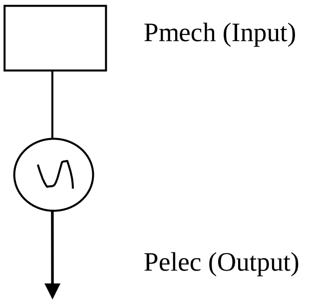
Generator Transients

Theoretical concepts

Single Generator Transients



P_{mech}: (Mechanical Power Input) Represents fuel input which either increases or decreases through governor valves according to the changes in electrical load.

P_{elect}: (Electrical Power Output) Represents electrical load.

Steady State Condition (Pre-Transient Condition)

$P_{mech} = P_{elect}$ + losses

If P_{elect} is 0% then P_{mech} is also 0% and if P_{elect} is 100% of rating then P_{mech} is also 100%.

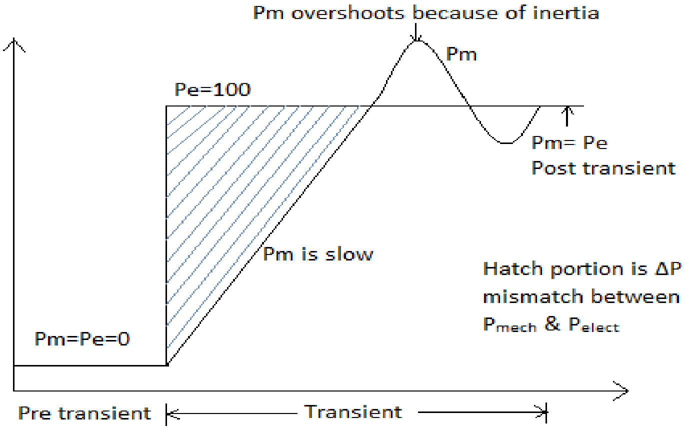
Here, P_{elect} & P_{mech} refers to active power referred in per unit (p.u) based on generator rating.

Transient Condition

Initially $P_{mech} = P_{elect}$ = 0% and then P_{elect} increases from 0% to 100%.

Now suddenly as transient P_{elect} rises to 100%. P_{mech} will increase due to governor action by opening fuel valve from 0% to 100%. But usually P_{mech} response is slow.

Based on governor parameters, P_{mech} & P_{elect} responses would be as shown below.



Generator Transients

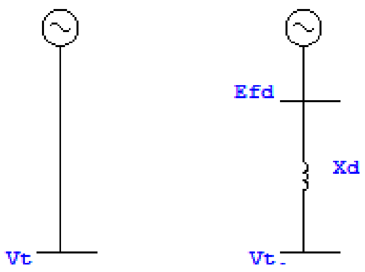
During transient, since P_{mech} responds slowly & P_{elect} increases fast $P_{elect} > P_{mech}$.
So there is a mismatch ΔP between P_{mech} & P_{elect}. ΔP is decelerating during this transient $P_{output} > P_{input}$.
So speed of generator falls & results in system frequency fall.
$f = \frac{NP}{120}$ or $N = \frac{120f}{P}$
Time required for frequency fall event is directly proportional to Inertia and inversely proportion to ΔP.

- Time for frequency fall α Inertia
- Time for frequency fall α $\frac{1}{\Delta P}$

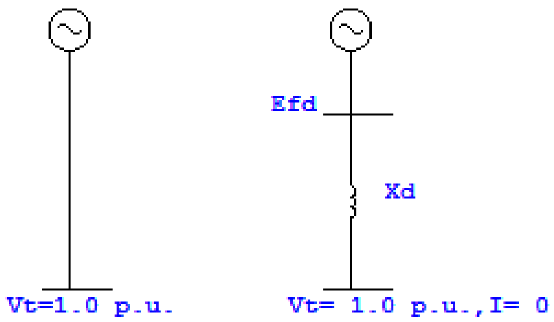
Thus, inertia & ΔP (mismatch of P_{mech} & P_{elect}) plays an important role in rate of frequency change during a transient load change. ΔP magnitude will depend on how fast governor responds to change P_{mech} as P_{elect} changes. Worst case of P_{elect} change in addition to load switch is 3- phase fault at generator terminal. During 3-phase fault, terminal voltage stays zero & active power becomes zero from its pre-fault value. So fault causes ΔP mismatch.
During fault Pe = 0, Pmech = Pinitial.
Hence, ΔP is Accelerating and speed will rise.
Following three cases are considered to study generator transients. These cases will indirectly test the generator response for load changes with governor & exciter/ AVR modelled.

1. 100% load application: For this $P_{mech} = P_{elect} = 0\%$ (initially) and
   Load of $P_{elect} = 100\%$ is switched ON.
2. 100% load rejection: For this $P_{mech} = P_{elect} = 100\%$ (initially) and
   Load of $P_{elect} = 100\%$ is switched OFF.

Generator model for calculation at the end of transient



Efd = voltage behind Xd



Generator Transients

Efd = Vt + jXd*I
   = Vt (If I= 0)
Efd > Vt by jXd*I if I > 0 at the end of transient.

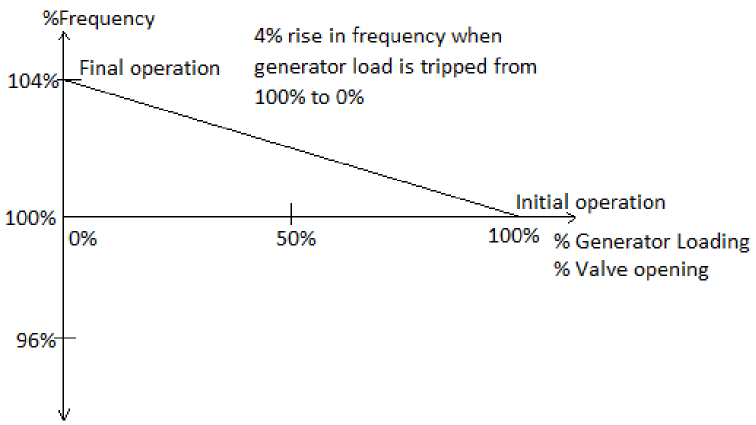
Droop mode of generator

Meaning of Droop: Frequency will continue to stay at higher value at No Load as compared to Full Load unless power reference setting is changed. Usual droop setting is 4%.

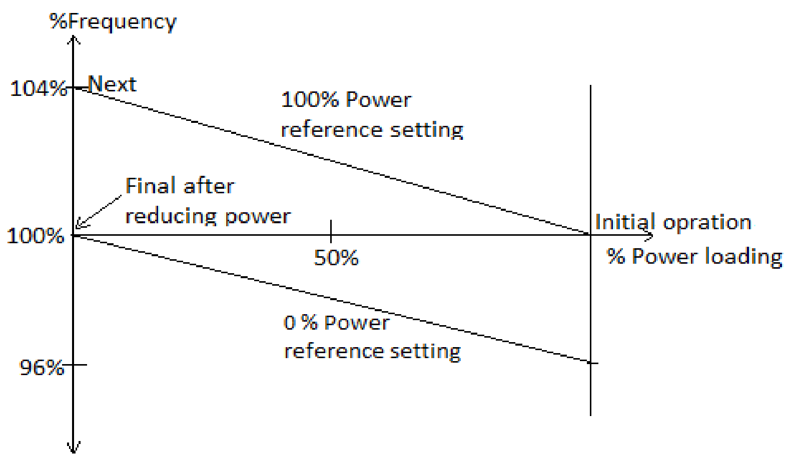
100% Load Throw off Case

When power reference setting is adjusted to 100% and full generator load is tripped then generator frequency rises to 104% as shown.

Droop for generator



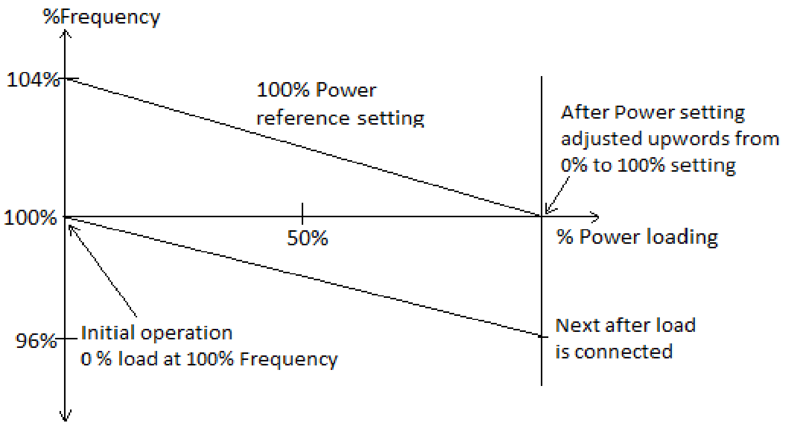
To bring frequency to 100% after full load throw off, power reference setting has to be adjusted downwards from 100% to 0% as shown in the figure.



Generator Transients

100% Load Application Case

If power reference setting is 0% and generator is fully loaded, generator will operate at second step continuously with -4% frequencies below 100%. To bring frequency to 100% after full load Application, power reference setting has to be adjusted upwards from 0% to 100%.

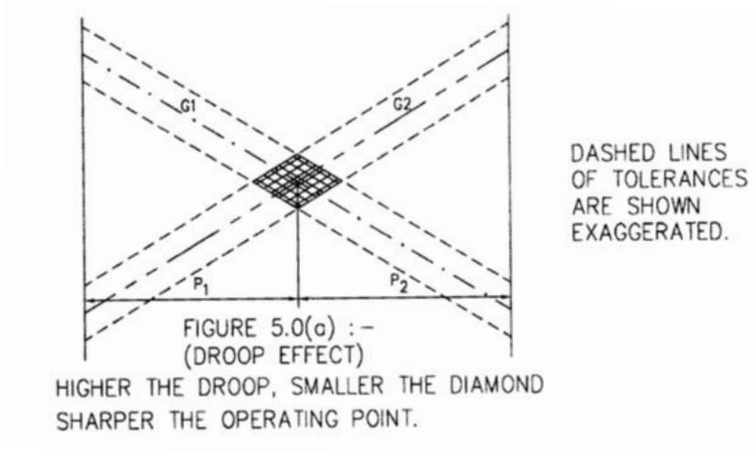


Droop mode is more stable when generators are operated in parallel as generators with equal droop will not only find a common operating point in the power speed droop diagram but will share the load equally.

Droop lines have tolerance and the common operating point. Depending on the upper or lower tolerance of governor droops can result in possible common operating point that lies in a diamond band. More the % droop, sharper the droop lines and smaller the band.

For lower droops, the band increases and equal sharing of load between generators becomes difficult. In the extreme conditions when droop becomes 0% i.e. if machines in parallel are set in isochronous mode, then the operating band increases resulting in load sharing problems and hunting or swing of load between machines leads to instability.

