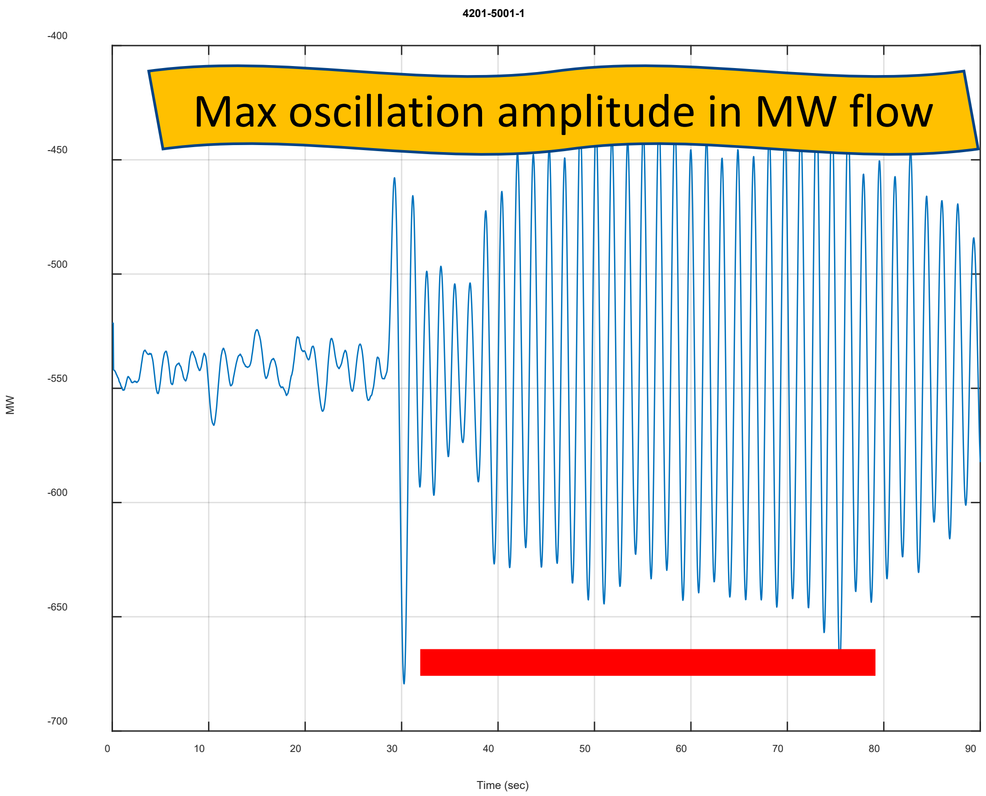




Case 10

Case	Frequency	Area	Bus	Asset Type	Controller	Comment
10	0.614	NORTH	6335	Generator	Governor	▪ Resonate with a natural mode ▪ Max oscillation amplitude in MW flow is not at the source ▪ Fault at bus 1131 at t=28s ▪ **Bus 3931 is not monitored by a PMU**
	1.218	CA	3931	Generator	Governor	



