2.3.1. Turbine and Governor

The turbine governor modelled is as per the data received from NTPC Nabinagar [7] as shown in Figure 5. The governor turbine parameters are tabulated in Table 5.

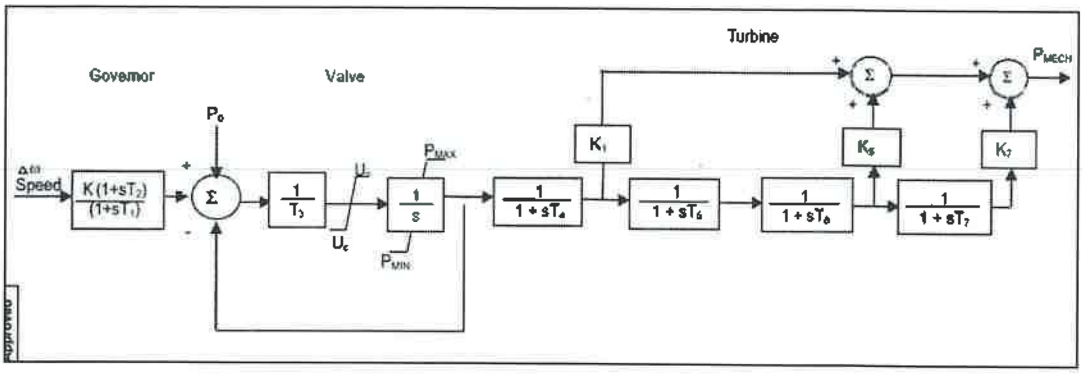

Figure 5: IEEEG1 turbine-governor model as shared by NTPC Nabinagar

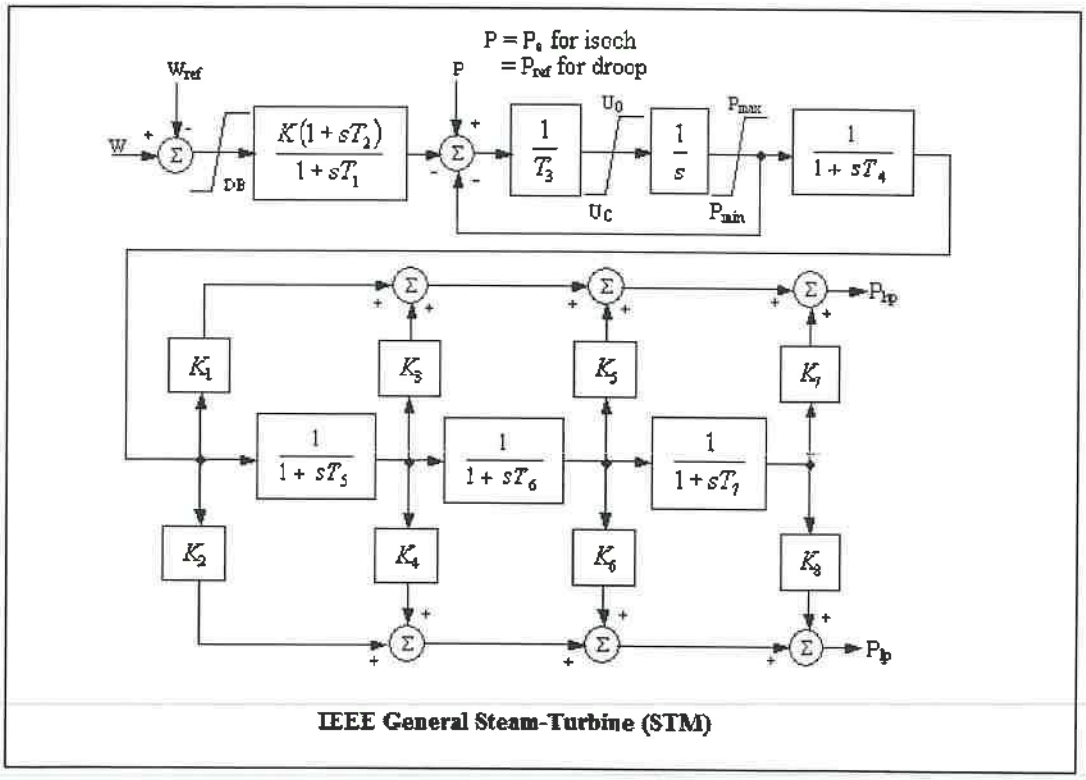

Figure 6: IEEE G1 turbine-governor modelled in ETAP

Table 5: Parameters for turbine-governor model

Sl No.	Parameters	Value	Description
1.	T1	0	Governor Lag (seconds)
2.	T2	0	Governor Lead Compensation (seconds)
3.	T3	0.004	Lag (>0) (seconds)
4.	T4	0.1	Delay due to HP-Turbine (seconds)
5.	T5	11	Expected reheater delay including hot and cold leads (seconds);
6.	T6	0.2	Delay due to IP-Turbine (seconds)
7.	T7	0.3	Delay due to LP-Turbine, cross-over pipes, and LP end hoods (seconds)
8.	K	20	1/Per Unit Regulation
9.	K1	0.289	Fraction HP-Turbine
10.	K5	0.489	Fraction IP-Turbine
11.	K7	0.289	Fraction LP-Turbine
12.	Uo	0.125	Valve opening time = 8 s (in connection with T3)
13.	Uc	-4	Valve closing time = 0.25 s (in connection with T3)
14.	PMAX	100	PMAX/%, Upper power limit
15.	PMIN	40	PMIN/%, Lower power limit of boiler based on TMCR

2.3.1.1. Validation of Turbine Governor system

Step response is simulated in turbine-governor model as shown in Figure 7. The turbine-governor model is validated by comparing simulation results and PFR test results as shown in Figure 8. The simulation result closely matches with the test results.

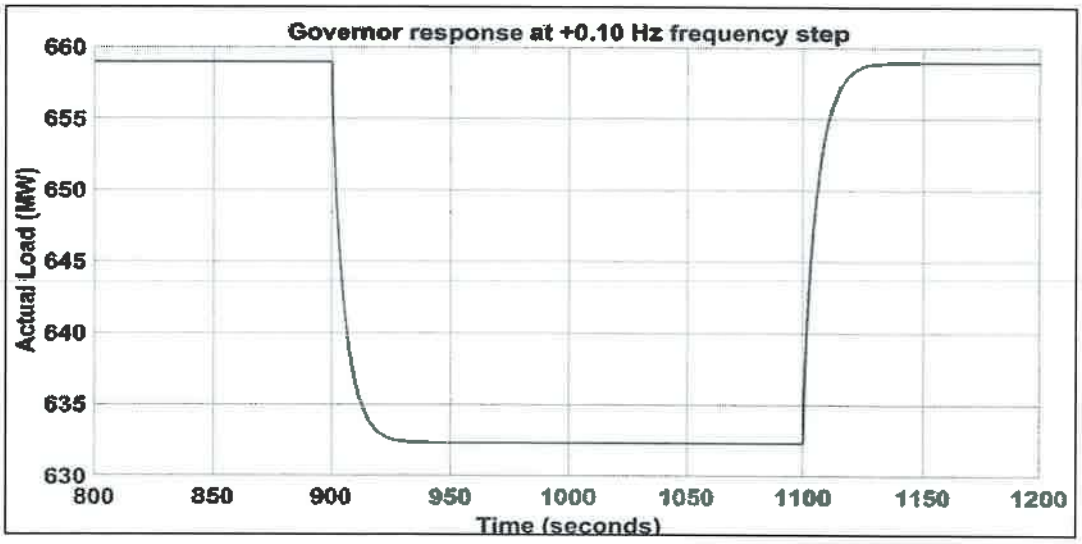

Figure 7: Step response simulation for ±0.10 Hz at 660 MW

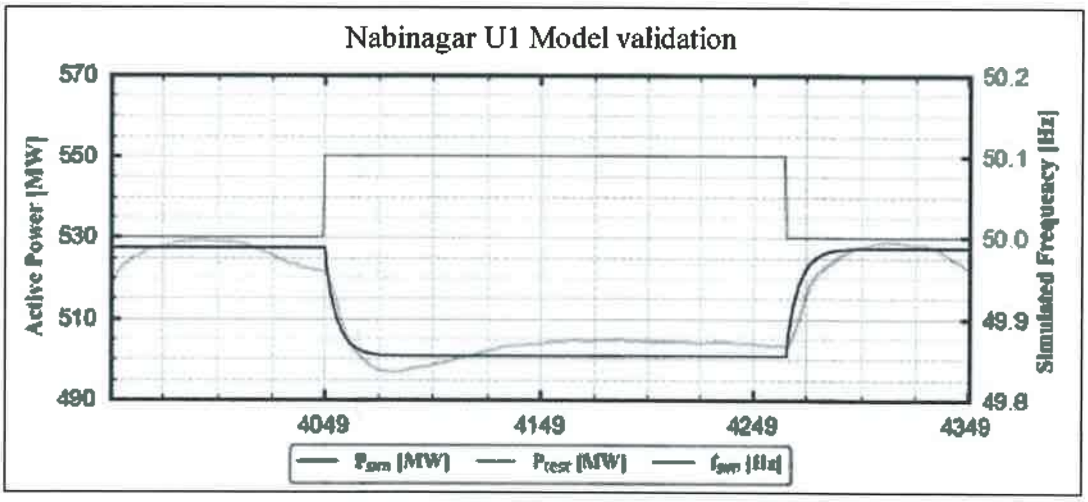

Figure 8: Turbine governor model- step response validation.

2.3.2. AVR and Excitation system

The AVR/exciter model is IEEE ST7B type based on the document provided by NTPC Nabinagar [8] as shown in Figure 10. The excitation system is modelled in ETAP and Simpow as shown in Figure 10. The corresponding parameters are shown in Table 6.

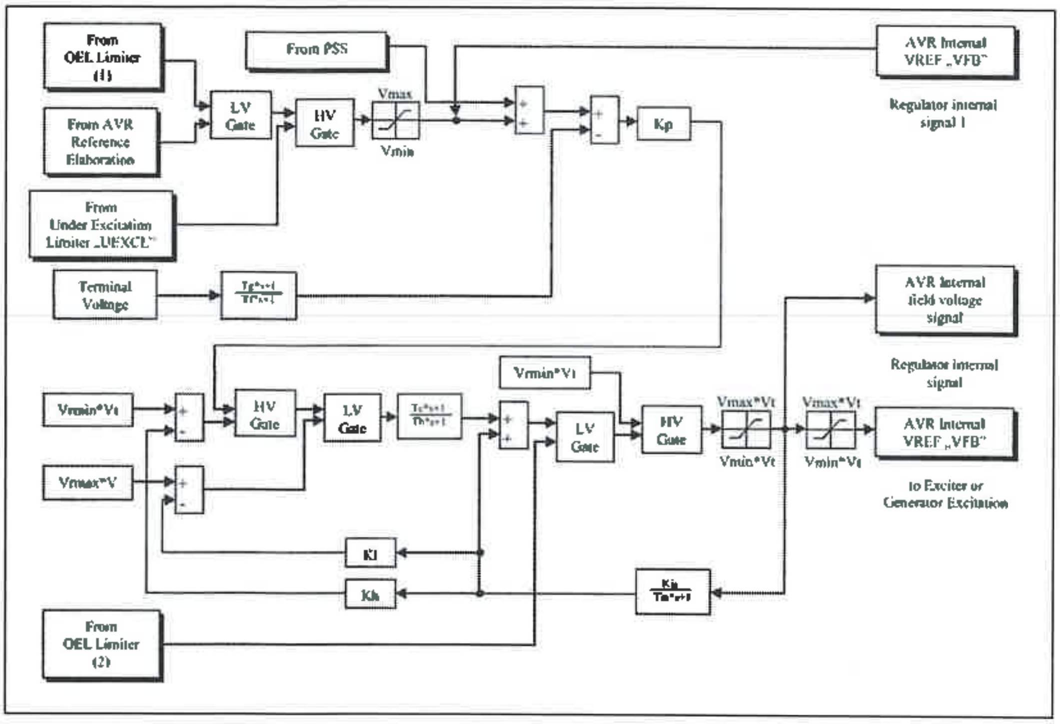

Figure 9: Potential-source excitation system ST7B.

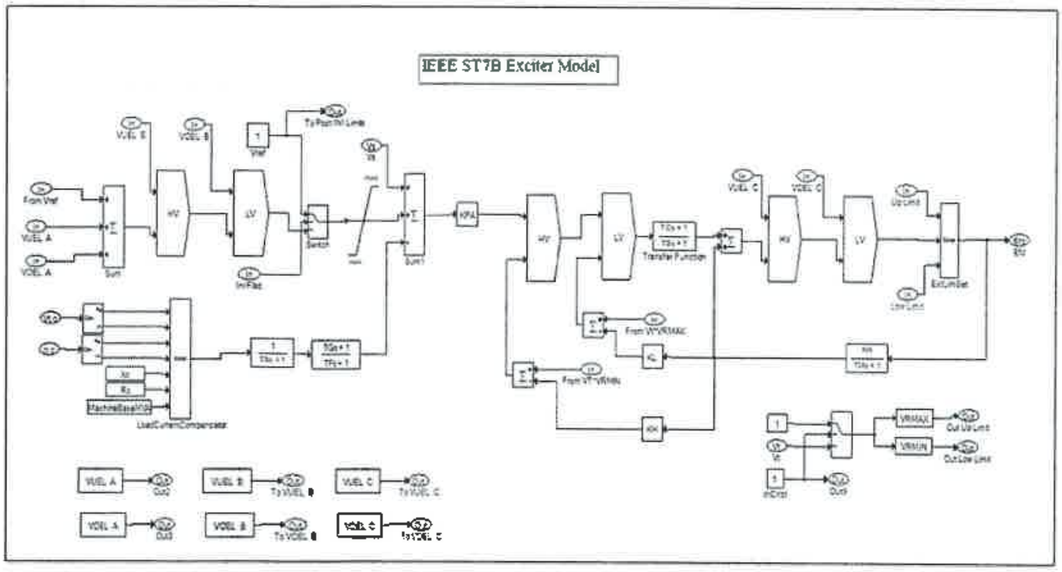

Figure 10: IEEE ST7B exciter model developed in ETAP.

Table 6: Parameters for AVR-ST7B as shared by NTPC Nabinagar

Sl No.	Parameters	Value	Description
1.	Kpa	43.84	Voltage regulator proportional gain (pu)
2.	Tia	3	Voltage regulator Integral time constant (s)
3.	Tc	1	Lead/lag filter numerator time constant (s)
4.	Tb	1	Lead/lag filter denominator time constant (s)
5.	Tg	1	Voltage feedback numerator time constant (s)
6.	Tf	1	Voltage feedback denominator time constant (s)
7.	Vmax	1.05	Positive limit of internal voltage reference (pu)
8.	Vmin	0.95	Negative limit of internal voltage reference (pu)
9.	Kl	1	Integral term validation for inner positive limitation
10.	Kh	0	Integral term validation for inner negative limitation
11.	Vrmax	5.158	Positive ceiling voltage with nominal generator voltage (pu)
12.	Vrmin	-5.158	Negative ceiling voltage with nominal generator voltage (pu)

2.3.2.1. **Validation of excitation system**

The excitation system model built in ETAP and Simpow is validated by comparing simulation results with the AVR step response tests results in no load and on load conditions shared by NTPC Nabinagar.

No load step test

When the generator is operating at no load, a step disturbance of 5% was introduced into the AVR reference which results in the change in generator voltage and excitation voltage as shown in Figure 11 and Figure 12. The settling time for the generator voltage subjected to the step change in AVR reference of 5% resulted in the settling of generator voltage within 0.304s. Figure 13 shows the test results shared by NTPC Nabinagar.

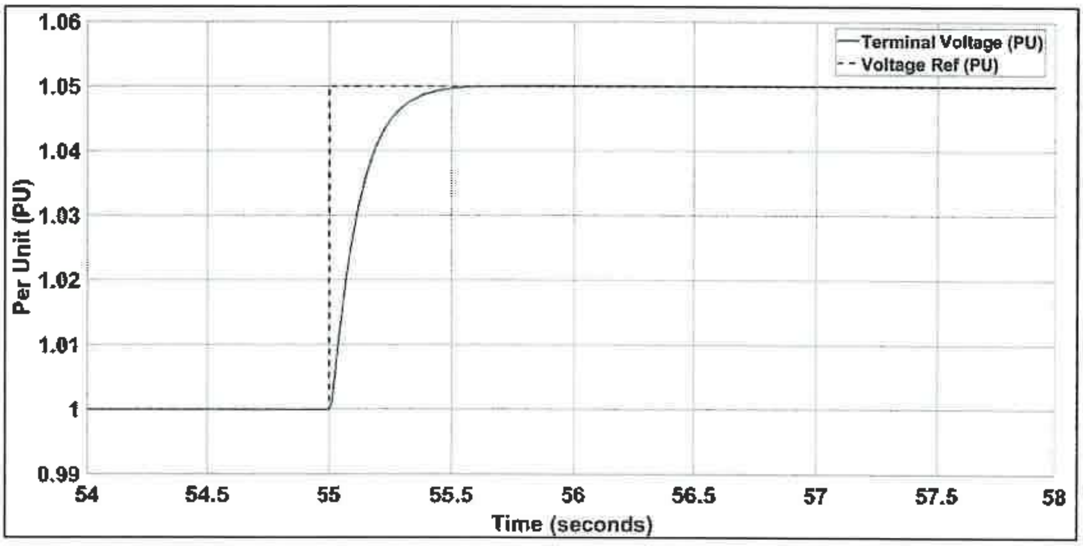

Figure 11: Generator voltage with 5% step disturbance at no load condition.

