Electrical grid simulation in the COLMENA framework

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December 12, 2024

1 Introduction

COLMENA is a decentralized framework that allows the coordination of multiple agents to solve complex problems. The framework is based on the concept of a colony of agents that can communicate and coordinate to solve a problem. The agents can be programmed to have different roles and behaviors. The objective of the project is to develop a test case for the COLMENA framework in the context of electrical grids using the simulation tools provided by ANDES [1](later on, potentially others). The resulting goal is to showcase the capabilities of COLMENA in the context of a decentralized electrical grid, providing useful use cases showing noticeable improvements to be derived from this architecture. The present document is an answer to Objective 1 - Development plan for the validation of the platform and the implementation can be accessed in the following **repository** [10].

2 Power Grid & Service definition

We define an electrical grid as a set of nodes called buses with electrical devices attached to them. The nodes are interconnected between them through branches, traditionally, power lines and/or transformers. The devices connected to each given bus are generators, loads or others types of devices. In ANDES, each device is defined by a set of differential and algebraic equations (DAE) that define how the devices' states change over time.

The electrical grid is defined by multiple magnitudes that define its overall state. Some of the more critical metrics that we consider are the following. The

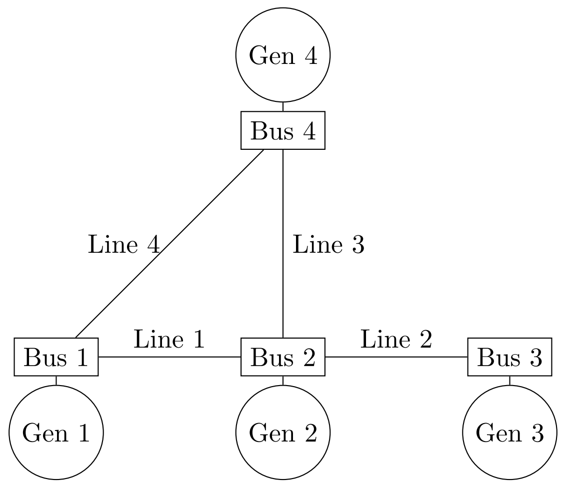

Figure 1: Simple power grid topology with buses and generators.

one most important to our use case is the frequency since it's linked with most other magnitudes and maintaining the frequency is one of the primary concerns of grid operators.

- **Frequency:** The frequency can be understood as a local measurement that describes the voltage at a specific bus. A device called Phasor Measurement Unit (PMU) can measure the frequency of the bus it is connected to. Maintaining the frequency at the nominal value (e.g. 50 Hz in Europe) is key for the proper functioning of the grid. Frequency values above or below this value can unbalance the grid from a power point of view or even damage certain components. It is worth mentioning that while the frequency is a local variable, it is often the case that the frequency is the same, or very similar, in all buses.
- **Synchronous Generator Shaft's Speed**: Synchronous generators are devices that generate power which is then injected to the grid. This is done by magnetically coupling a stator and a rotor that spins at a certain speed, ideally as close as to the nominal frequency. The value of the frequency in the grids buses and the angular speed of the rotor are closely linked and are frequently used interchangeably. In fact, generators can see a drop in their angular speed to mitigate a drop in frequency in a close bus.
- **Voltage Magnitude(V)**: The voltage is a magnitude linked to a specific bus and also needs to be as close to the nominal value as possible. Drops in frequency can be linked to drops in voltage.
- **Power injected/consumed (kW)**: The power injected is by a generator is the amount of power the . The objective of the grid supervisor is to

keep the balance of power as close to zero as possible. Raising the amount of power injected by a generator also tends to raise its synchronous speed. It's an important lever in controlling

Table 1: Summary of the metric's definition.

Magnitude	**Unit**	**Description**
Voltage	kV	Voltage at a bus
Generator Speed	Hz	Rotations of the shaft per second
Current	A	Current through a branch
Frequency	Hz	Number of voltage sine waves per second
RoCoF	Hz/s	Frequency's derivative
Power Injected	kW	Power injected to the grid by a generator.

