POLITECNICO
MILANO 1863

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

Electric Power Systems Project: Stability Analysis on Medium Sized Systems

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Academic Year 2019 - 2020

SUMMARY

INTRODUCTION

The purpose of this project is to analyze the stability of a given system when different contingencies occurs.

The system considered, which is shown in figure 1.1, is a 37-bus system operating at 345/138/69 kV.

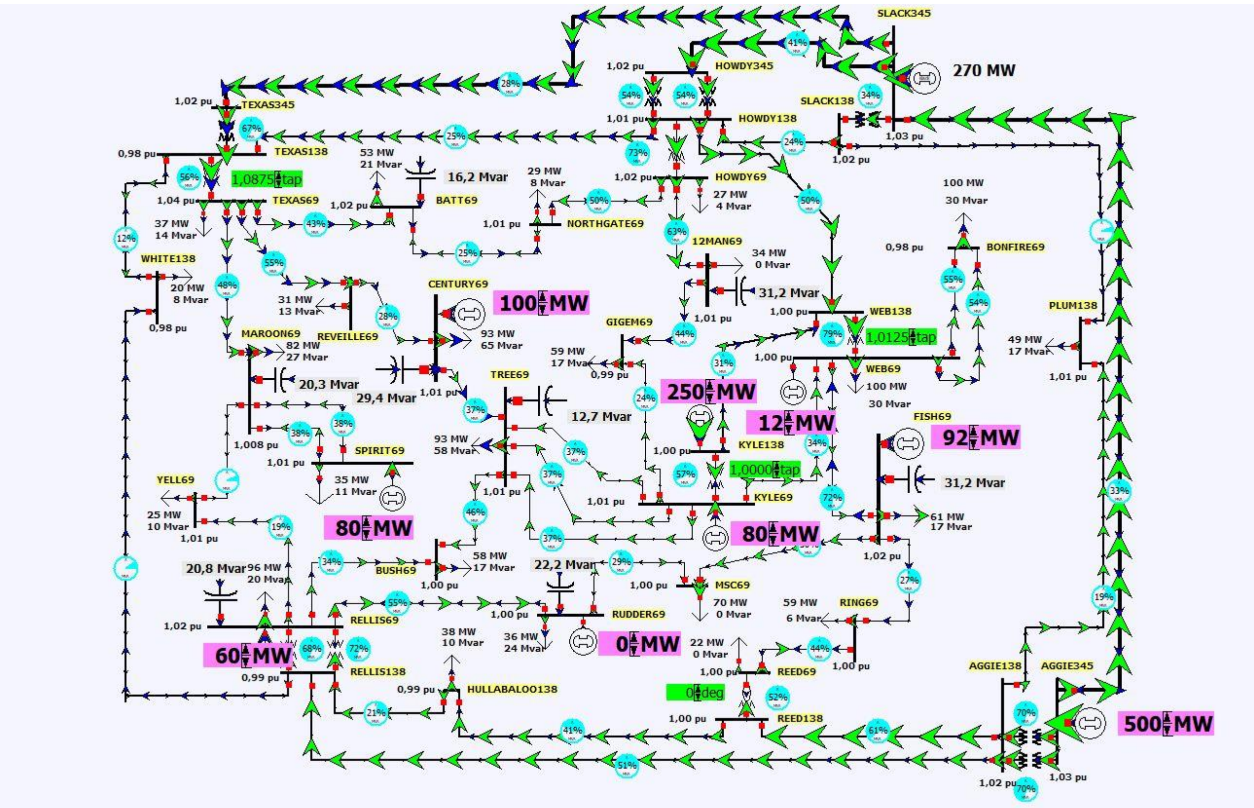


Figure 1   37-bus system considered

SPIRIT69 CONTINGENCY

The first case analyzed by the team is the contingency at SPIRIT69 generator. This simulation applies a balanced 3-phase fault on the SPIRIT69-MAROON69 branch and clears it in 0.1 seconds, by opening the breakers at both ends of the line. For the time in which the fault is applied (0.1 sec), the electrical power P_e injected by SPIRIT69 generator is equals to 0. Therefore, also the electromagnetic torque (opposite to the mechanical torque applied to the rotor) keeps the machine spin stable. The previous behavior is described by the swing equation:

$$M\frac{d^2\delta_m}{dt^2} = P_m - P_e$$

where M and δ_m represents the angular momentum of the machine and the rotor angle respectively. It is clear from the previous relation that the lack of P_e will lead to a positive value of the second derivative of δ_m, which means that the angle increases consequently to the acceleration of the rotor. In this phase, the rotor accumulates kinetic energy.

After the fault has been cleared, the electrical power generated is no more zero but has a higher value than the pre-fault condition (since δ_m is bigger than before) and the rotor is faster than the synchronous speed. From this moment, the kinetic energy previously stored in the rotor starts to be released as electric energy. In this condition $P_e > P_m$, the rotor slows down to the synchronous speed. It is worth to notice that until the rotor's speed is higher than the synchronous speed, δ_m continues to increase. When the synchronous condition is reached the rotor continue to decelerate (since $P_e > P_m$) so the angle reduces and when $P_e < P_m$ it restarts to increase. If a damping effect is not present, this condition leads to a never-ending oscillatory behavior of δ_m. Anyway, due to the presence of loads and other generators in our system, the damping effect is present, and oscillations reduce with time. It is worth to notice that if the fault clearing time is too long, the kinetic energy stored in the rotor will be too high and the maximum angle (that has to be reached in order to release it) will bring the machine to the loss of synchronism.

The "energetic" situation is represented in Figure 1.1, where the areas 1-2-3-4 and 4-5-6-7 are proportional to the kinetic energy stored and released respectively.

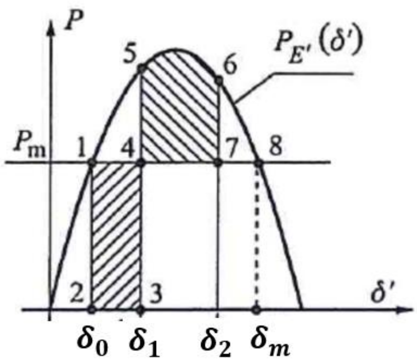


Figure 1.1 Equal Area Criterion

The graph reporting the rotor angles vs time for each generator of the system is shown in Figure 1.2. Particularly noteworthy is the behavior of the rotor's angle of other generators. Their curves are in opposition with the one of SPIRIT69. This phenomenon happens because of the lack of injected electric power during the fault. Since this missing power is requested by the loads, other generators have to provide for it and this will lead to a reduction of their rotor speed and so δ_m decreases. Then, when the fault is cleared, the behavior of the other generators is opposite to the SPIRIT69 one. This allows to keep the power balance among the system.

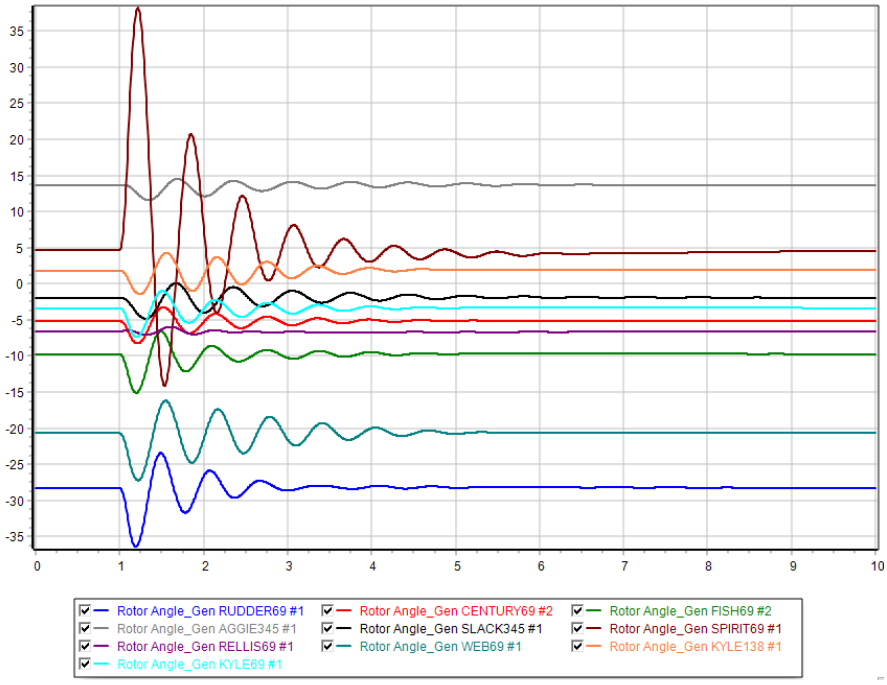


Figure 1.2

- **Critical clearing time with SPIRIT69 output of 80 MW**

In order to find the critical clearing time for the fault, the opening time of the branch SPIRIT69-MAROON69 has been iteratively changed in 0.01 second steps and the transient stability simulation has been repeated for each step; the obtained result is $t_{crit} = 0.20\ s$ and the behavior of the generator's rotor angle is reported in Figure 1.3.

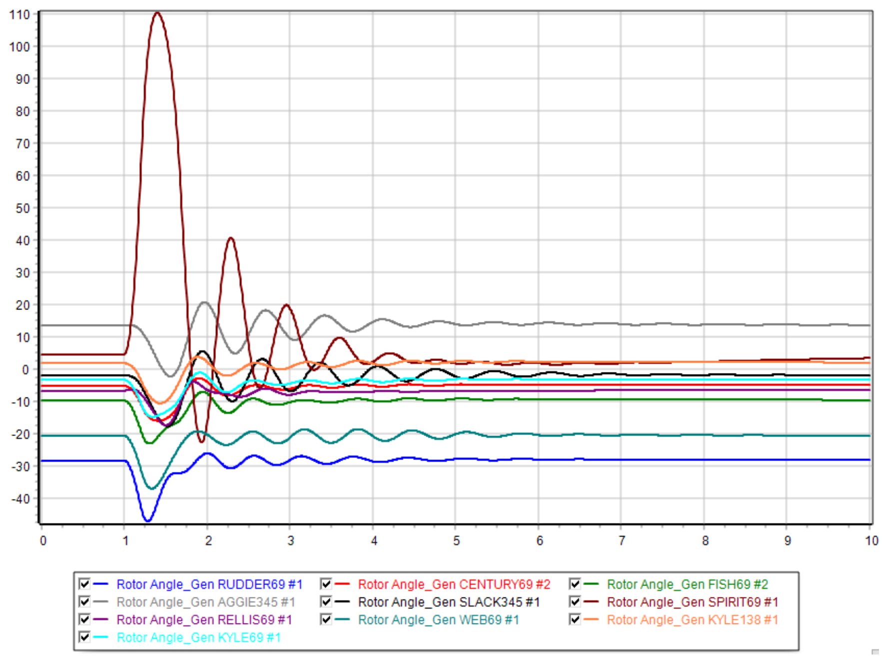


Figure 1.3 Generators' rotor angles for critical clearing time

By comparing Figure 1.2 and Figure 1.3 it is possible to notice that the maximum reached angle in the second case is much higher than the first. This means that a larger rotor angle than before is required in order to release all the kinetic energy stored in the machine during the acceleration of the rotor.