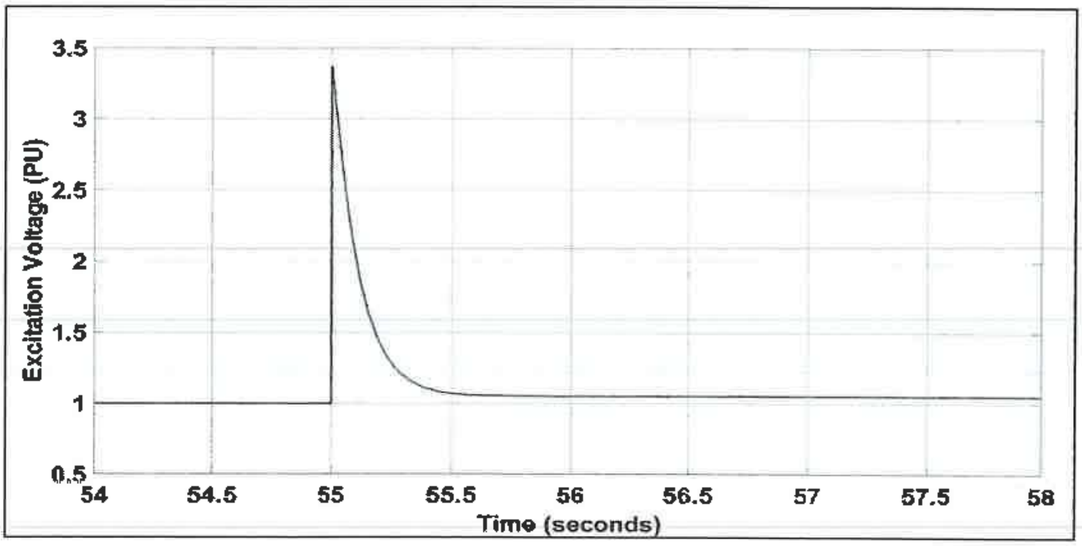

Figure 12: Excitation voltage with 5% step disturbance.

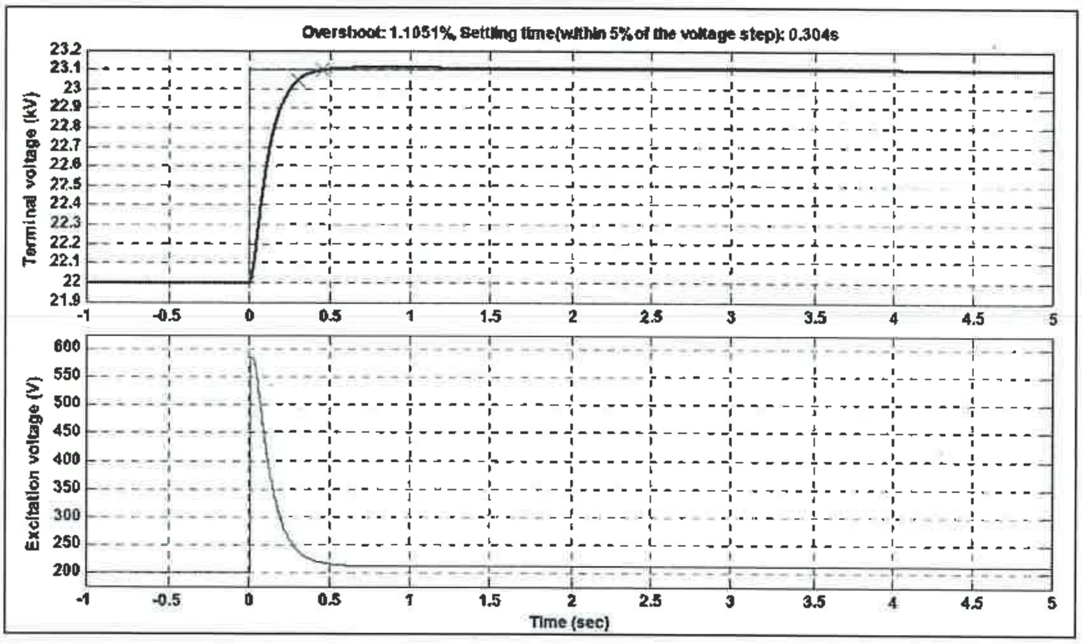

Figure 13: Simulation results of AVR at no load provided by NTPC Nabinagar [2].

On Load Step Test

Figure 14-Figure 17Figure 18 shows the simulation results of the AVR step response which has been validated with data received from NTPC Nabinagar [8].

During step disturbance simulation on AVR in loaded condition, the change in terminal voltage response, is shown in Figure 14.

The active power output of the generator experiences oscillations due to changes in excitation voltage and system dynamics, as shown in Figure 16.

Figure 18 show the results shared by NTPC Nabinagar. It can be seen from the figures below that simulated response matches with the response shared by NTPC Nabinagar to step disturbance in AVR in loaded condition.

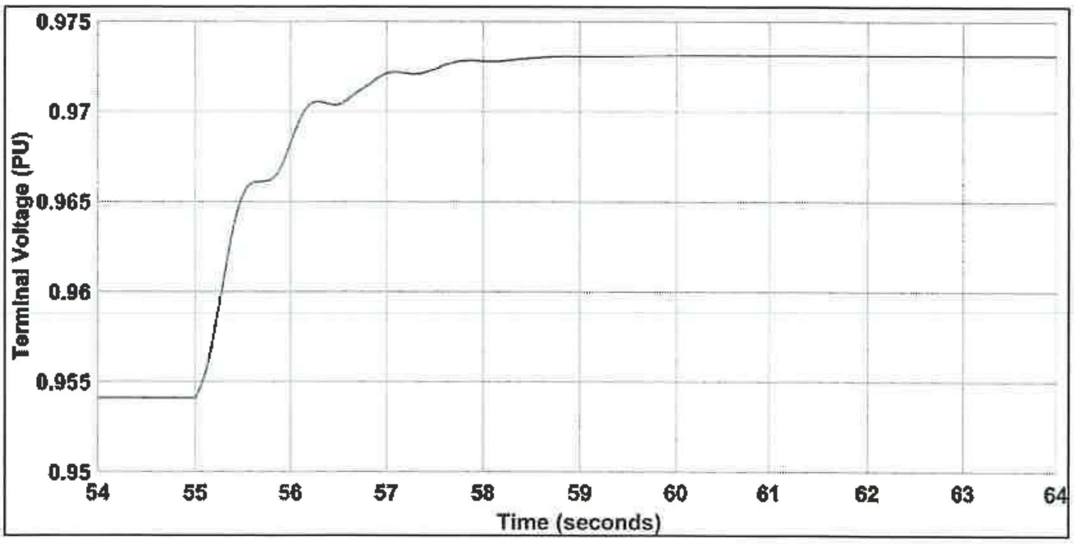

Figure 14: Generator unit terminal voltage with step disturbance.

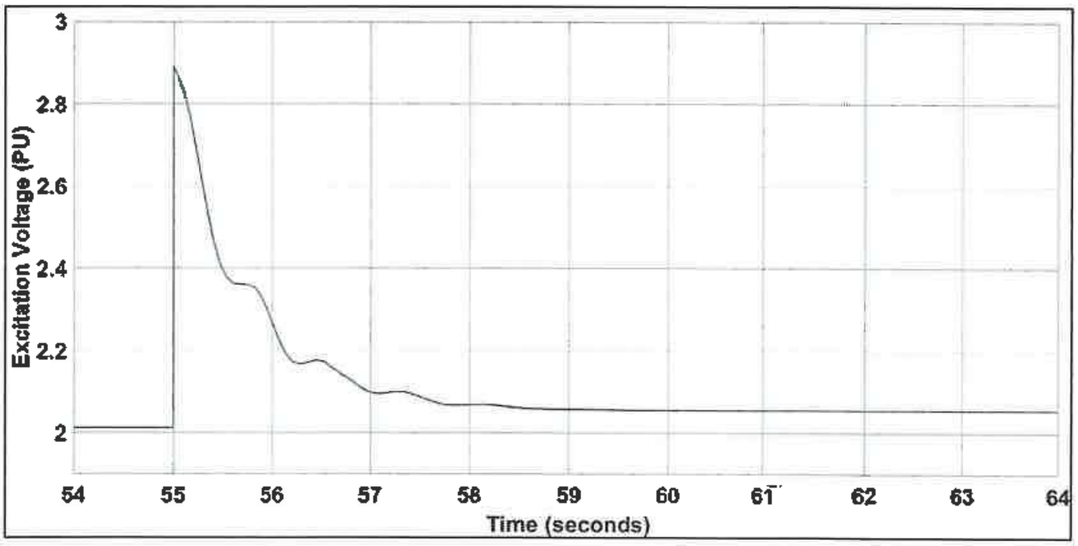

Figure 15: Field voltage with step disturbance.

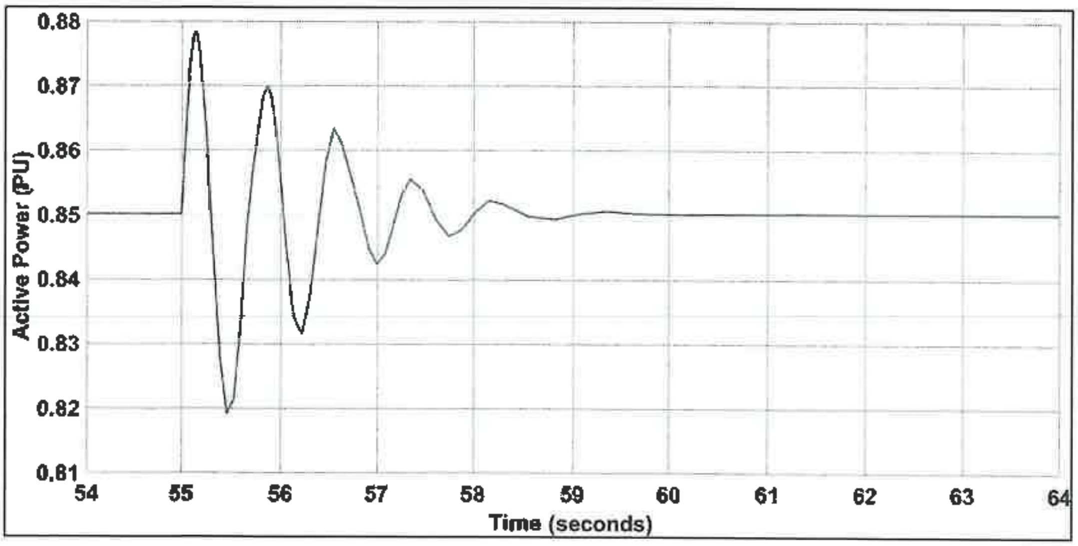

Figure 16: Active Power with step disturbance.

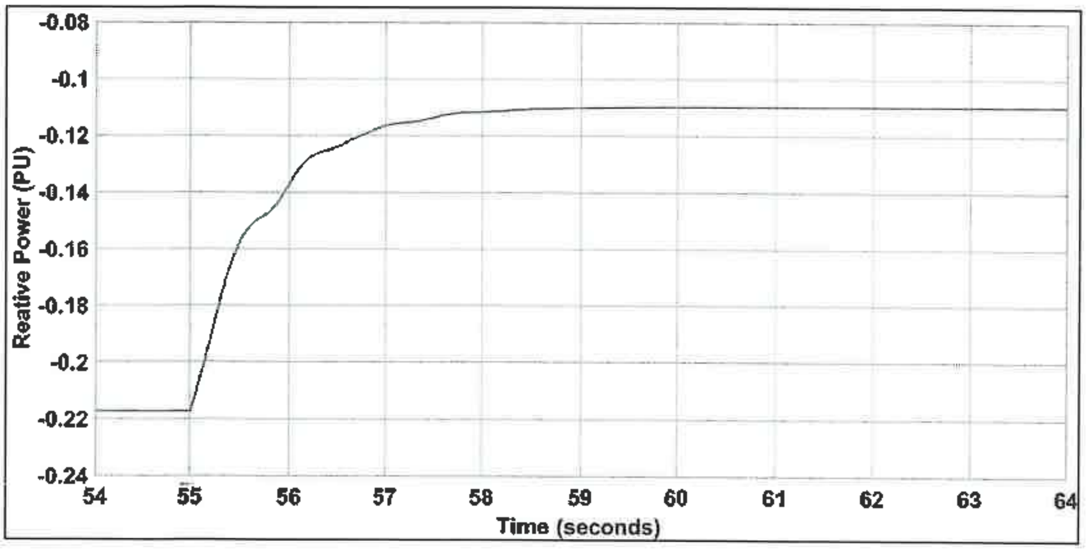

Figure 17: Reactive Power with step disturbance.

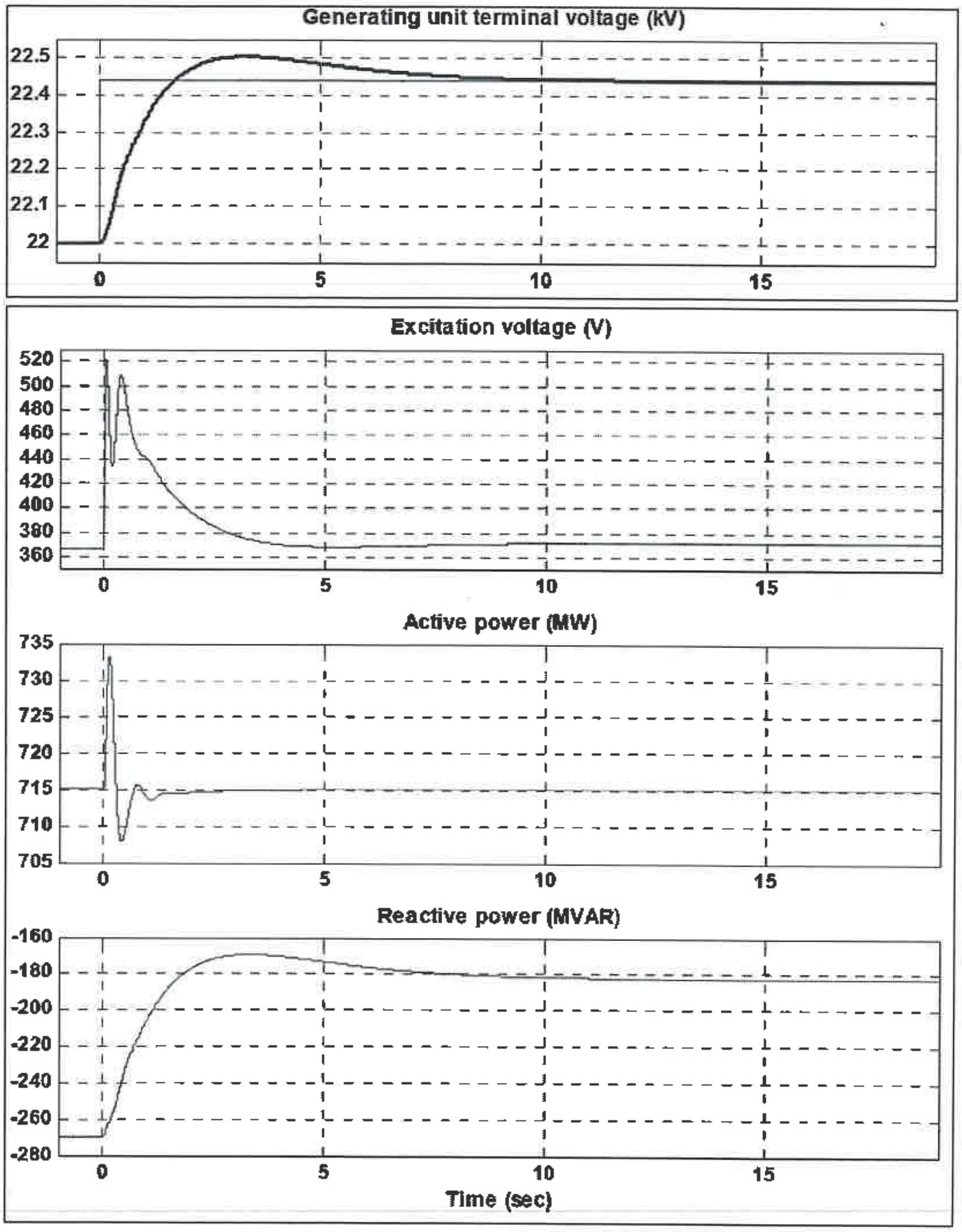

Figure 18: On load AVR step response results provided by NTPC Nabinagar

2.3.3. Plant loads

This section describes the loads within NTPC Nabinagar. All induction motors are considered as static loads as the motor modelling parameters were not provided. Other loads whose data has not been provided are also considered static loads. The plant load input data received and assumed parameters used for the modelling are tabulated in Table 7.

Table 7: Details of Load within plant received from NTPC Nabinagar

S.No.	Electrical Loads	Rating
1.	Line resistances and reactance	X/R =10 (assumed)
2.	All mills loads taken as one static load	3.48 MW
3.	BCW Pump +IA Compressor +PA Compressor + Station Aux. Cooling water pump+ Chemical Cleaning pump + Raw water pump	2.415 MW
4.	CE Pump	2.600 MW
5.	Ash handling pump	8.430 MW
6.	CHP Motors	5.290 MW
7.	AWRS Pump	430 KW
8.	MDBF Pump	2 x 10.5MW
9.	ID Fan	2 x 4.7MW
10.	CW Pump	2 x 3.07MW
11.	PA Fan	2 x 3.5MW
12.	FD Fan	2 x1.8MW
13.	Other loads	10MW
14.	Total Plant Load	≈ 80MW

Note:

- The sum of total plant loads shown in SLD is close to 70MW. An assumption of 10MW has been done to make the total plant load near to 80MW.
- Information regarding boiler loads is not clearly mentioned.
- Motors in ash handling package/ coal handling package which are connected at 3.3kV are modelled as static load.
- All induction motors are modelled as static load as the motor modelling parameters are not provided.

2.3.4. Transformers within generating station

Transformers from voltage level 400 kV to 0.433 kV are modelled as per the information received from NTPC Nabinagar. This also includes modelling of all three and two - winding transformers. The tap setting of transformers is not included in the modelling for reducing the modelling complexities. All the modelling parameters are tabulated in Table 8.

Table 8:Transformer type & parameters used for modelling in ETAP:

Sl. No.	Transformer Type	MVA Rating	LV Side kV	HV Side kV	Z%	R(pu) [Assumed]	X(pu) [Assumed]
1.	IBT #3	200	132	400	12.5	0.00278	0.12497
2.	GT # 3R	260	22	420/√3	15	0.033	0.15
3.	UT # 3A and #3B	35	22	11.5	9	0.0002	0.0089
4.	UAT #3A and #3B	16	3.45	11	12.5	0.000624	0.12497
5.	ESPT #3A, #3B & #3C	1.6	0.433	11	9	0.001315	0.00789
6.	UST #3C & 3D	2.5	0.433	11	12.5	0.001315	0.00789
7.	AET #3A & #3B	1	0.433	11	5	0.001315	0.00789
8.	CHP	2	0.433	11	10	0.001315	0.00789
9.	ST#3	90/45/45	11.5/11.5	132	ZHV-LV1=Z HV-LV2=21 LV1-LV2=37	R12=0.00278 R13=0.00278 R23= 0.00278	X12=0.125 X13=0.125 X23=0.125

3. Simulation Results

Several simulations cases were performed to develop the understanding of the dynamic behavior of the unit undergoing islanding. Respective cases and their simulation studies are described below.

