Application of Small-Signal Analysis

1.0 Overview

Below in Fig. 1 is a simulation of loss of Diablo-Midway 500 kV #2 when Diablo-Midway 500 kV #1 is out of service. We observe that:

1. The oscillations are growing; undamped!
2. The oscillations have about a period of about 28.7-25.3=3.4s. This corresponds to a frequency of 1/3.4=0.29Hz.
3. These two generators are oscillating approximately 180 degrees out of phase with each other.

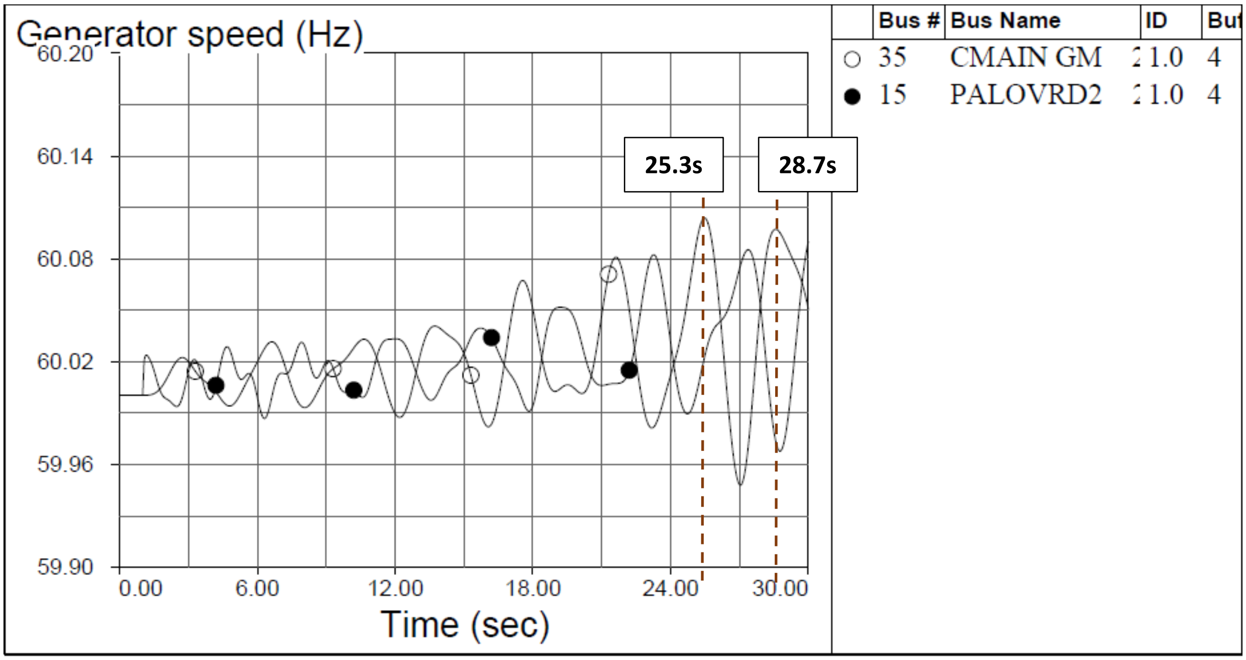

Fig. 1: Time domain response for 4-cycle fault followed by loss of Diablo-Midway 500 kV line #2 (with Diablo-Midway 500 kV line #1 out of service)

4. CMAIN GM is a generator in Canada, and PALOVRD2 is a generator in Arizona. (Actually, CMAIN GM is an equivalent). They are at opposite ends of the system. See one-line diagram on the next page, Fig. 2.

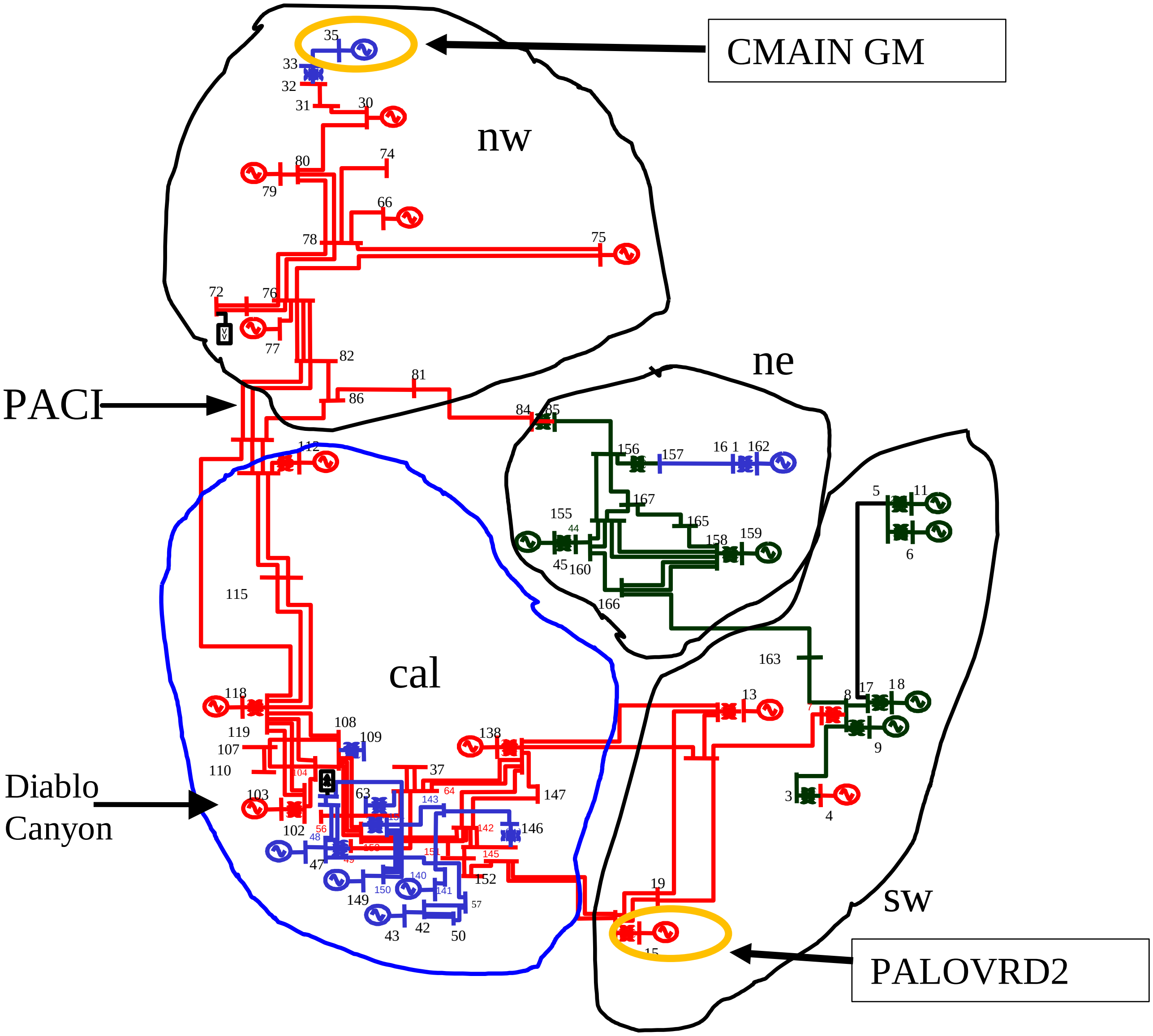

Fig. 2: One-line diagram showing location of generators plotted in Fig. 1

We want to understand influences on this oscillation, because if we can understand the influences, we can perhaps develop solutions for it.

Although our time-domain simulation is certainly effective for observing the oscillation, it is a little difficult to imagine an efficient method for identifying the influences on the oscillation. The best we might do is to make some educated guesses, then make corresponding changes, repeat the simulation, and observe the effect. You might call this "sensitivity analysis," but the "educated guesses" part do not lend themselves to systematic inquiry.

A better approach is to use eigenanalysis. Powertech has a tool for this purpose, called SSAT (Small-Signal Analysis Tool). SSAT is in "DSATools," the same toolbox containing PSAT and TSAT. We will use SSAT to assess the oscillation problem observed in our system for loss of Diablo-Midway 500 kV #2 when Diablo-Midway 500 kV #1 is out of service.

I will not go through the detailed steps to use SSAT (like I did for your time domain simulator in the project), as I am not asking you to actually use SSAT. Rather, I will just give you the main results. But first, there is a conceptual problem we must address…

Small-signal analysis for a large disturbance: The oscillation we observe from the time-domain simulation follows a "large disturbance" consisting of a 4-cycle fault followed by loss of a major 500 kV circuit. To what extent can "small-signal" analysis be applied to this situation? The question is motivated by the fact that everything we have done in eigenanalysis depended on the first step of taking only the first two terms of the Taylor series expansion and neglecting the higher order terms, a step that depended on the deviation $\Delta\underline{x}$ to be "small" (see p. 1 of notes called "Linearization of the Swing Equation"). The disturbance we have applied in this case is in no sense "small."

Our use of small-signal analysis here depends on (a) use of the right topology, and (b) an assumption.

(a) Topology and conditions: We do not apply eigenanalysis to the pre-disturbance equilibrium conditions (in this case, with Diablo-Midway #1 out and Diablo-Midway #2 in). Rather, we apply eigenanalysis to the post-disturbance equilibrium conditions (in this case, with Diablo-Midway #1 and #2 out). This means that our small-signal analysis is performed by linearizing about the condition identified from a power flow solution with Diablo-Midway #1 and #2 out.

(b) Assumption: We assume that the large-disturbance response cannot be stable if the post-disturbance equilibrium condition is small-signal unstable. This means

➔If the post-disturbance equlibrium condition has one or more right-half-plane poles (eigenvalues with positive real part), then the large-disturbance response must be unstable. Note:

- A small-signal unstable post-disturbance equilibrium is a ***sufficient*** condition for an unstable large-disturbance response [based on experience…if post-disturbance equilibrium is small-signal unstable, then large disturbance response definitely will be unstable; it would be interesting to see if this is theoretically true, i.e., can a large disturbance move a system from the region of attraction (ROA) of an unstable equilibrium to the ROA of a stable equilibrium, a question to which the answer is, I think, generally "no," but there might be some pathelogical cases where it is "yes."]
- A small-signal unstable post-disturbance equilibrium is not a ***necessary*** condition for an unstable large-disturbance response (a large-disturbance response may be unstable even when post-disturbance equilibrium is stable, e.g., a disturbance with a 30-cycle fault-on period is going to be unstable independent of the presence of a small-signal unstable post-disturbance equilibrium).

Experience indicates that, for damping problems showing up in the 5-30 second time-frame, the post-disturbance equilibrium always has one or more lightly damped or undamped modes that eigenanalysis finds. Moving the corresponding eigenvalues into the left-hand plane is usually the right approach to take in addressing the oscillatory (undamping) problem. We take this approach here.

