Soumyabrata Talukder

EE – 554

Project Report

I. Introduction

One of the key aspects of dynamic security study for a power system is to analyze its early swing stability in the face of the credible contingencies. This project work performs such an analysis for the bulk power transmission corridor that is used to evacuate the nuclear power generated at the Diablo-Canyon (DC) plant, a small part of the WECC system in the United States. In particular, the early swing stability is investigated for the system, while it is already weakened by outage of one line, by studying the time-domain simulation of the system's response after applying a fault on another line followed by its clearance. In other words, it illustrates the early swing stability of the system for the N-2 line contingencies in the transmission corridor emanating from the DC plant. The goal of the analysis is to find the maximum active power that can be delivered from the plant for each contingency-case such that the post contingency phase is early swing stable.

The rest of the report is organized as follows. Section II briefly describes the model used for the study, the common simulation parameters, and the contingency cases. Section III briefly discusses the implementational details. Section IV presents the simulation plots of the system variables of interests for each of the contingency cases so as to determine their respective active power limit. Section V summarizes the study results and concludes the report.

II. Model, Contingencies and Common Simulation Parameters

A 179-bus reduced model of the WECC system, as shown in Fig i) in form of a single line diagram (SLD), is used for the study. A closer view of the 2x1340 MW DC plant and its 500 kV transmission corridor is shown in Fig ii). The corridor includes a transmission line that connects Gates (bus # 104) to Diablo (bus # 102), and a double circuit transmission line connecting Diablo and Midway (bus # 108). The two circuits between Diablo and Midway are modeled to have identical line parameters. A generating transformer (between bus # 103 and # 102) steps up the generating voltage to the 500 kV transmission voltage. In the model, the two generating units at the DC plant are replaced by their single equivalent, assuming both the units swing together. Accordingly, the pair of generating transformers is also replaced by its single transformer equivalent. The loads are kept to the specified constant values while studying the different contingency cases.

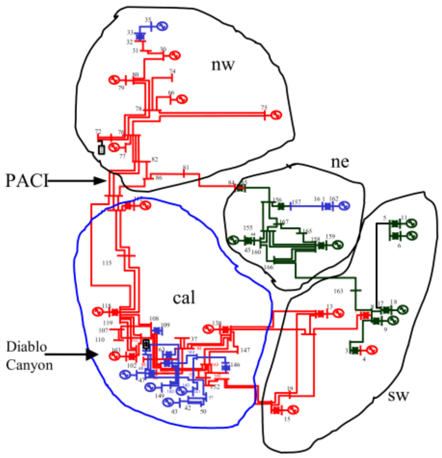

Fig i) WECC 179 bus model

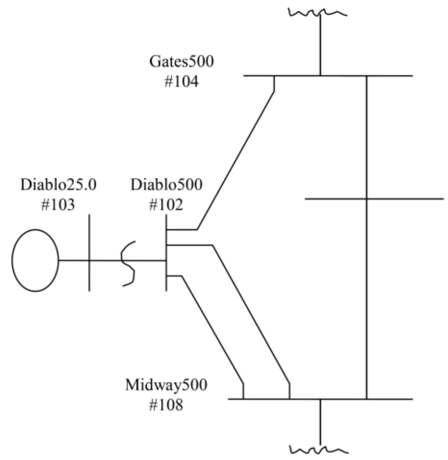

Fig ii) Diablo Canyon plant and associated transmission corridor

The contingency cases that are considered in this study are as follows:

TABLE I: List of Contingencies under Study

Sl. No.	Pre-fault configuration	Fault Description and Clearance
1	Diablo-Midway (102-108) Circuit II is out	Fault in Diablo-Gates line (102-104) near bus 102 the fault is cleared by opening the faulty line.
2	Diablo-Midway (102-108) Circuit II is out	Fault in Diablo-Midway (102-108) Circuit I near bus 102 and the fault is cleared by opening the faulty line.
3	Diablo-Gates line (102-104) is out	Fault in Diablo-Midway (102-108) Circuit I near bus 102 and the fault is cleared by opening the faulty line.

For all the three contingency cases, it is assumed that the system is operating at an equilibrium during the pre-fault phase. The fault is applied at 1 sec. and is cleared after 4 cycles (i.e. at 1.06 sec approximately). The time-domain simulation is performed for 10 sec. since the objective is to determine the active power delivery limit that ensures only the early-swing stability. The John Day generator is considered as the reference/slack generator for the whole study. The dispatch of all the non-slack generators except the one at the DC plant are held constant at their specified values, and any change in the DC plant generation schedule is compensated by the adjustment of dispatch of the slack generator computed by solving the power-flow equations. However, it is found that in all the cases investigated in this project, the delivered active power computed for the slack generator remains well within its permissible limit.

III. Implementational Details

The pre-fault operating point for each contingency case is obtained by solving the nonlinear power-flow equations using Newton-Rhapson method, implemented using the PSAT tool. The time domain simulation is performed using partitioned method of solving differential-algebraic equations (DAE) using an explicit approach, which is implemented using the TSAT tool. Both the PSAT and TSAT tools are parts of the main software package called DSATools.

Note that the early swing stability of the system is related monotonically with the DC plant active power in the sense that, if we continuously increase the value of the scheduled active power starting from zero, initially the system must be early swing stable (if the system complies NERC reliability criterion during design) and thereafter at some value the system will exhibit instability. This value is called the active power delivery limit for early swing stability, and for any active power value higher than this limit the system will continue to show early swing instability. Therefore, we can find this limit by a binary search for the start of early swing instability over the scalar variable active power. This binary search is implemented by manually adjusting the scheduled active power prior the solving the power-flow. A pseudo-code for the overall implementation is as shown below, where the constants P_h (resp. P_l) are chosen such that setting P_h (resp. P_l) as the generator active power leads the post-fault system to be unstable (resp. stable), and P_{rated} denotes the rated power of the equivalent DC generator i.e. 2680 MW:

Initialize $p_h = P_h \in [0, P_{rated}], p_l = P_l \in [0, P_{rated}], P_h > P_l;\ \epsilon = 0.02;\ \Delta = 2\epsilon$
Arbitrarily set $p \in [P_l, P_h]$.
While $\Delta \leq \epsilon$
    Solve power-flow using PSAT setting scheduled active power delivery as p.
    Run time-domain simulation according to Table I using TSAT, initializing the system by the power-flow solution and observe stability for 10 sec.
    $p_{old} = p$
    If $p \rightarrow$ stable
        $p_l = p$
        $p = (p + p_h) \times 0.5$
    Else
        $p_h = p$
        $p = (p + p_l) \times 0.5$
    $\Delta = (p - p_{old})/100$

To distinguish the stable cases from the unstable ones, the principle followed is: if the generator angle doesn't become very large causing the simulation to halt prior 10 sec. (i.e. the angle doesn't become nearly unbounded) and voltages of all buses during the first few swings remain above 0.7 p.u. then the simulation is regarded as stable, otherwise it is unstable.

IV. Results

In this section the results obtained using the algorithm shown in Section III are presented for the three respective contingency cases as enumerated in Table I. The system variables that are plotted are the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages. These are enough to distinguish stable/unstable cases based on the criteria mentioned in the last paragraph of Section III. Although the variables are plotted for the entire system, only a few variables are included in the legends for the sake of clarity. For the generator angle and frequency legends, the DC plant and a few geographically adjacent generators are chosen, while the Midway, DC and Gates buses are chosen for the bus voltage legends.

A. Contingency # 1:

Under this contingency, the binary search was not needed since even at the rated load (i.e. 2680 MW) of DC plant, the system is found to be early swing stable based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig iii) a.-c. respectively.

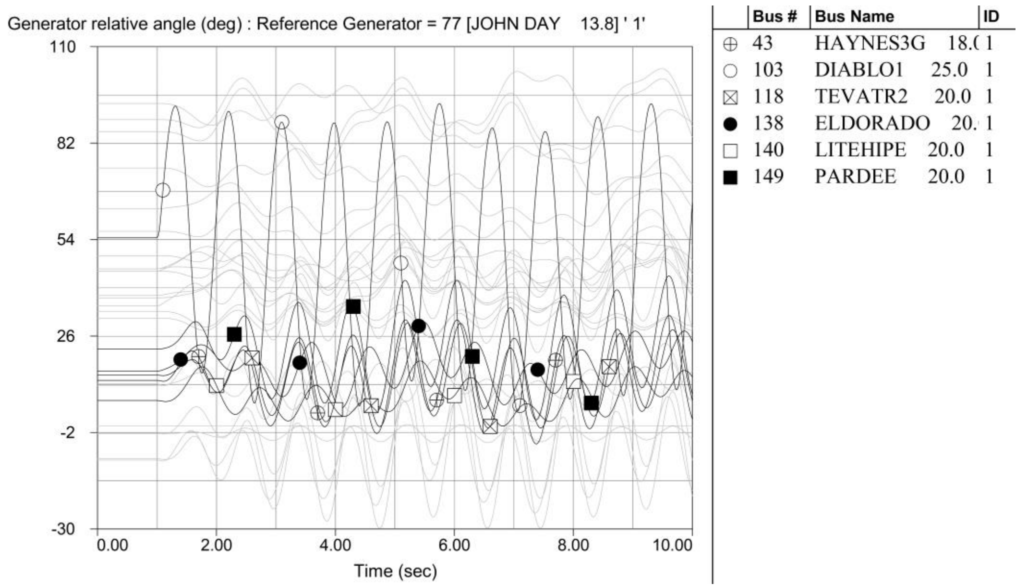

Fig iii) a.

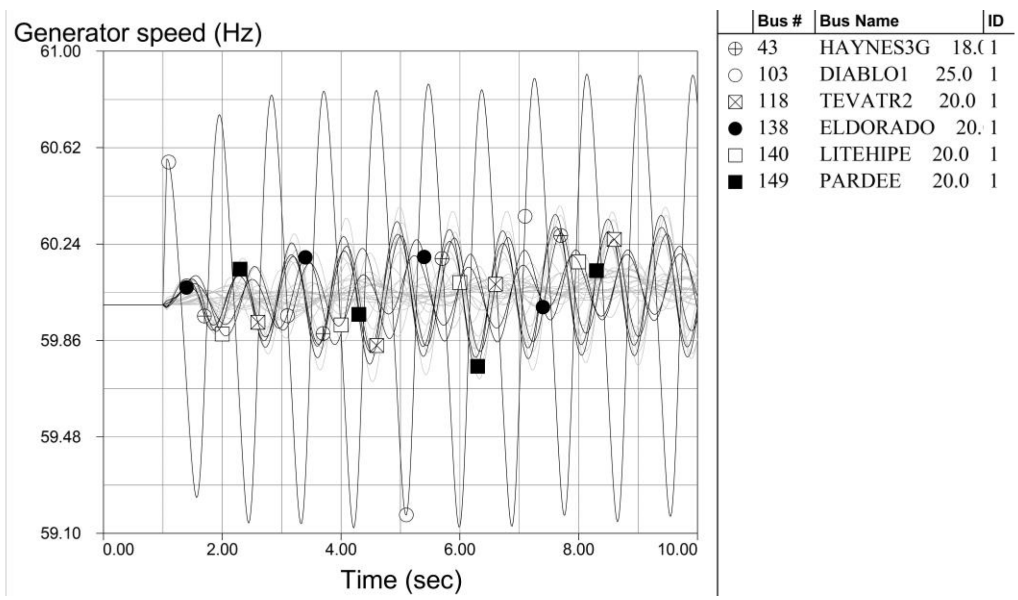

Fig iii) b.