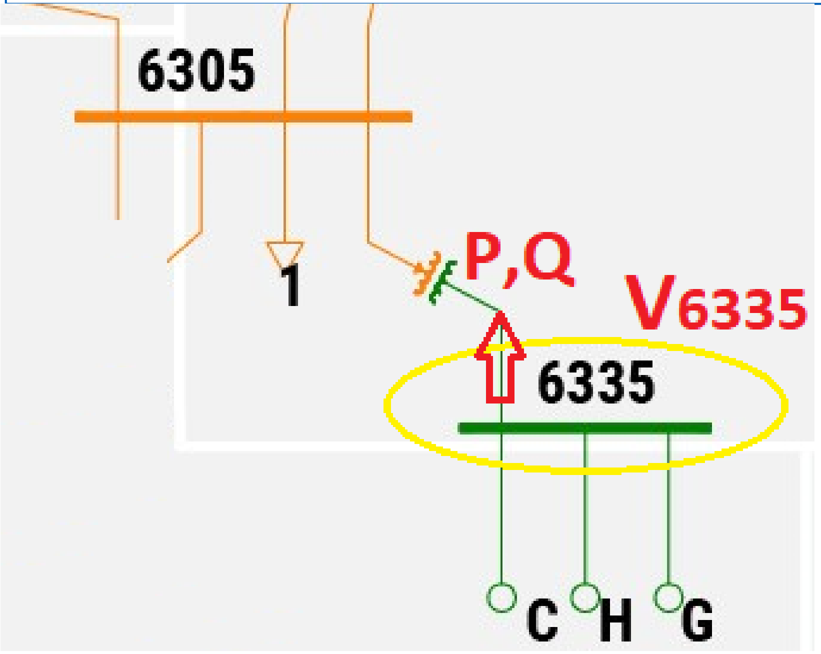


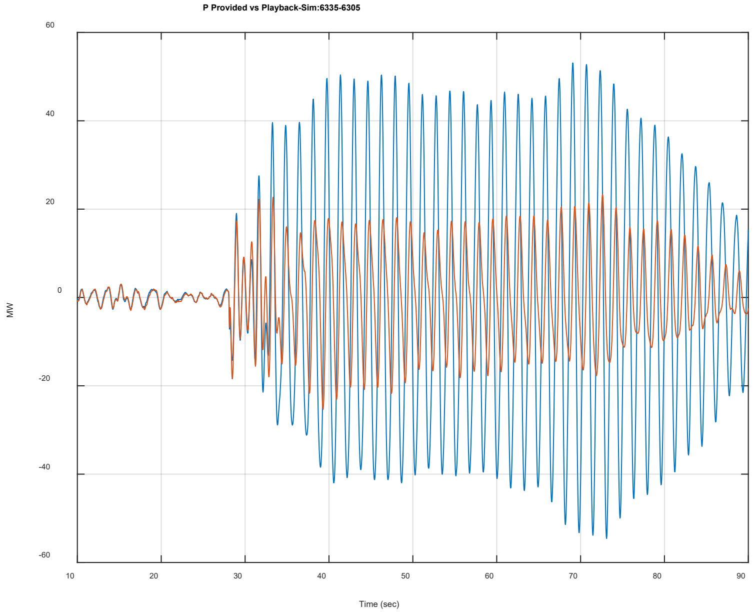
Case 10- 0.614 Hz

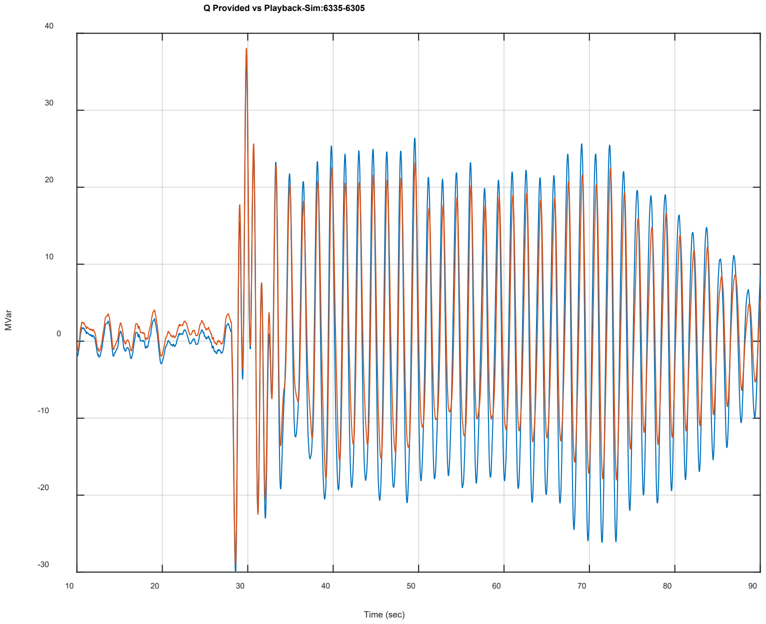
1. Machine learning classifier points to bus 6335
2. DEF flow factors shows oscillation source from bus 6335
3. Generators at bus 6335 is monitored (voltage and flow)
4. Verify the suspected OSL (Bus 6335)
   - Playback simulation at bus 6335 using flow "6335-6305-1"
   - Compare MW and Mvar residues

Bus	ML
6335	0.99485
3135	0.00315
2030	0.00065
4231	0.0003
5031	0.00029
2233	0.00028
2630	0.00022
2130	0.00018

