Speculation on the 23-Hz oscillations in ERCOT due to large loads

NERC Inverter-based Resource Performance Subcommittee (IRPS)

August 21st, 2025

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DE-EE0011474

SPRING: Stability Prediction for IBR-Penetrated Grids Enabled by Digital Twins

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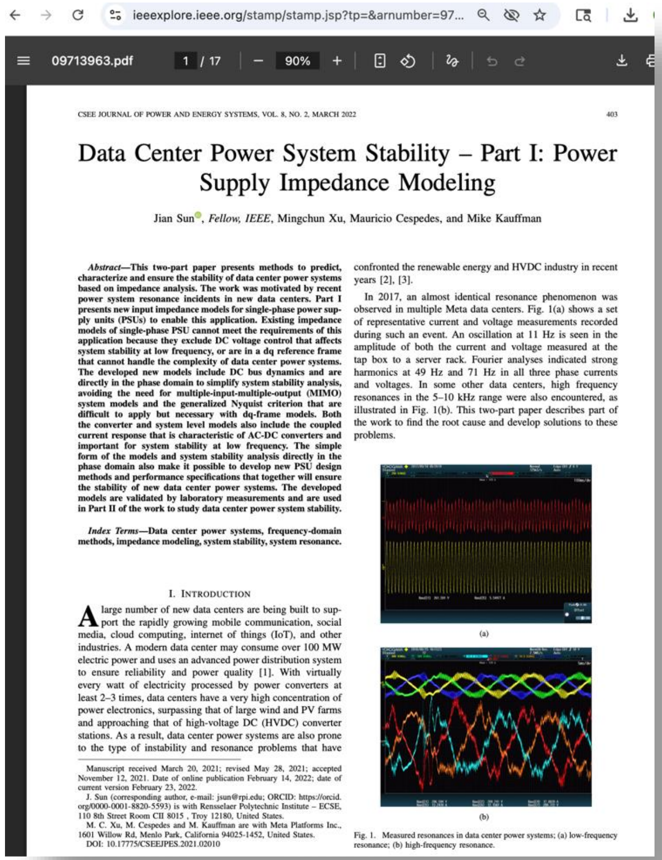
Page 8 – Test in Mid December to determine the root cause of oscillation



CSEE JOURNAL OF POWER AND ENERGY SYSTEMS, VOL. 8, NO. 2, MARCH 2022 403

Data Center Power System Stability – Part I: Power Supply Impedance Modeling

Jian Sun, *Fellow, IEEE*, Mingchun Xu, Mauricio Cespedes, and Mike Kauffman

***Abstract*—This two-part paper presents methods to predict, characterize and ensure the stability of data center power systems based on impedance analysis. The work was motivated by recent power system resonance incidents in new data centers. Part I presents new input impedance models for single-phase power supply units (PSUs) to enable this application. Existing impedance models of single-phase PSU cannot meet the requirements of this application because they exclude DC voltage control that affects system stability at low frequency, or are in a dq reference frame that cannot handle the complexity of data center power systems. The developed new models include DC bus dynamics and are directly in the phase domain to simplify system stability analysis, avoiding the need for multiple-input-multiple-output (MIMO) system models and the generalized Nyquist criterion that are difficult to apply but necessary with dq-frame models. Both the converter and system level models also include the coupled current response that is characteristic of AC-DC converters and important for system stability at low frequency. The simple form of the models and system stability analysis directly in the phase domain also make it possible to develop new PSU design methods and performance specifications that together will ensure the stability of new data center power systems. The developed models are validated by laboratory measurements and are used in Part II of the work to study data center power system stability.**

***Index Terms*—Data center power systems, frequency-domain methods, impedance modeling, system stability, system resonance.**

I. INTRODUCTION

A large number of new data centers are being built to support the rapidly growing mobile communication, social media, cloud computing, internet of things (IoT), and other industries. A modern data center may consume over 100 MW electric power and uses an advanced power distribution system to ensure reliability and power quality [1]. With virtually every watt of electricity processed by power converters at least 2–3 times, data centers have a very high concentration of power electronics, surpassing that of large wind and PV farms and approaching that of high-voltage DC (HVDC) converter stations. As a result, data center power systems are also prone to the type of instability and resonance problems that have confronted the renewable energy and HVDC industry in recent years [2], [3].

In 2017, an almost identical resonance phenomenon was observed in multiple Meta data centers. Fig. 1(a) shows a set of representative current and voltage measurements recorded during such an event. An oscillation at 11 Hz is seen in the amplitude of both the current and voltage measured at the tap box to a server rack. Fourier analyses indicated strong harmonics at 49 Hz and 71 Hz in all three phase currents and voltages. In some other data centers, high frequency resonances in the 5–10 kHz range were also encountered, as illustrated in Fig. 1(b). This two-part paper describes part of the work to find the root cause and develop solutions to these problems.

(a)

(b)

Fig. 1. Measured resonances in data center power systems; (a) low-frequency resonance; (b) high-frequency resonance.

Manuscript received March 20, 2021; revised May 28, 2021; accepted November 12, 2021. Date of online publication February 14, 2022; date of current version February 23, 2022.