3.1. Simulation Cases

Cases	Scenario	Description
Case 1	Maximum generation (660 MW) and Maximum load (640 MW)	There is a surplus of 20MW being fed to the grid, and simulation studies have been conducted at the island formation (48.4Hz).
Case 2	Maximum generation (660 MW) and Minimum load (500 MW)	There is a surplus of 160MW being supplied to the grid, and simulation studies have been conducted at the island formation (48.4Hz).
Case 3	Minimum generation (380MW) and Minimum Load (500MW)	Due to a deficit of 120MW in generation, simulation studies w.r.t suitable load shed has carried out taking unit stability and tripping limits into consideration.
Case 4	Minimum generation (380MW) and Maximum load (640MW)	Deficit of 260MW is being withdrawn from the grid, and simulation studies have been conducted at the island formation (48.4Hz).
Case 5	Calculations of Critical clearing time	A three phase to ground fault is simulated at the grid bus and the variation in power and load angle and system voltage has been studied. Worst fault clearing time is estimated.
Case 6	Load increment of 33.25MW (5.2% of island load) after island formation.	Referring case 1, after the formation of island network, load of 33.25MW is added and the dynamic behavior of the unit has been studied.
Case 7	Load increment of 42.75MW (6.67% of island load) after island formation	Referring case 1, after the formation of island network, load of 42.75MW is added and the dynamic behavior of the unit has been studied.
Case 8	Load increment of 52.25MW (8.2% of total island load) after island formation	Referring case 1, after the formation of island network, load of 52.25MW is added and the dynamic behavior of the unit has been studied.
Case 9	Rate of change of frequency (ROCOF) 0.5Hz/s Island formation (49Hz)	Referring case 1, simulation studies has been carried out with a rate of change of frequency of 0.5Hz/sec where island network is formed at 49Hz.

Cases	Scenario	Description
Case 10	Rate of change of frequency (ROCOF) 0.5Hz/s Island formation (48.4Hz)	Referring case 1, simulation studies has been carried out with a rate of change of frequency of 0.5Hz/sec where island network is formed at 48.4Hz.
Case 11	Island formation at 48.4Hz with a Rate of Frequency Change of 0.25Hz/s	Referring case 1, simulation studies has been carried out with a rate of change of frequency of 0.25Hz/sec where island network is formed at 48.4Hz.
Case 12	Optimal load reduction during island formation	Referring to case 3, during island formation a lesser load of 68MW is being shed in comparison to 74MW and comparative dynamic study has been performed for this case.
Case 13	Load increment of 12.5MW (2.5% of island load) after island formation	Referring case 3, after the island network formation, a load of 12.5MW is added and the dynamic behavior of the unit has been studied.
Case 14	Load increment of 20MW (4% of island load) after island formation	Referring case 3, after the island network formation, a load of 20MW is added and the dynamic behavior of the unit has been studied.
Case 15	Load increment of 22MW (4.4% of island load) after island formation	Referring case 3, after the island network formation, a load of 22MW is added and the dynamic behavior of the unit has been studied.
Case 16	Load shed with time delay	Load shedding was delayed compared to Case 3, and its dynamic study was performed to compare its effects.
Case 17	Island Formation (49Hz) with Rate of Change 0.5Hz/s	Referring case 3, simulation studies has been carried out with a rate of change of frequency of 0.5Hz/sec where island network is formed at 49Hz.
Case 18	Island Formation (48.4Hz) with Rate of Change 0.5Hz/s	Referring case 3, simulation studies has been carried out with a rate of change of frequency of 0.5Hz/sec where island network is formed at 48.4Hz.
Case 19	Effect of Linear and Non Linear valve behavior in Active Power.	In this case, the effect of linearity and non-linearity in the governor output, and its effect on the dynamic studies is performed.

3.1.1. Case 1: Maximum Generation and Maximum Load

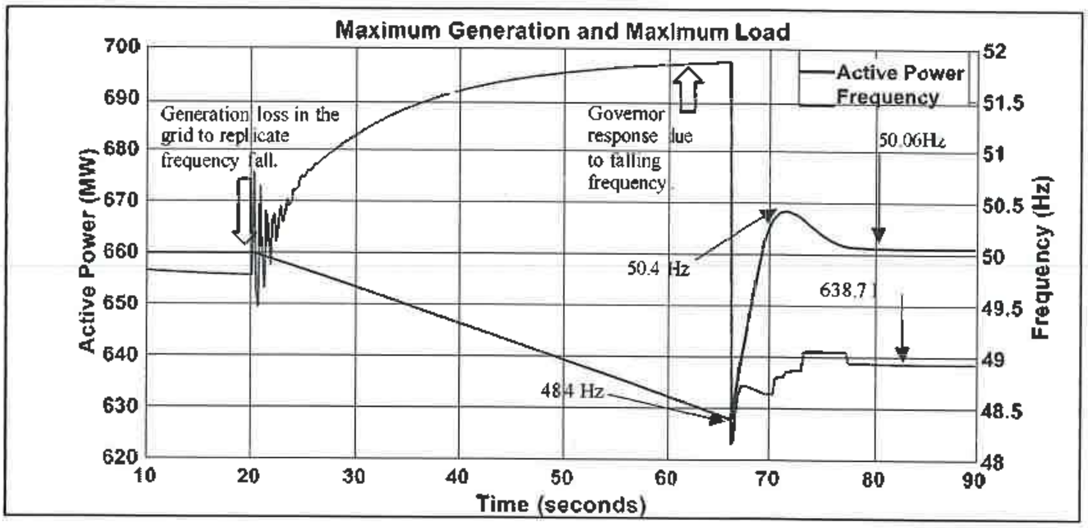

Figure 19: Variation in active power and frequency vs time during islanding.

For maximum generation and maximum load, unit generation is 660MW, island load demand is 640MW, there is surplus of 20MW from generation side which is fed to the grid.

A grid event (frequency fall) was created by tripping a large generator at the grid at 20th seconds, which resulted in an increase of electrical power of the unit undergoing islanding. Generator power increases during the frequency fall due to droop control in the governor. Unit was islanded from the network as soon as the system frequency reached 48.4 Hz. As there was surplus generation at the time of islanding, frequency rises after islanding. Governor action was able to stabilize the frequency after islanding without any load shedding as shown in Figure 19.

Simulation results for this scenario indicate a frequency fall at the rate of 0.035 Hz/sec when initiating an event of grid disturbance, followed by a frequency increase post islanding. Within 12 seconds the frequency stabilizes to its final value of 50.06 Hz, and the unit stabilizes to its final value of 638.7 MW. A sudden increase in frequency of 50.4 Hz was observed at the instant of island formation. Island frequency and voltages are well stabilized by the voltage and frequency control functions of the generator.

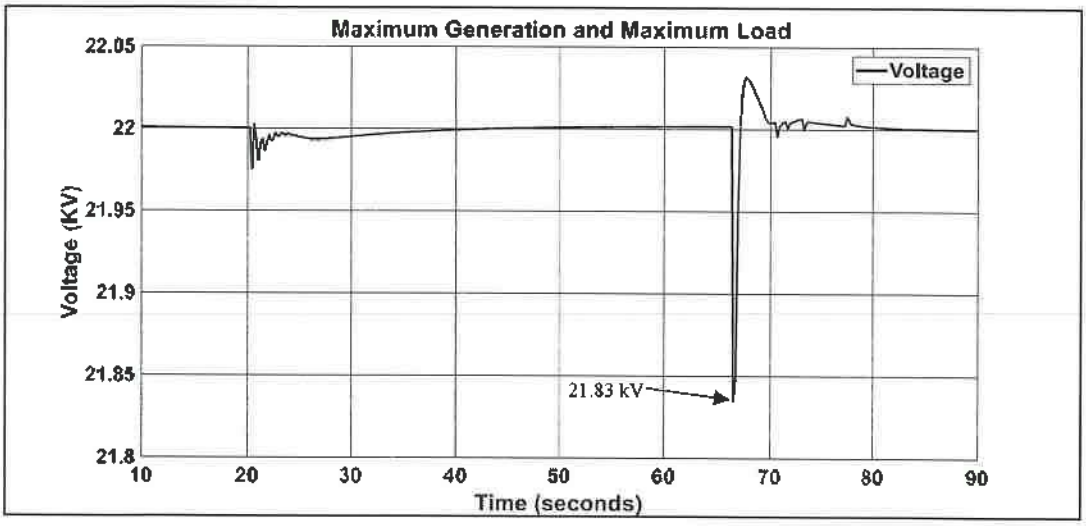

Figure 20:Variation in voltage vs time during islanding.

Generation is at 22kV, when the island is formed, the voltage initially experienced a sudden dip from 22kV to 21.83kV (0.91%) which further stabilized around 22kV.

3.1.2. Case 2: Maximum Generation and Minimum Load

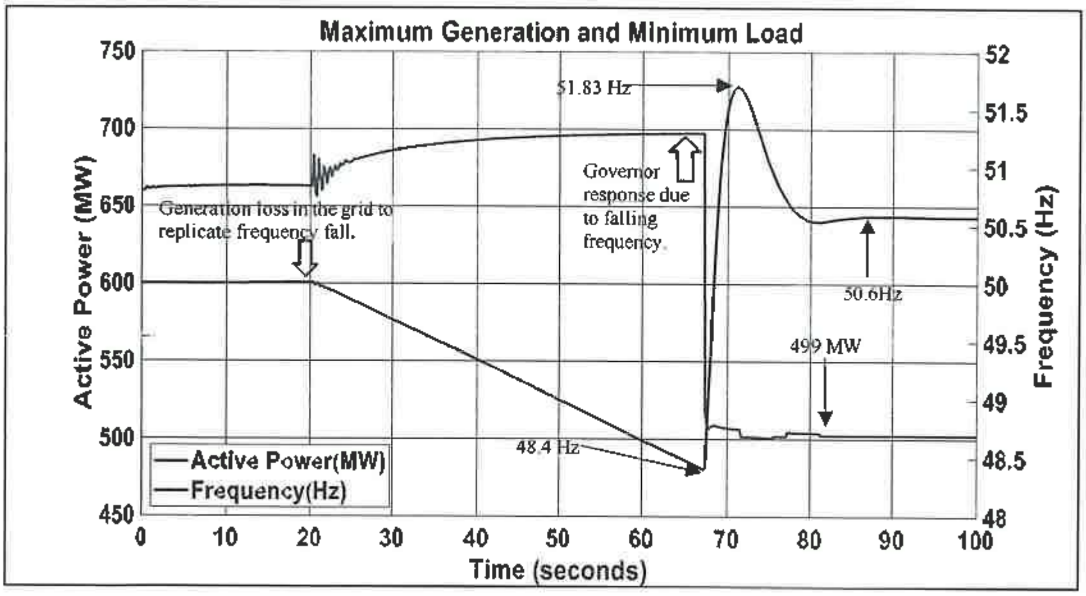

Figure 21: Variation in active power and frequency vs time during islanding.

For maximum generation and minimum load, unit generation was 660 MW and island load demand was 500 MW, thus there was surplus of 160 MW surplus inside the island.

A grid event (frequency fall) was created by tripping a large generator at the grid at 20th seconds, which resulted in an increase of electrical power of the unit undergoing islanding. Generator power increases during the frequency fall due to droop control in the governor. Unit was islanded from the network as soon as the system frequency reached 48.4 Hz. As there is surplus generation at the time of islanding, frequency rises after islanding. Governor action was able to stabilize the frequency after islanding without any load shedding as shown in Figure 21 results for this scenario indicate a frequency decrease of 0.035 Hz/sec when initiating islanding, followed by a frequency increase post islanding. Within 17.4 seconds the frequency stabilizes to its final value of 50.6Hz and the unit stabilizes to its final value of 499 MW. A sudden increase in frequency of 51.83Hz was observed at the instant of island formation.

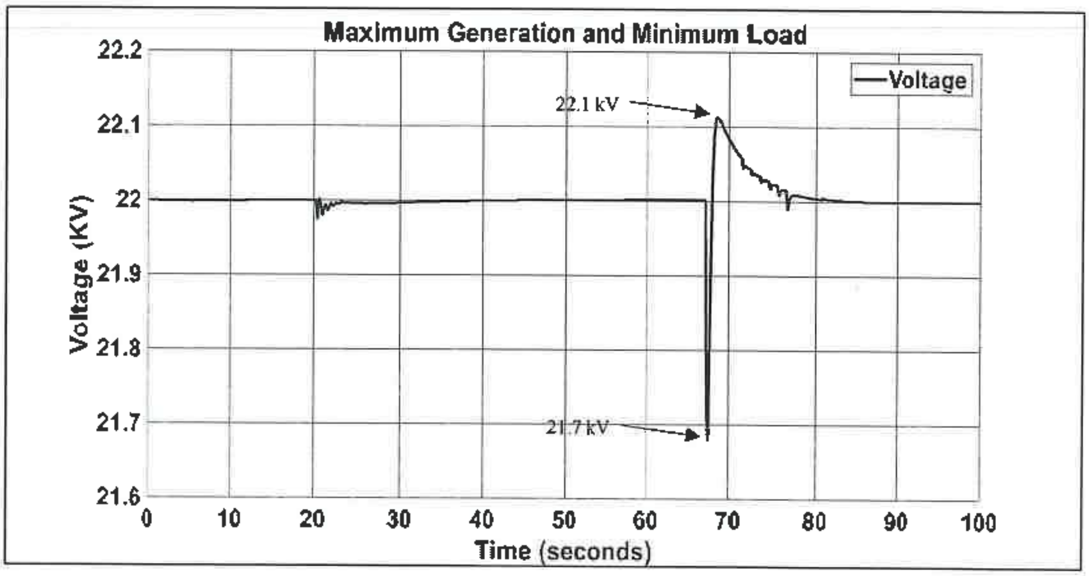

Figure 22: Variation in voltage vs time during islanding.

Generation is at 22kV, when the island was formed, the voltage initially experienced a sudden dip from 22kV to 21.7kV (1.3%) which further stabilized around 22kV. An overshoot of 22.1 kV was observed, while frequency was improving towards 50 Hz.

3.1.3. Case 3: Minimum Generation and Minimum Load

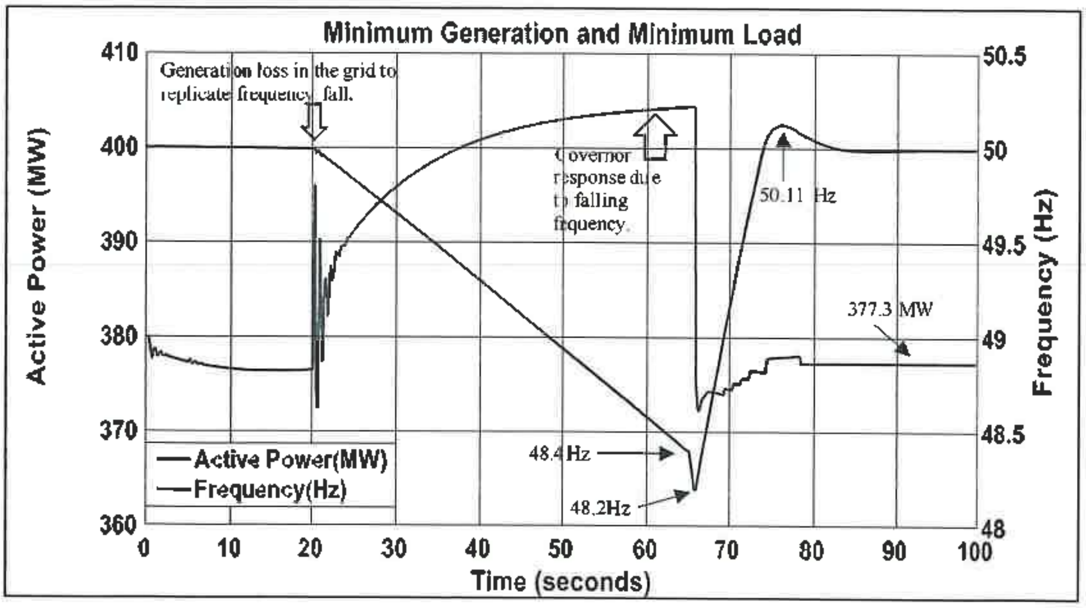

Figure 23: Variation in active power and frequency vs time during islanding.

For minimum generation and minimum load, unit generation was 380MW, island load demand was 500MW, thus there was deficit of 120MW from generation side which was being fed by the grid. In the event of a grid disturbance requiring unit islanding, strategic load shedding was necessary based on the criticality of the load to prevent the unit from tripping.

A grid event (frequency fall) was created by tripping a large generator in the grid at 20th seconds, generator power increases during frequency fall due to droop control in the governor however due to deficit in generation a load shed of 50MW (500-50=450) was initiated at 48.4 Hz, Since the generation was 380MW, shortfall persists, an additional island load shed of 74MW (450-74=376MW) was performed at 48.2Hz frequency. At 48.2Hz as generation was in surplus than Island load demand, thus frequency increased after islanding and stabilized at 49.99 Hz. To prevent the tripping of the unit by operation of under frequency relay, i.e., the island reaching a frequency of 47.4Hz, it was required to shed an additional load of 74MW at 48.2Hz.

Simulation results for this scenario indicate a frequency decrease of 0.035Hz/sec before initiating islanding, followed by a frequency increase post-load shedding. Frequency stabilizes to its final value of 49.99 Hz within 19.6 seconds corresponding to generation settling to of 377.3 MW. A sudden increase in frequency of 50.125Hz was observed at the instant of island formation.

