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Investigating Droop Control Contribution to Grid Resilience by Maintaining Frequency Stability During Grid Disturbances

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ABSTRACT
In contrast to conventional power plants, which are based on large synchronous generators with large inertia capabilities to dampen sudden disturbances, renewable energy sources, such as solar and wind, connected to the grid through power electronics converters, display low system inertia and overload limiting capabilities. Additionally, because they lack primary frequency regulation capabilities, they are unable to actively respond to the frequency response of the system. This research investigates the contribution of droop control strategies to grid resilience by focusing on their ability to maintain frequency stability during grid disturbances. The study employs a simulation-based approach using MATLAB/Simulink to model the Djoum power plant in Cameroun and implement droop control algorithm. The methodology involves designing and analyzing the system's response under sudden load changes using droop and supervisory control strategies. Parameters such as droop coefficients and control bandwidths were systematically varied to analyze their impact on frequency regulation and grid resilience. Results show that droop control maintains system operation by adjusting frequency and voltage under disturbance, while supervisory control acts as a secondary layer to fully restore parameters to their reference values thereby ensuring reliable operation during grid disturbances.

Keywords: Renewable Energy Integration, Droop Control, Frequency Stability, Grid Disturbances, MATLAB/Simulink.

INTRODUCTION
Renewable energy sources connected to the grid via power electronics interfaces, display low system inertia and overload limiting capabilities as compared to conventional power plants that are based on large synchronous generators with large inertia capabilities to dampen sudden disturbances [1] [2]. They do not have the ability of primary frequency regulation, so they cannot actively respond to the frequency response of the system. Connection of renewable energy resources to the grid often cause random fluctuations in output power. If the frequency

regulation capacity is insufficient, low-frequency load shedding protection action will be triggered, which would lead the system to disconnect in severe circumstances, compromising the power grid's safety. Additionally, the occurrence of unforeseen events such as sudden load changes, generator outages, and faults further disrupts the balance between power supply and demand, leading to frequency deviations and potential grid instability. Therefore, it is absolutely imperative to improve on the frequency stability of such a system in order to make the grid more resilient to disturbances. Traditional frequency control methods, such as governor control and automatic generation control (AGC), rely on centralized control schemes and may not adequately address the dynamic and decentralized nature of modern power systems. In this context, droop control strategies [3] [4] [5] [6] offer decentralized and responsive control mechanisms to maintain grid stability.

Despite the extensive application of droop control strategies in microgrids, the dynamic interaction between primary (droop-based) and secondary (supervisory) control mechanisms during significant grid disturbances, such as sudden load changes or generator outages, remains underexplored [7] [8] [9]. Current literature largely addresses these controls separately, with limited insights into their combined effectiveness in mitigating frequency and voltage deviations in renewable-dominated grids, particularly under high penetration of PV systems. Supervisory control plays a crucial role in addressing the steady-state restoration issues left unresolved by droop control. This research employs the combined use of droop and supervisory control strategies to address frequency and voltage deviations during sudden grid disturbances. The case study here is Djoum solar PV plant where an anti-windup proportional integral controller integrated in an inverter has been used to demonstrate their collective effectiveness in enhancing grid stability and resilience. The objective is to investigate the contribution of droop control strategy to grid resilience by focusing on their role in maintaining frequency stability during grid disturbances by developing an algorithm for proportional integral droop controller in a MATLAB/Simulink modeling environment [10] [11]. The proportional integral droop controller designed experiment is expected to respond to frequency droop control in the grid under various sudden grid disturbance scenarios. It is hypothesized that proportional integral (PI) droop control mitigates frequency deviations thereby minimizing the impact on grid stability by varying load disturbances. This study will help in the understanding of methods to control or mitigate frequency drooping in grid-connected renewable energy resources [12] [13]. It offers opportunities to improve on the performance reliability and efficiency of microgrid systems and contribute to the transition to a more sustainable energy future.

PROBLEM DESCRIPTION

Renewable energy sources connected to the grid via power electronics interfaces display low system inertia, output power fluctuations and overload limiting capabilities as compared to conventional power plants that are based on large synchronous generators with large inertia capabilities to dampen sudden disturbances. They do not have primary frequency regulation ability and cannot actively respond to the system's frequency response. If the frequency regulation capacity is insufficient, low-frequency load shedding protection action will be triggered leading to system disconnection in severe circumstances. Additionally, unforeseen disturbances like sudden load changes disrupts the balance between power supply and demand leading to frequency deviations and potential grid instability. Therefore, it is imperative to improve on the frequency stability of such a system in order to make the grid more resilient to disturbances. Traditional frequency control methods, such as governor control and automatic generation control (AGC) rely on centralized control schemes and do not adequately address the dynamic and decentralized nature of modern power systems. Droop control has become an alternative for frequency regulation.