The metrics just introduced are key to defining the performance of a grid and to the frequency control response of a power grid. The objective of the frequency response is multiple. On a first time scale (primary response)[2], the control aims to take the system from a transient to a stable condition and avoiding critical values for the frequency. During the secondary response, the objective is to restore the steady state values to their nominal values. Finally, the last response's objective is to restore the the power reserves to their original value [3].

The objective of the service implemented in COLMENA will be then to aid to the frequency control response by implementing decentralized roles that can improve the performance of the control. These roles will take the form of changing set-points for certain devices, connecting or disconnecting devices such as secondary generators and others.

Additionally, we will define the different metrics in relations to their context in the grid. This means that every metric is measured in a specific context like a given area or a type of electrical device. This way we can group the values of the previously defined metrics in specific contexts such as the following and develop more specific insights.

- Local: Measurements that can be done in the same device.
- Semi-Local: Measurements that can be done in the devices connected to the same bus.
- Regional: Measurements that can be done in the devices from the same given area.
- Categorical: Measurements that can be done in the devices of the same type.

- Adjacent: Measurements that can be done in the devices that are just one connection away.

2.1 Devices

Power system simulations, such as the ones performed by the ANDES package, are organized around devices. Each device at a given time t is defined by the value's of the algebraic variables and state variables. Devices of the same type have the same variables. In the context of the frequency service control we have found the following devices that can be useful to the simulation and also present some sort of decentralized control.

- Synchronous Generators: Traditional sources that convert mechanical energy into electricity to be injected to the grid.
- Converters & distributed generations: Used to convert power from distributed generation from DC to AC, usually associated to some sort of distributed generation.
- Loads: They consume power from the grid.
- Lines: They connect different buses.
- Switches: They allow the flow of power through a Line.

In the following sections we will se how these devices fit with the service of controlling the frequency.

Synchronous Generators

Generators are devices that inject power to the grid. A synchronous generator injects electrical power from a rotating part that spins synchronously to the grid's frequency. The synchronous generators in the simulation will be defined by two internal states: $\omega \in \mathbb{R}$ the angular velocity and $\theta \in \mathbb{R}$ the shaft's angular position. The generator's turbine can set the value of the power being injected by the generator's or the set point for the reference angular speed ω_{ref}. Controlling these set points is key to improve the performance of the grid and impacts the directly on the grid. The generator model used in the simulation can be consulted at [4] and [5], it also includes the governor's and the exciter's model.

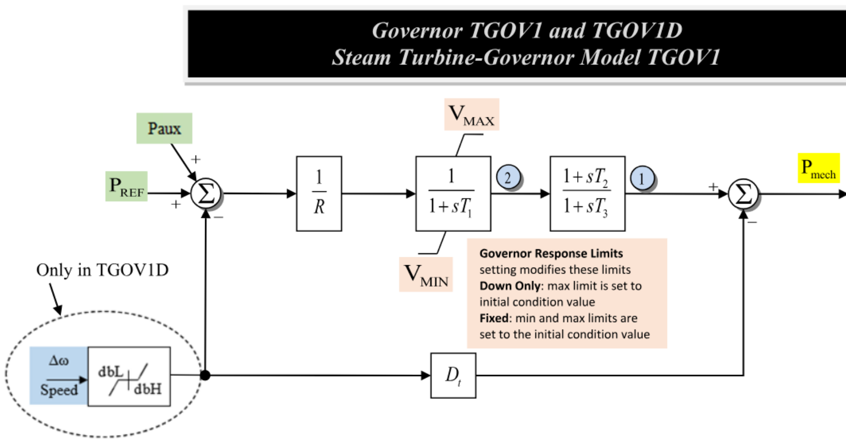

Figure 2: Block diagram of a generator's governor controlling the injected power. [4]

Converters & distributed generation

Converters can take the form of a Voltage Source Converter (VSC). A VSC is a converter that converts a DC voltage to an AC voltage waveform. They are commonly used to track the angle of the grid at a bus and inject (or absorb) active and reactive power from an energy source. They are usually paired with DC sources of energy, such as PV plants, as a way to connect them to the grid. We consider a VSC that can operate in two modes: 'Grid following'(GFL) and 'Grid forming'(GFM).