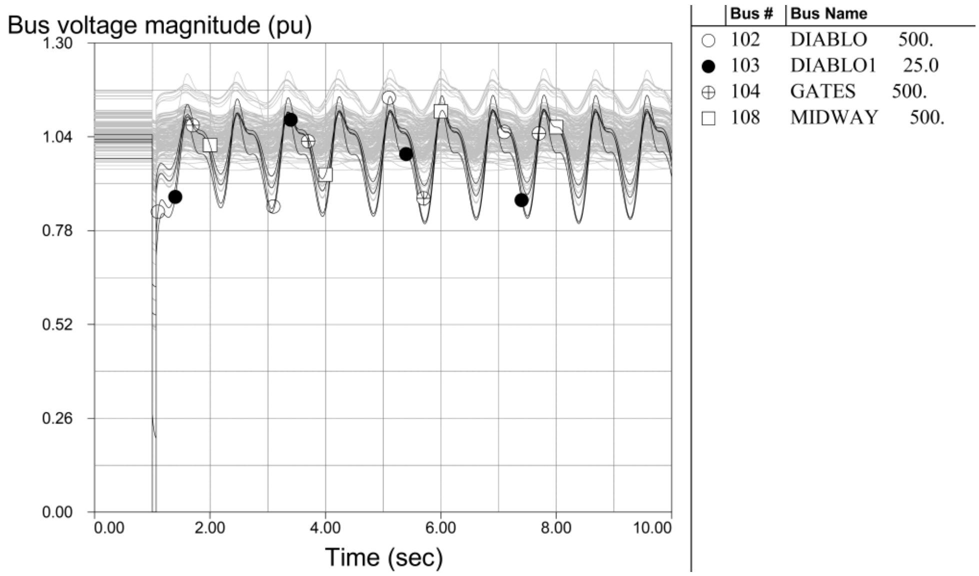

Fig iii) c.

B. Contingency # 2:

Under this contingency, the binary search was initialized with $P_h = 2500$ MW, $P_l = 2000$ MW and $p = P_l$. The results of each of the search steps are presented below:

Step 1: Scheduled active power (p) = 2000 MW

The system with DC plant's active power set at 2000MW is found to be early swing stable under contingency # 2, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig iv) a.-c. respectively.

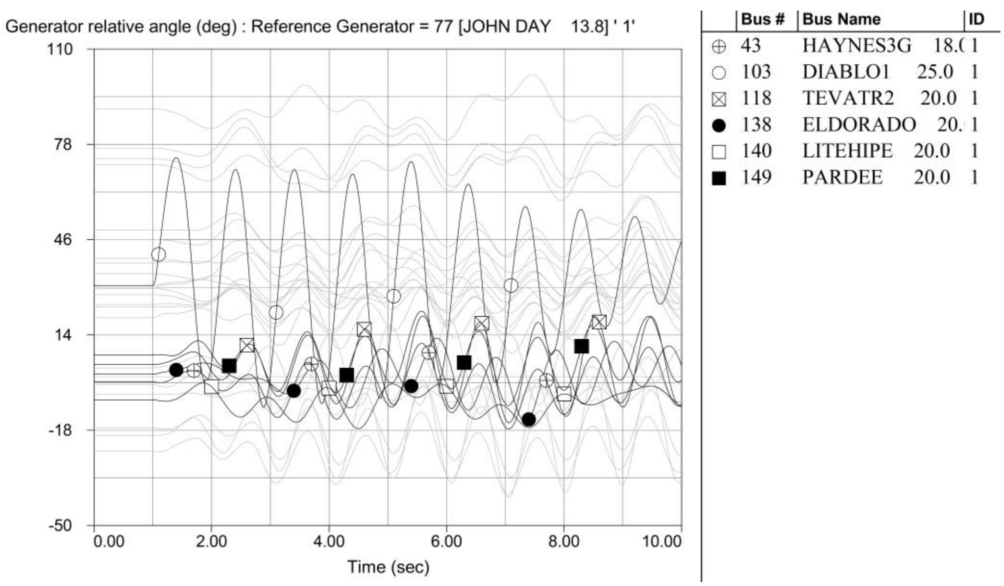

Fig iv) a.

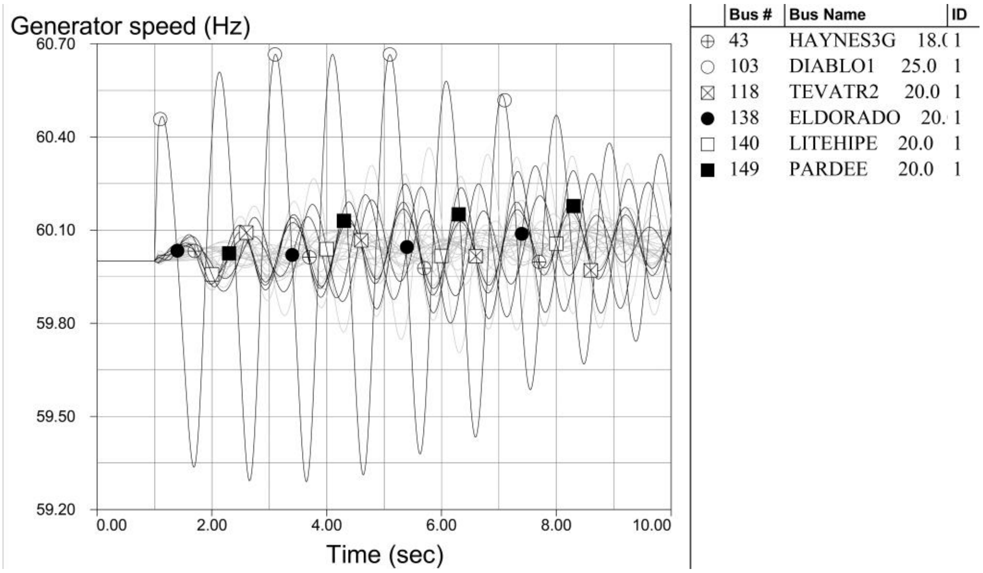

Fig iv) b.

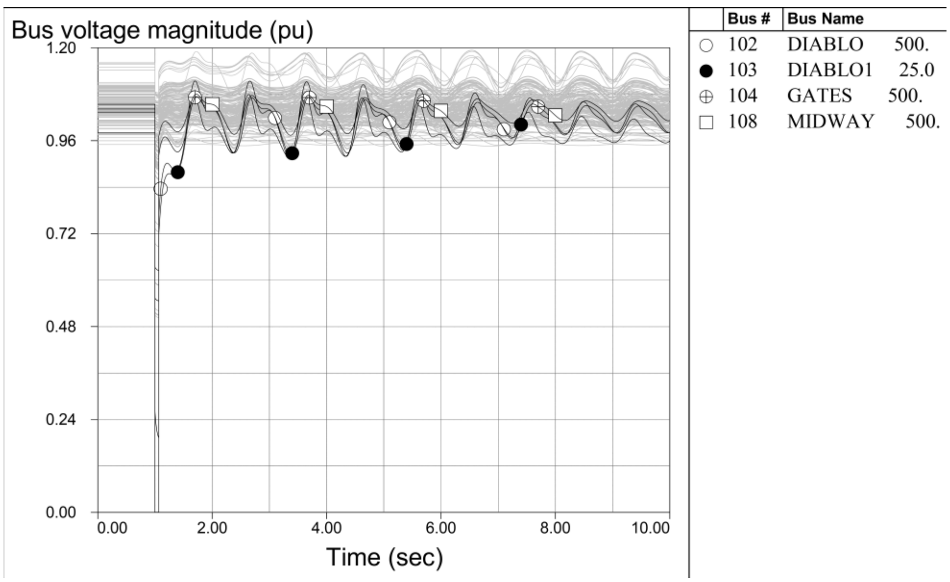

Fig iv) c.

Step 2: Scheduled active power (p) = 2500 MW

The system with DC plant's active power set at 2500MW is found to be early swing unstable under contingency # 2, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig v) a.-c. respectively.

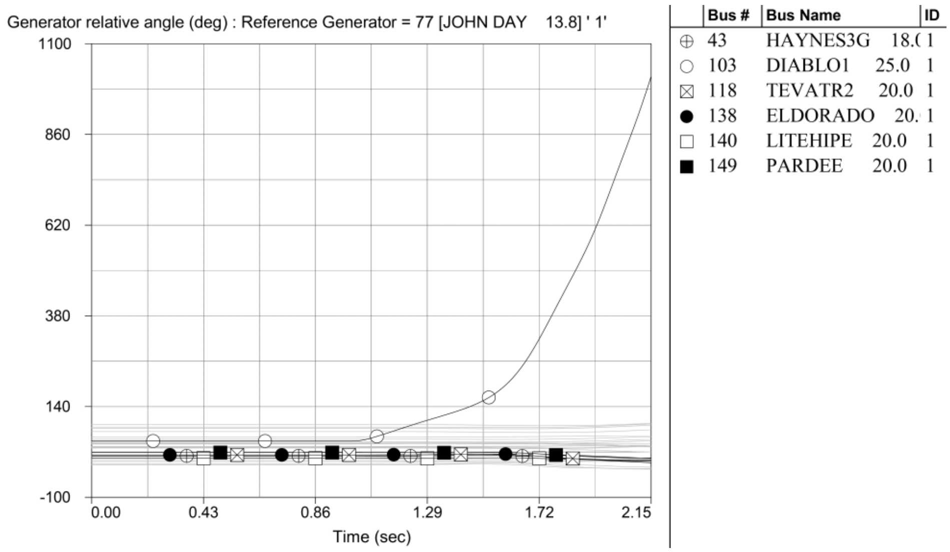
Generator relative angle (deg) : Reference Generator = 77 [JOHN DAY 13.8] ' 1'
1100
860
620
380
140
-100
0.00
0.43
0.86
1.29
1.72
2.15
Time (sec)
Bus #
Bus Name
ID
43 HAYNES3G 18.(1
103 DIABLO1 25.0 1
118 TEVATR2 20.0 1
138 ELDORADO 20. 1
140 LITEHIPE 20.0 1
149 PARDEE 20.0 1

Fig v) a.