If a $t_{clear} > t_{crit}$ is set, for example equal to 0.21, the machine accelerates too much and the angle that has to be reached (in order to convert all the kinetic energy) leads to an unstable behavior of system, bringing the generators to the loss of synchronism. This last situation is reported in Figure 1.4, which shows a divergent behavior of the rotor angles.

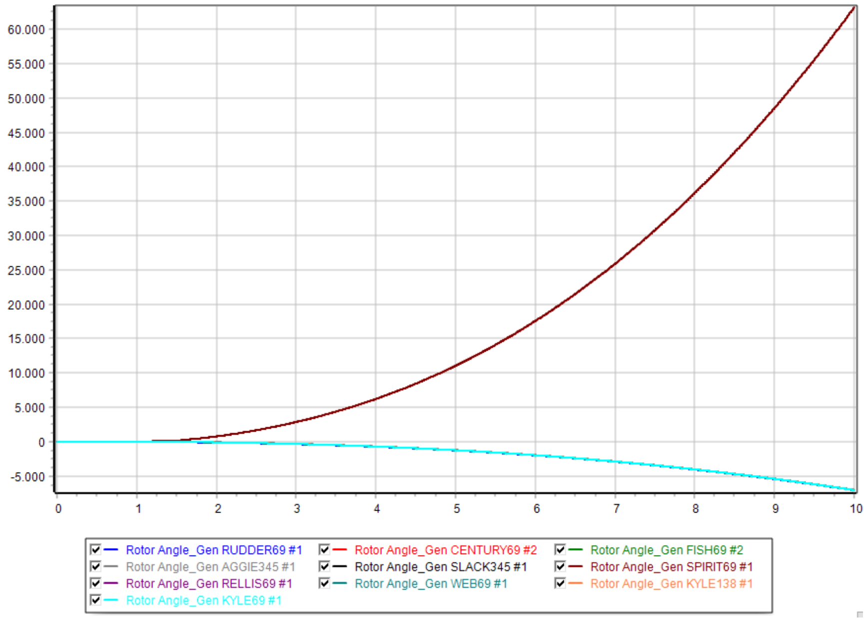


Figure 1.4   Unstable condition due to a too long clearing time

- **Critical clearing time with SPIRIT69 output of 40 MW**

As requested, a further analysis by changing the injected power of SPIRIT69 from 80 MW to 40 MW is presented. It is reasonable to expect that a reduction of electric power in the output of the generator leads to a reduction in the mechanical power applied to the rotor. Hence, since P_m is lower than before, an equal clearing time with respect to the previous case leads to less kinetic energy stored in the rotor. This effect is well represented by the plot in Figure 1.1, where the area below P_m is proportional to the increase of the kinetic energy. Therefore, the less P_m the less the kinetic energy accumulated in the machine during the fault.

Since the stored energy is less than before for an equal clearing time, it follows that the critical clearing time has to be higher. Hence, the less P_m the more the time until the critical rotor angle is reached and the more stable the situation.

The previous statement is confirmed by the simulation. By setting the critical clearing time of the previous case (0.20 s), Figure 1.5 shows that the maximum rotor angle reached is less than before. Figure 1.6 shows the stable behavior for t=0.21 s, while in the previous case the system was unstable.

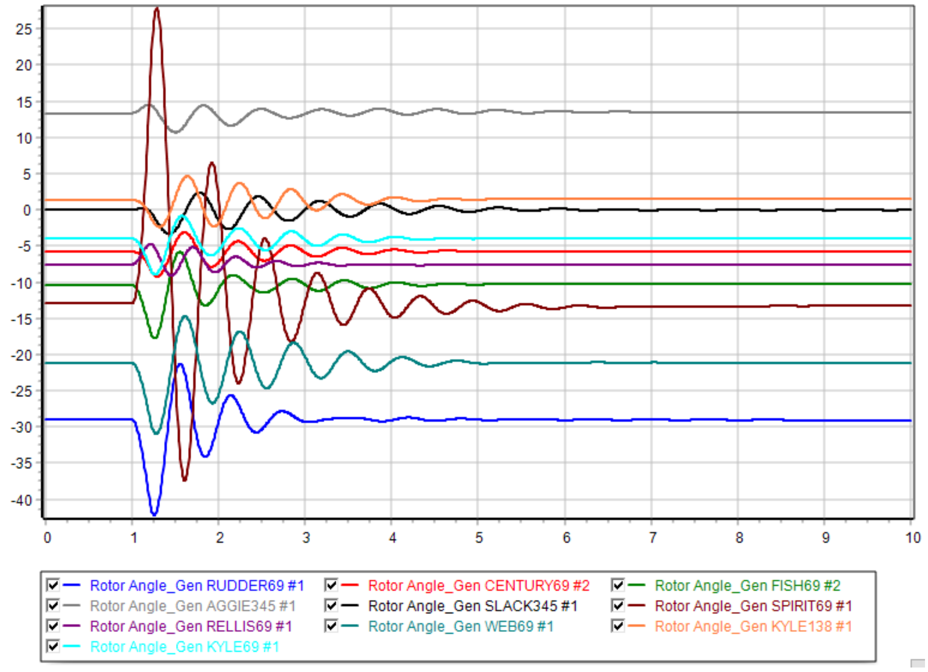


Figure 1.5 Generators' rotor angles for clearing time 0.20 s (40 MW)

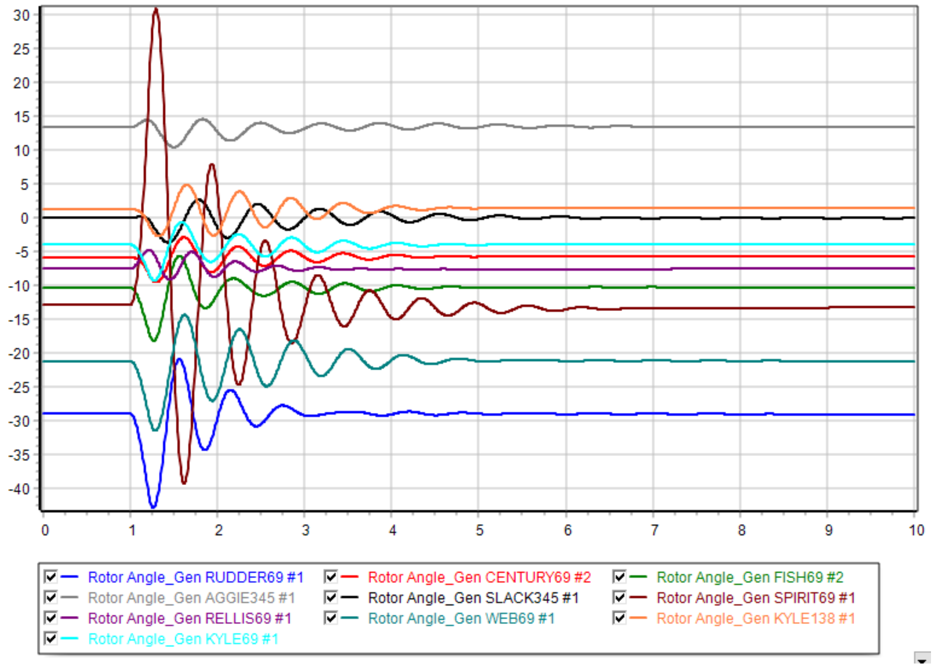


Figure 1.6 Generators' rotor angles for clearing time 0.21 s (40 MW)

The critical clearing time for this case has been found by following the same procedure as for the previous case. The obtained result is $t_{crit} = 0.38\ s$ and the behavior of the generators' rotor angle is reported in Figure 1.7.

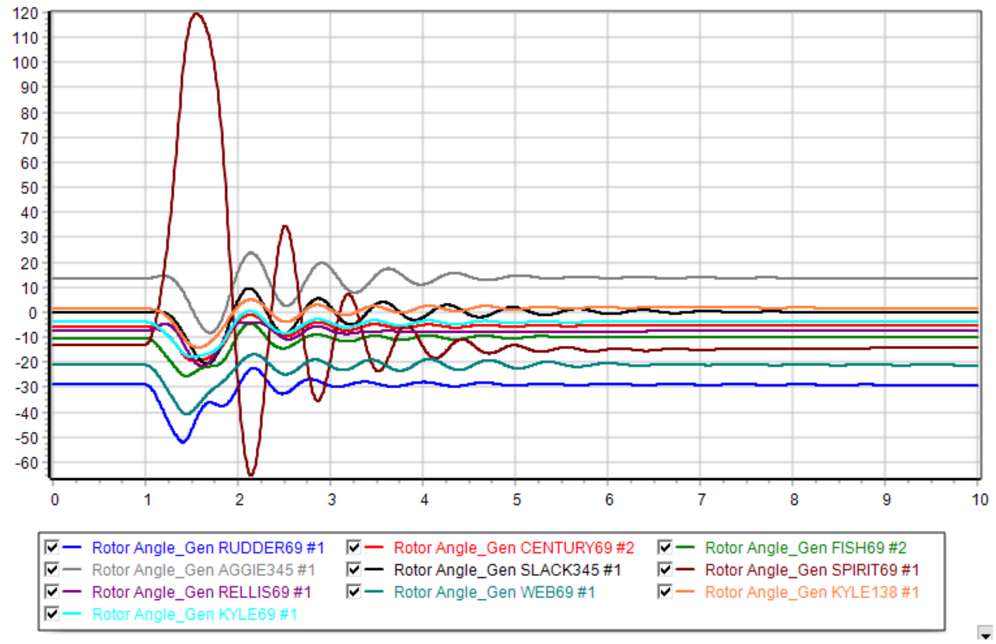


Figure 1.7 Generators' rotor angles for critical clearing time (40 MW)

By setting a $t_{clear} > t_{crit}$, for example equal to 0.39, the system is no more stable and loses synchronism. The last situation is reported in Figure 1.8.