RESEARCH OBJECTIVES

The primary objective is to investigate droop control contribution to grid resilience in maintaining frequency stability during grid disturbances.

Specific Objectives

1. To implement an identified control method
2. Develop an algorithm for innovative Proportional Integral droop controller in a MATLAB/Simulink modeling environment
3. To evaluate the algorithm using a case study: Djoum 369.48KW PV plant

METHODOLOGY

The study utilizes a simulation-based approach, leveraging MATLAB/Simulink as the primary modelling platform.

Experimental Design

The experiment uses an anti-windup PI droop controller under various grid disturbance scenarios to determine its impact on grid resilience.

Factors:

Two main factors will be considered:

1. Droop Control Strategy: Examining the performance of Proportional-Integral (PI) Droop.
2. Grid condition-Disturbance Scenarios: Simulating three distinct grid disturbance scenarios to replicate real-world events: no sudden load change, Sudden Load Change with and without droop control.

Experimental Procedure:

1. Initialization: Set up the initial conditions of the simulation model and configure droop control parameters.
2. Execution: The simulation is executed for each grid condition-disturbance scenario.
3. Data Analysis: Analyze the results to assess the performance of droop control under the different experimental conditions.
4. Replication: This experimental procedure is replicated multiple times to ensure the reliability and consistency of the results.

Conceptual Design:

The PI droop controller has been designed to regulate the power output of distributed energy resources (DERs) connected to the grid. The controller will use a proportional-integral (PI) control algorithm [14] [15] to adjust the power output of DERs in response to frequency deviations from the nominal value thereby stabilizing the frequency within its predefined limits.

Algorithm:

1. Initialize controller parameters: Proportional gain (K_p), Integral gain (K_i), Nominal frequency (f_{nom}), Desired power output ($P_{desired}$) and Integration time step (dt) [16] [17] [18].
2. Repeat for each time step:
   a) Measures the current frequency deviation (Δf) from the nominal frequency.
   b) Calculates the proportional control action (P_{prop}) using the formula:
   $$P_{prop} = K_p * \Delta f \qquad \text{Equation 1}$$
   c) Integrates the frequency deviation over time to compute the integral control action (P_{int}):
   $$P_{int} = P_{int} + K_i * \Delta f * dt \qquad \text{Equation 2}$$
   d) Calculates the total power adjustment ($P_{adjustment}$) as the sum of the proportional and integral control actions:
   $$P_{adjustment} = P_{prop} + P_{int} \qquad \text{Equation 3}$$
   e) Calculate the desired power output ($P_{desired}$) based on the nominal power output and the total power adjustment:
   $$P_{desired} = P_{nominal} + P_{adjustment} \qquad \text{Equation 4}$$
   f) Adjust the power output of the DERs to match the desired power output ($P_{desired}$).
   g) Repeat the control loop for the next time step

Explanation of Algorithm:

a. The controller initializes the proportional and integral gains, nominal frequency, desired power output, and integration time step.
b. At each time step, the controller measures the current frequency deviation from the nominal frequency.
c. The proportional control action is calculated based on the proportional gain and the frequency deviation. This action provides an immediate response to frequency deviations.
d. The frequency deviation is integrated over time to compute the integral control action. This action accumulates over time and helps eliminate steady-state error.
e. The total power adjustment is calculated as the sum of the proportional and integral control actions.
f. The desired power output is adjusted based on the nominal power output and the total power adjustment.
g. Finally, the power output of the DERs is adjusted to match the desired power output, and the control loop repeats for the next time step.

This algorithm incorporates both proportional and integral control actions to regulate the power output of DERs and maintain grid stability in the face of frequency deviations.