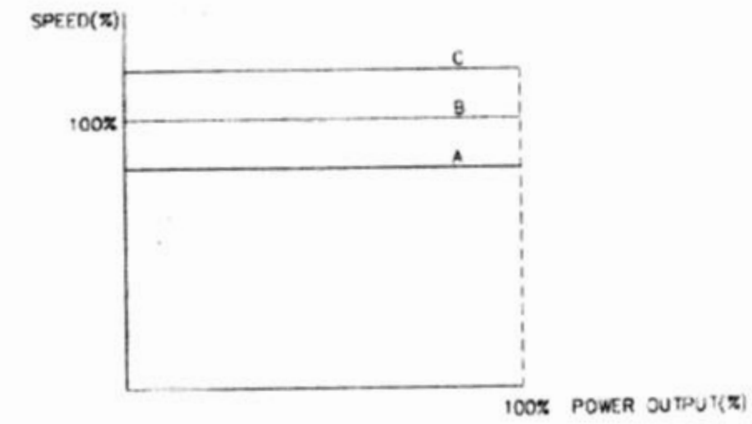
Refer to droop comparison shown below



Generator Transients

Isochronous mode of generator

The isochronous governor characteristics as shown, with a series of speed settings represented by horizontal lines and each line representing a particular speed setting.



(b) ISOCHRONOUS GOVERNOR

In an isolated system if a machine is operated with isochronous governor speed setting set at governor speed characteristics ‘A’, the speed will remain constant as the load is increased from zero to full load, beyond which the speed will drop.

Paralleling of a generator, in isochronous governor setting mode, with the infinite grid is not practical since any slight deviation from synchronous speed setting, under such parallel configuration, would result in generator loading at either full fuel or at minimum fuel position, depending on whether the setting is low or high.

A more usual arrangement is to have one isochronous unit operating in parallel with one or more units in speed droop mode. Such an arrangement has the advantages of maintaining constant system frequency.

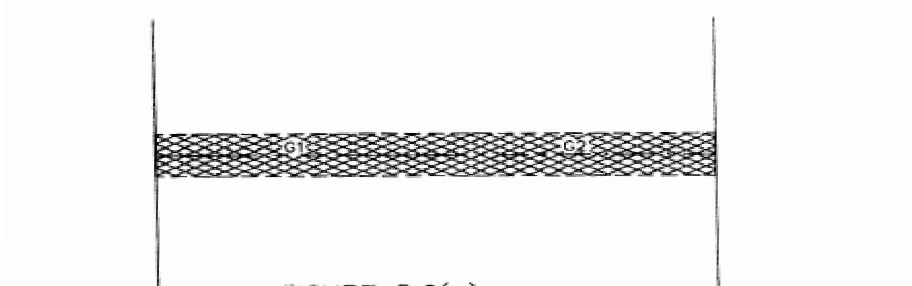
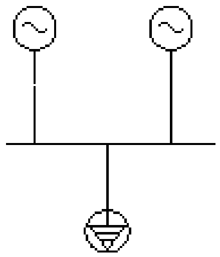


FIGURE 5.0(c) :–
(NO DROOP EFFECT. NOTE THE WIDE RANGE OF MESHED OPERATING REGIME POSING DIFFICULTY IN ARRIVING AT A SENSIBLE OPERATING POINT.)

Generator Transients

Per unit load sharing with 2 machines set in equal % or p.u droop.



Say for machine1, $R_1 = \frac{\Delta f1}{\Delta P1}$

Where, R_1 is droop,

Δf_1- pu frequency &

ΔP_1 - active power changes in pu

Similarly, for machine2, $R_2 = \frac{\Delta f2}{\Delta P2}$

Case 1- Machines with equal droop

$R_1 = R_2$ (same droop)

If load increases, then frequency falls and both machines will see same drop in frequency

$R_1 = \frac{\Delta f}{\Delta P1}$ & $R_2 = \frac{\Delta f}{\Delta P2}$

$\Delta P_1 = \frac{\Delta f}{R1}$ & $\Delta P_2 = \frac{\Delta f}{R2}$

If R_1 & R_2 are equal then $\Delta P_1 = \Delta P_{2,}$

Both machines with equal droop will share load in equal proportion of ratings.

Case 2 – Machine 1 - Isochronous and Machine 2 - droop setting = R2

If load increases, then there will be a frequency drop and both machines with see the same Δf

$\Delta P_1 = \frac{\Delta f1}{R1}$ & $\Delta P_2 = \frac{\Delta f2}{R2}$

If $\Delta f_1 = \Delta f_2 = \Delta f$

Then $\Delta P_1 = \frac{\Delta f}{R1}$ & $\Delta P_2 = \frac{\Delta f}{R2}$

If R_1 is as low as 0 (Isochronous mode), ΔP_1 will be high so machine in Isochronous takes all the excess load. So in this case load sharing is not proper and frequency will be controlled.

Load Sharing and frequency control in different modes

	Droop	**Isochronous**
Load sharing	Good	Not good
Frequency control	Not good	Good

Droop mode is required for load sharing but droop mode results in poor frequency control. Both load sharing & frequency control are important in plant operation.

Both modes require operator or automatic control

- To Control frequency with machine in droop during load changes
- Load sharing control for machine in isochronous mode during load changes.

Generator Transients

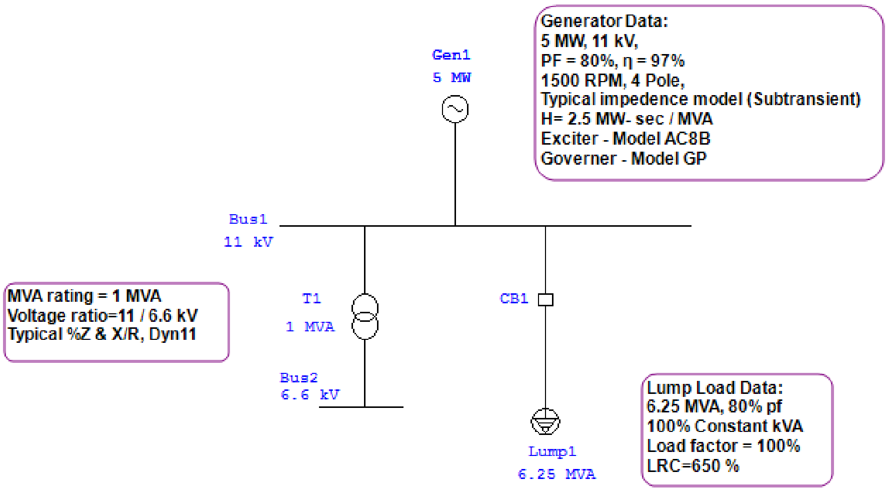
Purpose and Description

The purpose of this exercise is to study the transient behavior of generator during load switching i.e.100% load application & 100% load throw on single generator.

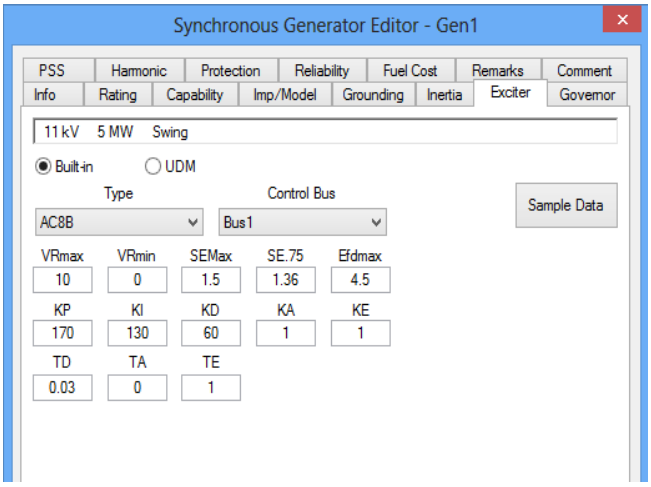
Procedure

Case 1: 100% Load Application Transient study on single generator

1. Create a new project with name ‘Single Generator Transient’.
2. Drag and drop the generator, bus, lump load, circuit breaker, transformer on the OLV. Connect these elements and enter the data as shown below.

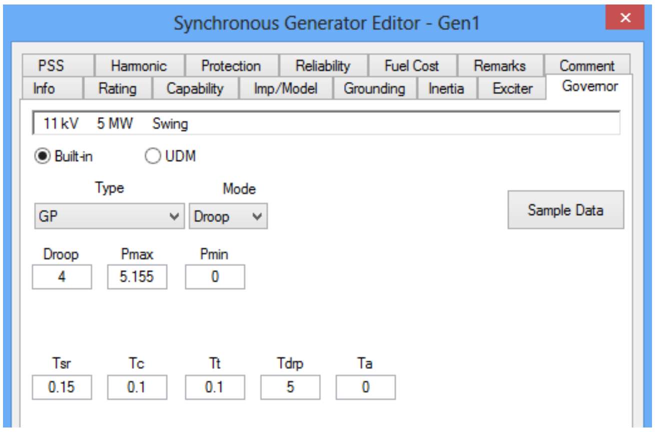


3. Click on synchronous generator, go to Exciter page and select Type as AC8B with sample data & Control Bus as Bus1 from the drop down list as shown.

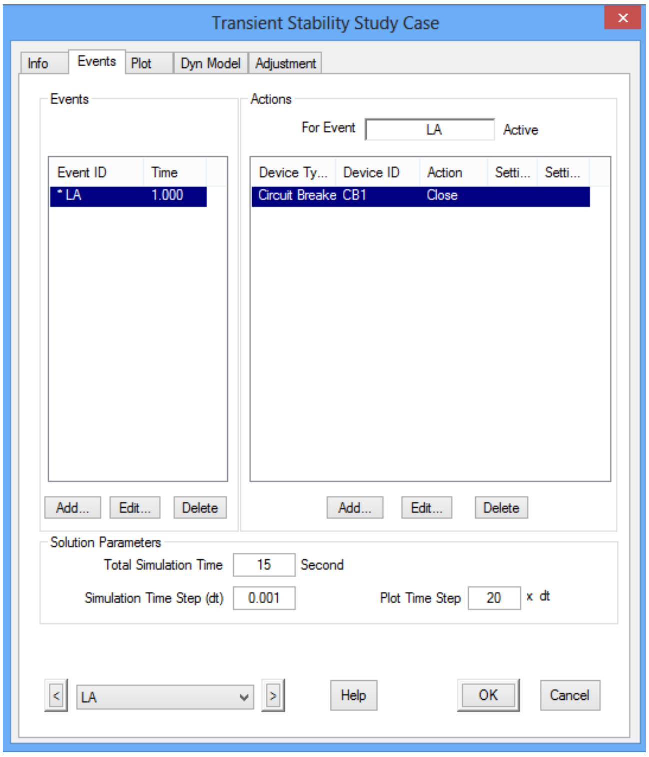


4. Go to governor page and select Type as GP with sample data and change the droop setting to 4% as shown below.

Generator Transients

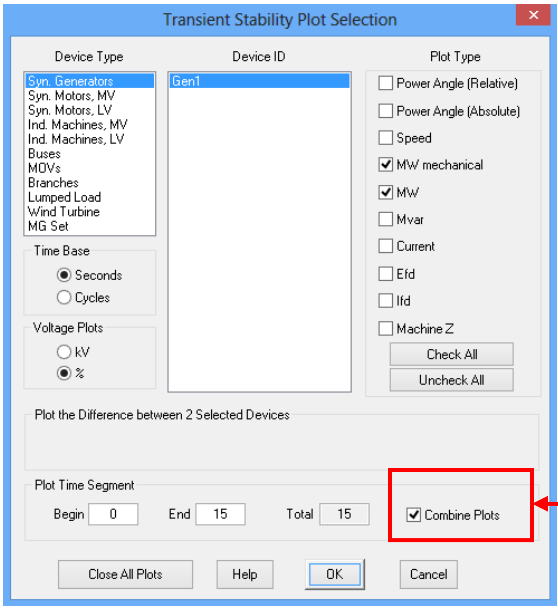


5. To study load application on single generator, Initially Open CB1 connected to load.
6. Create a new study case as 'LA'.
7. Go to Events page and add an event to close CB1 at 1.0 sec as shown below.