2.0 Results from SSAT

We first solve the power flow (PSAT or PSS\E power flow) for the post-disturbance conditions corresponding to the plot of both Diablo-Midway 500kV lines 1 & 2 out of service. I used a Diablo generation of 700 MW. SSAT uses the power flow conditions to initialize, just as TSAT does (but of course the power flow used by TSAT is the pre-disturbance equilibrium condition whereas the power flow used by SSAT is the post-disturbance equilibrium conditions).

Next, we use SSAT to compute the eigenvalues. SSAT has different algorithms to do this. If the system is not too large, one can use the "QR" method, which computes all eigenvalues of the system. SSAT allows this approach if total no. of states is ≤ 1000. In our system, the no. of modes is only 316 (so no. of states must be ≤ 632); we can use this approach[1].

I computed all eigenvalues and then sorted them from most positive real part to most negative real part. The first 19 eigenvalues are below. Note:

- a dominant state is identified; we will see that this is the state with the largest participation factor in the given mode;
- the first two modes listed have positive real parts (in right-half plane);
- the second mode is purely real - I suspect this is a problem local to North G (maybe a data error) and will not investigate further;
- the first mode is oscillatory, with frequency of 0.28 Hz. Recall our "eyeballed" frequency of 0.29Hz observed in time domain simulation.

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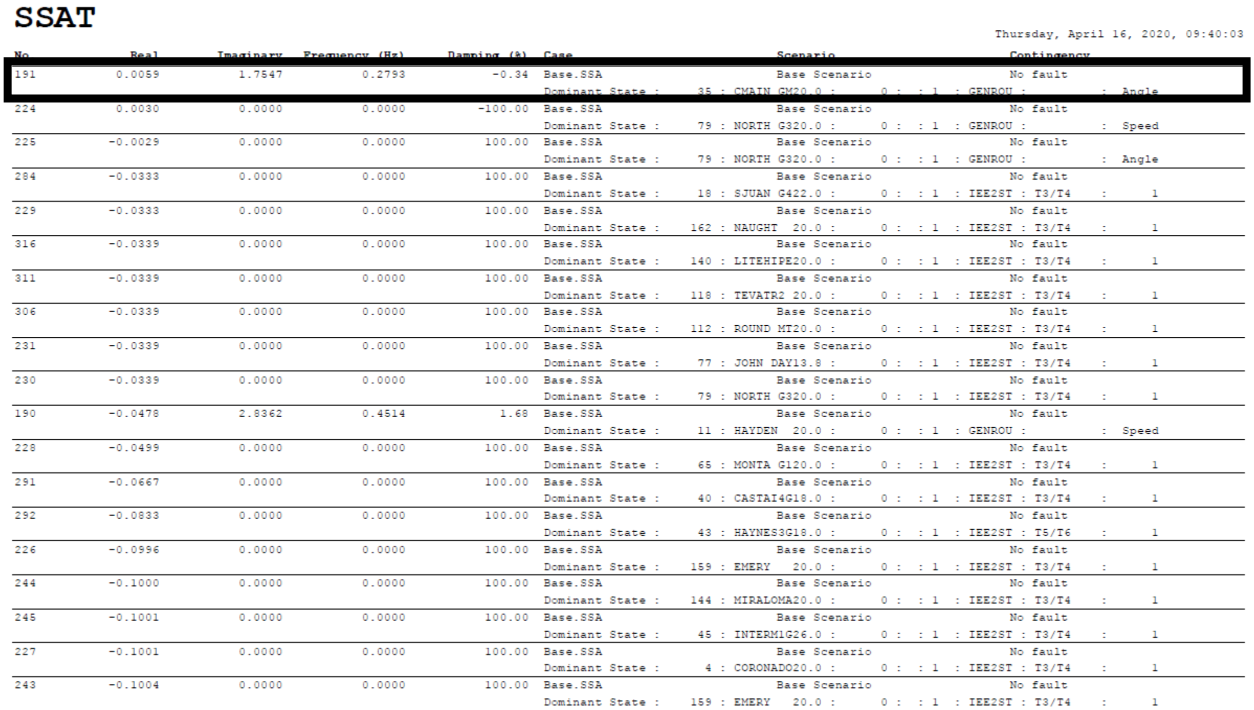
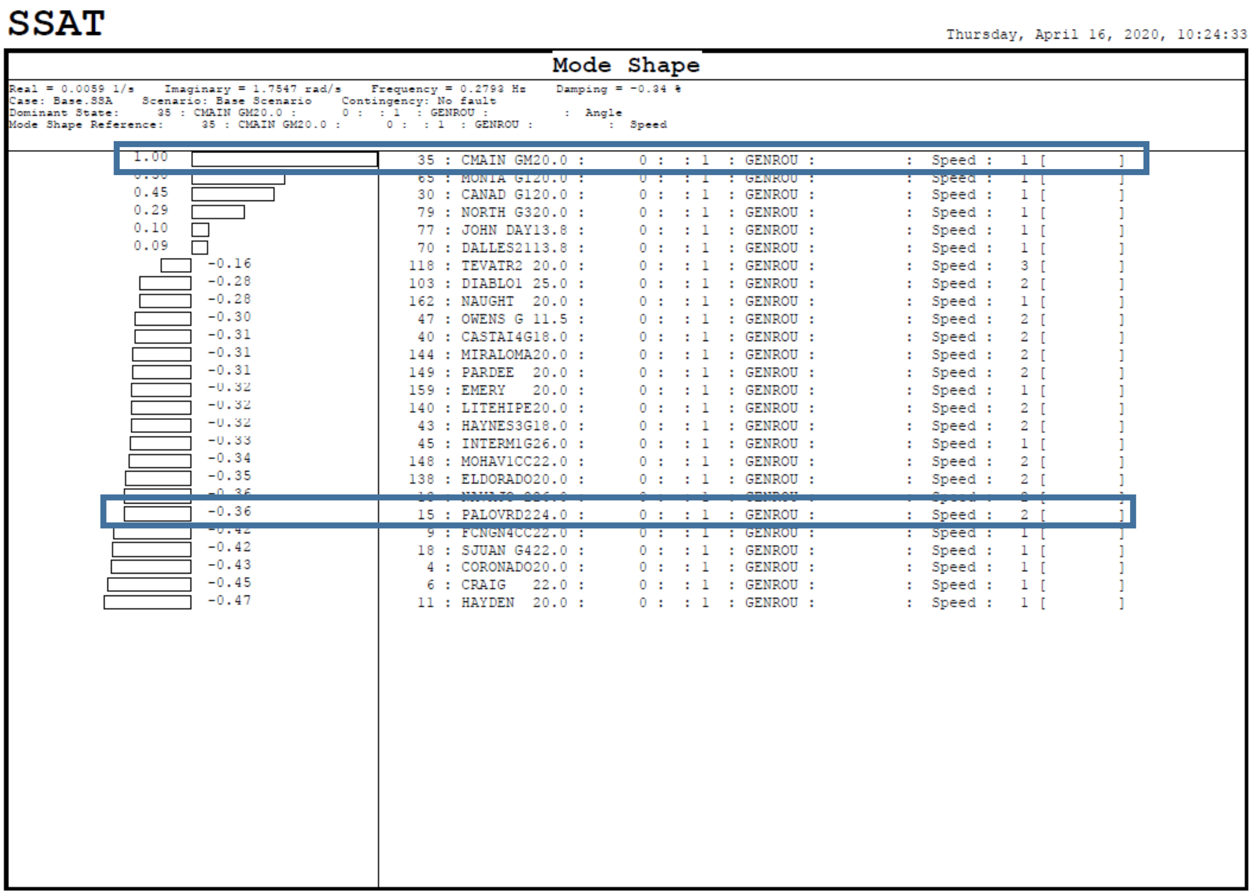
[1] The QR method is computationally intractable for large systems, so SSAT offers other methods; the most heavily used one is the Arnoldi method. This method requires the user to specify a frequency and damping range (a "box" in the real-imaginary plane). Then SSAT computes only corresponding eigenvalues in that box.

Table 1: Modal Data for Base Case



```
SSAT
                                                                                                                                         Thursday, April 16, 2020, 09:40:03
No              Real       Imaginary  Frequency (Hz)     Damping (%)   Case                             Scenario                        Contingency
191           0.0059          1.7547          0.2793           -0.34   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    35 : CMAIN GM20.0 :      0 :   : 1  : GENROU :           :  Angle
224           0.0030          0.0000          0.0000         -100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    79 : NORTH G320.0 :      0 :   : 1  : GENROU :           :  Speed
225          -0.0029          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    79 : NORTH G320.0 :      0 :   : 1  : GENROU :           :  Angle
284          -0.0333          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    18 : SJUAN G422.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
229          -0.0333          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :   162 : NAUGHT  20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
316          -0.0339          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :   140 : LITEHIPE20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
311          -0.0339          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :   118 : TEVATR2 20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
306          -0.0339          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :   112 : ROUND MT20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
231          -0.0339          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    77 : JOHN DAY13.8 :      0 :   : 1  : IEE2ST : T3/T4     :      1
230          -0.0339          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    79 : NORTH G320.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
190          -0.0478          2.8362          0.4514            1.68   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    11 : HAYDEN  20.0 :      0 :   : 1  : GENROU :           :  Speed
228          -0.0499          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    65 : MONTA G120.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
291          -0.0667          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    40 : CASTAI4G18.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
292          -0.0833          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    43 : HAYNES3G18.0 :      0 :   : 1  : IEE2ST : T5/T6     :      1
226          -0.0996          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :   159 : EMERY   20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
244          -0.1000          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :   144 : MIRALOMA20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
245          -0.1001          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :    45 : INTERM1G26.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
227          -0.1001          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :     4 : CORONADO20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
243          -0.1004          0.0000          0.0000          100.00   Base.SSA                         Base Scenario                   No fault
                                                                       Dominant State :   159 : EMERY   20.0 :      0 :   : 1  : IEE2ST : T3/T4     :      1
```