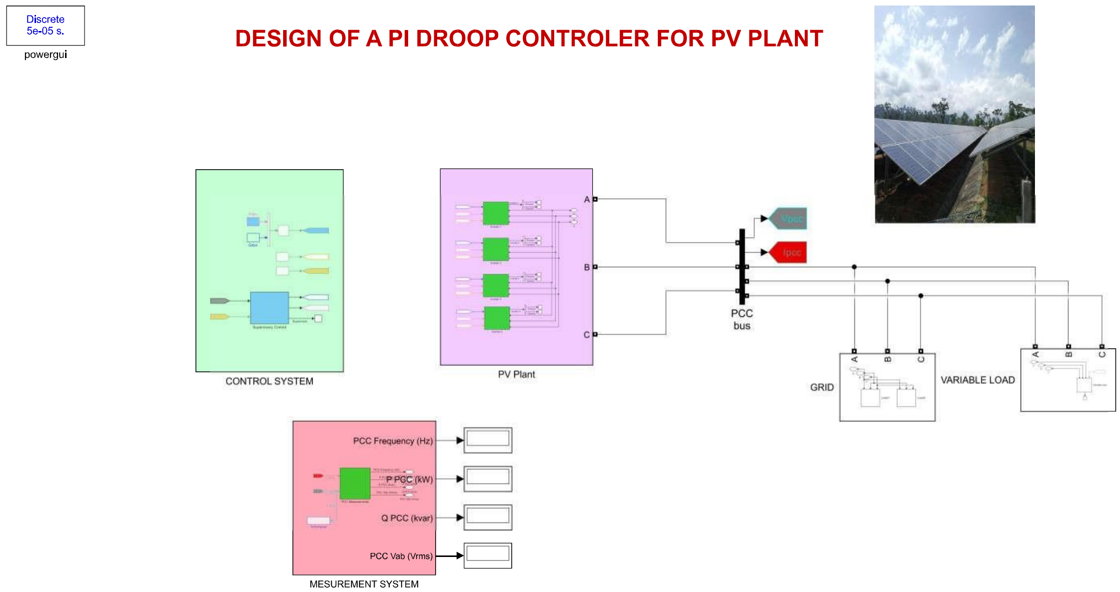

Figure 1: Matlab/Simulink Design of Djoum PV Plant

- The **control system** is responsible for managing the operation of the inverters. This includes implementing droop control to regulate power-sharing and grid stability.
- The **PV plant** is composed of solar panels connected to the inverters.
- The **grid** is illustrated by two (02) fixed three-phase RLC load.
- The **variable load** represents the dynamic active and reactive load on the grid.
- The **measurement system** is used to monitor electrical parameters at the time of simulation.

Paramatisation

- **Grid subsystem**
- **Load 1**
  - Active power = 1000kW
  - Inductive Reactive power = 200Var
  - Capacitive Reactive power = 0Var
  - Frequency = 50Hz
  - Voltage = 400Vrms
- **Load 2**
  - Active power = 500kW
  - Inductive Reactive power = 0Var
  - Capacitive Reactive power = 0Var
  - Frequency = 50Hz
  - Voltage = 400Vrms

- **Inverter subsystem**
- **Variable load**
  - Active power = 300kW to 1000kW depending on scenario,
  - Inductive Reactive power = 100Var to 250 depending on scenario
  - Capacitive Reactive power=0Var
  - Frequency = 0Hz
  - Voltage = 400Vrms

- Voltage = 400V
- Frequency Regulator:
- Propotional gain = 0.3
- Integral gain = 2
- Voltage Regulator :
- Propotional gain = 0.1
- Integral gain = 7

Measurement filter (fn) = 10Hz

- **Supervisory Control**
  Frequency = 50Hz
- **Inverter**
- Power = 400kW
- Frequency = 50Hz
- Primary line voltage = 400Vrms
- Secondary line voltage = 480Vrms
- Dc link voltage = 1000V
- **Droop values**:
- Frequency droop = 1%
- Voltage droop = 4%
- **Current Regulator**
- Propotional gain = 0.3
- Integral gain = 20
- **Voltage Regulator**
- Propotional gain = 2
- Integral gain = 14
- Measurement filter (fn) = 10Hz
- **PMW generator**
- Switching frequency = 2700Hz
- Carrier initial phase angle = 90°
- Sample time = Ts = 5^{e}-05

SIMULATION RESULTS AND DISCUSSIONS

System without any Disturbance

In this simulation, there is no sudden increase in load. This represents the normal load (active load=500KW, reactive load=0 KVar) operation without any grid disturbance. The figures below illustrate the scenario.

