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DATA-DRIVEN CONTROL OF ENERGY STORAGE

Power Engineering Advanced Research Lab

The Research Questions?

How can we **control energy storage to ‘play nicely’ with other devices?**

How can we **maximize performance of energy storage in low inertia systems?**

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Why RTDS/Real-Time Simulation

First stages of testing

Quickly gather datasets

Scope for expanding, PHIL/CHIL

Presentation Outline

Introduction of Data-Driven Control

The problem – Grid Supporting Energy Storage

Solving the problem with Data-Driven Control

Results and Conclusions

RTDS UGM - Melbourne 2019

Introduction of Data-Driven Control

Daniel Ryan - 3rd October 2019

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Two Approaches to Tuning Controllers

MODEL-BASED

- Physics - Differential equations
- Unmodelled dynamics
- Pre-construction
- Deep underlying knowledge of the system

DATA-DRIVEN

- Heuristic Tuning - Zeigler-Nichols PID tuning – 1942
- System Identification
- Requires the system for testing (constructed or accurate simulation)

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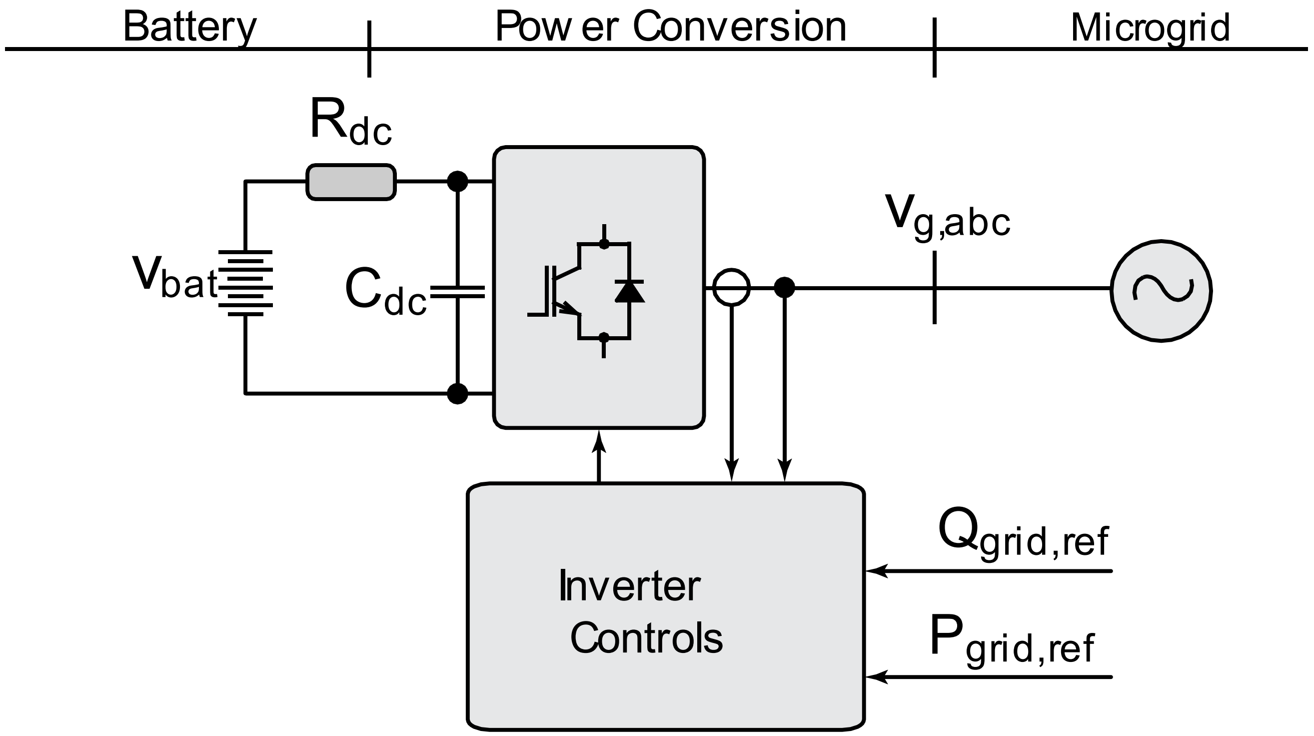
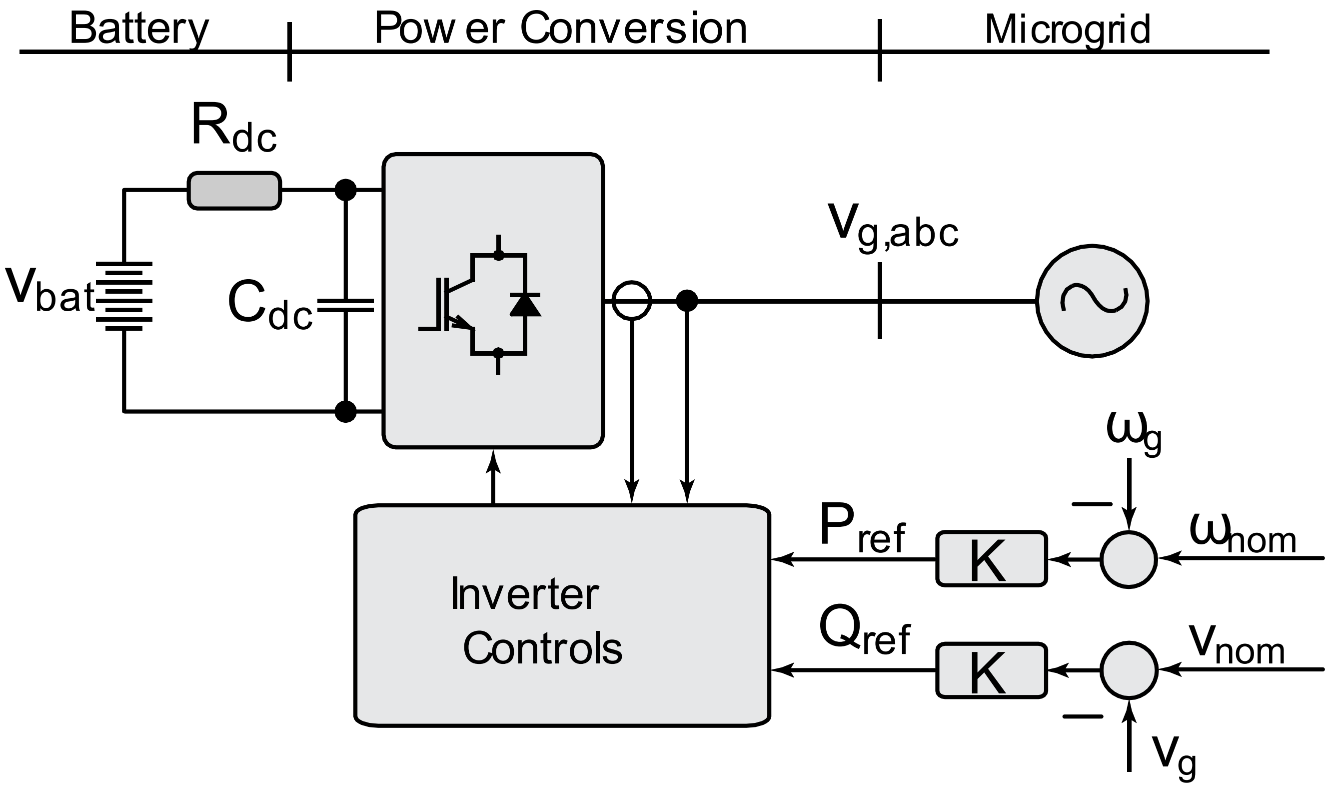
What is a Grid-Following Inverters?