- Grid Following: In the GFL mode, the converter tracks the grid's frequency and injects a controlled power, acting as an ideal current source.
- Grid Forming: In the GFM mode, the converter creates its own frequency and imposes a voltage acting as an ideal voltage source.

In terms of control, both GFM and GFL have reference values they have to track with controllers. The control is built with the goal of following the reference value as close as possible. For the GFL mode the reference value usually refers to the power injected, while for the GFM its the frequency or voltage. This GFM behavior is quite close to one of a typical synchronous generator. The flexibility and the different set points of this type of converter fit well with the decentralized control principle of COLMENA.

Modelling distributed generation is usually done by combining a DC current source and sometimes a battery that are connected to a AC-DC converter.

The converter that is paired to this ensemble can control both the active and reactive power that is injected to the grid and that is stored in the battery (if present). The control of the setup is defined by the parameters $\gamma_p, \gamma_q \in [0, 1]$. These parameters define which proportion of the active and reactive power respectively and generated by the setup is injected to the grid. We can therefore define different set points for the distributed generation depending on the power injected. The power that is not injected is then saved by the battery. This can be expressed as these three different set points:

- $\gamma_p = 1$ all of the power generated is injected to the grid.
- $\gamma_p = 0$ all of the power generated is stored in the battery.
- $\gamma_p = 0.5$ half of the power generated is injected to the grid and half is stored in the battery.

Loads

A load is an electrical model that is connected to a bus and consumes a given amount of active and reactive(P(MW), Q(Mvar) respectively). In the context of the frequency control service, the load device can have varying values of P and Q depending on the state of the grid. More specifically, operators can control the power consumed by enforcing load shedding which consist in reducing part of the power being used. This response can be very useful to the grid in order to adapt to drops in generation or line faults.

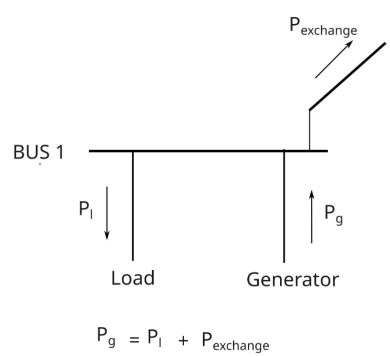

Figure 3: Bus power exchange diagram.

Switches

Switches are controllable elements that control the connection state of a Line. In this case the set states are just 'Open' or 'Closed'. In the open state no current travels directly between the buses while in the Closed state the line works at normal operation.

2.2 Andes-COLMENA Integration requirements

In this section we explain how ANDES and COLMENA will work during the simulation and how they will communicate. As a standalone, ANDES simulates the time domain response of the power grid for a pre-set amount of time. The package solves the equations numerically and returns the solution but it does not simulate the grid in real time. To enable the integration with COLMENA we modify ANDES into running for a given step-size only when the real time is greater than the simulation time in order for it to catch-up to. ANDES is run parallel to COLMENA on an independent app run on an separate device not part of COLMENA's colony of agents. Specific COLMENA Agents will periodically send requests to the ANDES App to get the simulation's information and to send changes.

From the COLMENA's side, we will define specific COLMENA-agents that will be paired with a single ANDES-device in the grid. The COLMENA-agent will have two main roles in a continuous manner. They will read their device's variables, store the values internally, and send the behavior changes in the form of new set-point and parameter changes for the paired device. These roles will be the building blocks of the COLMENA-ANDES integration.

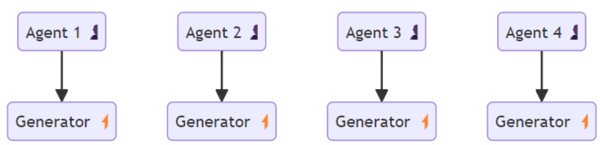

Figure 4: COMENA-Agent pairing diagram.