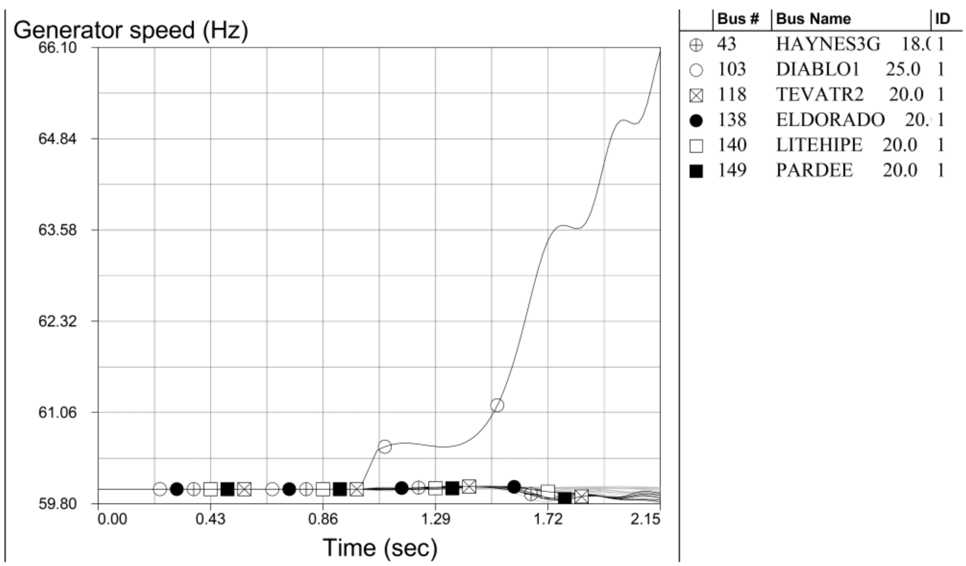
Generator speed (Hz)
66.10
64.84
63.58
62.32
61.06
59.80
0.00
0.43
0.86
1.29
1.72
2.15
Time (sec)
Bus #
Bus Name
ID
43 HAYNES3G 18.(1
103 DIABLO1 25.0 1
118 TEVATR2 20.0 1
138 ELDORADO 20. 1
140 LITEHIPE 20.0 1
149 PARDEE 20.0 1

Fig v) b.

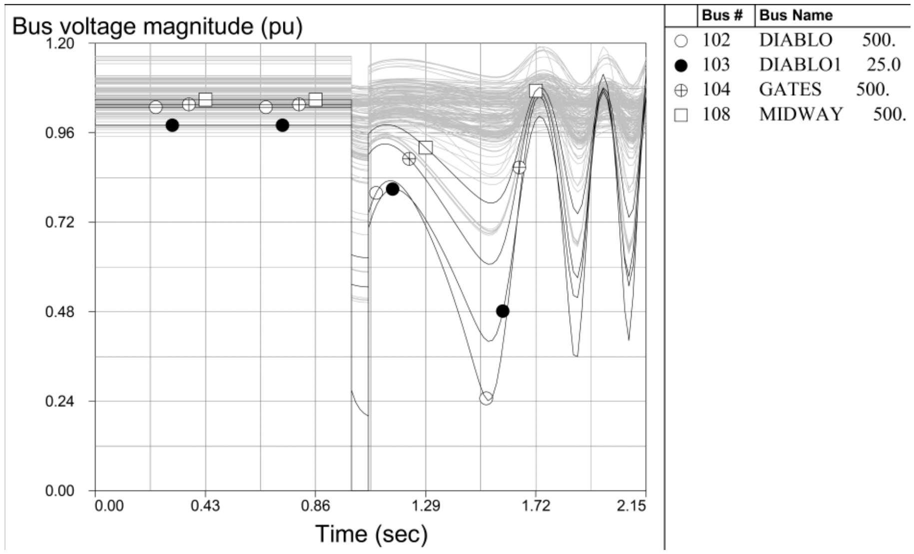

Fig v) c.

Step 3: Scheduled active power (p) = 2250 MW

The system with DC plant's active power set at 2250MW is found to be early swing unstable under contingency # 2, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig vi) a.-c. respectively.

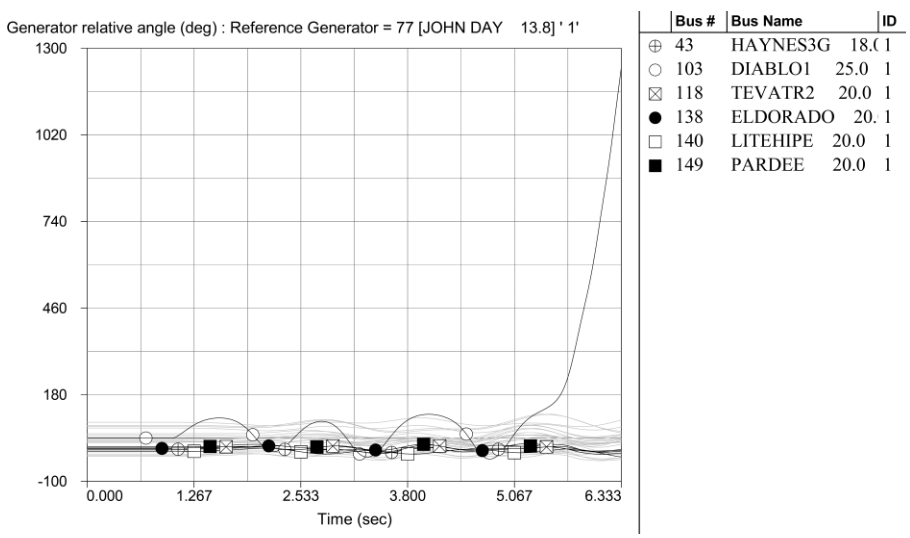

Fig vi) a.

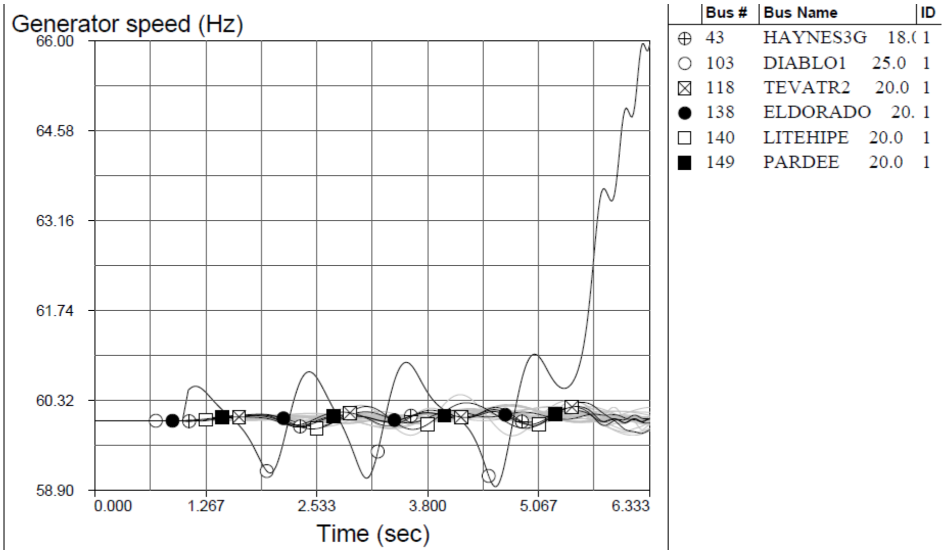

Fig vi) b.

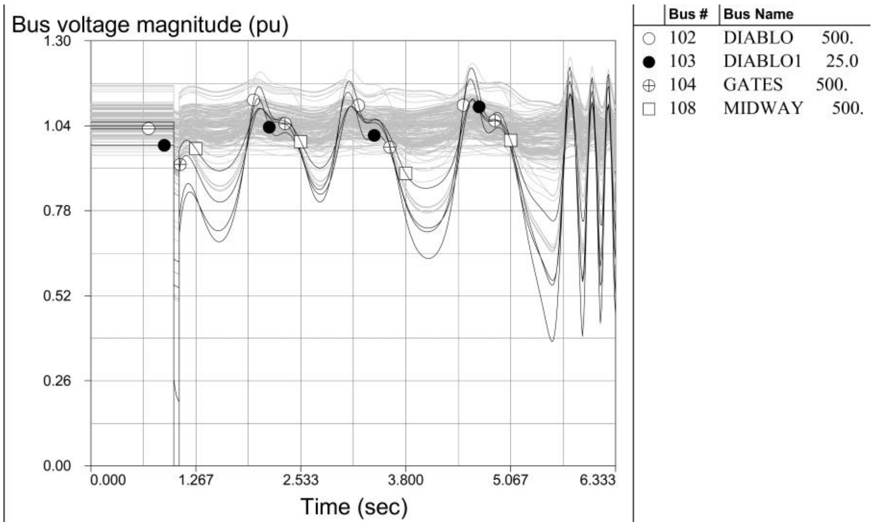

Fig vi) c.

Step 4: Scheduled active power (p) = 2125 MW

The system with DC plant's active power set at 2125MW is found to be early swing unstable under contingency # 2, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig vii) a.-c. respectively.

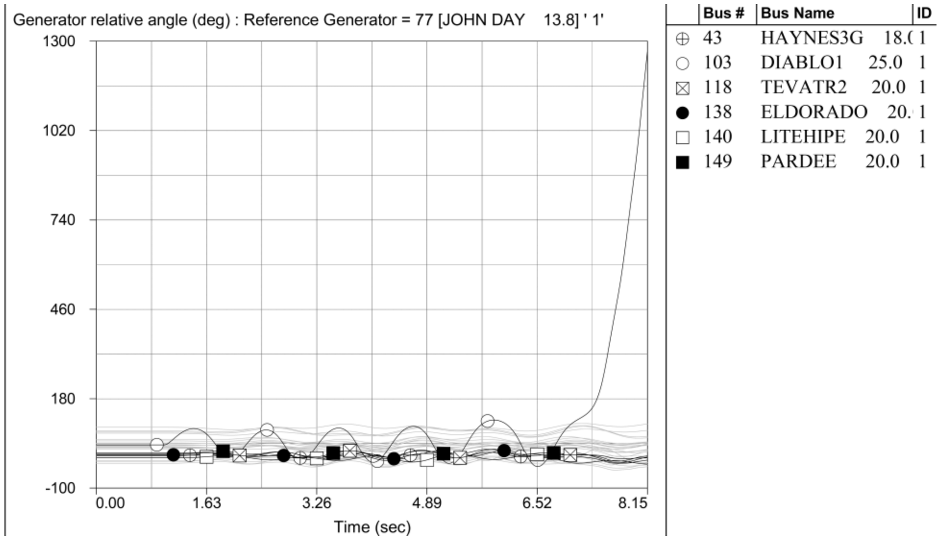

Fig vii) a.