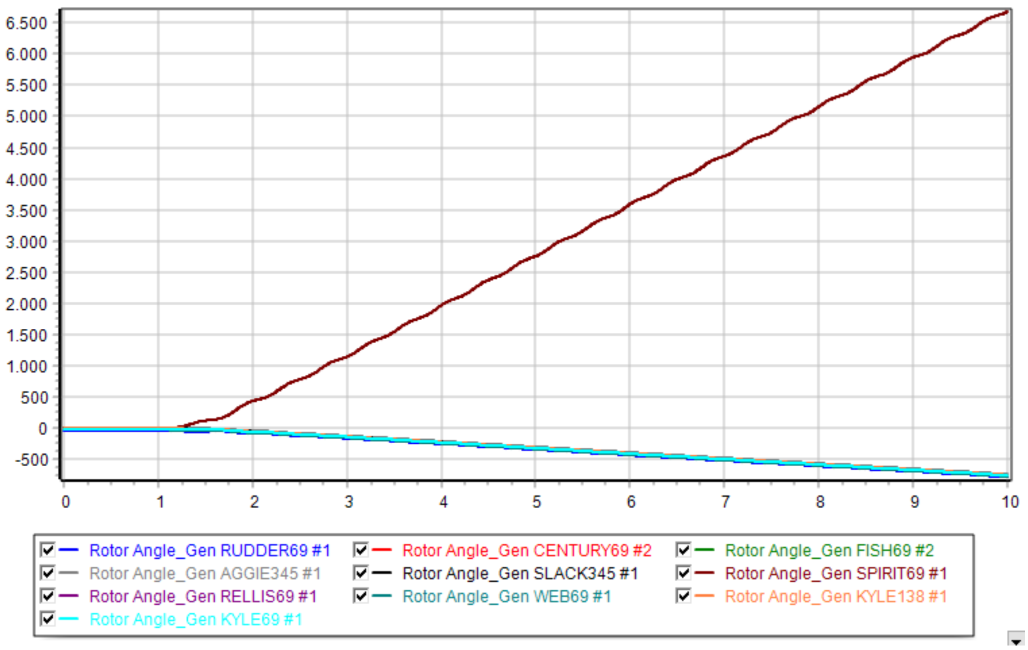


Figure 1.8 Unstable condition (40 MW)

It is interesting to notice that even if both Figure 1.4 and Figure 1.8 represent unstable conditions, the last one presents a less slope in the increase of the rotor angle since the mechanical power provided is less than in the first case. Therefore, the acceleration is more contained.

KYLE138 CONTINGENCY

In this occurrence it has been changed the contingency to Kyle138, which simulates a fault on the 138 kV transmission line between the Kyle and WEB substations.

The simulation on PowerWorld shows that until the time $t = 1.22s$ the stability is kept, while after this value the behavior of the generator becomes unstable; therefore, the t_{crit} is 0.22 s. The behavior of the generators' rotor angles is shown in Figure 2.1, while Figure 2.2 shows the trend for a t_{crit} of 0.23 s.

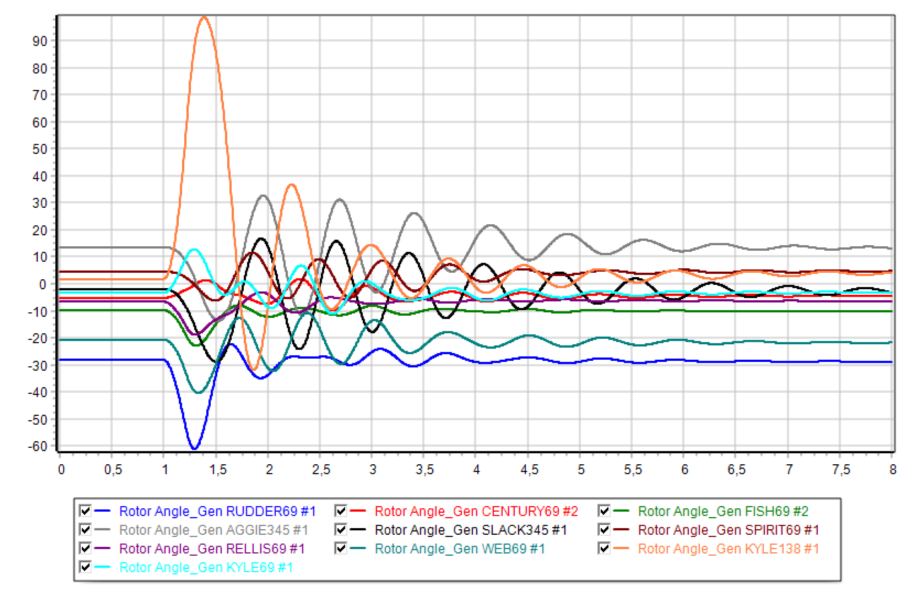


Figure 2.1 Rotor angles for a critical time of 0.22 s

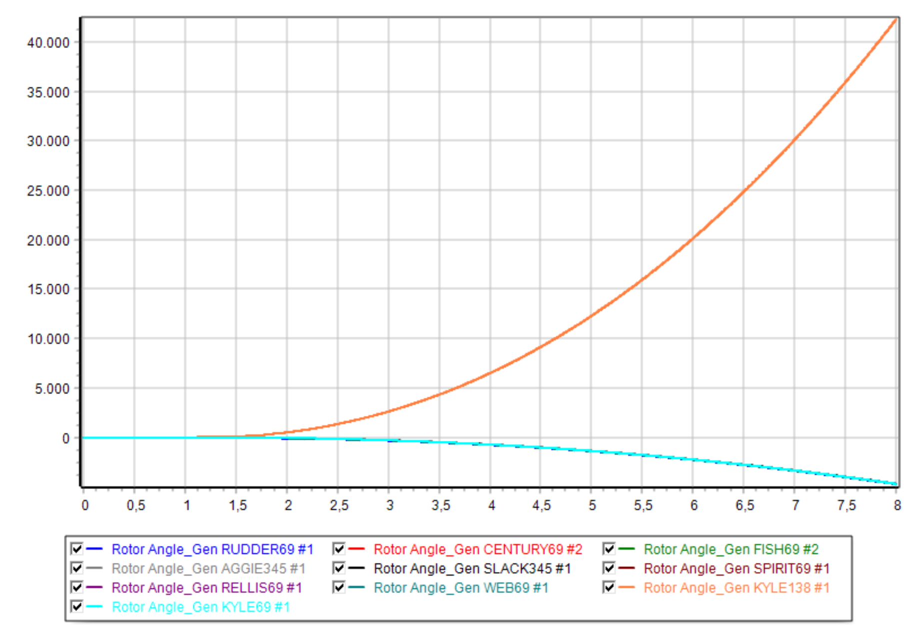


Figure 2.2 Rotor angles for a clearing time of 0.23 s

Again, since the mechanical power provided is pretty high, the slope in the increase of the rotor angle has a square trend (the acceleration of the rotor is emphasized).

It is interesting to notice that in generators' rotor angle diagram the width of the first oscillation is larger if the clearing time increases.

Figure 2.3 shows the same situation but with $t = 1.10s$

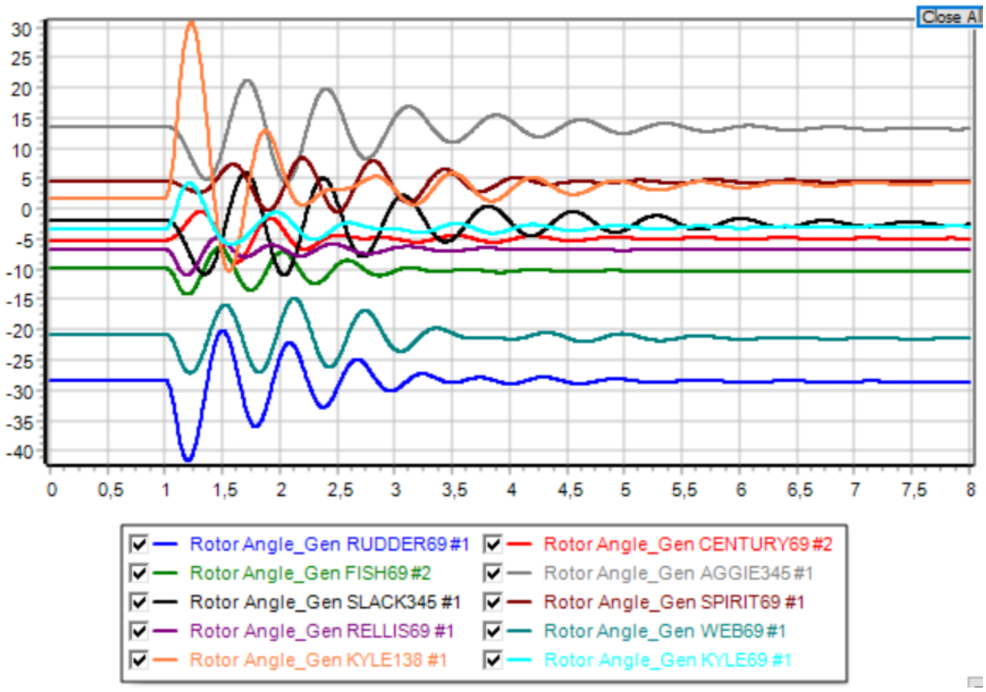


Figure 2.3 Rotor angles for a clearing time of 0.10 s

This phenomenon can be explained by the fact that the higher the t_{crit}, the higher the kinetic energy released from the rotor to the grid. Hence, the time to achieve the final angle is higher. This statement has an equivalent meaning from an energy point of view.
It is known that the area under the curve of the power represents the energy that the generator releases to the grid. In fact, by plotting the generated power of Kyle138 (Figure 2.4) confirms that the energy released (during the first oscillation) is higher.
Interesting to notice the double pick in the chart: it means that the stability margin is not really large. Thus, the generator is close to instability (as it has to be using the $t_{clear} = t_{crit}$).

Instead figure 2.5 shows the generated power of Kyle138 with $t_{clear} < t_{crit}$, $t = 1.10s$. There is not the double pick as before, thus the margin for the stability is larger as expected and the power generated after the breakers open is lower (about 415MW respect to 490MW with t_{crit}).