Branch	DEF
"6335-6305-1"	1
"6101-4003-1"	0.26491
"6102-6103-1"	-0.2062
"6202-6201-1"	-0.15733
"6202-4102-1"	0.1565
"3906-4001-1"	-0.13127
"3906-4001-2"	-0.13127
"8001-4001-1"	-0.12394

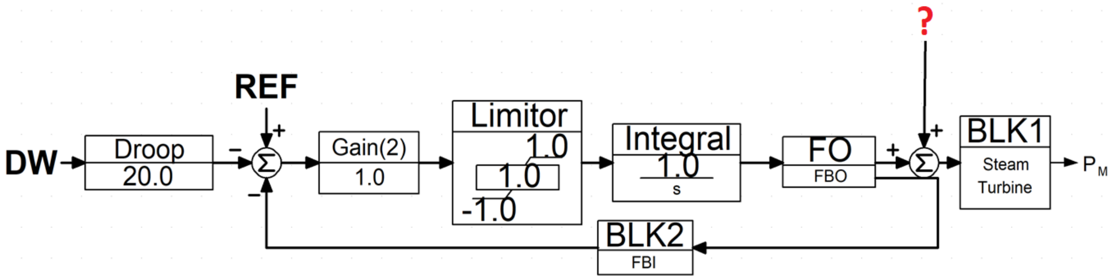


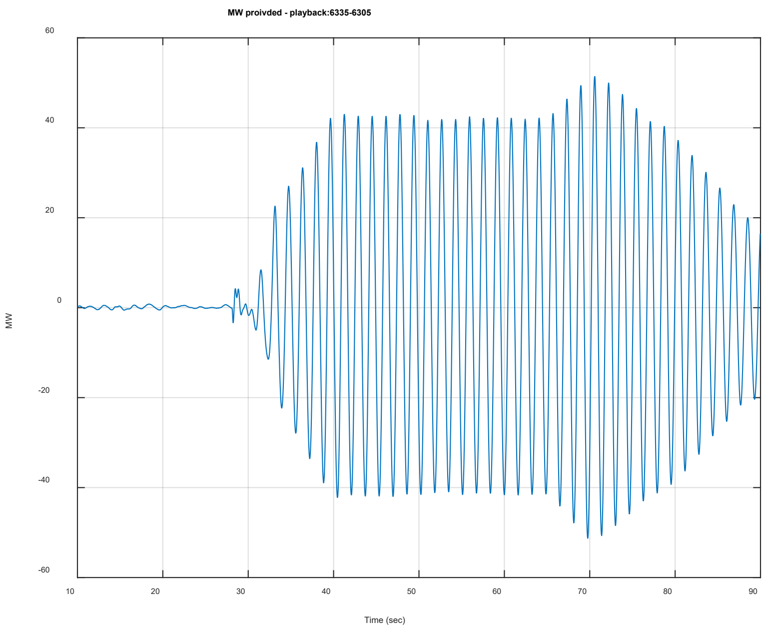


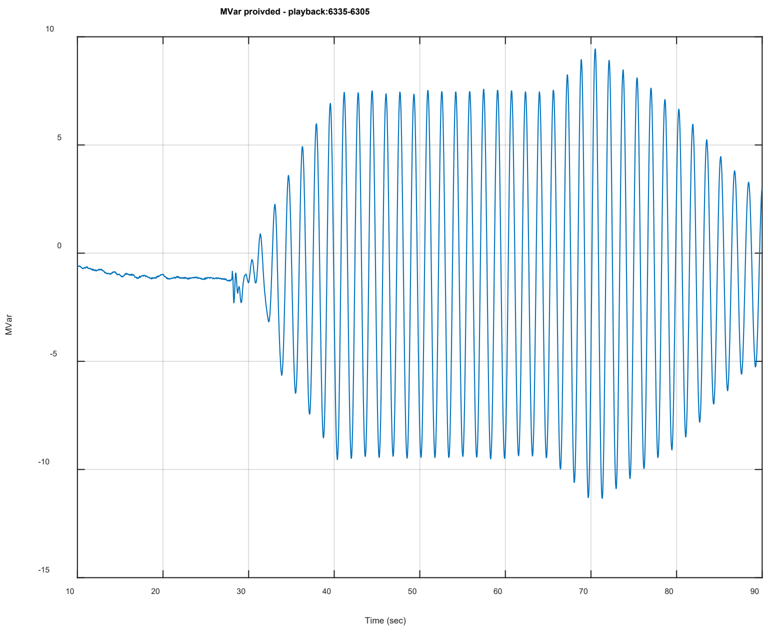


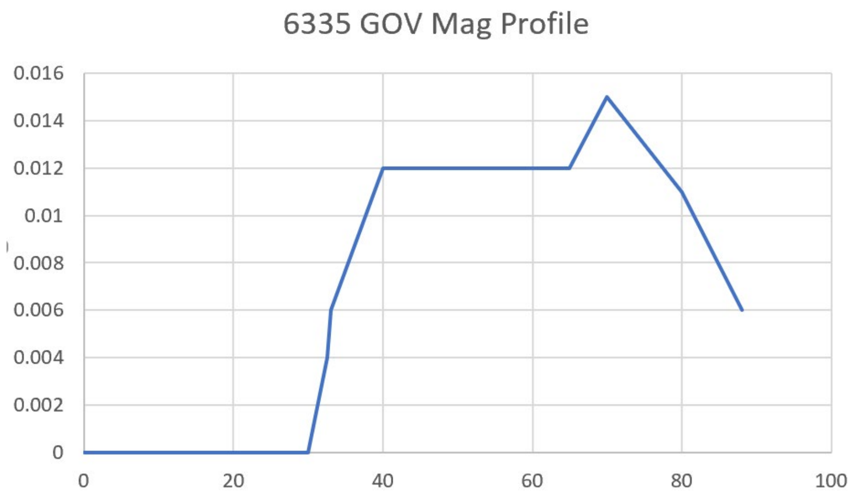
Case 10- 0.614 Hz- continued

5. Determine Controller Type: GOV or EXC?
   - Model calibration type of optimization problem…
   - Estimate the changed variable to minimize the residues