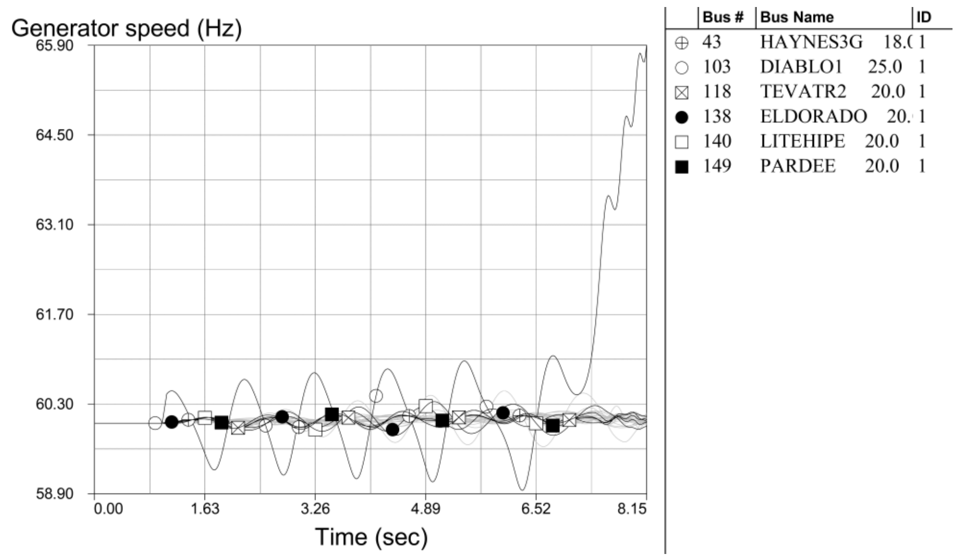

Fig vii) b.

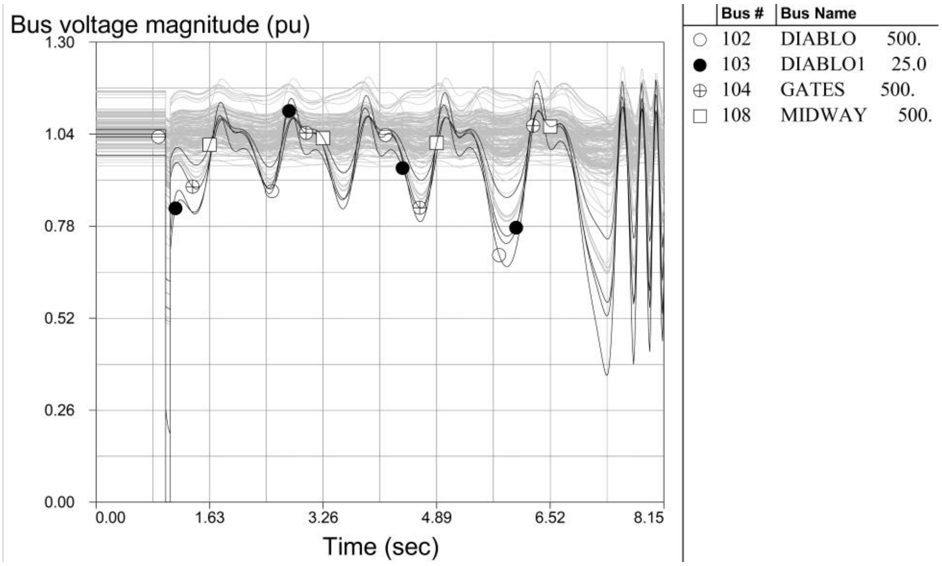

Fig vii) c.

Step 5: Scheduled active power (p) = 2062 MW

The system with DC plant's active power set at 2062MW is found to be early swing unstable under contingency # 2, based on the criteria mentioned in the last paragraph of Section III. In particular, the voltage of several of the buses fall below 0.72 p.u. during the simulation. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig viii) a.-c. respectively.

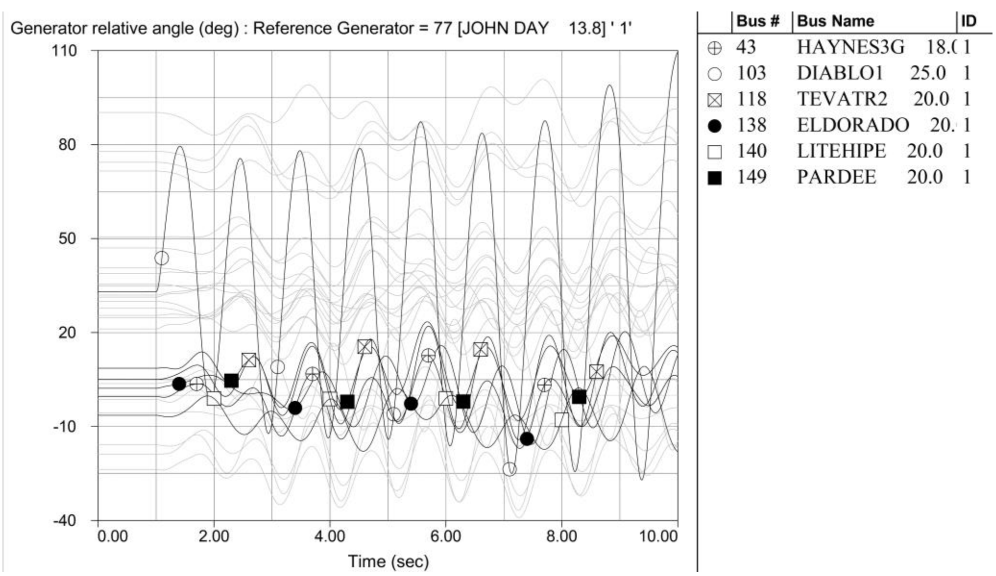

Fig viii) a.

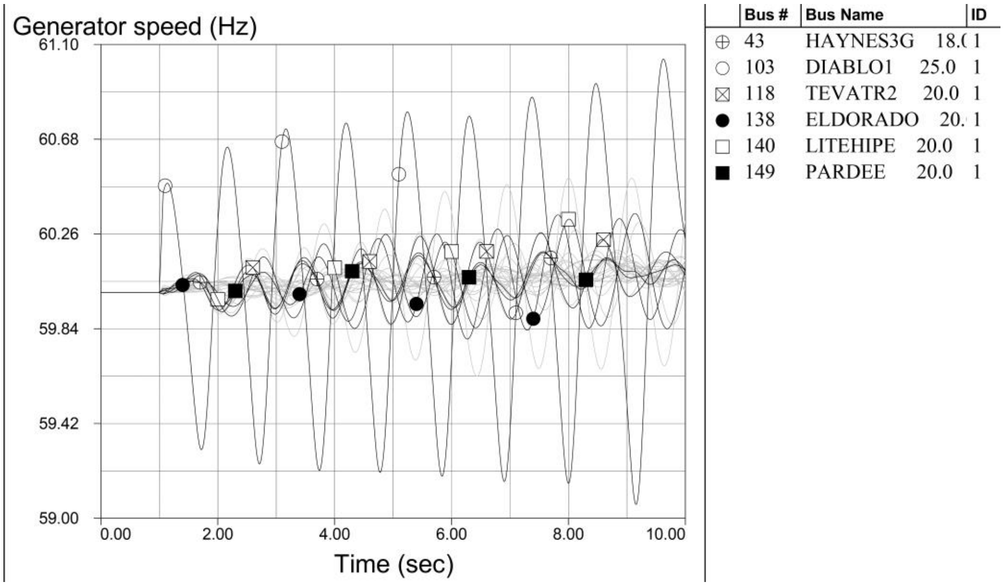

Fig viii) b.

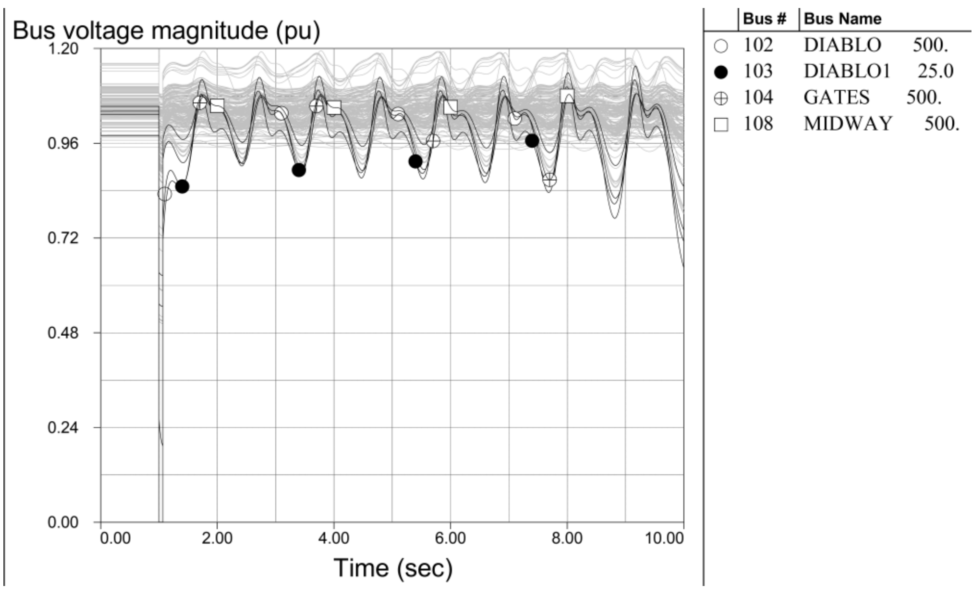

Fig viii) c.

Step 6: Scheduled active power (p) = 2031 MW

The system with DC plant's active power set at 2031MW is found to be early swing stable under contingency # 2, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig ix) a.-c. respectively.

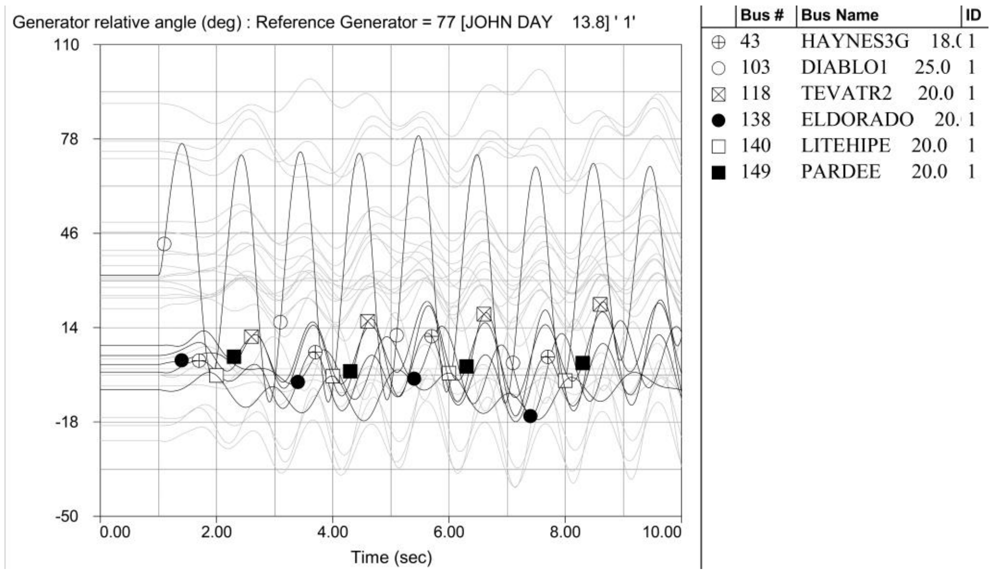

Fig ix) a.