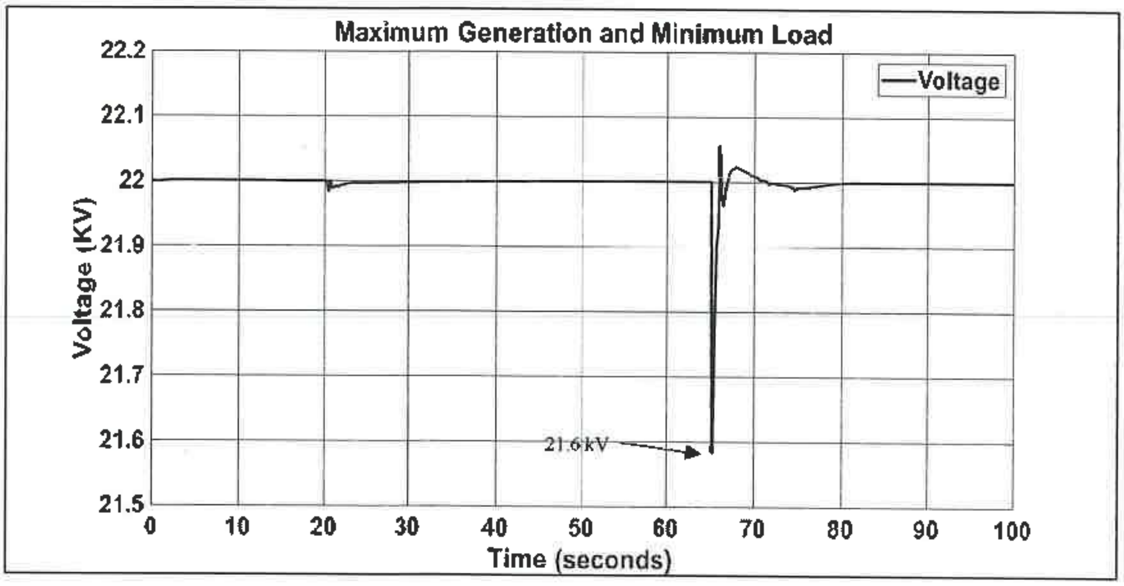

Figure 24: Variation in voltage vs time during islanding.

Generation is at 22kV, when the island formed, the voltage initially experienced a sudden rise from 22kV to 21.6kV (i.e., 1.81%) which further stabilized around 22kV.

3.1.4. Case 4: Minimum Generation and Maximum Load

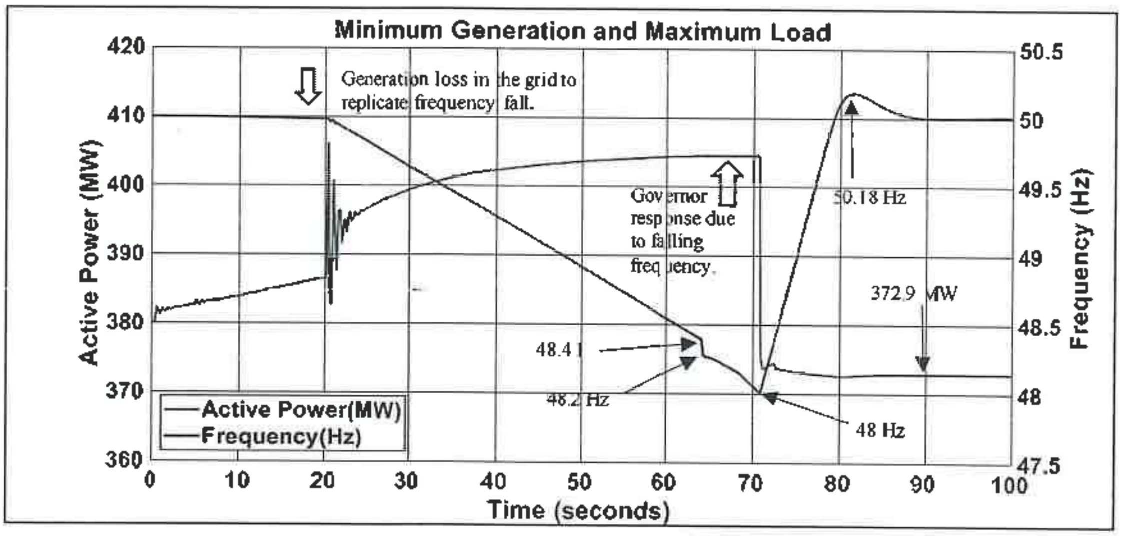

Figure 25: Variation in active power and frequency vs time during islanding.

For minimum generation and maximum load, unit generation was 380MW, island load demand was 640MW, thus there was a deficit of 260MW from generation side which was being fed by the grid. In the event of a grid disturbance requiring unit islanding, strategic load shedding was necessary based on the criticality of the load to prevent the unit from tripping.

A grid event (frequency fall) was created by tripping a large generator at the grid at 20th seconds, which resulted in an increase of electrical power of the unit undergoing islanding. When the frequency reaches 48.4 Hz, at the point of islanding, generation was 380MW and island load demand was 640 MW. Hence the generation was 260MW deficit inside the island. Thus, to limit the rate of fast frequency fall an additional load of 150 MW was shed at the instant of island formation i.e. 48.4 Hz.

The total island load was 640 MW which includes unit essential load of 80MW, hence the available load to shed was 640-80 = 560 MW. At the instant of island formation even after load shed from the total island load was 410MW (560-150 = 410 MW) a short fall in generation persists. At further frequency of 48.2 Hz, 20% of the remaining island load i.e. 0.2*410 = 82 MW was tripped and the total island load was 408MW (328MW (island load) + 80MW (NPGC essential load) = 408 MW) which was still more than the generation, so an additional load shed was required till the load and generation are balanced.

A further load shed of 10 % of the remaining island load i.e. 0.1*328 = 32.8 MW was tripped at 48.0 Hz, and the total island load would become 375.2MW (295.2MW (island load) + 80 MW (Unit essential load) = 375.2 MW) which was less than the generation (380MW), hence the island was generation rich with 4.8 MW and the unit stabilizes to 50.01 Hz in 18.4 seconds with a peak frequency of 50.18 Hz.

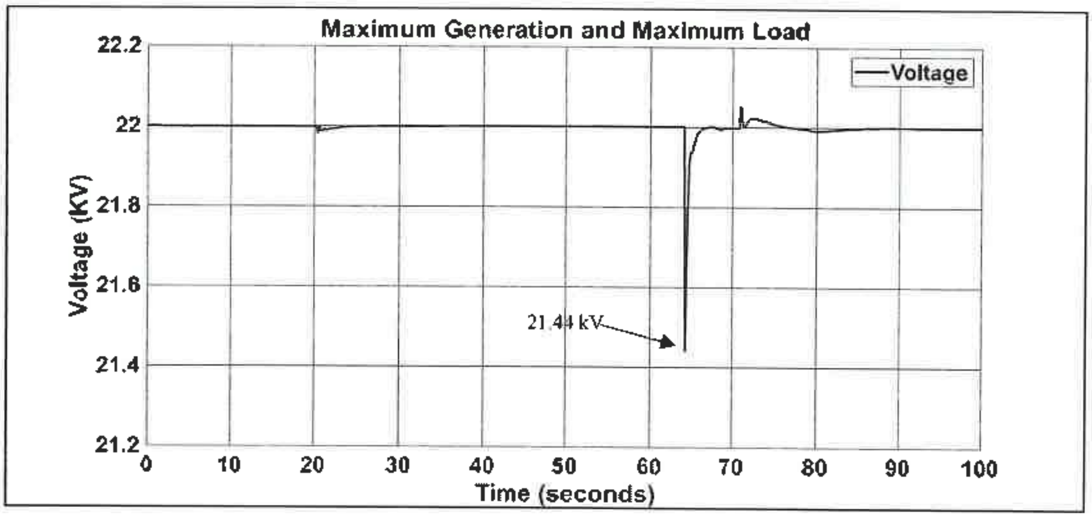

Figure 26: Variation in voltage vs time during islanding.

It can be observed from Figure 26 that at the instant of island formation voltage decreases from 22kV to 21.44 kV (2.54%) for a very short duration of about 0.5 second and finally stabilizes to 22 kV.

3.1.5. Case 5: Critical Clearing Time

In order to determine the critical clearing time a three phase to ground fault was simulated at grid bus, and it was observed that the critical clearing time was 220 milliseconds. The power-delta curve is shown in Figure 27 and variation in generator voltage is shown in Figure 28.

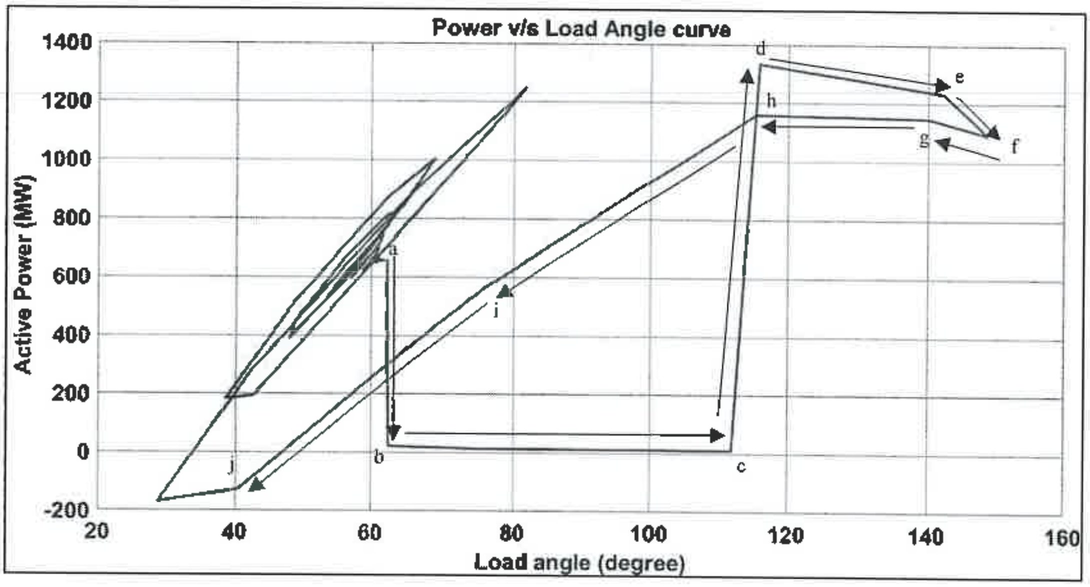

Figure 27: Critical clearing time for the unit in response to a three-phase to ground fault occurring in the grid was determined to be 220 milliseconds, before the unit loses its synchronism.

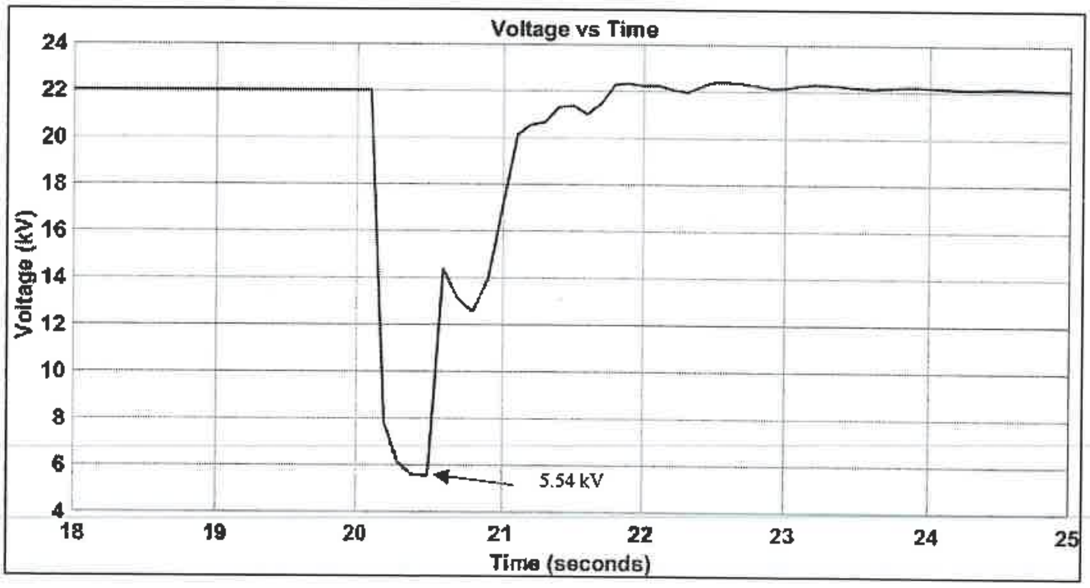

Figure 28: Voltage variation in response to the occurrence of three phase to ground fault and clearing the fault before the unit losses its synchronism.

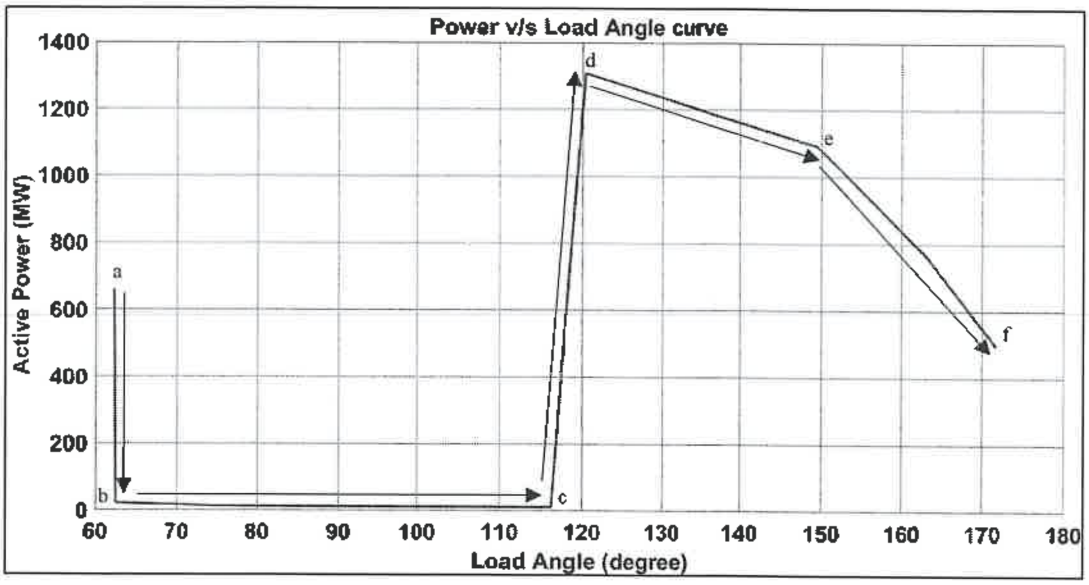

Figure 29: Loss of synchronism of the unit in response to the occurrence of three phase to ground fault at grid and clearing it in 221 milliseconds, load angle reaching close to 180 degree is indicative of Unstable operation of the unit.

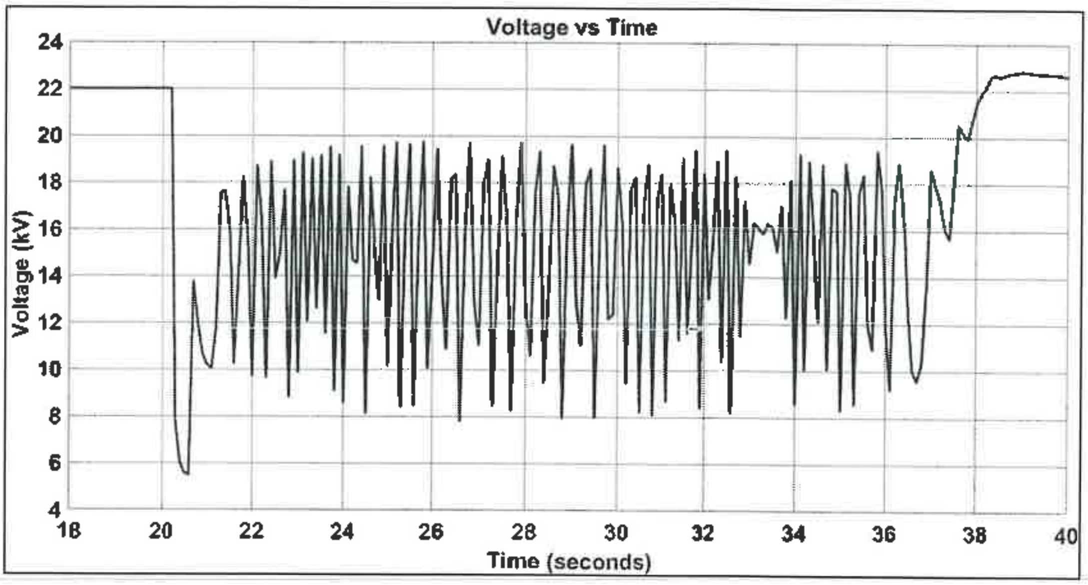

Figure 30: Voltage variation for the unstable operation of the unit, indicating unit loses its synchronism if fault was cleared beyond the critical clearing time of 220 milliseconds.

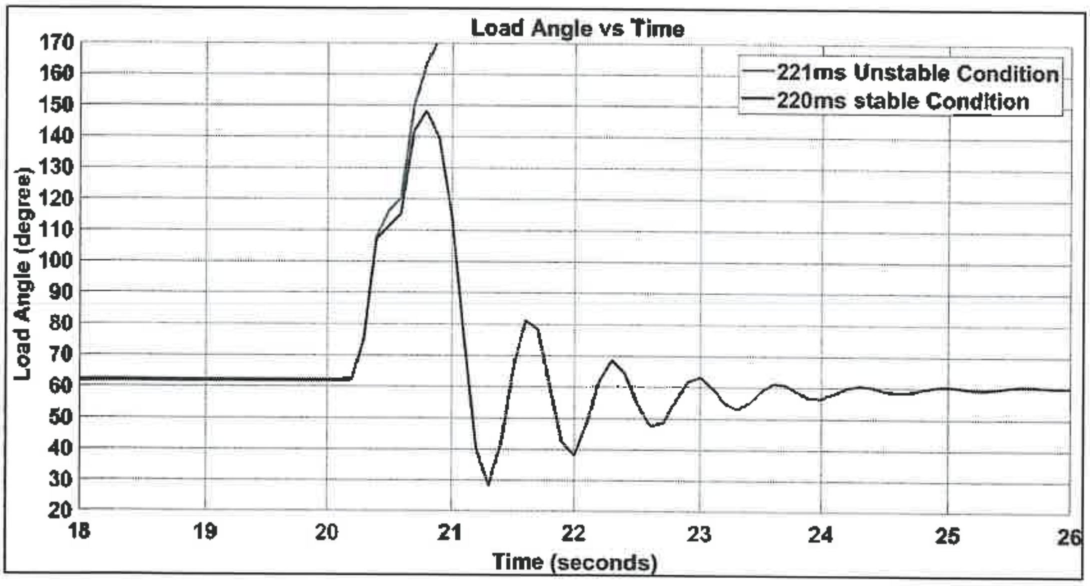

Figure 31: Load angle versus time for the unit under stable and unstable mode of operation resulting from the fault clearance at or beyond the critical clearing time of 220 milliseconds.