SSAT provides mode shape (the angle of the element a+jb, atan(b/a), in the right eigenvector) for the speed states having largest right-eigenvector magnitudes. Magnitudes are normalized to the element having the largest magnitude. The plot shows whether the angle is negative or positive. Note that the magnitude information is only a part of the participation factor and so cannot be used alone to identify dominant states (but it is *a part* of the participation factor). But the angles are directly useful for identifying states that are in anti-phase and thus swinging against one another.



```
SSAT                                                                         Thursday, April 16, 2020, 10:24:33
                                              Mode Shape
Real = 0.0059 1/s    Imaginary = 1.7547 rad/s    Frequency = 0.2793 Hz    Damping = -0.34 %
Case: Base.SSA    Scenario: Base Scenario    Contingency: No fault
Dominant State:     35 : CMAIN GM20.0 :       0 :   : 1   : GENROU :          :  Angle
Mode Shape Reference:     35 : CMAIN GM20.0 :      0 :   : 1   : GENROU :          :  Speed

 1.00          35 : CMAIN GM20.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
 0.50          65 : MONTA G120.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
 0.45          30 : CANAD G120.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
 0.29          79 : NORTH G320.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
 0.10          77 : JOHN DAY13.8 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
 0.09          70 : DALLES2113.8 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.16   118 : TEVATR2 20.0 :       0 :   : 1   : GENROU :           :  Speed :   3 [          ]
      -0.28   103 : DIABLO1 25.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.28   162 : NAUGHT  20.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.30    47 : OWENS G 11.5 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.31    40 : CASTAI4G18.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.31   144 : MIRALOMA20.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.31   149 : PARDEE  20.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.32   159 : EMERY   20.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.32   140 : LITEHIPE20.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.32    43 : HAYNES3G18.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.33    45 : INTERM1G26.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.34   148 : MOHAV1CC22.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.35   138 : ELDORADO20.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.36    10 : NAVAJO 226.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.36    15 : PALOVRD224.0 :       0 :   : 1   : GENROU :           :  Speed :   2 [          ]
      -0.42     9 : FCNGN4CC22.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.42    18 : SJUAN G422.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.43     4 : CORONADO20.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.45     6 : CRAIG   22.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
      -0.47    11 : HAYDEN  20.0 :       0 :   : 1   : GENROU :           :  Speed :   1 [          ]
```

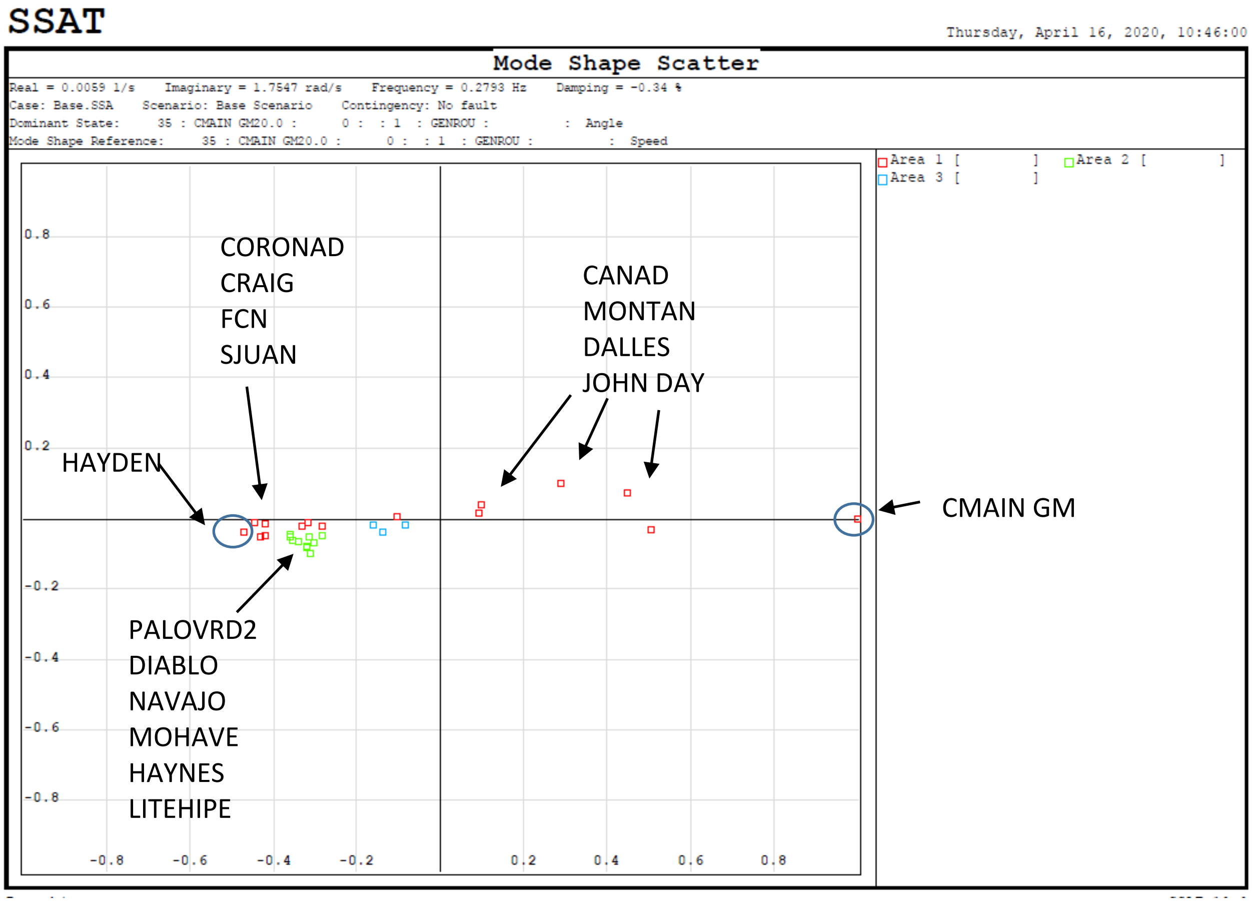
Fig. 3: Mode Shape for 0.28 Hz mode, basecase

From this data, we observe that

- CMAIN G has the largest right eigenvector element and has positive phase.
- PALOVRD2 has a large (though not largest) right eigenvalue element with negative phase.
- HAYDEN has the largest right eigenvalue with negative phase.

We could now use TSAT to plot speed for CMAIN GM and HAYDEN.

SSAT offers another way to inspect mode shape, called Scatterplot. Scatterplot plots each right eigenvector element in the real-imaginary plane. I provide the scatterplot corresponding to our case in Fig. 4 below. The right-hand pane is a facility to identify the states corresponding to each dot in the plot. I have used this facility to identify a few of them for you.



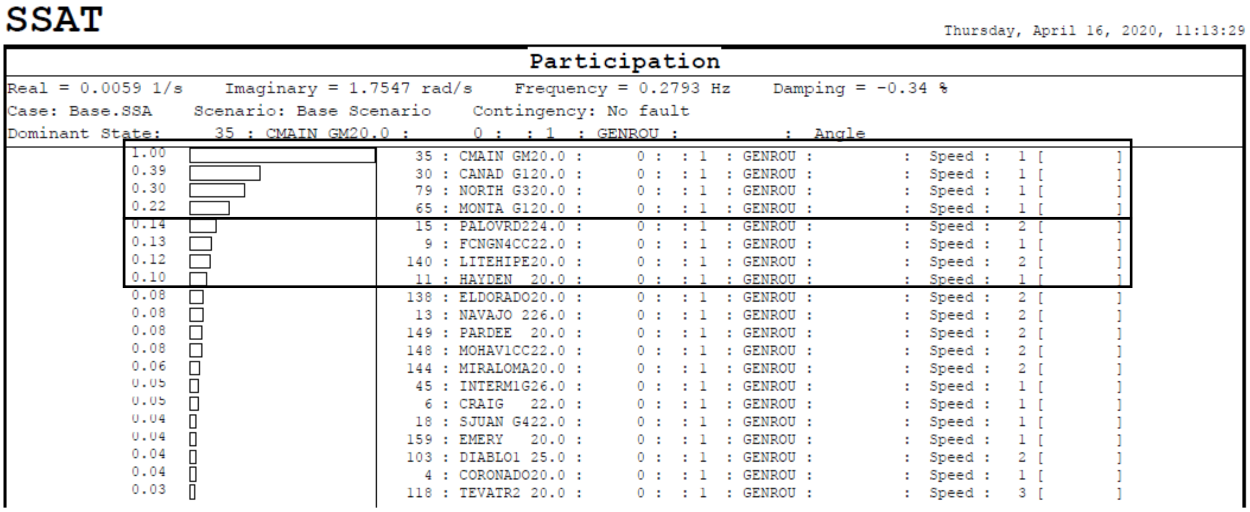
```
Real = 0.0059 1/s     Imaginary = 1.7547 rad/s     Frequency = 0.2793 Hz     Damping = -0.34 %
Case: Base.SSA     Scenario: Base Scenario     Contingency: No fault
Dominant State:      35 : CMAIN GM20.0 :       0 :   : 1   : GENROU :            :  Angle
Mode Shape Reference:      35 : CMAIN GM20.0 :       0 :   : 1   : GENROU :            :  Speed
```

Fig. 4: Scatterplot for 0.28 Hz mode, basecase

Locating the various units on our one-line diagram confirms that this mode has speed states in the Southern California/Arizona area that are in anti-phase with speed states in Canada, Washington, and Montana.

You can rightly think of this in terms of kinetic energy (KE) exchange: when generators in the north speed up (increase KE), generators in the south slow down (decrease KE), and vice-versa.

Now let’s investigate participation factors to see which generators are most heavily participating in this mode. These will be the generators that are the best targets to adjust in some way. SSAT identifies the states having the largest participation in the specified mode, as indicated in Fig. 5 below.



```
SSAT                                                        Thursday, April 16, 2020, 11:13:29
                                  Participation
Real = 0.0059 1/s    Imaginary = 1.7547 rad/s    Frequency = 0.2793 Hz    Damping = -0.34 %
Case: Base.SSA    Scenario: Base Scenario    Contingency: No fault
Dominant State:     35 : CMAIN GM20.0 :       0 :   : 1   : GENROU :            :  Angle
          1.00          35 : CMAIN GM20.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.39          30 : CANAD G120.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.30          79 : NORTH G320.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.22          65 : MONTA G120.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.14          15 : PALOVRD224.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.13           9 : FCNGN4CC22.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.12         140 : LITEHIPE20.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.10          11 : HAYDEN  20.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.08         138 : ELDORADO20.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.08          13 : NAVAJO 226.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.08         149 : PARDEE  20.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.08         148 : MOHAV1CC22.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.06         144 : MIRALOMA20.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.05          45 : INTERM1G26.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.05           6 : CRAIG   22.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.04          18 : SJUAN G422.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.04         159 : EMERY   20.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.04         103 : DIABLO1 25.0 :       0 :   : 1  : GENROU :          :  Speed :   2 [         ]
          0.04           4 : CORONADO20.0 :       0 :   : 1  : GENROU :          :  Speed :   1 [         ]
          0.03         118 : TEVATR2 20.0 :       0 :   : 1  : GENROU :          :  Speed :   3 [         ]
```

Fig. 5: Participation factors for 0.28 Hz mode, basecase

Here we see the units most heavily participating in this 0.28Hz mode. This information, together with the mode shape information, tells us that this is a mode where generators in the north are swinging against generators in the south:

In the north: CMAIN GM, CANAD G, NORTH G, MONTA G,

and

In the south: PALOVRD2, FCNGN4CC, LITEHIPE, HAYDEN

This has provided us with very useful information, and the approach to take is to adjust the most participatory generators in the north and the most participatory generators in the south.