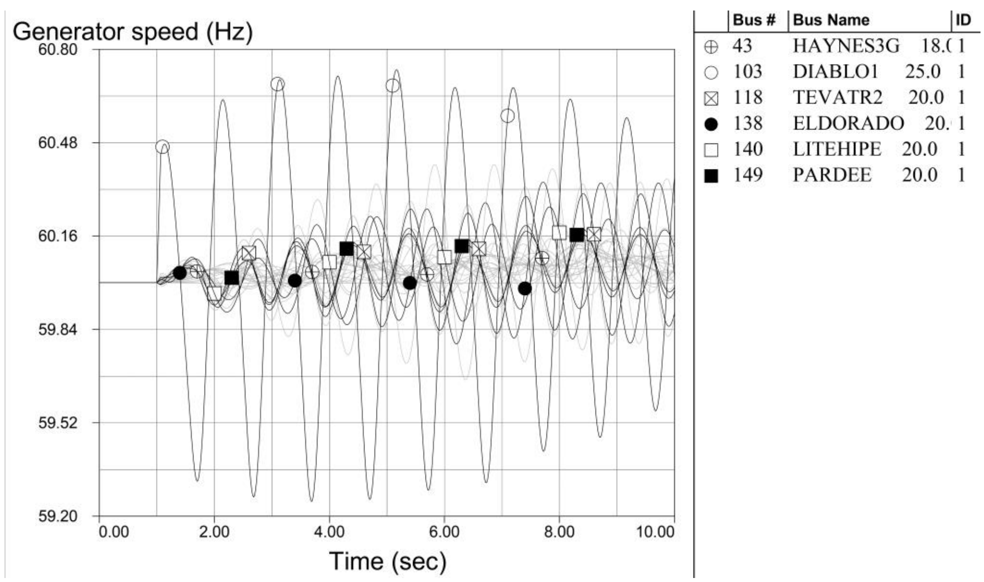

Fig ix) b.

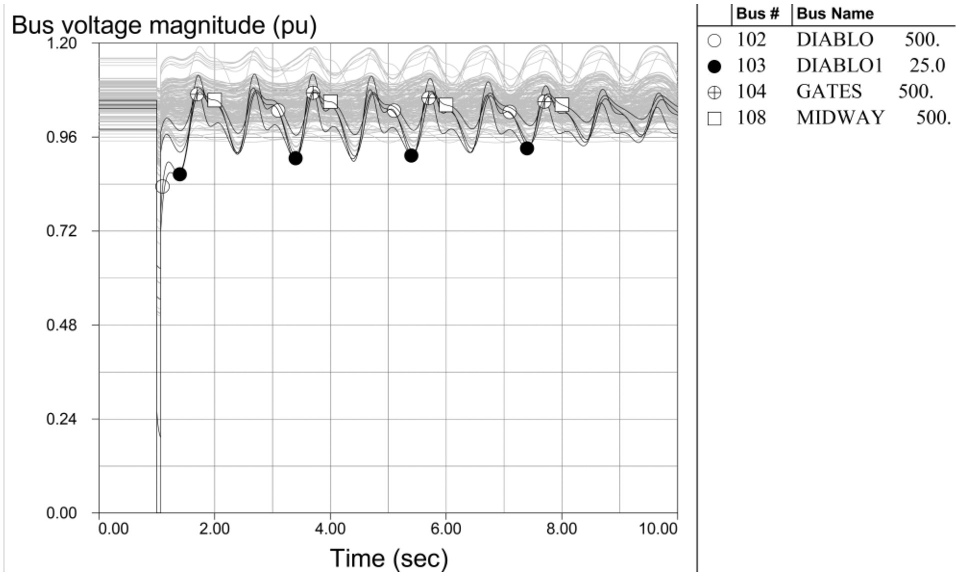

Fig ix) c.

The summary of the binary search under the contingency # 2 is tabulated below, where the final converged active power limit for the DC plant is found to be 2031 MW:

TABLE II: Summary of Binary Search Algorithm under Contingency # 2

Step #	DC Plant Active Power (MW)	Early Swing Stability	Convergence
1	2000	Stable	Not converged
2	2500	Unstable	Not converged
3	2250	Unstable	Not converged
4	2125	Unstable	Not converged
5	2062	Unstable	Not converged
6	**2031**	**Stable**	**Converged**

Contingency # 3

Under this contingency, the binary search was initialized with the parameters set to the values same to those under contingency # 2. The results of each of the search steps are presented below:

Step 1: Scheduled active power (p) = 2000 MW

The system with DC plant's active power set at 2000MW is found to be early swing stable under contingency # 3, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig x) a.-c. respectively.

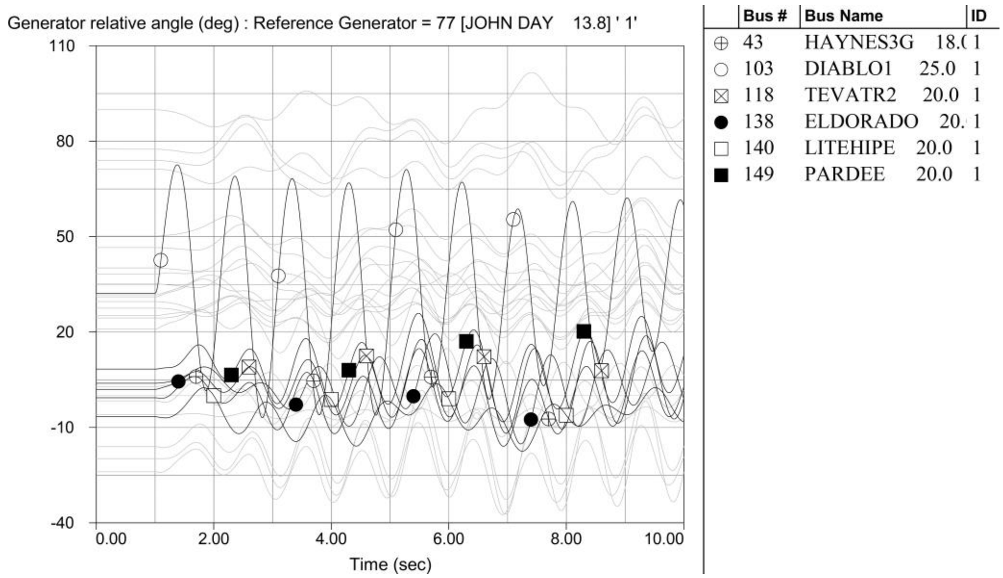
Generator relative angle (deg) : Reference Generator = 77 [JOHN DAY 13.8] ' 1'
110
80
50
20
-10
-40
0.00
2.00
4.00
6.00
8.00
10.00
Time (sec)
Bus #
Bus Name
ID
43 HAYNES3G 18.(1
103 DIABLO1 25.0 1
118 TEVATR2 20.0 1
138 ELDORADO 20. 1
140 LITEHIPE 20.0 1
149 PARDEE 20.0 1

Fig x) a.

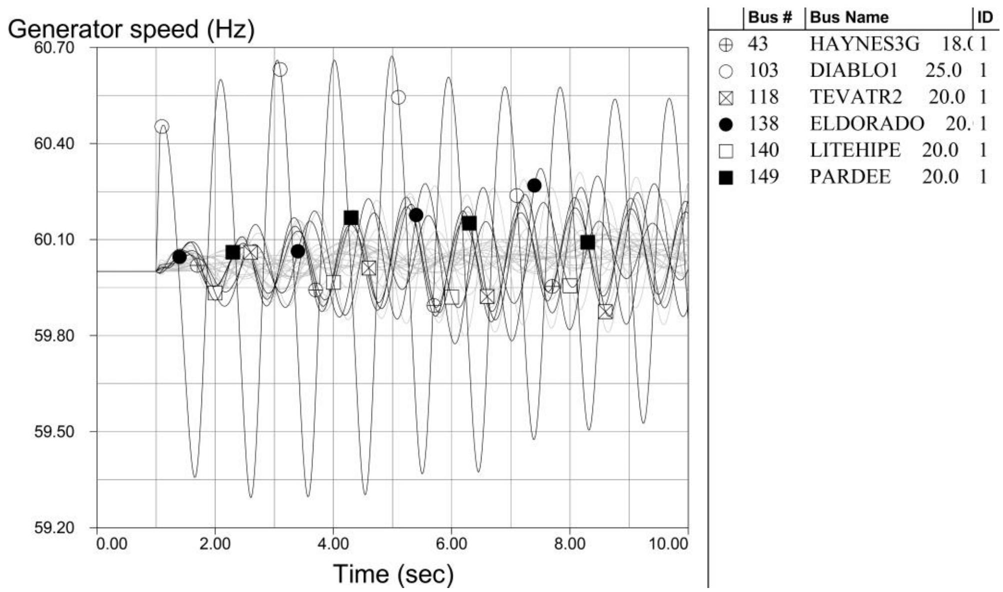
Generator speed (Hz)
60.70
60.40
60.10
59.80
59.50
59.20
0.00
2.00
4.00
6.00
8.00
10.00
Time (sec)
Bus #
Bus Name
ID
43 HAYNES3G 18.(1
103 DIABLO1 25.0 1
118 TEVATR2 20.0 1
138 ELDORADO 20. 1
140 LITEHIPE 20.0 1
149 PARDEE 20.0 1

Fig x) b.

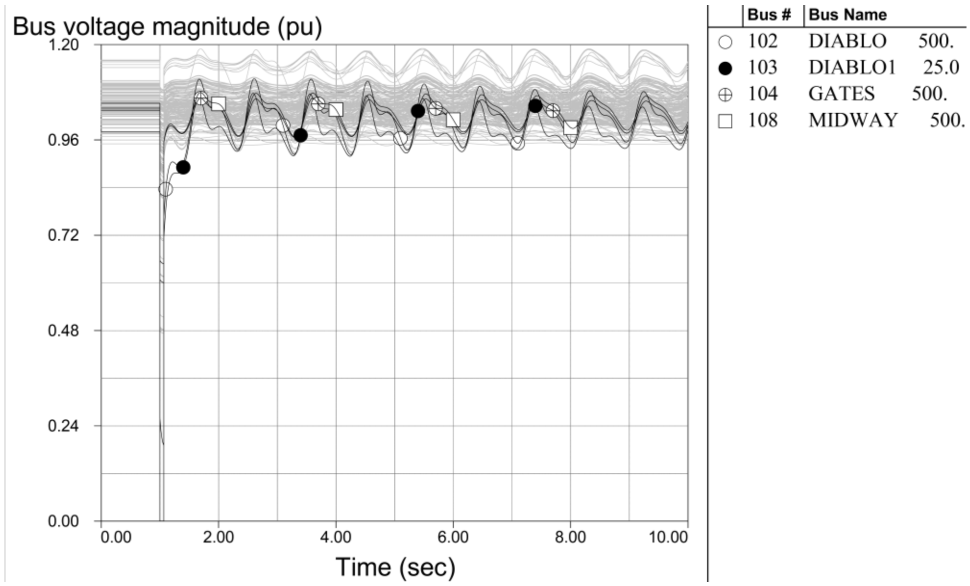

Fig x) c.