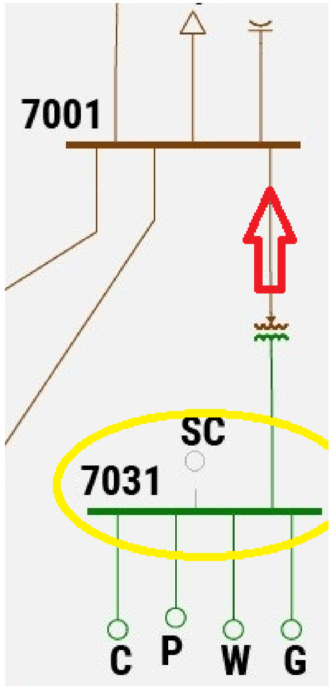


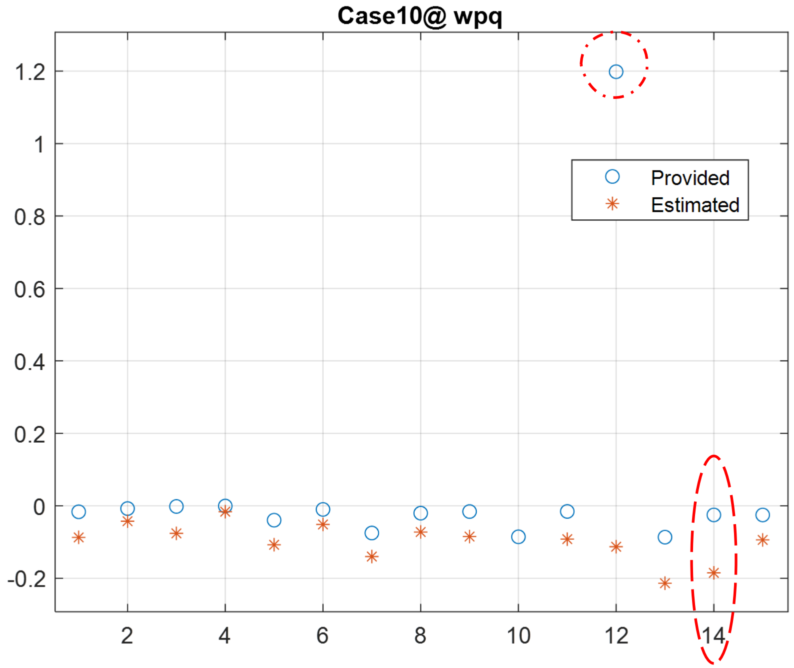


Case 10- 0.614 Hz- continued

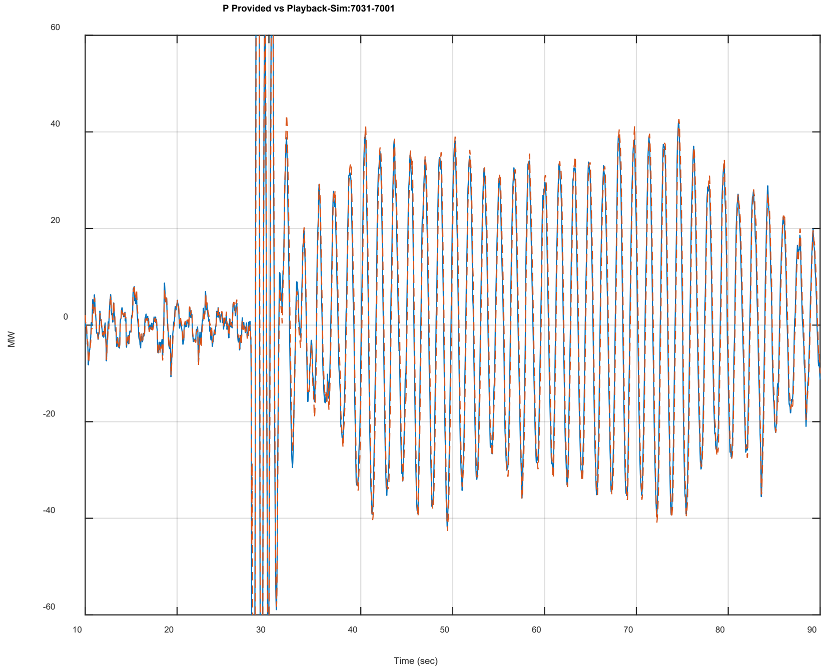
Additional Info:

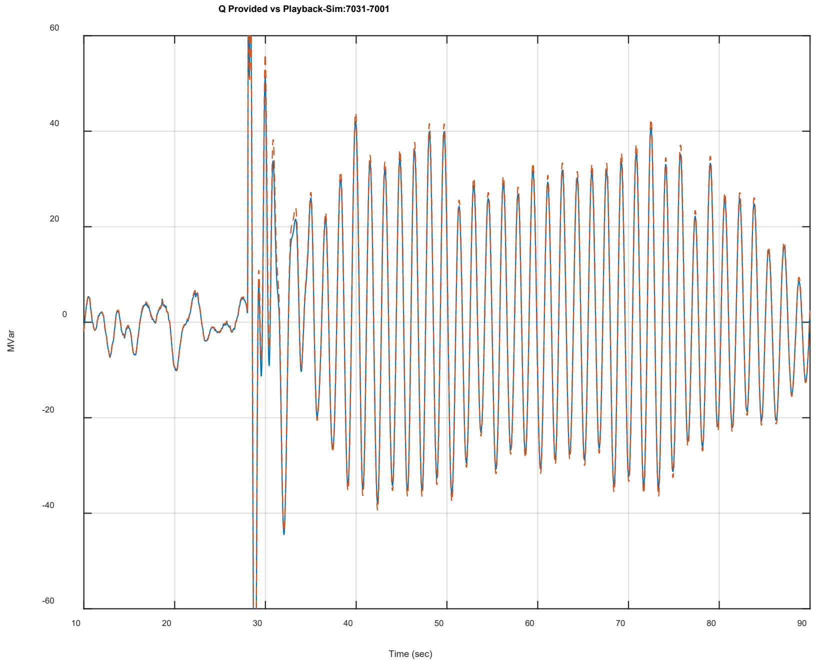
1. What about other Gens who were also monitored…
   - take gen bus 7031 as example
2. Do need to compare MW&Mvar for all Gens? No…
   - A quick plot handy to check damping deviations





"5032-5002"	-0.0859
"6333-6303"	-0.0235
"6335-6305"	1.2100
"6533-6503"	-0.0585
"7031-7001"	-0.1093
"7032-7002"	-0.0193