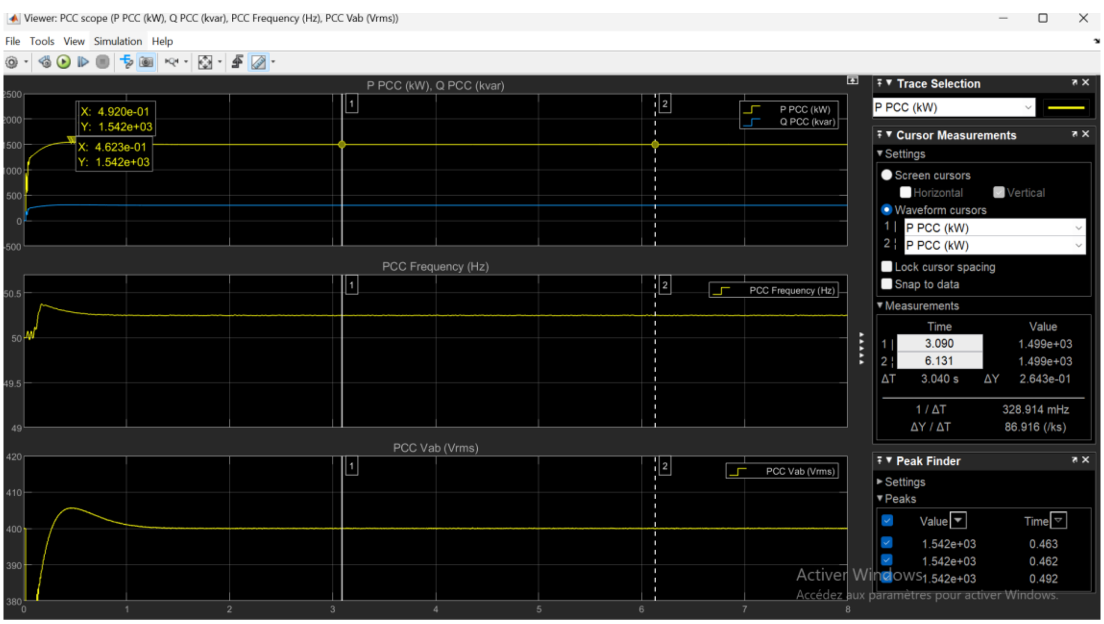

Figure 2: No sudden increase in load-normal operation without any grid disturbance. Frequency (50Hz) and voltage (400Vrms) are stable as shown on the curves.

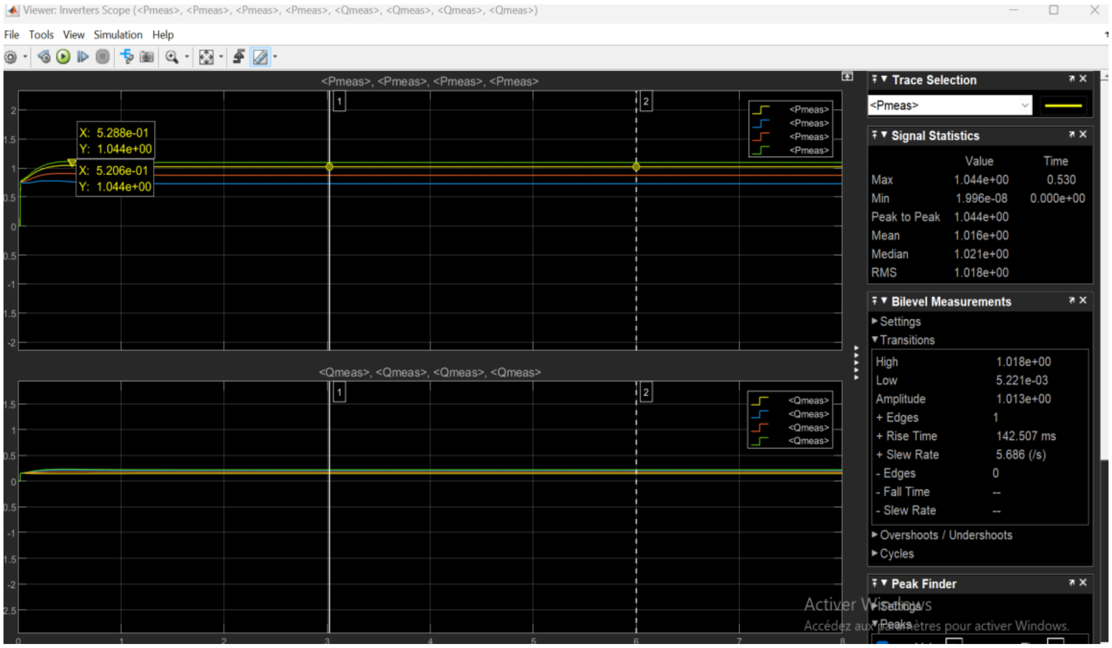

Figure 3: No sudden increase in load-normal operation without any grid disturbance. Inverters active power (P) & reactive power (Q) output normal for each of the four inverters.