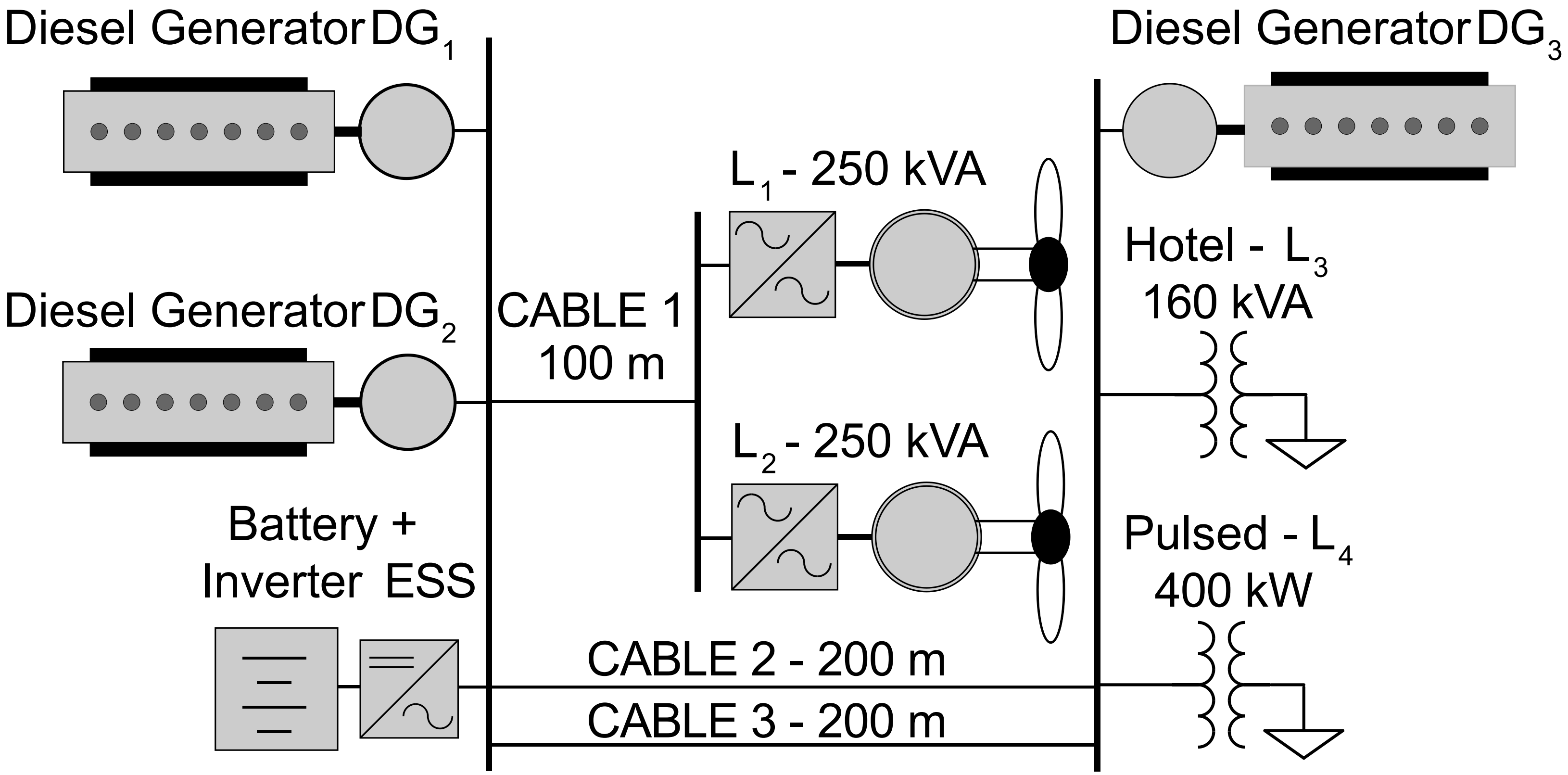


Droop Control of Grid Following Inverters



Shipboard Power System

Generators, 250kW, BESS,100kW cont., 300kW (5s)