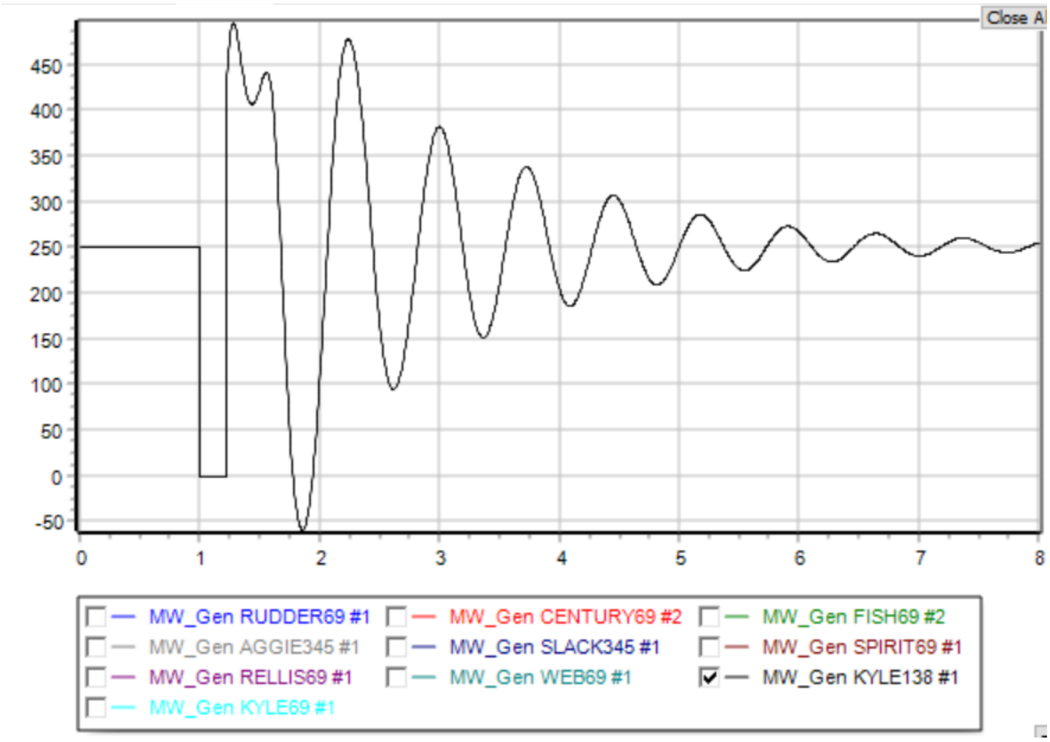


Figure 2.4

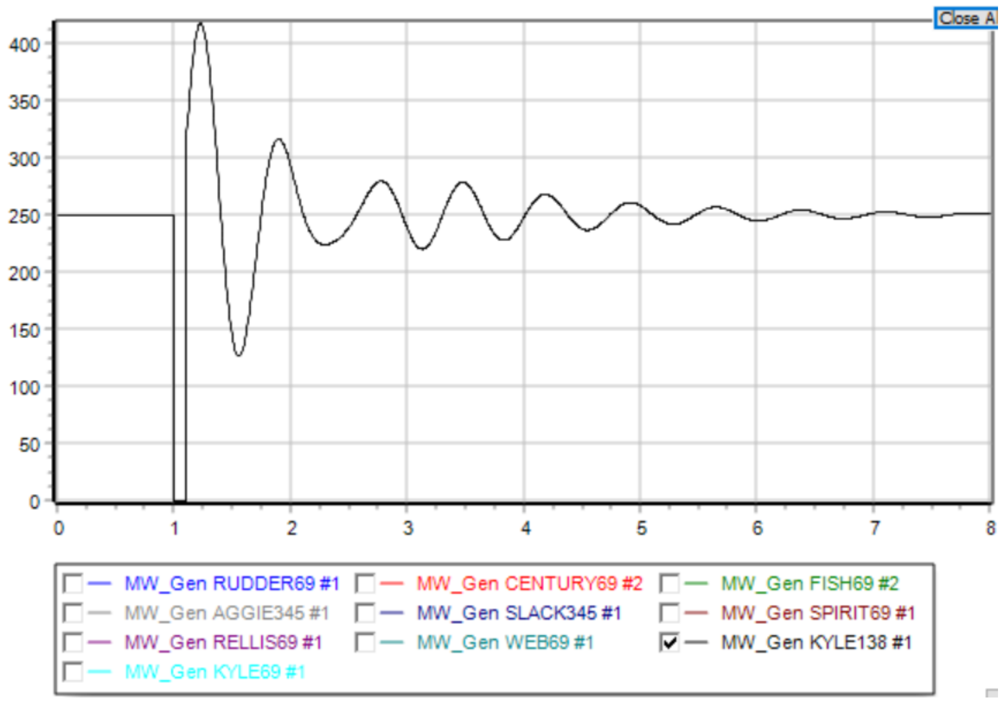


Figure 2.5

Lastly, it can be noticed that the output of the generator Kyle138 is 250 MW while the Spirit69 one is 80 MW. This statement underlines the fact that Kyle138 has a higher P_m, thus a higher stored kinetic energy than the Spirit69 one. (Their inertia H = 3 is equal for both the generators)

By this reason, the higher the P_m the worse for the stability of the generator and therefore the shorter the t_{crit}.

However, the t_{crit} is higher than the Spirit69 one; it means that the gap δ_{cr} - δ_0 of the Kyle138 is larger than the Spirit69 one.

$$t_{cr} = \sqrt{\frac{4H(\delta_{cr} - \delta_0)}{\Omega_s p_m}}$$

- **Critical clearing time increasing KYLE138's H**

As requested, a further analysis has been done by changing the Inertia Constant H of Kyle138 from 3.0 $\frac{MJ}{MVA}$ to 6.0 $\frac{MJ}{MVA}$. From a physical point of view $H = 6$ means that the kinetic energy stored can feed the rated load for 6s. By definition, $H = \frac{\frac{1}{2}J\Omega^2{}_{sm}}{S}$, so the gain of H is related to an increase of the momentum of inertia J of the generator. Higher J means a slower respond to the perturbation. Therefore, it's reasonable to expect a longer critical time with respect to the previous case, proportionally to $t_{cr} = \sqrt{\frac{4H(\delta_{cr}-\delta_0)}{\Omega_s p_m}}$. Hence, the more H the more the time until the critical rotor angle is reached and the more stable the situation.

The previous statement is confirmed by the simulation. By setting the critical clearing time of the previous case (0.22 s), Figure 2.6 shows that the maximum rotor angle reached is less than before.

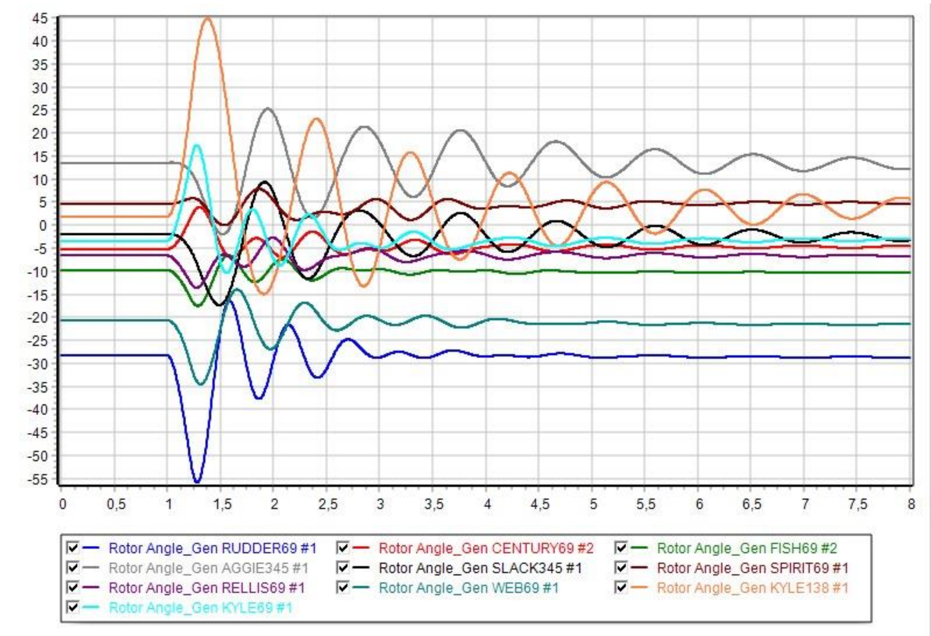


Figure 2.6

The critical clearing time for this case has been found in the same way of the previous ones, by increasing the opening time through 0.01 steps, until the loss of synchronism. The obtained result is $t_{crit} = 0.36\ s$, 0,14s higher than the result obtained before. The behavior of the generators' rotor angle is reported in Figure 2.7.

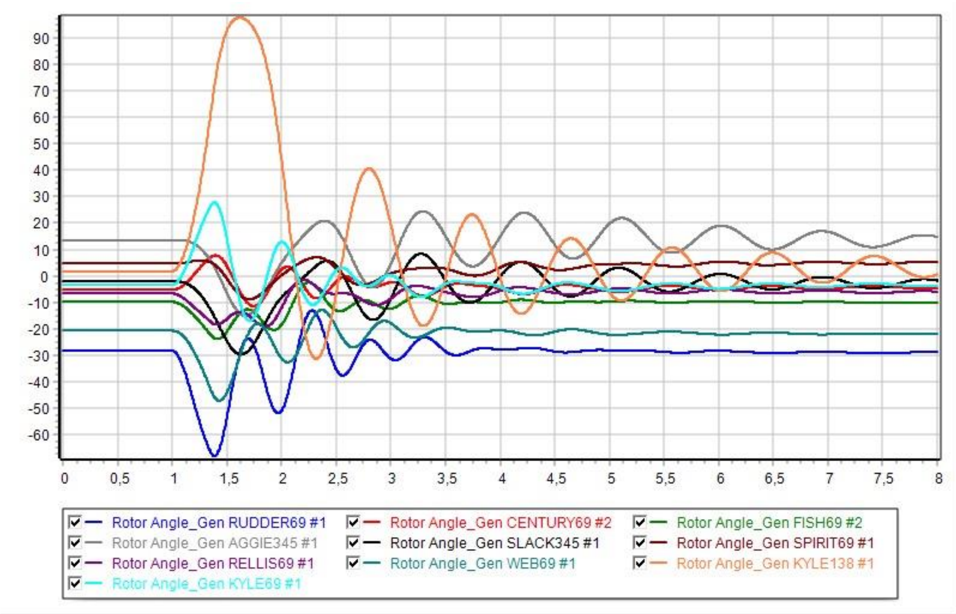


Figure 2.7

By setting a $t_{clear} > t_{crit}$, for example equal to 0.37, the system is no more stable. This situation is reported in Figure 2.8.