3 Use Case Specification

Having explained the objectives of the project, we want to chose specific scenarios that are well adapted to evaluate these objectives. In this particular case, we are looking for power grids of considerable size, and with the appropriate types of devices presented earlier such as generators and converters to facilitate the integration of distributed generators. Additionally, we would want to choose use cases in which the grid can be separated into different areas to properly implement different geographical contexts to take into account. Finally, we also consider the ease to access information and data about the modeled grid. We consider the following as interesting candidates:

- Kundur 2-area system [6]
- IEEE-118 bus test case [7]
- IEEE 300 bus test case [8]
- ACTIVSg 2000 bus test case [9]

For the first use case we propose first using the grid defined in the Kundur two area system [6]. This grid consists of 10 buses divided in 2 areas. Each area includes two synchronous generators. Additionally, this simulation includes a line failure at a specific time step (Line 8, at $t = 2$ s). The objective of this is to showcase how the decentralized nature of COLMENA can adapt to unexpected events in the grid such as failures and avoid cascading failures in the grid.

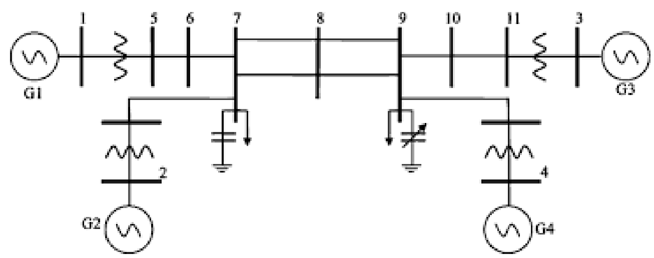

Figure 5: Kundur grid scheme. [6]

In this specific use case the COLMENA-Agent will be paired with a generator and monitor the values provided by the ANDES simulation. Moreover, this agent will be able to modify some of the generators values such as the power injected or internal controlling parameters. The objective is to overtime include different sources of generation and the proposed GFL-GFM converters. Let's see a proof of concept of what the integration could look like. In this use case one of the COLMENA Agents is able to modify the inertia parameter of the generator 1 inside the simulation depending of the value of the generator's speed ω. By modifying the inertia parameter M we expect to see is the generator's angular velocity ω having 2 distinct behaviors.

Operating State	KPI	Parameter M value
A	$\omega \in [1 - \varepsilon, 1 + \varepsilon]$	12
B	$\omega \notin [1 - \varepsilon, 1 + \varepsilon]$	120

Table 2: Generator set-points summary.

Once this more accessible use case is deployed, our next goal is to scale the simulation to a more extensive grid that could be able to showcase the

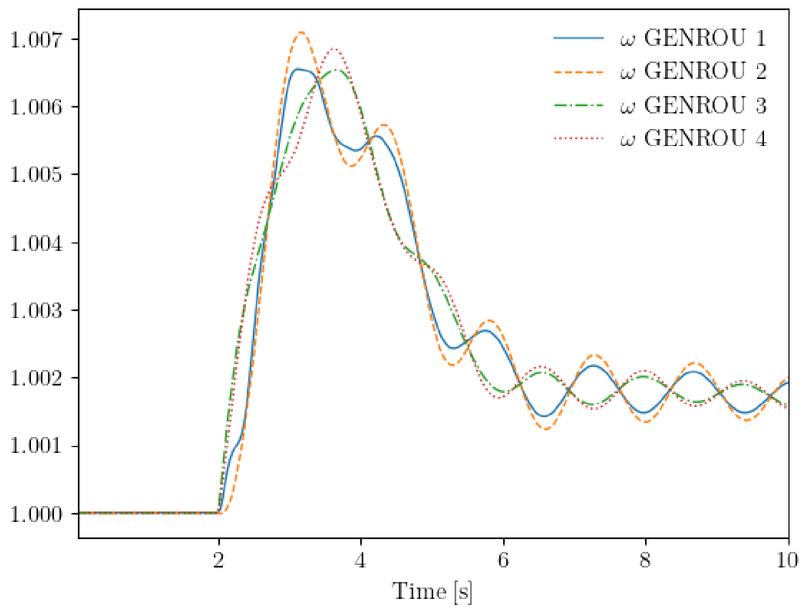

Figure 6: Time series of the distributed generator's frequency.

performance of COLMENA in a more complicated environment, with more varieties of models and more complicated controls overall. The objective is to eventually run the simulation in larger grids with a larger number of agents. For this we can use other test grids such as the IEEE 118 bus case [7]. This test grid is composed by 118 buses, 54 generators and 99 Loads. Additionally, some of the generators are synchronous condensers which are essentially synchronous motors whose shaft is not connected to any mechanical load. Their main function is to provide reactive power compensation. Moreover, it uses the same models as the ones used in the previous tests cases so transferring the already developed models is feasible.

