UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

Analysis of Modern Converter-based Power Systems (AMCPS)
VSC ACTIVITY REPORT - Assignment 3

Joseph Usman
joseph.usman@estudiantat.upc.edu

Stephanie Matta
stephanie.mattabobadilla@estudiantat.upc.edu

Yorick Van de Paar
yorik.vandepaar@estudiantat.upc.edu

June 23, 2025

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

Contents

List of Figures

1 Problem 1: Understanding the fundamentals of network inertia, droop control and multi-machine systems

The model shows a synchronous generator system with inertia but no droop control. On the left, a -0.1 pu step is applied to electrical power, simulating a sudden load decrease, while mechanical power stays constant. The imbalance passes through the inertia block (1/2H), producing the frequency's rate of change, which is integrated to get frequency deviation.
On the right, a +0.1 pu step simulates a load increase, following the same structure. The model displays pure inertial response to sudden load changes, without any active control or frequency regulation.

1.1 Question block 1- Model with system inertia, without frequency control (pu)

Figure 1 below represents the system's frequency response under varying generator inertia values H, in the model without frequency control (purely open-loop). These results shows the impact of inertia on frequency dynamics during a disturbance (load step changes).

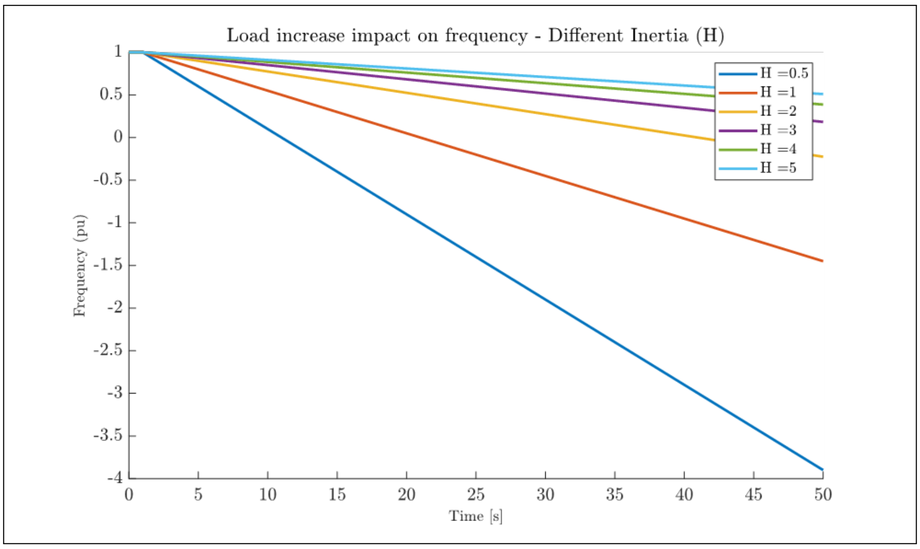

Figure 1: Impact of load increase on frequency response for different values of inertia (H)

In Fig. 1, the system is subjected to a sudden load increase (where $P_m < P_e$), leading to a frequency drop. The rate of decline is steepest for the smallest inertia $H = 0.5$, while larger H values reduce the rate of frequency decline, clearly illustrating that higher inertia slows frequency deviations.
The opposite occurs during a load decrease (where $P_m > P_e$), causing the frequency to increase. Again, a higher inertia dampens this rise, while a lower inertia results in a steeper and faster

increase. These results are not shown, as the graph is just a mirrored version along the x-axis of figure 1.
It should be noted that the frequency deviation rate is inversely proportional to inertia; therefore, lower H leads to faster frequency changes. Without frequency control (droop or governor action), the system cannot stabilize and the frequency continuously deviates. These dynamics are governed by the swing equation.

$$\frac{d\omega}{dt} = \frac{P_m - P_e}{2H}$$

Therefore, system inertia is a critical factor in determining how robust the grid is to sudden changes in load or generation.

1.2 Questions block 2 - Model with system inertia with droop frequency control (pu)

Droop control is a simple, decentralized way for generators to react to changes in frequency and voltage. With P-f droop, if the system frequency drops a bit, the governor increases the prime mover's torque, which means the generator puts out more active power. This helps share the load between machines without needing fast communication. Same idea with Q-V droop — if the voltage at the generator terminals changes, the excitation system adjusts to inject or absorb reactive power, keeping voltage levels steady. Droop control doesn't perfectly push to the setpoint steady state frequency or voltage, but by allowing small steady-state errors, it makes sure multiple generators work together and the system stays stable.

1.2.1 Frequency response for different values of inertia (H)

The figure shows the frequency response of a synchronous generator with droop control after a sudden load increase, for different values of inertia H. When the load increases, the electrical power demand becomes higher than the mechanical power input, which causes the frequency to drop. The speed and depth of this drop depend on the system's inertia. With low H values (for example, $H = 0.5$), the frequency drops faster and more sharply. Higher inertia values (such as $H = 5$) slow down the frequency change and reduce the deviation. This behaviour is visible in Fig. 2.

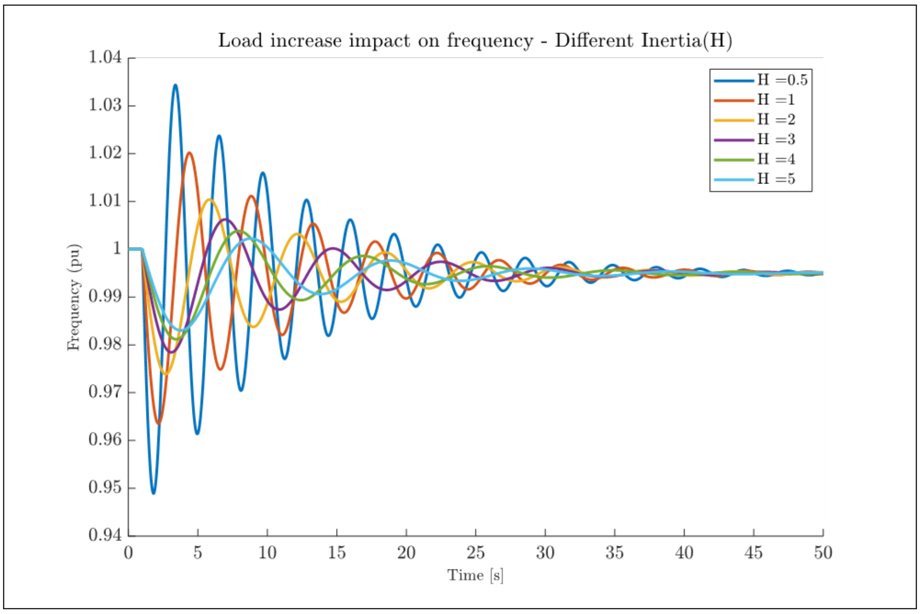

Figure 2: Impact of load increase on frequency response for different values of inertia (H) for system with 5% droop frequency control

After the disturbance, the system shows oscillations, which depend on the inertia. Lower inertia leads to larger swings and slower settling, while higher inertia results in smoother, more damped frequency behaviour. Over time, droop control brings the frequency to a new steady-state, matching the increased load but with the expected steady state error.

In the case of a sudden load decrease, mechanical power exceeds electrical demand, causing the frequency to rise. Systems with low inertia ($H = 0.5$) show a steeper overshoot and stronger oscillations. With higher inertia ($H = 5$), the frequency rises more slowly and with better damping. In both cases, droop control stabilizes the frequency at a higher steady-state value. These results show that higher inertia improves system stability and reduces transient effects for both load increases and decreases.

The frequency response for the load decrease case is not shown, as it is a mirrored version along the frequency axis of Fig. 2.

1.2.2 Frequency response for different values of droop constant

Fig. 3 shows the frequency response after a sudden load increase for different droop gains. With higher droop gains ($k_{\text{droop}} = 0.05$), the frequency drops quickly but shows stronger overshoot and more oscillations before settling. Lower droop gains ($k_{\text{droop}} = 0.01$) slow down the response but result in smoother behaviour with fewer oscillations.

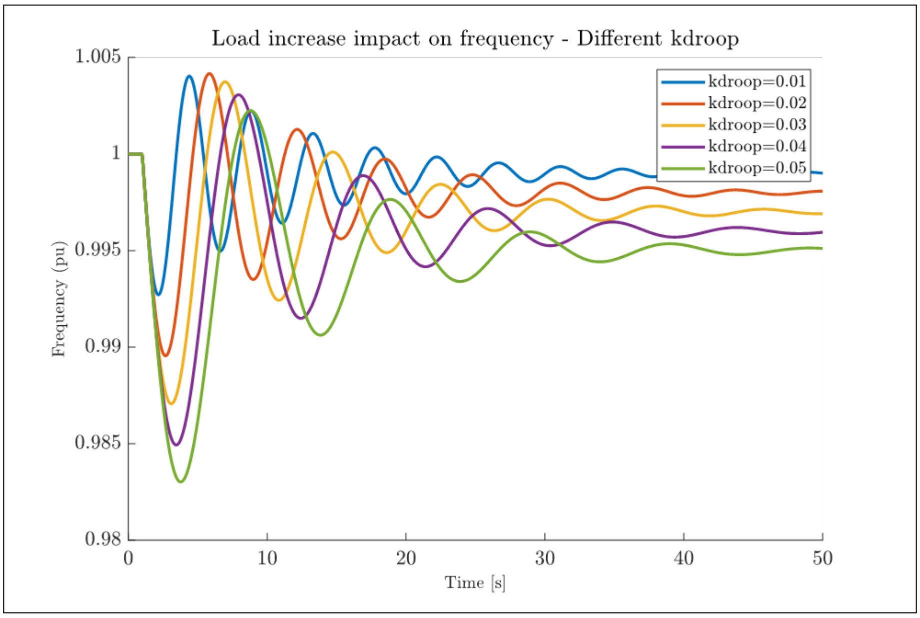

Figure 3: Impact of load increase on frequency response for different droop values

A similar effect is seen for a sudden load decrease. Higher droop gains speed up the response but cause larger overshoot and more oscillations. Lower droop gains slow down the adjustment but improve damping and stability. The plot for this case is not included, as the response is a mirrored version of Fig. 3 along the frequency axis.

1.2.3 Frequency response for different values of τ_{gen}

The turbine time constant, τ_{gen}, defines how quickly the mechanical torque from the prime mover reacts to the governor signal. Smaller τ_{gen} values mean the turbine reacts faster to frequency changes, which can help limit frequency dips but may also introduce more oscillations. Larger τ_{gen} gives a slower torque response, which smooths things out but leads to a deeper and slower frequency recovery.

Fig. 4 shows the frequency response after a sudden load increase for different τ_{gen} values. With lower τ_{gen} (e.g., $\tau_{\text{gen}} = 2$), the frequency drops more gradually, with smaller overshoot and quicker settling. As τ_{gen} increases, the system shows a faster initial drop, larger overshoot, more oscillations, and longer settling time. For the highest τ_{gen} tested (e.g., $\tau_{\text{gen}} = 20$), the frequency recovery is slow, with significant oscillations and the longest settling time.

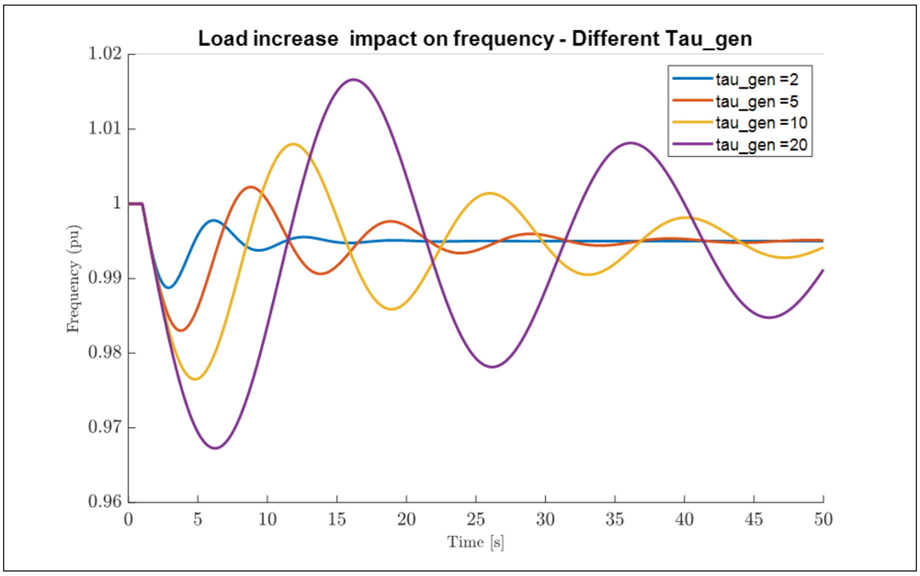

Figure 4: Impact of load increase on frequency response for different τ_{gen} values

The same effect is seen for a sudden load decrease. Lower τ_{gen} results in slower but smoother frequency rise with less overshoot and quicker settling. Higher τ_{gen} leads to a faster frequency increase, but with more overshoot, stronger oscillations, and longer settling time.
In general, larger τ_{gen} reduces system stability and increases oscillations, while smaller τ_{gen} gives smoother, more stable behaviour but slows down the system's response. The choice of τ_{gen} depends on the trade-off between response speed and stability required for the system.