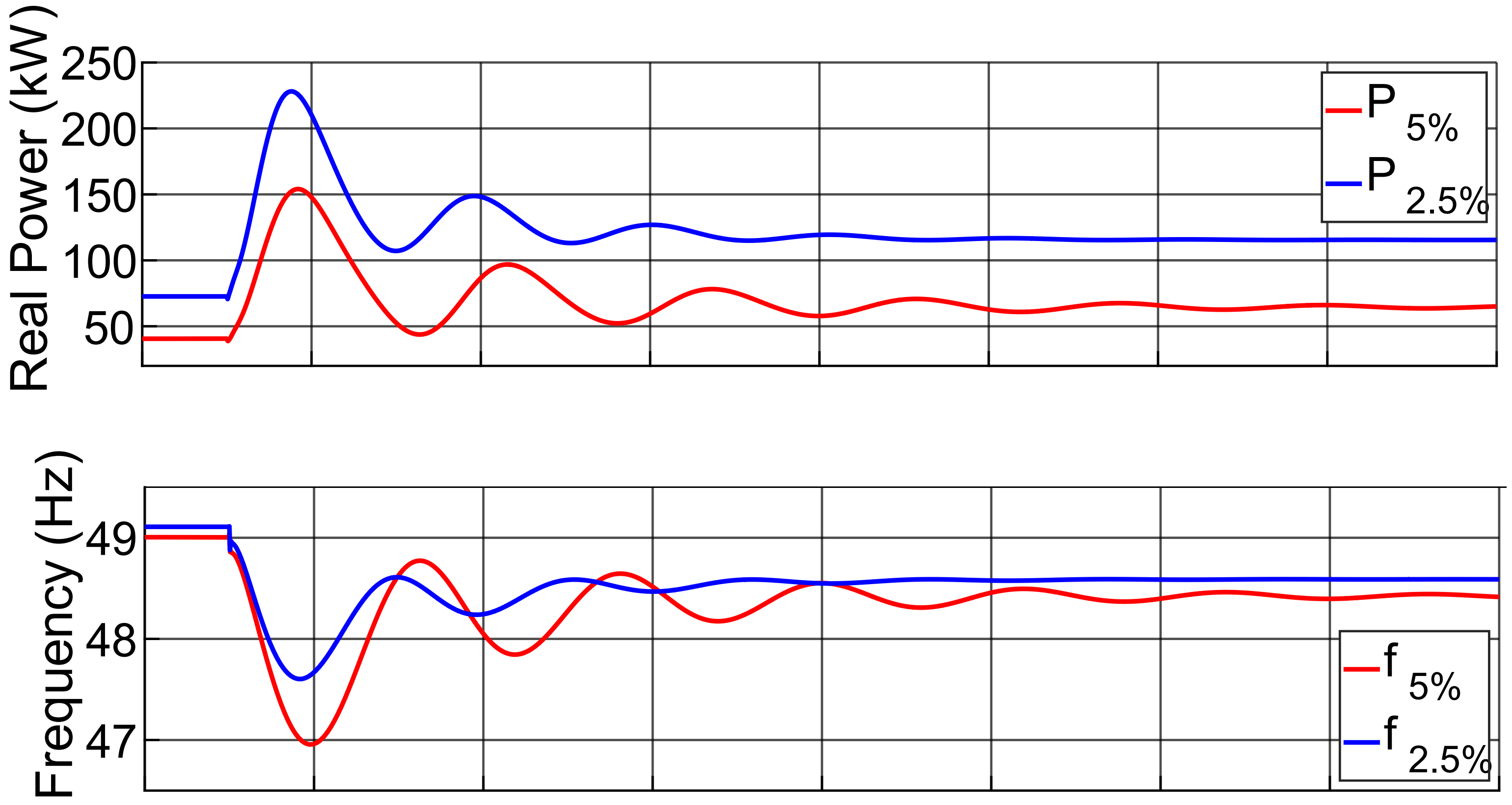


Changing Droop Gain of BESS

Initially, entire system is operating with 5% droop

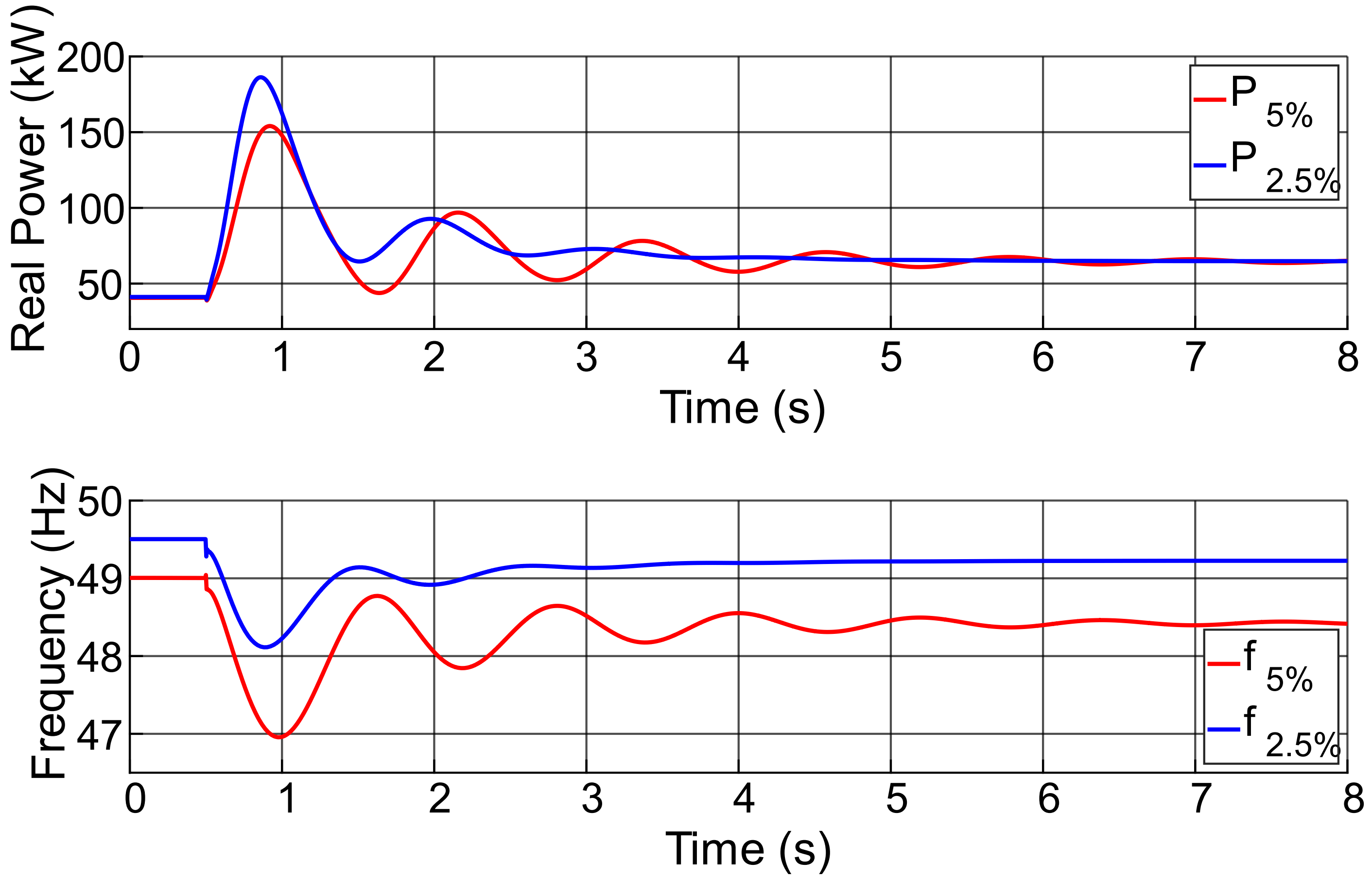
250kVA load step pf 0.8

2.5% droop – BESS only, 5% droop Generators



Increase Gain of Battery + Generators

2.5% droop – 250kVA load step pf 0.8



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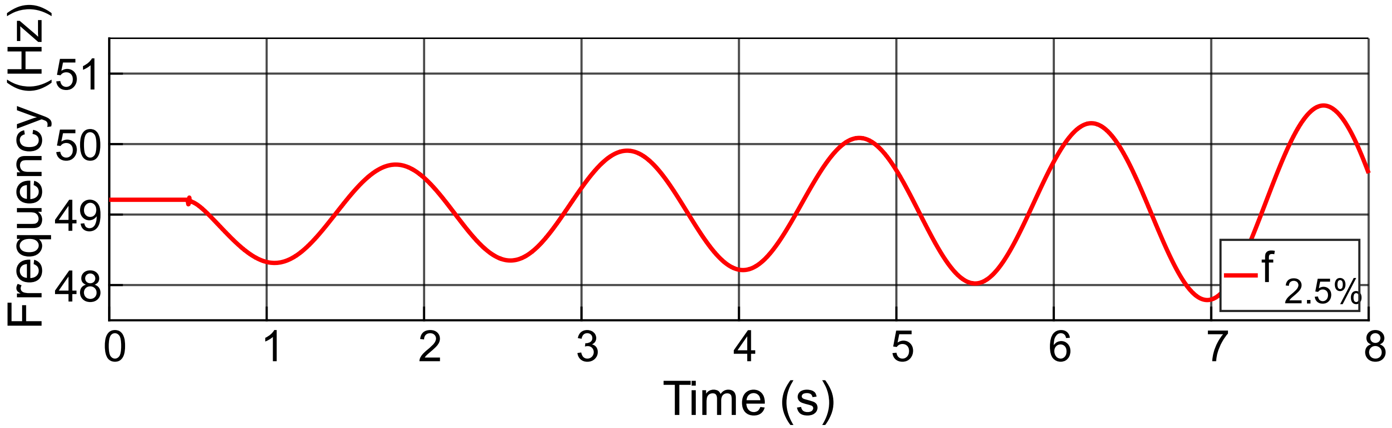
What happens if the battery disconnects?



System becomes unstable

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Applying Data Drive Control

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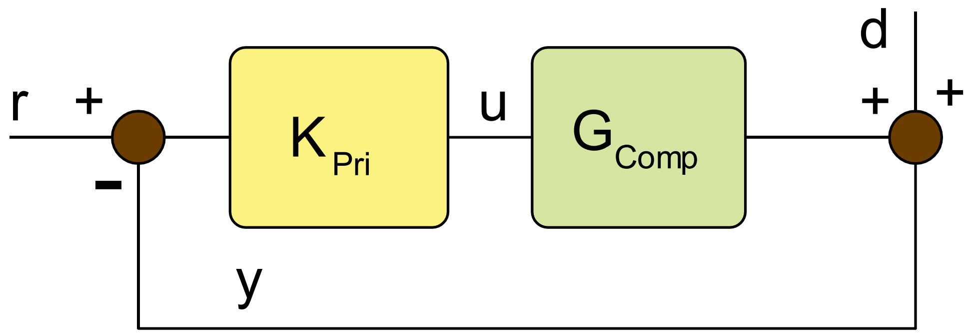
Thinking More like a Control systems Engineer