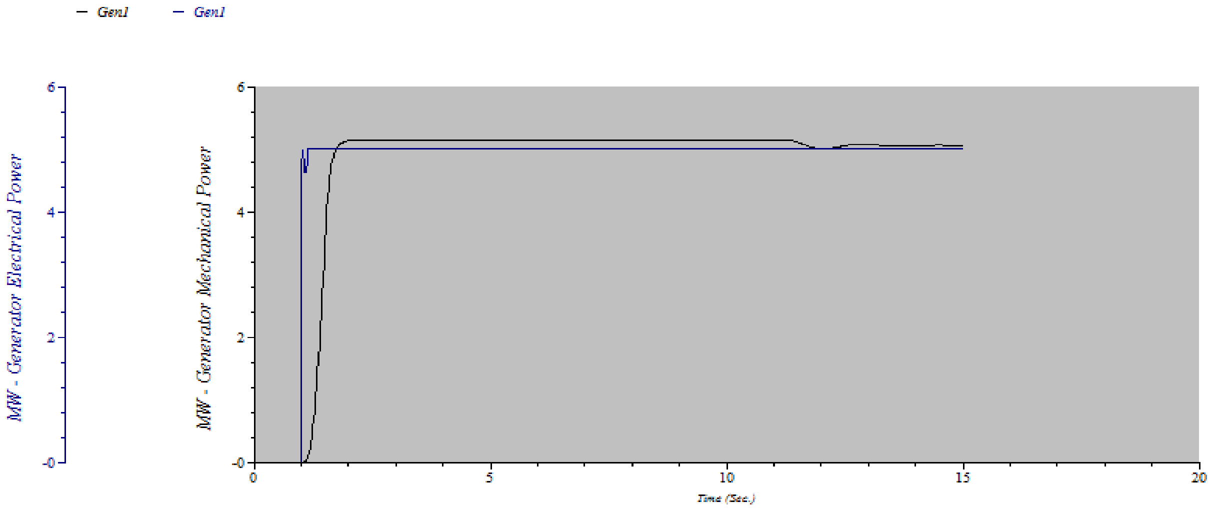
8. Go to plot page, Select Gen1 in Syn. Generator & Bus1 in Buses.
9. Run Transient stability, with output report name 'Load Application'.
10. Go to transient stability plots, Select Gen1 in Device ID and Check for Generator electrical power and mechanical power plots as shown.

Generator Transients



To generate a combined plot for generator electrical power and mechanical power. Select the check box for Combine Plots.

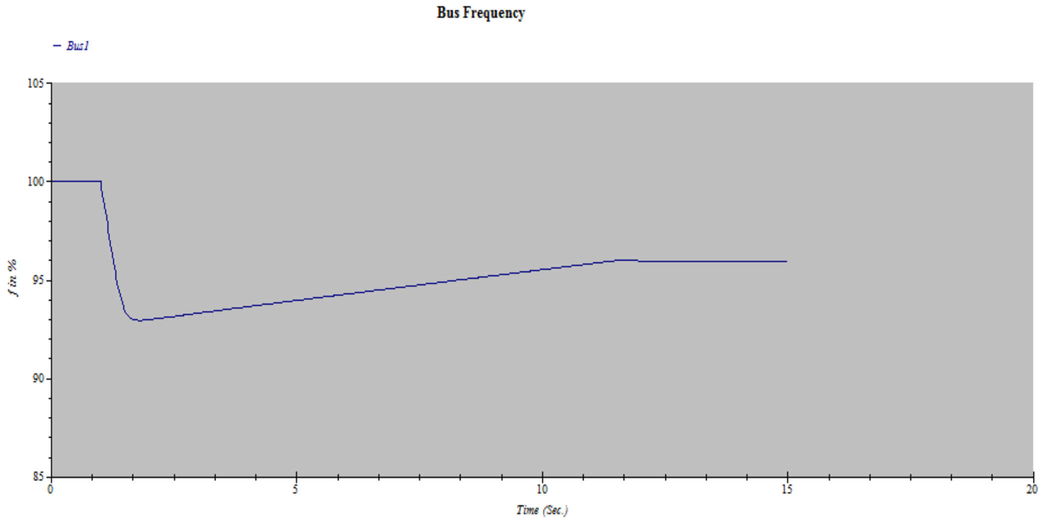
Gen1 Mechanical & Electrical power



Generator Transients

11. Also check for Gen1 Exciter Voltage (Efd), Bus1 voltage, Bus1 frequency plots individually.

Bus1 Frequency

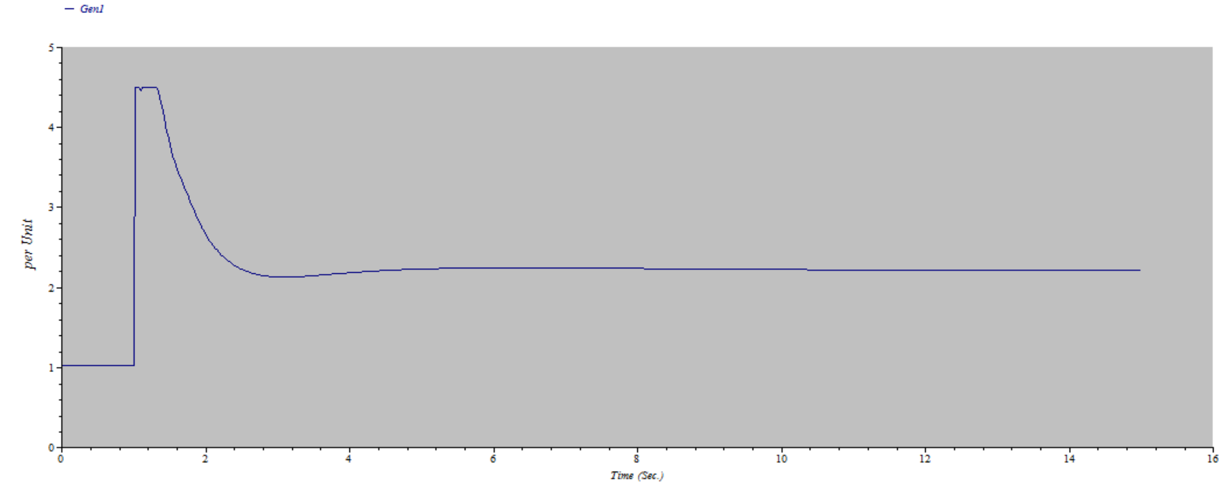


The following are the conclusions from Bus frequency plot:

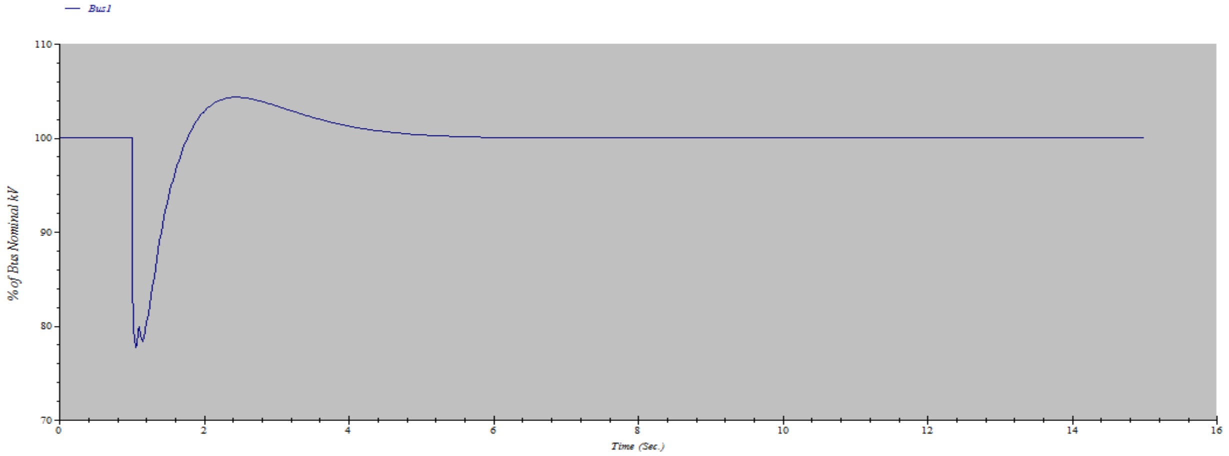
1. Pe > Pm when load is switched on.
2. Δ P is decelerating.
3. Speed and frequency reduces due to decelerating event of load addition
4. Frequency falls below 4% (Due to inertia) and settles with 4% less frequency because of 4% droop setting in the governor.