1.3 Block 3 - Model with 2 SGs (with inertia) incorporating droop frequency control (pu)

1.3.1 Frequency response for different values of inertia (H) of two machines

When a sudden load increase occurs, the two-machine system experiences a power imbalance: electrical demand exceeds mechanical input, causing rotor speed and system frequency to drop. This is shown in Fig. 5. With low inertia, the frequency drops quickly and the machines swing noticeably against each other, producing large, sustained oscillations before the system settles. At higher inertia, the frequency drop is smaller, the oscillations are slower and better damped, and the system returns to nominal frequency more smoothly.

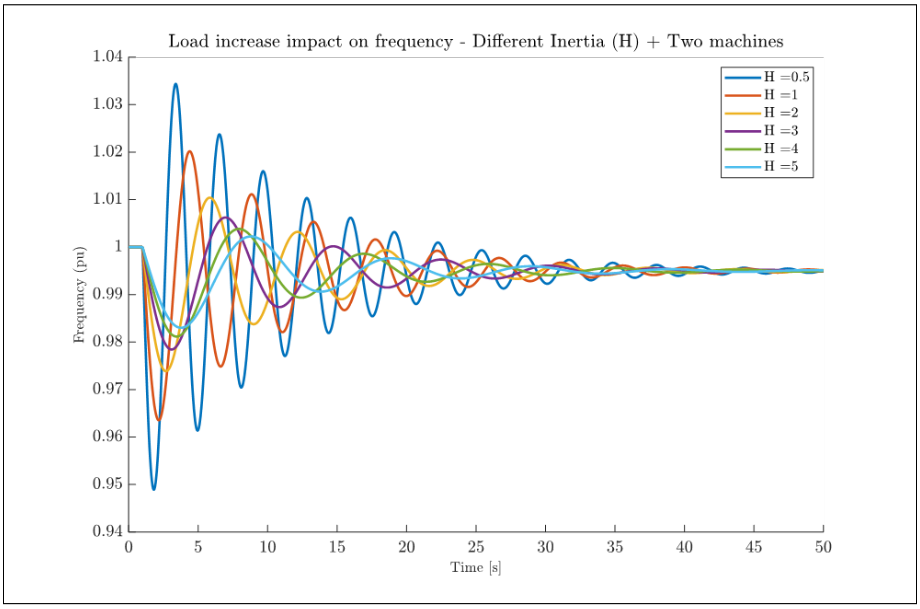

Figure 5: Impact of load increase on frequency response for different values of inertia (H) for 2 SGs with droop frequency control (pu)

For a step decrease in load, the system has a temporary power excess, causing rotor speed and frequency to rise. With low inertia, the frequency rises sharply, followed by strong oscillations as the machines share the excess power. As inertia increases, the spike becomes smaller, and the oscillations die out faster. In both cases, higher inertia slows down the system's response but improves damping and overall stability.

In this setup, both generators have half the inertia compared to the single-generator case. Since the total system inertia stays the same, the overall frequency response is identical to the single-generator system with double the inertia. The same applies to load sharing: both generators have identical droop settings, so they each take on half the required power change. This keeps the system balanced and ensures that both machines contribute equally to stabilizing the frequency.

1.3.2 Frequency response for different droop values for 2 SGs (with inertia) and droop frequency control (pu)

When the load suddenly increases, each generator's droop setting (k_{droop}) determines how much its mechanical power rises as frequency falls. Fig. 6 shows this effect. With $k_{\text{droop}} = 0.01$, the frequency dips to around 0.992 pu, with noticeable oscillations that settle after about 40 s. As droop increases to 0.05, the initial dip is deeper (down to about 0.983 pu), but oscillations reduce, and the system returns to steady state faster. In all cases, the final frequency remains slightly below 1.0 pu, which is expected with droop control as the system settles at a new steady-state level.

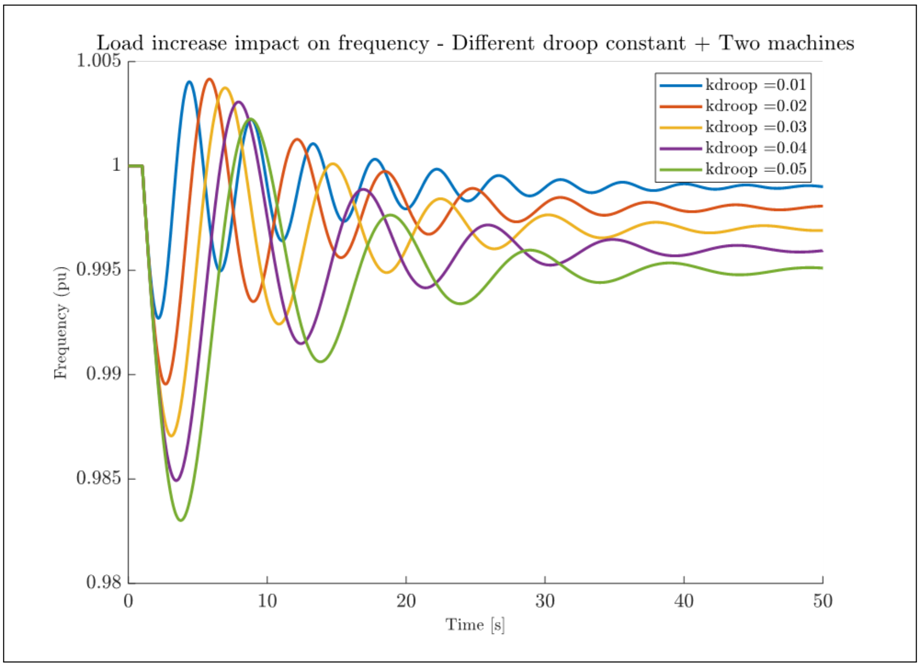

Figure 6: Impact of load increase on frequency response for different droop values for 2 SGs with droop frequency control (pu)

1.3.3 Changing only one of the machines τ values. How does the machines synchronize, slower or faster?

If one machine's governor time constant (τ) is changed while the other remains the same, their speed responses no longer match. The machine with the smaller τ acts quickly, adjusting its power output almost immediately when frequency shifts. Meanwhile, the slower machine lags behind, causing the two to drift apart briefly. Until the slow machine catches up, they oscillate against each other, and the overall settling time increases. In essence, mismatched τ values mean the faster machine "leads" and the slower one "lags," so synchronization takes longer and the oscillations persist.

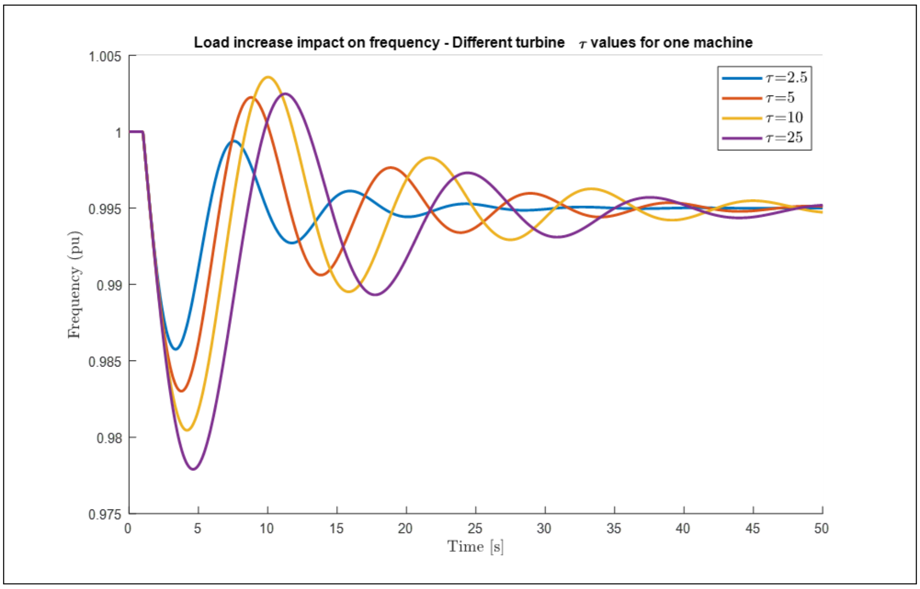

Figure 7: Impact of load increase on frequency response for changing only one of the machines time constant (τ)

1.3.4 Changing only one of the machines droop values. How does the machines synchronize, slower or faster?

Altering only one machine's droop constant (k_{droop}) similarly disrupts their shared response. The machine with a higher droop value will change its power output more aggressively for a given frequency change, while the other machine remains relatively stiffer. This imbalance means the stiff machine ends up carrying more of the load change, and the flexible machine takes longer to adjust. As a result, there would be a larger initial frequency deviation and a longer settling period before both machines converge on the same speed. The pair only lock in once the high-droop unit catches up, producing bigger swings and slower synchronization.

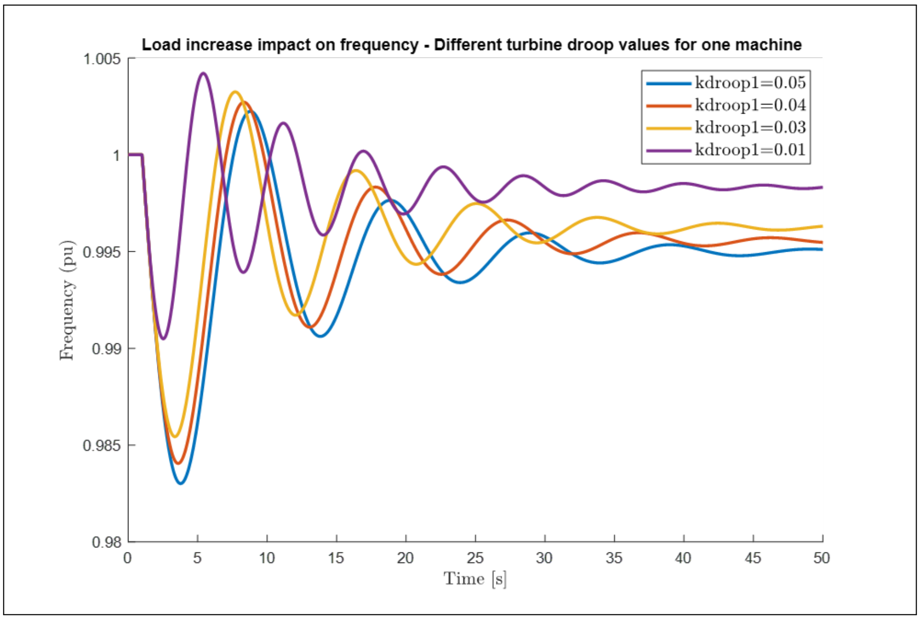

Figure 8: Change in Power for varying only one of the machine's droop constant

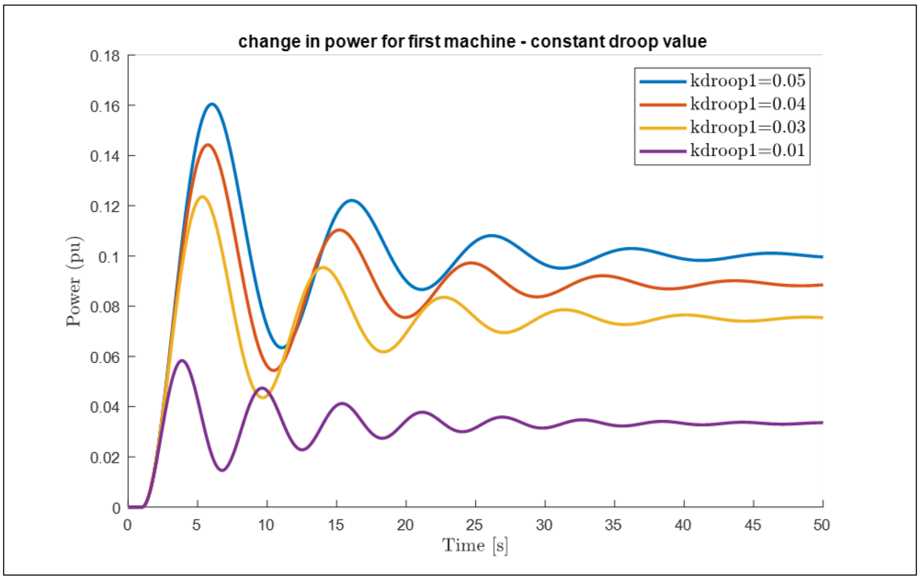

Figure 9: Change in Power for varying only one of the machine's droop constant

Overall, any mismatch in τ or k_{droop} between two machines slows down their ability to synchronize smoothly. The unit with the faster or flatter setting sets the pace, and the other follows more sluggishly. To achieve quick, balanced sharing of disturbances and tight frequency matching, it's best to keep both machines' τ and k_{droop} values as closely aligned as possible.

