ACTIVITY 1
BASIC UNDERSTANDING OF THE SYNCHRONOUS GENERATOR (SG)

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- UPC -

Contents

1 Single generator connected to a load

By opening the file 'Assign Task1and2.slx' in matlab, the following concepts were studied. The simulation depicts a simple load connected to a synchronous generator without any droop control, as we will see, any power mismatch will destabilise the grid frequency and stall the generator.

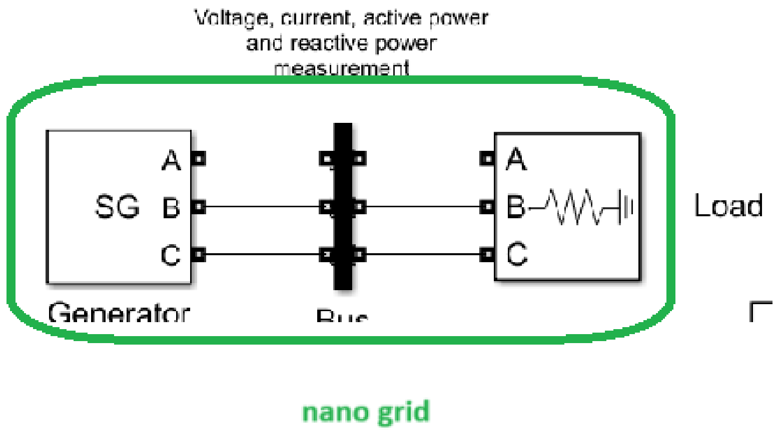

Figure 1: simulink blocks for generator and load

1.1 Power from the generator

At around 11 seconds the generator simulation stalls and is never recovering. Its also worth to notice the high frequency noise created by the inductive generator resonating with the inductive load, and how this same noise is much less frequency with a capacitive load.

Both the inductive and cases are demanding more power from the generator because that's the way we setting the parametric simulation, 50% for the resistive case and 100% for the rest Figure 2.

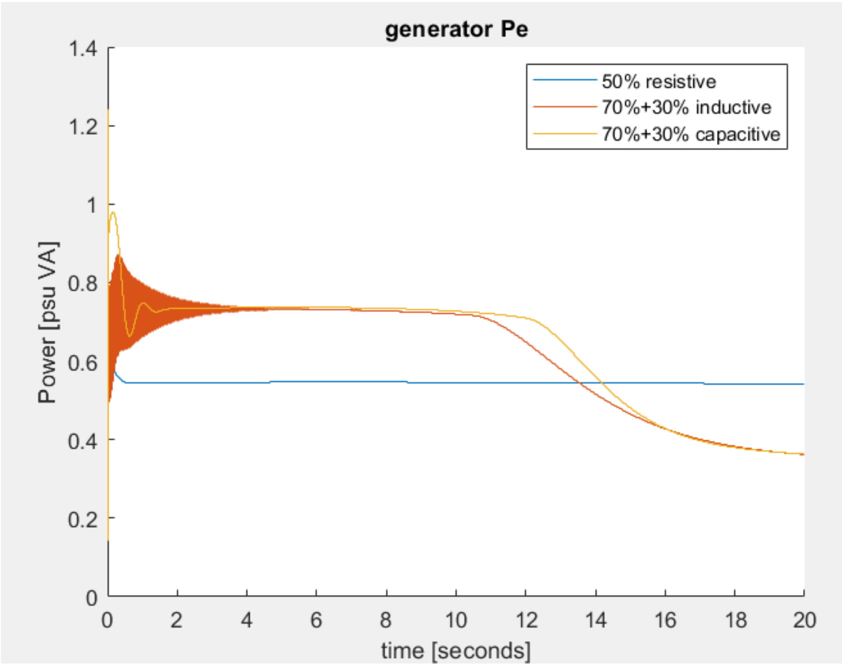

Figure 2: generator Pe

1.2 Power at the load P&Q

In Figure 3 , the most evident characteristic is that reactive power for the resistive case is non-existent, whereas for inductive load, Q becomes positive, and for capacitive load Q becomes negative.

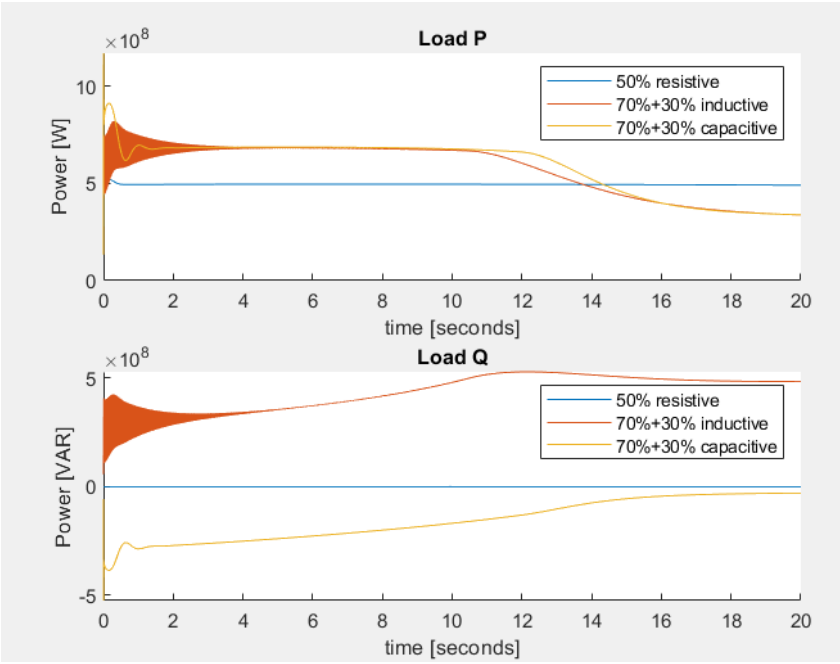

Figure 3: loadPQ

1.3 Grid frequency in pu

The generator has a fixed mechanical power input. When the load requires more power than the generator can supply, the generator's electrical frequency decreases. This happens because the load draws power from both the generator and its own momentum, effectively slowing down the generator's physical rotation speed. Figure 4

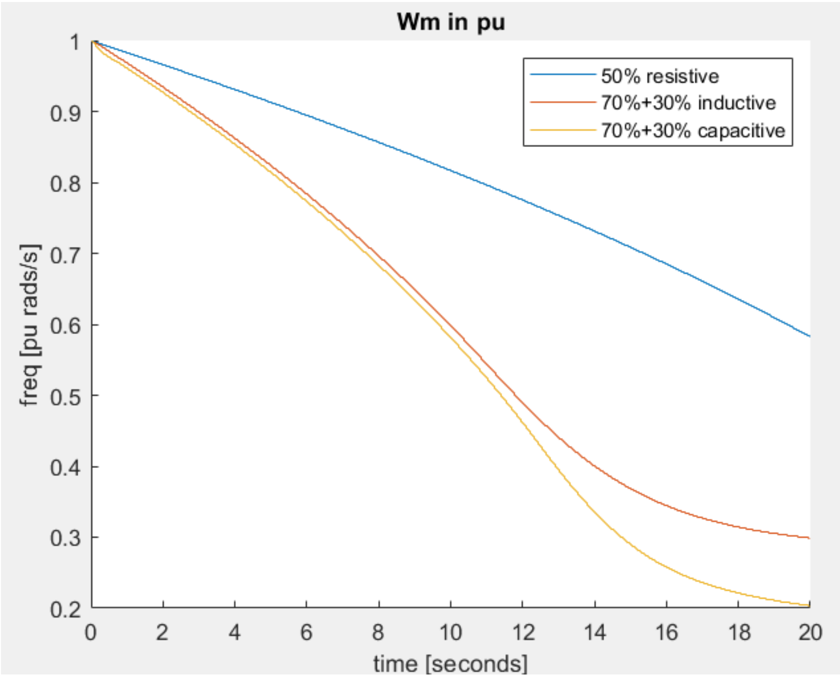

Figure 4: Generator deceleration for each load case

If the load were to be only 10% the synchronous generator would be producing more power than the one demanded by the load (about 30% Pe), this would cause the generator to store the excess energy in form of increased electrical rotation speed, effectively increasing our "nanogrid" frequency Figure 5 . Its not a surprise that matching generation and demand will result in a stable unmodified grid frequency.