Now, what do we mean by “adjust”?

There are two approaches:

1. Change the conditions;
2. Change the controls.

3.0 Adjust by changing the conditions

This 0.28Hz mode, as a result of the fact that it has heavy participation from two groups of machines in different areas, is called an interarea mode. Generally, interarea mode damping is made worse when the power transfer between the two areas is increased. So I assessed the power transfer from the northern area into California, along the Pacific AC Intertie (PACI), and it was about 2000 MW. The lines over which this flow is occuring are 82-83 (via the not shown 95-96-97-98-83), 82-83 (via the not-shown 91-92-93-94-83), and 82-87 (via the not shown 88-86-90-89-83), as shown by the dashed line in the one-line diagram of Fig. 6.

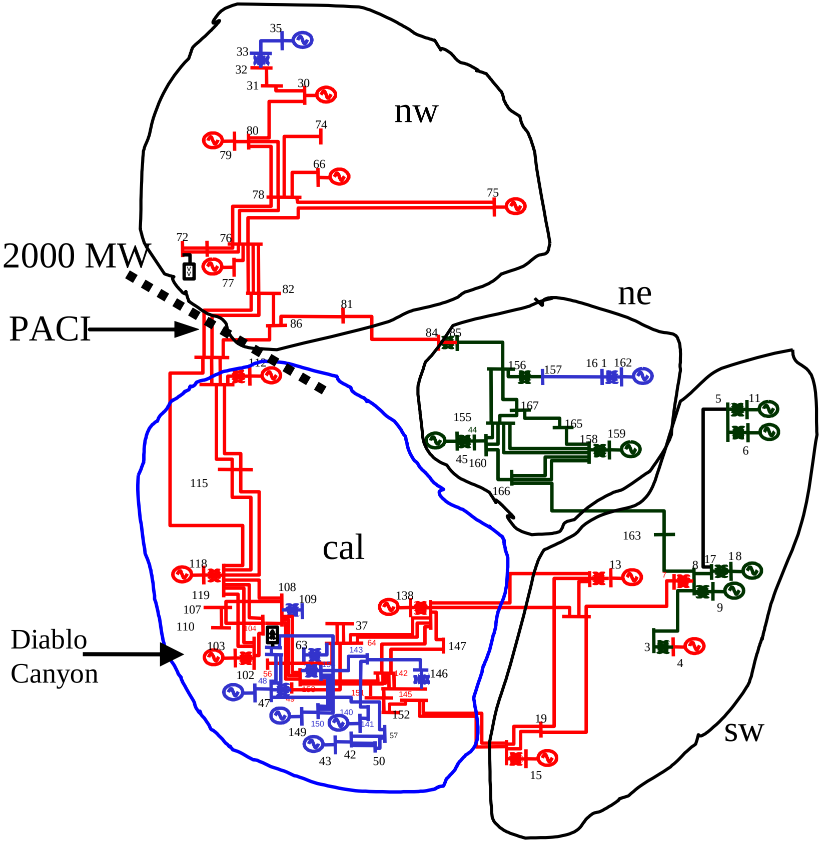


Fig. 6: 2000 MW north-to-south transfer along PACI

And so we want to decrease this 2000MW North-to-South transfer. To do this, I made the generation changes according to Table 2.

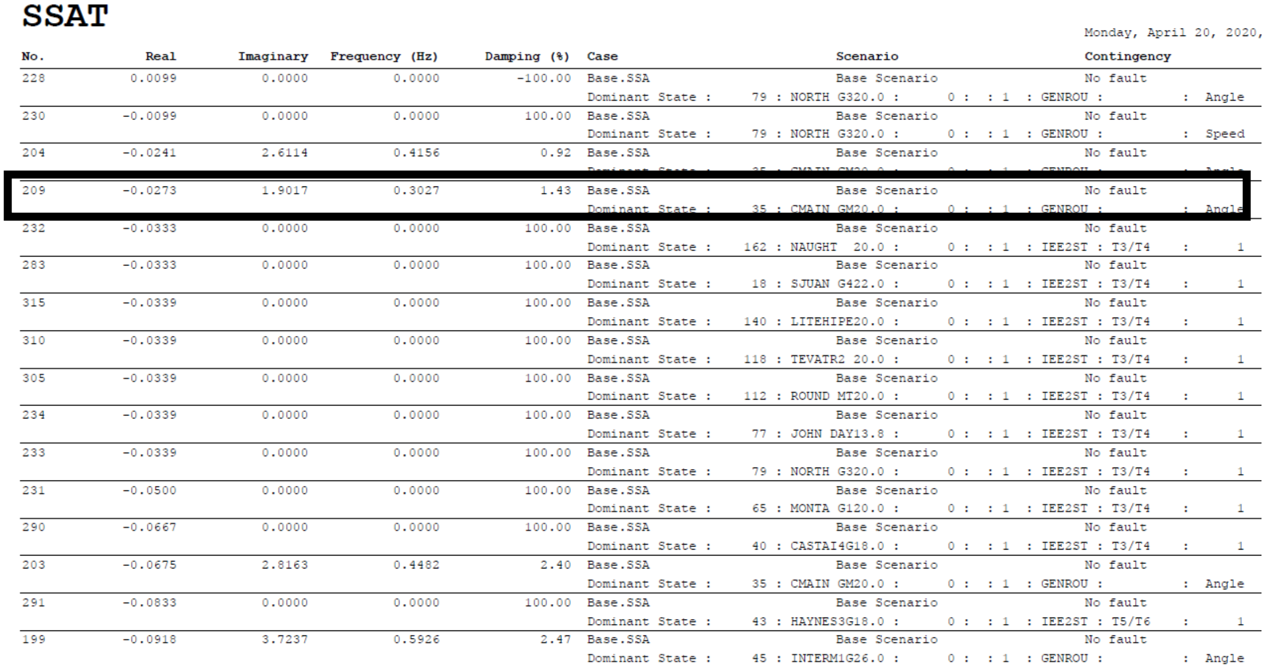
Table 2: Gen changes to reduce north-to-south power transfer

North Gens	ΔP_{gen}	South Gens	ΔP_{gen}
CMAIN GM,	-500	PALOVRD2	+500
CANAD G,	-500	FCNGN4CC	+500
NORTH G,	-500	LITEHIPE	+500
MONTA G,	-500	HAYDEN	+500

The reason I made changes to these generators is because they are the most participatory generators in this mode.

After making these changes, I again used SSAT to perform eigenanalysis. Results are in Table 3 (analagous to Table 1) where I identified the mode of interest within the box. How do I know this is the mode of interest?...

Table 3: Modal Data for Change Case #1



```
SSAT
                                                                                                  Monday, April 20, 2020,
No.       Real     Imaginary  Frequency (Hz)    Damping (%)  Case                          Scenario                     Contingency
228      0.0099       0.0000         0.0000        -100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    79 : NORTH G320.0 :      0 :  : 1  : GENROU :              :  Angle
230     -0.0099       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    79 : NORTH G320.0 :      0 :  : 1  : GENROU :              :  Speed
204     -0.0241       2.6114         0.4156           0.92   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    35 : CMAIN GM20.0 :      0 :  : 1  : GENROU :              :  Angle
209     -0.0273       1.9017         0.3027           1.43   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    35 : CMAIN GM20.0 :      0 :  : 1  : GENROU :              :  Angle
232     -0.0333       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :   162 : NAUGHT  20.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
283     -0.0333       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    18 : SJUAN G422.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
315     -0.0339       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :   140 : LITEHIPE20.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
310     -0.0339       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :   118 : TEVATR2 20.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
305     -0.0339       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :   112 : ROUND MT20.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
234     -0.0339       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    77 : JOHN DAY13.8 :      0 :  : 1  : IEE2ST : T3/T4    :        1
233     -0.0339       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    79 : NORTH G320.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
231     -0.0500       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    65 : MONTA G120.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
290     -0.0667       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    40 : CASTAI4G18.0 :      0 :  : 1  : IEE2ST : T3/T4    :        1
203     -0.0675       2.8163         0.4482           2.40   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    35 : CMAIN GM20.0 :      0 :  : 1  : GENROU :              :  Angle
291     -0.0833       0.0000         0.0000         100.00   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    43 : HAYNES3G18.0 :      0 :  : 1  : IEE2ST : T5/T6    :        1
199     -0.0918       3.7237         0.5926           2.47   Base.SSA                      Base Scenario                No fault
                                                             Dominant State :    45 : INTERM1G26.0 :      0 :  : 1  : GENROU :              :  Angle
```

First of all, what do we mean by the “mode of interest”?

➔We mean, by that, that we want to find the the same mode we were examining before, that was unstable in the basecase.

Now, why do I identify the mode in the box as the “mode of interest”? There are three clues:

1. The frequency is close. We previously had a frequency of 0.28. The frequency of this mode is 0.30 Hz.
2. The damping is close. We previously had real part of +0.0069. The real part of this mode is -0.0273.
3. The dominant state is still the angle state of CMAIN GM.

However, there are still two things to check: are mode shape and participation similar? If either mode shape or participation is very different, then it may be an indication we are looking at a different mode[2].

Figure 7 shows the mode shape for this 0.30 Hz mode. Although the sign of the angles for the two different groups are reversed, the basic information, in terms of which units are swinging against each other, is the same as the information provided in Fig. 3.