Integrator

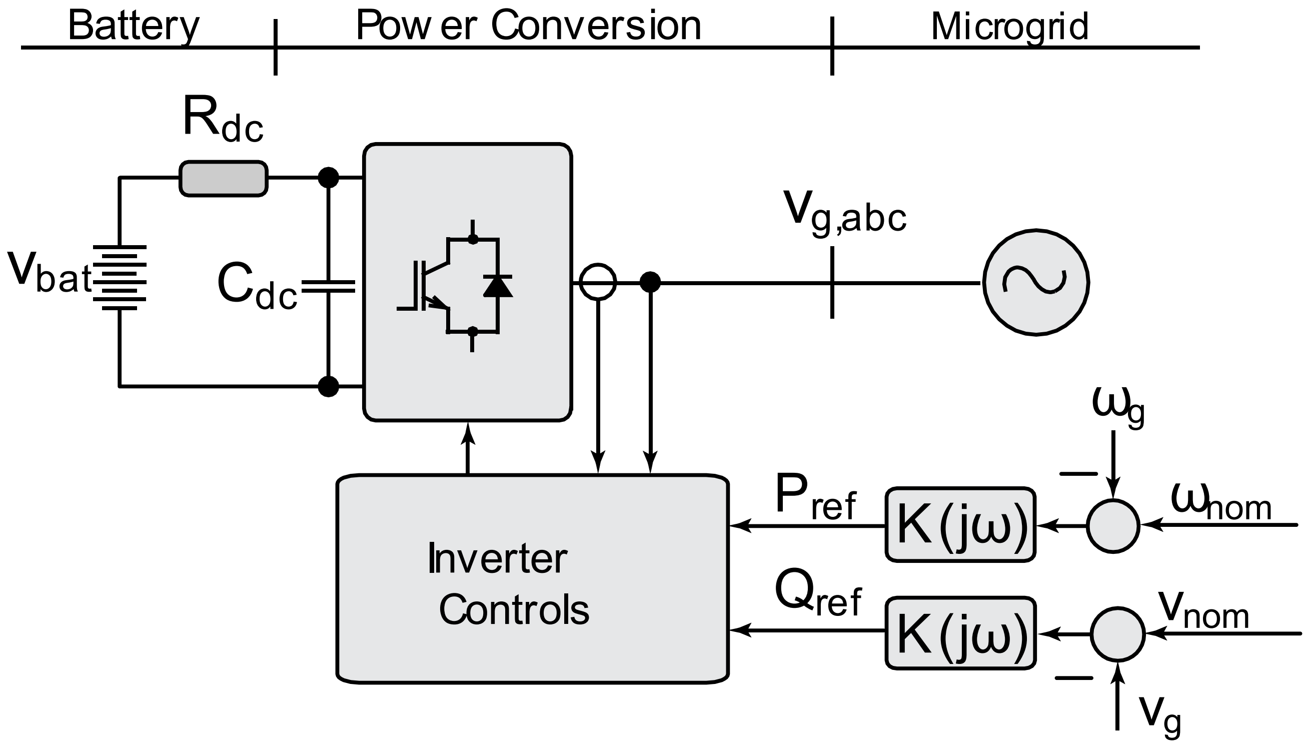
$$H_{int}(s) = \frac{1}{s}$$

Pole at s = 0

The 'droop' constraint is:

All devices in the network must have controller gain that is proportional to their power rating, **at 0 Hz**.

Alterative Controller Structure



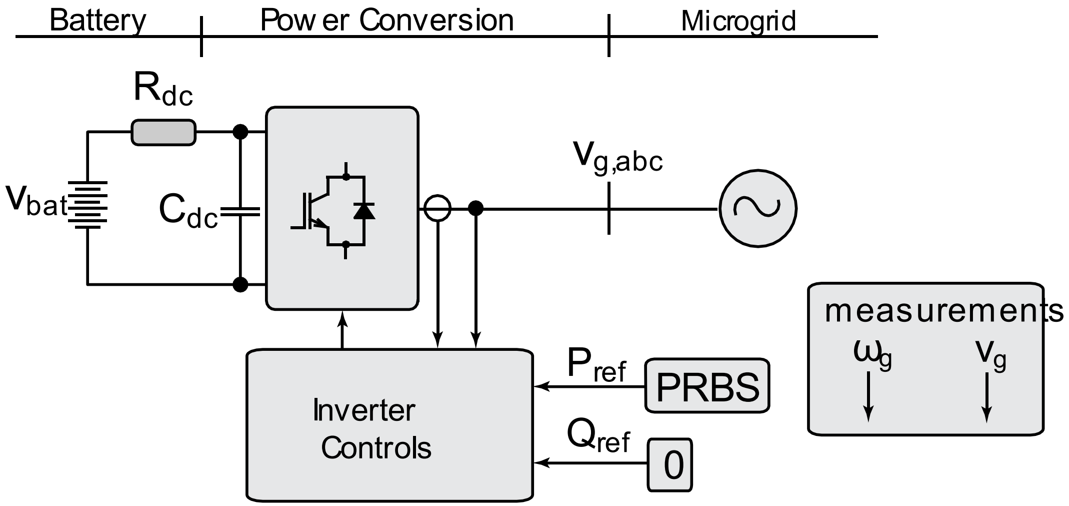
$$K(s) = \frac{a_0 s + a_1 s + \cdots}{b_0 s + b_1 s + \cdots}$$

$$K(z) = \frac{a_0 z + a_1 z + \cdots}{b_0 s + b_1 s + \cdots}$$

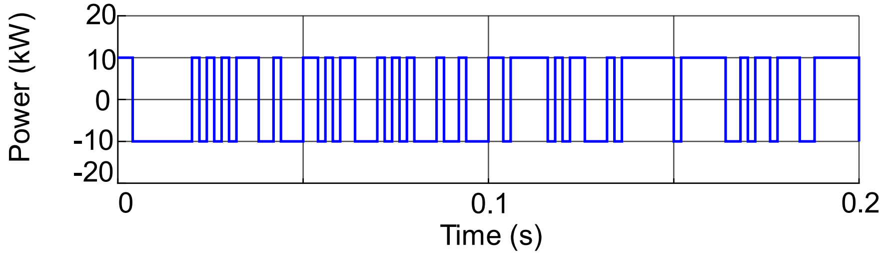
But, now we have more parameters to tune