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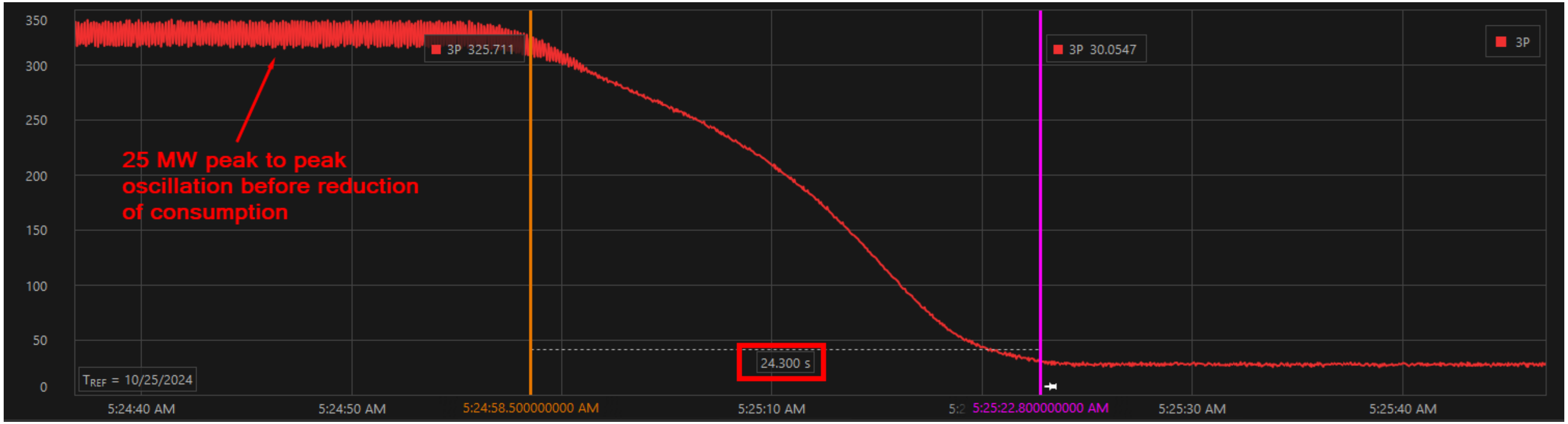
DOI: 10.17775/CSEEJPES.2021.02010

analysis

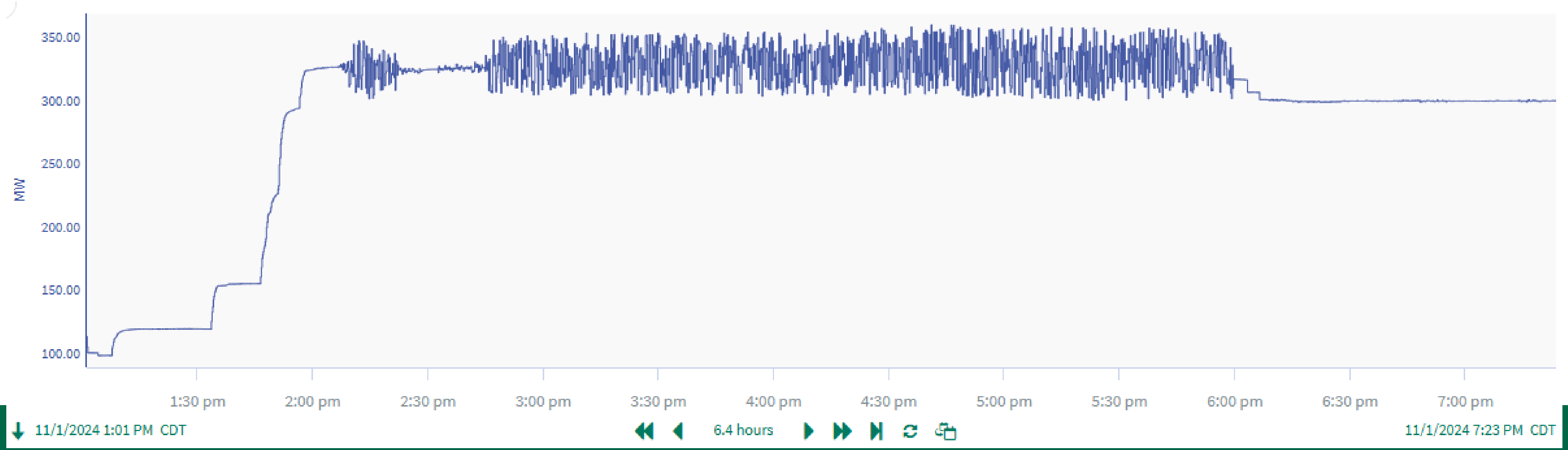
October 25 Event

- ERCOT observed the load dropped ~300 MW within a single telemetry scan on Oct. 25
- Load had increased consumption to ~330 MW over the previous week
- ERCOT sent RFI to interconnecting TO and requested PMU data from TO of POIB
- PMU data showed no fault preceding drop in consumption; load reduced ~300 MW over 24 second period
- Oscillation magnitude preceding reduction was **~25 MW peak to peak** and ~7.5 Hz (later determined true oscillation mode was **~23 Hz** from higher resolution data)
- Cause of reduction was reported to be an offsite telecommunication failure that triggered a load control issue