Sudden Load Change

During the simulation, the model goes through the following stages:

a. **Load Variation**
   - ✓ At 1 second, the total load on the microgrid increases from 1500 kW/200 kvar to 2000kW/400 kvar.
   - ✓ The inverters share the increased load based on their rated capacities, thanks to the droop control.

b. **Droop Control Activation:** At 1 seconds, the droop control is enabled on all inverters, allowing for proportional load sharing without central coordination.

c. **Supervisory Control:** At 3 seconds, the supervisory control is activated, which adjusts the droop set points to restore the system's voltage and frequency to nominal values (50 Hz and 400V).

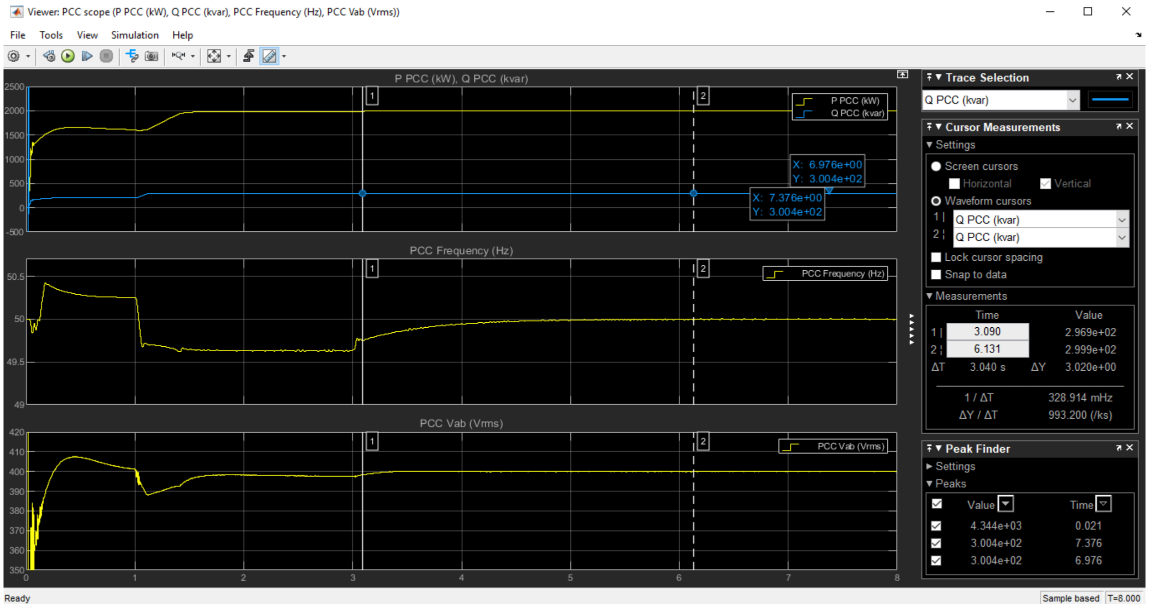

Figure 4: Sudden load change- At 1 second, the droop control is enabled on all inverters, allowing for proportional load sharing without central coordination. At 3 seconds, the supervisory control is activated, which adjusts the droop set points to restore the system's voltage and frequency to nominal values (50 Hz and 400V).