2 Problem 2: Response of grid-forming and grid-following converters connected to a synchronous generator during a load step change

2.1 Block 1a: Explanation of the Grid-Following Converter (GFOL) Control Structure

Grid-following converters work as current sources that stay in sync with the grid voltage using a Phase-Locked Loop (PLL). They rely on an external voltage and frequency reference, usually from synchronous machines or grid-forming converters. Without this reference, GFOL converters can't control the frequency or voltage themselves.

The control setup involves a couple of cascaded loops. The PLL tracks the grid's phase angle, and from there, the outer controllers regulate active and reactive power using P-Q control. Frequency support comes from a droop mechanism that adjusts the active power reference, while the voltage magnitude deviation changes the reactive power reference. These references then go into the inner current control loop, which manages the i_d and i_q components of the converter's output.

Although GFOL converters do help support the grid, they do so by following external setpoints. Their response isn't inherent in their behaviour—they just match the grid's conditions and don't contribute to grid formation. Their role is mainly to follow the setpoints provided by the grid or other external controllers.

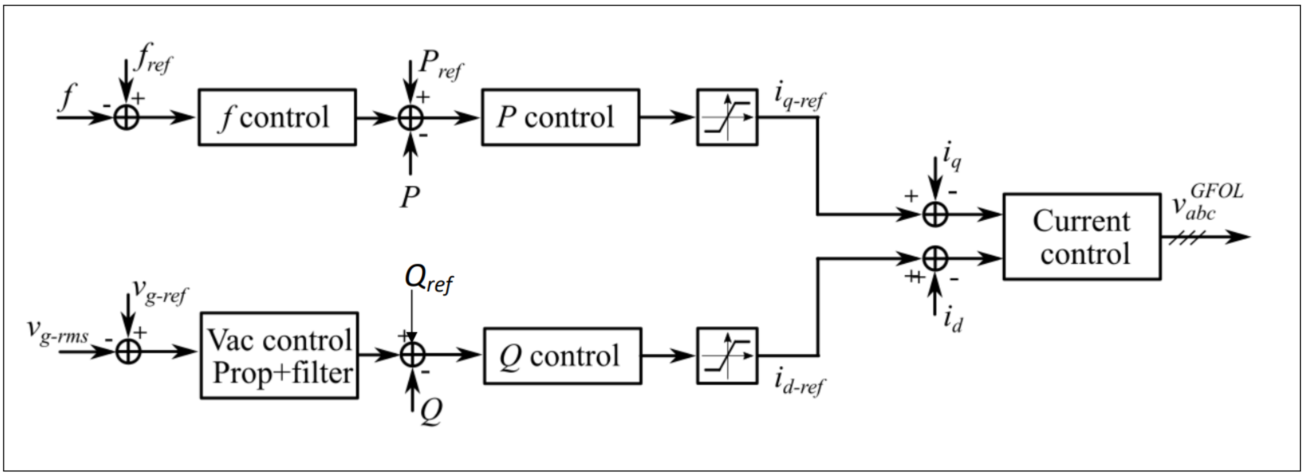

Figure 10: Grid-Following Converter (GFOL) Complete Control Structure

2.1.1 Top Control Loop – Frequency Support (Active Power Control)

- **PLL Measurement:** The frequency f is measured using a Phase-Locked Loop (PLL), which tracks the grid phase angle. Although fast, the PLL introduces measurement delays, especially under noisy or weak-grid conditions.

- **Frequency Control:** A droop controller compares the measured frequency to a setpoint f_{ref} and calculates a frequency deviation. This deviation feeds a control block that generates an adjusted active power reference:

  $$\Delta P_{\text{d}} = K_d(f_{\text{ref}} - f)$$

  Inertia emulation can also be implemented by including a derivative term (rate-of-change of frequency or RoCoF):

  $$\Delta P_{\text{i}} = K_i \frac{df}{dt}$$

  These two components (droop and inertia) are added to the base power reference to form a dynamic power response.

- **P Controller:** Converts the power error $P_{\text{ref}} - P$ into a current reference i_q^{ref}. Since active power is controlled through the q-axis current, this loop adjusts i_q accordingly.

The basic power balance relation governing the system frequency dynamics with converter support can be expressed as:

$$\frac{d\omega}{dt} = P_{+} + \Delta P - P_L,$$

where:

- ω is the grid frequency,
- P_{+} is the nominal power contribution from the converter,
- ΔP is the additional power injected by the converter (e.g., from droop or inertia emulation),
- P_L is the system load.

In practice, both droop and inertia emulation can be combined into a single power reference:

$$\frac{d\omega}{dt} = P_{+} + \Delta P_d + \Delta P_i - P_L = \frac{1}{M + M_i},$$

where:

- ΔP_d: droop-based support,
- ΔP_i: inertia-based support,
- M_i: equivalent inertia emulated by the converter.

2.1.2 Limitations of Grid-Following Frequency Support

Although this control scheme can be effective for enhancing frequency stability, grid-following converters exhibit several limitations:

- **Reactive behavior:** Converter support is activated only after a frequency deviation is detected.
- **Control delays:** Phase-Locked Loop (PLL), current control, and power loop introduce latency in the frequency response.
- **Lack of voltage-source behavior:** Unlike synchronous generators, grid-following converters behave as current sources, regulating only P and Q without directly controlling the voltage angle.

2.1.3 Bottom Control Loop – Voltage Support (Reactive Power Control)

- **Voltage Measurement:** The converter measures $V_{g,\text{rms}}$, the grid voltage magnitude, which is compared to a voltage reference $V_{g,\text{ref}}$.
- **Voltage Controller (Proportional + Filter):** This proportional controller, with filtering, generates a reactive power reference Q_{ref} based on voltage deviation:

$$\Delta Q = K_v(V_{g,\text{ref}} - V_{g,\text{rms}})$$

- **Q Controller:** Processes the error between Q_{ref} and actual reactive power Q, generating a d-axis current reference i_d^{ref}.

2.1.4 Inner Current Control Loop – Fast Current Tracking

- **Inputs:** Reference currents $i_q^{\text{ref}}, i_d^{\text{ref}}$ and actual currents i_q, i_d.
- **Control Action:** Uses PI controllers in the rotating dq-frame to compute the required voltage signals v_{abc}^{GFOL} that are passed to the PWM inverter.

  The current controller ensures fast and accurate current injection to match the desired active and reactive power flows.

2.2 Question block 1b: Explanation of the Control Structure of Grid-Forming Converters (GFOR)

Grid-forming converters are essential in modern power systems, particularly in low-inertia networks where synchronous machines are replaced or supplemented by power electronics. Unlike grid-following converters that track an external voltage and frequency, grid-forming converters create the grid voltage and frequency reference, enabling them to behave like ideal voltage sources at their connection points, partially mimicking the behavior of synchronous generators. This gives them the ability to perform cold starts -as they don't need a grid to follow- thereby also being able to operate in stand-alone mode.

2.2.1 Hardware Configurations

Grid-forming behavior can be implemented across different hardware platforms, with typical configurations including:

- **LCL Filter (no isolation):** Common in low-to-medium power applications where compactness is prioritized.
- **LC Filter + Transformer:** Often used in two-level or three-level converters, providing galvanic isolation and harmonic attenuation.
- **L Filter + Transformer:** Preferred in high-power applications, where simplicity and robustness are vital.

2.2.2 Grid-Forming Control Approaches

Focusing on the control side of the grid-forming converters, typical structures are:

- **A. Voltage and Current Control in Cascade:**
  This method combines a slower outer voltage loop with a faster inner current loop. The voltage loop is responsible for managing the output voltage's magnitude and phase, while the current loop ensures that the converter injects the correct current rapidly and accurately. The converter generates its own grid angle internally, serving as a virtual reference.

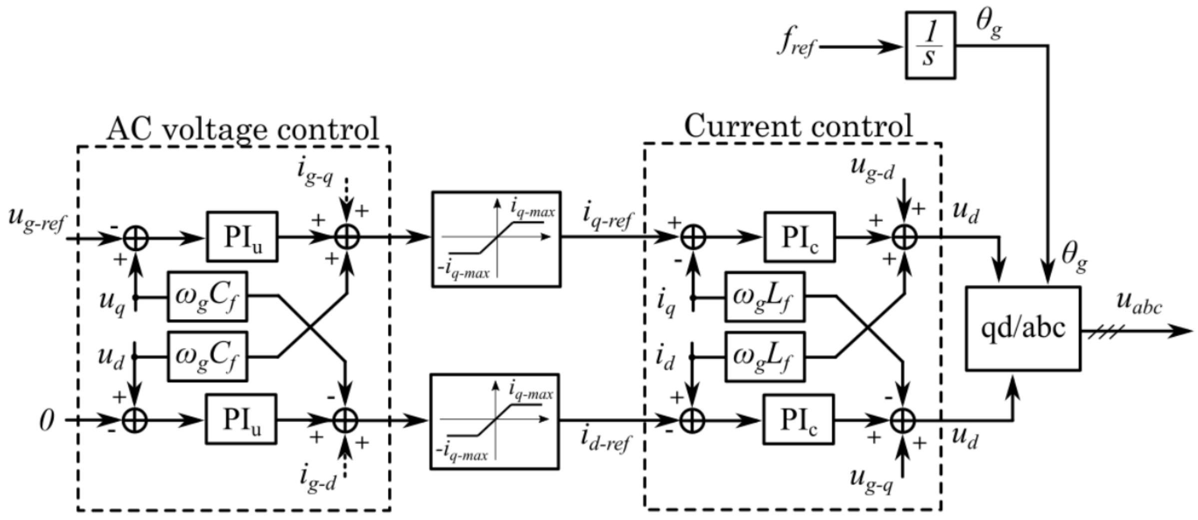

Figure 11: Voltage and Current Control in Cascade Control Structure

- **B. Voltage-Only Control:**

  This technique relies solely on voltage regulation, without the inner current loop. The converter sets both the output voltage magnitude and angle directly, making it suitable for applications where hardware elements (like transformers) inherently restrict current. Its simplicity allows for near-ideal voltage source behavior. However, the absence of current control means that system performance may be more affected by the interaction between the controller and physical hardware.

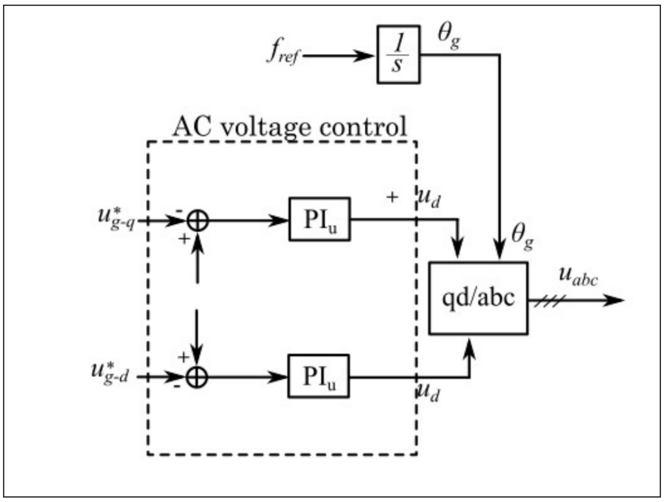

Figure 12: Voltage-only Control Structure

- **C. Direct Voltage Control:**

  In this setup, the voltage signal is applied directly to the converter's output terminals with no voltage feedback. The converter determines the waveform's magnitude and angle internally. To prevent instability during large disturbances, protective loops may be added. Although this method enables very fast response, it lacks robustness due to the absence of current control, making it sensitive to grid events or transient conditions.

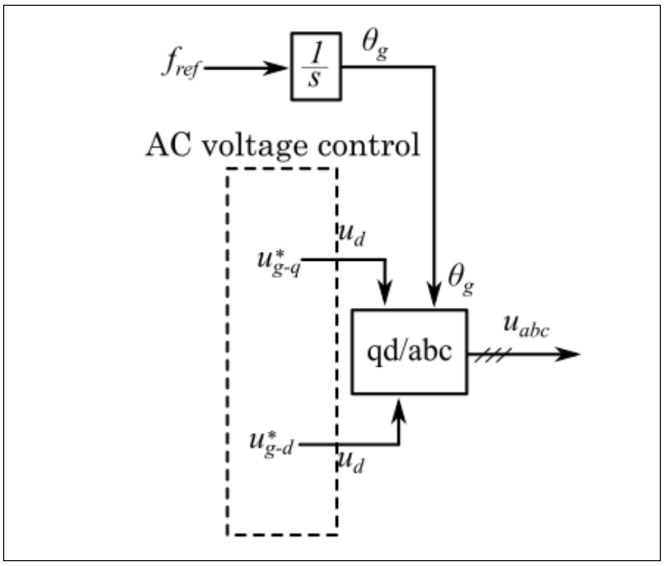

Figure 13: Direct Voltage Control Structure

- **D. Virtual Impedance Control (Admittance-Based):**
  This method simulates a voltage source operating behind a configurable impedance, such as an RL network. A virtual admittance is programmed into the controller, allowing the converter to behave like it has a physical impedance. Current control is typically included to keep output current within limits. This approach enhances stability in weak grid conditions and aligns well with synchronous generators, making it a strong candidate for hybrid grids and microgrids.