Step 2: Scheduled active power (p) = 2500 MW

The system with DC plant's active power set at 2500MW is found to be early swing unstable under contingency # 3, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig xi) a.-c. respectively.

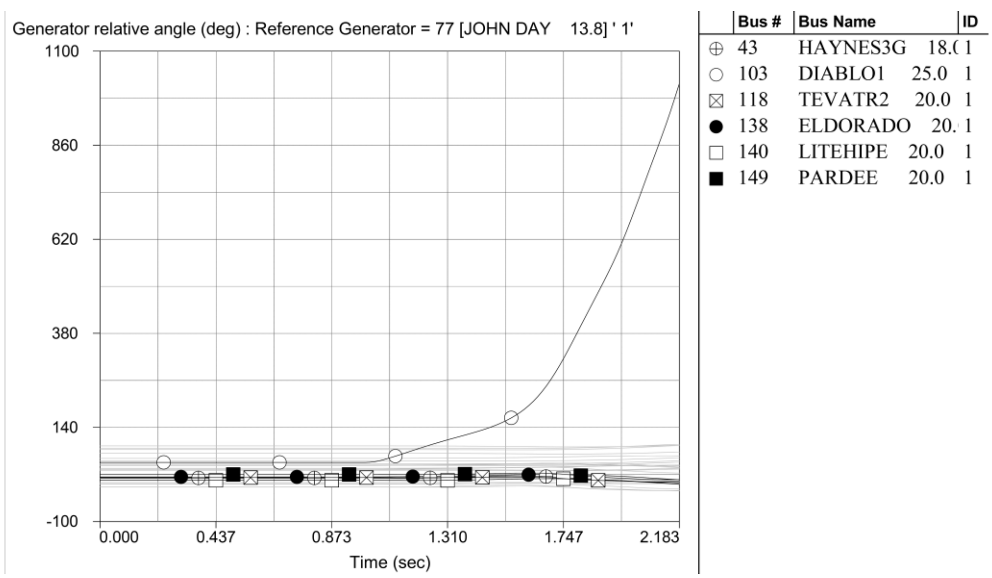

Fig xi) a.

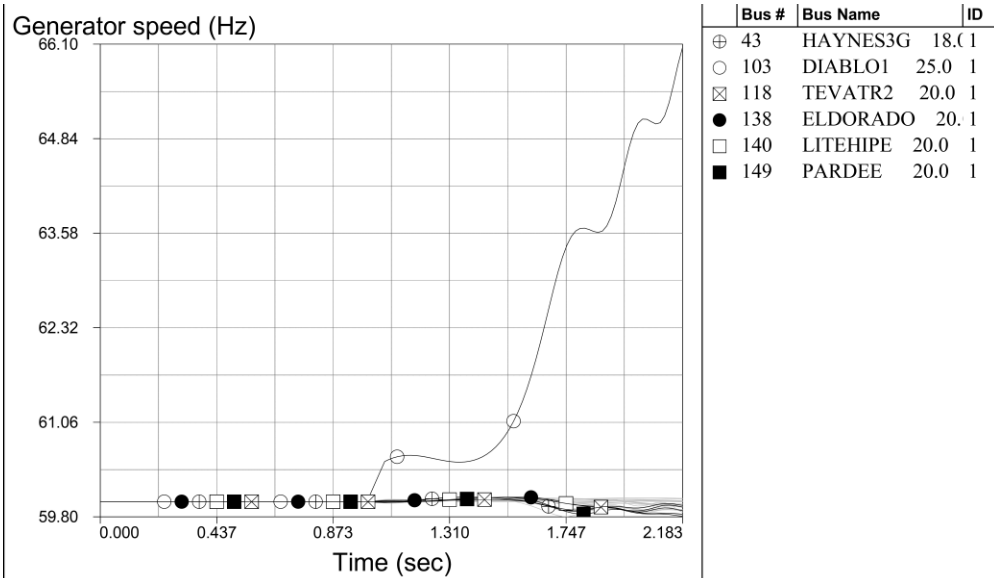

Fig xi) b.

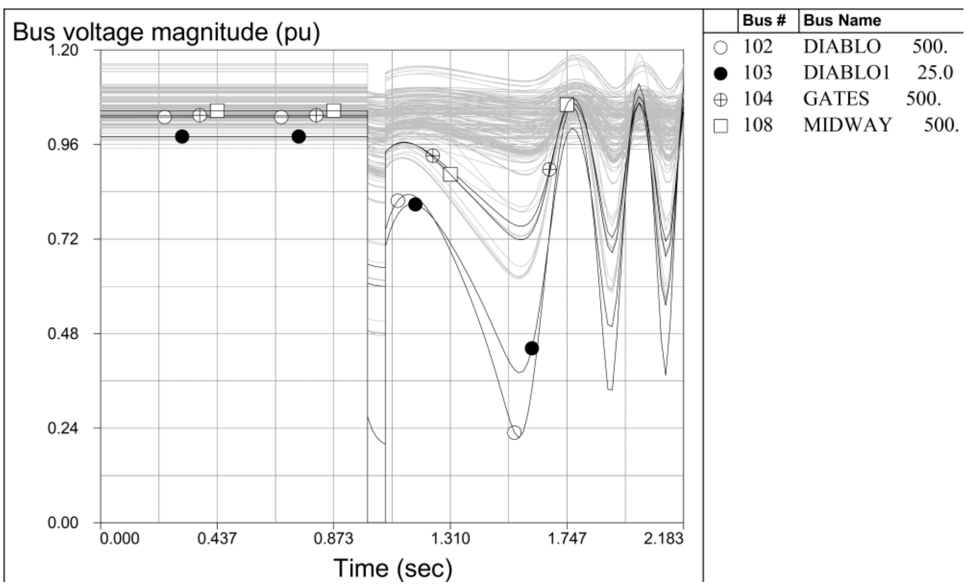

Fig xi) c.

Step 3: Scheduled active power (p) = 2250 MW

The system with DC plant's active power set at 2250MW is found to be early swing unstable under contingency # 3, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig xii) a.-c. respectively.

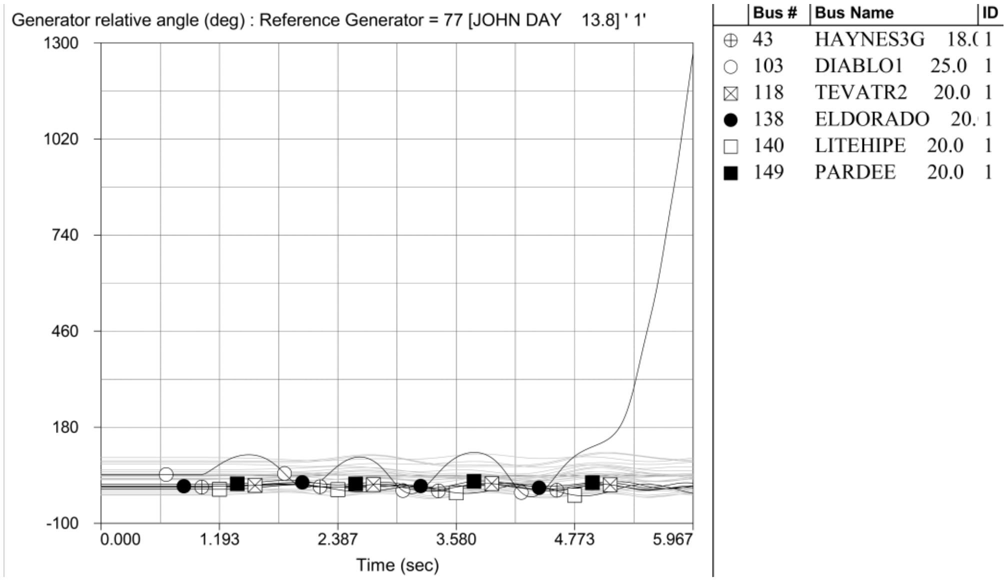

Fig xii) a.

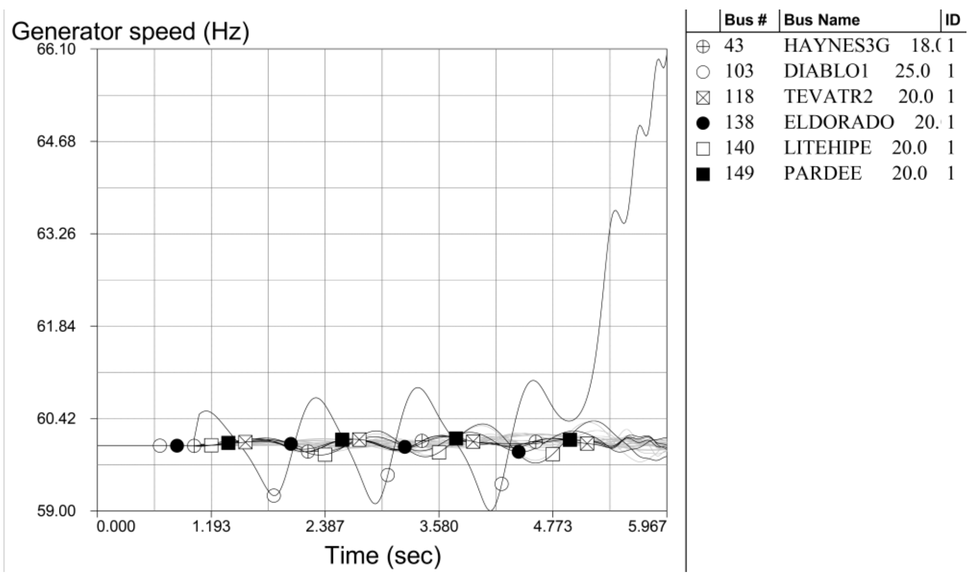

Fig xii) b.