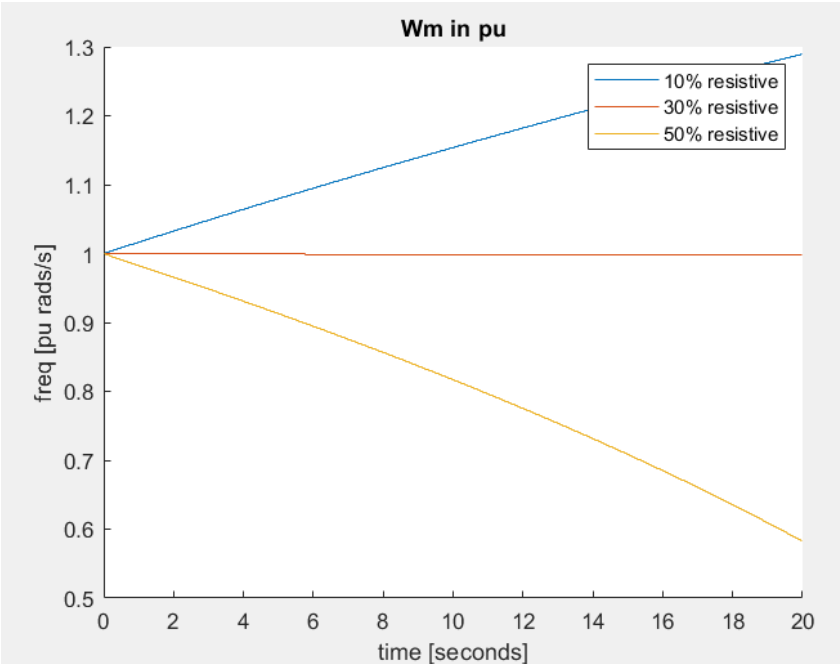

Figure 5: generator accelerating or braking depending on load power

2 Single generator connected to a bus

Opening "Assign Task1and2.slx" in simulink and discussing the following aspects. The nanogrid is still very simple, now we are simulating the effects of an extra load connection scenario in t=10s Figure 6, there is also an ideal voltage generator acting as the "slack bus".

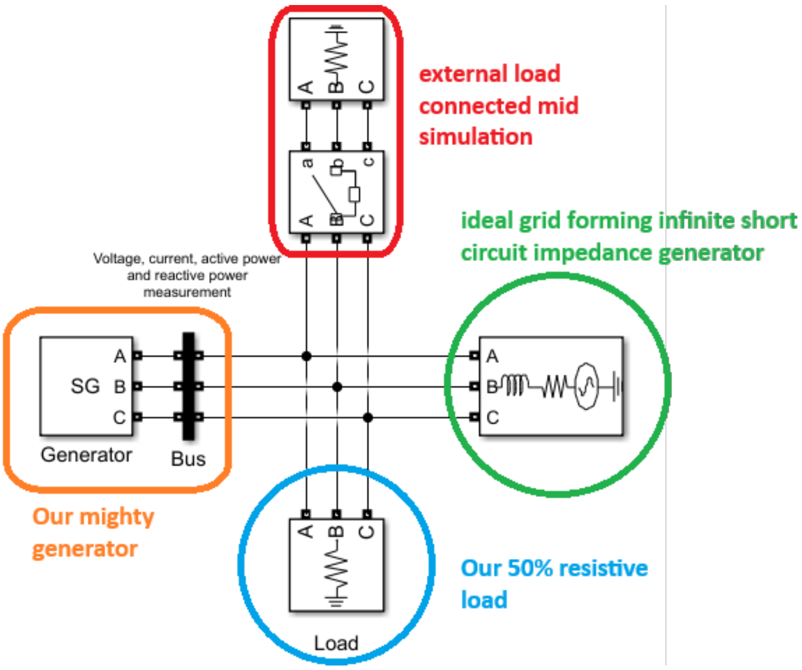

Figure 6: the simulink blocks

2.1 Load connection mid-operation

If no internal impedance (or unlimited instantaneous power delivering), the green block on the right Figure 6 acts as the perfect grid that will compensate any power transient due to load connection, no disturbances are shown in any metrics when load is connected to the bus.Figure 7, Figure 8, Figure 9.

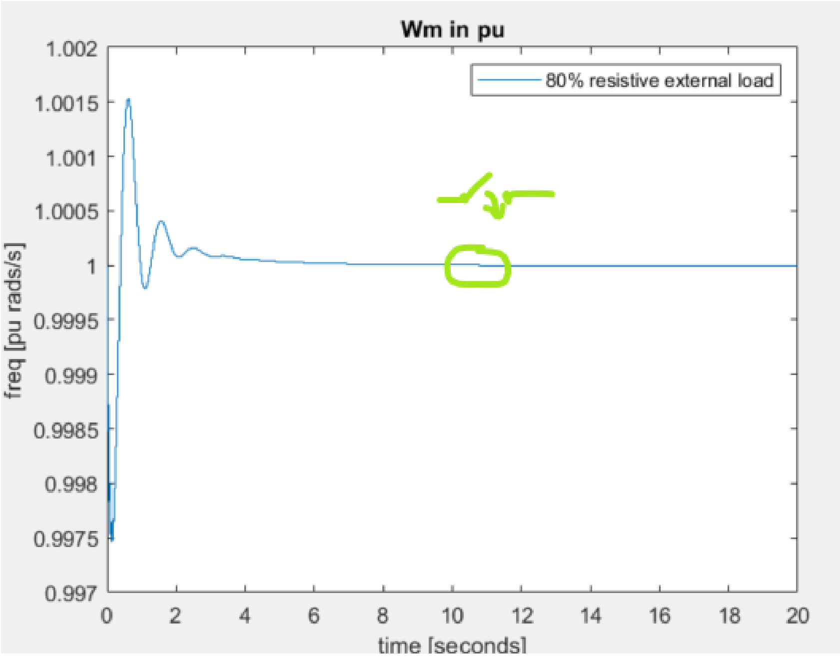

Figure 7: grid frequency without noticeable disturbance

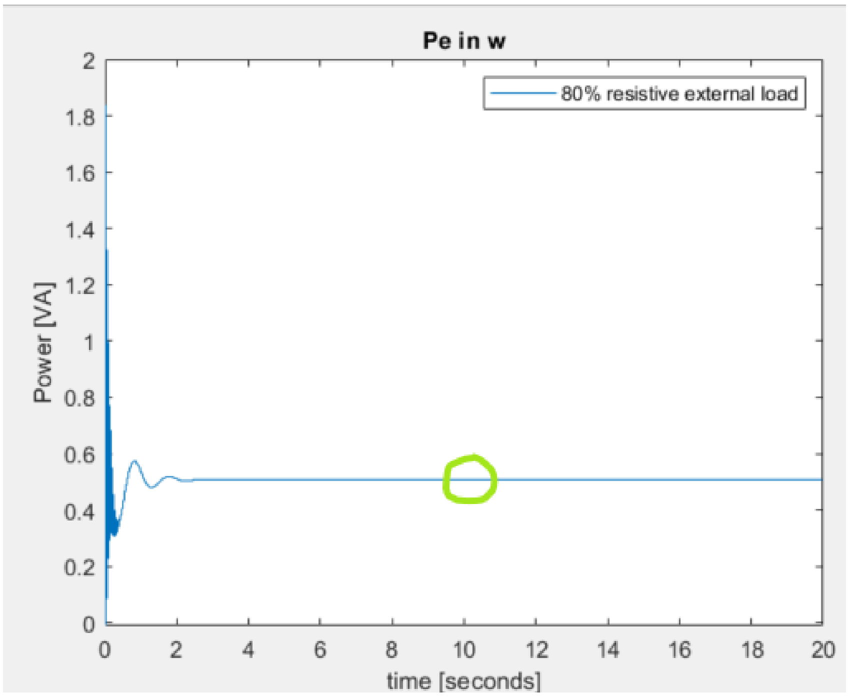

Figure 8: Power delivered by the generator, no disturbance

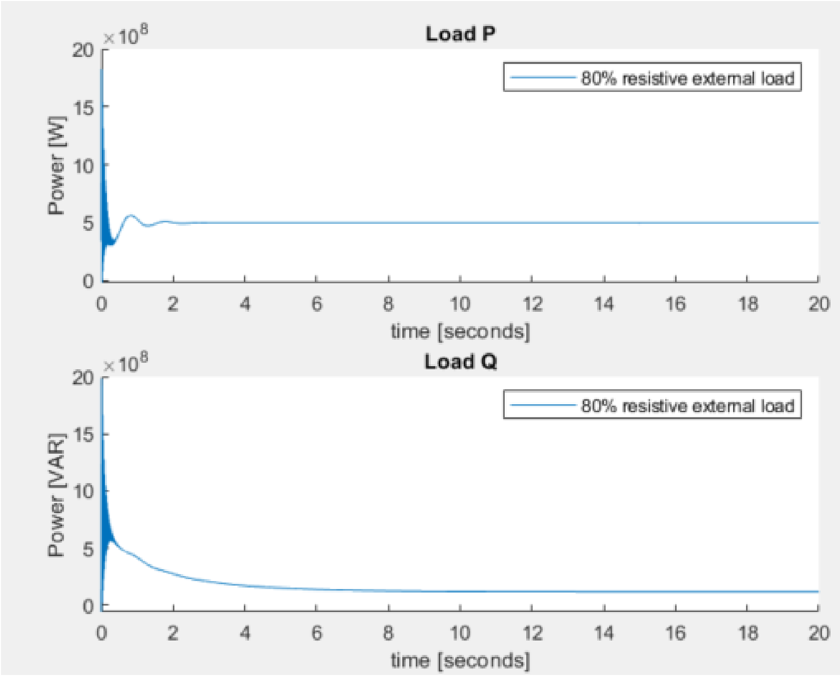

Figure 9: P and Q power flowing trough the bus,again no disturbance

2.2 Load connection mid-operation, now for different short-circuit level ratings

When real power ratings are integrated into the grid-forming source (introducing impedance that limits the power flow) , we begin to observe transients at t=10 seconds upon introducing the load. These transients affect the grid frequency Figure 10, the power supplied by the synchronous generator Figure 11, and the active (P) and reactive (Q) power flowing from the bus Figure 12. All transients get "worse" in duration and amplitude the lower is the short circuit capability of the grid forming source.