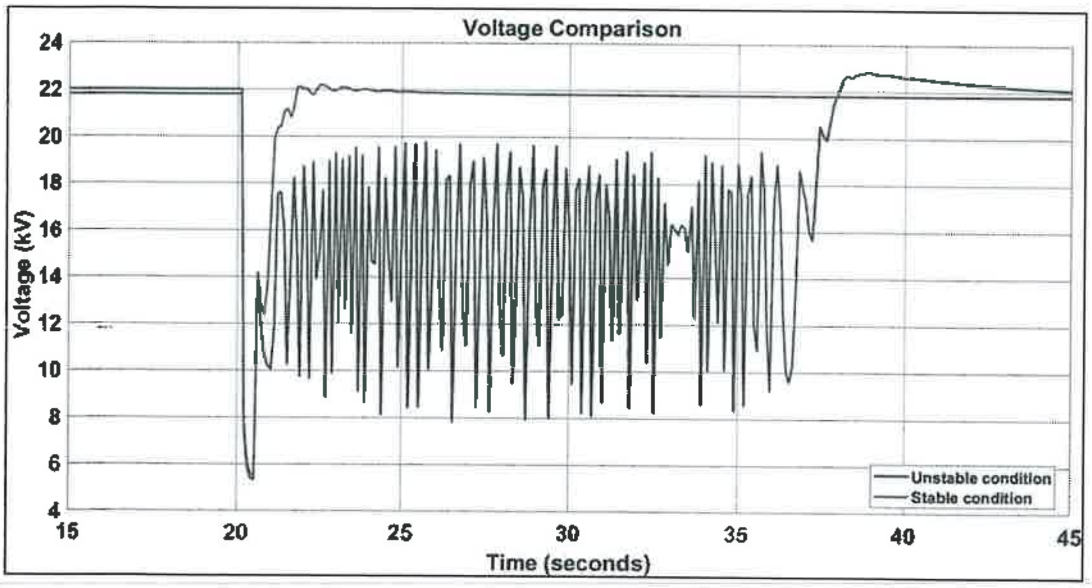

Figure 32: Voltage variation of the unit during the event of fault and clearing in and beyond the critical clearing time of 220 milliseconds.

3.1.6. Case 6: Load increment of 33.25MW post island formation.

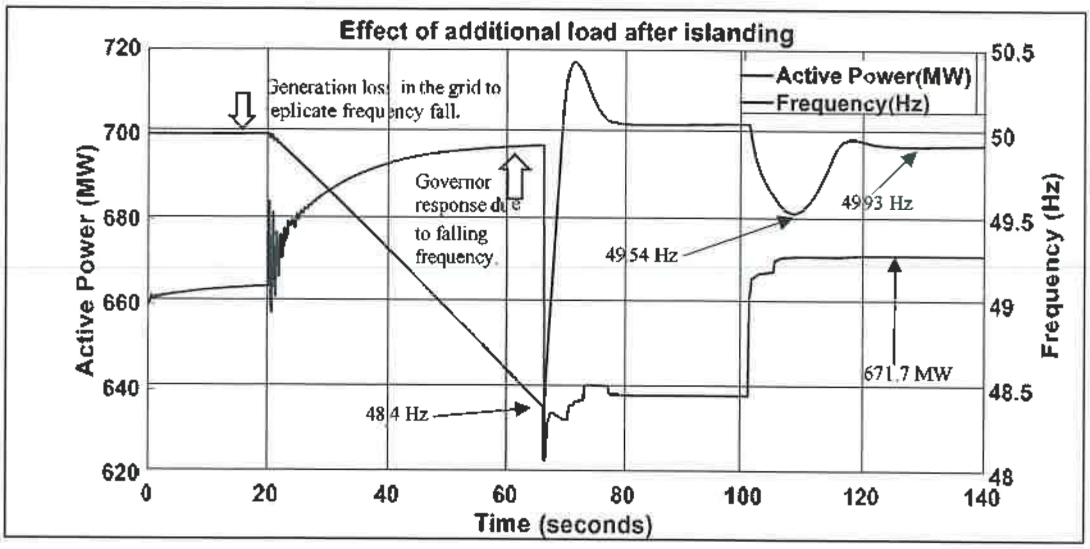

Figure 33: Variation in active power and frequency vs time due to load increment of 33.25 MW after islanding.

In reference to Case 1: (Generation=660MW and Load=640MW) an additional load of 33.25MW has been added into the network post island formation.

Simulation results for this case reveal that with the subsequent inclusion of 33.25MW in the network post-island formation a decrement in frequency of 49.54Hz has been observed for over a duration of 23.8 seconds. With generation increasing to 671.7MW, final frequency of the island stabilizes to 49.93Hz.

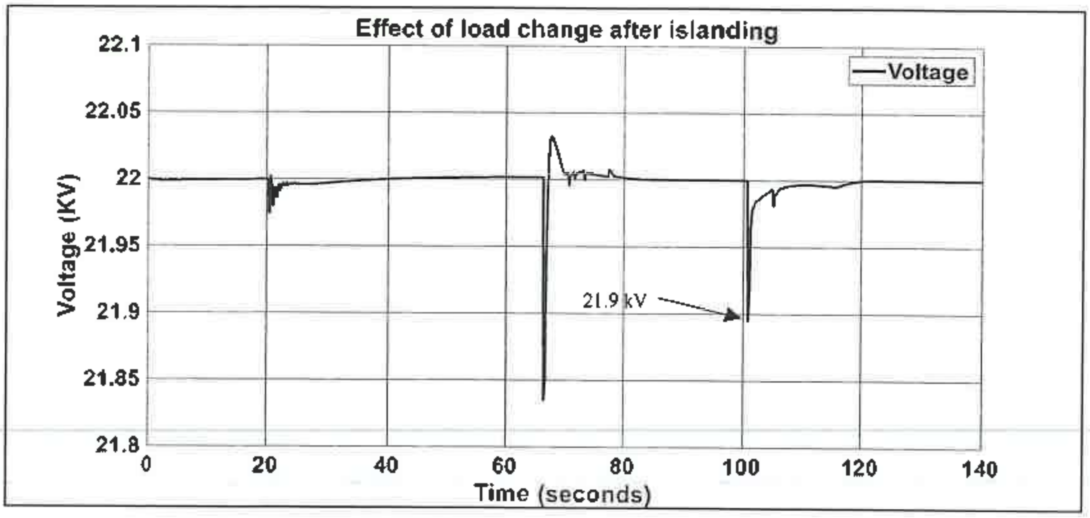

Figure 34: Variation in voltage vs time due to load increment of 33.25 MW after islanding.

Figure 34 shows voltage change due to addition of 5.2% of total island load. The voltage initially experiences a sudden dip from 22 kV to 21.9 kV (0.45%) which further stabilizes to 22kV.

3.1.7. Case 7: Load increment of 42.75MW after island formation.

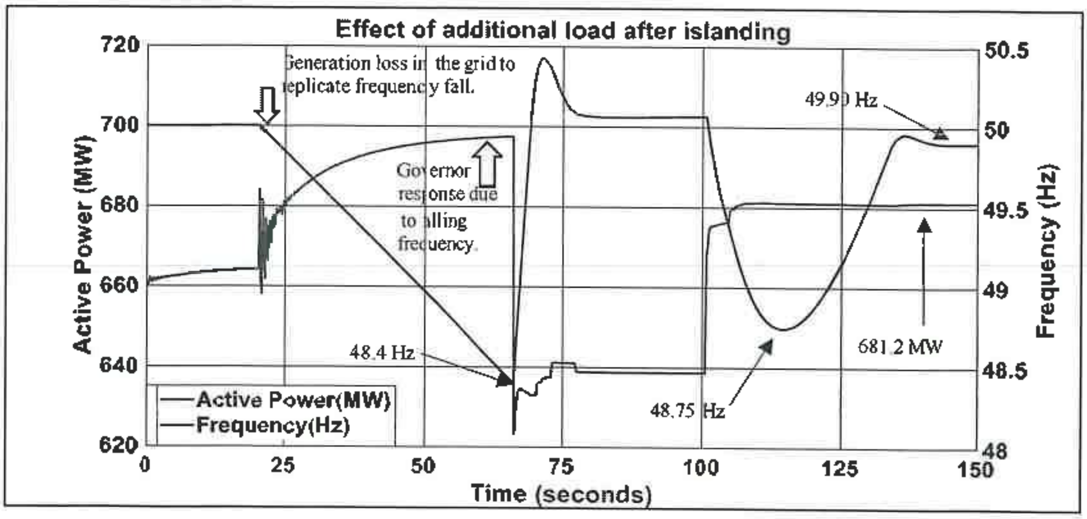

Figure 35: Variation in active power and frequency vs time due to load increment of 42.75 MW after islanding.

In reference to Case:1 (Generation=660MW and Load=640MW) an additional load of 42.75MW has been added into the network post island formation.

Simulation results for this case reveal that with the subsequent inclusion of 42.75MW in the network post-island formation a decrement in frequency of 48.75Hz has been observed over a duration of 41.8 seconds. With generation increasing to 681.2MW, final frequency of the island stabilizes to 49.90Hz.

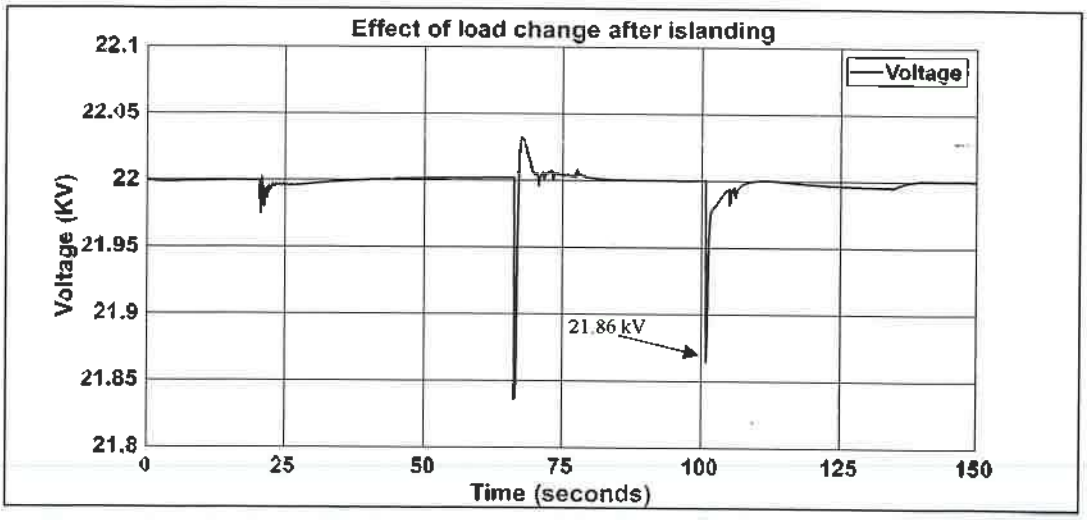

Figure 36: Variation in voltage vs time due to load increment of 42.75 MW after islanding.

Figure 36 shows the voltage change due to the addition of 6.5% of total load. The voltage initially experienced a sudden dip of 21.86kV (0.63%) which further stabilizes to 22kV.

3.1.8. Case 8: Load increment of 52.25MW after island formation.

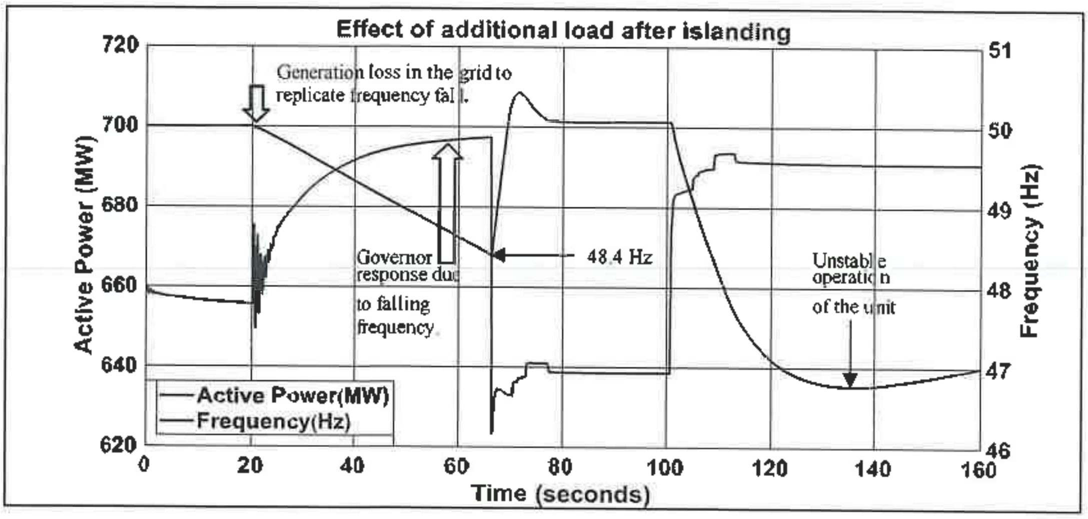

Figure 37: Variation in active power and frequency vs time due to load increment of 52.25 MW after islanding.

In reference to Case:1 (Generation=660MW and Load=640MW) an additional load of 52.25MW has been integrated into the network post island formation.

Simulation results for this case reveal that with the subsequent inclusion of 52.25MW load in the network post-island formation a continuous decline in frequency resulting in tripping of the unit was observed, suggesting that unit couldn't increase the active power for the corresponding increase in load.

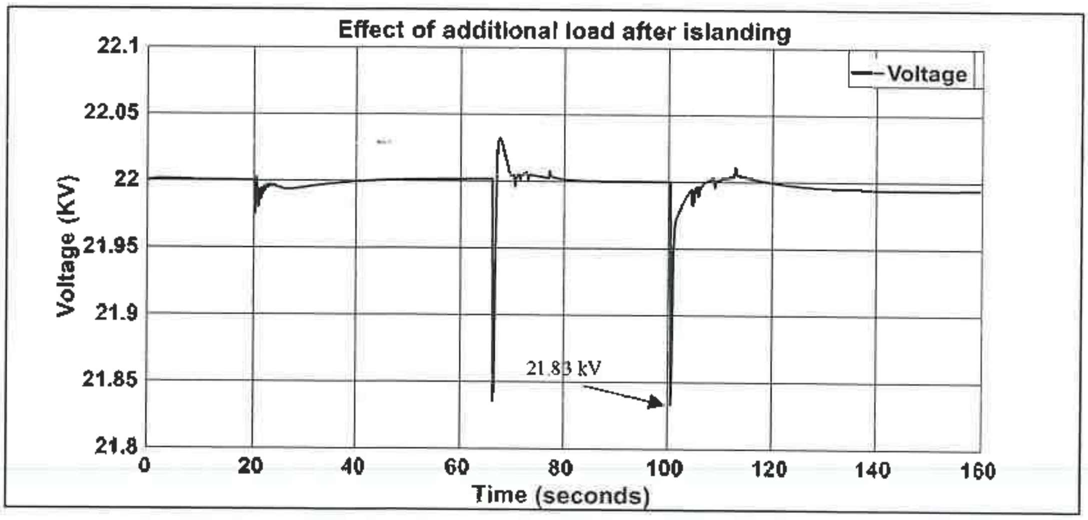

Figure 38: Variation in voltage vs time due to load increment of 52.25 MW after islanding.

Figure 38 shows voltage change due to the addition of 10% of total load. The voltage initially experienced a sudden dip from 22kV to 21.83 (0.77%) which further stabilizes to 22kV.

3.1.9. Case 9: Island formation at 49Hz with f_{rate} = 0.5Hz/s

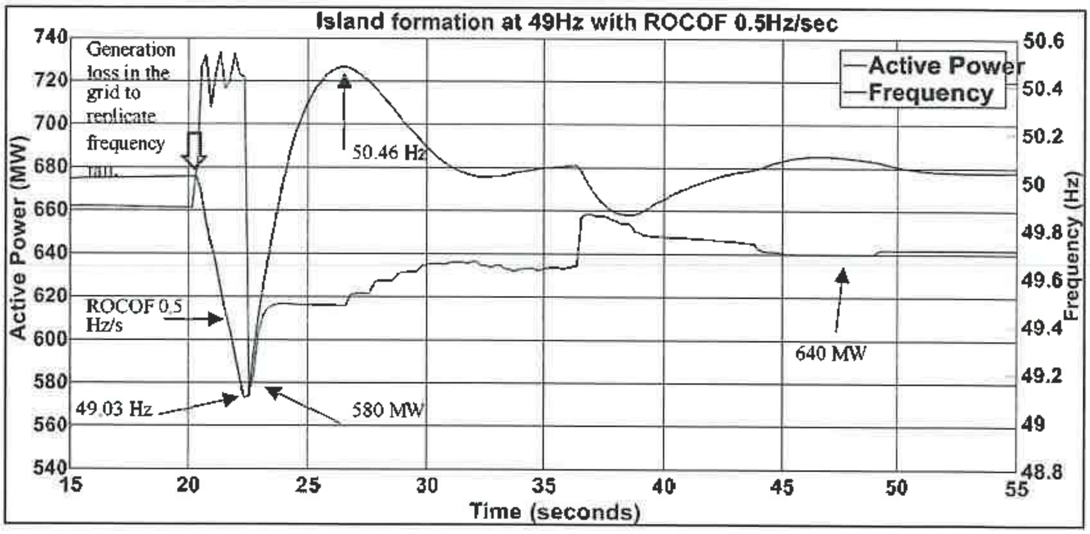

Figure 39: Variation in active power and frequency vs time during island formation at 49 Hz with ROCOF 0.5 Hz/s.