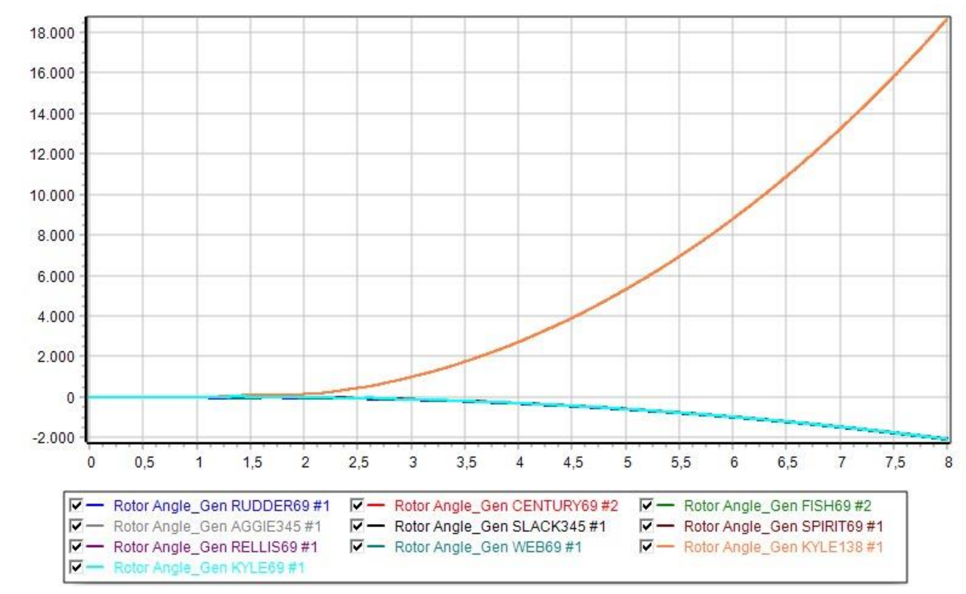


Figure 2.8

It is interesting to notice that both Figure 2.2 and Figure 2.8 represent unstable conditions, and the last one presents a less slope in the increase of the rotor angle since the inertia of the machine is bigger. Therefore, the acceleration is more contained, and this instance is more stable.

- **Comparison between critical time of KYLE138, SPIRIT69, CENTURY69 and FISH69**

In this section a comparison between the t_{crit} computed using the equal area criterion and t_{crit} provided by the simulator is done.
From the theory it is known that the expressions of the δ_{crit} and t_{crit} are:

$$\delta_{crit} = arcos[-cos(\delta_0) + \sin(\delta_0)(\pi - 2\delta_0)]$$

$$t_{crit} = \sqrt{\frac{4H(\delta_{crit} - \delta_0)}{\Omega_s p_m}}$$

These last equations are correct if considering the generators modelled as shown in Figure 2.9, with the angle θ taken as reference.

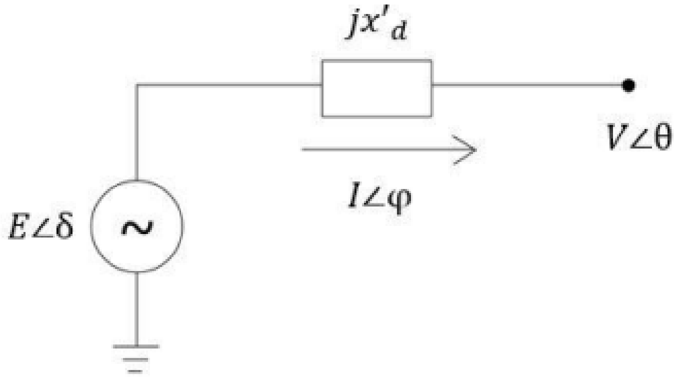


Figure 2.9

Since PowerWorld does not set the terminal bus of the faulted generator as reference, the expressions for δ_{crit} and t_{crit} must be corrected by considering the actual value of the bus angle θ_0; the updated equations are reported below.

$$\delta_{crit} = arcos[-cos(\delta_0 - \theta_0) + \sin(\delta_0 - \theta_0)(\pi - 2(\delta_0 - \theta_0))]$$

$$t_{crit} = \sqrt{\frac{4H(\delta_{crit} - (\delta_0 - \theta_0))}{\Omega_s p_m}}$$

The obtained results are reported in Table 2.1, while generators' data in Table 2.2.

GEN	**Θ0**	**δ0**	**δcrit**	**t_{crit} computed**	**t_{crit} simulation**	**Faulted Line**
KYLE138	-0,39655	0,03218	1,53072	**0,290**	**0,368**	K138-W138
SPIRIT69	-0,4432	0,08105	1,38774	**0,175**	**0,201**	S69-M69
CENTURY69	-0,45227	-0,09023	1,64981	**0,221**	**0,256**	C69-R69
FISH69	-0,48184	-0,17034	1,75174	**0,254**	**0,279**	F69-W69

Table 2.1

GEN	**P_m [p.u.]**	**H**
KYLE138	0.833	6
SPIRIT69	0.89	3
CENTURY69	0.833	3
FISH69	0.706	3

Table 2.2

As it can be seen, the two critical time are quite different from each other; the reason is to search in the model of the system adopted in the manual computation, shown in Figure 2.10, from where it is possible to notice that the bus at the far-end of the faulted line is considered as the infinite bus.

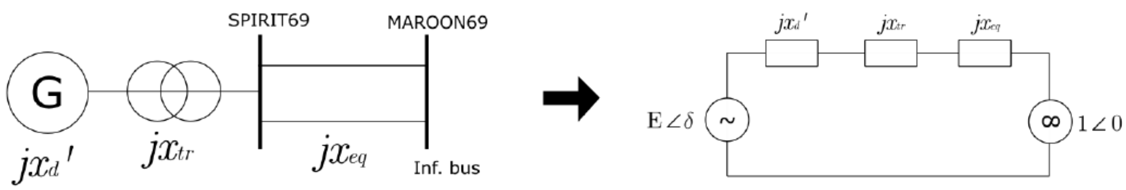


Figure 2.10

This simplification leads to an underestimation of the critical clearing time, since in the simulated case the system connected to the end of the line has a finite power.

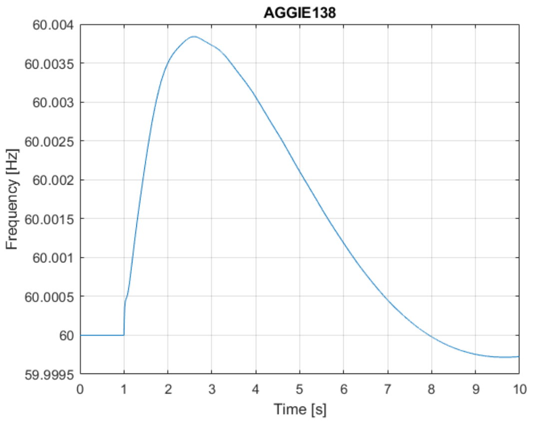
In conclusion it is possible to say that, since the critical area criterion provides a smaller t_{crit} than the simulation, using this last represent a more secure assumption than using the simulated one.

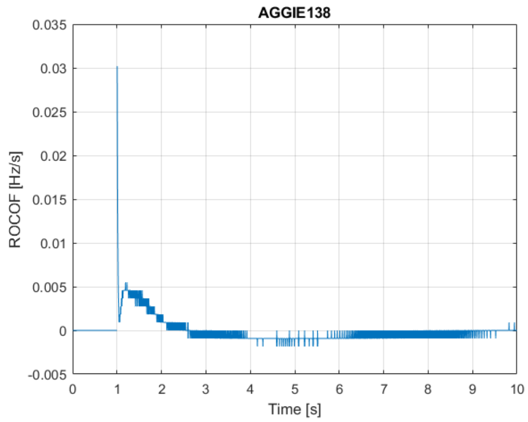
RUDDER69 CONTINGENCY

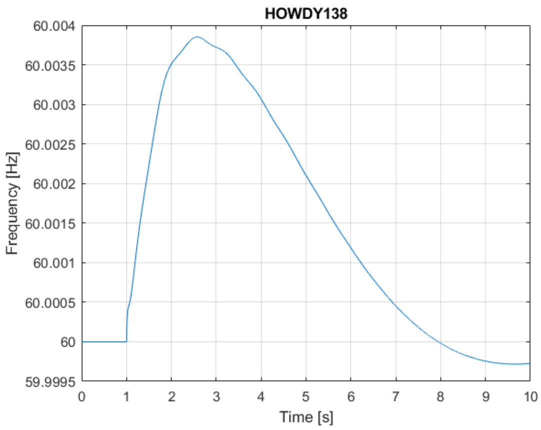
In this section the contingency of RUDDER69 generator is studied, focusing on the frequency response of the system and on the changes in voltage profiles. In order to evaluate this, the team has taken data from ten buses on the 138 kV grid. More precisely, the considered buses are AGGIE138, HOWDY138, REED138, TEXAS138, KYLE138, HULLABALOO138, RELLIS138, WHITE138, WEB 138 and PLUM138.

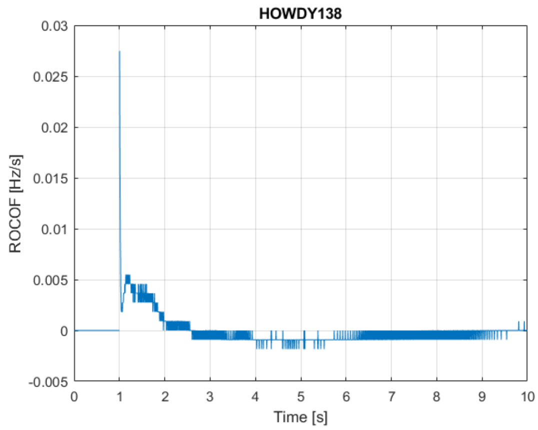
It is worth to notice that in order to consider both frequency and voltage controls, governors have been activated on the largest generators, which are KYLE138, AGGIE345, FISH69, CENTURY69 and SPIRIT69. Before starting the simulation, the team has checked both active and reactive power injection from RUDDER69, which are respectively 0 MW and 5 MVAR, hence the generator works as a pure reactive power source.

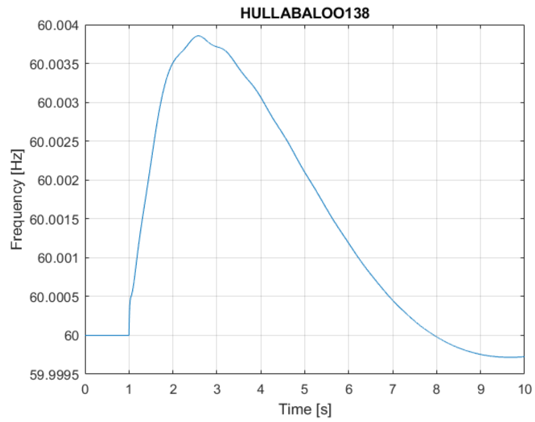
After the fault has been applied (at t=1 s), the obtained results of frequency and RoCoF have been plotted for each of the considered bus. The behaviors are shown in the following pictures.