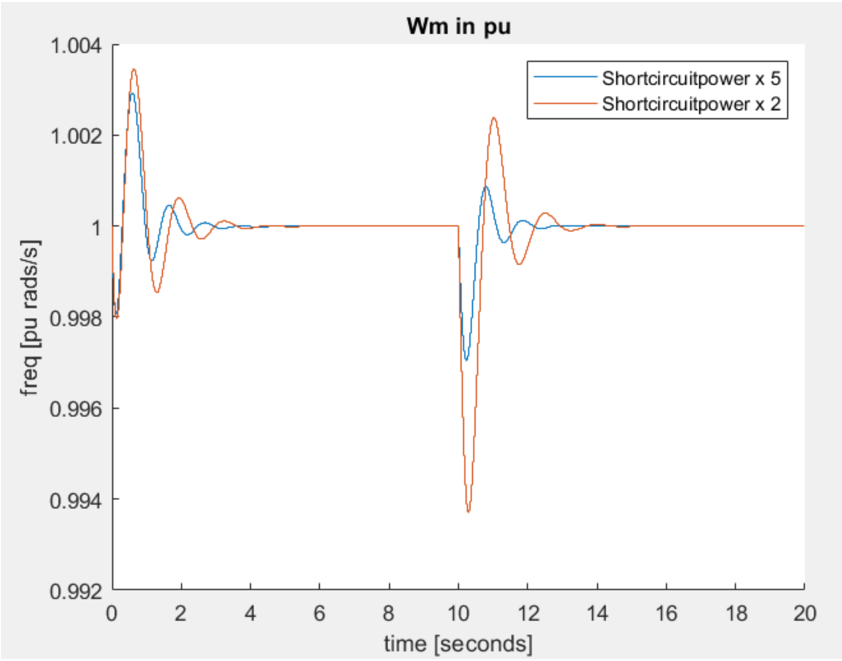

Figure 10: frequency with load connection at 10s

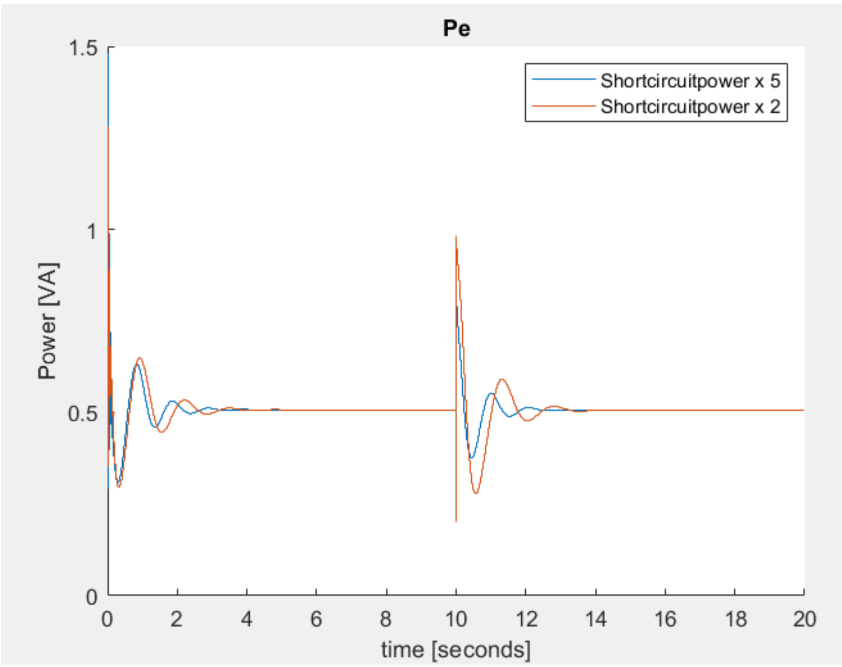

Figure 11: Power delivered by the generator

After the transient of about 2 seconds, the load connection disturbance clears and the P returns to steady state value of 5MW. It is also worth noticing how the generator is delivering Q after t=10s load connection, in order to overcome the drop in bus voltage.Figure 12, lower short circuit power requires less additional Q needed.

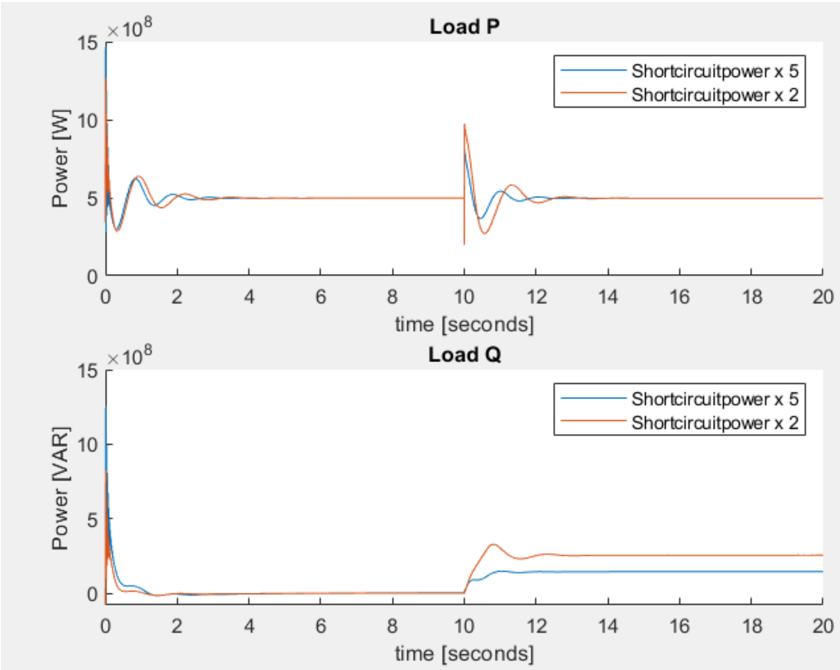

Figure 12: P and Q in the bus

Due to these transients at t=10s, the synchronous generator experiences mechanical stress and its Efd (excitation voltage) is altered. As seen in previous cases, a higher short-circuit power from the grid-forming generator results in shorter durations and reduced amplitudes of the transient. In our case study, there's a critical section where the synchronous generator reaches the limit of its Efd when short-circuit power is doubled Figure 13.