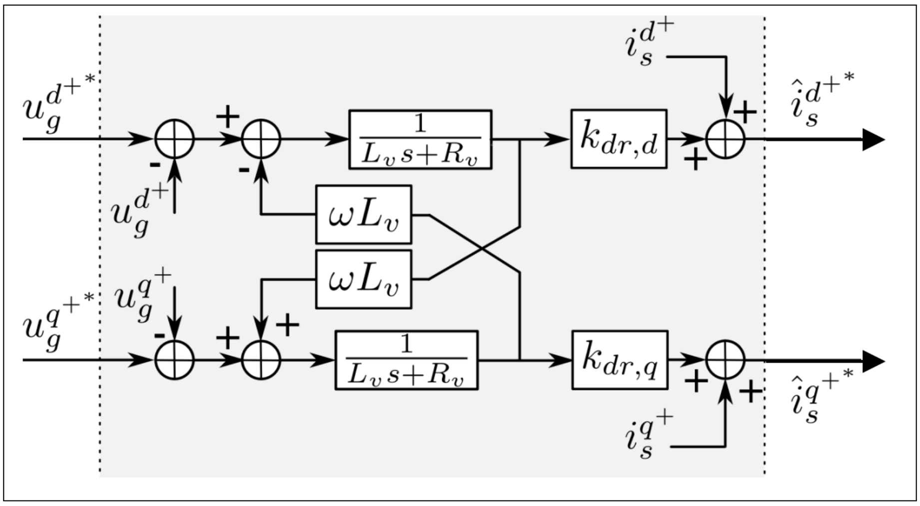

Figure 14: Virtual Impedance Control Structure(Admittance-Based)

2.3 Question block 1c: Simulation Results and Discussion: Frequency and Power Dynamics of VSC

The Figs. 15 and 16 illustrate the transient behavior of a synchronous generators (SGs) operating alongside either a grid-forming (GFOR) or grid-following (GFOL) voltage source converter (VSC). A power step is introduced at $t = 20\,\text{s}$, and the plots compare how each configuration responds in terms of frequency (top subplot) and active power (bottom subplot).

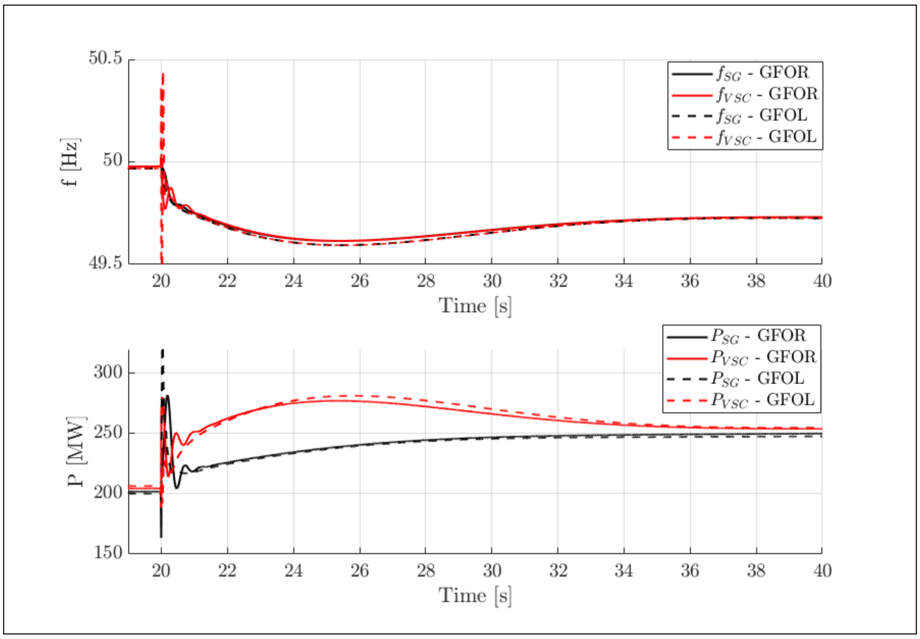

Figure 15: System frequency and active power response under a power step at $t = 20\,\text{s}$.

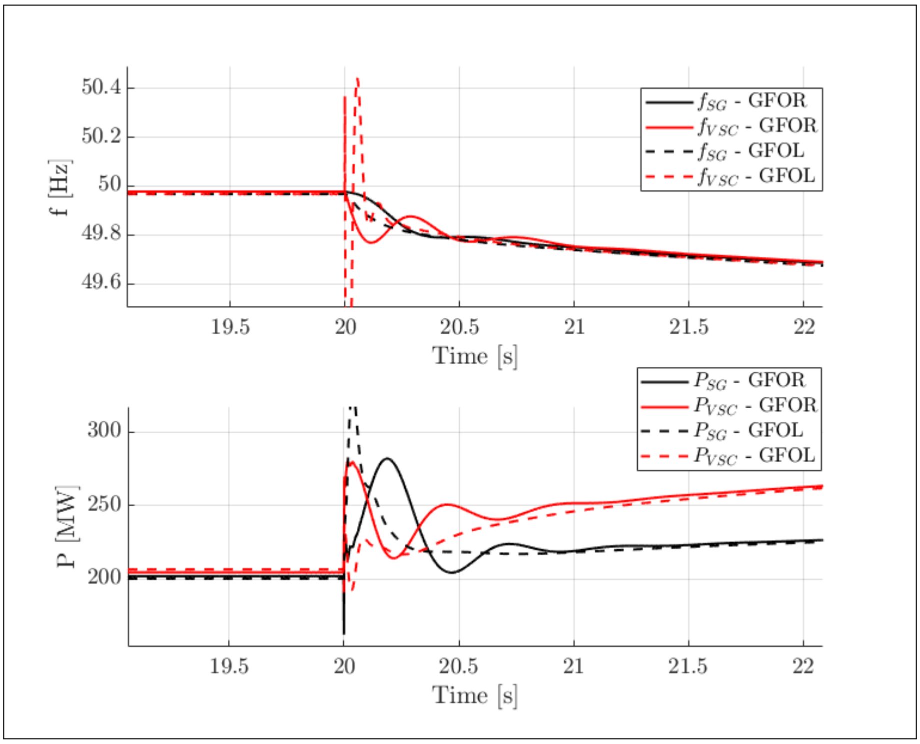

Figure 16: System frequency and active power response under a power step at $t = 20\,\text{s}$, zoomed

2.3.1 Response of Grid-Following (GFOL) Converter

Upon the power step at 20s, the GFOL converter injects power almost instantly, causing a sharp but short peak in power, as shown in the power graph (bottom plot). This peak does not last, and the converter fails to support the grid in the long term.

The frequency response of the GFOL shows a high peak shortly after the power step, indicating the converter's inability to maintain grid stability in the short term. Although the frequency eventually stabilizes through droop control, the GFOL reacts to frequency deviations only after they are detected, highlighting its reactive nature.

2.3.2 Response of Grid-Forming (GFOR) Converter

The GFOR converter behaves as a voltage source and provides a steady power injection. The power increases more smoothly and remains stable, supporting the grid more effectively during the power mismatch.

Since the GFOR generates its own grid angle, it responds proactively to changes in grid demand, leading to better power sharing and frequency support. The frequency drop is more gradual, and both the SG and the converter synchronize quickly, stabilizing the system more effectively than the GFOL converter.

2.4 Question block 2a: Focusing on the grid-following control model-response of the system for different SG inertia values (H)

Control Structure GFOL Matches the AC grid voltage and frequency (typically using a PLL), control structures involve in both schemes (GFOL/GFOR): Inner Loop (current), Outer Loop (P/Vdc - Q/Vac) as setpoints directly from the PLL output to synchronize. Needing this reference.

In the simulation, PLL blocks, frequency support without droop, PQ Control and Current regulator are considered.

(Including something of this): Grid-following limitations have been clearly highlighted:

- Does not provide a 'voltage-source' inherent behavior
- They need a stiff grid to operate (orient the PLL structure)
- Cannot operated in isolated mode
- Cannot black start the network
- Provides 'delayed' frequency support after the SGs change their speed

Control Structure GFOR, as said before, same control blocks but reference not from PLL but from Synchronization, being able to regulate both instantaneous AC frequency and AC voltage.

Grid-forming capabilities are the following:

- Provides a 'voltage-source' inherent behavior
- Does not need a stiff grid to operate (doesn't rely on a PLL)
- Can operate isolated
- Can black start the network

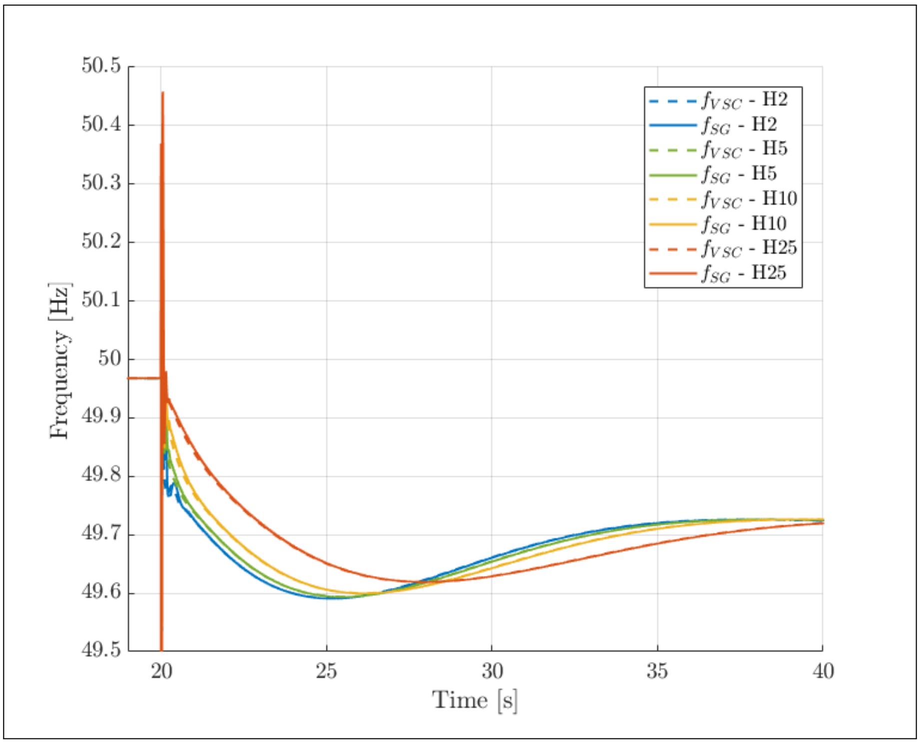

Figure 17: System frequency response for varying inertia values ($H = 2, 5, 10, 25$).

- Can handle an ‘open-circuit’ test
- Provides inherent support due to voltage source operation
- Can incorporate conventional supporting structures (f-droop, V-droop)

Comparing the control structure with GFOL, no PLL Blocks are implemented, and the frequency support is enhanced by adding a droop control, also including an AC Voltage control, with a different structure from de GFOL PQ Control and considering the same current regulator control strategy.
From the AC side, capacitors are being added changing the layout for current ref.
Considering that GFOR operation requires to be compatible with the current elemnts operating in the system, such as the Synchronous Generators and existing GFOL.

2.4.1 Results of the influence of the system Inertia H

The influence of the system inertia on the dynamic response following a load step is shown in Figs. 17–19. As the inertia constant H increases, the system’s frequency nadir becomes less extreme and the rate of change of frequency (RoCoF) decreases, leading to a more gradual and stable response after the disturbance. This is clearly visible in the frequency plot (Figure 17). It shows that the lowest nadir and smoothest frequency trajectory are associated with the highest inertia ($H = 25$). Conversely, for low inertia ($H = 2$), the frequency dips rapidly and exhibits a faster, less damped response.