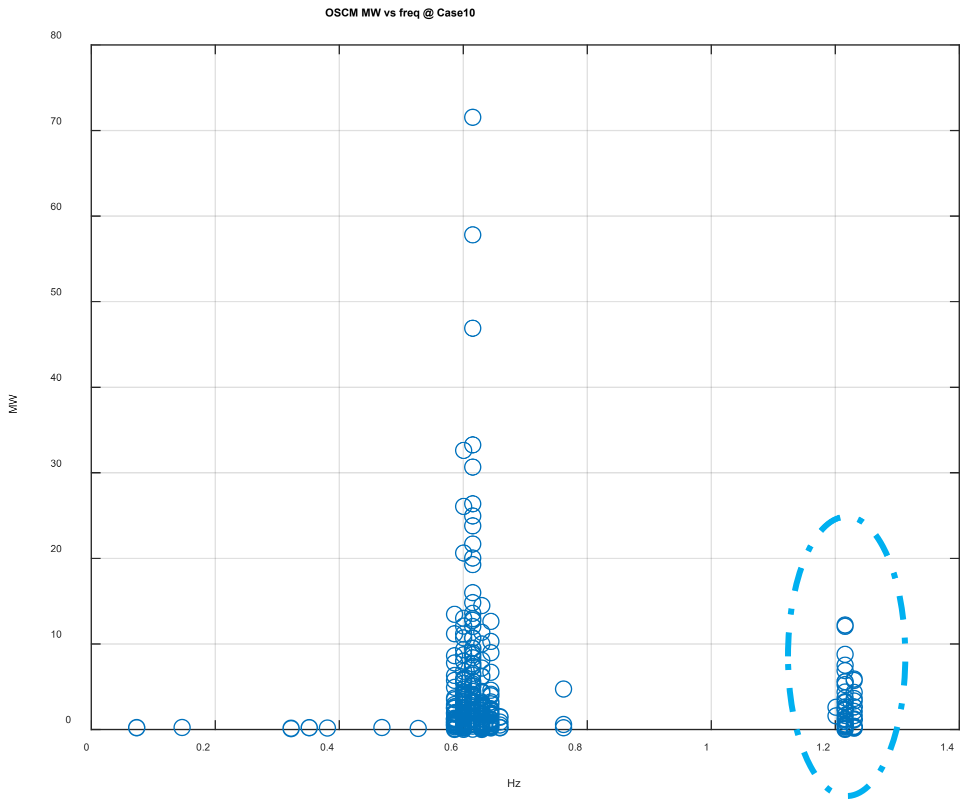


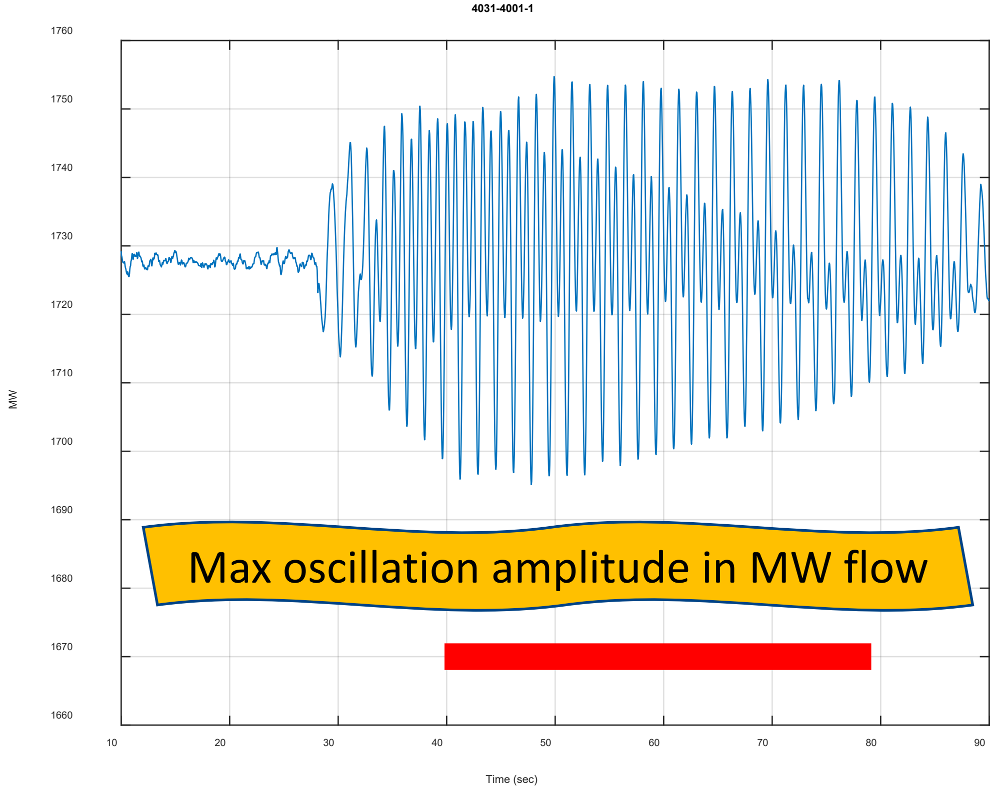
Case 10- 1.218 Hz

1. Machine learning classifier points to bus 3931
2. DEF flow factors shows oscillation source near bus 3906
3. Generators at bus 3931 is <u>not</u> monitored

Bus	ML
3931	0.99965
6333	9.85E-05