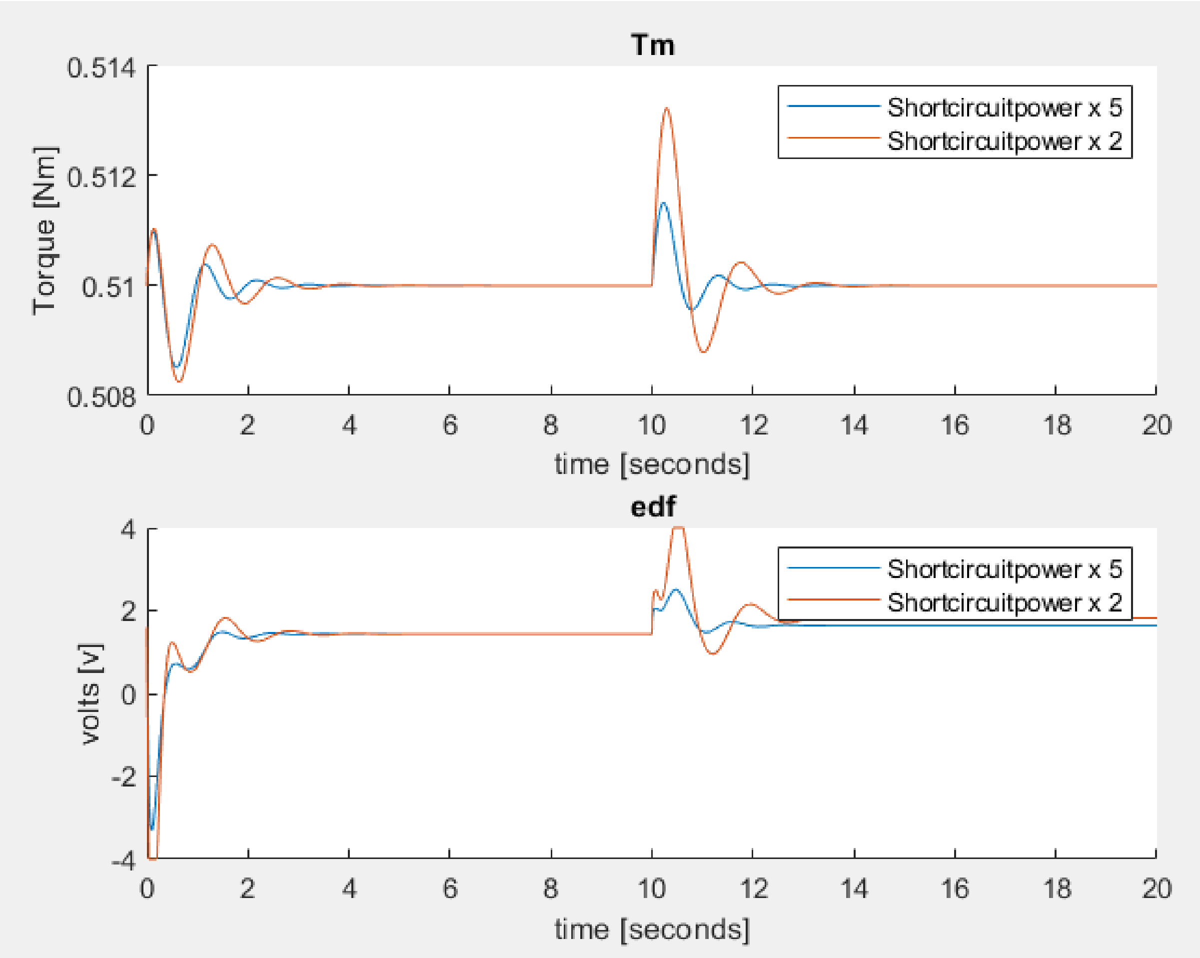

Figure 13: mechanical torque and excitation voltage of the synchronous generator

3 The role of inertia in the swing equation

Opening "Assign Task3and4.slx" in simulink and running parametric simulations varying the inertia of the synchronous generator, this time without voltage source acting as slack bus.

The secondary load is initially disconnected, connects at t=10seconds.

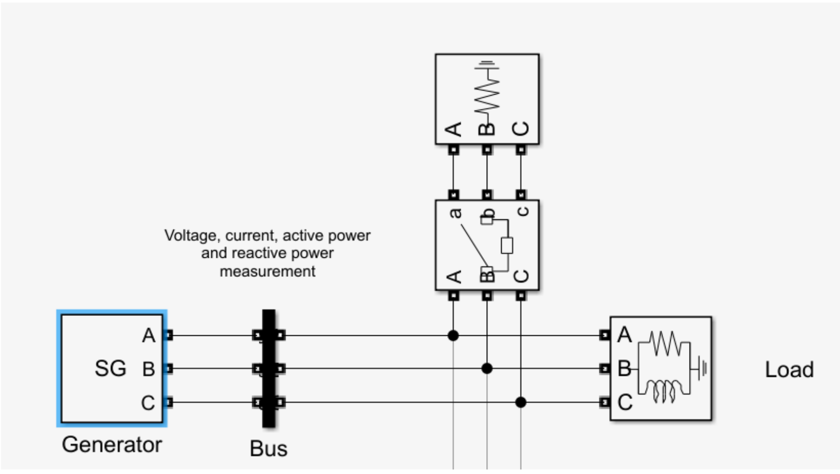

Figure 14: Simulation blocks, just our trusty synchronous generator and two loads, one of them connected mid simulation

Inertia acts as a multiplier in the direct relation between frequency and Power Figure 15. It is therefore to be expected ,a lower inertia will result in quicker reaction of wm to Power changes.

$$J\omega_{\mathrm{m}}\frac{d^2\delta_{\mathrm{m}}}{dt^2} = P_a = P_{\mathrm{m}} - P_{\mathrm{e}} \text{ W}$$

Figure 15: Swing equation relating wm , power and Inertia

3.1 Effects of inertia

When the second load is connected, the generator will eventually drop its speed and stall, this can be seen clearly in Figure 16.
The generator inertia acts as a physical "capacitor" opposing changes in wm, the lower the value of inertia the faster the generator slows down.Figure 15

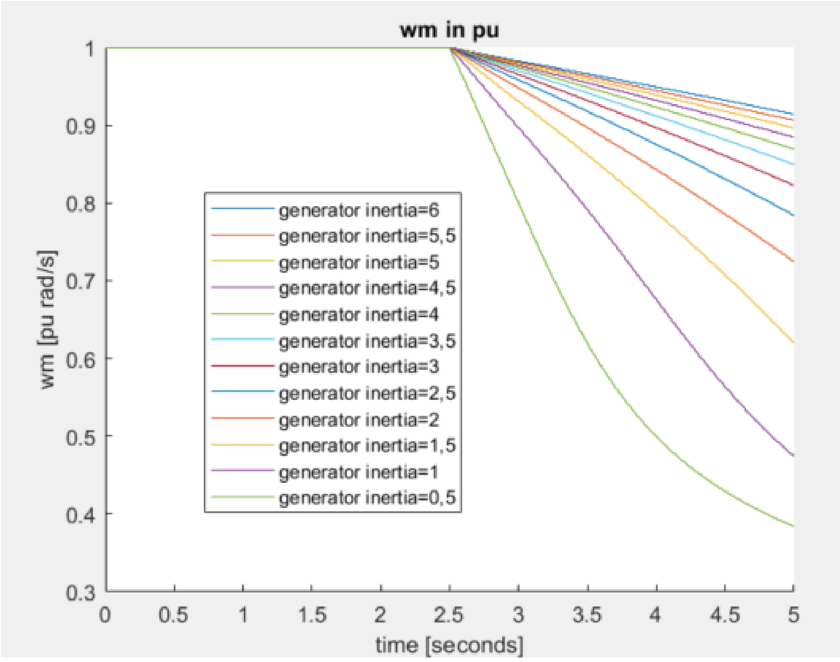

Figure 16: Frequency of the system for various inertia constants of the synchrnous generator

Active power in the bus is related to the frequency deviation, the generator tries to compensate for the new load and for the drop in wm, the smaller the inertia , the faster P drops.

In a similar manner, Q rises uncontrollably trying to compensate for voltage drops.

As there is no grid forming capability, wm , P and Q will drop (or rise) without reaching stationary values untill the generator stalls.

Figure 17.