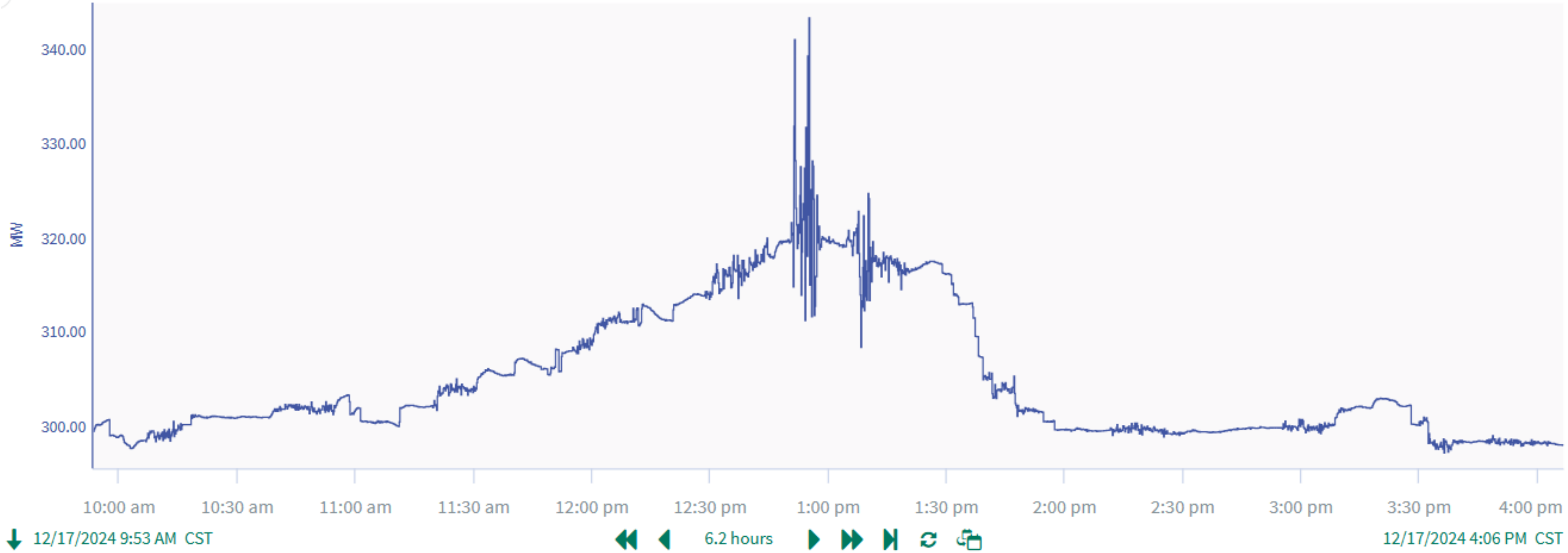
Mitigation Action – November 1, 2024

- ERCOT notified interconnecting TO that control room will give an Operating Instruction to reduce consumption of the load to 120 MW (below level at which oscillation originally appeared in July)
- TO notified load owner and operator that they will need to reduce consumption
- ERCOT met with TO and load owner/operator and agreed that load could be reduced to level that oscillation is no longer present in load telemetry and verified with PMU data
- ERCOT gave Operating Instruction and load reduced consumption to 300 MW; oscillations were no longer present in load telemetry



Initial Test – Mid December

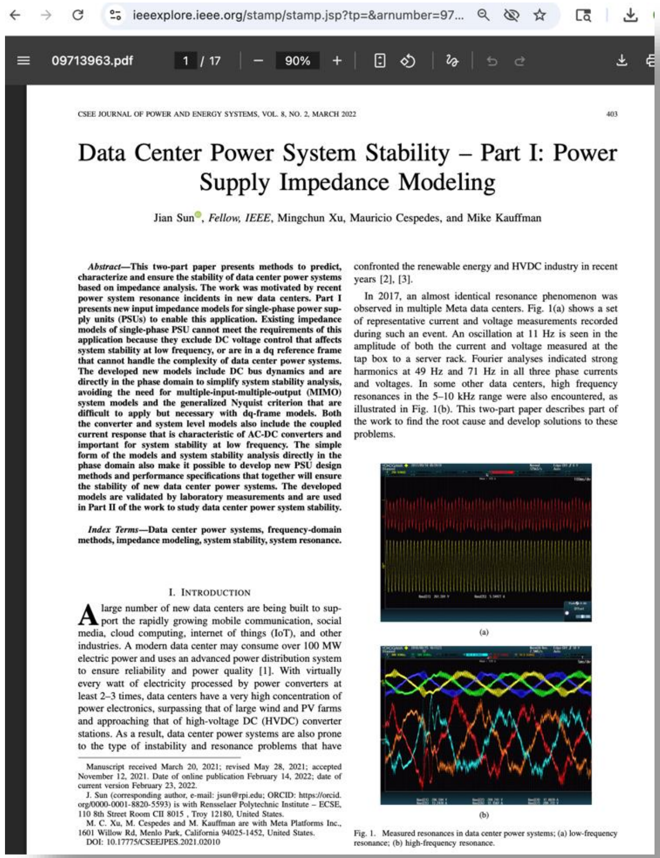
- Load owner and operator developed test plan to help determine root cause of oscillation
- Test plan involved increasing load consumption in 2 MW intervals while collecting data
- ERCOT approved test plan and coordinated with load operator to monitor for oscillations during test
- Oscillation was observed when load consumption increased to ~320 MW
- Load ramped back down to 300 MW after test



Remarks on the 23-Hz oscillations

- Real power has the most significant oscillations.
- When the load consumes more than 300 MW, oscillations appear.
- When the old firmware of certain equipment was updated over the holidays, no oscillations observed.
- Initial speculation:
  - This is sort of dynamic voltage stability issue: with more load demand, voltage at the load becomes more sensitive to the real power.
  - It also has to do with some firmware: this could be **power electronic converter's control.**

2017: Meta data centers' oscillations [2]



Data Center Power System Stability – Part I: Power Supply Impedance Modeling

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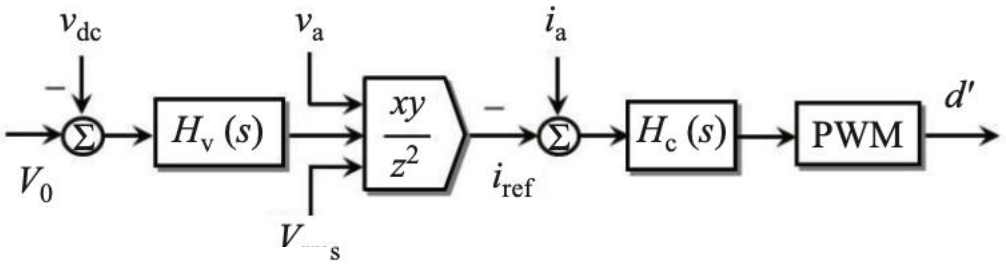
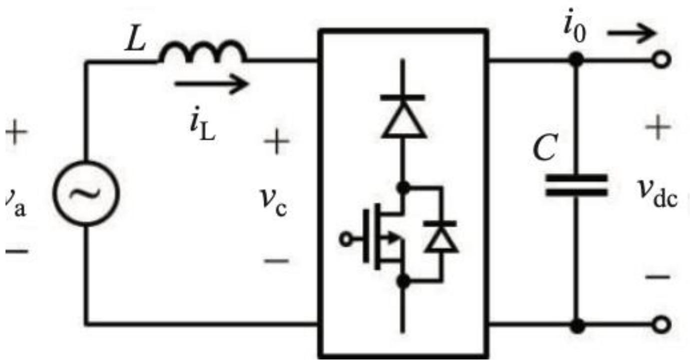
- Oscillation frequency: in the phase currents, 49 Hz and 71 Hz ➔ in power, 11 Hz.