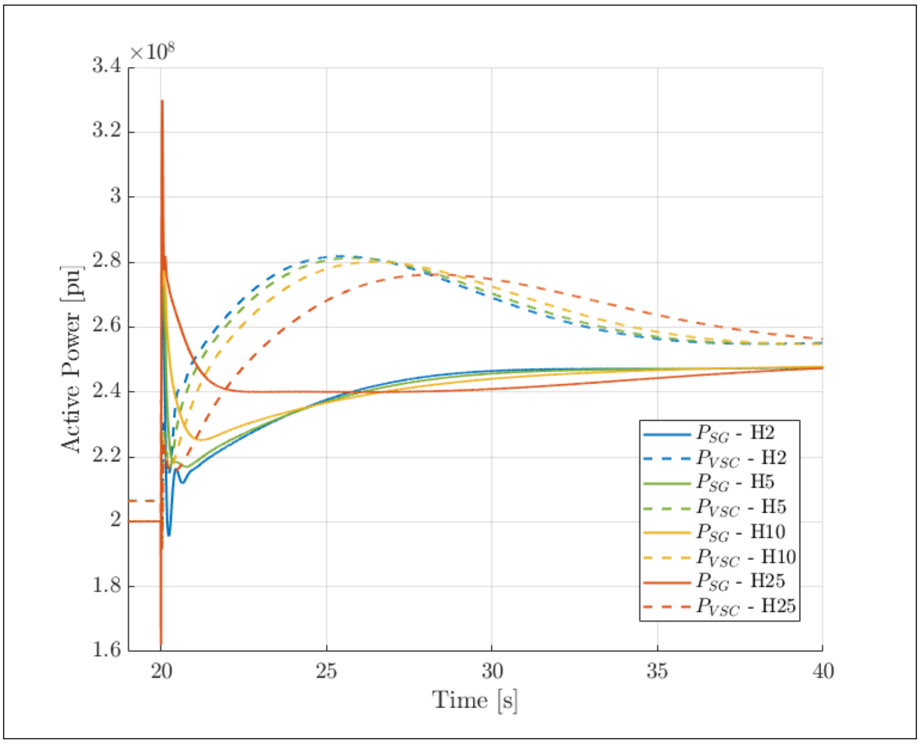

Figure 18: Active power response for different inertia values.

Similarly, the active power plots (Figure 18) show that higher inertia delays the peak power injection of both the synchronous generator (SG) and the voltage source converter (VSC), while reducing overshoot. The system's ability to resist sudden frequency changes is thus directly linked to its total inertia, with higher values providing greater stability at the cost of slower response.

The reactive power behavior (Figure 19) is less sensitive to the inertia setting. After a transient, the reactive power outputs of both the SG and VSC converge to a common steady-state value, indicating that inertia predominantly affects the active power and frequency channels in the system.

2.4.2 Influence of Droop on System Steady-State and Transients

The impact of droop variation on system frequency and power sharing is illustrated in Fig. 20–22.

As the droop value is increased from 1% to 10%, the system frequency displays a larger steady-state deviation after the load step. This is a well-known consequence of droop control in isolated systems: higher droop values correspond to less "stiff" frequency regulation, and therefore, for a given change in power, a greater deviation from the nominal frequency is allowed in steady-state.

From Fig. 21, it is evident that the division of active power between the synchronous generator and the VSC remains balanced when their droop settings are matched. However, the frequency at which this balance is achieved goes down as the droop increases. The transient overshoot in

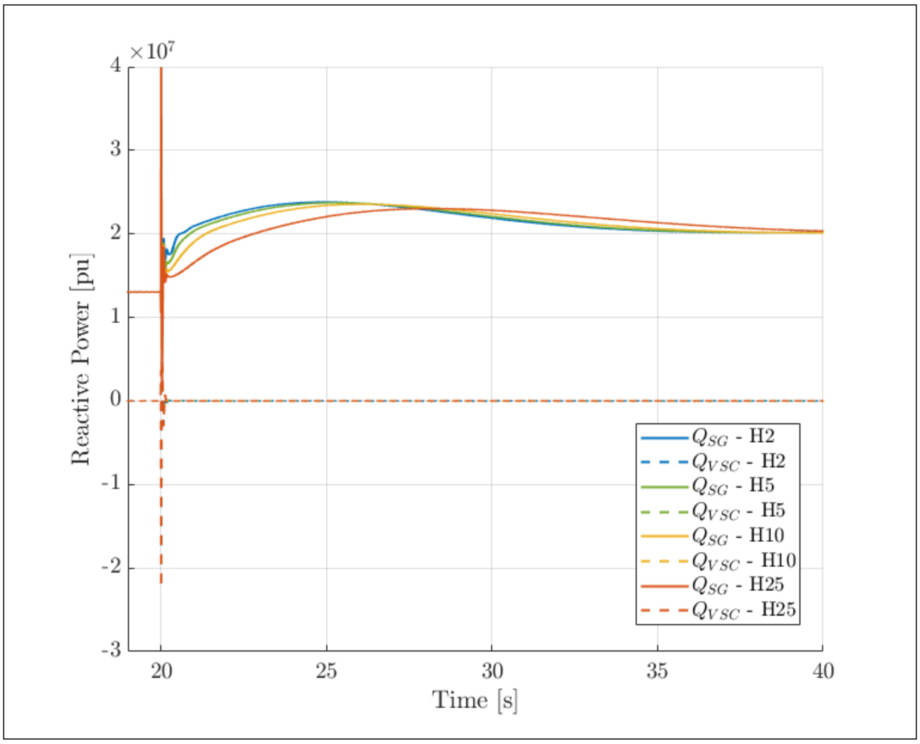

Figure 19: Reactive power response for different inertia values.

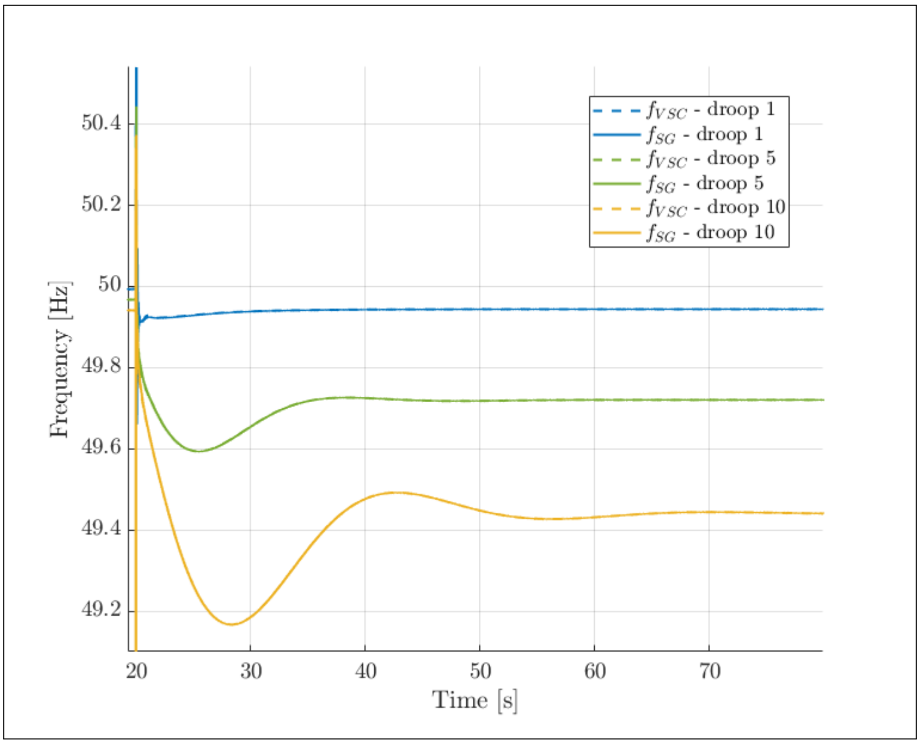

Figure 20: Frequency response for varying droop values in both machines.

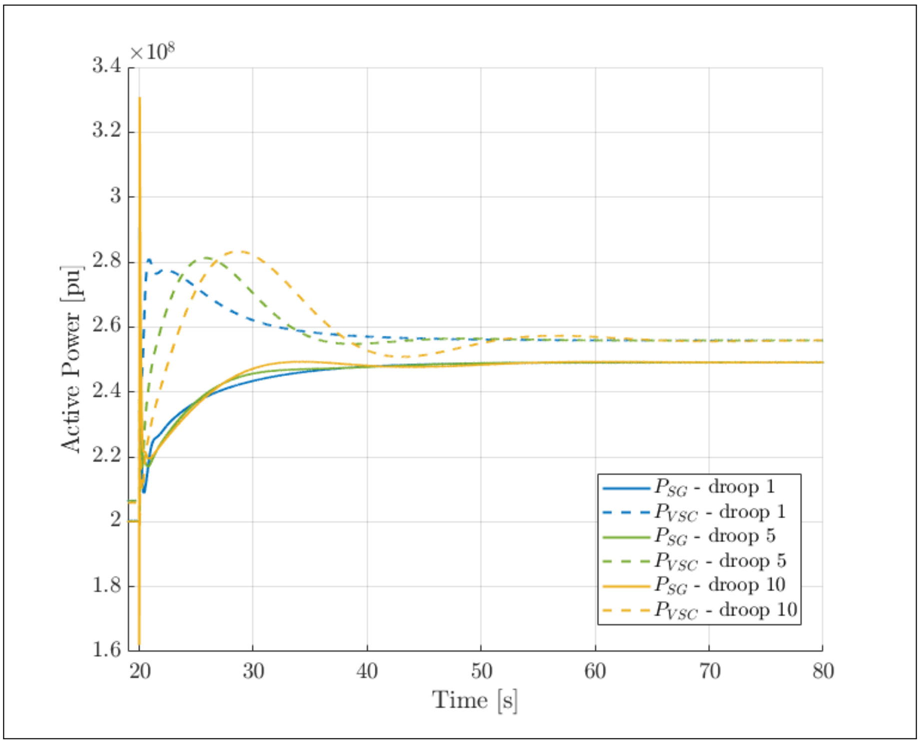

Figure 21: Active power response for varying droop values in both machines.

power is slightly higher for higher droop values, reflecting the reduced effectiveness of frequency support.

The reactive power results, presented in Fig. 22, confirm that the reactive power response is largely unaffected by the droop setting for active power. Both machines return to nearly identical steady-state values, and the effect of droop is only visible in the transient period immediately after the disturbance. This further demonstrates that in this control configuration, reactive power dynamics are mostly decoupled from the active power droop setting.

2.5 Questions block 3 - Focusing on the grid-forming control model

2.5.1 Inertia H Results

The influence of varying the inertia constant H within the grid-forming control model is clearly visible in both transient and steady-state dynamics.

As shown in Fig. 23, a larger inertia leads to a noticeably slower frequency deviation after the load step, with a less extreme nadir and slower recovery. In contrast, a system with low inertia ($H = 2$) shows a sharper frequency drop and more rapid oscillations. The increased inertia effectively slows the system's response to disturbances, providing better stability but at the cost of reduced speed in frequency settling.

The active power response (Fig. 24) similarly demonstrates that increasing inertia results in smoother power transitions for both the synchronous generator and the grid-forming converter. Low inertia cases display larger overshoots and more rapid oscillations in active power immediately after the disturbance. As H increases, the transient oscillations are damped, and both

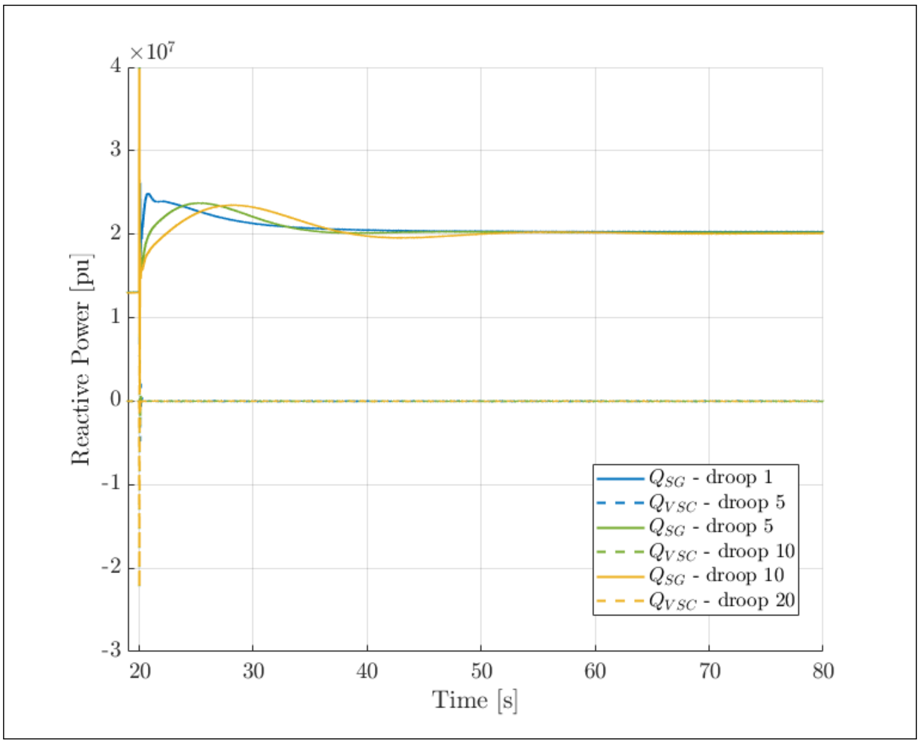

Figure 22: Reactive power response for varying droop values in both machines.