3.1 Grid's Performance & Key Performance Indicators

In the first section we have defined a set of metrics and states that are key to defining the grids state, specifically when dealing with the frequency response. These include the frequency, the angular speed of the synchronous generators and others. We aim to define key performance indicators (KPI) starting from the metrics defined previously. These KPIs define the performance of the grid with respect to the frequency service control.

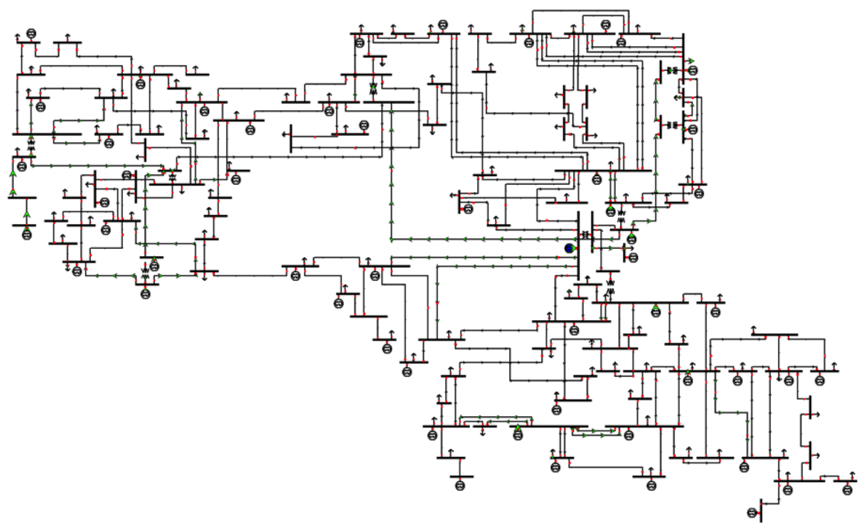

Figure 7: IEEE118 grid scheme. [7]

- Minimum and maximum of the generator's frequency.
- Minimum and maximum of the mean bus frequency in an area from the nominal frequency.
- Voltage steady state values.
- Rate of Change of Frequency (RoCoF).
- Available power reserves.
- Power Balance & regional power exchanges.
- N-1 criteria
- Power Losses

Minimum and maximum of the generator's frequency

This KPIs is usually used with regards to the primary response in the frequency control response. The objective would be to maintain the generator's frequency ω as close to the nominal value. In moderately strong power grids a common value for this KPI would be around 0.1% around the nominal value. This is true for both the generator's frequency and the buses' frequency.

RoCoF

The Rate of Change of Frequency is the frequency's time derivative measured in a given bus. It signals sudden changes in frequency and if its close to 0 for a given amount of time it can also signal the grid reaching a steady state. Therefore the RoCoF is key to measure the performance of the grid during transients.

Available Power Reserves

The available power reserves is the amount of power that can be activated in a given amount of time in case of need but its not being used. It usually considers an horizon of 10 to 30 minutes. Additionally, we also need to consider the ramp up and ramp down capabilities of these power reserves. The ramp up measured in kW/s and is the speed with which this reserve power can come online. These power reserves come in the form of battery storage and ancillary generators that can be ramped up when necessary. Similarly, ramp down The grid operator usually defines minimum requirements for available power values.

Maximum line current

The current through a line is limited by a maximum value for security purposes. If the current through a line surpasses the maximum value for a specific amount of time the line can disconnect to avoid being damaged.

Regional monitoring & power exchanges

Regional power imbalances can occur within interconnected grids. To monitor and manage these regional imbalances, a key indicator is the Area Control Error (ACE). The ACE of a region is defined as the difference between the scheduled power exchange and the actual power exchanged neighboring regions. A well-performing grid aims to keep the ACE values of all regions close to zero, indicating that actual power flows are aligned with the planned schedules. Excessive reliance on interconnections to balance regional loads can compromise grid security and resilience. Furthermore, imbalances in one region can propagate to neighboring regions through interconnections, potentially leading to cascading failures and widespread blackouts. Therefore, it's essential to monitor the power exchanges between regions.