3432	7.69E-05
3333	6.54E-05
1333	3.84E-05
6433	2.83E-05
5031	2.40E-05
1232	6.20E-06

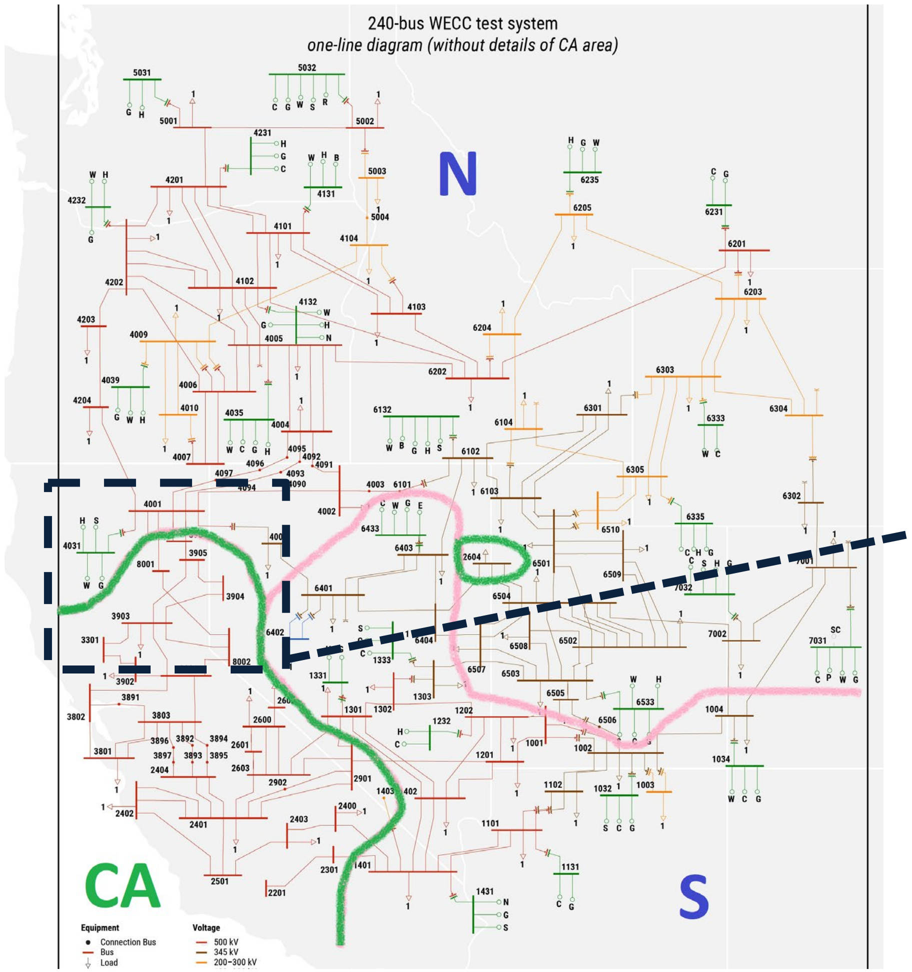
Branch	DEF
"3906-4001-1"	1
"3906-4001-2"	1
"4031-4001-1"	-0.55981
"4131-4101-1"	-0.45557
"3903-3905-9"	-0.33832
"3933-3923-1"	-0.23259
"3903-3301-1"	0.20926
"3903-3904-1"	-0.13518