HULLABALOO138
Frequency [Hz]
Time [s]
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60.0035
60.003
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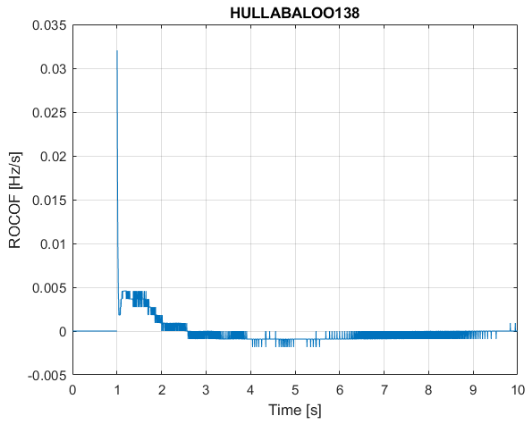
0 1 2 3 4 5 6 7 8 9 10


HULLABALOO138
ROCOF [Hz/s]
Time [s]
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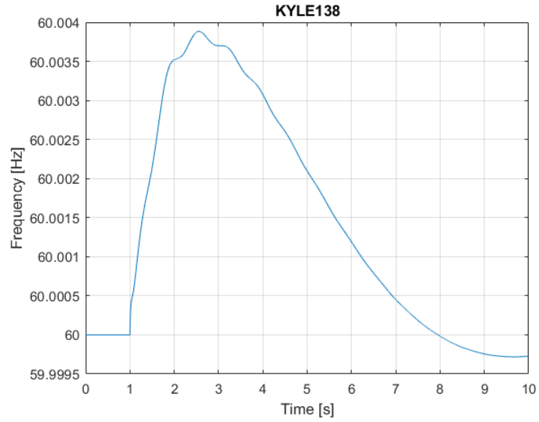
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Time [s]
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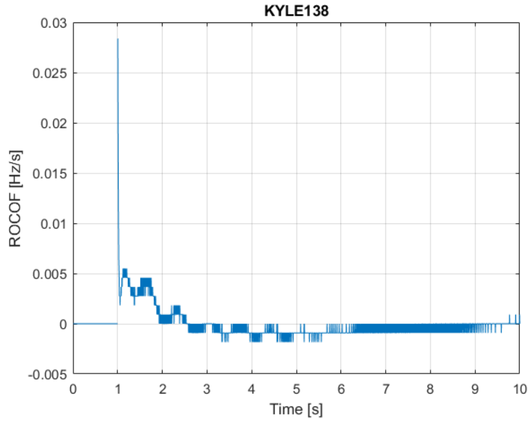
KYLE138
ROCOF [Hz/s]
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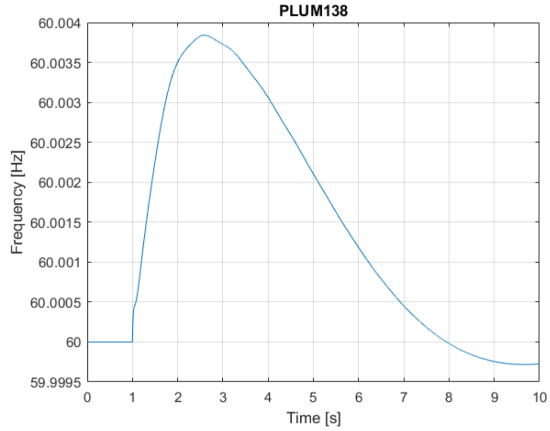
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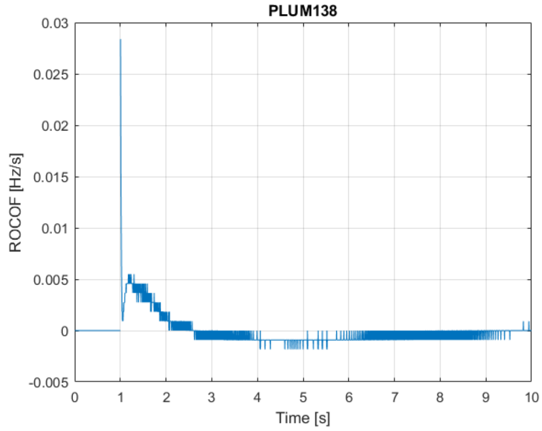
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Time [s]
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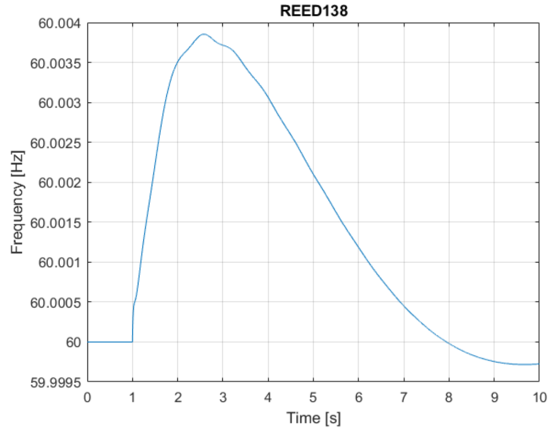
REED138
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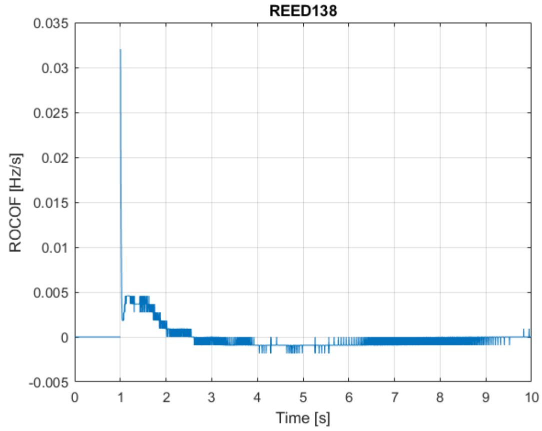
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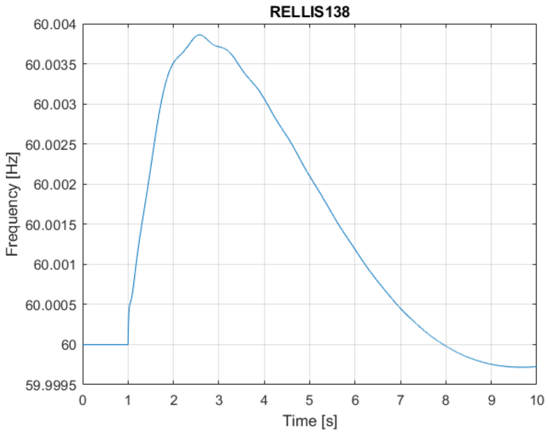
RELLIS138
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60.001
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59.9995
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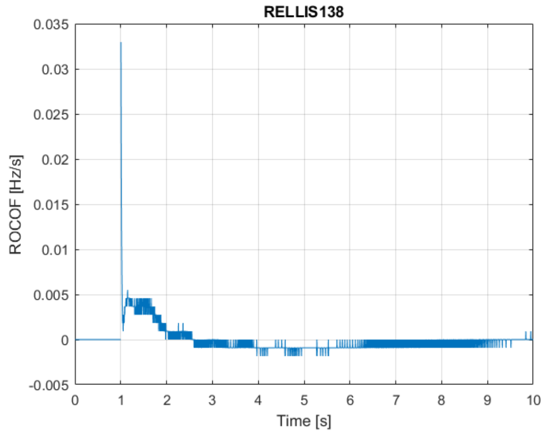
Time [s]


RELLIS138
ROCOF [Hz/s]
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0.03
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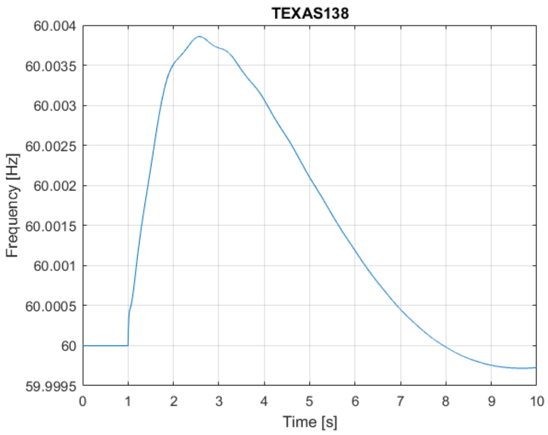
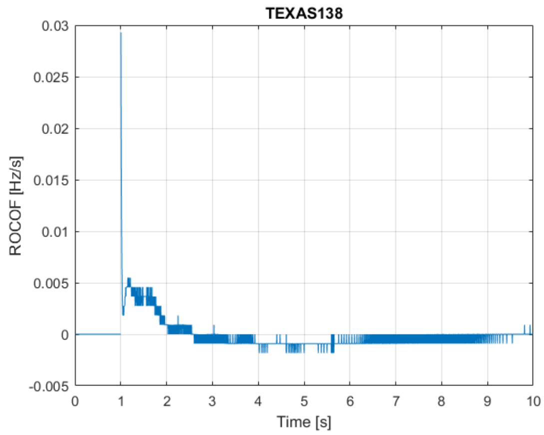
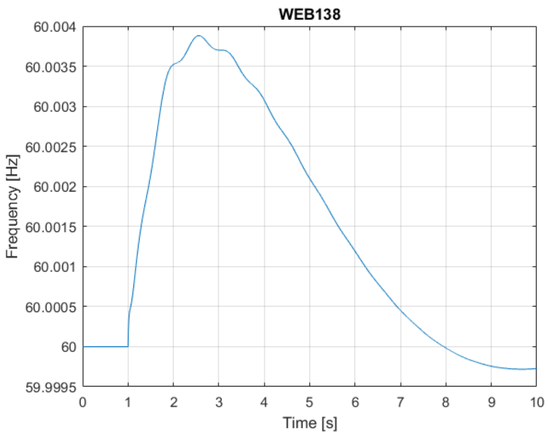
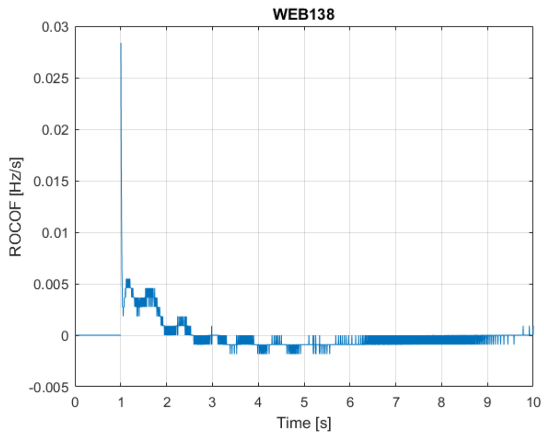
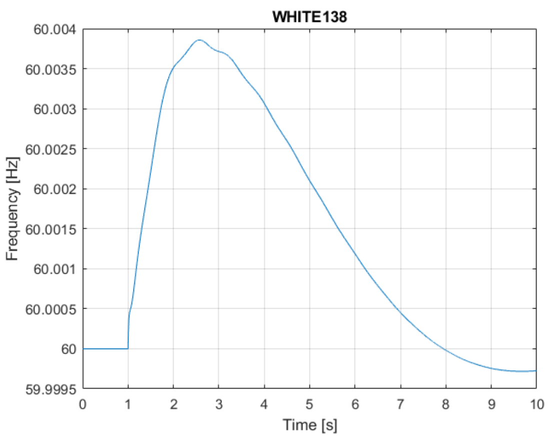
-0.005
0 1 2 3 4 5 6 7 8 9 10
Time [s]