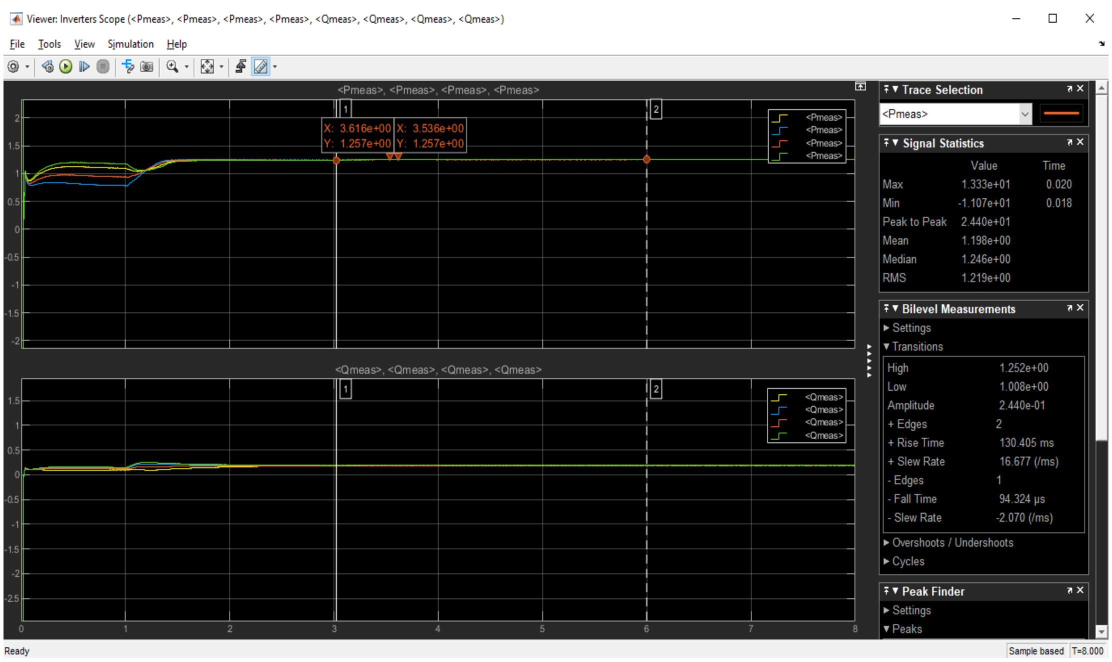

Figure 5: Sudden load change- At 1 second, the power output of the inverters are readjusted.

Sudden Load Change without Droop Control

During the simulation, the model goes through the following stages:

a. **Load Variation**

- ✓ At 1 second, the total load on the microgrid increases from 1500 kW/200 kvar to 1900kW/300 kvar.

- ✓ The inverters are overwhelmed due to frequency droop and so the system collapses.

b. **Droop Control Activation**

Droop control is not activated.