"Meta data centers are designed to use the Open Compute Project (OCP) architecture [1]. The electrical system employs 480/277 V or 208/120 AC distribution, with a 48 V DC battery backup unit (BBU) integrated with a server power supply. The 480/277 V AC is fed from the utility grid through a distribution network that starts from a substation and includes medium- voltage (13.2 kV) pad-mounted transformers (PTX), backup generators, and several layers of switchboards and protection panels. **Each power supply unit (PSU) receives a single-phase AC input and produces a 12 V or 48 V DC output. A PSU employs an AC-DC converter with power factor correction (PFC) and an isolated DC-DC converter.** AC UPSs are also used in some parts of the data center, but the majority of PSUs are supplied directly from the building power system."

Lab replication [2]





Zs

Zal

$$L(s) = \frac{Z_s(s)}{Z_{al}(s)} = Y_{al}(s)Z_s(s)$$

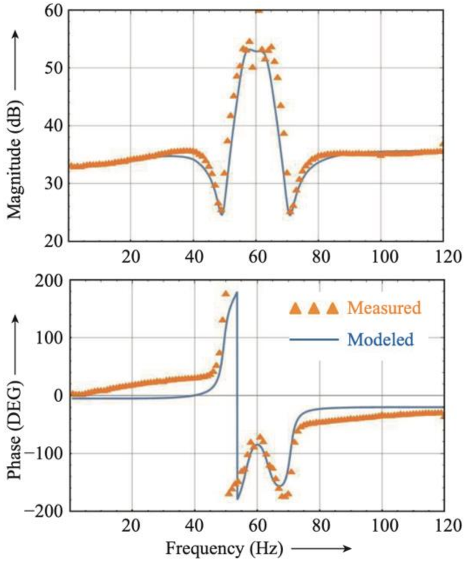


Fig. 15. Comparison of frequency response predicted by $Z_a(s)$ with laboratory measurement of a power supply.

Meta's PSU input impedance measurement: in the static abc frame.

1. PSU's impedance magnitude dips at two frequency points: 50 Hz and 70 Hz, and shows negative resistance (damping) near those dipping points.

2. DC-link dynamics and dc-link voltage control attribute to the negative damping.

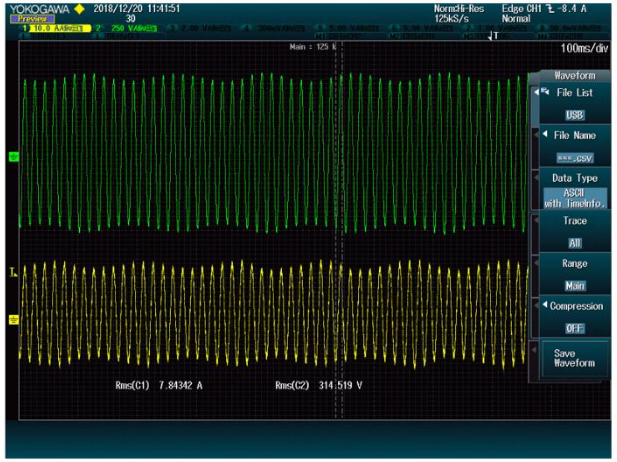


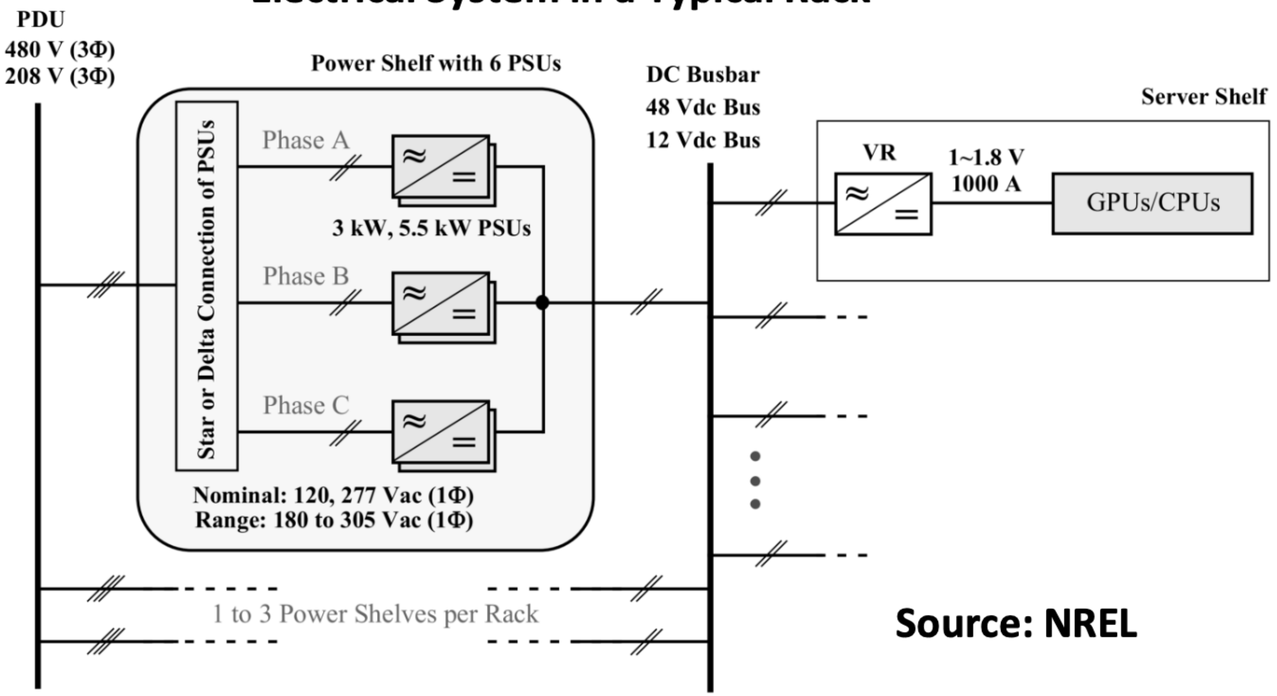
Fig. 16. Low-frequency resonance measured in a power supply operating with a high-impedance source.