Generator Transients

Gen1 Exciter voltage



Bus1 Voltage



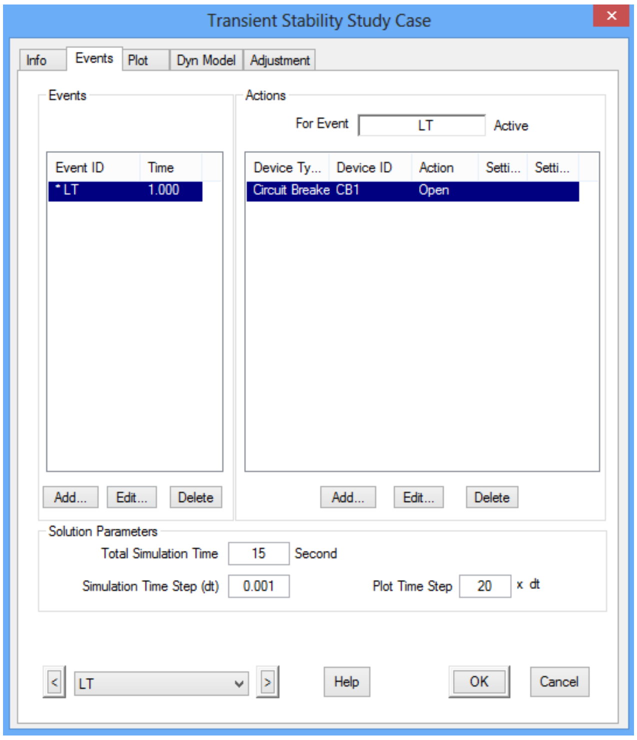
The following are the conclusions from Generator exciter voltage & Bus voltage plots:

1. Ceiling voltage is 4.5 p.u as set in exciter model.
2. Efd = Vt + jI.Xd
   Efd > Vt by jXd. I   if I > 0
3. Here I = FLC at end of transient so Efd will be greater than Vt.
   If I = 0 (Load is zero pre transient load switching) Efd = Vt = 1 p.u.

Generator Transients

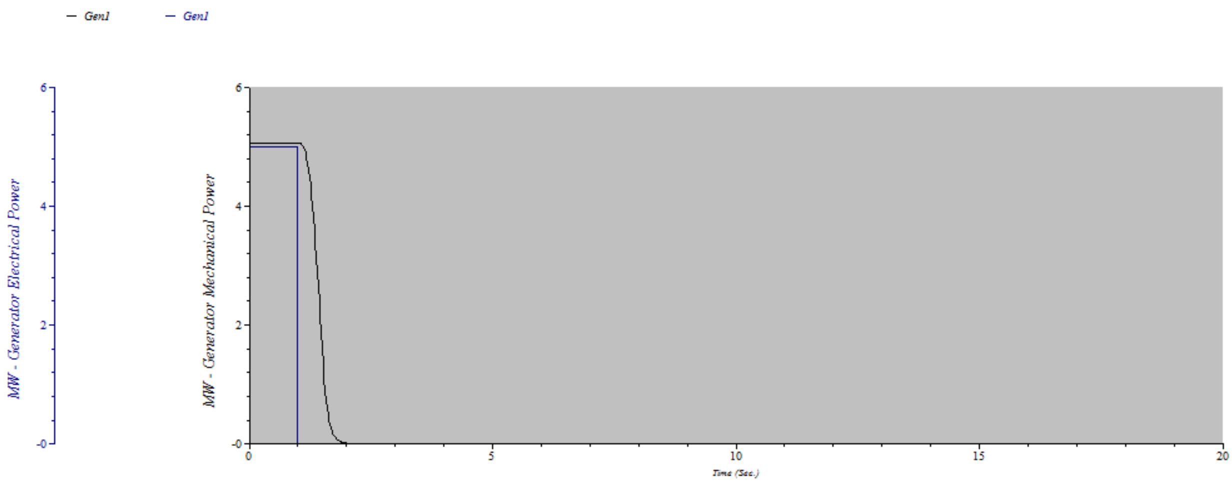
Case 2: 100% Load Throw Transient study on single generator

1. To study load Throw on single generator, initially close CB1 connected to load.
2. Create a new study case as ‘LT’.
3. Go to Events page and add an event to close CB1 at 1.0 sec as shown below.



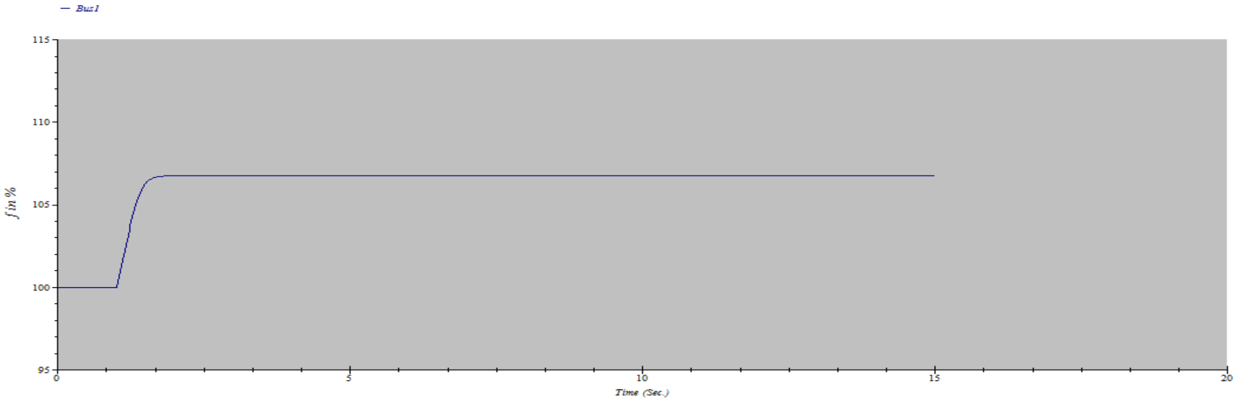
4. Go to plot page, Select Gen1 in Syn. Generator & Bus1 in Buses.
5. Run Transient stability, with output report name ‘Load Throw’.
6. Plot Generator electrical power and mechanical power, Generator Exciter Voltage (Efd), Bus voltage, Bus frequency as shown.

Gen1 Mechanical and Electrical power



Generator Transients

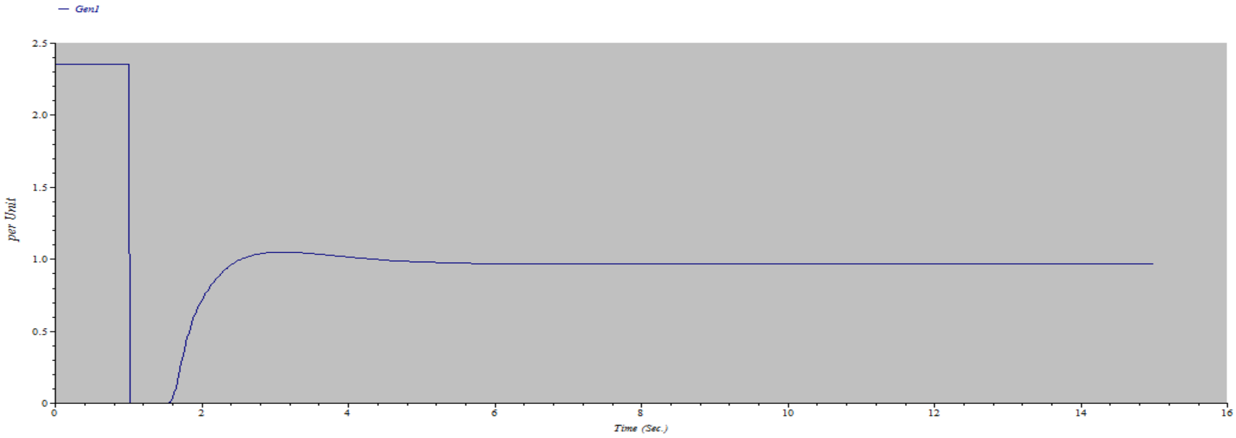
Bus1 Frequency



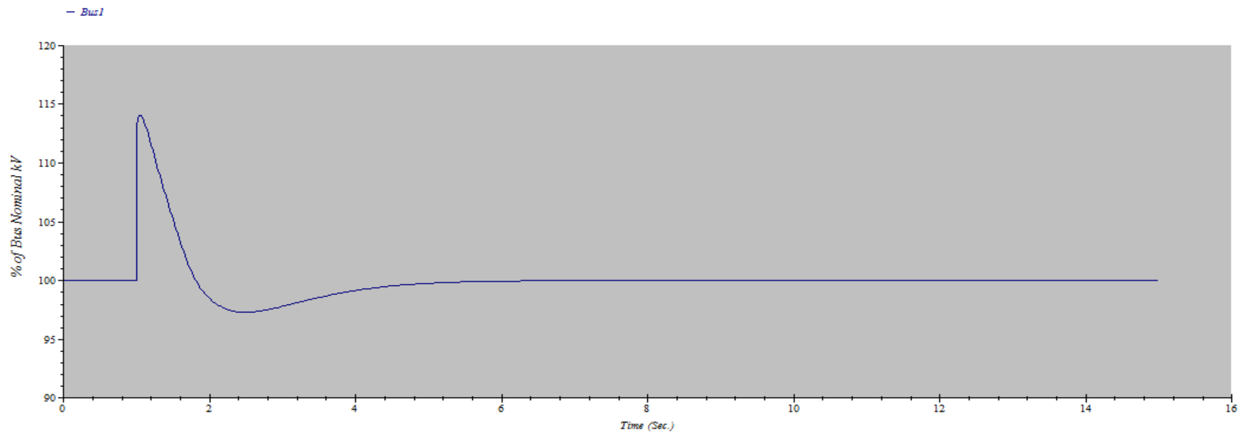
The following are the conclusions from Bus frequency plot:

a) Pm > Pe when load is switched off
b) Δ P is accelerating.
c) Speed and frequency increases due to accelerating event of load throw.
d) Frequency rises above 4% (Due to inertia) and settles with 4% more frequency because of 4% droop setting in the governor.

Gen1 Exciter voltage



Bus1 Voltage



Generator Transients

The following are the conclusions from Generator Exciter voltage & Bus voltage plots:

a) Initially, Efd > Vt because I is at full load
   Efd = Vt + jI.Xd
b) Finally, Efd = Vt = 1.0 pu when load is thrown OFF.

<u>Two Generator Out of step transients</u>

Generators are Equally Loaded

If there are multiple generators say two, each are equally loaded in pu proportional to their rating, during pre-fault conditions. During fault & pre fault conditions, P_{mech} & P_{elect} will be as follows.

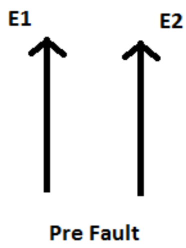
	Generator 1	Generator 2
Pre fault	$P_{mech} = P_{elect} = 50\%$	$P_{mech} = P_{elect} = 50\%$
During fault	$P_{elect} = 0\%$ $P_{mech} = 50\%$ $\Delta P = P_{mech} - P_{elect}$ = Accelerating	$P_{elect} = 0\%$ $P_{mech} = 50\%$ $\Delta P = P_{mech} - P_{elect}$ = Accelerating

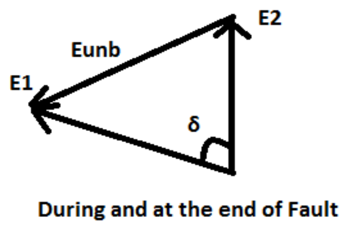
In this case, machines will have same ΔP, Inertia Constant H in MW-sec/MVA and governor. So during fault, both machines speed up at same rate & hence they will never go out of synchronism.