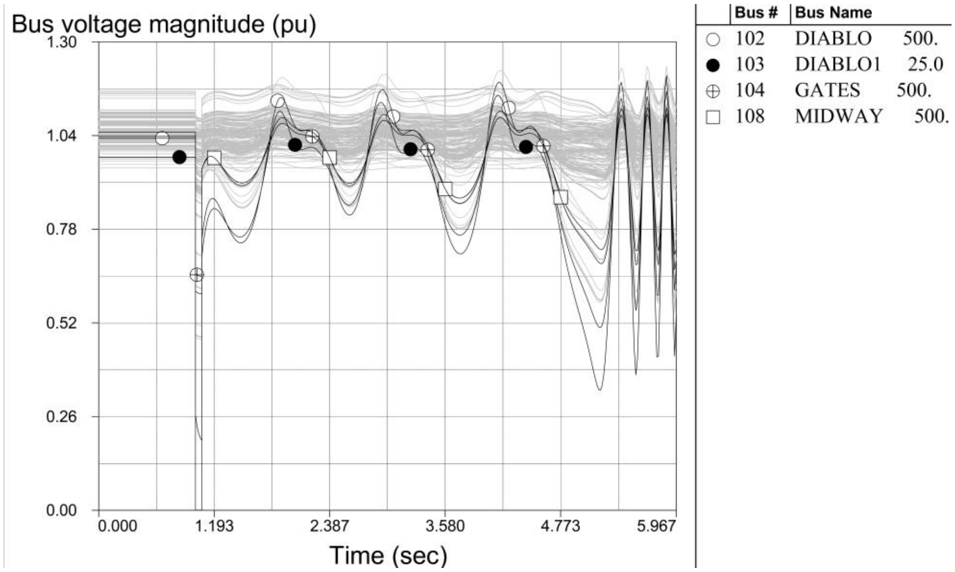

Fig xii) c.

Step 4: Scheduled active power (p) = 2125 MW

The system with DC plant's active power set at 2125 MW is found to be early swing unstable under contingency # 3, based on the criteria mentioned in the last paragraph of Section III. In particular, the voltage of several of the buses fall below 0.65 p.u. during the simulation. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig xiii) a.-c. respectively.

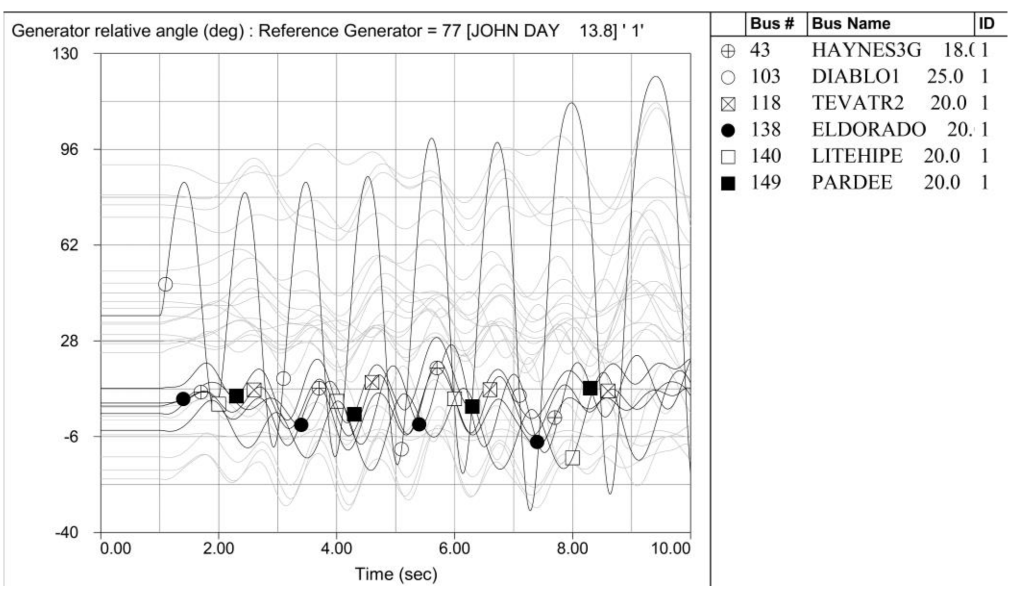

Fig xiii) a.

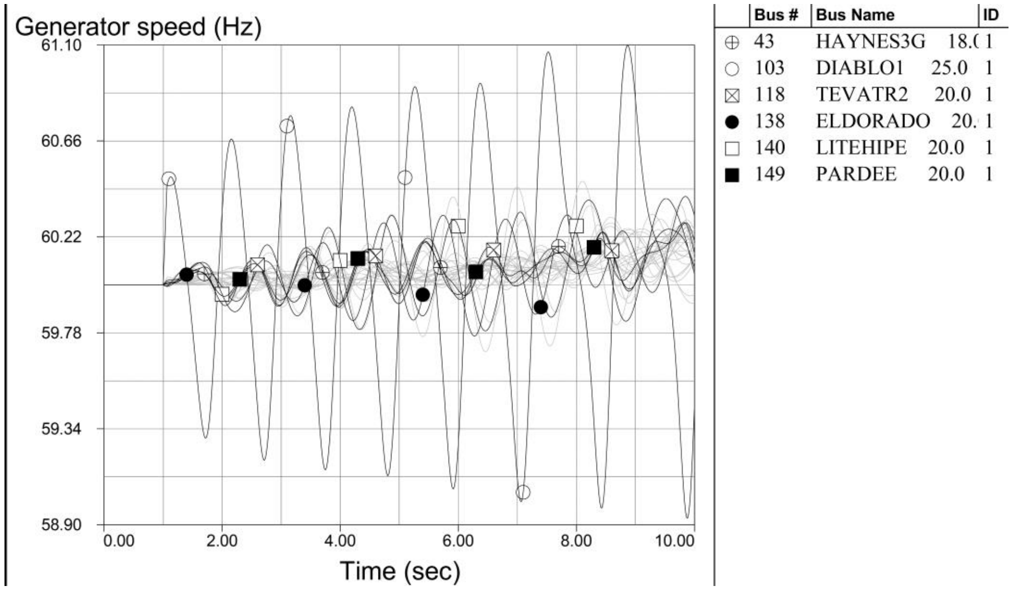

Fig xiii) b.

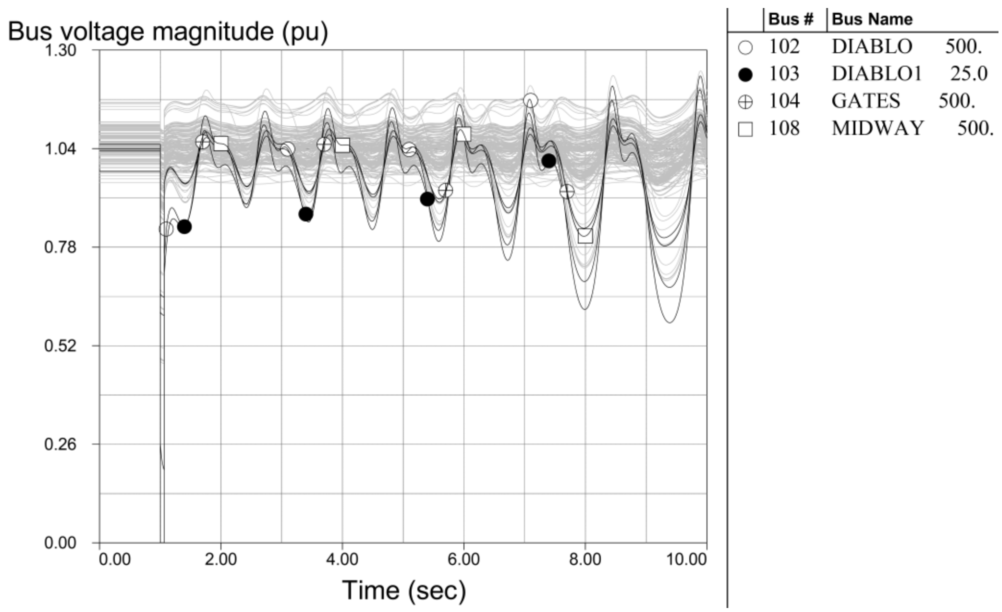

Fig xiii) c.

Step 5: Scheduled active power (p) = 2062 MW

The system with DC plant's active power set at 2062 MW is found to be early swing stable under contingency # 3, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig xiv) a.-c. respectively.

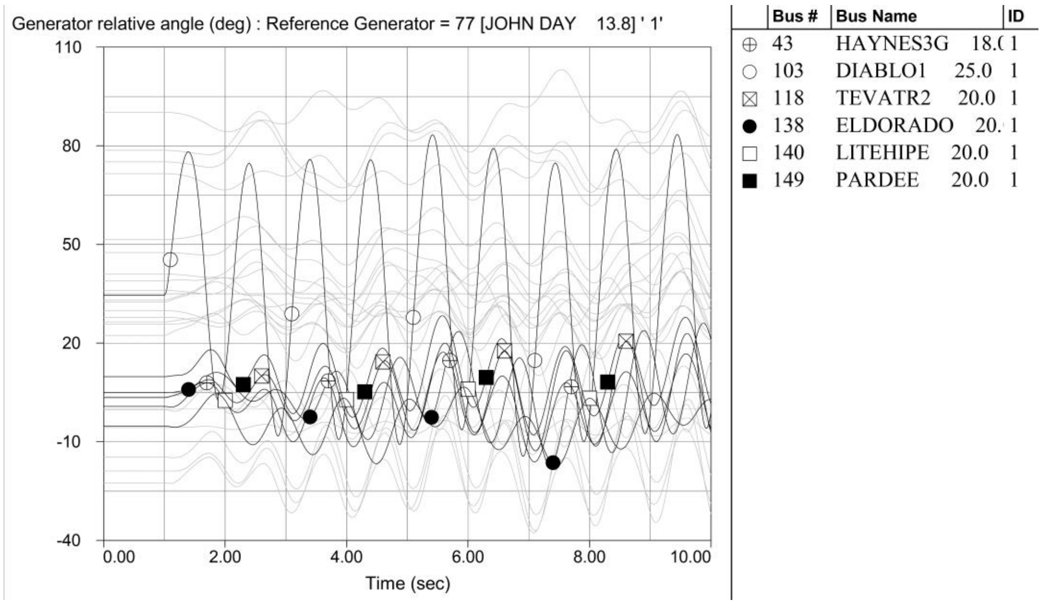

Fig xiv) a.

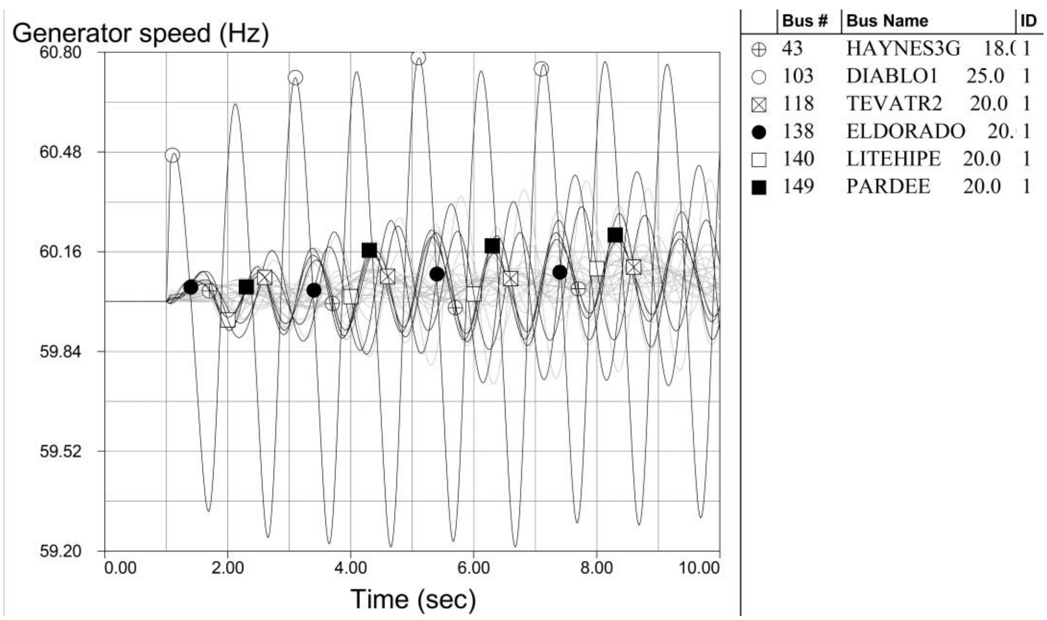

Fig xiv) b.