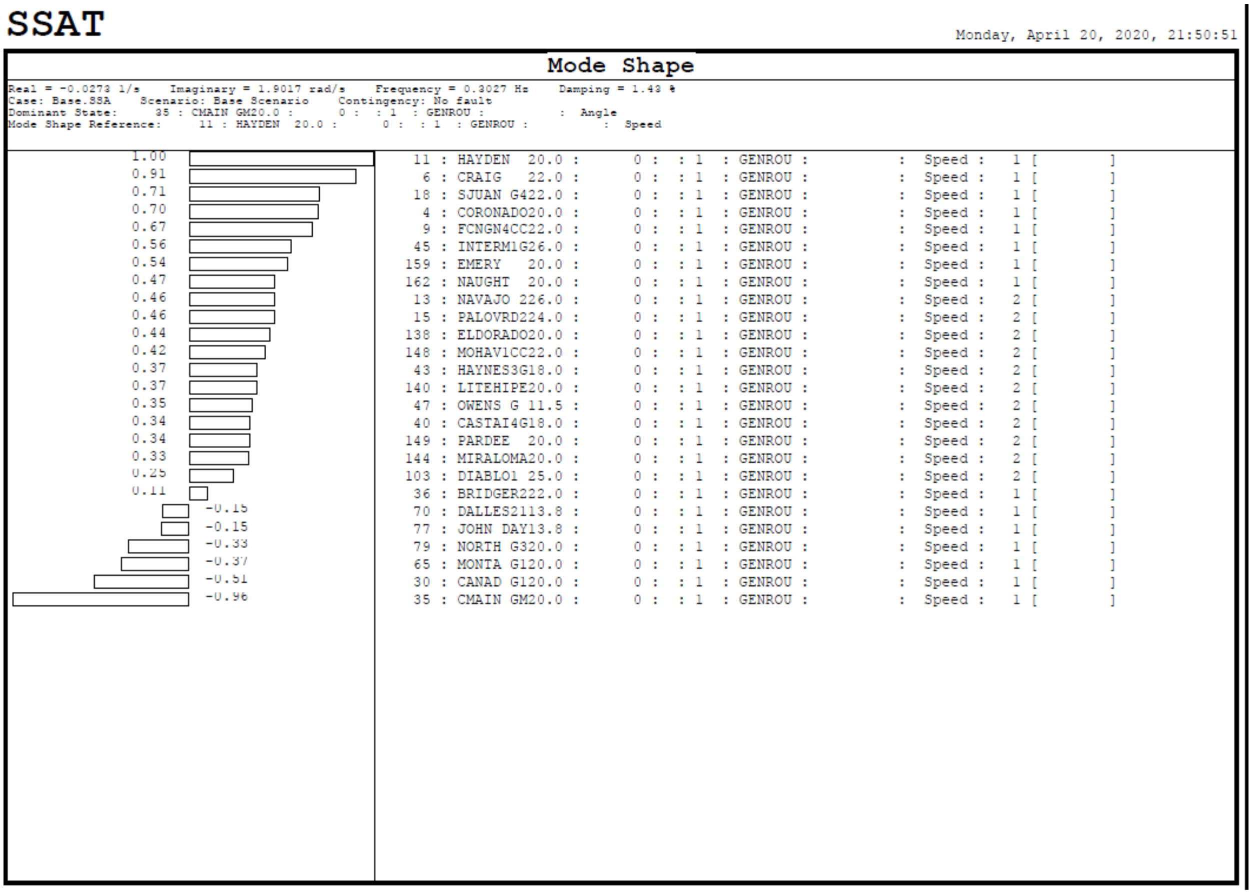
Likewise, we should observe that the participation in this mode has not changed much. To that end, we observe in Fig. 8 the most heavily participating generators in this 0.30Hz mode. Although the order is different, the generators high on the list before (bolded below) are still high on the list. This information, together with the mode shape information, tells us that this is a mode where generators in the north are swinging against generators in the south:

In the north: **CMAIN GM**, **CANAD G**, **MONTA G**, **NORTH G**.

In the south: **HAYDEN**, CRAIG, SANJUAN, CORONADO, **FCNGN4CC**, INTERM, EMERY, NAUGHT, NAVAJO, **PALOVRD2**, ELDORADO, MOHAVE, HAYNES, **LITEHIPE**.

---

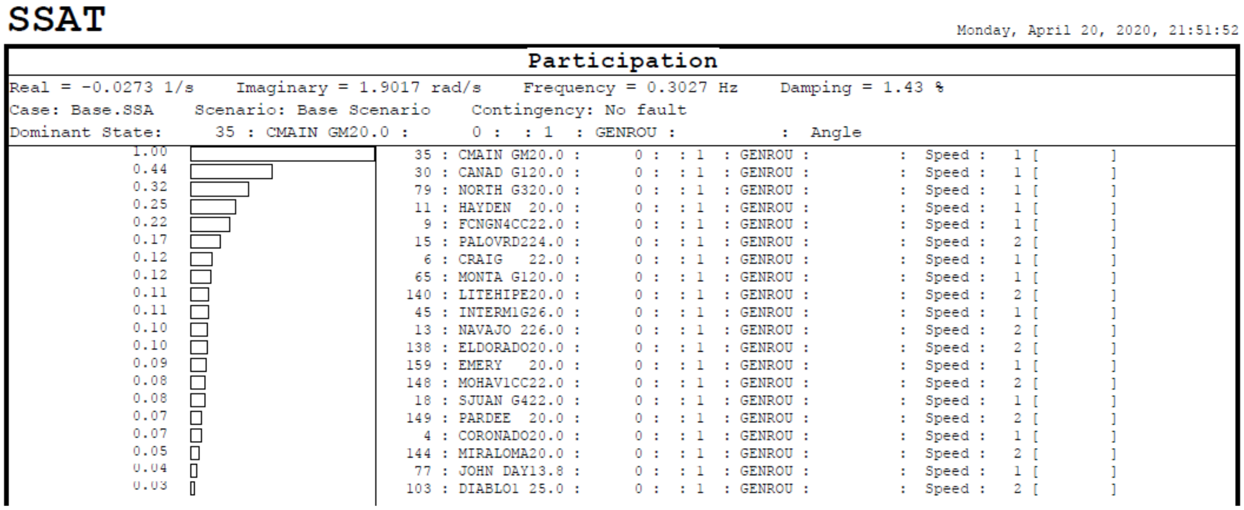
[2] When either condition/topology or control changes are made, the location on the complex plane of some modes will not change much, but the location of other modes may change significantly. But all modes will change to one degree or another, i.e., modes tend to "move around" the complex plane when changes are made in condition/topology or control. For those of you who have had a basic controls course, it will be meaningful to you to think of this modal movement on the complex plane in the same way that varying transfer function gain affects a root locus.



```
SSAT
                                                              Monday, April 20, 2020, 21:50:51
                                  Mode Shape
Real = -0.0273 1/s    Imaginary = 1.9017 rad/s    Frequency = 0.3027 Hz    Damping = 1.43 %
Case: Base.SSA    Scenario: Base Scenario    Contingency: No fault
Dominant State:     35 : CMAIN GM20.0 :      0 :  : 1  : GENROU :          :  Angle
Mode Shape Reference:     11 : HAYDEN  20.0 :      0 :  : 1  : GENROU :          :  Speed

 1.00     11 : HAYDEN   20.0 :      0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.91      6 : CRAIG    22.0 :      0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.71     18 : SJUAN G422.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.70      4 : CORONADO20.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.67      9 : FCNGN4CC22.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.56     45 : INTERM1G26.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.54    159 : EMERY    20.0 :      0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.47    162 : NAUGHT   20.0 :      0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.46     13 : NAVAJO 226.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.46     15 : PALOVRD224.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.44    138 : ELDORADO20.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.42    148 : MOHAV1CC22.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.37     43 : HAYNES3G18.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.37    140 : LITEHIPE20.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.35     47 : OWENS G 11.5 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.34     40 : CASTAI4G18.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.34    149 : PARDEE   20.0 :      0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.33    144 : MIRALOMA20.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.25    103 : DIABLO1 25.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.11     36 : BRIDGER222.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
-0.15     70 : DALLES2113.8 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
-0.15     77 : JOHN DAY13.8 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
-0.33     79 : NORTH G320.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
-0.37     65 : MONTA G120.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
-0.51     30 : CANAD G120.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
-0.96     35 : CMAIN GM20.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
```

Fig. 7: Mode Shape for 0.30 Hz mode, change case#1



```
SSAT
                                                              Monday, April 20, 2020, 21:51:52
                                  Participation
Real = -0.0273 1/s    Imaginary = 1.9017 rad/s    Frequency = 0.3027 Hz    Damping = 1.43 %
Case: Base.SSA    Scenario: Base Scenario    Contingency: No fault
Dominant State:     35 : CMAIN GM20.0 :      0 :  : 1  : GENROU :          :  Angle

 1.00     35 : CMAIN GM20.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.44     30 : CANAD G120.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.32     79 : NORTH G320.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.25     11 : HAYDEN   20.0 :      0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.22      9 : FCNGN4CC22.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.17     15 : PALOVRD224.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.12      6 : CRAIG    22.0 :      0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.12     65 : MONTA G120.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.11    140 : LITEHIPE20.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.11     45 : INTERM1G26.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.10     13 : NAVAJO 226.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.10    138 : ELDORADO20.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.09    159 : EMERY    20.0 :      0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.08    148 : MOHAV1CC22.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.08     18 : SJUAN G422.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.07    149 : PARDEE   20.0 :      0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.07      4 : CORONADO20.0 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.05    144 : MIRALOMA20.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
 0.04     77 : JOHN DAY13.8 :       0 :  : 1  : GENROU :          :  Speed :   1 [         ]
 0.03    103 : DIABLO1 25.0 :       0 :  : 1  : GENROU :          :  Speed :   2 [         ]
```

Fig. 8: Participation factors for 0.30 Hz mode, change case#1

So now it is appropriate to check using time-domain-simulation to see if we have stabilized the case. Figure 9 shows the time-domain simulation. There are two generators losing synchronism at about 25 seconds; CRAIG and HAYDEN, but no other units. Hmmm. Did we do something wrong? Let's look a little deeper…

We observe two things about this oscillation:

1. It involves only 2 units that were participatory in the 0.30 Hz mode of Fig 8, but neither of these were *most* participatory in the 0.30 Hz mode; indeed, their participation might be assessed as "modest." (units that were most participatory in this mode are more stable).
2. The oscillation of these two units has a period of about 2.5 seconds, which translates to a frequency of 0.4Hz. This is fairly different than our previous frequency of interest, which was about 0.3Hz.

These observations raise some uncertainty about whether the mode causing the instability is the mode of original concern (the 0.3Hz mode). To check this, we should inspect the eigenanalysis a bit more.