Generators are Unequally Loaded

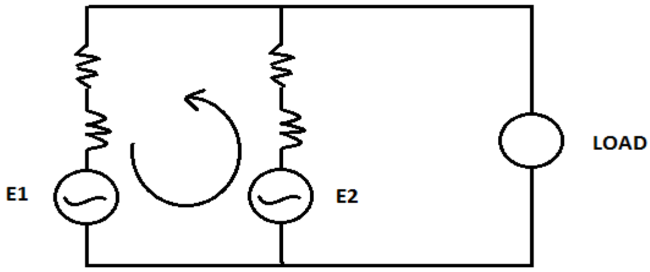
	Generator 1	Generator 2
Pre fault	$P_{mech} = P_{elect} = 90\%$	$P_{mech} = P_{elect} = 10\%$
During fault	$P_{elect} = 0\%$ $P_{mech} = 90\%$ $\Delta P = P_{mech} - P_{elect}$ = Accelerating	$P_{elect} = 0\%$ $P_{mech} = 10\%$ $\Delta P = P_{mech} - P_{elect}$ = Accelerating

Since machines are not equally loaded, both machines will rise to different speed during fault and when fault is cleared, both machines will be back in unsynchronized condition.
Unsynchronized re-switching of two generators, one with high speed & other with lower speed means one generator advances in terms of angle 'δ' with respect to other.

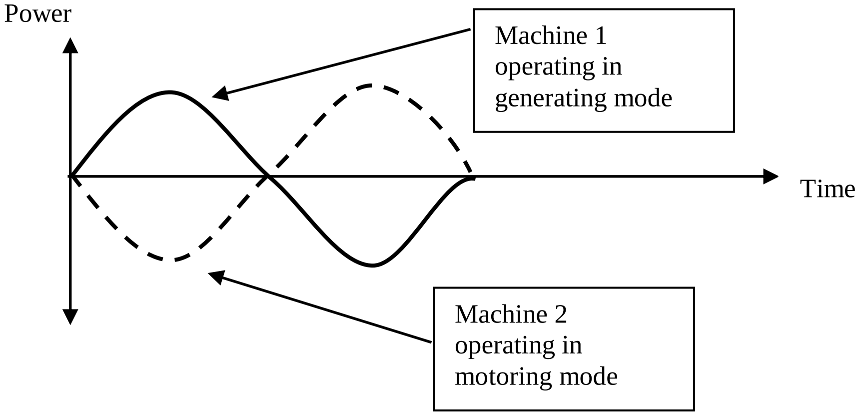




Generator Transients



Unbalance voltage (E_{unb}) causes circulating current between two machines i.e.one motoring and other generating causing power circulation between generators called "Power Swing".
For example please refer to power swing between the two generators as shown below.



Peaks of the power swing may exceed machine rating and swing acts as alternating twisting force applied on the shaft that tries to twist and break shaft and coupling.
Swing equation explains the above phenomenon as shown below

$$\delta 1(t) = \delta 1(t=0) + \frac{\Delta P1 \,.\Delta t_1^2 .Ws}{4H}$$

$$\delta 2(t) = \delta 2(t=0) + \frac{\Delta P2 \,.\Delta t_2^2 .Ws}{4H}$$

Where,

1 refers to machine 1 and δ1 is in radians
2 refers to machine 2 and δ2 is in radians
ΔP1 & ΔP2 in pu are mismatch seen by machine 1 & machine 2 respectively during transient for time Δt1 & Δt2 in sec.
Ws = 2 Π fs (where fs = 50 Hz or 60 Hz)
H refers to Inertia constant of both generator & turbine in MWsec/MVA.

Generator Transients

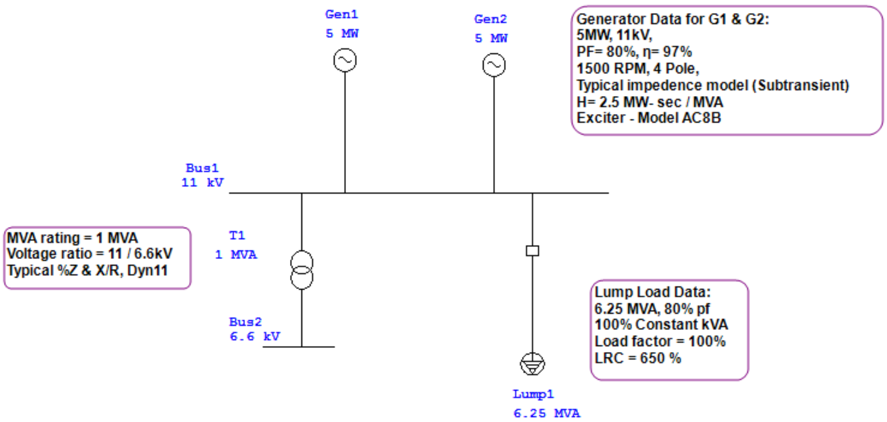
Purpose and Description

The purpose of this exercise is to study two generator faulted transients, relative rotor angle deviation and transient behavior of generators at the end of faulted transients.

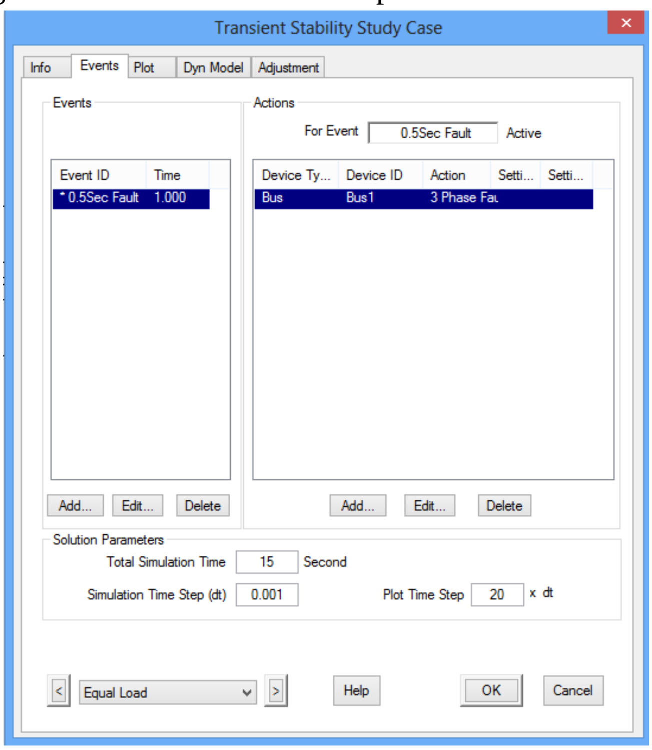
Procedure

Case 1: Two machines are equally loaded

1. Open Single Generator Transient OTI file and connect one more generator to Bus 1 with same data as Gen1 as shown below.

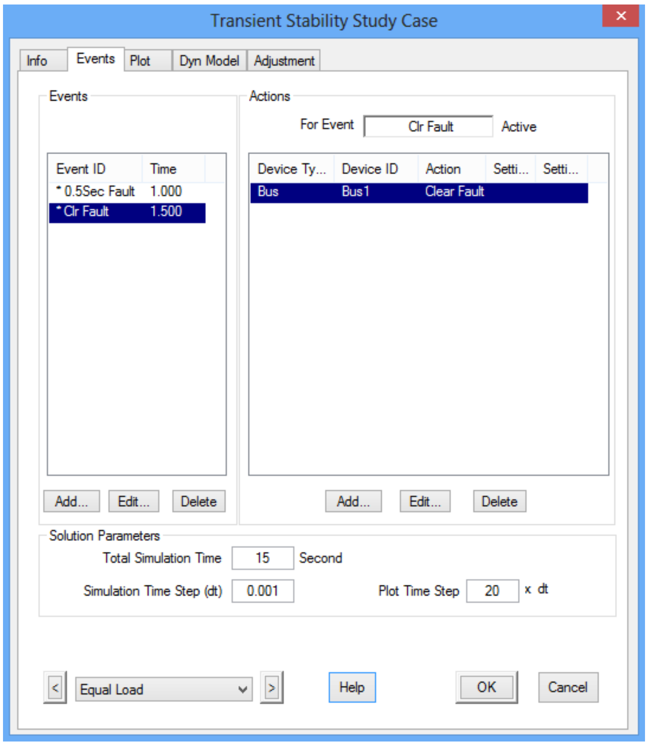


2. Set both the generators in swing mode.
3. Create a New study case as ‘Equal Load’.
4. Go to Events page and create an event for a 3-phase fault on Bus1 at 1 sec.