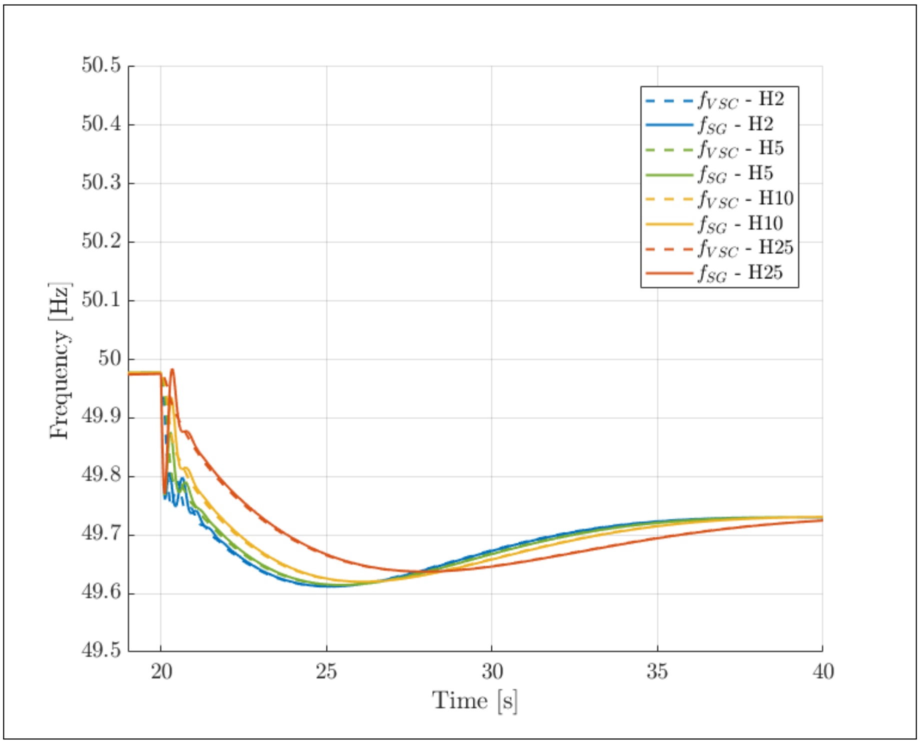

Figure 23: Frequency response for different synchronous generator inertia values (H) in the grid-forming control model.

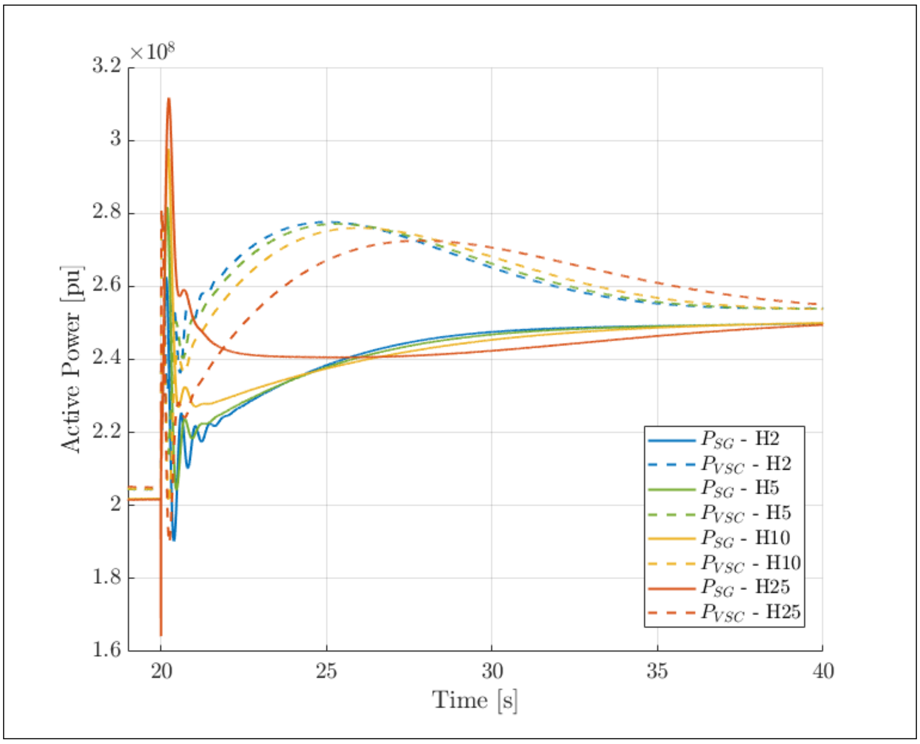

Figure 24: Active power response for different synchronous generator inertia values (H) in the grid-forming control model.

devices reach their steady-state output more gradually.

Figure 25 shows the corresponding reactive power dynamics. While the impact of inertia on reactive power is less than for frequency or active power, a lower inertia still results in higher initial oscillations in Q following the load step. As inertia is increased, the amplitude and frequency of these oscillations decrease, and the system reaches to its steady-state reactive power sharing. This shpows that inertia not only influences active power-frequency dynamics, but can also affect the initial settling of voltage and reactive power when strong coupling exists in the grid-forming control structure.

2.5.2 Droop Results

The effect of droop variation in the grid-forming control model is clearly visible in the system's frequency, active power, and reactive power responses.

As shown in Fig. 26, increasing the droop value from 1% to 10% leads to a larger steady-state frequency deviation after a load disturbance. This occurs because higher droop reduces the ”stiffness” of frequency control, so the system tolerates a greater deviation from nominal frequency to share the load between the synchronous generator and converter. The transient response is also affected: higher droop causes a deeper frequency nadir and a more oscillatory recovery, while a lower droop results in a quicker return to steady-state.

The corresponding active power results (Fig. 27) show that, for each droop value, the synchronous generator and VSC reach the same new steady-state active power balance following the load step. When both droop settings are matched, active power is always shared equally, in-

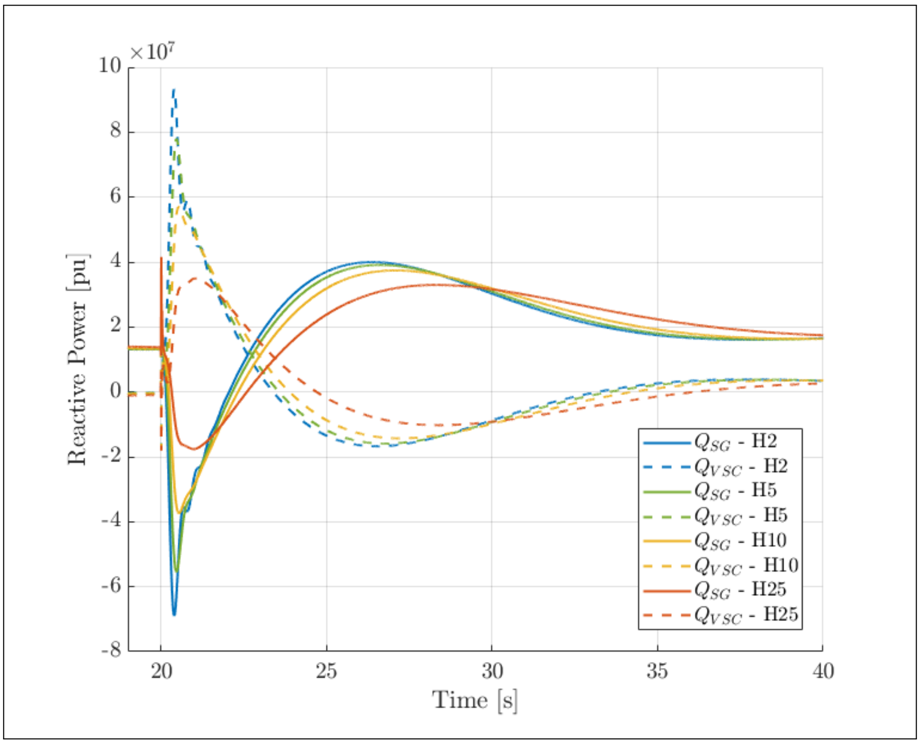

Figure 25: Reactive power response for different synchronous generator inertia values (H) in the grid-forming control model.

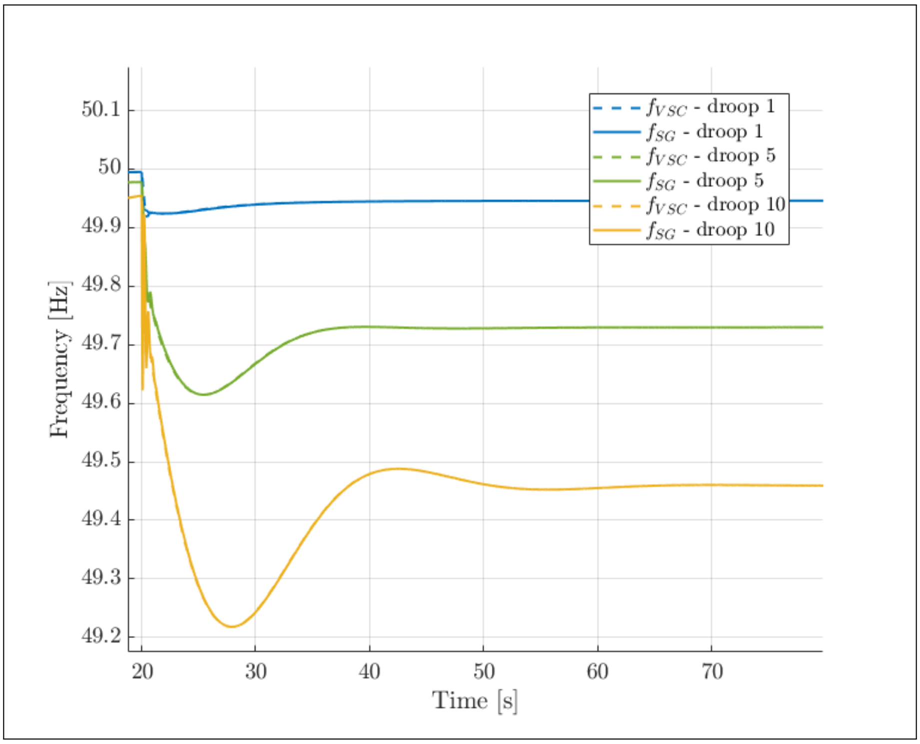

Figure 26: Frequency response for different droop values in the grid-forming control model.

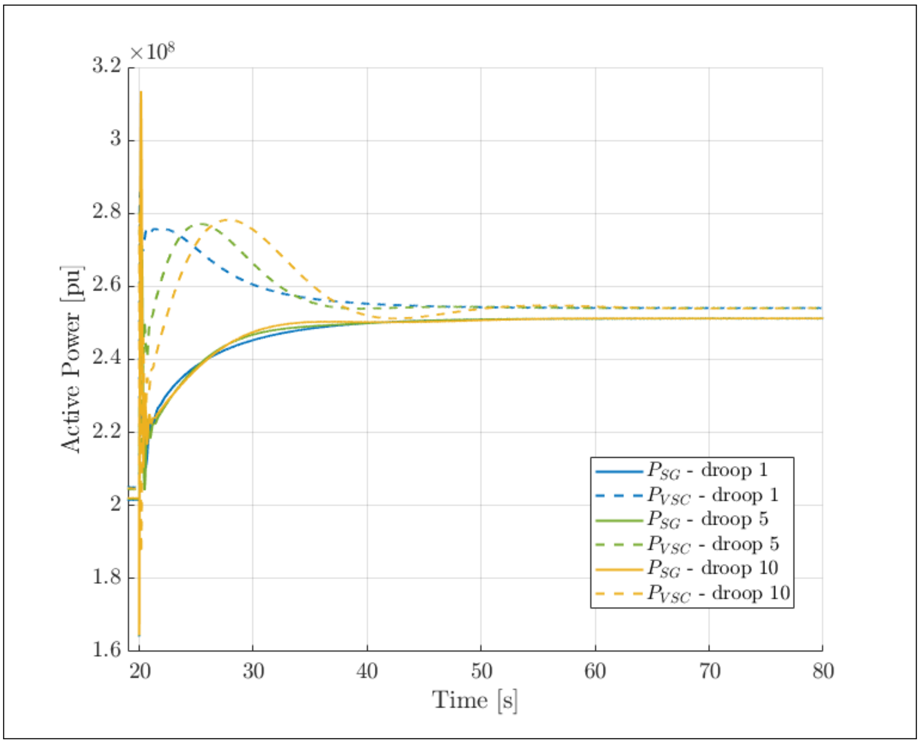

Figure 27: Active power response for different droop values in the grid-forming control model.

dependent of the absolute value of the droop. However, the equilibrium frequency at which this sharing occurs decreases with increasing droop. The transient overshoot in active power also grows with higher droop, reflecting the system's reduced ability to counteract rapid changes in frequency.