Source: Farshid Salehi “**Integration of Large Electronic Loads (LELs): Opportunities and Challenges**”, **IEEE PESGM 2025**

Architecture Inside Server Racks

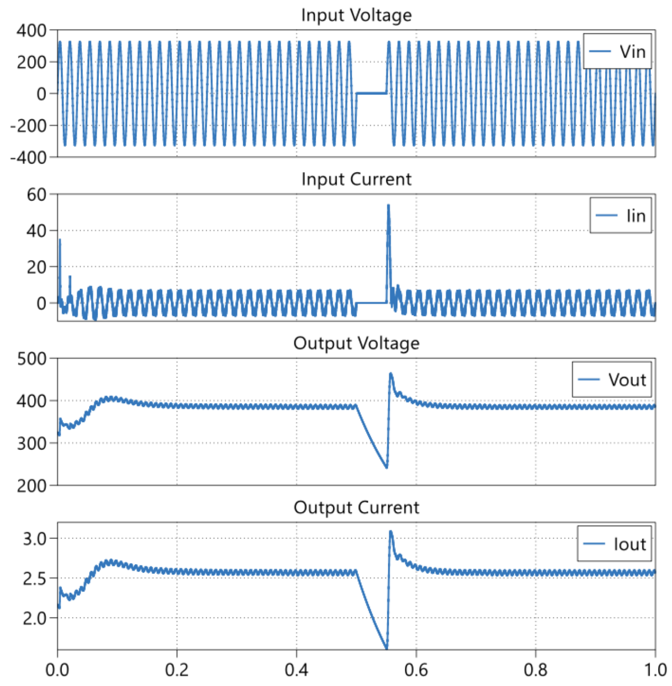
The PSUs are the most substantial loads within data centers, incorporating AC/DC converters.

Electrical System in a Typical Rack



Source: NREL

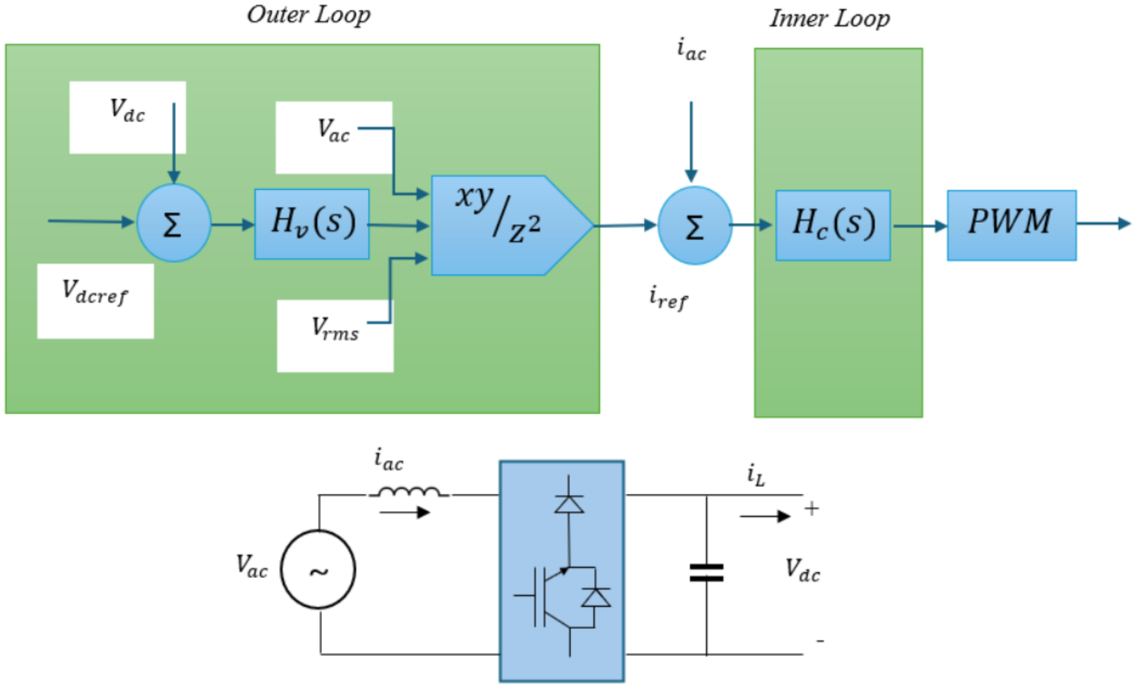
PSU Response to ZVRT for 50 ms



Servers

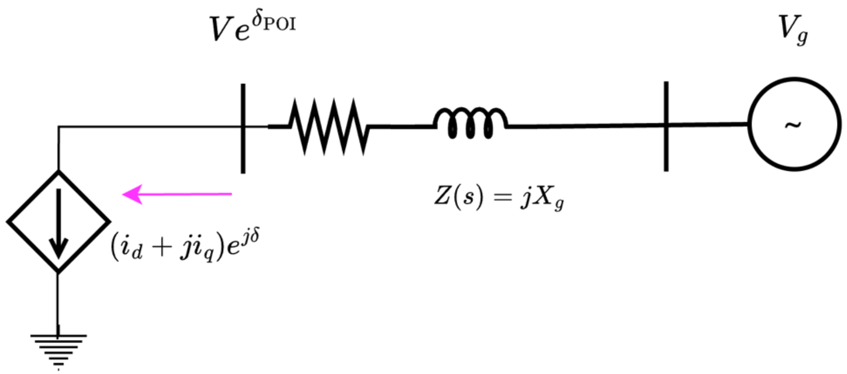
Power Supply Units (PSUs)

- Under Normal ECO mode the PSUs is the main interface with the grid.
- Detailed EMT modeling of PSUs is critical for reliability risk assessment



J. Sun, M. Xu, M. Cespedes and M. Kauffman, "Data Center Power System Stability — Part I: Power Supply Impedance Modeling," in *CSEE Journal of Power and Energy Systems*, vol. 8, no. 2, pp. 403-419, March 2022,

Analysis



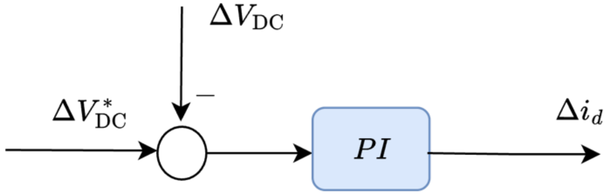
DC-link voltage Control (DVC)

PSU's dc-link voltage control influences real current/power consumption

More power consumption reduces AC voltage at the load

Grid effect

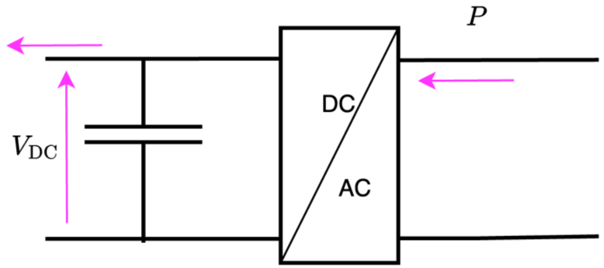
V/P becomes more sensitive for weaker grid and higher power consumption.