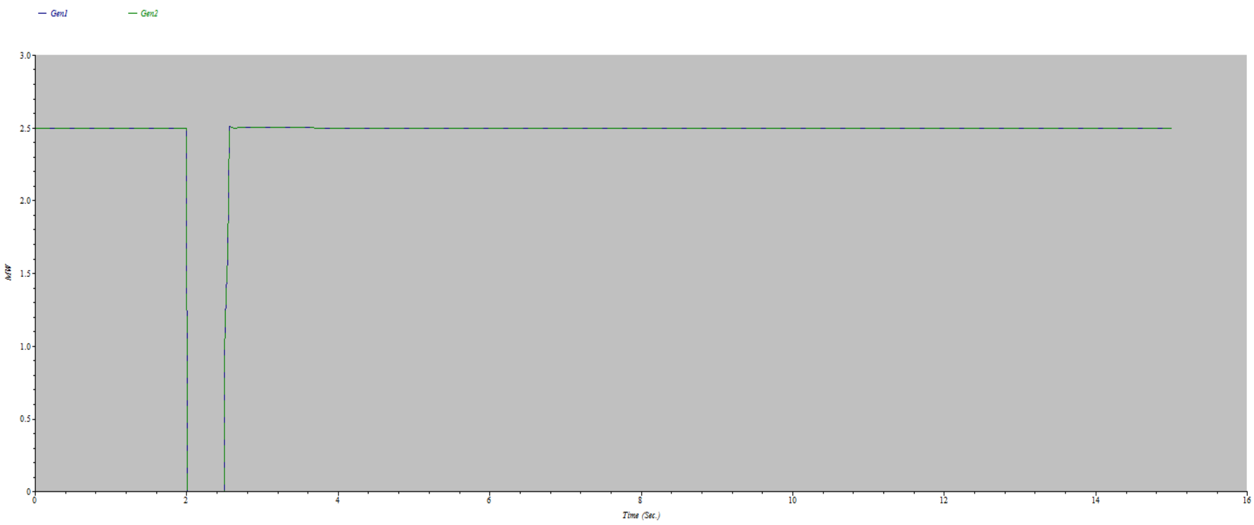
Generator Transients

5. Create one more event to clear the fault on Bus1 at 1.5 sec.



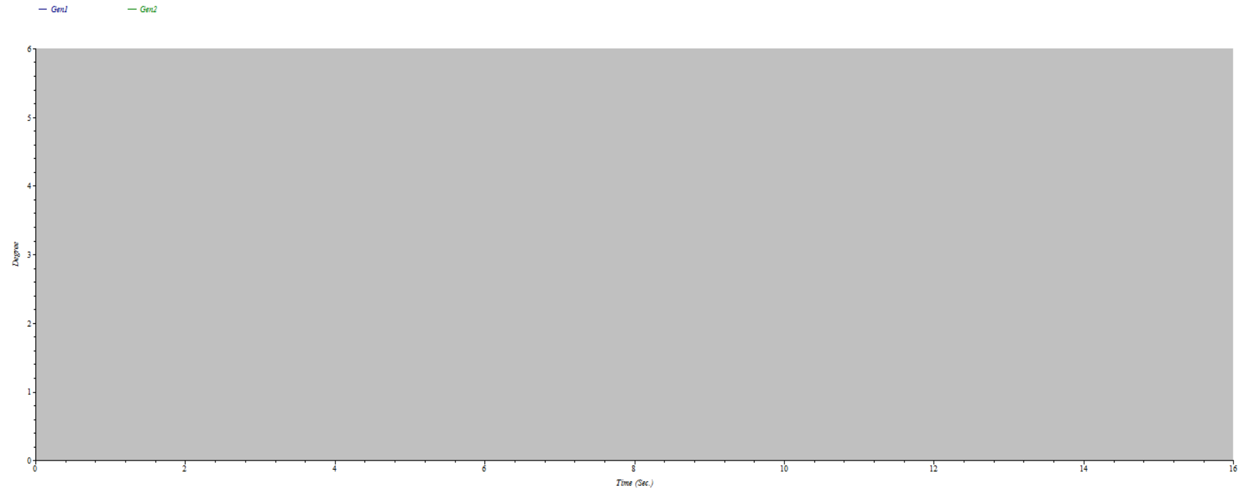
6. Go to plot page and plot Gen1 & Gen2 and Bus1.
7. Run transient stability with output report name as 'Equal Load'.
8. Plot generator electrical power and relative power angle for both the generators.

Generators Electrical Power



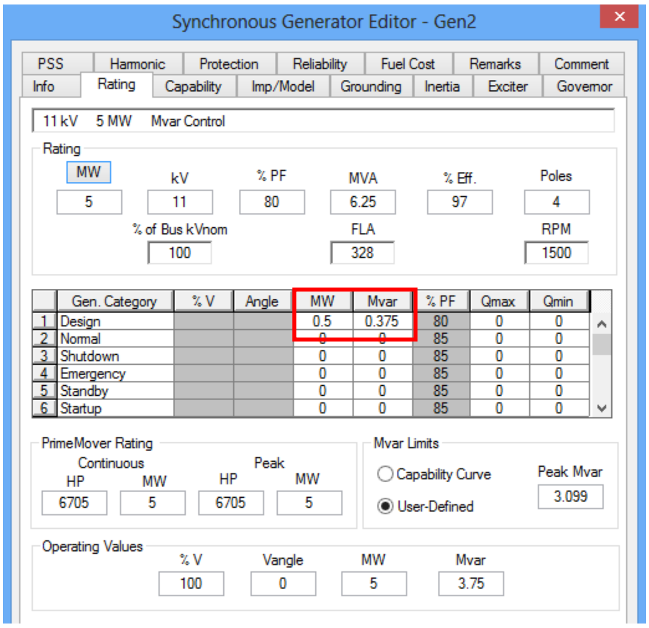
Generator Transients

Generators Relative Power Angle



<u>Case 2(A): Generators are unequally loaded with a fault for 0.5 sec</u>

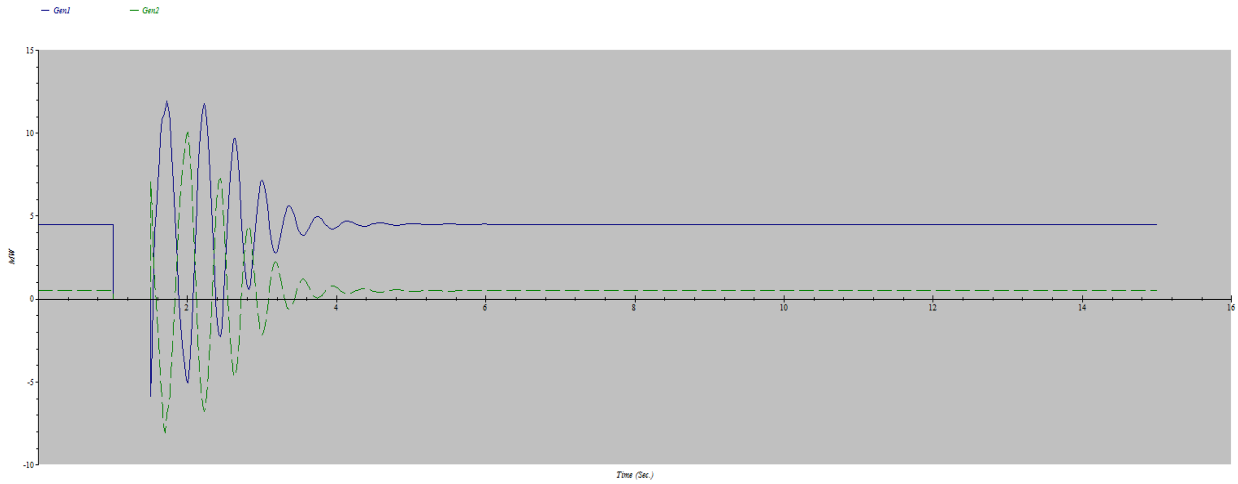
1. Double click on Gen2, Go to info page & select operating mode as ‘Mvar Control’.
2. Go to rating page, enter MW and Mvar ratings as shown.



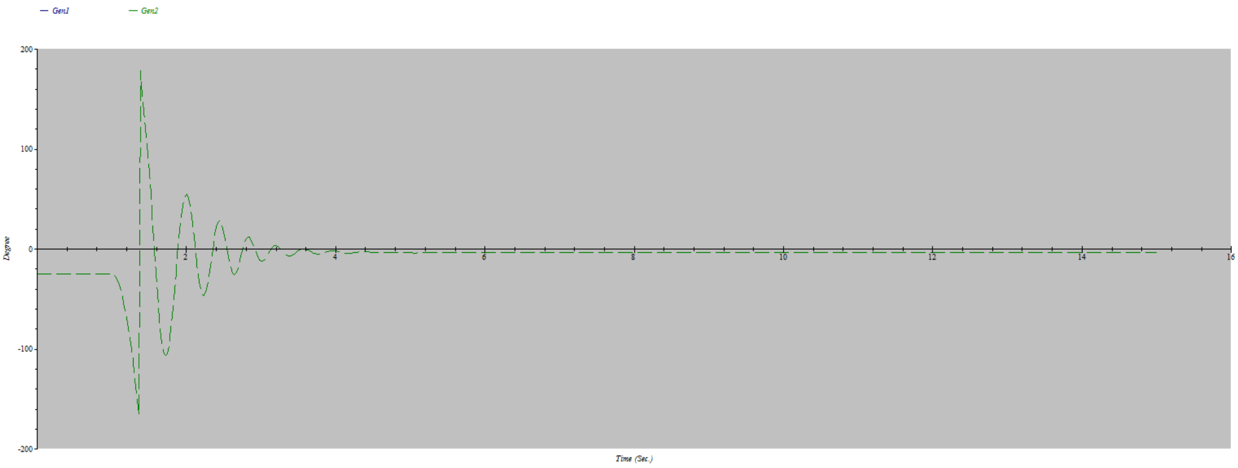
3. Create a new study case with name ‘Unequal Load’.
4. Go to Events page and create an event for a 3-phase fault on Bus1 at 1 sec.
5. Create one more event to clear the fault on Bus1 at 1.5 sec.
6. Go to plot page and plot Gen1, Gen2 and Bus1.
7. Run transient stability with output report name ‘Unequal load A’.
8. Plot generator electrical power and relative power angle for both generators.

Generator Transients

Generators Electrical Power



Generators Relative Power Angle



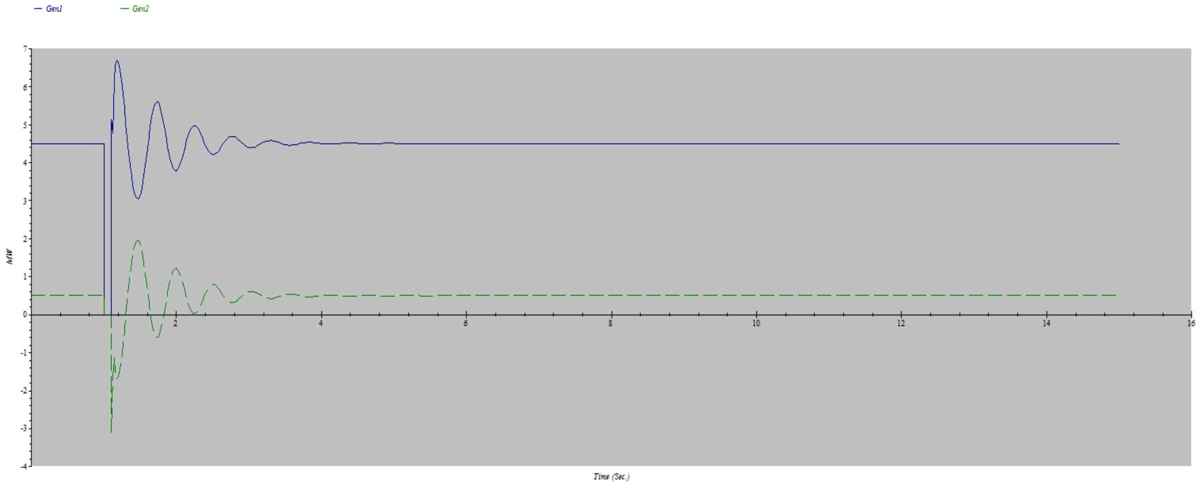
Notice that relative power angle exceeds 120 degrees in the first swing itself and power swings are high for both generators.