Figure 28 depicts the reactive power dynamics. While the steady-state reactive power output is largely unaffected by the choice of droop, higher droop settings lead to more pronounced oscillations in the initial moments after the disturbance. This suggests some coupling between active power droop and transient voltage/reactive power behavior in this grid-forming scenario. However, after the system settles, the reactive power sharing converges to similar values regardless of the droop, indicating that reactive power is still primarily determined by voltage control settings rather than the active power droop characteristic.

2.5.3 Droop Filter Results

The effect of varying the droop filter time constant (τ) is depicted in Figs. 29–31. The droop filter is a low-pass filter applied to the measured active power before it is fed into the droop control, smoothing out high-frequency noise and fluctuations. This filter determines how rapidly the converter's control reacts to changes in measured power.

As shown in Fig. 29, decreasing the filter time constant (τ) leads to a more rapid and oscillatory frequency response following the disturbance. A smaller filter time constant allows the converter to respond more quickly to power changes, but can also introduce oscillations or even instability due to a lack of damping. Conversely, increasing τ smooths the response, resulting in a slower

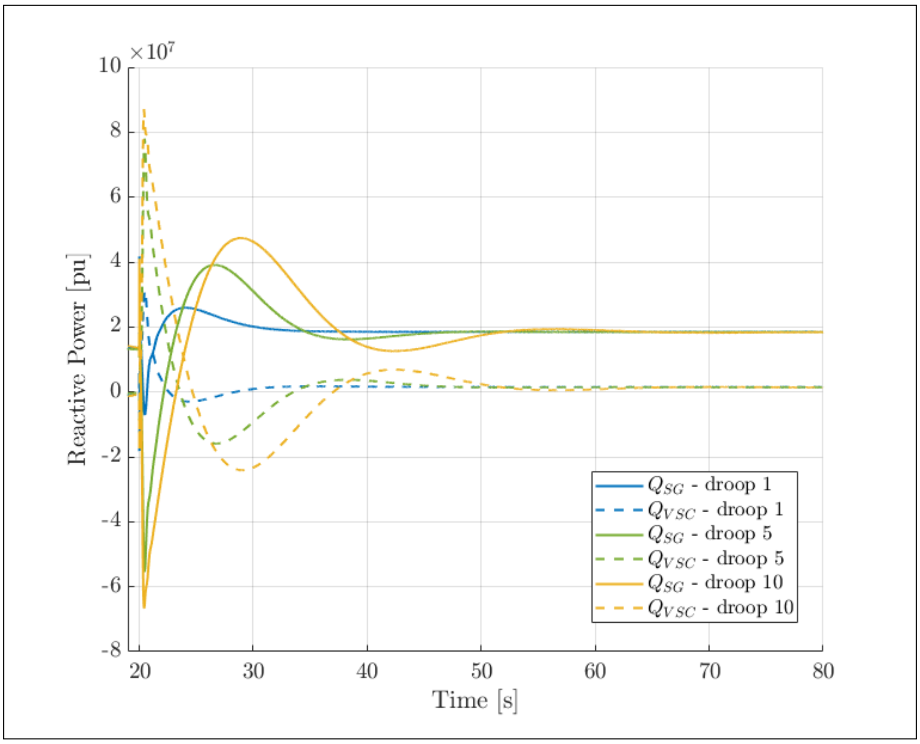

Figure 28: Reactive power response for different droop values in the grid-forming control model.

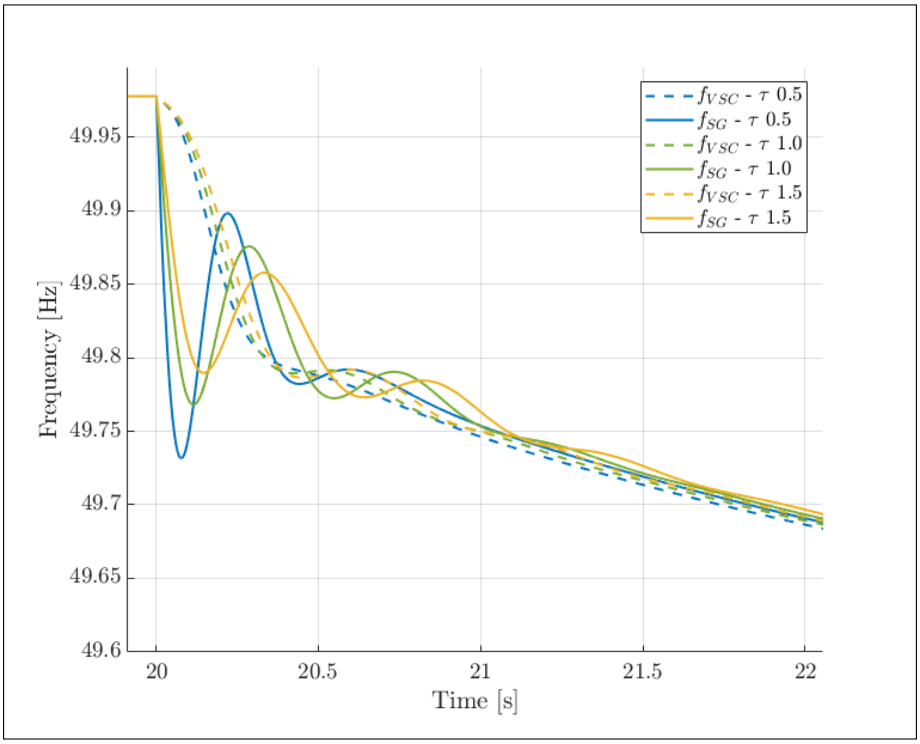

Figure 29: Frequency response for different droop filter time constants (τ) in the grid-forming control model.

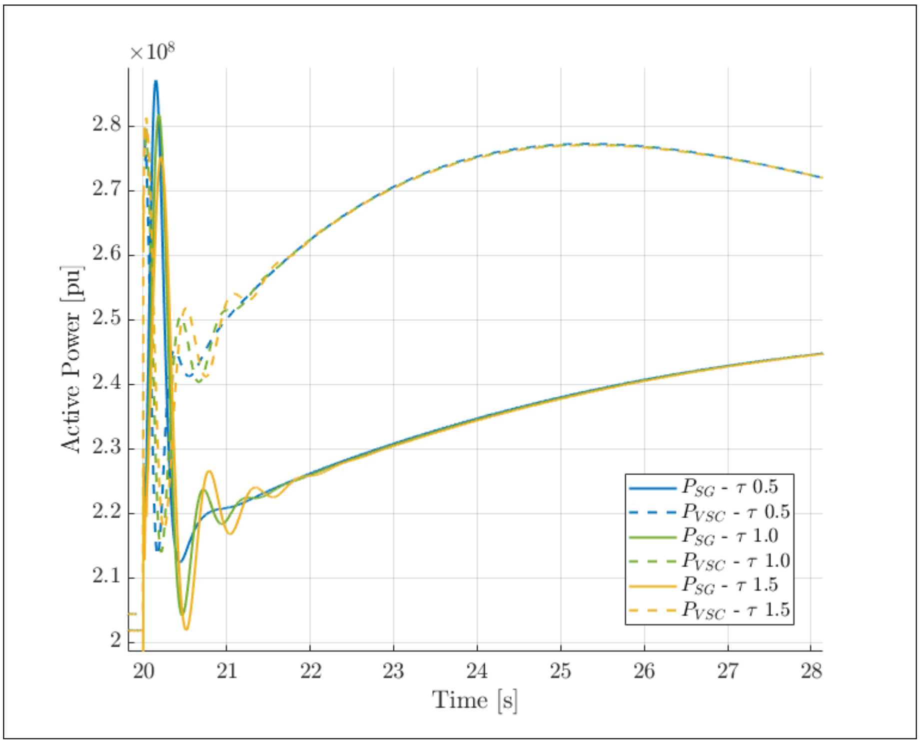

Figure 30: Active power response for different droop filter time constants (τ) in the grid-forming control model.

but more damped recovery toward the steady-state frequency.

The corresponding active power results (Fig. 30) show that a smaller τ produces a sharper and more oscillatory transient in active power for both the synchronous generator and the VSC. As the filter time constant increases, these oscillations are attenuated, and the active power response becomes more gradual. The steady-state value of active power remains unaffected by the choice of τ, confirming that the droop filter predominantly influences transient performance rather than steady-state sharing.

The influence on reactive power is illustrated in Fig. 31. In contrast to the frequency and active power responses, the choice of droop filter time constant (τ) has negligible impact on the reactive power dynamics. Both the transient and steady-state values of reactive power are nearly identical for all tested values of τ. This suggests that, in this model, the droop filter applied to the active power measurement does not significantly affect the reactive power behavior of either the synchronous generator or the VSC.

In summary, tuning the droop filter time constant provides a trade-off between responsiveness and stability in the converter's control system. A smaller filter time constant results in a faster but potentially oscillatory response, while a larger filter enhances stability at the expense of a slower dynamic reaction.

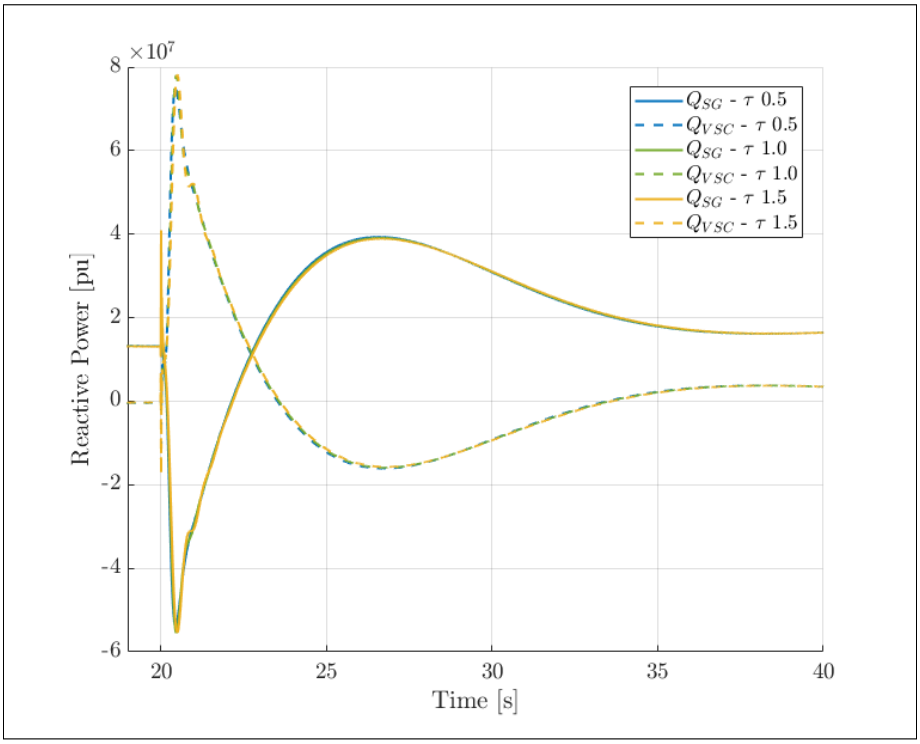

Figure 31: Reactive power response for different droop filter time constants (τ) in the grid-forming control model.

3 Problem 3: Constructing an Alternative Grid-Forming Structure

3.1 Alternative Voltage Control: Virtual Impedance

Grid-forming inverters replicate the essential functionalities of conventional synchronous machines by actively regulating voltage and frequency in weak or islanded networks. Virtual impedance can help play a role in this functionality. It emulates a controllable impedance in series with the output voltage, typically inductive, to decouple active and reactive power flows, damp circulating currents, and enhance stability during parallel inverter operation. This approach enables the inverter to adapt dynamically to changing grid conditions without relying on external communications [1], [2].

The control structure implemented in this study integrates the virtual impedance layer in front of the voltage control loop. The block diagram of the complete control system is shown in Figure 32.