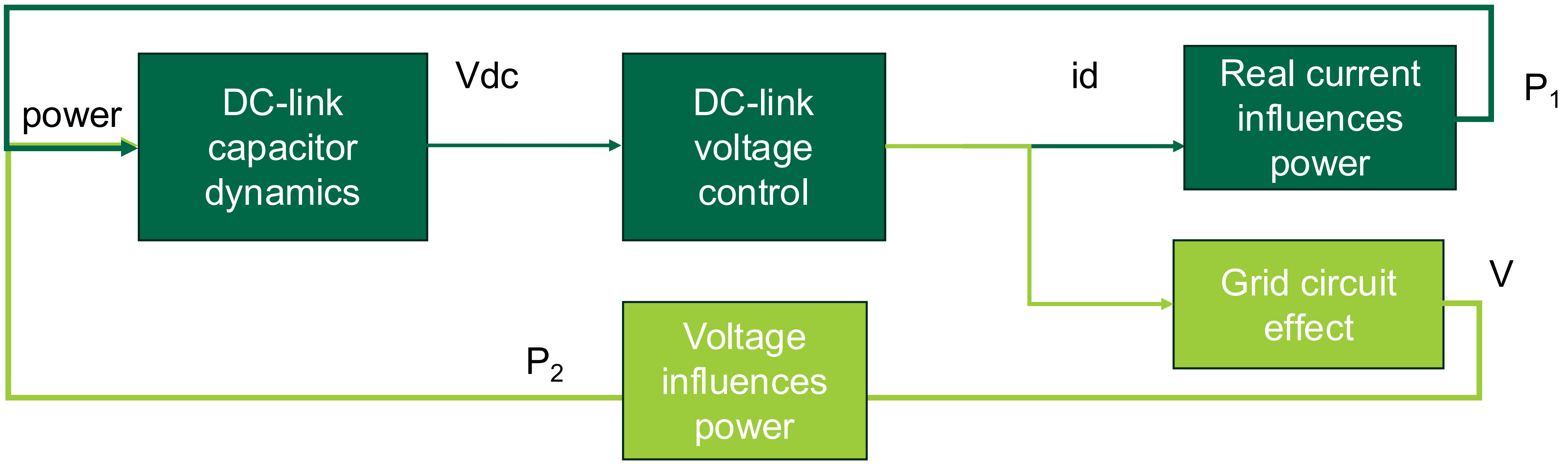


DC-link voltage control

AC voltage influences power consumption and further dc-link dynamics

DC-link dynamics

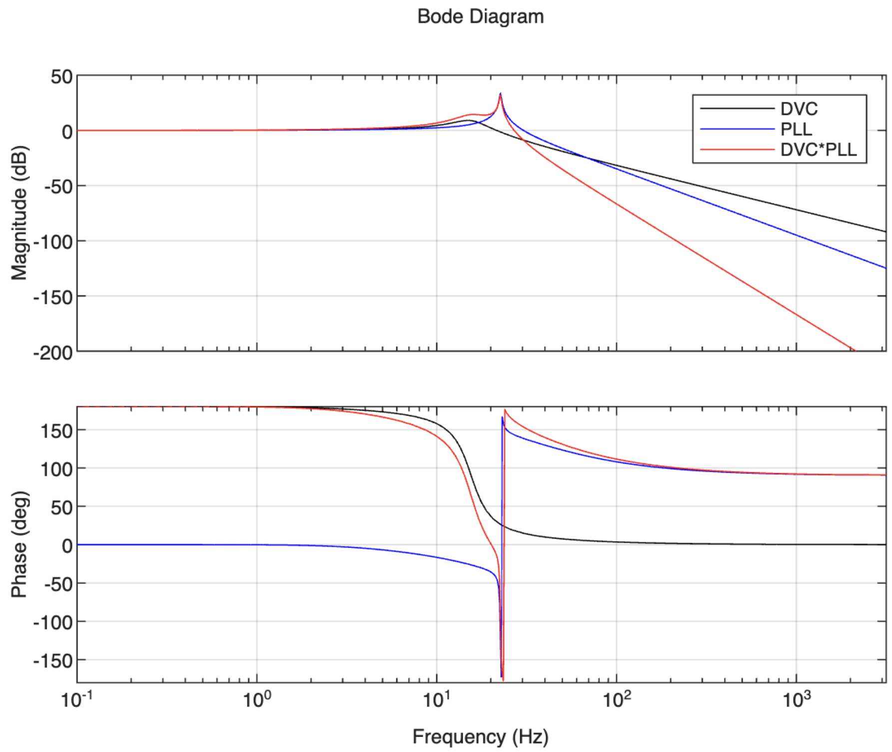


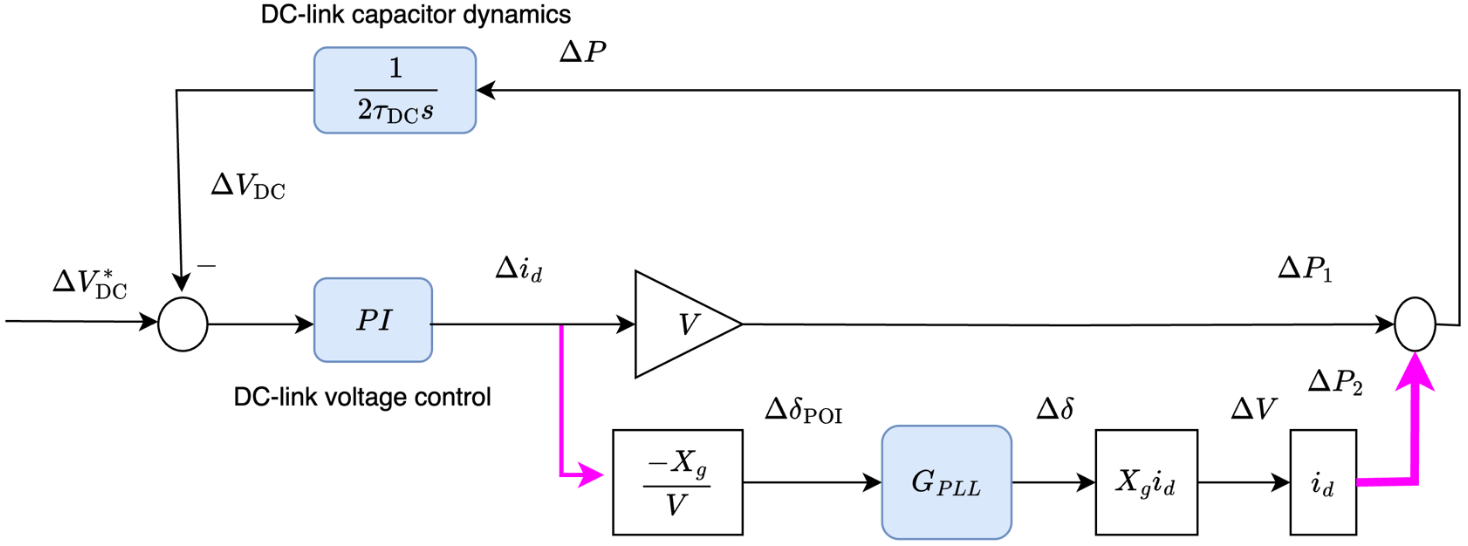


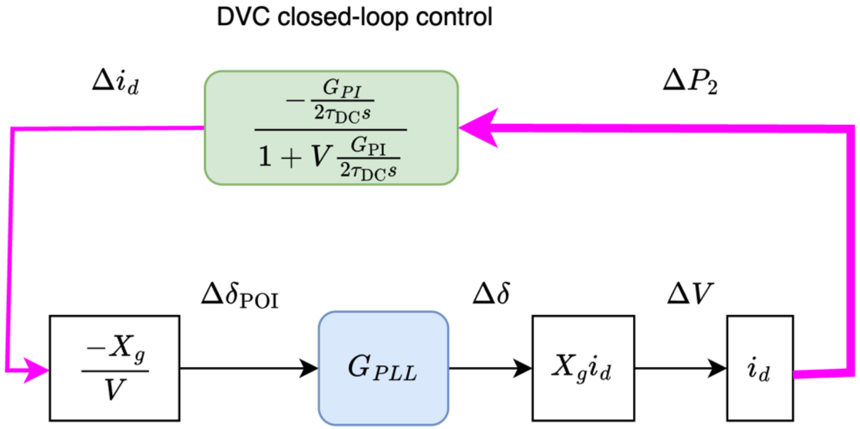
At the design stage, the dc-link voltage control design is usually based on the dark green loop only, by assuming that the Vac is stiff. This loop is usually stable without any issue.