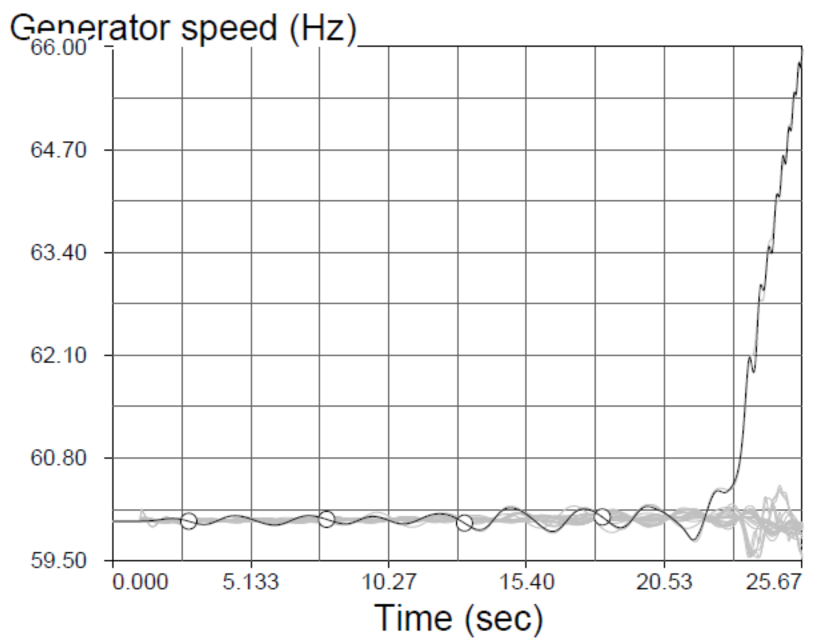
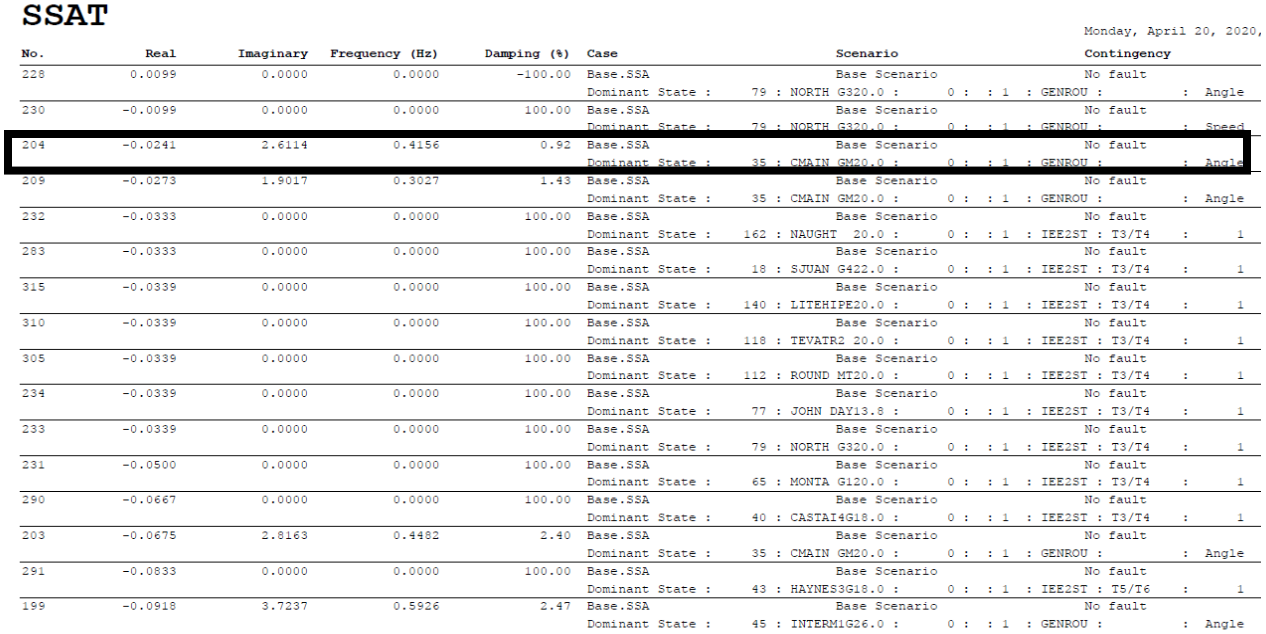


Fig. 9: Time domain simulation of Diablo-Midway#1 outage, with generation conditions changed consistent with change case #1

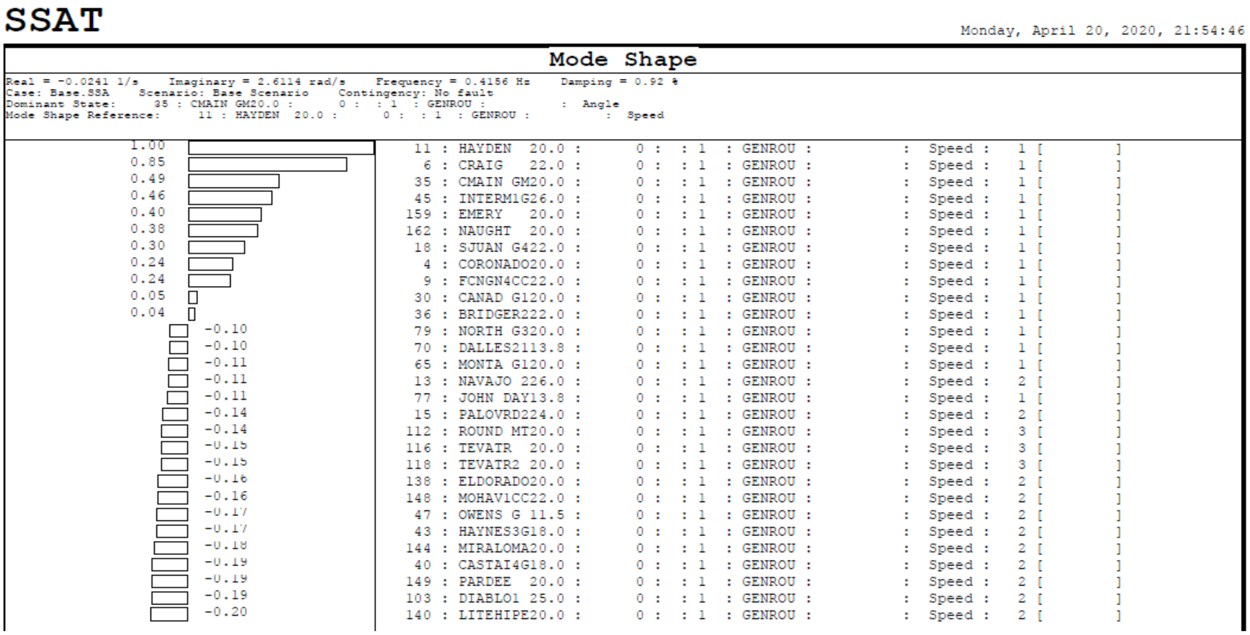
Check the eigenvalues in Table 3 (repeated here for convenience), and we observe there is a lightly damped mode at 0.4156Hz, indicated by the box. This is very close to the 0.4Hz frequency we "eyeballed" in the time-domain plot of Fig. 8.

Table 3: Modal Data for Change Case #1



```
SSAT
                                                                                          Monday, April 20, 2020,
No.         Real     Imaginary  Frequency (Hz)    Damping (%)  Case                        Scenario                    Contingency
228       0.0099        0.0000          0.0000        -100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   79 : NORTH G320.0 :     0 :  : 1  : GENROU :            :  Angle
230      -0.0099        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   79 : NORTH G320.0 :     0 :  : 1  : GENROU :            :  Speed
204      -0.0241        2.6114          0.4156           0.92  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   35 : CMAIN GM20.0 :     0 :  : 1  : GENROU :            :  Angle
209      -0.0273        1.9017          0.3027           1.43  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   35 : CMAIN GM20.0 :     0 :  : 1  : GENROU :            :  Angle
232      -0.0333        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :  162 : NAUGHT  20.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
283      -0.0333        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   18 : SJUAN G422.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
315      -0.0339        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :  140 : LITEHIPE20.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
310      -0.0339        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :  118 : TEVATR2 20.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
305      -0.0339        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :  112 : ROUND MT20.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
234      -0.0339        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   77 : JOHN DAY13.8 :     0 :  : 1  : IEE2ST : T3/T4      :      1
233      -0.0339        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   79 : NORTH G320.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
231      -0.0500        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   65 : MONTA G120.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
290      -0.0667        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   40 : CASTAI4G18.0 :     0 :  : 1  : IEE2ST : T3/T4      :      1
203      -0.0675        2.8163          0.4482           2.40  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   35 : CMAIN GM20.0 :     0 :  : 1  : GENROU :            :  Angle
291      -0.0833        0.0000          0.0000         100.00  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   43 : HAYNES3G18.0 :     0 :  : 1  : IEE2ST : T5/T6      :      1
199      -0.0918        3.7237          0.5926           2.47  Base.SSA                    Base Scenario               No fault
                                                               Dominant State :   45 : INTERM1G26.0 :     0 :  : 1  : GENROU :            :  Angle
```

So let's check out this lightly-damped 0.4156Hz mode.



```
SSAT                                                                      Monday, April 20, 2020, 21:54:46
                                          Mode Shape
Real = -0.0241 1/s    Imaginary = 2.6114 rad/s    Frequency = 0.4156 Hz    Damping = 0.92 %
Case: Base.SSA    Scenario: Base Scenario    Contingency: No fault
Dominant State:     35 : CMAIN GM20.0 :     0 :   : 1  : GENROU :          :  Angle
Mode Shape Reference:     11 : HAYDEN  20.0 :     0 :  : 1  : GENROU :          :  Speed

   1.00          11 : HAYDEN  20.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.85           6 : CRAIG   22.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.49          35 : CMAIN GM20.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.46          45 : INTERM1G26.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.40         159 : EMERY   20.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.38         162 : NAUGHT  20.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.30          18 : SJUAN G422.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.24           4 : CORONADO20.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.24           9 : FCNGN4CC22.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.05          30 : CANAD G120.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
   0.04          36 : BRIDGER222.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
      -0.10      79 : NORTH G320.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
      -0.10      70 : DALLES2113.8 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
      -0.11      65 : MONTA G120.0 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
      -0.11      13 : NAVAJO 226.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.11      77 : JOHN DAY13.8 :    0 :  : 1  : GENROU :         :  Speed :  1 [       ]
      -0.14      15 : PALOVRD224.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.14     112 : ROUND MT20.0 :    0 :  : 1  : GENROU :         :  Speed :  3 [       ]
      -0.15     116 : TEVATR  20.0 :    0 :  : 1  : GENROU :         :  Speed :  3 [       ]
      -0.15     118 : TEVATR2 20.0 :    0 :  : 1  : GENROU :         :  Speed :  3 [       ]
      -0.16     138 : ELDORADO20.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.16     148 : MOHAV1CC22.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.17      47 : OWENS G 11.5 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.17      43 : HAYNES3G18.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.18     144 : MIRALOMA20.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.19      40 : CASTAI4G18.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.19     149 : PARDEE  20.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.19     103 : DIABLO1 25.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
      -0.20     140 : LITEHIPE20.0 :    0 :  : 1  : GENROU :         :  Speed :  2 [       ]
```

Fig. 10: Mode Shape for 0.4156 Hz mode, change case#1

We observe that the two generators that lose synchronism in the time-domain simulation, HAYDEN and CRAIG (two coal plants in Colorado), CMAINGM (far north, in Canada), INTERMT (in Utah) and others in this region are swinging against generators in Southern California (LITEHOPE, DIABLO, PARDEE, CASTAIC, MIRALOMA) and Arizona (PALOVRD), as indicated in Fig. 10.