Generator Transients

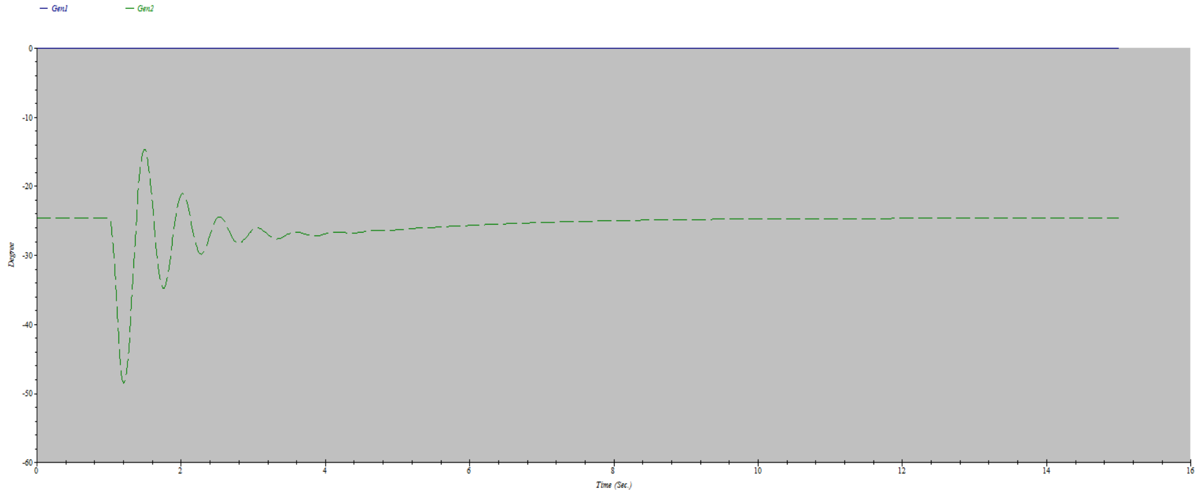
Case 2(B): Generators are unequally loaded with fault for 0.1 sec

1. Create a new study case with name ‘Uneq. Load B’.
2. Go to Events page create an event for a 3-phase fault on Bus1.
3. Create one more event ‘ClrFault’ to clear the fault on Bus1 at 1.1 sec.
4. Go to plot page and plot Gen, Gen2 and Bus1.
5. Run transient stability with output report name ‘Unequal load B’.
6. Plot generator electrical power and relative power angle for both the generators.

Generators Electrical Power



Generators Relative Power Angle



Notice that relative power angle swing is less as compared to previous case and power swings are minor for both generators.

Generator Transients

Under frequency Load Shedding

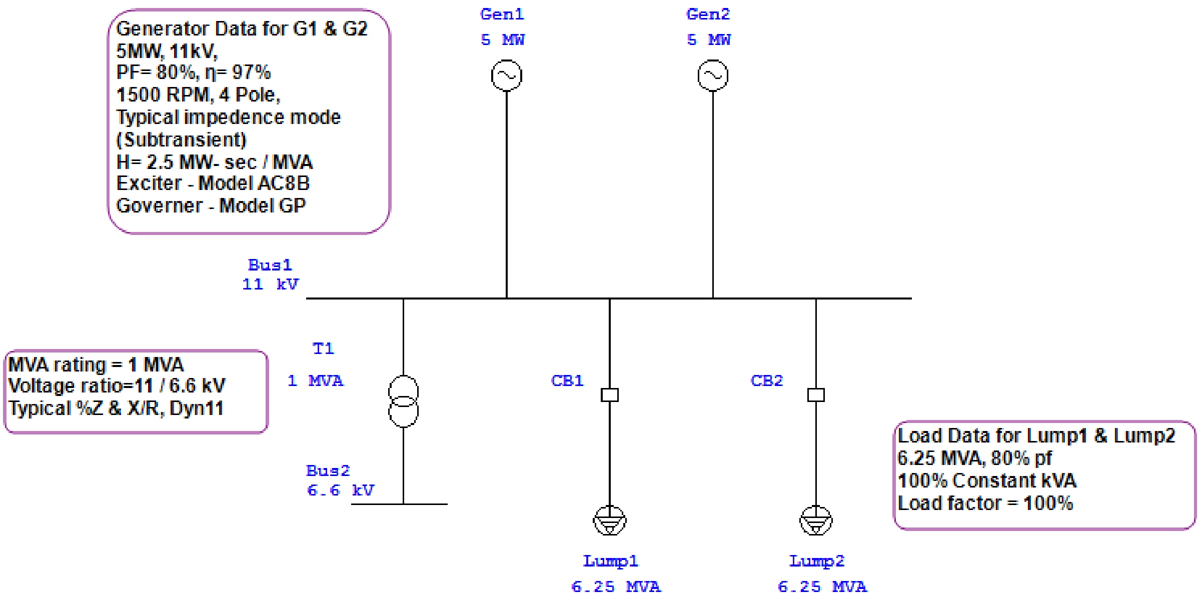
Purpose and Description

The purpose of this exercise is to study transient behavior of generators during loss of generation and to understand load shedding due to loss of generation using frequency relay.

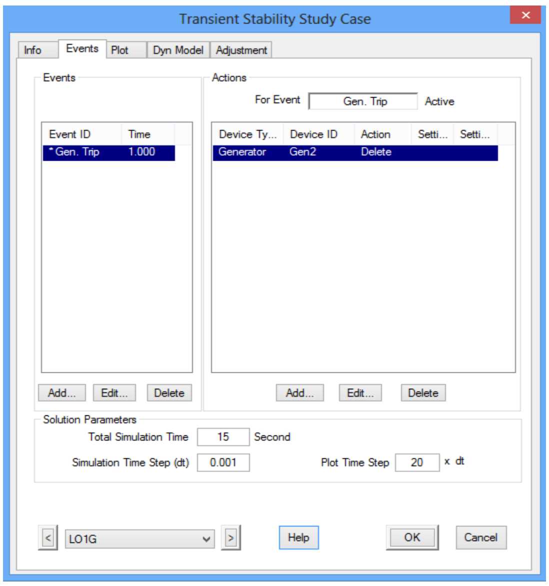
Procedure

Case 1: Loss of one generator without frequency relay

1. Open ETAP project file created in 'Single Generator Transient' case and create one more generator with same data as Gen1. Create one more Lump load with same data as Lump1 and connect newly created elements as shown below.



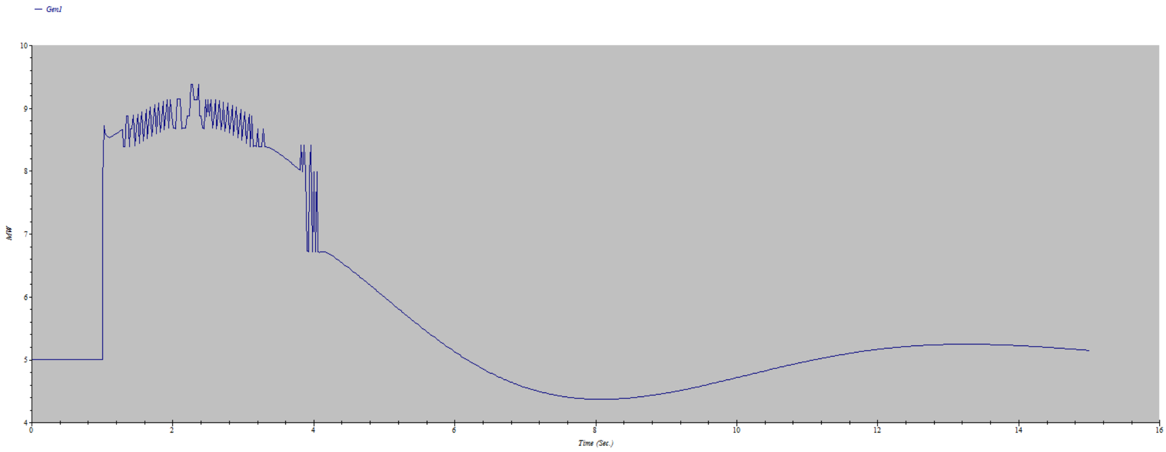
2. Create a new study case as 'LO1G'.Go to Events page and create a new event for tripping Gen2 at 1 sec.



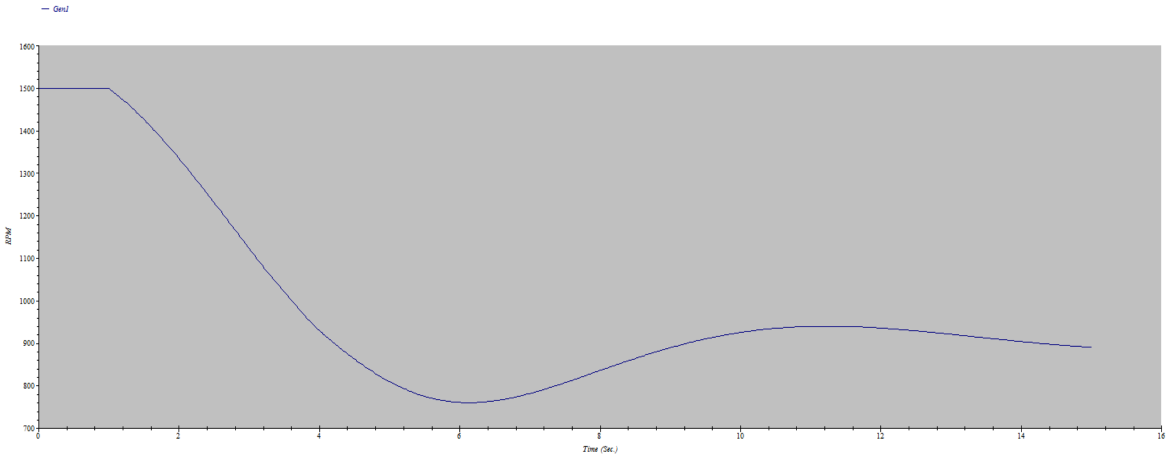
Generator Transients

3. Go to plot page. Plot Gen1 and Bus1.
4. Run transient stability, with output report name '1 Generator trip'.
5. Plot generator electrical power & speed of Gen 1. Plot frequency of Bus1.