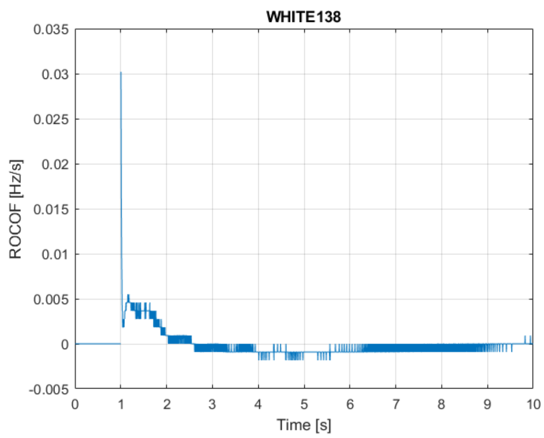

TEXAS138
Frequency [Hz]
60.004
60.0035
60.003
60.0025
60.002
60.0015
60.001
60.0005
60
59.9995
0 1 2 3 4 5 6 7 8 9 10
Time [s]


TEXAS138
ROCOF [Hz/s]
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0 1 2 3 4 5 6 7 8 9 10
Time [s]


WEB138
Frequency [Hz]
60.004
60.0035
60.003
60.0025
60.002
60.0015
60.001
60.0005
60
59.9995
0 1 2 3 4 5 6 7 8 9 10
Time [s]


WEB138
ROCOF [Hz/s]
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0 1 2 3 4 5 6 7 8 9 10
Time [s]


WHITE138
Frequency [Hz]
60.004
60.0035
60.003
60.0025
60.002
60.0015
60.001
60.0005
60
59.9995
0 1 2 3 4 5 6 7 8 9 10
Time [s]


WHITE138
ROCOF [Hz/s]
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0 1 2 3 4 5 6 7 8 9 10
Time [s]

Through a first glance, both frequency and RoCoF follow a similar trend on each bus. After the fault, the first reach their maximum and then return to a new frequency close to 60 Hz. Being the RoCoF the derivative in time of the frequency, its behavior is coherent with the first one, showing positive values before t=2.5 s (frequency peak) and negative ones after.
As shown in Figure 3.1, it is interesting to notice that by increasing the simulation time to 30 s, frequencies follow a slow damped oscillating pattern due to the primary frequency control.

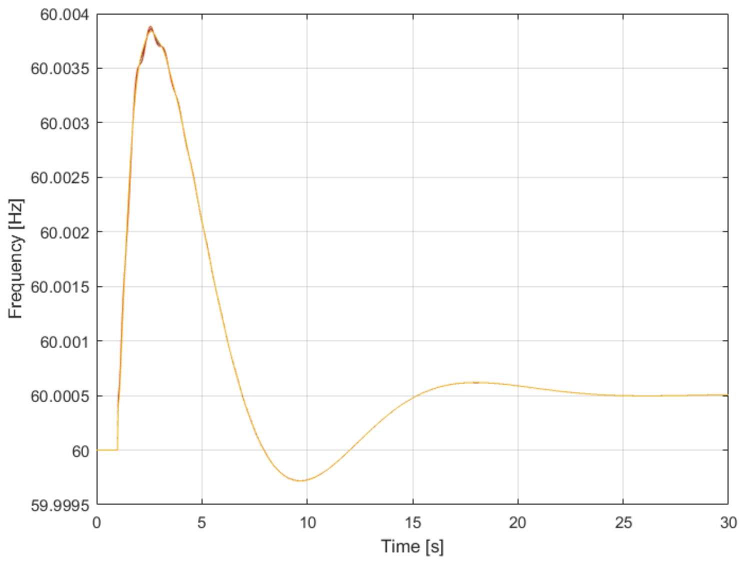


Figure 3.1   Frequency of all buses with 30 seconds simulation

This behavior of the frequency can be explained by looking at the active power withdrawn by load connected to RUDDER69 bus. Its plot is shown in Figure 3.2 from where it is possible to see a reduction in the withdrawn active power due to the fault. Hence, since the active power decreases, the frequency initially increases.

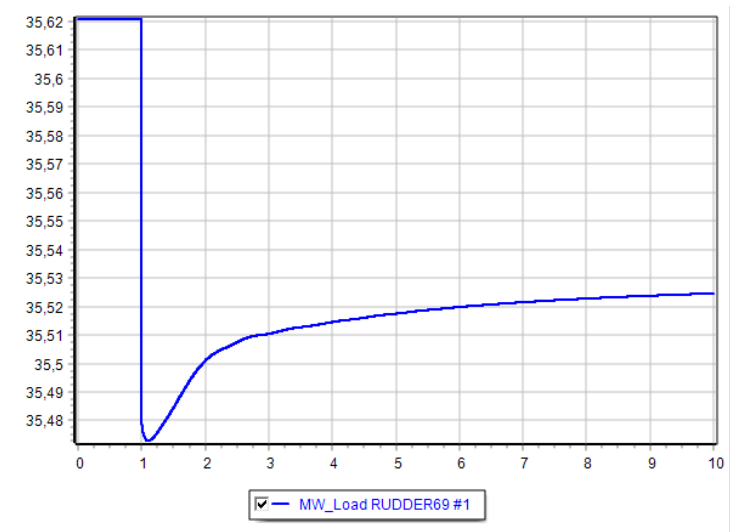


Figure 3.2   RUDDER69 Load's active Power

Values of frequency and RoCoF of each bus are reported in Table 3.1.

Bus	Max Frequency [Hz]	Min Frequency [Hz]	Max RoCoF [Hz/s]
AGGIE138	60.0038	59.997	0.0302
HOWDY138	60.0039	59.997	0.0275
HULLABALOO138	60.0039	59.997	0.0320
KYLE138	60.0039	59.997	0.0284
PLUM138	60.0038	59.997	0.0284
REED138	60.0039	59.997	0.0320
RELLIS138	60.0039	59.997	0.0330
TEXAS138	60.0039	59.997	0.0293
WEB138	60.0039	59.997	0.0284
WHITE138	60.0039	59.997	0.0302

Table 3.1

In Figure 3.3 is reported the trend of the p.u. voltage magnitudes for each considered bus.

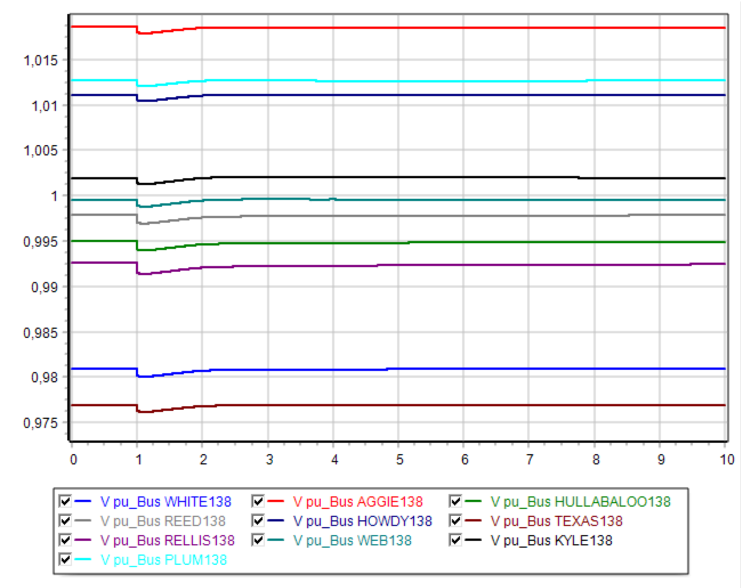


Figure 3.3 p.u. voltages

It is possible to notice that all the voltages suddenly decrease in the instant in which the fault occurs and then return to their fixed value after a transient. The reduction is caused by the lack of reactive power injected by the faulted generator, which helped to keep the voltages at the fixed point. Since the other generators increase their reactive injection after the fault and thanks to the governors which provide for voltage control, a steady state value is then reached. The reactive power flows of the five generators is reported in Figure 3.4.

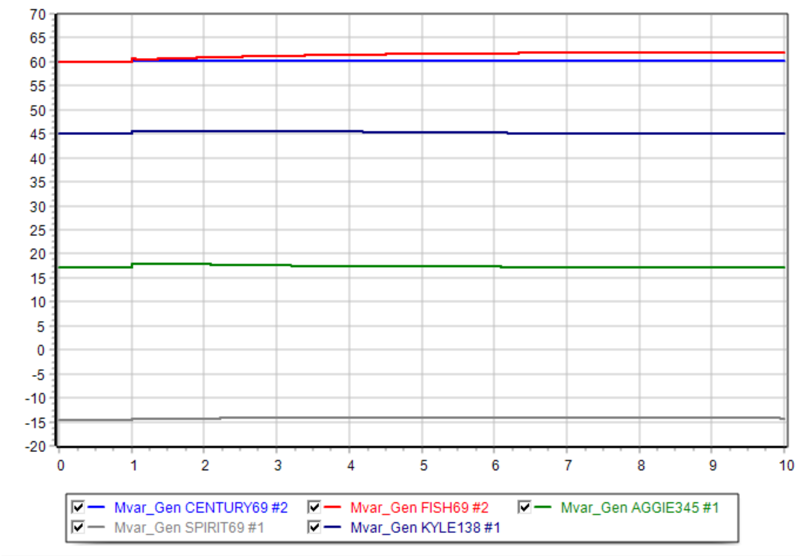


Figure 3.4 MVAr injection

The recorded values of minimum voltage for each considered bus are reported in Table 3.2.

Bus	**Min V [p.u.]**
AGGIE138	1.0179
HOWDY138	1.0104
HULLABALOO138	0.9939
KYLE138	1.0012
PLUM138	1.0120
REED138	0.9969
RELLIS138	0.9914
TEXAS138	0.9761
WEB138	0.9988
WHITE138	0.98

Table 3.2

RUDDER69 & RELLIS69 CONTINGENCIES

For this step the team has chosen to open RELLIS69 generator at t=1, which cause a lack of 60 MW and 40 MVAr injected. By summing the effects of this last contingency and the previous one (which also occurs at t=1), the total loss in generation amounts to 60 MW and 45 MVAr.

The governors have been activated on the same generators as before and the buses on which frequencies and voltages are evaluated are the same as in the previous point.