System Identification - RTDS

First we need to know something about the plant



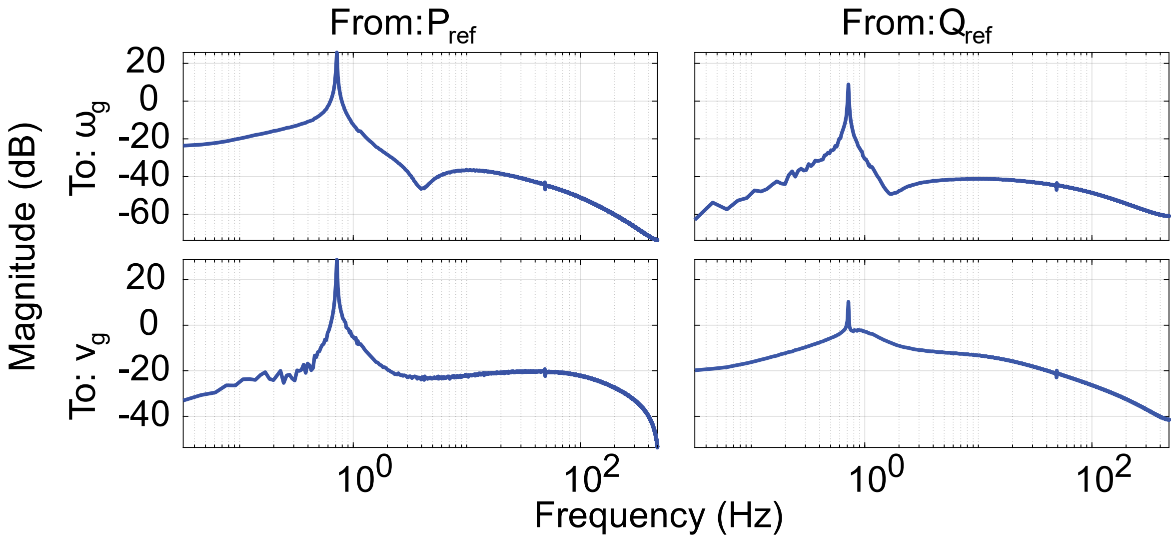
PRBS



System Identification - RTDS

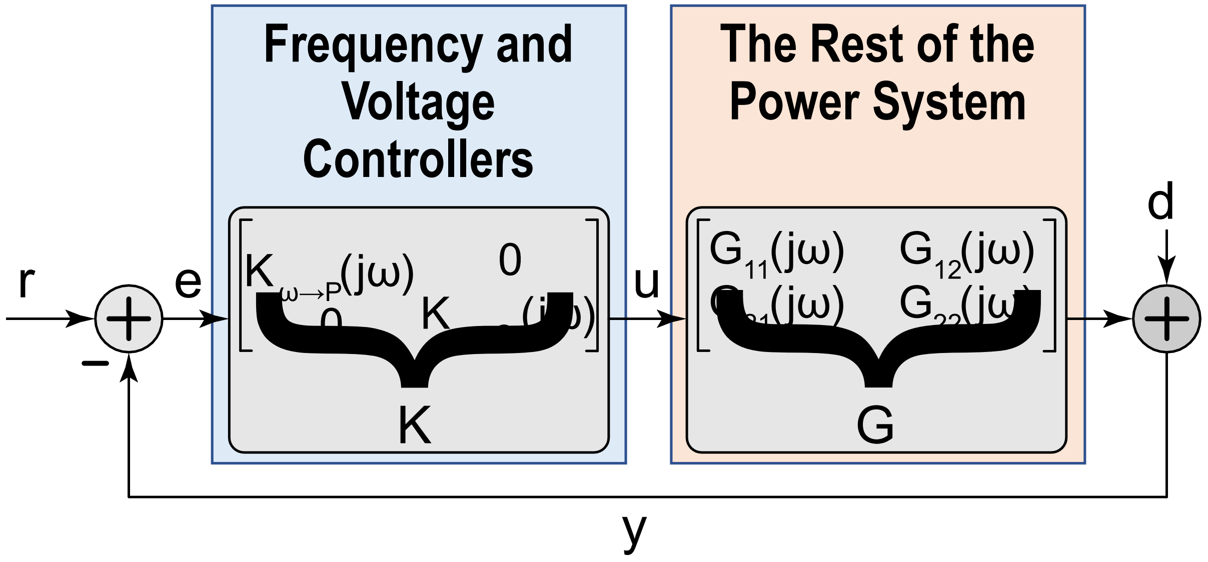
Then, with a little Fourier analysis (just mathematic some transforms)

$$G(j\hat{\omega}) = \frac{\mathcal{DFT}(R_{uy})}{\mathcal{DFT}(R_{uu})}$$



This can be accomplished in other ways! Doesn’t have to be PRBS

Data Driven Control



What about droop?

Constrain

$K(j\omega = 0)$

Performance in the Frequency Domain

Bandwidth, Gain Margin, Phase Margin, Disturbances, Sensitivities…..

Invaluable Textbook [3] – Feedback Control Theory

Tuning The Controller

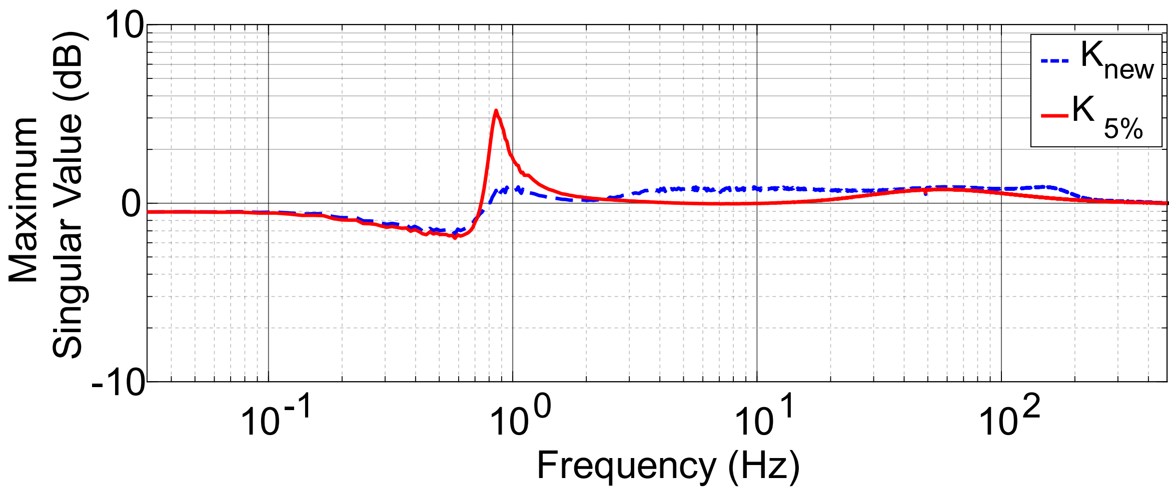
Performance in the Frequency Domain

Optimisation of controllers parameters.

Solve an Optimisation Problem to Tune the Parameters

We minimised the frequency response for $\mathbf{d} \rightarrow \mathbf{e}$

What about droop? Constrain $\mathrm{K}(j\omega = 0)$



There is a Matlab toolbox from EPFL for this optimisation – [2]

https://www.epfl.ch/labs/la/research/page-67797-en-html/page-67814-en-html/fdrc_toolbox/

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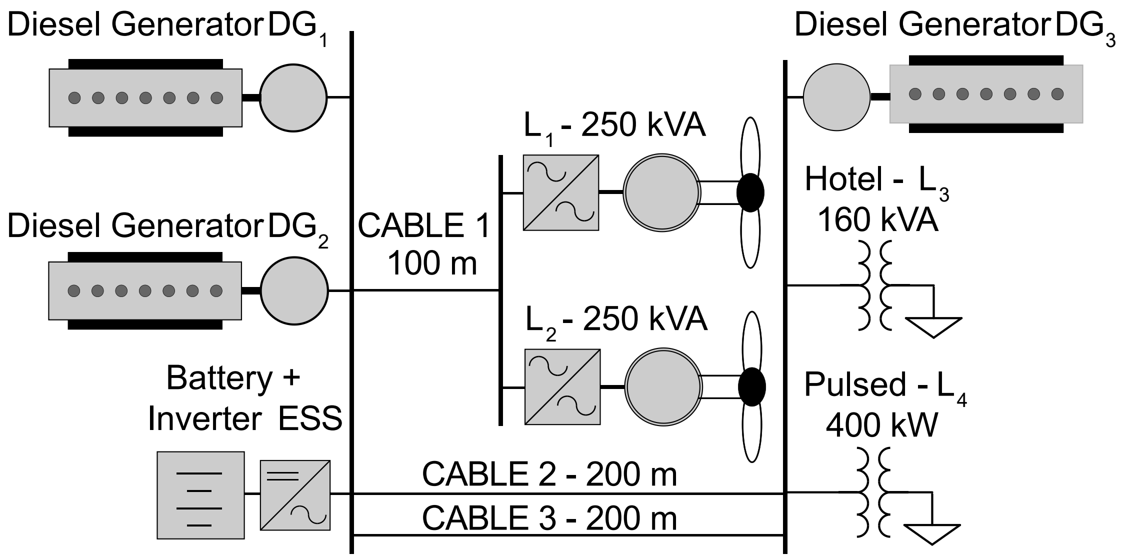
Testing Platform