In operation, when the grid effect is included (weak grid, high power), the addition of the light green loop may introduce oscillations.

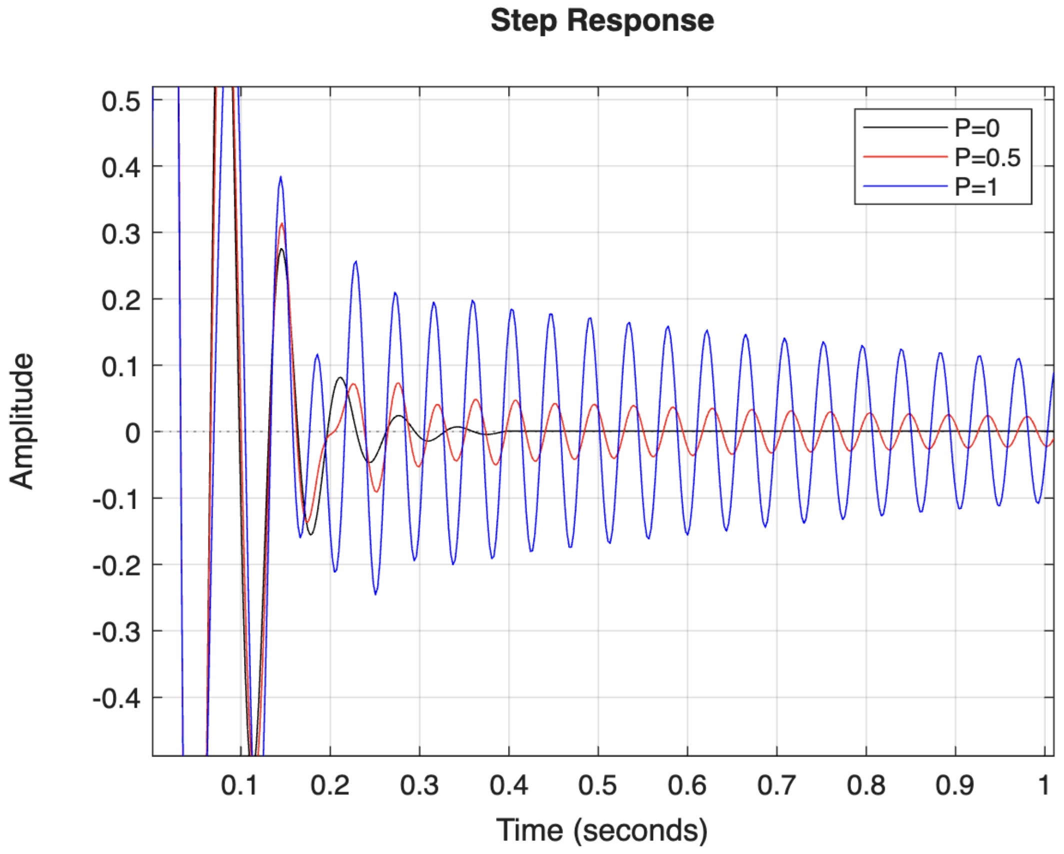
Here we assume that a PLL is used to track the angle. In [2], angle tracking is done differently through directly control the ac current to be in phase with the ac voltage.