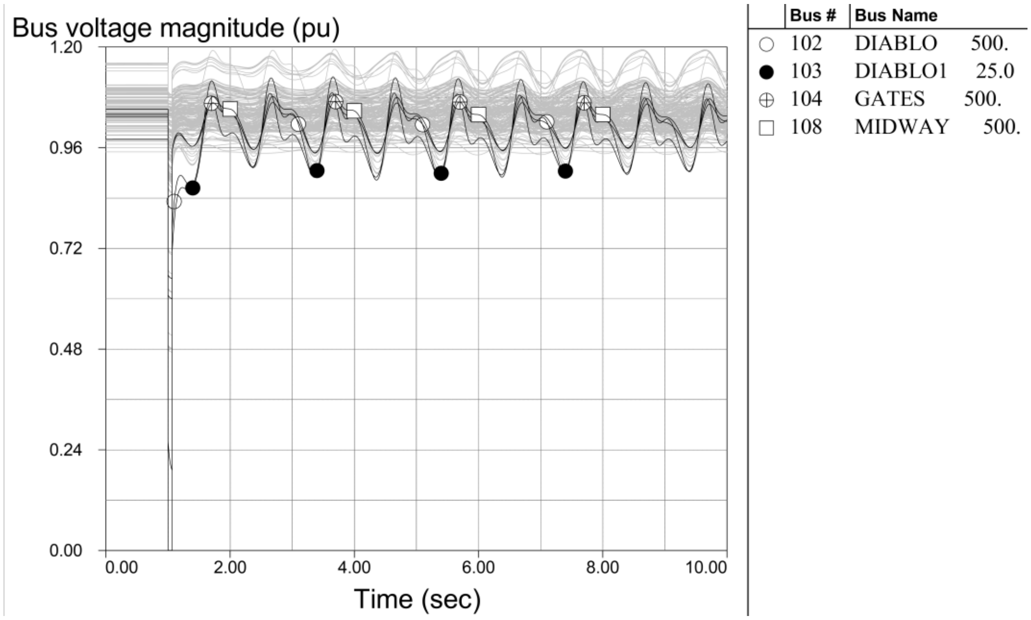

Fig xiv) c.

Step 6: Scheduled active power (p) = 2093 MW

The system with DC plant's active power set at 2093 MW is found to be early swing stable under contingency # 3, based on the criteria mentioned in the last paragraph of Section III. The plots of the non-reference generator angles (relative to the reference one), the generator frequencies and the bus voltages are shown below in Fig xv) a.-c. respectively.

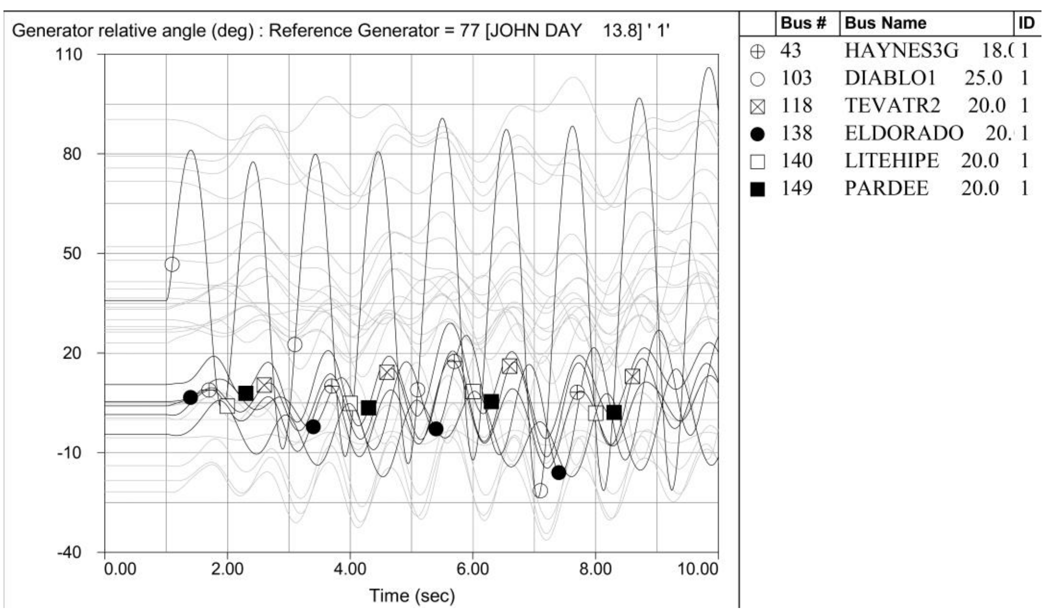

Fig xv) a.

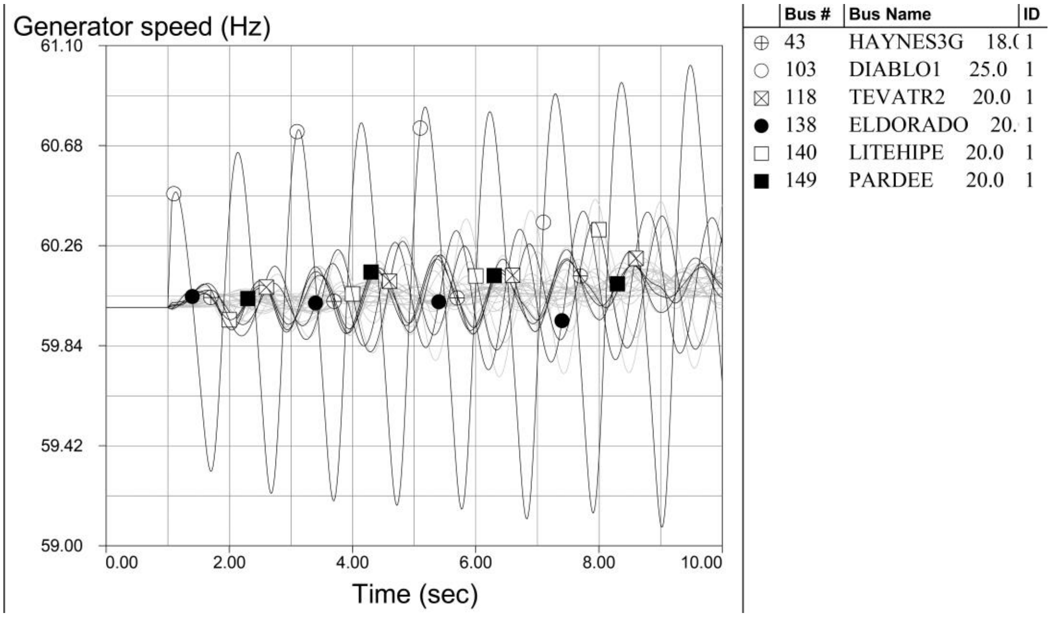

Fig xv) b.

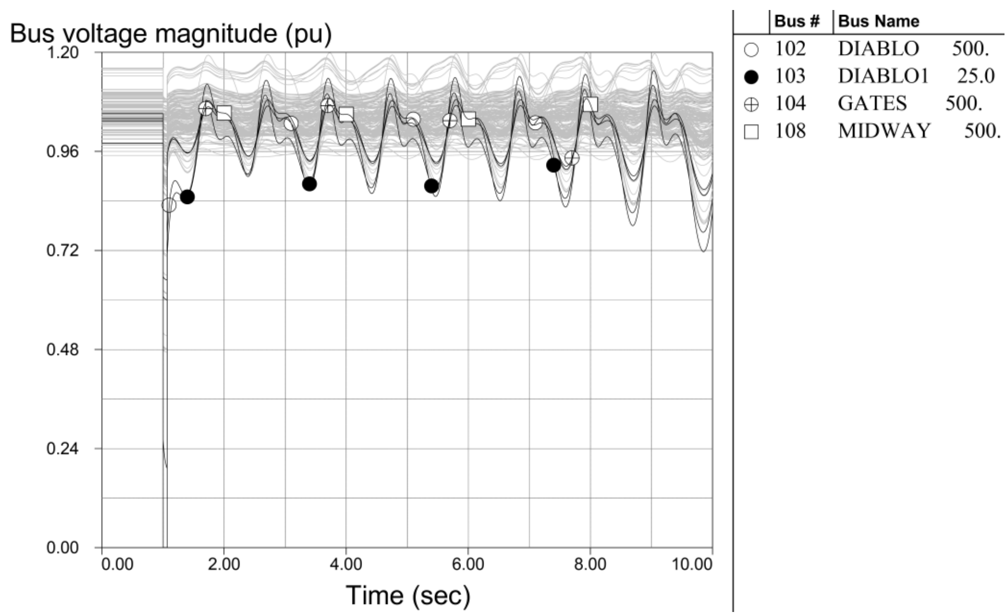

Fig xv) c.

The summary of the binary search for the contingency # 3 is tabulated below, where the final converged active power limit for the DC plant is found to be 2093 MW:

TABLE III: Summary of Binary Search Algorithm under Contingency # 3

Step #	DC Plant Active Power (MW)	Early Swing Stability	Convergence
1	2000	Stable	Not converged
2	2500	Unstable	Not converged
3	2250	Unstable	Not converged
4	2125	Unstable	Not converged
5	2062	Stable	Not converged
6	**2093**	**Stable**	**Converged**

V. Conclusion and Discussion

In this project, the early swing stability is analyzed for the bulk power transmission corridor that is used to evacuate the nuclear power generated at the Diablo-Canyon (DC) plant. The analysis shows that when anyone of the circuit in the Diablo-Midway line is out, the active power dispatch from the DC plant must be limited to 2031 MW (i.e. the minimum of the result of contingency # 1 and # 2) so as to avoid early swing instability of the system due to the imminent line contingencies over the transmission corridor, whereas the limit is 2093 MW (i.e. the result of contingency # 3) when the Diablo-Gates line is out. It is important to note that although these limits ensure early swing stability, the system may exhibit instability in the long term due to the slower oscillatory modes as evident from a few of the stable plots. The operator must ensure that appropriate measures are enforced (by appropriately designing either a control or dispatch adjustments) in order to damp out such oscillations.