Simulate Power System

Timestep 50us



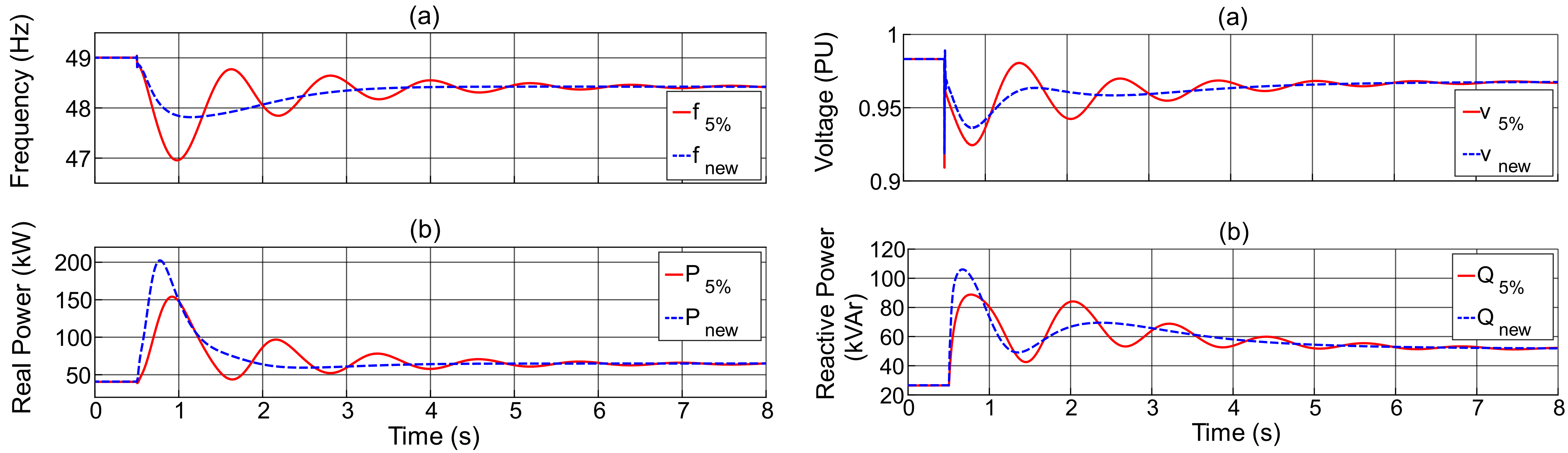
Controller

Lives in a c-function block running at 1ms

```c
// ------------------------------------------------
// Place C code here which runs on the RTDS. The
// code below is entered once each simulation
// step.
// ------------------------------------------------
allocateMemory(error,16);  // memory allocated in 32 bit words
allocateMemory(output,16); // 2 x 32 bit words per double

if(step%Steps == 0) {
for(counter=1; counter<8; counter++){
    output[counter] = output[counter-1];
    error[counter] = error[counter-1];
}
error[0] = err;

for(counter=0; counter<8; counter++){
    if(error[counter] > 10000)  {
        error[counter] = 10000;
    }
    if(output[counter] > 10000) {
         output[counter] = 10000;
    }
}

cont = b0*error[0] + b1*error[1] + b2*error[2]
+ b3*error[3] + b4*error[4] + b5*error[5] - (a1*output[1] + a2*output[2] + a3*output[3] + a4*output[4]
+ a5*output[5]);
output[0] = cont;
}
step++;

// ------------ End of CODE: Section -------------
```

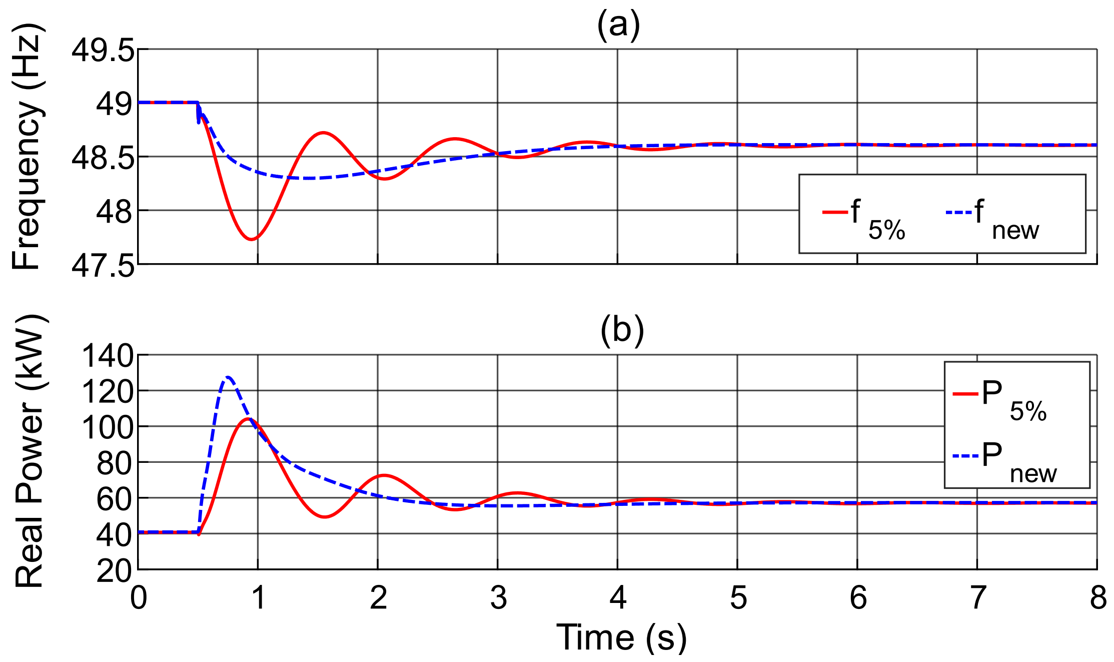
Data-Driven Controller

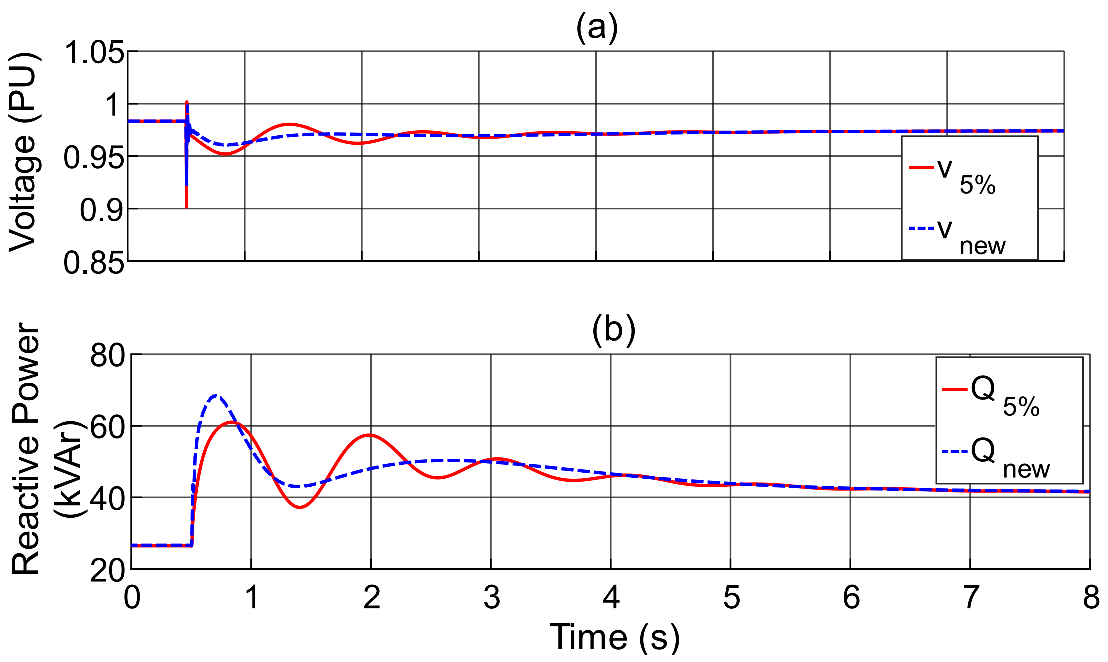
250kVA load step pf 0.8, 5% droop Generators



Data-Driven Controller

Generator Failure, 5% droop Generators





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Conclusions

Fast and accurate simulations enable data-driven control

- Quickly gather datasets for different inputs/outputs
- Heuristic methods for tuning control systems have limitations.
- Faster systems (i.e. low inertia) systems, require improved methods for tuning controllers. Simply increasing gains lowers stability margins.

Data-driven control methods require less knowledge of underlying system

- Improved tuning for black or grey box systems.