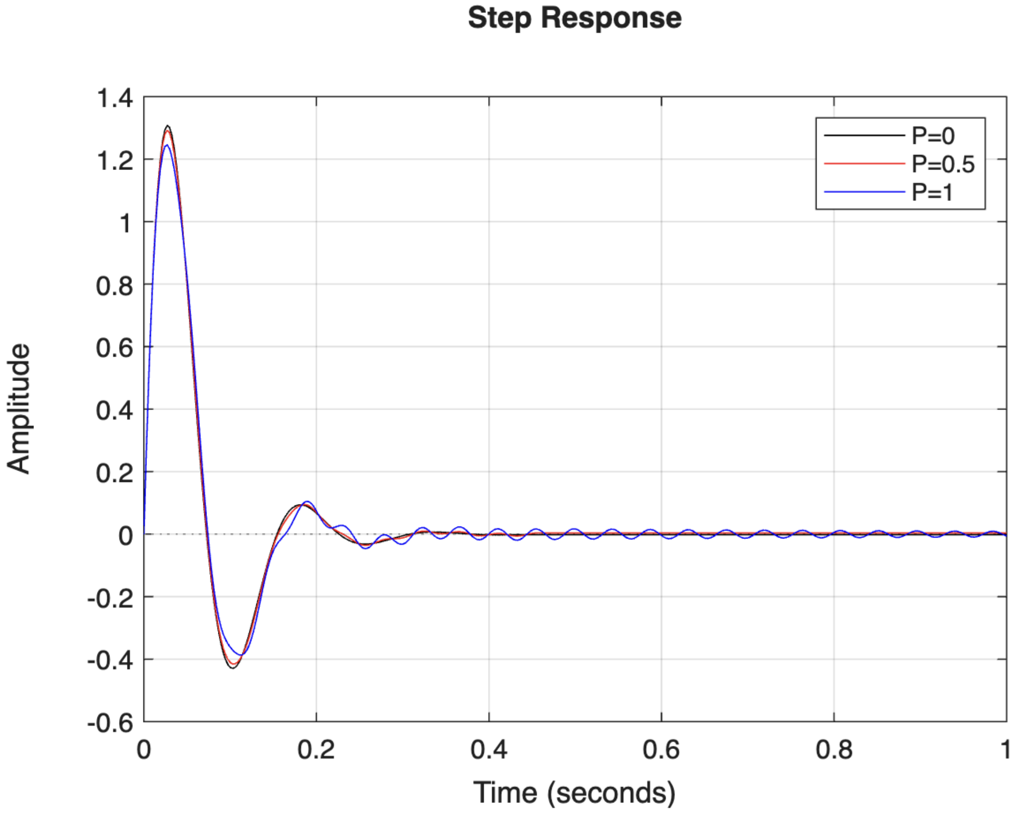
Linear system analysis results



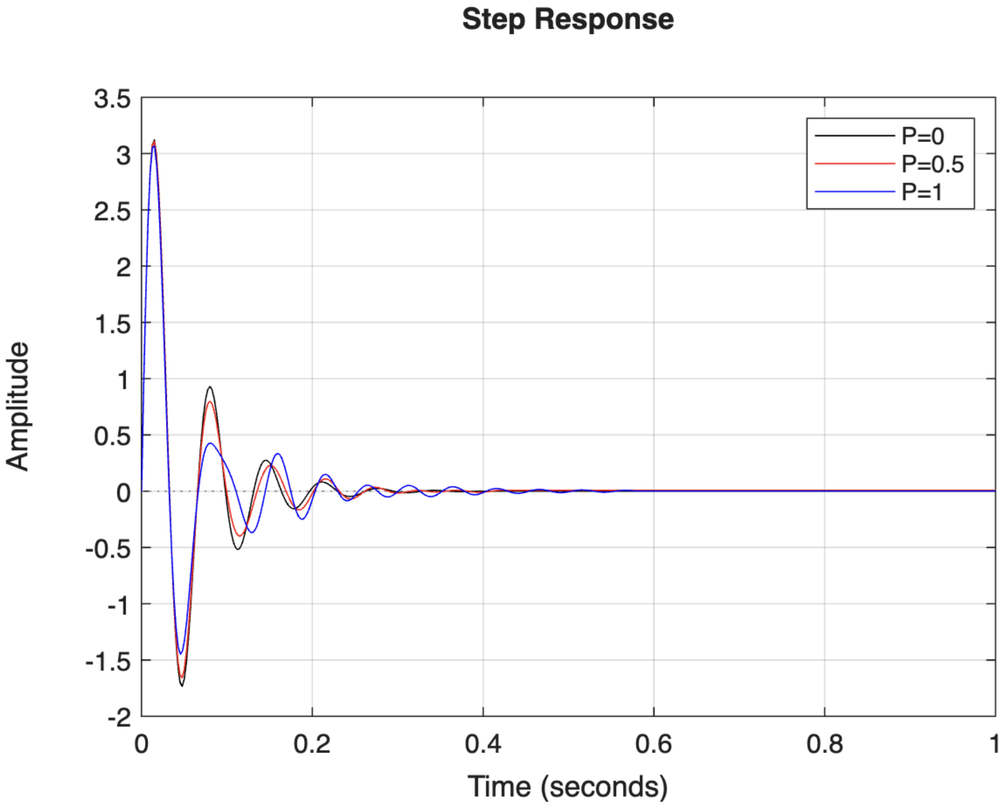
- Numerical case: Xg = 0.2, DVC bandwidth 56 Hz.
- Mitigation in converter control
  - Reduce DVC bandwidth so that the open loop gain's magnitude reduces at the 20-Hz region
  - Add PLL's damping
  - Both can be done by firmware upgrade

Reduce DVC bandwidth vs Increase PLL damping

DVC bandwidth: 5.56 Hz
PLL 2nd-order filter ζ = 0.707



DVC bandwidth: 56 Hz,
PLL 2nd-order filter ζ =1



- **To do list:**

  1. EMT simulation;

  2. More info collection and analysis on the power supply unit control algorithms and how they influence dynamics