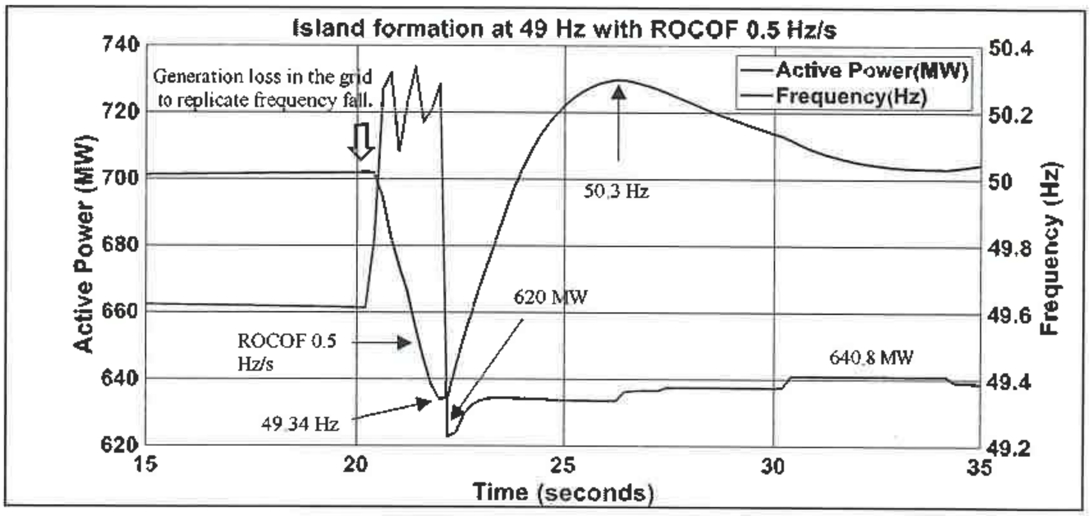

Figure 40: Variation in active power and frequency vs time during island formation at 49.34 Hz with ROCOF 0.5 Hz/s.

In reference to Case:1 (Generation=660MW and Load= 640MW) island was formed at 49Hz frequency with rate of change of frequency is 0.5Hz per seconds.

During an event of grid disturbance, rate of change of frequency (ROCOF) of 0.5Hz /sec was simulated, and the unit was islanded at 49Hz (Figure 39) and 49.34 Hz (Figure 40).

The simulations revealed that when the unit was islanded at 49 Hz a dip of 80 MW was observed and when it was islanded at 49.34 Hz the dip was 40 MW.

Continuous fluctuation in active power from the moment the frequency began to fall was observed. This indicates that the unit would have difficulty sustaining such continuous oscillations till the frequency restores near to 50Hz.

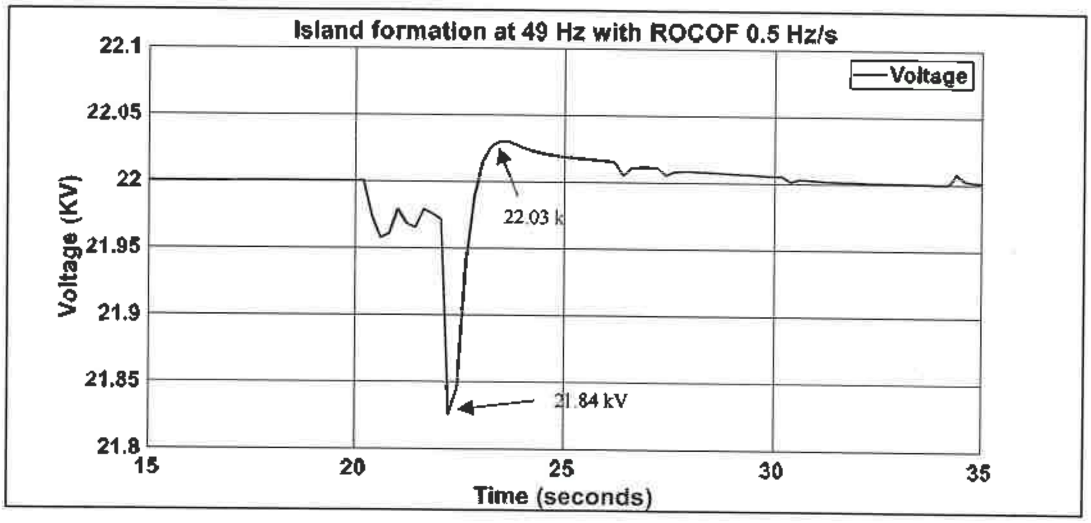

Figure 41: Variation in voltage vs time during island formation at 49 Hz with ROCOF 0.5 Hz/s.

For a ROCOF of 0.5Hz/sec, the decrease in voltage at the instant of islanding (49Hz) was 21.84kV from 22kV. A voltage variation of 0.77% was observed when the unit undergoes islanding.

3.1.10. Case 10: Island formation at 48.4Hz with ROCOF (f_{rate}) = 0.5Hz/s

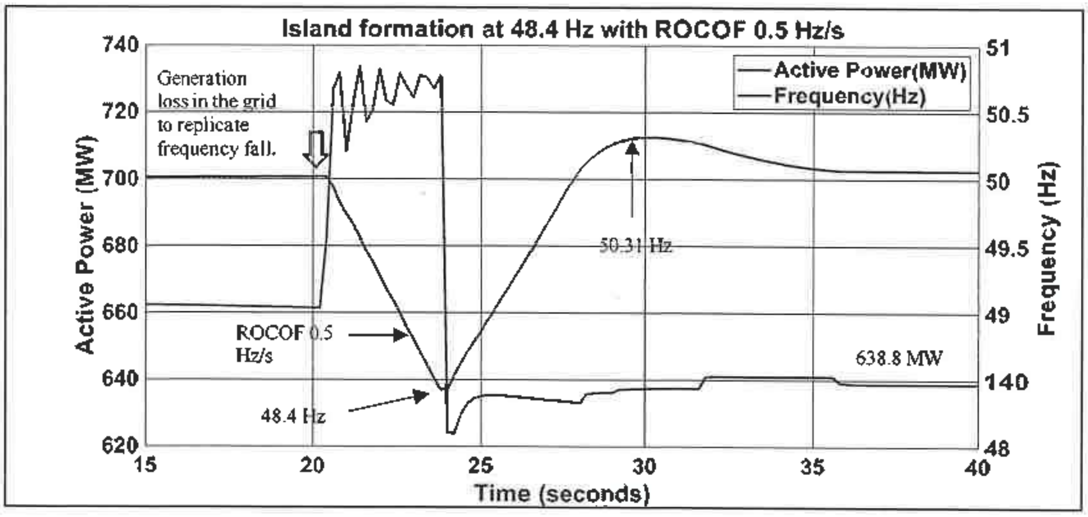

Figure 42: Variation in active power and frequency vs time during island formation at 48.4 Hz with ROCOF 0.5 Hz/s.

In reference to Case:1 (Generation=660MW and Load=640MW) island is formed at 48.4Hz frequency with rate of change of frequency is 0.5Hz per seconds.

During an event of grid disturbance, rate of change of frequency (ROCOF) of 0.5Hz /sec is simulated, and the unit islanded at 48.4Hz. The simulations revealed a continuous fluctuation in active power from the moment the frequency began to fall. This indicates that the unit would have difficulty sustaining such continuous oscillations till the frequency restores near to 50Hz.

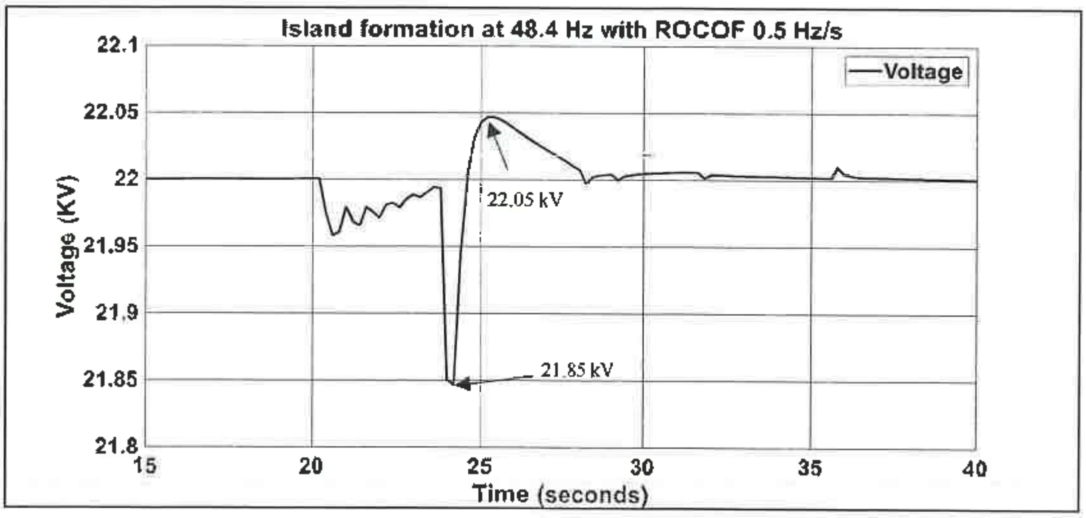

Figure 43: Variation in voltage vs time during island formation at 49 Hz with ROCOF 0.5 Hz/s.

For a ROCOF of 0.5Hz/sec, the decrease in voltage at the instant of islanding (48.4Hz) was 21.85kV from 22kV. A voltage variation of 0.78% was observed when the unit undergoes islanding.

3.1.11. Case 11: Island formation at 48.4Hz with f_{rate} = 0.25Hz/s

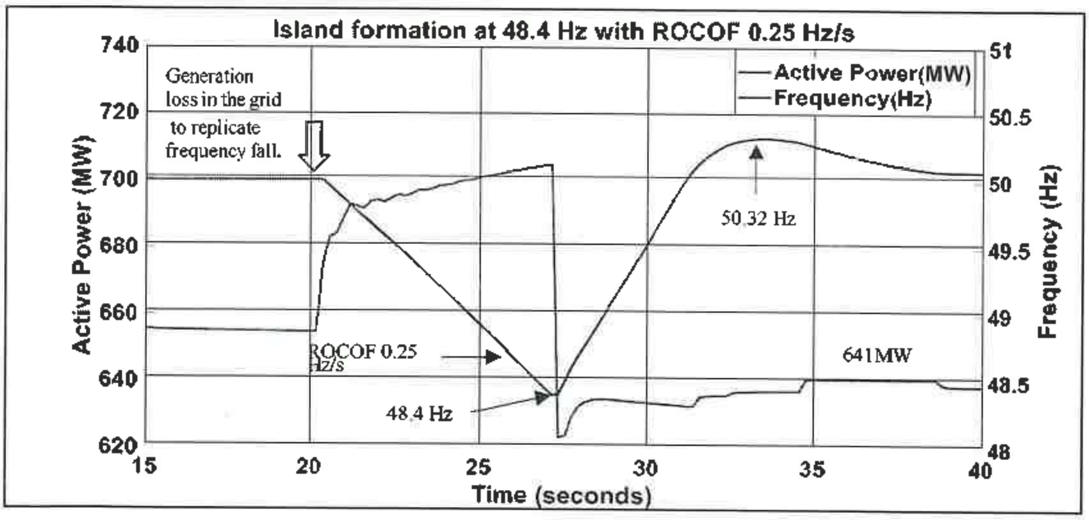

Figure 44: Variation in active power and frequency vs time during island formation at 48.4 Hz with ROCOF 0.25 Hz/s.

In reference to Case:1 (Generation=660 MW and Load=640 MW) island is formed at 48.4Hz frequency with rate of change of frequency is 0.25Hz per seconds.

During an event of grid disturbance, rate of change of frequency (ROCOF) of 0.25Hz /sec is simulated, and the unit islanded at 48.4Hz. The simulations revealed a negligible fluctuation in active power from the moment the frequency began to fall. This indicates that the unit can sustain in island when the rate of change of frequency is 0.25Hz per second.

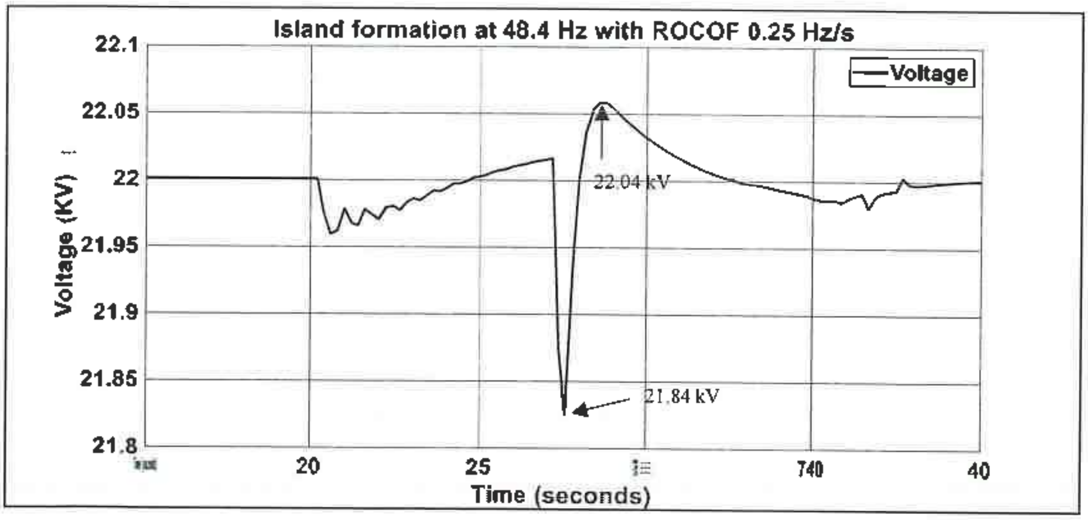

Figure 45: Variation in voltage vs time during island formation at 48.4 Hz with ROCOF 0.25 Hz/s.

For a ROCOF of 0.25Hz/sec, the decrease in voltage at the instant of islanding (48.4Hz) was 21.84kV from 22kV. A voltage variation of 0.77% was observed when the unit undergoes islanding.

3.1.12. Case 12: Optimal load reduction during island formation

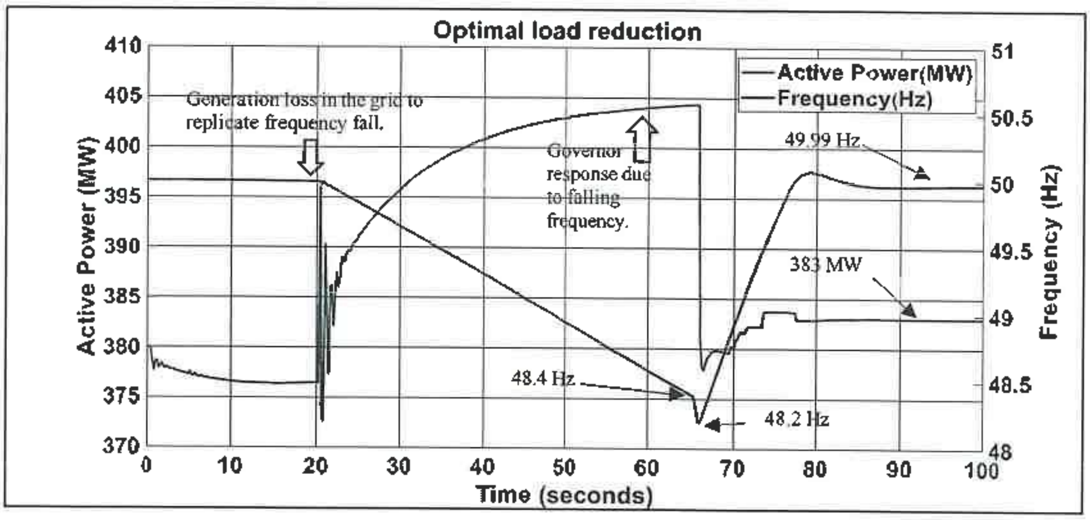

Figure 46: Variation in active power and frequency vs time due to optimal load reduction of 68 MW after islanding.

In reference to Case:3 (Generation=380 MW and Load = 500 MW), a reduction of load shed of 68MW instead of 74MW has been introduced into the network at the instant of 48.2 Hz.

Simulation outcomes for this case reveal that subsequent decrement of 68 MW at 48.2Hz in the network. Frequency stabilizes to its final value of 49.99 Hz corresponding to generation of 383 MW within 9.5 seconds.

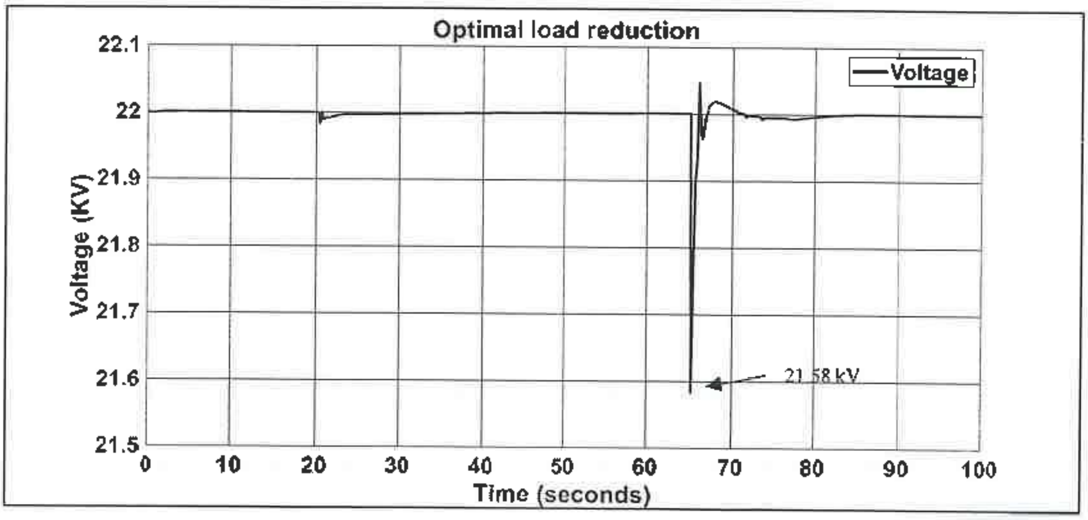

Figure 47: Variation in voltage vs time due to optimal load reduction of 68 MW after islanding.

Generation is at 22kV, when the island formed, the voltage initially experienced a sudden dip from 22kV to 21.58kV (i.e., 1.9%) which further stabilized around 22kV.