N-1 criteria

The N-1 criterion is a standard used in power system planning and operation to ensure reliability and resilience. It specifies that a power system should be able to withstand the loss of any single element (like a generator, transformer, or transmission line) without causing a system-wide failure. New devices could be connected or scheduled by the COLMENA agents to help ensure the criterion is respected.

Power Losses

Grid performance is also influenced by power losses and reactive compensation. Power losses, primarily due to resistance in transmission lines, reduce overall efficiency and increase operational costs. To mitigate these losses, reactive compensation is used, which balances reactive power in the grid, improving voltage stability and reducing strain on transmission infrastructure.

3.2 Role Definitions

The envisioned integration of Andes and COLMENA places a special focus on the grid's frequency control response. For this purpose we propose a set of roles that can be taken by the COLMENA agents in order to control the grid in a decentralized grid. The roles are explained descriptively.

Device Monitoring Role

The device monitoring role monitors the values of the different states and variables of a specific electrical device and then publishes the necessary metrics to evaluate the state of the grid. The agent that takes on this role is supposed to be paired to a single device of type generator, although we can consider this role being taken multiple times by the same agent in order to control multiple devices. In this case the device monitoring roles is persistent and has the following functions:

- Stores the state and algebraic variables relative to the device it is paired up.
- Publishes the necessary data to the appropriates channels

Taking the example of a generator device this role has the requirement of having a generator and at least these one channels:

- Channel Generator measurements: where it publishes the frequency of the generator every time step.

Rotor Speed Optimizer

This role is specific to agents with the "generator" requirement. It is activated when the rotor's speed exhibits unusual behavior, such as high values or high Rate of Change of Frequency (RoCoF). This role defines the optimal reference value for the rotor's speed, $\omega_{ref}$to facilitate frequency control during transient states. One objective of this role is to avoid excessive oscillation in the frequency and getting to a steady state during the primary response.

The role can be subdivided into transient and steady-state modes, as its behavior may differ depending on the grid's overall state.

Rotor Speed Setter

This role, specific to agents with the "generator" requirement, receives a reference rotor speed ω_{ref} and modifies the generator's parameters to achieve this target value. The set of actions performed are actions are:

- Reading the ω_{ref} continuously.
- Adapt the control strategy in Andes through a parameter change.
- Deactivate the role when the $\omega \in [\omega_{ref} - \varepsilon, \omega_{ref} + \varepsilon]$ in the steady state.

This role will usually adapt the generator's power in order to get the desired speed. More generally, we can imagine this role being extended to set other types of variables in a given device. This could be implemented through a feedback control loop or through a feed forward control loop. These are strategies that can be represented as a block diagram where the input signal is the difference between a reference value and the real value.

Voltage Optimizer Role

This role, specific to COLMENA agents paired with electrical devices and capable of control, computes the optimal voltage when deviations occur from the desired voltage set point, considering multiple objectives such as minimizing power losses, maximizing voltage stability, and ensuring system security.

For example, the role would:

- Prioritize voltage stability: If the system is experiencing voltage fluctuations, the role may prioritize actions that stabilize the voltage, even if it means slightly increasing power losses.
- Optimize power losses: During periods of high demand, the role might focus on minimizing power losses by adjusting the voltage to reduce resistive losses in transmission lines.

The specific optimization techniques used will depend on the capabilities of the agent and the specific requirements of the grid.

Load Shedding Role

This role can be taken by agents associated with a load consuming device in the grid. It is activated in the secondary response to counter a drop in frequency.

- Continuously diminishes the power being used by the load.
- When the frequency is back to a nominal value, it goes back to the desired power.

Reserve Activation Role

This role can be taken by agents associated with ancillary generation or batteries consuming device in the grid. It is activated in the secondary response to counter a drop in frequency.

- Connect or Disconnect the reserve to the grid.
- Set the power injected to the grid.

Area Monitoring Role

This role can be taken by agents associated with in a specific geographical area. The role monitors the power balance of that area with the rest of the grid. It has access to the appropriate communication channels. When activated it's charged with:

- Monitoring the power balance in the area.
- Flagging failure in the scheduling of the power exchanges.
- Isolate problematic regions that could provoke a cascading failure.