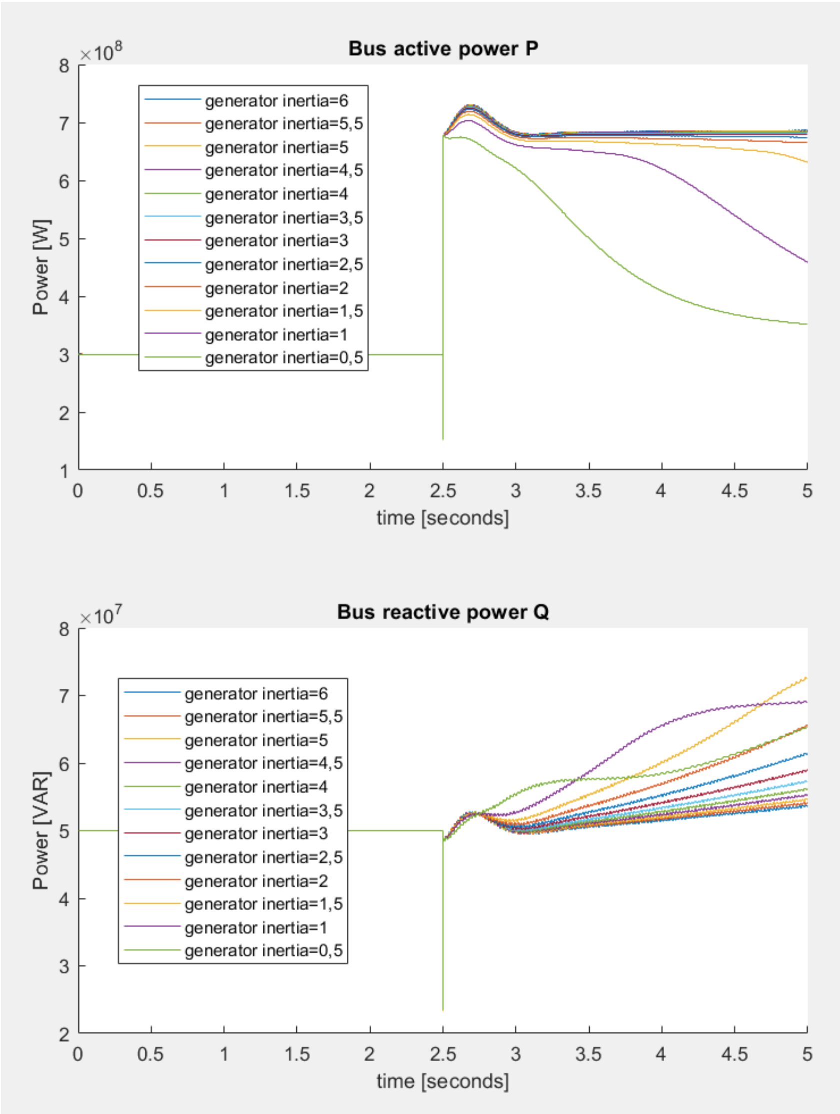

Figure 17: parametric simulations of P and Q flowing from the generator to both loads

3.2 Effects of inertia, randomizing loads

Modelling a mix between residential commercial and industrial loads Figure 18, they are modelled as individual random generators.

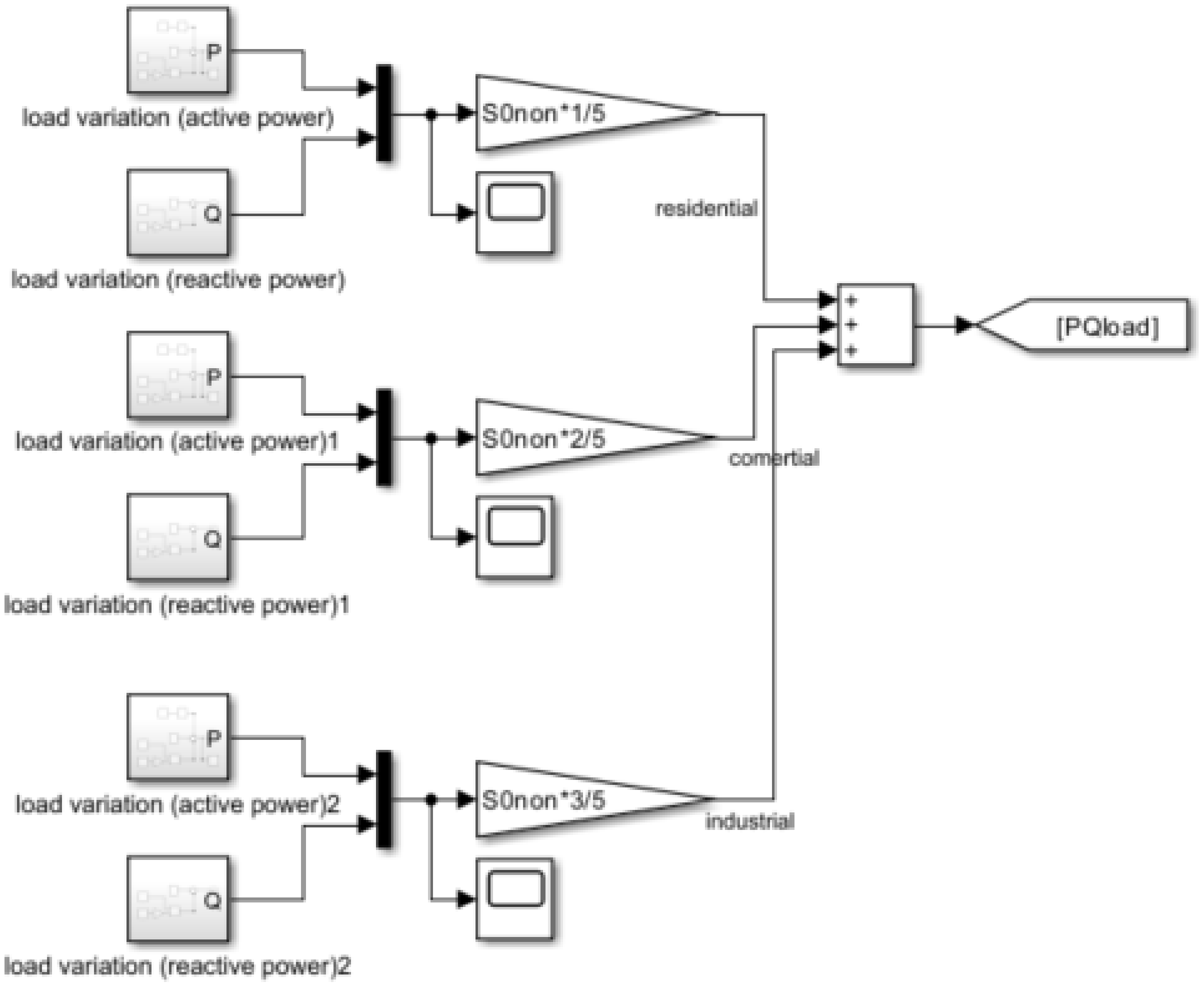

Figure 18: different loads simulation

- Residential load: low quantity low but frequent variations.
  averaged 16% of nominal power, 20% deviation from average, updated every 10 milliseconds.

- Commercial load: medium quantity medium variations.
  averaged 33% of nominal power, 50% deviation from average, updated every 50 milliseconds.

- Residential load: High quantity high and infrequent variations.
  averaged 50% of nominal power, 40% deviation from average, updated every 100 milliseconds.

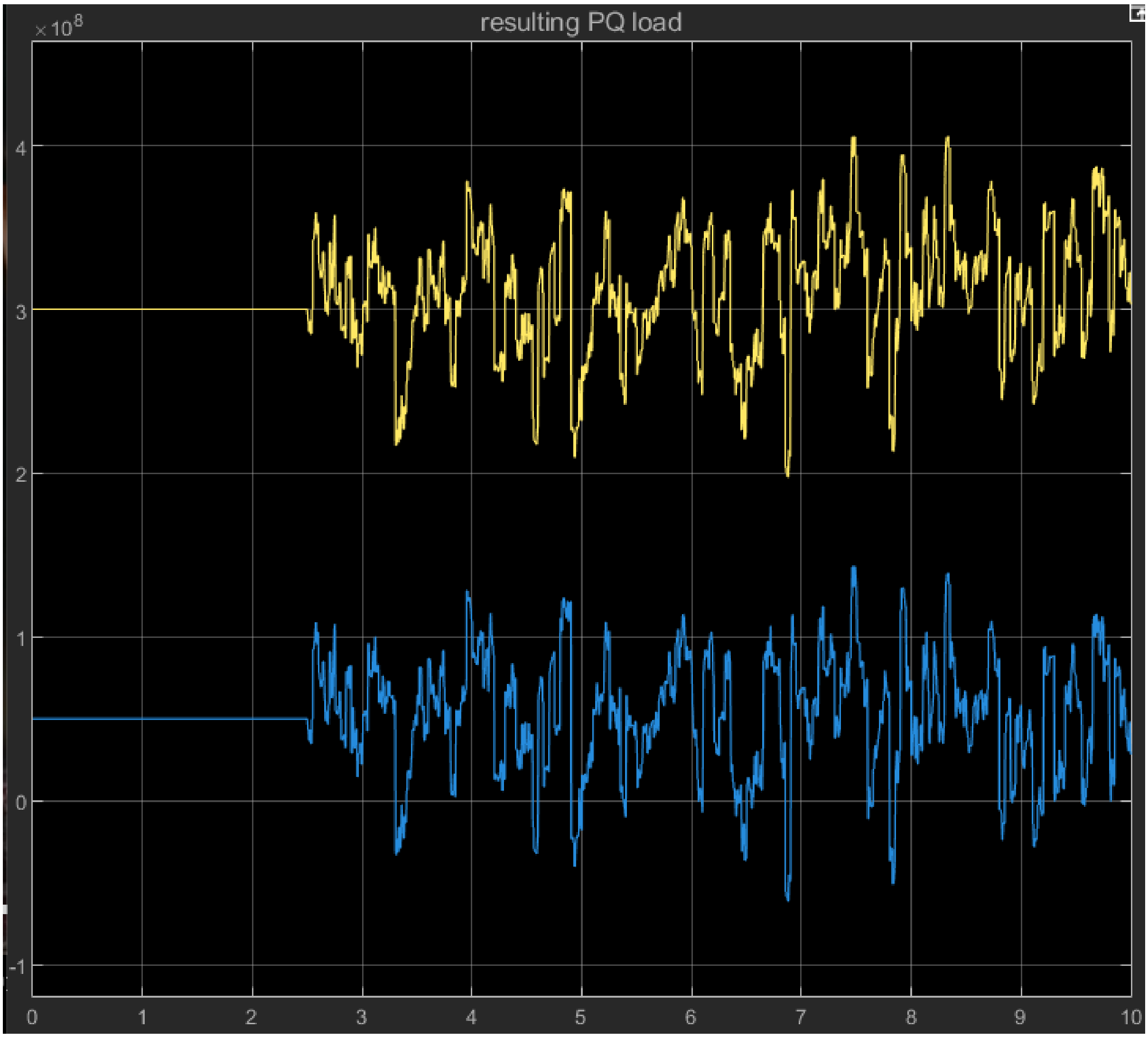

Figure 19: Resulting P(yellow) and Q(blue) signals, from aggregated residential+commercial+industrial loads