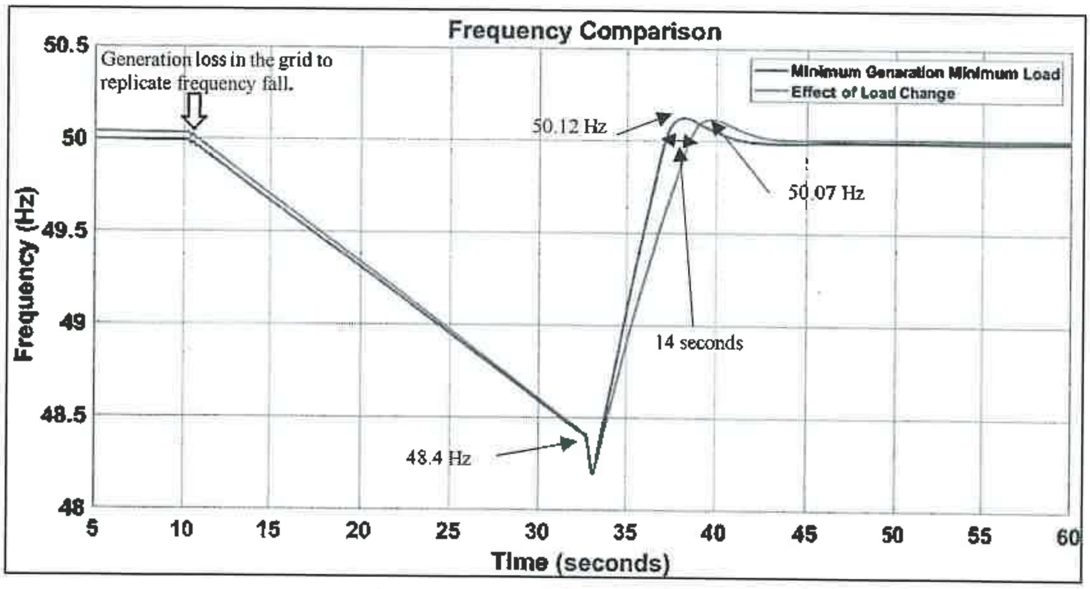

Figure 48: Frequency comparison between Case 3 and Case 13

As seen from the above Figure 48, 14 seconds of time difference is observed while the frequency was stabilizing to its final value. This is observed when simulating a load shed of 68MW compared to 74 MW at the moment of island formation.

3.1.13. Case 13: Load increment of 12.5MW after island formation

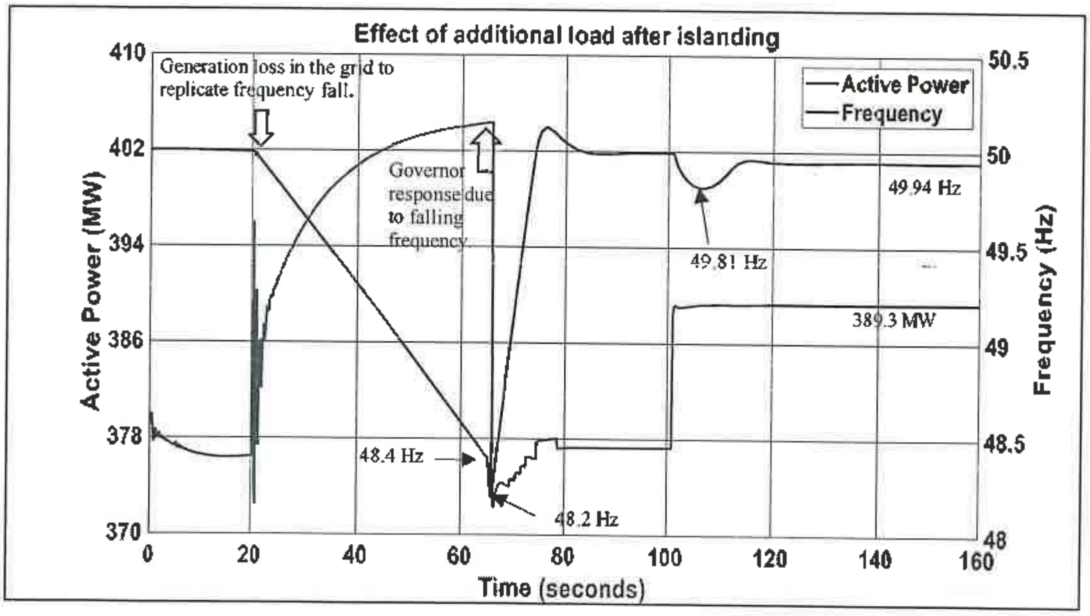

Figure 49: Variation in active power and frequency vs time due to load increment of 12.5 MW after islanding.

In reference to Case:3 (Generation=380 MW and Load = 500 MW), an increment of load of 12.5 MW i.e., 2.5% of the initial load has been added into the network post island formation.

Simulation outcomes for this case reveal that subsequent inclusion of 12.5 MW in the network post-islanding formation a decrement in frequency 49.81 Hz has been observed over a duration of 20.8 seconds. Frequency stabilizes to its final value of 49.94 Hz corresponding to generation of 388 MW.

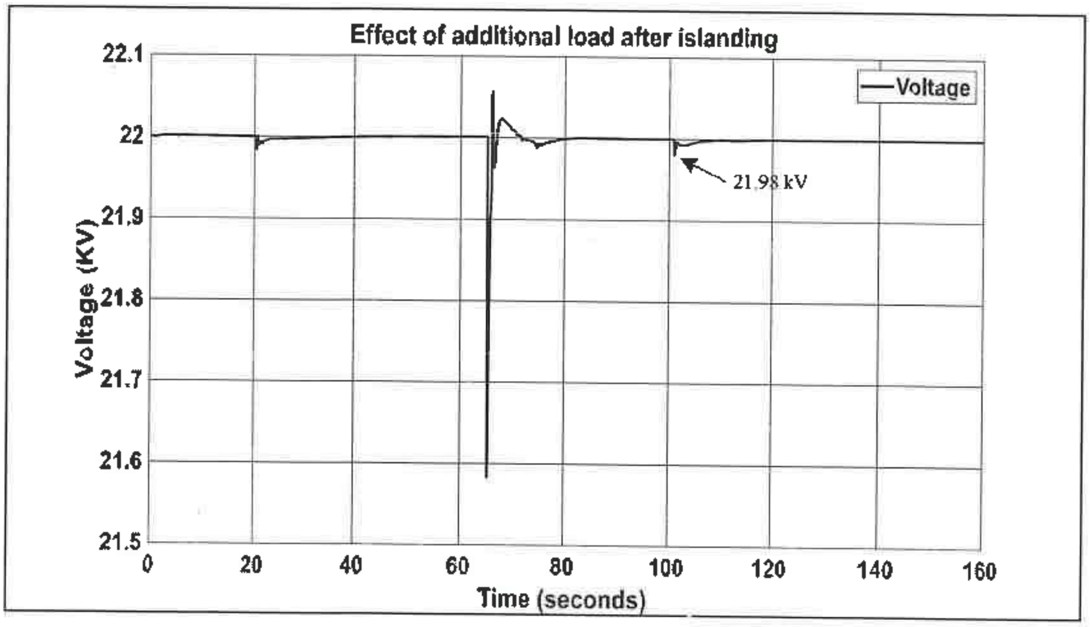

Figure 50: Variation in voltage vs time due to load increment of 12.5 MW after islanding.

Generation is at 22kV, when load added after the island was formed, the voltage experienced a sudden dip from 22kV to 21.98kV (i.e., 0.09%) which further stabilized around 22kV.

3.1.14. Case 14: Load increment of 20 MW after island formation

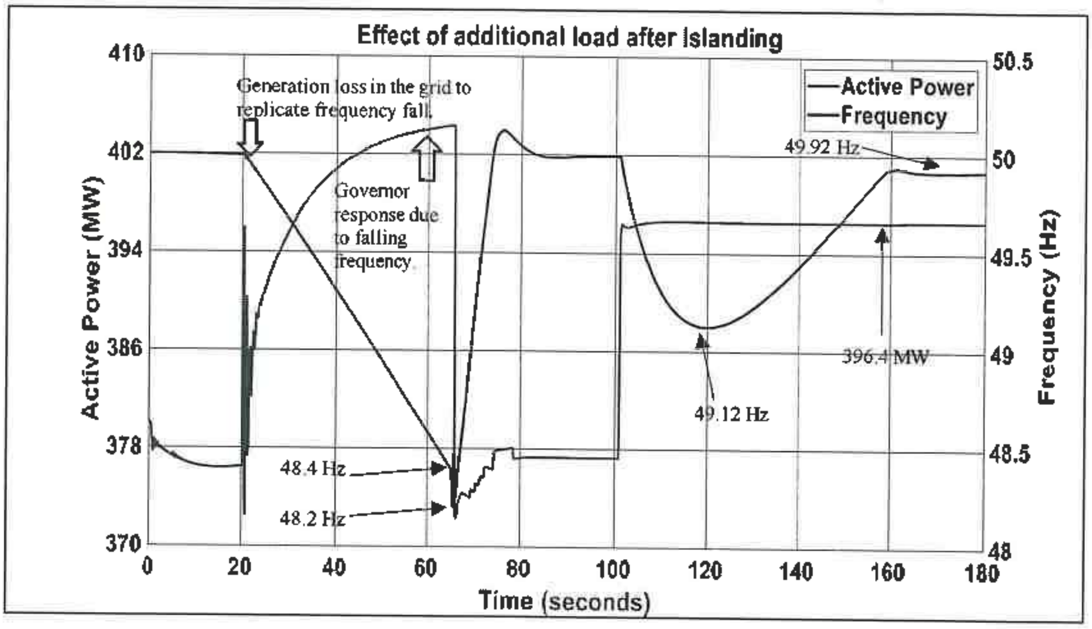

Figure 51: Variation in active power and frequency vs time due to load increment of 20 MW after islanding.

In reference to Case:3 (Generation=380 MW and Load = 500 MW), an increment of load of 20 MW i.e., 4% of the initial load has been integrated into the network post island formation.

Simulation outcomes for this case reveal that subsequent inclusion of 20 MW in the network post-islanding formation a decrement in frequency 49.12 Hz has been observed over a duration of 34.1 seconds. Frequency stabilizes to its final value of 49.92 Hz corresponding to the generation of 396.4 MW.

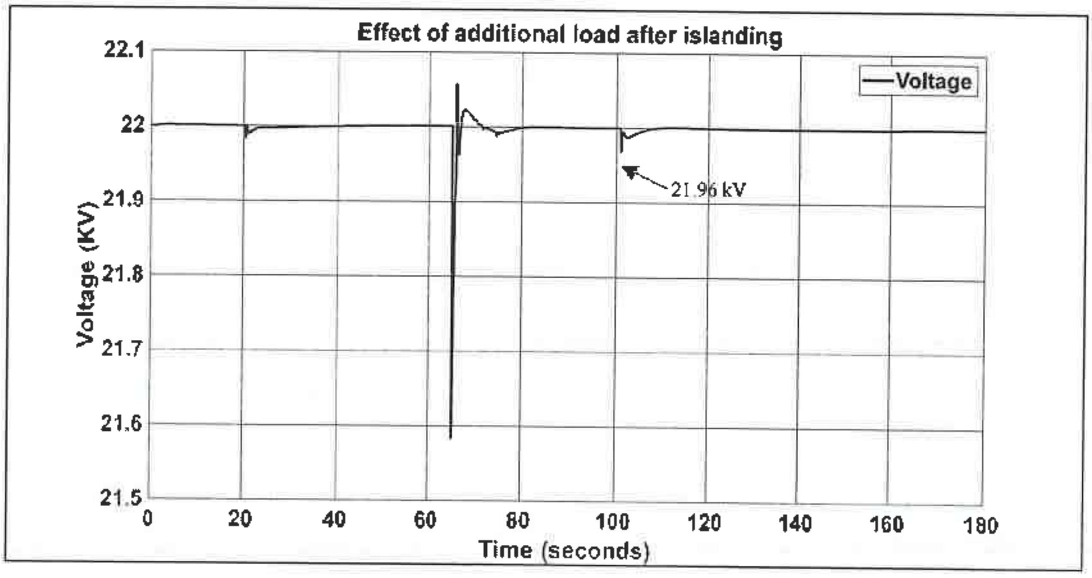

Figure 52: Variation in voltage vs time due to load increment of 20 MW after islanding.

Generation is at 22kV, when load added after the island was formed, the voltage initially experienced a sudden dip from 22kV to 21.96kV (i.e., 0.18%) which further stabilized around 22kV.

3.1.15. Case 15: Load increment of 22 MW after island formation

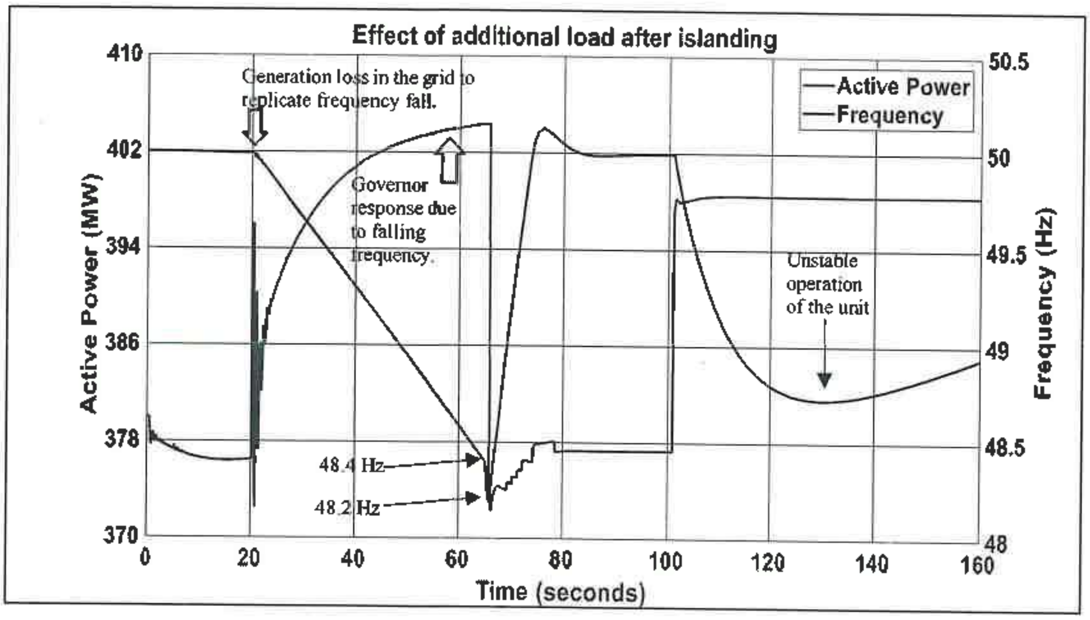

Figure 53: Variation in active power and frequency vs time due to load increment of 22 MW after islanding.

In reference to Case:3 (Generation=380 MW and Load = 500 MW), an increment of load of 22 MW i.e., 4.4% of the initial load has been integrated into the network post island formation.

Simulation outcomes for this case reveal that subsequent inclusion of 22 MW in the network post-islanding formation a decrement in frequency has been observed. With generation increasing to 396.4 MW and final frequency could not get stabilized since the unit was not able to hold the additional load of 22 MW, resulting in in the unstable operation of the unit.

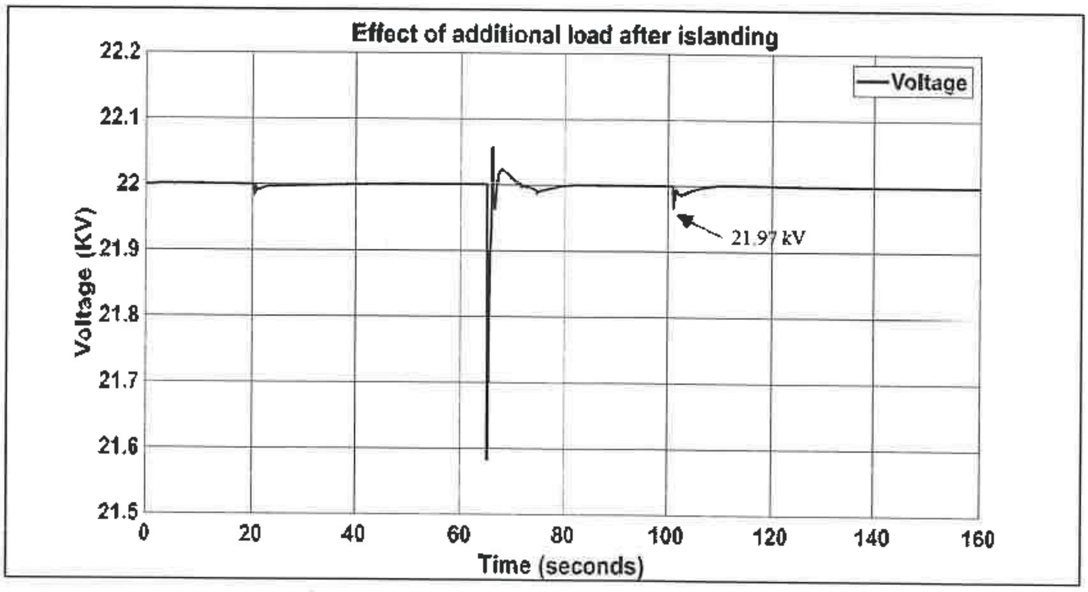

Figure 54: Variation in voltage vs time due to load increment of 22 MW after islanding.

Generation is at 22kV, when load added after the island was formed, the voltage initially experienced a sudden dip from 22kV to 21.97kV (i.e., 0.14%) which further stabilized around 22kV.