Current Security role

If the intensity's value through the line is above the security current then publish the change of behavior in the appropriate channel. It also disconnects line to avoid a cascading failure in the grid. This role could be expanded to take into account other types of failure that damage the grid such as short-circuited lines and gives appropriate adaptations to the grid. Finally, it tries to reconnect the faulted line by adapting the voltage at each end bus and reconnect the grid if possible.

4 Current Work

4.1 Current Grid Requirements & Milestone analysis

In relation with the current work we define the following milestones:

Milestone 1: Requirement analysis for the use case

A comprehensive analysis of the specific requirements of the selected use case(s) will be performed. It is anticipated that such use cases will deal with large networks, potentially with thousands of nodes, as is the case with of nodes, as is the case in the Spanish network. As such, scenarios containing hundreds of converters will be considered for converters will be considered to represent distributed renewable generation, which would act together as a swarm. The idea is to have numerous control variables that condition the operation of the system and that their optimal determination is favored by the use of the technologies the use of the techniques developed in COLMENA.

The Kundur system presented in 3 serves as a good stepping stone for analyzing the different requirements of the implementation. In this power grid the failure of a power line near the beginning of the simulation ($t = 2$ s) destabilizes the grid's frequency and showcases the service's main objective: the frequency response. The line failure provokes a rise in the 4 synchronous generator's (from 1 per unit (p.u.) to 1.006 p.u.). Additionally, after the transient state the system reaches a steady state where the generator's frequencies still deviate substantially from the nominal frequency. Modifying the power provided by the generator would make the frequencies come back to their nominal state.

All in all, this first use case delivers a first application for COLMENA that is tasked with the frequency response. Its objective is to ensure the frequency of the electrical devices as close to the nominal value as possible. For this we require to simulate the behavior of the grid, to monitor the values defining the state of the grid and also to be able to modify the grid's topology and parameters dynamically during the simulation since these are the ways COLMENA will interact with the simulation. The synchronous generators that will eventually be paired with COLMENA agents act as a decentralize control affecting the grid.

Milestone 2: Use case specification, with KPI definition

This milestone will focus on selecting standard and open network models, such as IEEE 118, ACTIVSg 2000, PEGASE 9241, among others. The aim is for the network to have a sufficiently high number of nodes, be capable of experiencing voltage collapses in case of poor operation, and offer room for improvement by integrating distributed renewable generation units throughout the network. Some potential indicators reflecting the system's state include: percentage of losses, maximum and minimum voltages, maximum branch loading, compliance with the $N-1$ or $N-2$ criteria, maximum short-circuit currents, rate of frequency change due to demand increases, among others.

Regarding this milestone the different metrics and KPIs introduced in 3.1 serve as values that can engage and disengage potential COLMENA roles that act upon the frequency response service. The main KPIs and metrics are the mean frequency deviation to the nominal frequency as well as the mean voltage. As seen in 3 the objective is to apply changes to the grid when these KPIs are not suitable for normal operation of the grid. Other KPIs that are not specific to the frequency response but are important for grid operations such as voltage values, or short-circuit occurrences have also been considered.

In fact, the next use cases will include other types of devices available and that will increase the amount of ways that the grid can be changed dynamically throughout the simulation by the agents. These new devices include GFM converters that can adapt their apparent voltage, flexible loads and renewable generation. These new devices that we have already introduced 2.1 will bring new ways of changing and adapting the grid dynamically to the requirements of the frequency control response.

4.2 Implementation

The current state of the work can be accessed in the Github following **repository** [10]. The current work can be separated into three main parts:

- A modified version of Andes Curent to be run in parallel to the service application.

- The implementation of the Frequency Control Service using the COLMENA package.

4.2.1 Modified Andes

The original Andes package is set up to run a Time Domain Simulation (TDS) from a steady state initial configuration. From these initial conditions the TDS runs offline until the final time that has been set beforehand. To integrate Andes into COLMENA we need to run the simulation online, that means running andes with the same clock as a real life scenario, and being able to affect the grid in real time through the roles actions. For this purpose we modify the original andes code to allow for the following behavior. In this case, Andes simulation time runs parallel to the real time which enables proper communication between both tools. More specifically, Andes first loads the appropriate grid and then runs the simulation online.