As there is no governor control and the mechanic power is fixed, any extra power demanded by the loads will be taken from the spining momentum thus slowing down the generator (or revving up when loads are small enough)

Referring again to the same behaviour modeled by the swing equation (Figure 15), When facing the randomised load , our generator will stall quicker the lower its inertia constant is. The lower the inertia , the harder is the exciter having to fight against voltage changes in the bus, its interesting to take notice in Figure 20 how in the low inertia case the exciter starts to saturate and ends up stalling completely way sooner than the generator with higher inertia in blue.

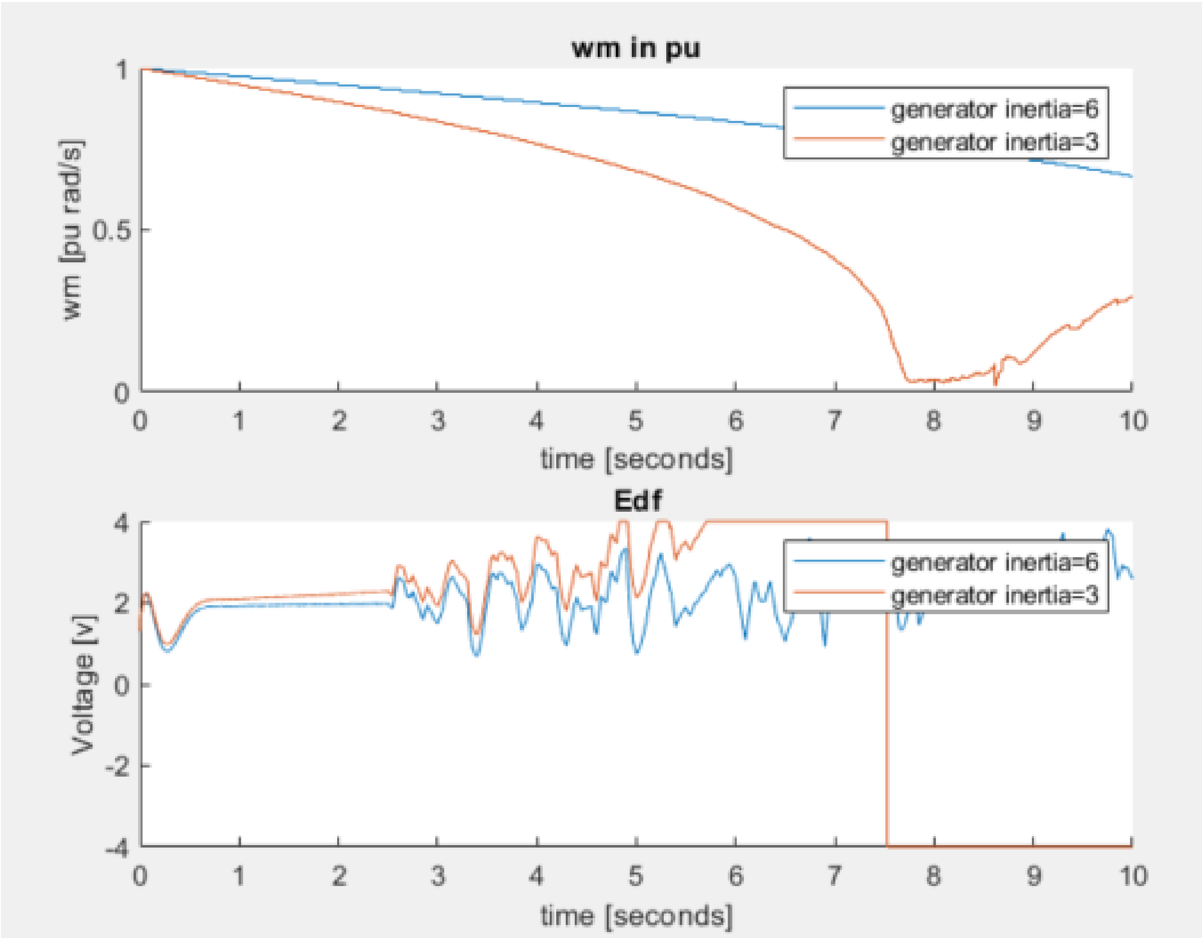

Figure 20: speed and voltage from the exciter to the generator

The resulting Q flowing trough the bus has significantly higher spikes when the generator stalled Figure 21.

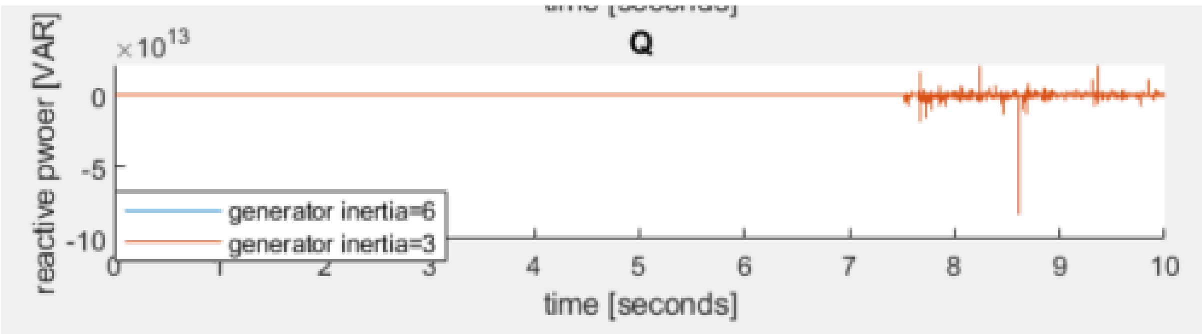

Figure 21: Resulting Q

Otherwise , zooming in the parts the generator with lower inertia didn't stalled, there is a higher Q flowing trough the bus Figure 22.

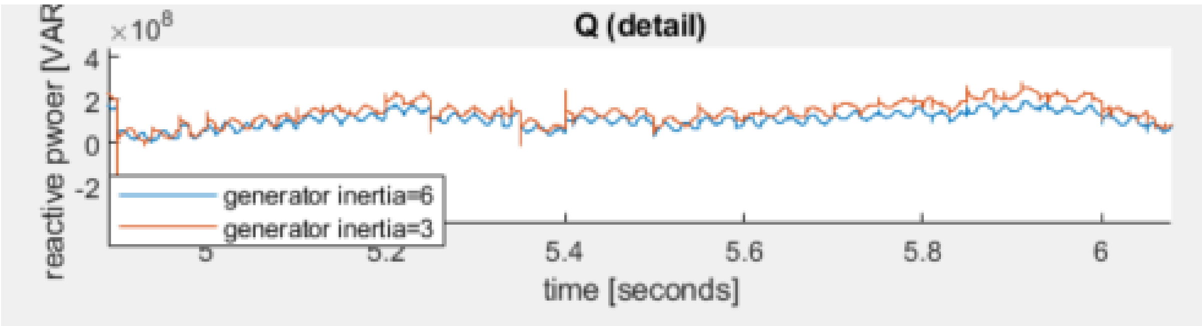

Figure 22: detail resulting Q

4 The role of active/reactive powers in frequency/voltage regulation

Opening "Assign Task3and4.slx" in simulink , similar to previous points, there is a synchronous generator with droop control connected to a load, we are going to study what happens when another heavily inductive load is connected mid simulation.