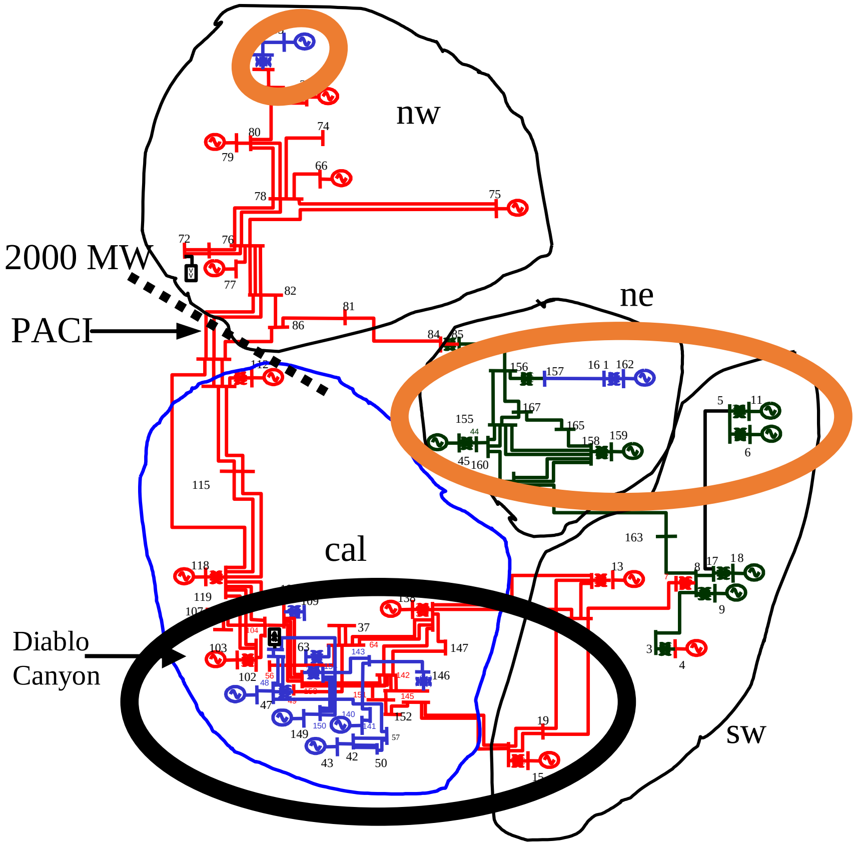
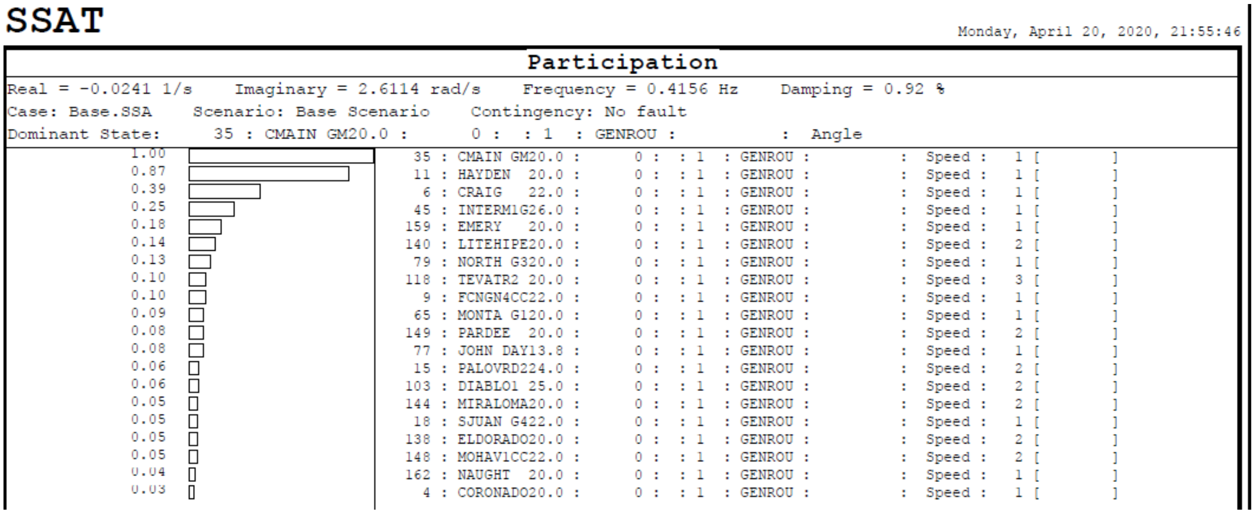


Fig. 10: Generators from mode shape swinging in 0.4156Hz mode

Now we are beginning to be confident that the unstable mode in the time-domain simulation is this 0.4156Hz mode. But let’s check one more thing – the participation factors for this mode, indicated in Fig. 11.



```
SSAT
                                                                     Monday, April 20, 2020, 21:55:46
                                          Participation
Real = -0.0241 1/s    Imaginary = 2.6114 rad/s    Frequency = 0.4156 Hz    Damping = 0.92 %
Case: Base.SSA    Scenario: Base Scenario    Contingency: No fault
Dominant State:     35 : CMAIN GM20.0 :      0 :   : 1   : GENROU :            :  Angle
             1.00        35 : CMAIN GM20.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.87        11 : HAYDEN  20.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.39         6 : CRAIG   22.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.25        45 : INTERM1G26.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.18       159 : EMERY   20.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.14       140 : LITEHIPE20.0 :      0 :  : 1  : GENROU :           :  Speed :   2 [        ]
             0.13        79 : NORTH G320.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.10       118 : TEVATR2 20.0 :      0 :  : 1  : GENROU :           :  Speed :   3 [        ]
             0.10         9 : FCNGN4CC22.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.09        65 : MONTA G120.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.08       149 : PARDEE  20.0 :      0 :  : 1  : GENROU :           :  Speed :   2 [        ]
             0.08        77 : JOHN DAY13.8 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.06        15 : PALOVRD224.0 :      0 :  : 1  : GENROU :           :  Speed :   2 [        ]
             0.06       103 : DIABLO1 25.0 :      0 :  : 1  : GENROU :           :  Speed :   2 [        ]
             0.05       144 : MIRALOMA20.0 :      0 :  : 1  : GENROU :           :  Speed :   2 [        ]
             0.05        18 : SJUAN G422.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.05       138 : ELDORADO20.0 :      0 :  : 1  : GENROU :           :  Speed :   2 [        ]
             0.05       148 : MOHAV1CC22.0 :      0 :  : 1  : GENROU :           :  Speed :   2 [        ]
             0.04       162 : NAUGHT  20.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
             0.03         4 : CORONADO20.0 :      0 :  : 1  : GENROU :           :  Speed :   1 [        ]
```

Fig. 11: Participation factors for change case #1, 0.4156Hz mode

The participation factors indicate that, for the northern group, CMAINGM, HAYDEN, and CRAIG are the top three units, and for the southern group, LITEHIPE, TEVATR2, and PARDEE are the top three units. The speed deviation plots for these six units from time-domain simulation are shown in Fig. 12.

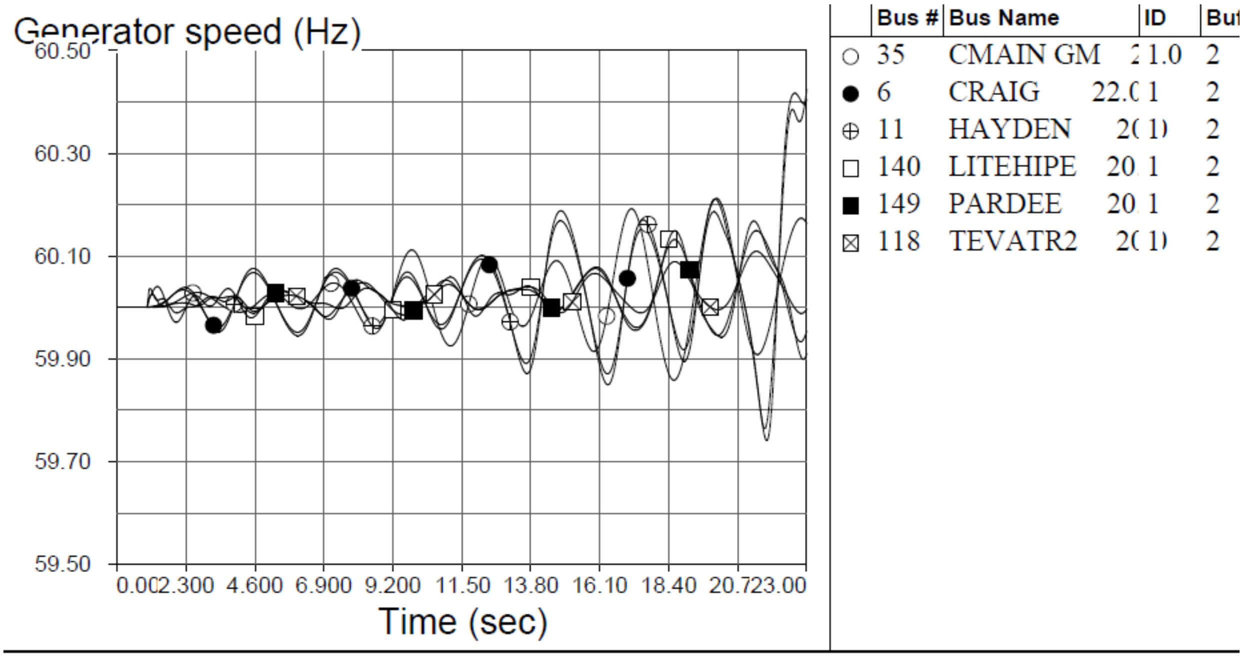


Fig. 12: Time domain simulation of Diablo-Midway#1 outage, with generation conditions changed consistent with change case #1; plots of most highly participating speed deviation states

Note that in Fig. 12 the simulation was terminated at 23 sec, before CRAIG and HAYDEN speed deviation plots increased too much, to keep all of the trace on the plot while keeping the scale tight enough to observe the earlier behavior. It is interesting to observe in Fig. 12 that

- The two generators going out of step at the end of the simulation are CRAIG and HAYDEN. One can observe at the end of the simulation another unit in phase with these two that, although having a lower swing amplitude, may also be growing; this is CMAINGM.
- Generators in the north are 180 degrees out of phase with generators in the south, consistent with the mode shape information.

This agreement between time domain simulation phase and mode shape information, and between time domain swing amplitude and participation factor information, is strong confirmation that this instability is caused by the 0.4156Hz mode.