QUESTIONS

Research Scope

Grid-Following Inverters

Microgrids

Primary Control Systems

Linear Control Systems

Future Work

Future Work:

- Applying to systems with multiple BESSs.
- Applying to larger power systems.
- Gathering knowledge of good performance criterion.
- Testing frequency and voltage control methods experimentally, via HiL tests.

References

[1] – Ziegler J. G., Nichols N. B. (1942), Optimum Settings for Automatic Controllers, Journal of Dynamic Systems, Measurement, and Control

[2] – Karimi A. (2013), Frequency Domain Robust Control Toolbox, 52nd IEEE Conference on Decision and Control

[3] – Doyle J. C., Francis B. A., Tannenbaum A. R. (1992), Feedback Control Theory, Dover Publications

[4] – A. Karimi, C. Kammer (2017), A data-driven approach to robust control of multivariable systems by convex optimization, Automatica

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Frequency vs time Domain

A change in the way of thinking:

- Time domain
- Frequency domain

Frequency Domain:

- Can handle dead times/delays well
- Good stability proofs/ definitions for robustness
- Better knowledge of the system than step response
- Better methods for dealing with multi-input multi-output systems

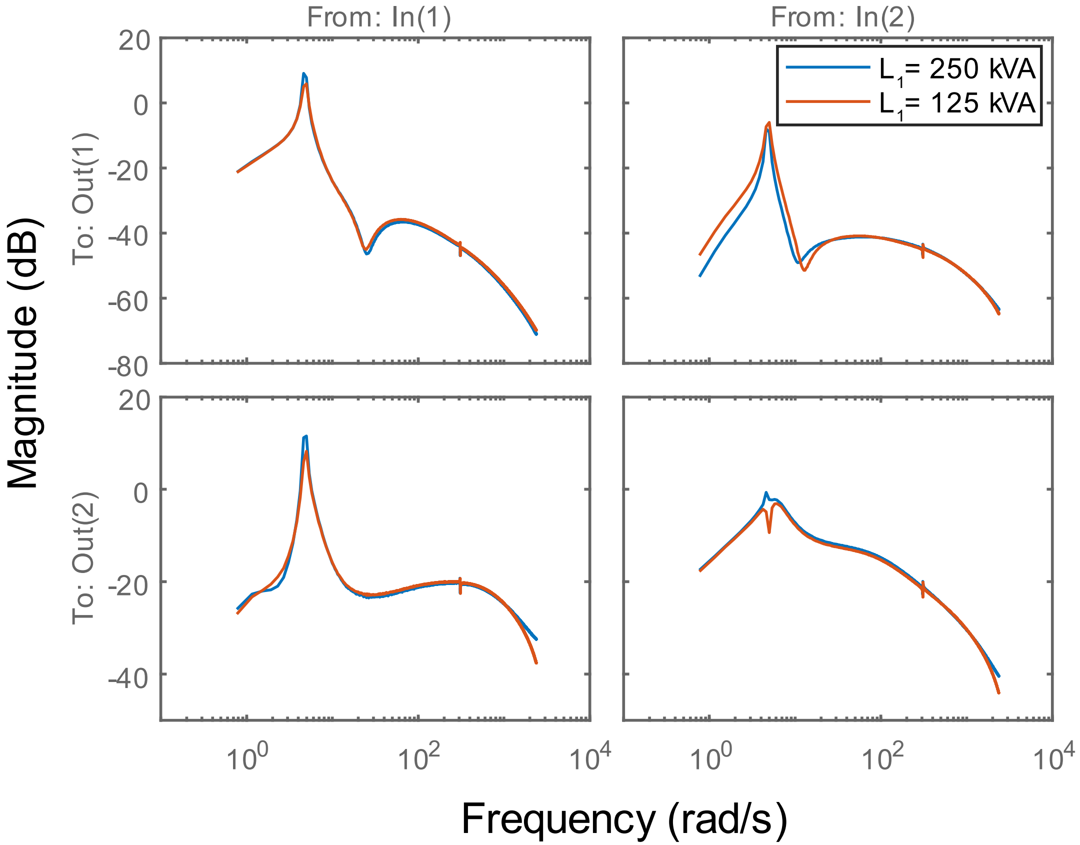
More About Control Design Tools

Can be used for other control problems, some examples:

- Inverter control systems - Current controllers and DC-link voltage controllers.
- Motion control - gyroscopes
- Damping inter-area oscillations
- UPS/ voltage controlled inverters
- High precision Magnet Power Supplie

What if the Power System Changes?

Comparing Identified FRD for at Different Load



- Simulation lets you identify the power system at many different operating points. The can all be incorporated into optimisation.