By analyzing the frequency, it is possible to notice that its behavior is quite the same for all the considered buses such as for the RoCoF, as reported in Figure 4.1 and Figure 4.2. At t=1 the frequency starts to decrease due to the contingencies, since all the non-faulted generators slow in order to provide for the missing power. Thanks to the governors, which provides for primary frequency control, this last stop to decrease and restart to increase in order to reach a new steady state. By comparing the two following pictures, it is possible to see that the RoCoF is coherent with the frequency, crossing the 0 axis when the frequency reaches its minimum.

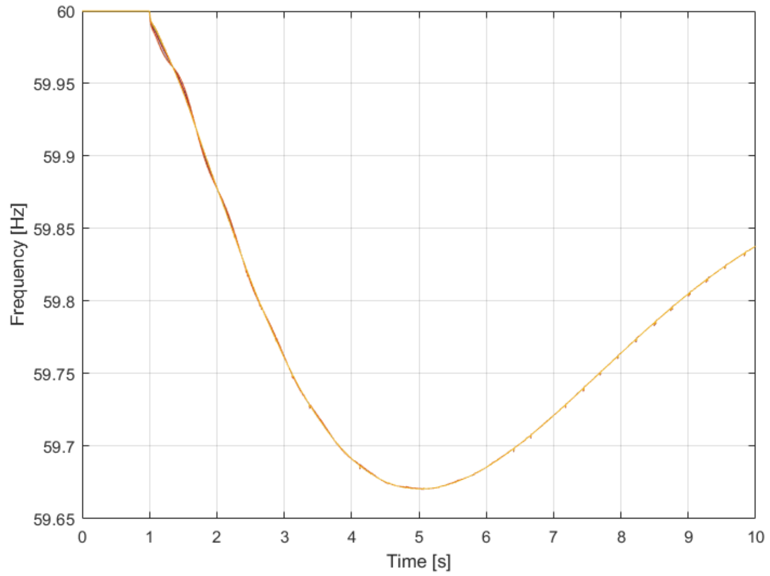


Figure 4.1 Frequency of all buses

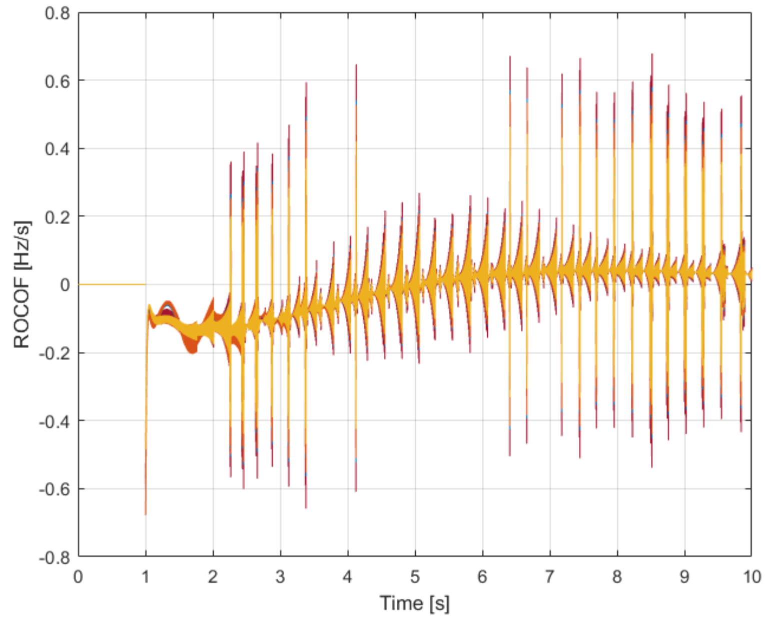


Figure 4.2 RoCoF of all buses

As shown in Figure 4.3, by increasing the simulation time from 10 to 30 seconds it is also possible to see the effect of the frequency control.

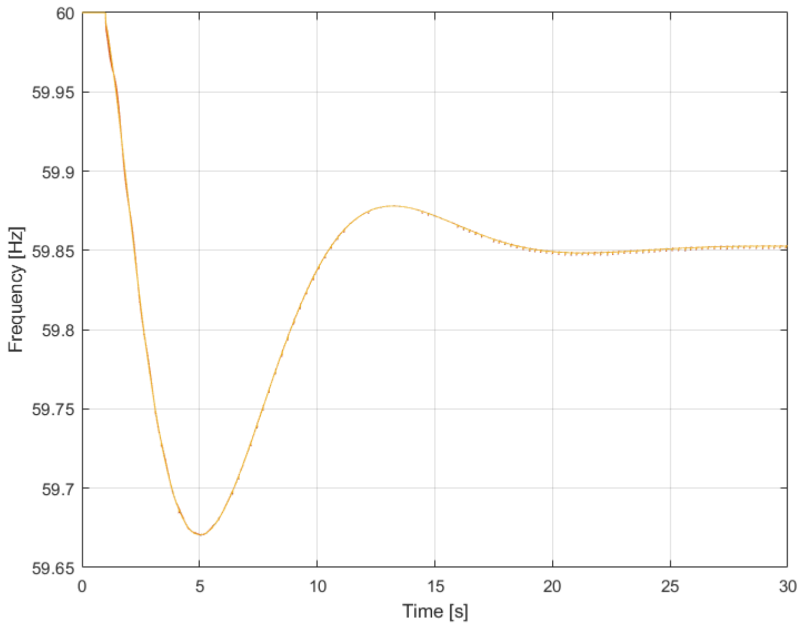


Figure 4.3   Frequencies behavior for 30 seconds simulation

Values of frequency and RoCoF for each bus are reported in Table 4.1.

Bus	Max Frequency [Hz]	Min Frequency [Hz]	Max RoCoF [Hz/s]
AGGIE138	60	59.6703	-0.4506
HOWDY138	60	59.6702	-0.5712
HULLABALOO138	60	59.6701	-0.6245
KYLE138	60	59.6702	-0.6774
PLUM138	60	59.6702	-0.4852
REED138	60	59.6701	-0.6016
RELLIS138	60	59.6701	-0.6584
TEXAS138	60	59.6701	-0.5987
WEB138	60	59.6702	-0.6765
WHITE138	60	59.6701	-0.6309

Table 4.1

Further consideration can be done by considering the voltage trends on buses, which are plotted in Figure 4.4. Since there is a lack in the reactive power provided by the faulted generators, all the voltages suddenly decrease in the beginning. Then, thanks to the reactive power generated by the other generators and to the voltage regulation provided by the governors, a new steady state is reached.

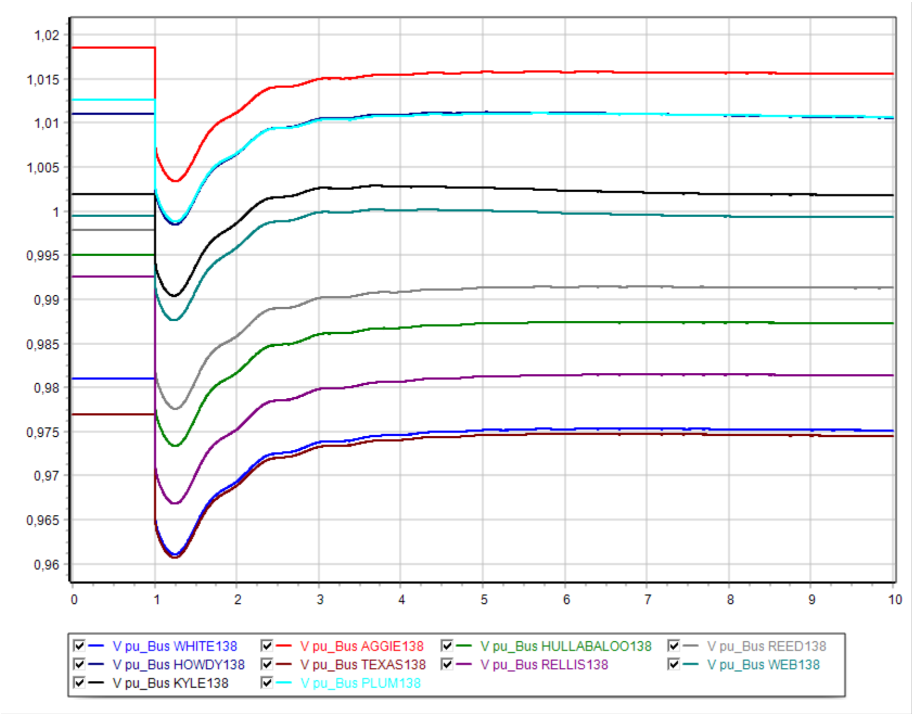


Figure 4.4 Bus Voltages

The minimum values of the bus voltages are reported in Table 4.2.

Bus	**Min V [p.u.]**
AGGIE138	1.0034
HOWDY138	0.9985
HULLABALOO138	0.9734
KYLE138	0.9904
PLUM138	0.9988
REED138	0.9776
RELLIS138	0.9668
TEXAS138	0.9607
WEB138	0.9876
WHITE138	0.9611

Table 4.2

- **Comparison between RUDDER69 and RUDDER69 + RELLIS69 faults**

A quick comparison between the two analyzed case can be done.

The main difference is shown in the behavior of the frequencies. In fact in the first case there is only a lack in reactive power (and a small reduction in the absorbed power), while in the second the fault causes a lack in both active and reactive powers; this lead to a reduction in

frequency in the second case and an increase in the first. It is worth to notice that the changes in frequencies have very different values: in the first case, the reduction in the withdrawn active power from the load at bus RUDDER69 (which causes a mean frequency increase less than 0.004 Hz) is of 0.15 MW, while the reduction in the injected active power due to the fault of RELLIS69 generator (which cause a mean frequency reduction of 0.35 Hz) is of 60 MW.
The voltages trends follow quite the same trend in both cases but have different entities. In fact, since the lost reactive power in the first case is smaller than in the other situation, the voltages present a smaller variation due to the loss of RUDDER69 than losing both RUDDER69 and RELLIS69 (5 MVAr vs 45 MVAr).

GENERAL PROCEDURE AND ADVICES

In order to keep the stability of the system, a proper choice of the clearing times for each fault is crucial. As seen from the previous points, the critical time founded with the PowerWorld simulation keeps a too low security margin and each possible delay in fault clearing (even if small) could lead to the instability of the system. Hence, a better choice is represented by using the simulation as a confirm of the critical time obtained with the equal area criterion, which keeps a larger margin and keeping this last as limit time; in this way, the system is kept in a more secure state.
Another issue that is worth to consider is represented by the generators loading. As shown in the SPIRIT69 contingency, if generators are working close to their limits, the initial δ_0 is high and the critical angle is reached before than in less-loading condition (and so critical time is smaller). Hence, if possible, it is better to not have generators working close to their limit conditions.