3.1.16. Case 16: Load shed time delay.

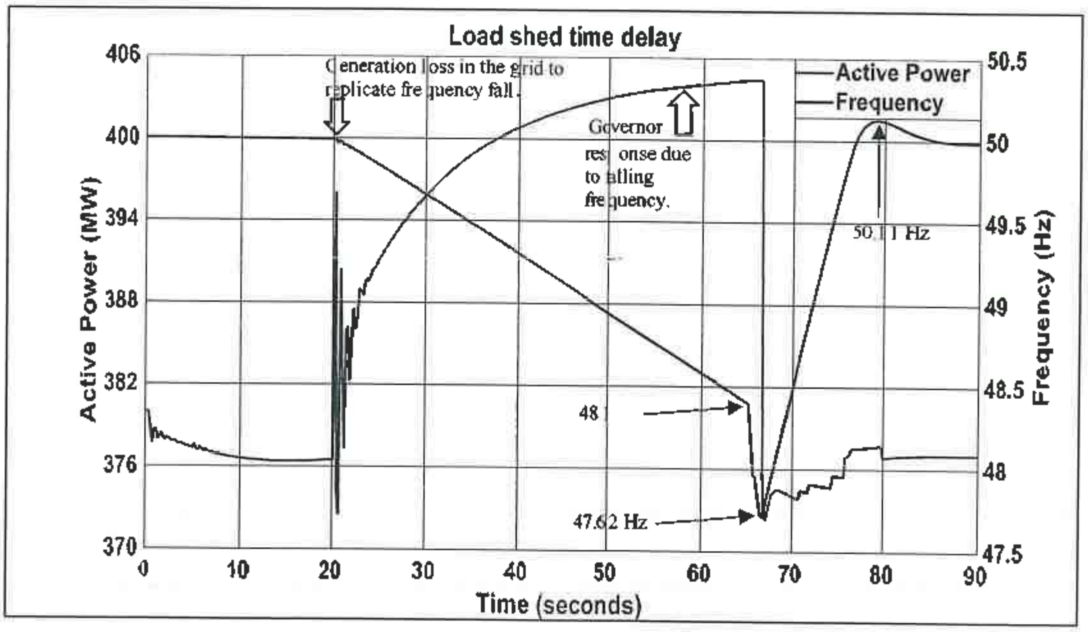

Figure 55: Variation in active power and frequency vs time due to effect of load shed time delay in reference to Case 3.

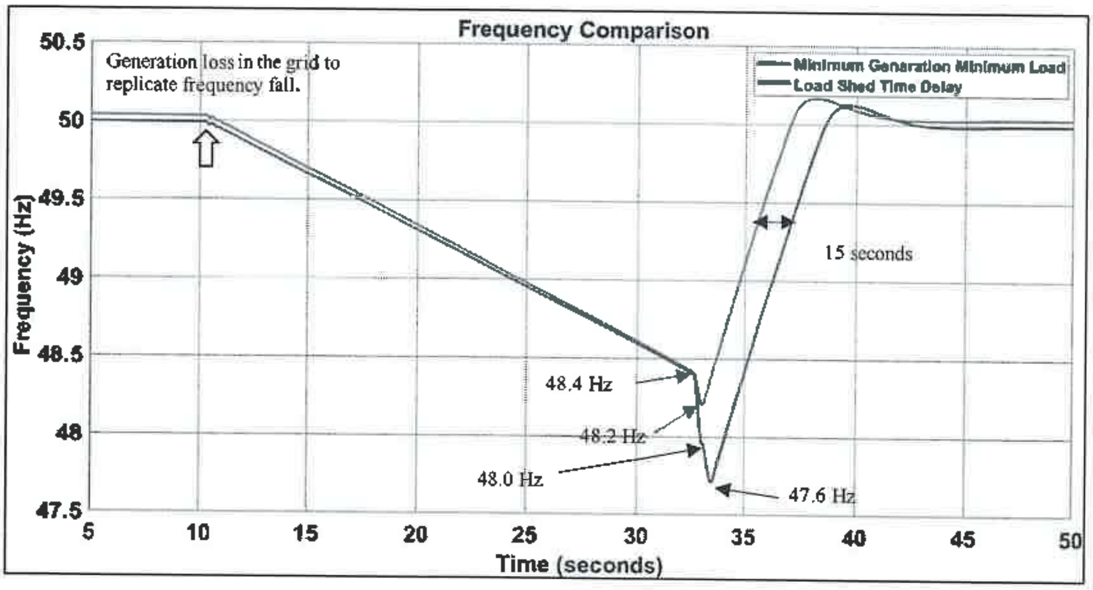

Figure 56 : Frequency comparison between Case 3 and Case 17

In reference to case 3, a delay of 600 milliseconds was introduced in load shedding at the moment of island formation. As compared to case 3, 50 MW load is tripped at 48 Hz. Furthermore, additional load of 74 MW is tripped at 47.62 Hz as shown in Figure 55 and finally the frequency stabilizes to 50 Hz.

The time taken by the frequency to stabilize from the moment of island formation of the unit is 9.8 seconds in case 3 whereas 11.1 seconds is observed for this case.

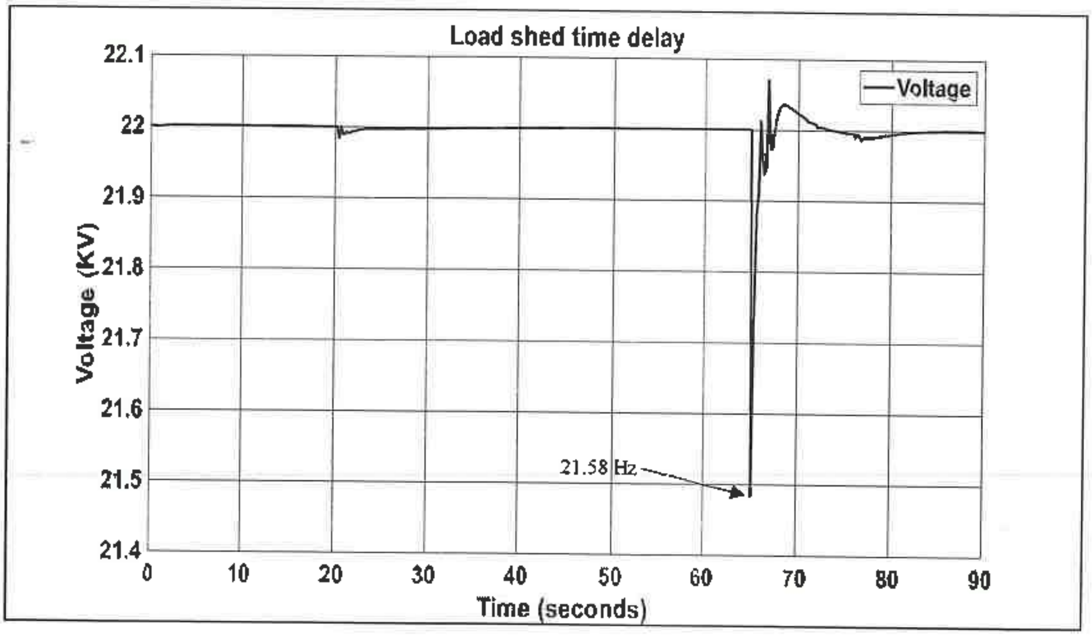

Figure 57: Variation in voltage vs time due to effect of load shed time delay in reference to case 3.

Generation is at 22kV, when the island formed, the voltage initially experienced a sudden dip from 22kV to 21.58kV (i.e., 1.9%) which further stabilized around 22kV.

3.1.17. Case 17: Island Formation (49Hz) with Rate of Change 0.5Hz/s

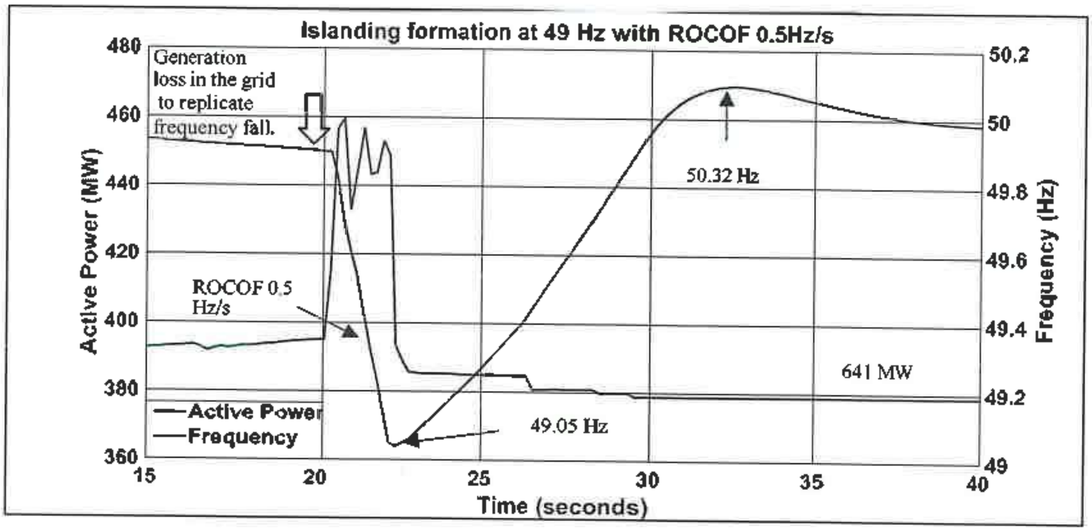

Figure 58: Variation in active power and frequency vs time during island formation at 49 Hz with ROCOF 0.5 Hz/s.

In reference to Case:3 (Generation=380MW and Load=500MW) island is formed at 49.05 Hz frequency with rate of change of frequency is 0.5Hz per seconds.

During an event of grid disturbance, rate of change of frequency (ROCOF) of 0.5Hz /sec is simulated, and the unit islanded at 49.05 Hz. The simulations revealed a continuous fluctuation for 1.8 seconds in active power from the moment the frequency began to fall, to balance the mismatch between the generation and island network load demand, a load shed of 124MW was performed at 49.05 Hz.

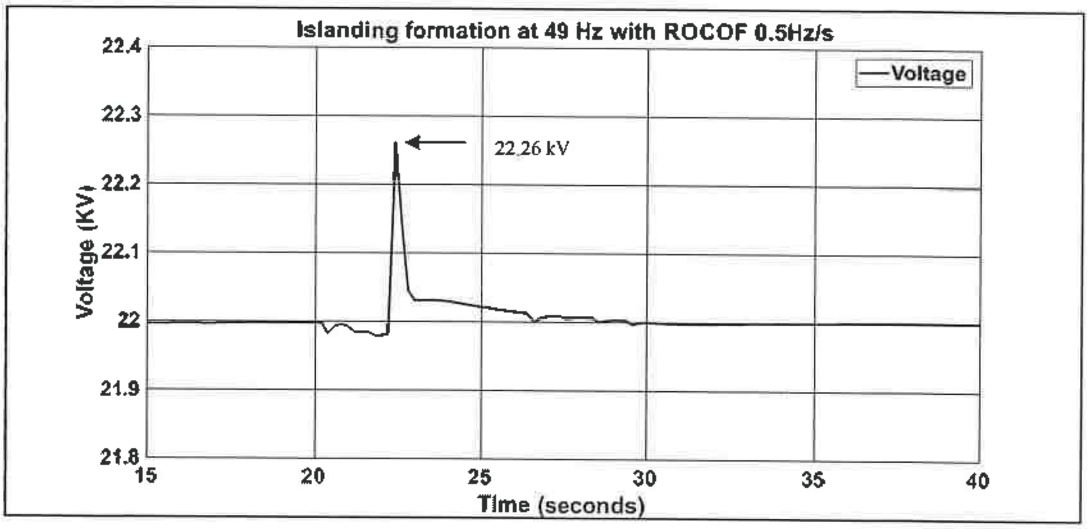

Figure 59 :Variation in voltage vs time during island formation at 49 Hz with ROCOF 0.5 Hz/s.

For a ROCOF of 0.5Hz/sec, a voltage variation of 1.18% was observed when the unit undergoes islanding.

3.1.18. Case 18: Island Formation (48.4Hz) with Rate of Change of frequency 0.5Hz/s

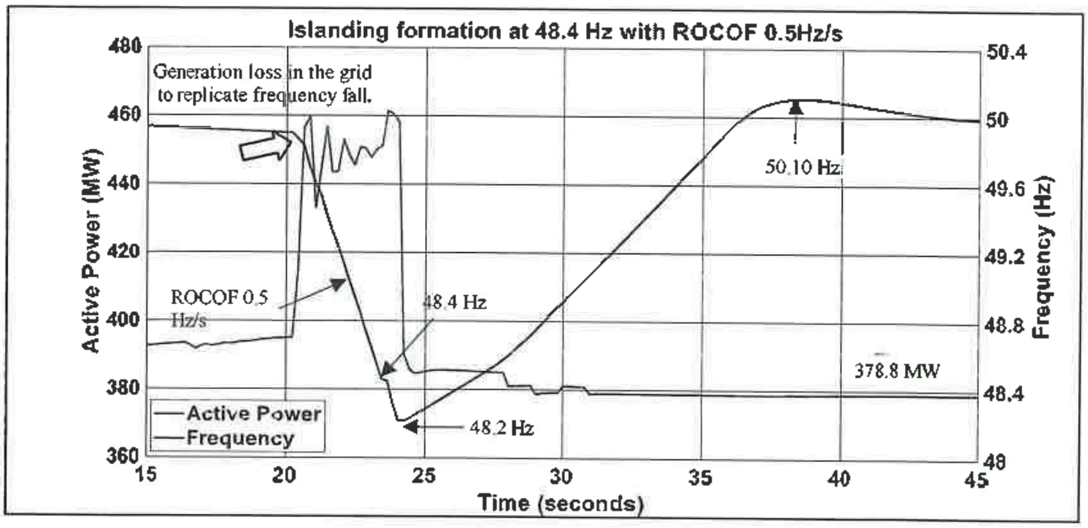

Figure 60 : Variation in active power and frequency vs time during island formation at 48.4 Hz with ROCOF 0.5 Hz/s.

In reference to Case:3 (Generation=380MW and Load=500MW) island is formed at 49.05 Hz frequency with rate of change of frequency is 0.5Hz per seconds.

During an event of grid disturbance, rate of change of frequency (ROCOF) of 0.5Hz /sec is simulated, and the unit islanded at 48.4 Hz, along with the load shed of 50MW at 48.4Hz, further a load shed of 74MW was simulated at 48.2Hz. The simulations revealed a continuous fluctuation in active power for 4.2 seconds from the moment the frequency began to fall to balance the mismatch between the generation and island network load demand. This indicates that the unit would have difficulty sustaining such continuous oscillations till the frequency restores finally to 50Hz.

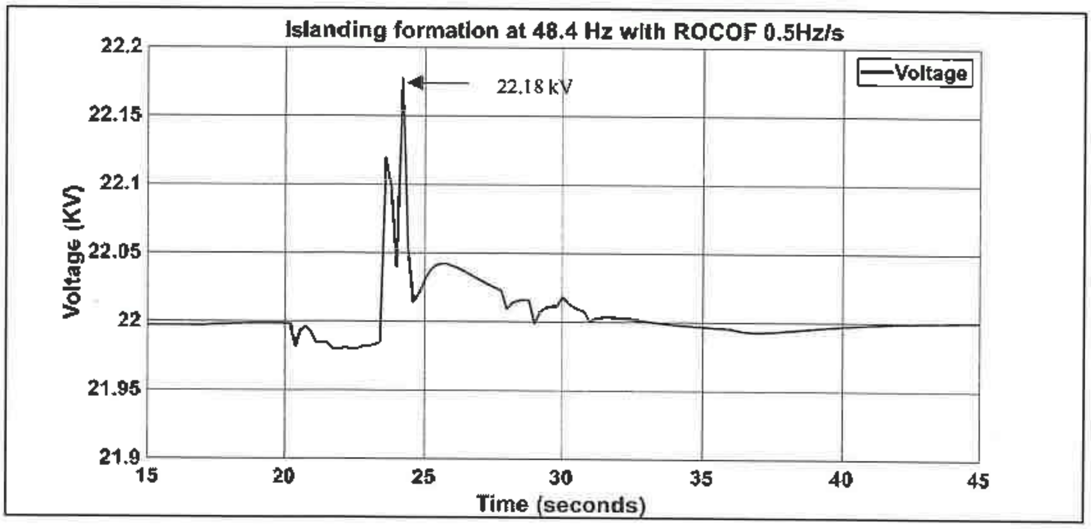

Figure 61 :Variation in active power and frequency vs time during island formation at 48.4 Hz with ROCOF 0.25 Hz/s.

For a ROCOF of 0.5Hz/sec, an increase in voltage at the instant of islanding (49Hz) was 22.26 kV from 22kV. A voltage variation of 1.18% was observed when the unit undergoes islanding.

3.1.19. Case 19: Effect of Linear and Non-Linear Valve behavior on Active Power

In all the above simulation cases performed, a linear relation between the governor output and active power was assumed as shown in Figure 62.

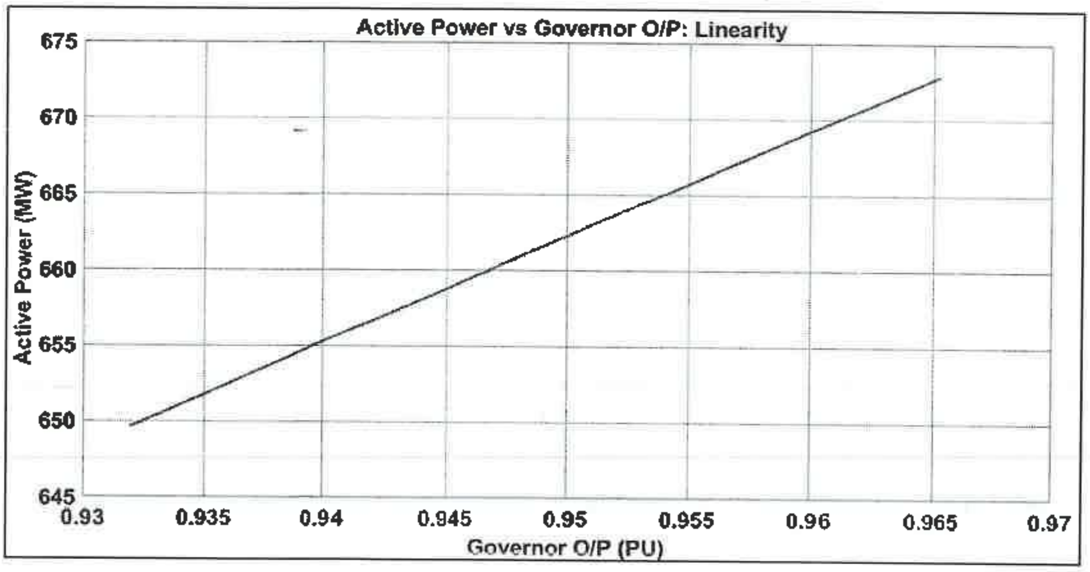

Figure 62:Linear behavior in governor output and Active Power.