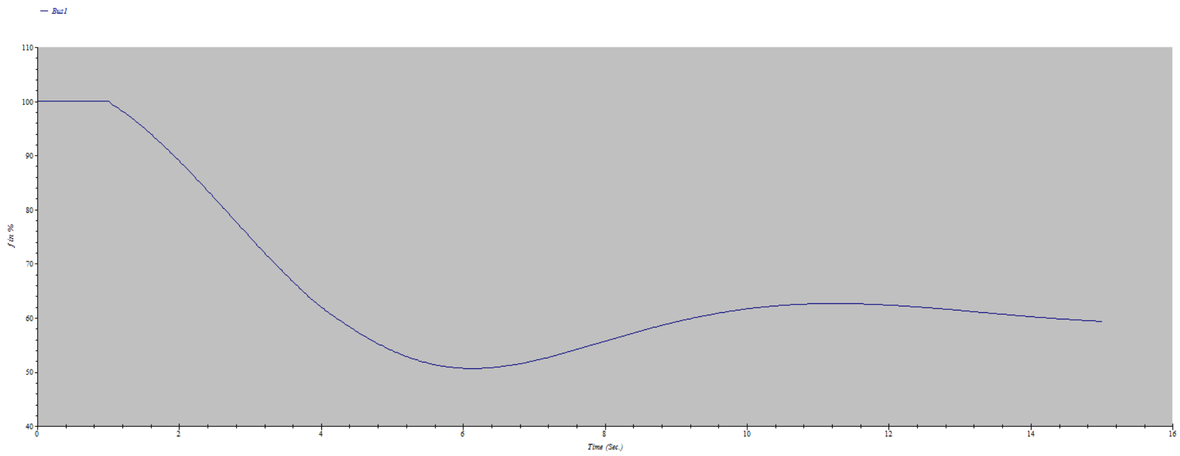
Gen1 Electrical Power



Gen1 Speed



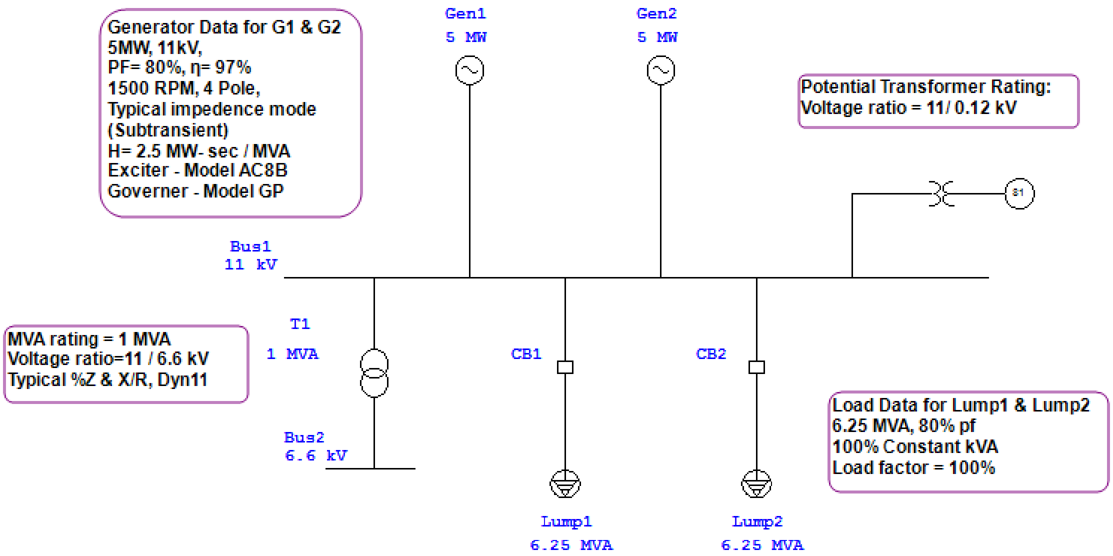
Bus1 Frequency



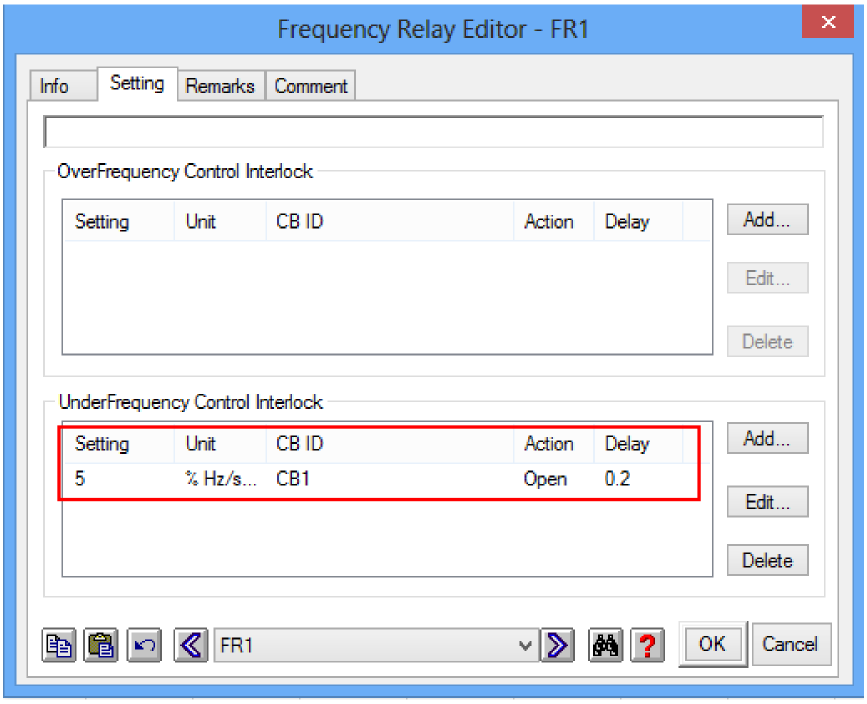
Generator Transients

Case 2: Load Shedding due to loss of one generator with frequency relay

1. Drag and drop frequency relay (81) & potential transformer on OLV. Connect them to Bus1 as shown below.



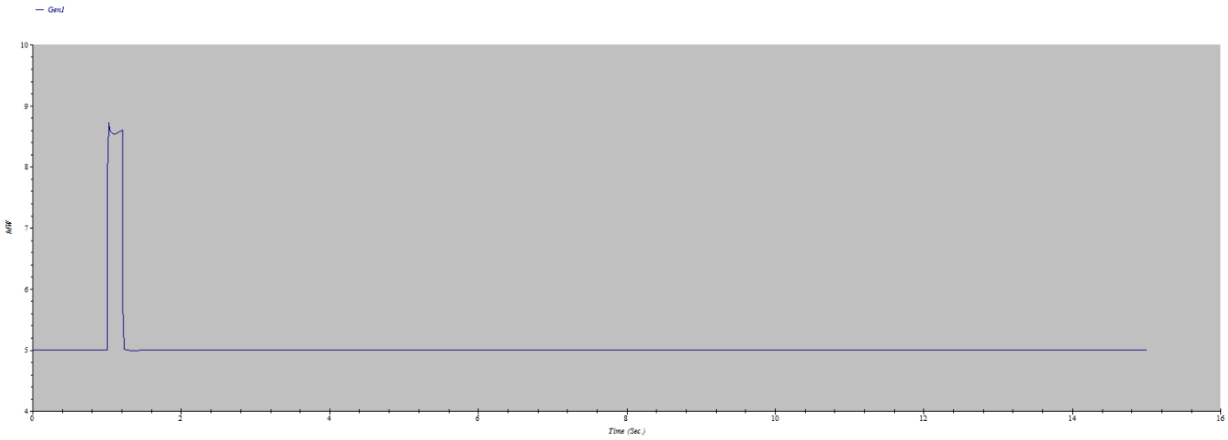
2. Double click on Frequency relay & enter the values in under frequency control interlock as shown below.



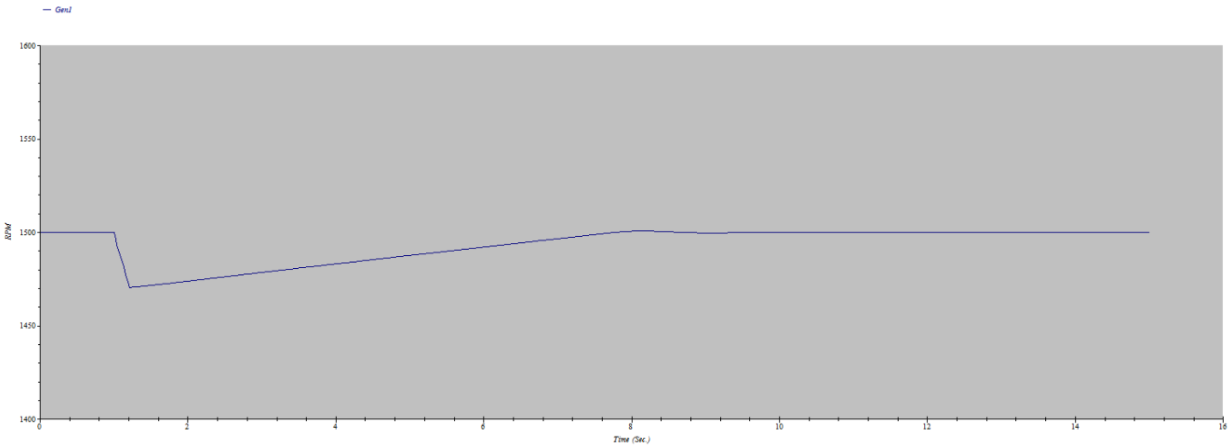
3. Run transient stability again with study case LO1G.
4. Plot Generator electrical power & speed for Gen1 and Frequency of Bus1.

Generator Transients

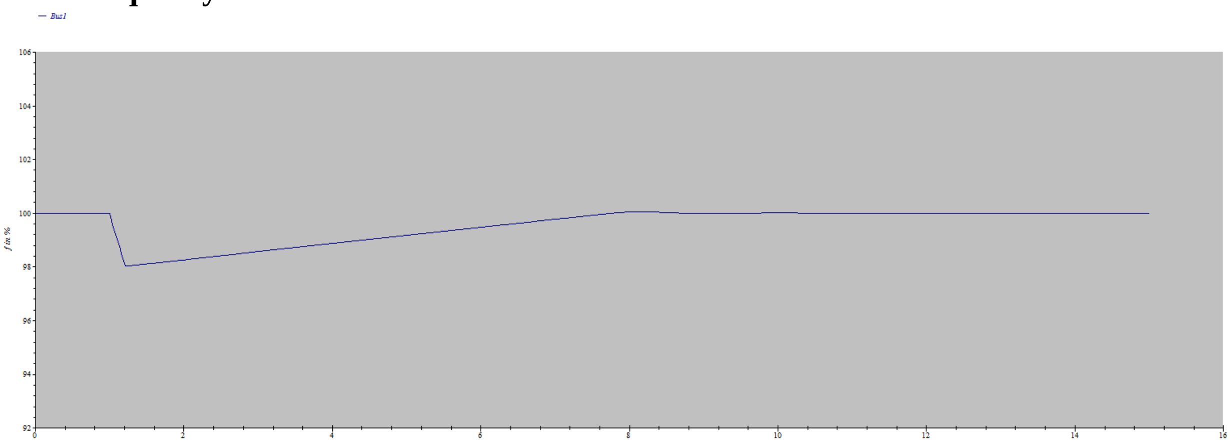
Gen1 Electrical Power



Gen1 Speed



Bus1 Frequency



Notice that initially frequency decrease and then it comes back to normal value in 8 to 10 seconds.