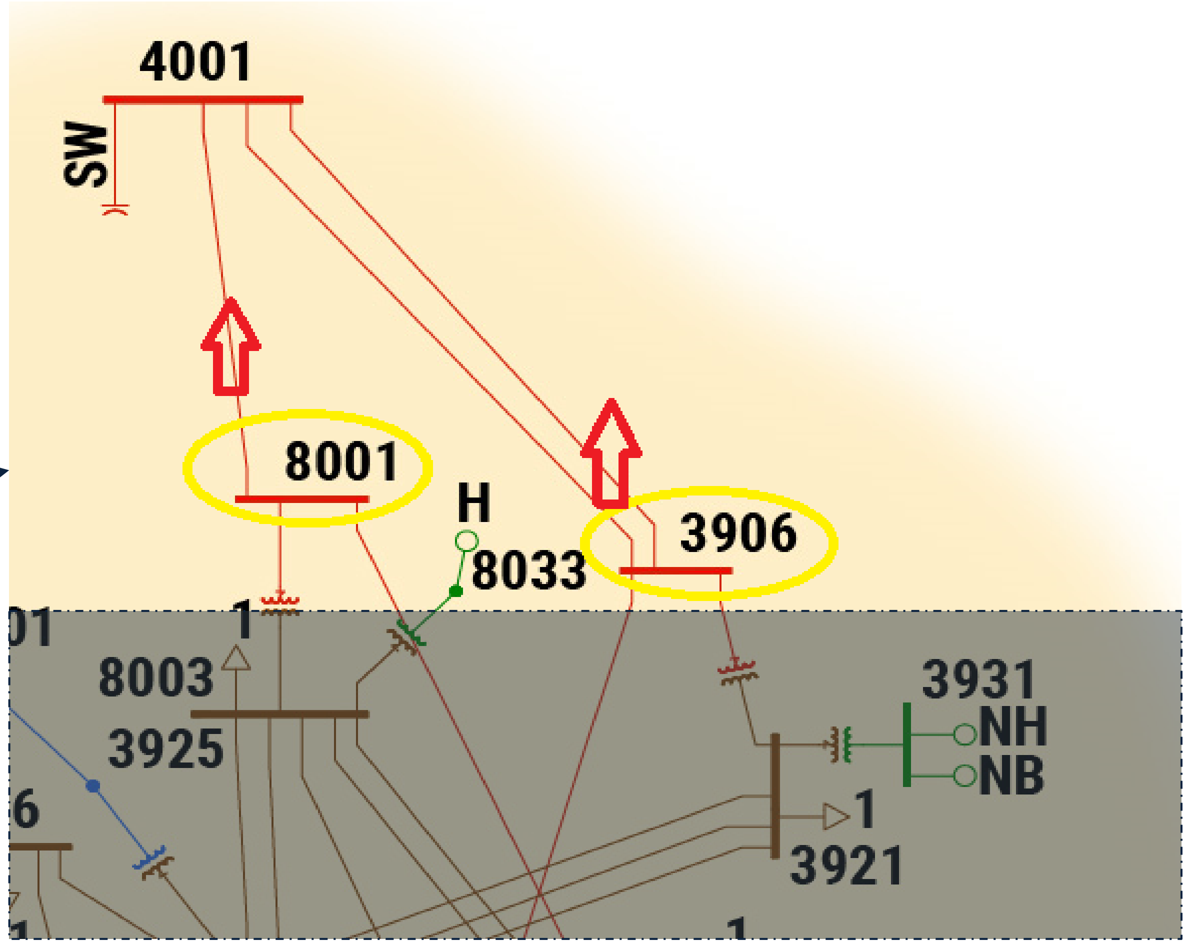




Case 10- 1.218 Hz- continued

5. Region near bus 4001, 4031, 3931





Summary

- ML complements DEF:
  1. handle the network conditions
  2. estimate the OSL in unobserved network

- Dynamic models and model-based analysis:
  1. verify the estimated OSL
  2. estimate device/controller type