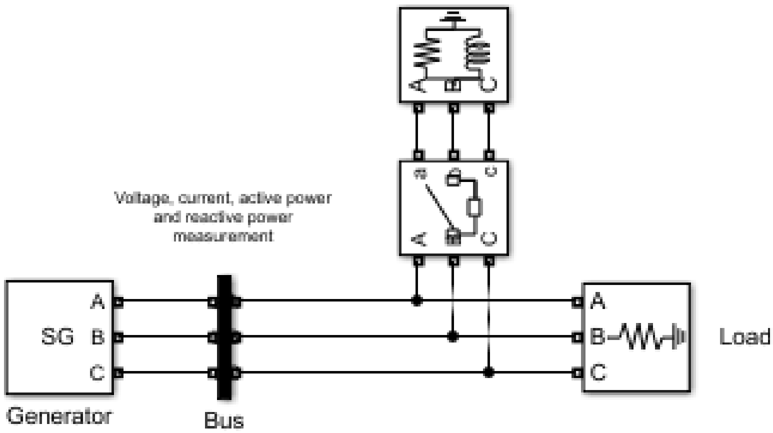

Figure 23: Same simulink blocks

4.1 Droop control action & frequency control

We are simulating a small islanded system with a single power source, but if there was another power source present and we don't implement droop control they would be competing against each other rendering the system unstable.

The droop action consists in a simple P loop with grid frequency error as input and power to the turbine as output, all in per unit.

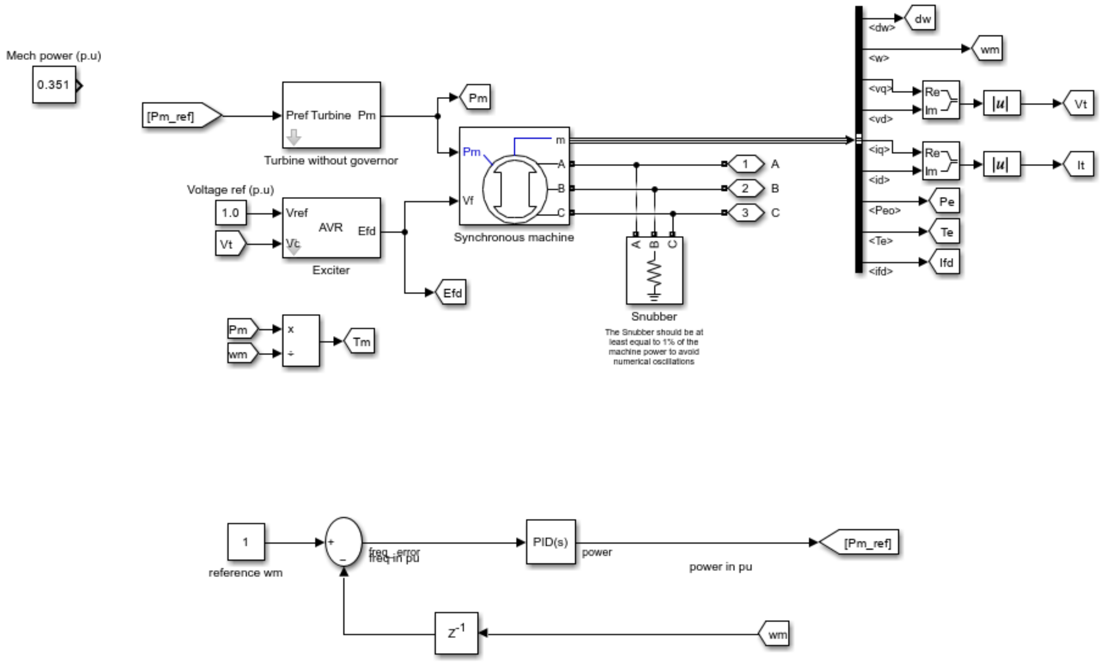

Figure 24: simulation detail of the turbine + droop control loop

In order to obtain the Operative slope value we should follow the next expression:

$$S_p = \frac{1}{R} \times \frac{\text{Nominal machine power}}{\text{Nominal frequency}}$$

Figure 25: Operative slope ecuation

$$Sp = \frac{1}{0.05} x \frac{1000MW}{50Hz} = 400MW/Hz$$

The droop characteristic of 5% is confirmed looking at the relative slope between frequency and Power.

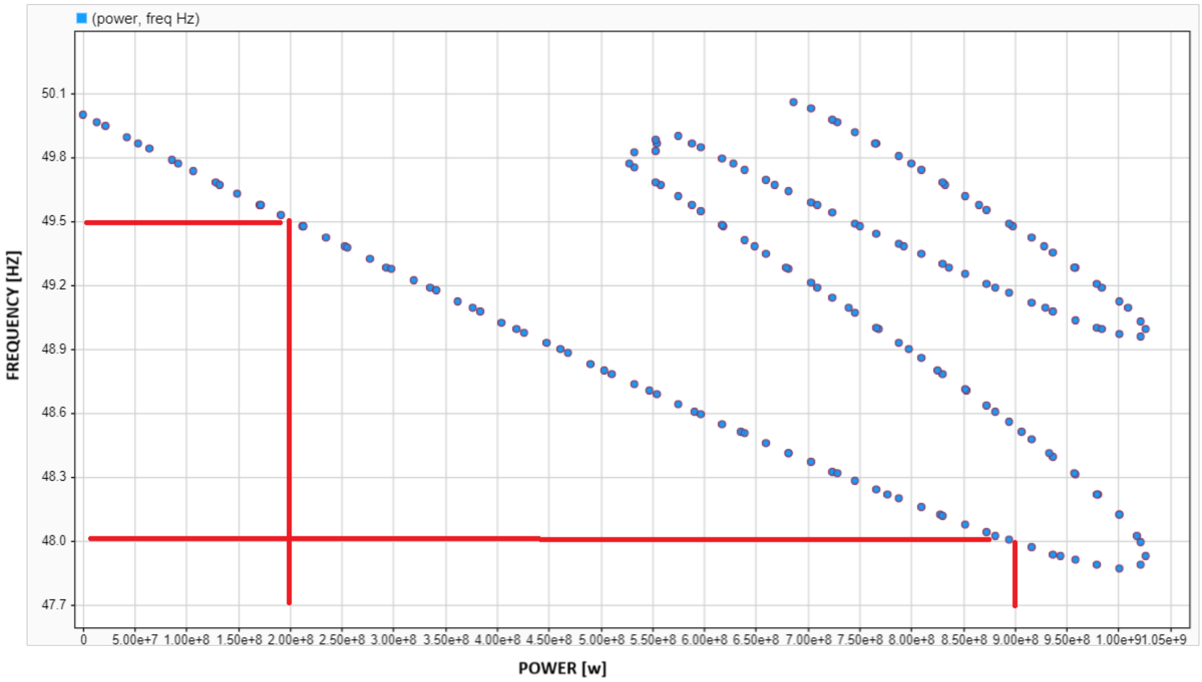

Figure 26: R calculation from simulated data

$$R = \frac{\mathrm{d}f(pu)}{\mathrm{d}P(pu)} = \frac{0,032}{0,7} = 0,04571 \equiv 5\% frequencydroopcharacteristic$$

4.2 Effect of frequency Droop characteristic in wm

A smaller R means an increase on how sensible the generator is towards fluctuations of wm. A R of 2% translates to the generator happily providing 100% power when the frequency deviates 2% from 50Hz.

In Figure 27 we see a R=2% clears the wm dip due to load changes in just 7seconds. But a R=10% clears the dip in about 30 seconds.

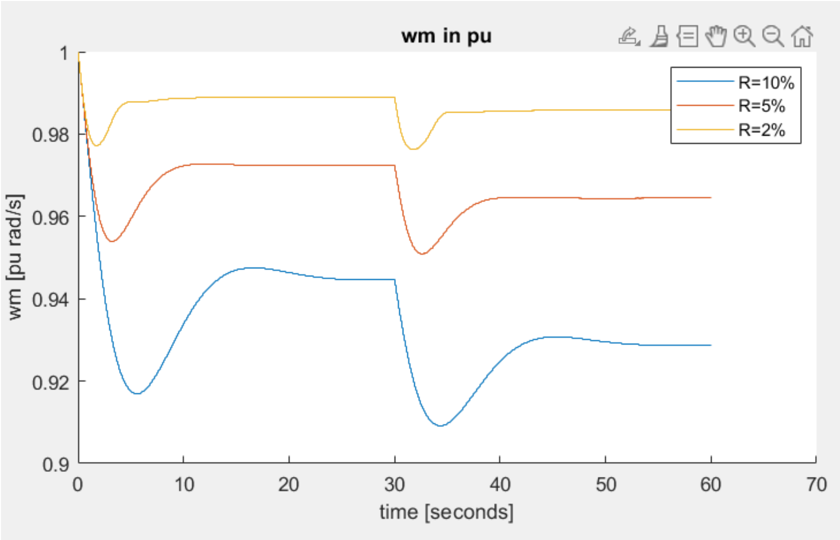

Figure 27: wm evolution for different R values

If we chose to include a Integrator part in the control, the droop would lose its power sharing capabilities when more than one generator is present, but the frequency would return to nominal value with error 0.Figure 28