The implication of this is that the operational changes we made earlier (to shift 2000MW of generation from the north to the south) did indeed stabilize the 0.30Hz mode, but it simultaneously destabilized this 0.4156Hz mode.

Reference to Table 2, repeated below for convenience, indicates that HAYDEN and LITEHIPE were two units for which we increased generation by 500MW in stabilizing the 0.3Hz mode.

Table 2: Gen changes to reduce north-to-south power transfer

North Gens	ΔP_{gen}	South Gens	ΔP_{gen}
CMAIN GM,	-500	PALOVRD2	+500
CANAD G,	-500	FCNGN4CC	+500
NORTH G,	-500	LITEHIPE	+500
MONTA G,	-500	HAYDEN	+500

Let’s shift 250MW from HAYDEN, CRAIG, and LITEHIPE in an attempt to stabilize this 0.4156Hz mode. We choose to shift that generation to MOHAVE (+500 MW) and HAYNES (+250MW); criteria used in identifying these units is that they are low in participation of both the 0.4156Hz mode and the 0.3Hz mode. We call this change case #2. The resulting time-domain simulation is shown in Fig. 13. Observe that the scale of Figs. 12 and 13 are the same. Although Fig. 13 is still exhibiting growing oscillations, the performance is improved relative to that of Fig. 12.

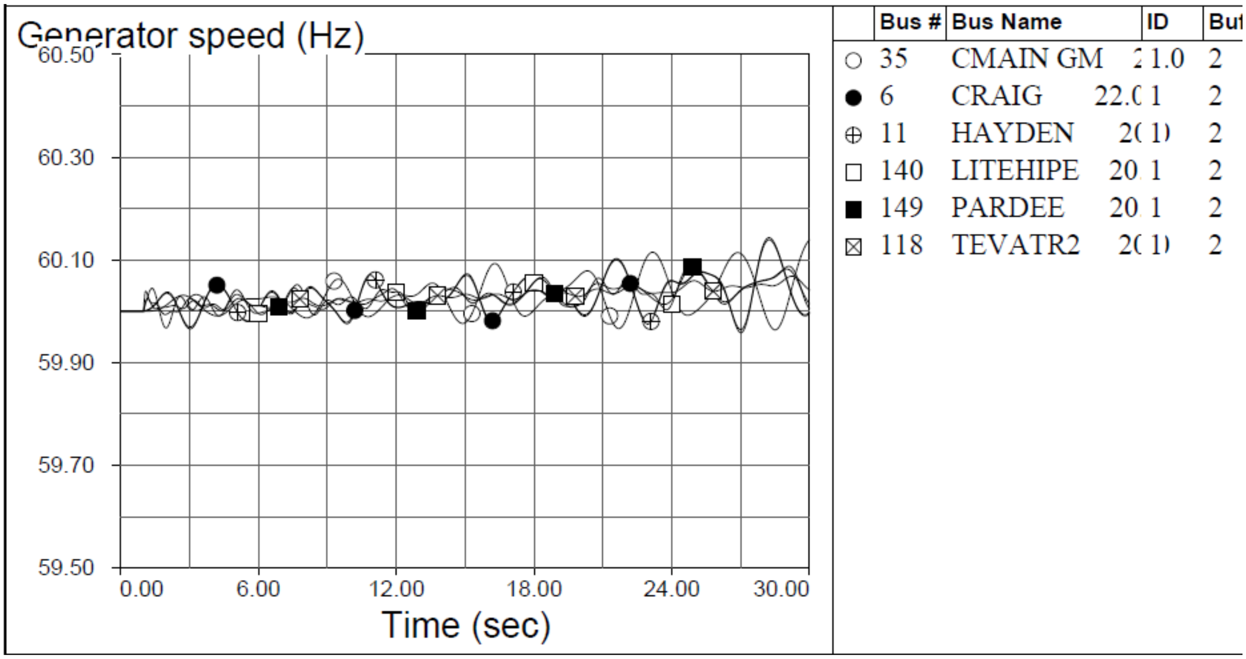


Fig. 13: Time domain simulation of Diablo-Midway#1 outage, with generation conditions changed consistent with change case #2; plots of most highly participating speed deviation states

Additional generation shifts can be performed to stabilize the system, but these changes will need to be made carefully in order to avoid destabilizing some other mode(s).

As a last comment here, we should be aware that power systems are not so easy to destabilize as this system. The reason for that is due to a 1969 IEEE paper by Charles Concordia and Paul deMello, which provided the insight necessary to design supplementary controllers for excitation systems. These supplementary controllers are now called power system stabilizers (PSS) and are the “control” response to the question posed at the top of page 9 in these notes, which read:

Now, what do we mean by “adjust”? There are two approaches:

1. Change the conditions;
2. Change the controls.

We address the second approach, via, PSS, in the next set of notes.

But one last comment on the project. When using TSAT, if you checked the “Messages” file in TSAT, identified from the “Results” menu, you would have seen 29 messages that read as follows:

```
#WARNING# - PTI PSS/E DATA CONVERSION
   STABILIZER AT BUS#     4 [CORONADO    20.0] ID  1: TYPE IEE2ST
  INPUT TYPE = 6 IS NOT SUPPORTED. THE STABILIZER IS IGNORED.
```

The 29 messages is because there are 29 machines modeled in your system. IEE2ST is a PSS\E model for a power system stabilizer, which TSAT does accept. But TSAT does not accept Input Type=6. This means that none of the 29 machines in the dynamic data, when using TSAT or SSAT, are modeling a PSS. This is the reason why we are seeing so many modal problems in this system when running it in TSAT and SSAT.

You can observe this data issue in any of the IEE2ST models in your dyr file. They look like this (with the offending “6” highlighted).

```
     70 'IEE2ST'  1       6     0     1     0
       0.00000  10.00000   0.00000   0.00000   3.00000
       3.00000   0.15000   0.05000   0.15000   0.05000
       0.15000   0.05000   0.05000  -0.05000   0.00000
       0.00000  /
```

Just to show you the benefits of this, I re-ran the original case (without any operational changes); Fig. 14 is the result.

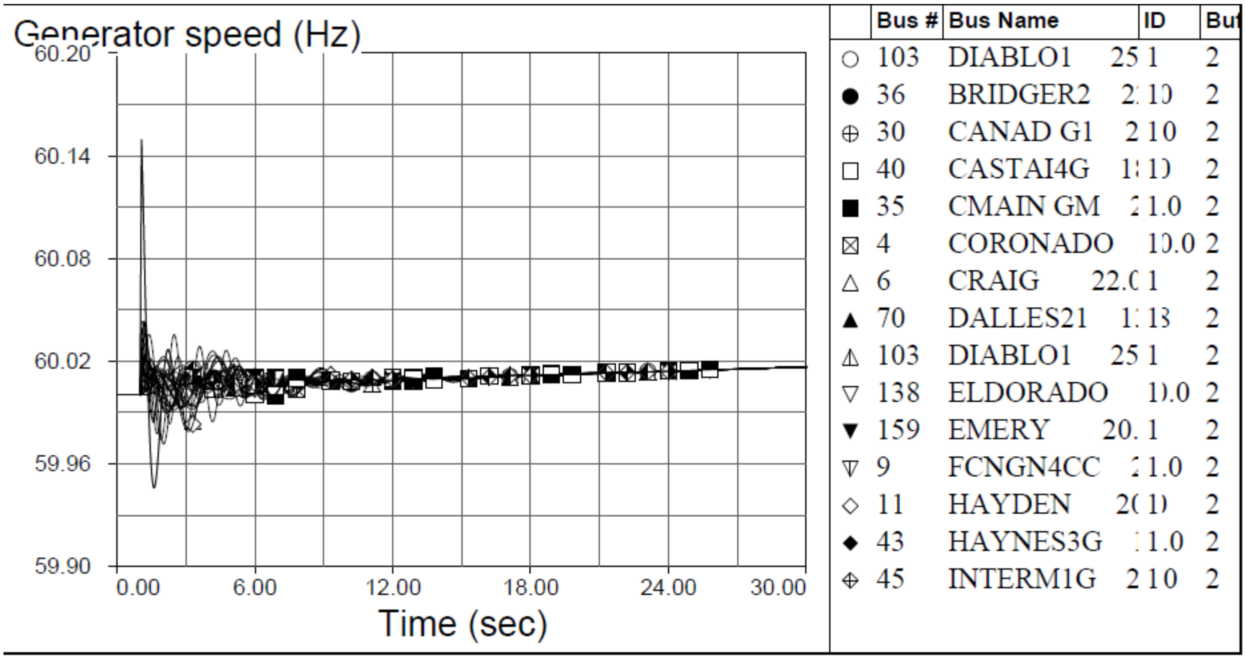


Fig. 14: Time domain simulation of Diablo-Midway#1 outage, base case, with all gens having PSS

It is pretty clear that having PSS on all (or at least most) machines is important. For that reason, many years ago, late 1970's, the WECC (called WSCC then) started to require PSS on all machines above a certain rating. WECC was very worried about this because they were seeing a lot of modal problems, due to their long transmission lines (the Eastern Interconnection has not seen so many modal problems as a result of their system being much more dense). Throughout the years, many things were done to increase the percentage of generation capacity that had PSS, with one change coming in 2017 when NERC and WECC brought to FERC the following petition:

JOINT PETITION OF THE NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION AND WESTERN ELECTRICITY COORDINATING COUNCIL FOR APPROVAL OF PROPOSED REGIONAL RELIABILITY STANDARD VAR-501-WECC-3

See www.nerc.com/FilingsOrders/us/NERC%20Filings%20to%20FERC%20DL/VAR-501-WECC-3%20Petition.pdf

It said this:

Power System Stabilizers damp oscillations that can occur between geographic areas within the Western Interconnection and have played an important role in the stability of the Western Interconnection. Over the past several decades, WECC and related working groups have developed policies and guidelines, conducted studies, and approved a Regional Reliability Standard to help manage power system stabilizer use in the Western Interconnection. With the development of proposed Regional Reliability Standard VAR-501-WECC-3, WECC seeks to incorporate elements from its policies, guidelines, and lessons learned from studies into clarified, mandatory requirements. The purpose of proposed Regional Reliability Standard VAR-501-WECC-3 is to ensure the Western Interconnection is operated in a coordinated manner under normal and abnormal conditions by establishing the performance criteria for power system stabilizers. Proposed Regional Reliability Standard VAR-501-WECC-3 includes requirements that address the following: (1) providing Transmission Operators with procedures or other documents that inform the Transmission Operator of when a power system stabilizer will be out of service; (2) having the power system stabilizer in service at all times except during specific circumstances; (3) tuning power system stabilizers to stated criteria; (4) installing and completing start-up testing of a power system stabilizer; and (5) repairing or replacing a power system stabilizer within a specified time period.