In order to run Andes as a separate instance that can communicate with COLMENA we run it as a Flask app that can receive HTML messages. In the current setup the current machine initializes the flask app by executing the `app_andes_interface.py` file. The flask app then runs in a local port and is ready to receive GET and POST HTML messages from COLMENA when running. The long term objective is to run this app in an independent machine that can reliably communicate with the COLMENA devices.

Algorithm 1 Andes App Simulation Pseudocode

Load Grid data
Run Power Flow
while $t_{andes} + \Delta t \leq t_{real}$ **do**
    Get changes from roles
    Apply changes
    Run the simulation for Δt.
    $t_{andes} \leftarrow t + \Delta t$.
end while

```python
# Function to run andes in real time
@app.route('/run_real_time', methods=['GET'])
def run_real_time():
    t_run = request.args.get('t_run')
    t_run = float(t_run)
    t_now = time.time()
    try:
        while system.dae.t <= t_run:
            if time.time() - t_now >= system.dae.h:
                system.TDS_stepwise.run_andes_inapp(system.dae.h)
                t_now = time.time()
        return jsonify({"Message": 'Success', "Time":system.dae.t}), 200
    except Exception as e:
        print(e)
        traceback.print_exc()
        return jsonify({"error": str(e)}), 500
```

Listing 1: Function to run Andes in real-time using Flask.

4.3 Frequency Service Deployment

With regards to the service and role implementations they can be found in the folder `AndesRoles`. In the same folder there is the file `data.json` that describes the electrical device the simulated agent is paired to. This is useful when running the agent through the programming model, this way the roles running know what device they are linked to and what parameters they need to change if necessary. As of now, when running the roles through an agent in a docker container the roles don't have access to that file so it would be necessary to think of an alternative that could bypass this limitation.

Right now the roles can be executed in two ways: the first one that is more flexible is running them directly on the computer by using the function `.execute_role()` on each role included in a service. The second one, closer to the final objective, is first deploying a docker container and then running the services and its roles and that container using zenoh to communicate. In order to show a proof of concept we run a frequency control service with a single agent where the monitoring role and the frequency optimizer role are executed.

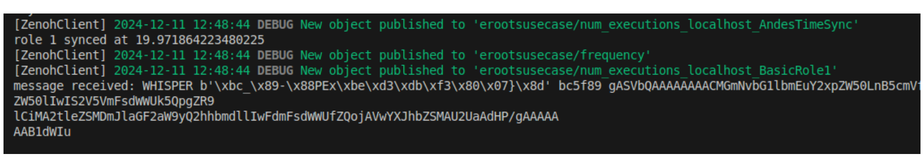

Figure 8: Terminal during role execution

For the second test, we first need to create the docker container with a specific policy, in this case "EAGER", and a given requirement in this case 'GENERATOR'. For this specific service we also develop a simple context and requirements for the roles. The electrical device to be monitored is defined in the role definition although this is to be changed in later iterations. Finally, running the deployment tool deploys the agent in the container.

5 Conclusion & Future work

Grid performance through decentralized control strategies presents an interesting opportunity for the COLMENA framework. By pairing agents with grid components, such as generators and converters, COLMENA could enable real-time monitoring and control adjustments that enhance grid stability, particularly in response to frequency disturbances and power imbalances. This approach was explored using the Kundur test case to showcase the potential of COLMENA. COLMENA could change the behavior of agents in response to changes in KPIs such as frequency stability. The agents would then send messages through the appropriate channels signaling changes in the set point of the devices that would be reflected in the ANDES simulation.

Future work should focus on expanding the scope and complexity of the use cases. This includes integrating a broader range of devices, such as advanced energy storage systems, and simulating additional scenarios that include renewable energy sources and demand response mechanisms. More specifically, we want to deploy a use case in the IEEE 118 bus system. Additionally, we will focus on clearly defining the communication channels between COLMENA agents, and the contexts and requirements that define the agents in the COLMENA framework for this use case. Finally, we also want to develop and implement more complex roles that could control multiple devices at a time in a specific area and coordinate the response between different areas.

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