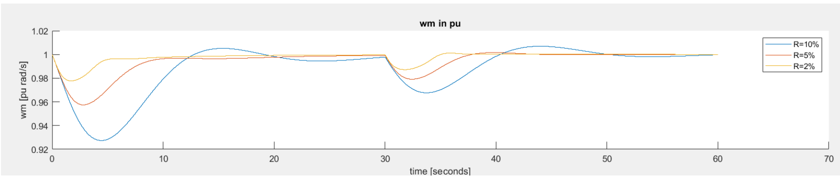

Figure 28: wm evolution for different R values (PI)

The active power Figure 31 doesn't depend of the R value as its dictated by the loads. Reactive power Q on the other hand will depend on the inductive pars of the introduced load as its impedance depends of the grid frequency.Figure 30

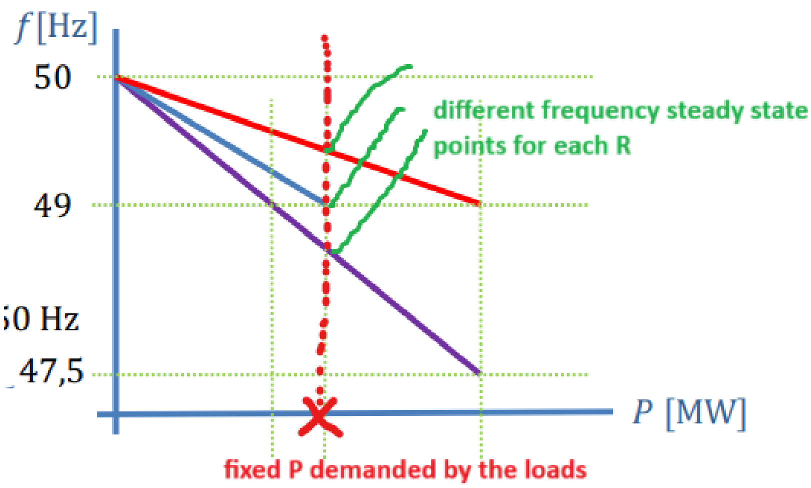

Figure 29: frequency vs active power

For each different generator speed, the "exciter" will increase the voltage providing a different Q to the bus.

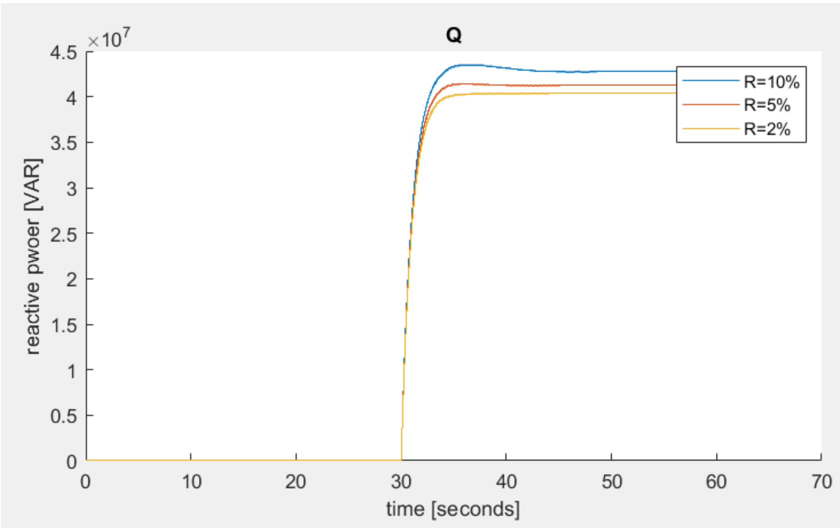

Figure 30: reactive power Q for various R values

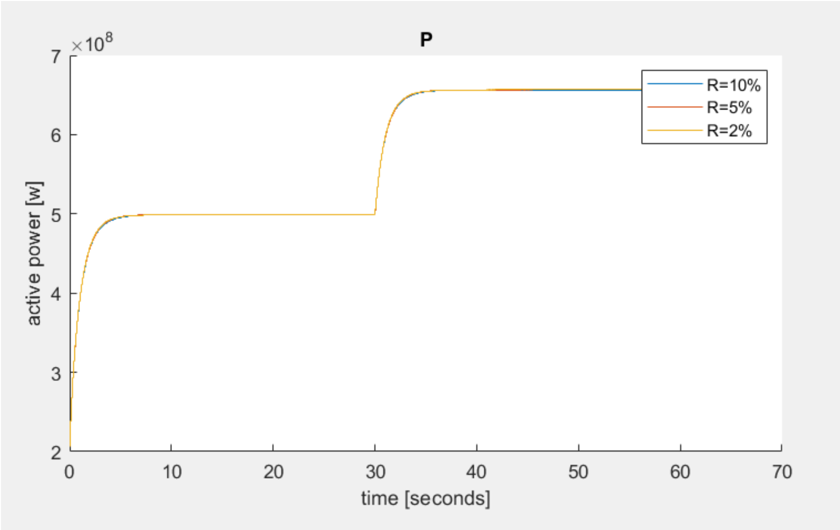

Figure 31: active power Q for various R values

4.3 Effect of generator's inertia in wm

A smaller Inertia means our generator is more susceptible to load changes, it stores less mechanical energy.

That's why in Figure 32 we see a more pronounced frequency dip for the lower value of generator inertia.

Using again the electric accumulator simil, if our generator has lower inertia (capacity in farads) it will drop its speed (voltage) faster when energy is demanded from it.

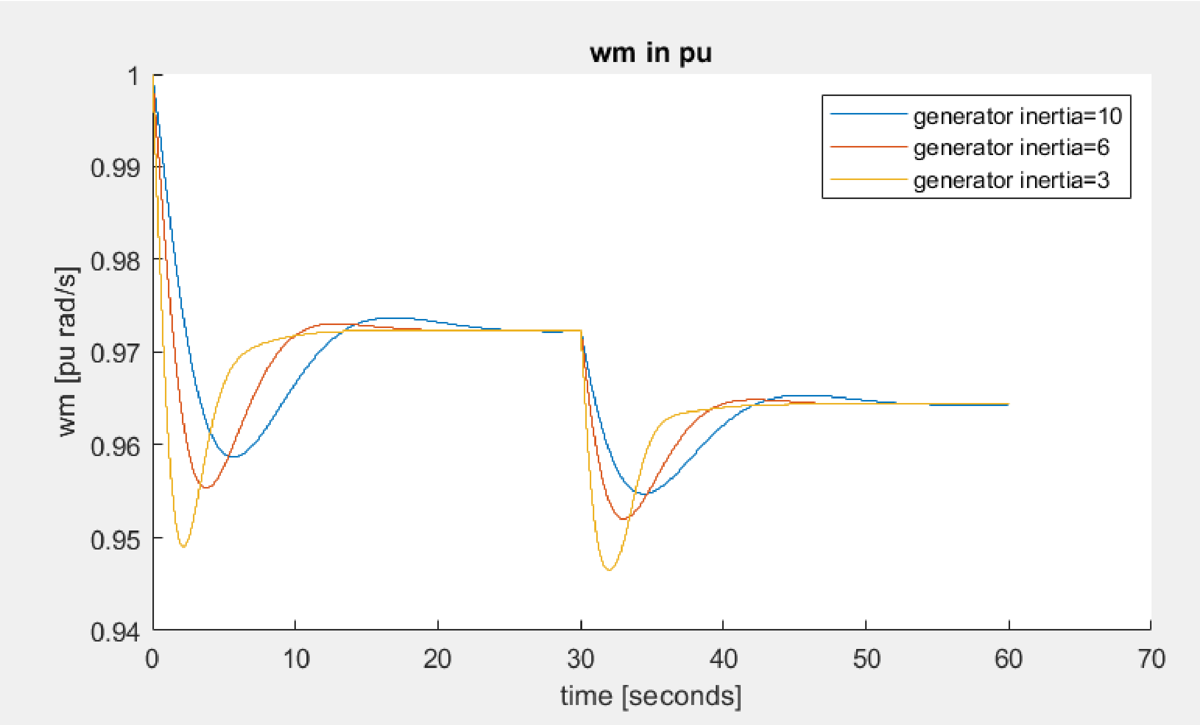

Figure 32: wm evolution for different inertia values

5 Code

Code available in **this Github repo**