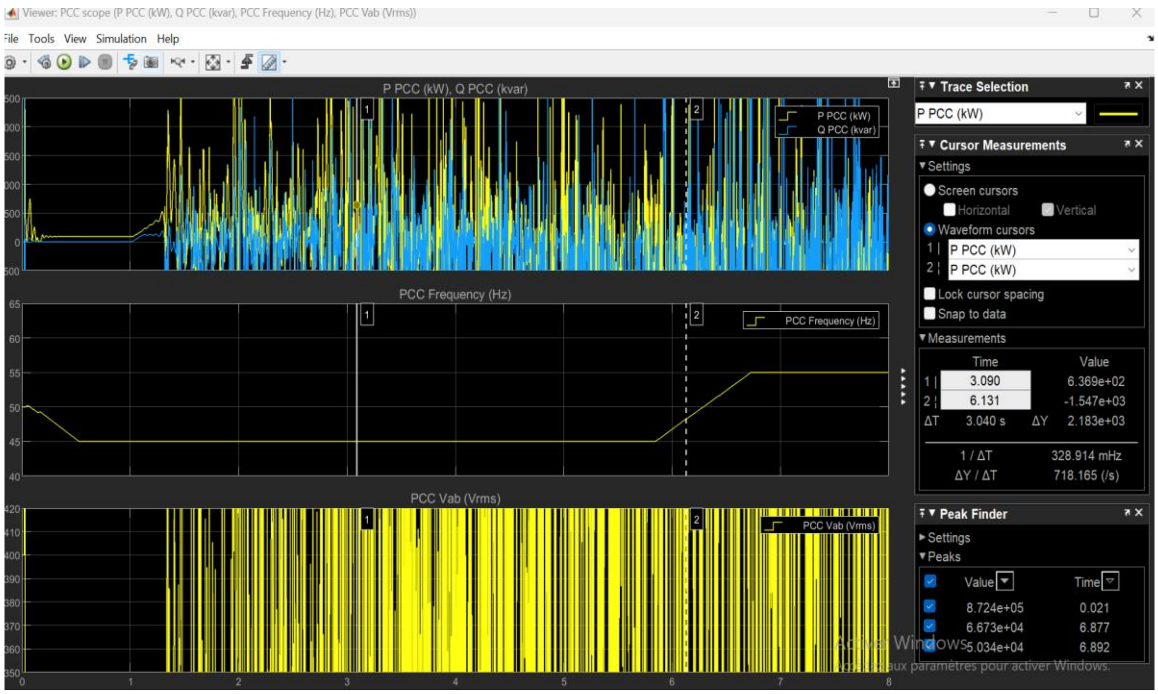

Figure 6: Sudden load change with no drop action-At 1 second, the total load on the microgrid increases from 1500 kW/200 kvar to 1900kW/300 kvar. The inverters are overwhelmed due frequency droop and so the system collapses.

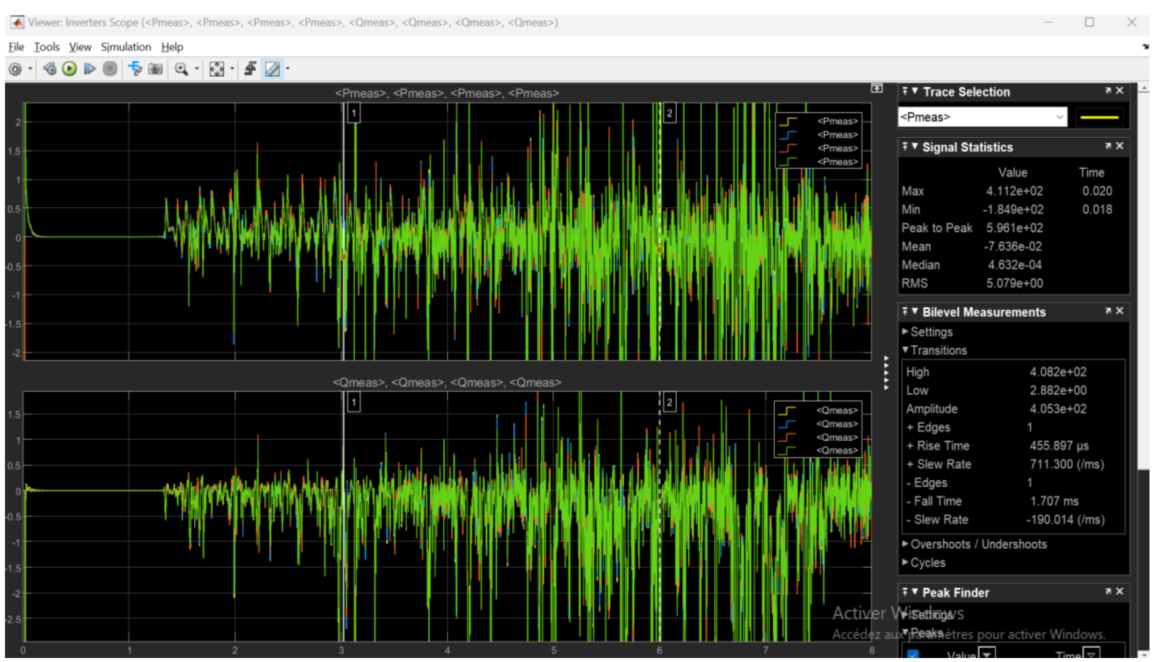

Figure 7: Sudden load change with no drop action-the system collapses. No power output from the inverters.

CONCLUSION

This experiment illustrates that droop control maintains system operation by adjusting frequency and voltage under disturbances, while supervisory control acts as a secondary layer to fully restore parameters to their reference values, ensuring reliable operation during grid disturbances. It is recommended to test the model under larger grid configurations or higher penetration of distributed energy resources to provide insights into the scalability of the proposed control strategy. Considering the rise of cyber threats in grid-connected systems, it is recommended that future research should investigate incorporating cybersecurity measures to protect control systems from attacks that could destabilize the grid.

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List of Symbols

Symbol	Meaning	Unit
Padjustment	Power adjustment	W
Pnominal	Nominal power	W
f	Frequency	Hz
Vrms	root-mean-square voltage	V
Var	Reactive power	Var
V	voltage	V
Kp	Proportional gain	
Ki	Integral gain	
fnom	Nominal frequency	f
Pdesired	Desired power	W
dt	Integration step time	s
Δf	frequency deviation	f
Pprop	Proportional control action	
Pint	Integral control action	

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