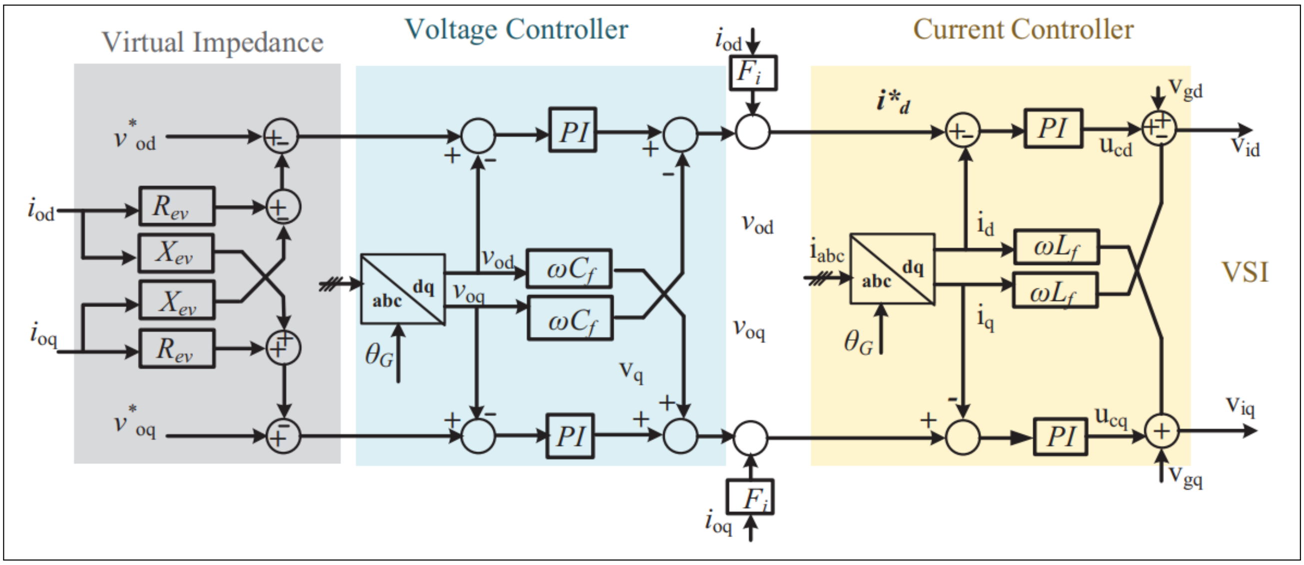

Figure 32: Block diagram of Virtual Impedance integration with voltage and current loops for the Grid-Forming (GFOR) inverter system. Image adapted from [2].

3.2 Virtual Impedance implementation and results

The virtual impedance loop works by dynamically modifying the inverter's output impedance through an additional feedback path that adjusts the voltage reference signals v_{od} and v_{oq} fed into the inner voltage controller. By feeding back the measured PCC currents i_{od} and i_{oq} and adding their processed signals to the voltage references, the inverter can emulate a desired impedance profile. Most commonly a complex impedance $Z_{\text{ev}} = R_{\text{ev}} + jX_{\text{ev}}$ to achieve various objectives. In both islanded and grid-connected modes, virtual impedance has been employed to improve power sharing across unequal feeder impedances, damp oscillations, limit fault currents, and reduce active/reactive power coupling, especially in resistive network conditions. While fixed values for R_{ev} or L_{ev} can be effective, adaptive tuning methods better balance enhanced stability with preservation of voltage quality.
The implemented values used for the virtual impedance are taken from [1]:

$$R_{v-base} = 0.025\Omega$$

$$L_{v-base} = 1\text{e}^{-4}\ \text{H}$$

These base values are tested along with the same values multiplied by 10 and 100 to test the influence of varying parameters.

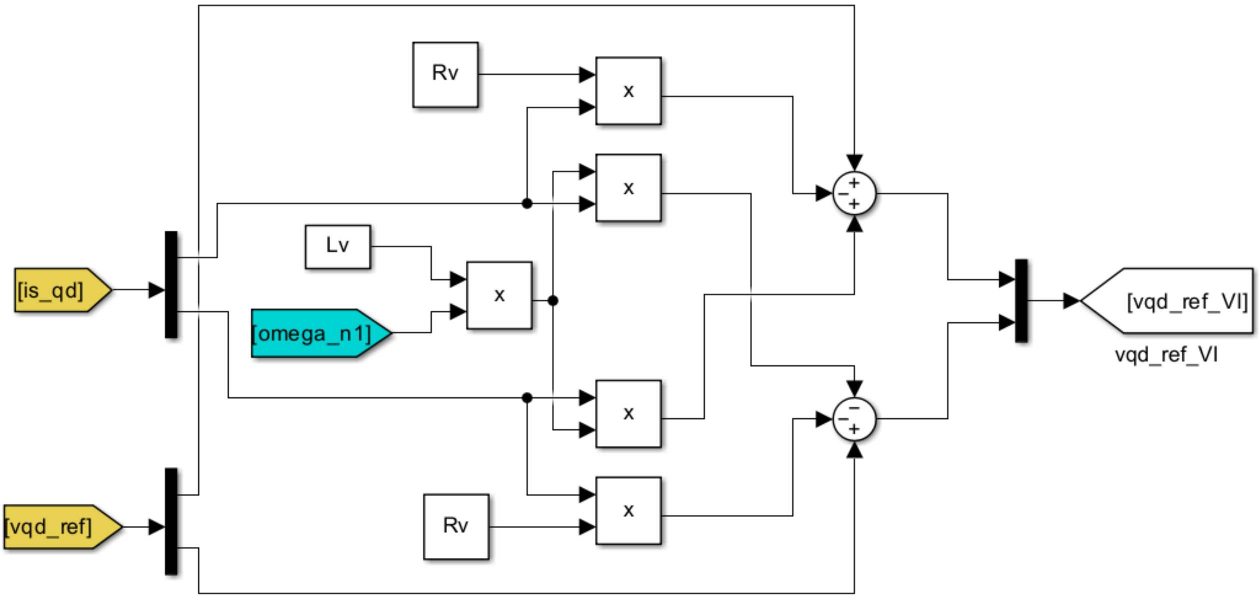

Figure 33: Implementation of the virtual impedance control block in the GFIM model.

The virtual impedance implementation shown in Figure 33 adds a virtual voltage drop proportional to the converter current. This effectively emulates an internal impedance and modifies the converter dynamics. As illustrated in Figure 34, increasing the virtual resistance R_v results in reduced oscillations in the reactive power response, indicating improved damping. However, the VSC also injects more steady-state reactive power to compensate for the added virtual voltage drop. This behavior reflects the need for additional reactive support to maintain the voltage at the point of common coupling (PCC) when internal impedance is emulated. Consequently, the synchronous generator contributes less reactive power, shifting the reactive burden to the VSC. This demonstrates that virtual impedance not only stabilizes dynamic behavior but also affects steady-state power sharing.

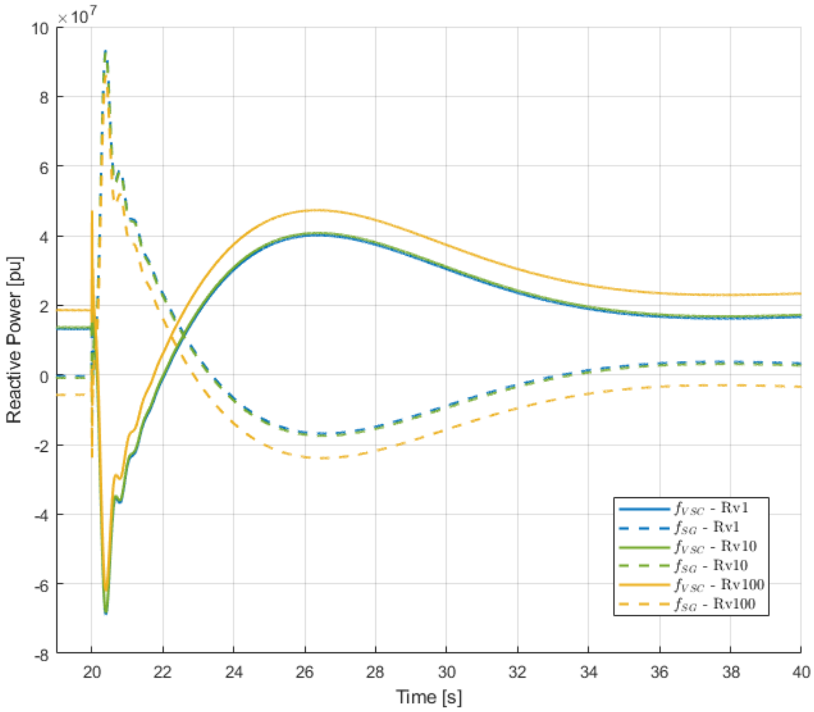

Figure 34: Reactive power response of the SG and VSC for increasing virtual resistance values $R_v = [1, 10, 100] \cdot R_{v-base}$

Notably, variations in the virtual inductance L_v and the virtual resistance did not produce observable differences in the dynamic response of the active power or frequency plots. Neither did the virtual resistance R_v to the active power dynamics. The influence of the virtual impedance in the form of resistance R_v was primarily visible in the reactive power response shown in Figure 34. This suggests that the virtual impedance mainly alters the converter's voltage–reactive power characteristics, without significantly impacting active power sharing or frequency dynamics in this setup. However, the values taken from the literature are for a converter of different order of magnitude, with proper tuning it is probable boht R_v and L_v will show effect in the active and reactive power dynamics.

3.3 Virtual Synchronous Machine

Unlike traditional synchronous generators, grid-forming voltage source converters (VSCs) do not automatically adjust their output frequency in response to changes in power exchange. Instead, any imbalance manifests as a variation in the DC-link voltage, placing additional demand on the DC energy source. If the control scheme does not include frequency modulation, the converter remains locked at its nominal 50 Hz, regardless of load or generation shifts. When such a "stiff" frequency source is tied to a larger network, even small frequency mismatches prevent proper power transfer and ultimately lead to loss of synchronism. To overcome this, a dedicated synchronization mechanism, such as a Virtual Synchronous Machine loop is integrated, ensuring that the converter's frequency behavior closely emulates that of a synchronous machine and thus maintains stable, bidirectional power flow.

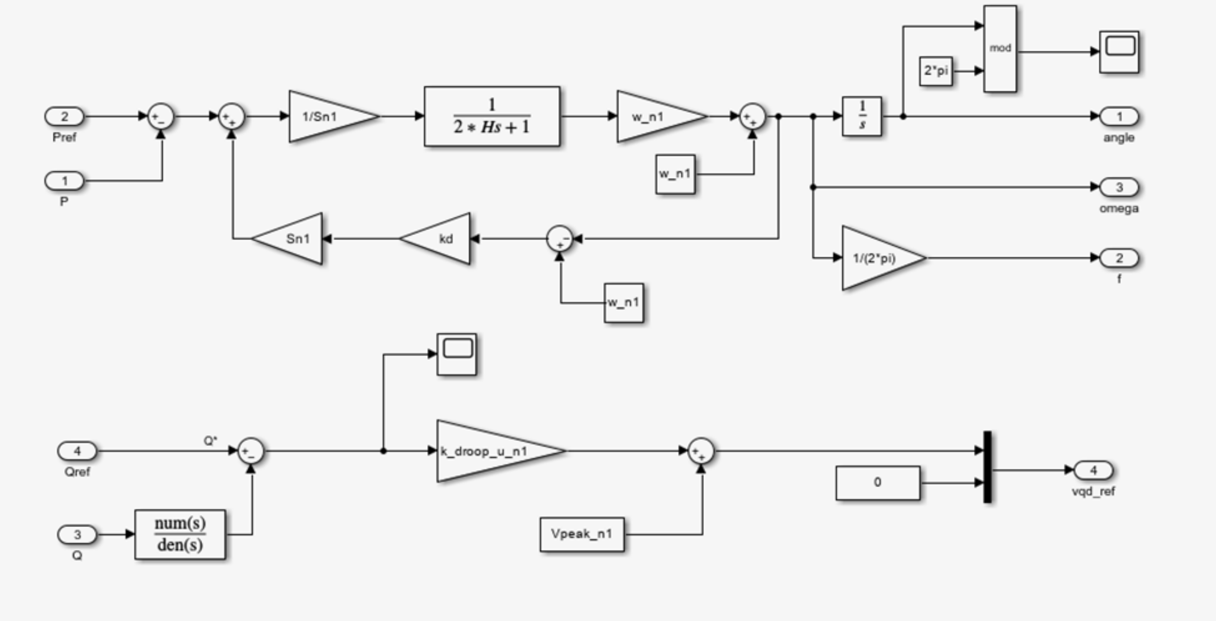

Figure 35: Virtual Synchronous Machine Implementation

References

[1] C. Fan, X. Qin, L. Qi, H. Liu, B. Ding, and Z. Meng, “The function mechanism of virtual impedance in grid-forming droop control and an adaptive parameter tuning method for virtual impedance based on network equivalent identification,” in *2024 IEEE 2nd International Conference on Power Science and Technology (ICPST)*, 2024, pp. 2171–2176. DOI: 10.1109/ICPST61417.2024.10602455.

[2] K. Rahman, J. Hashimoto, and D. Orihara, “Virtual impedance control for enhanced current limitation in grid-forming inverters,” in *2024 IEEE Third International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2024, pp. 1078–1083. DOI: 10.1109/ICPEICES62430.2024.10719306.