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More About These Tools

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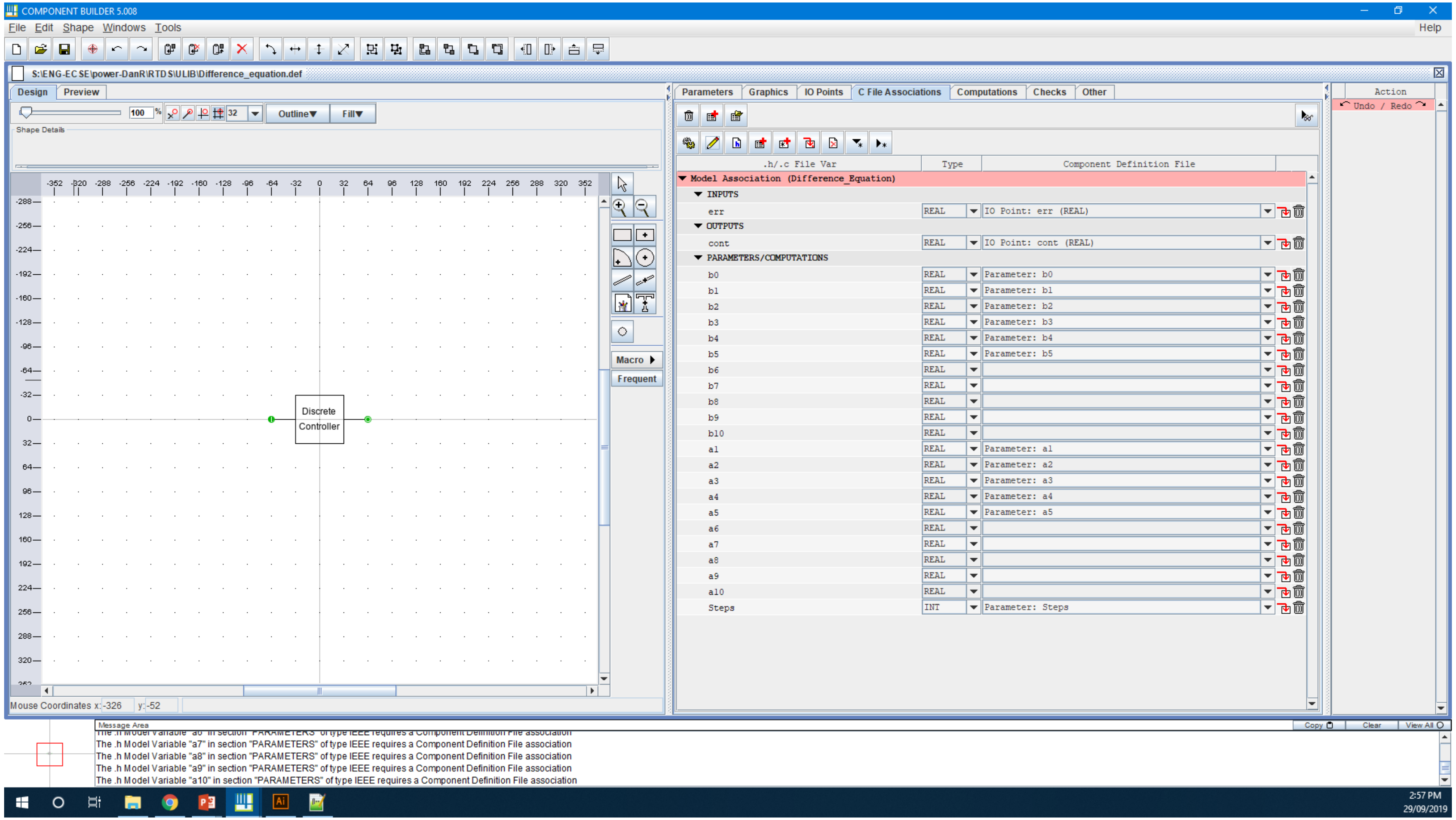
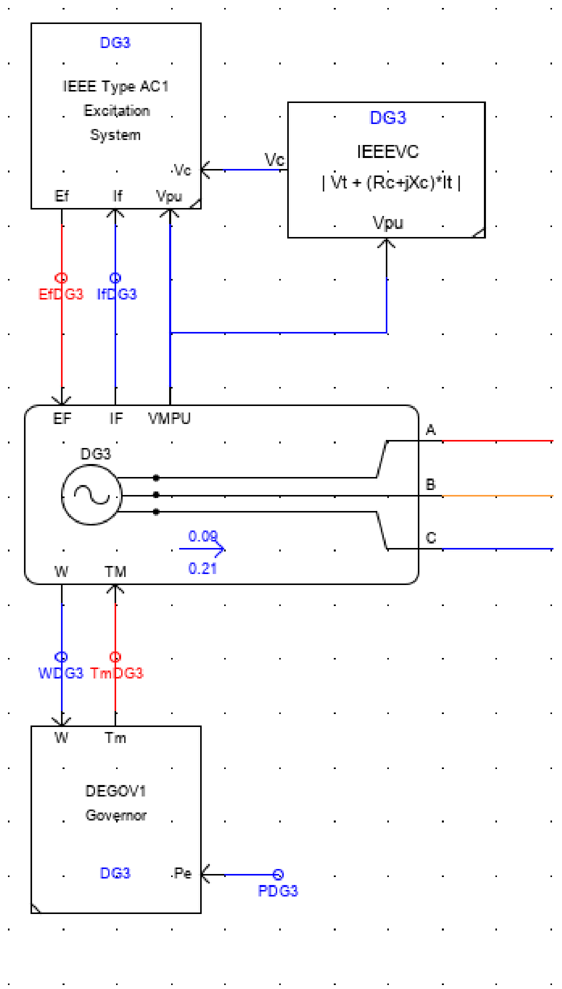
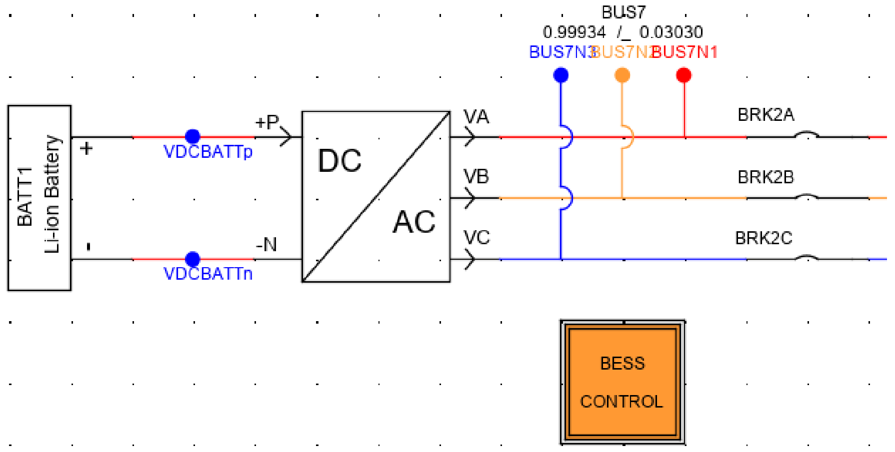
More About Test System

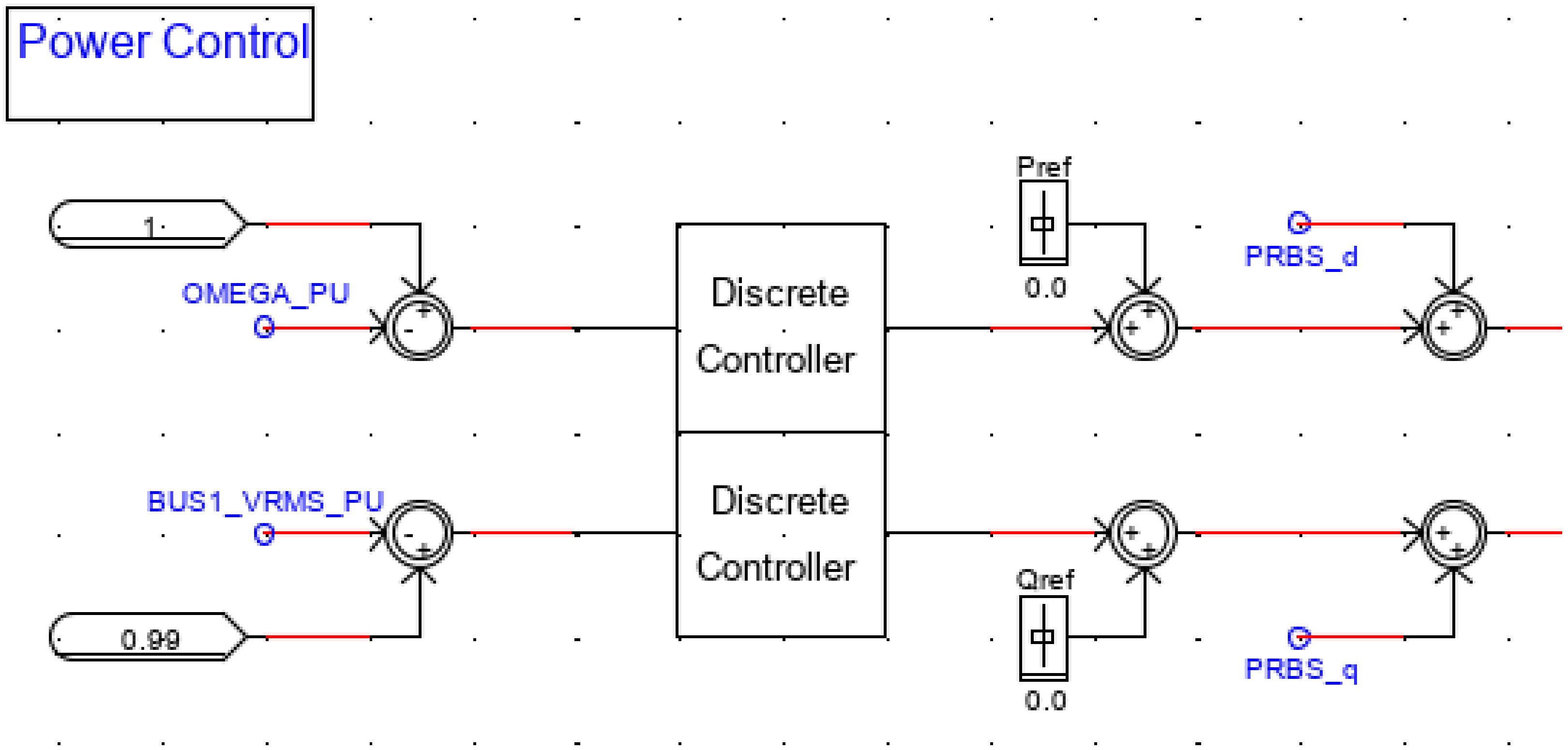


More About Test System





More About Test System



Linear Control

LINEAR SYSTEMS

Common forms:

State-space:

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u}$$
$$\boldsymbol{y} = C\boldsymbol{x} + D\boldsymbol{u}$$

Transfer function:

$$G(s) = \frac{\omega_n^2}{s + 2\zeta\omega_n + \omega_n^2}$$

Frequency Response – $G(j\omega)$