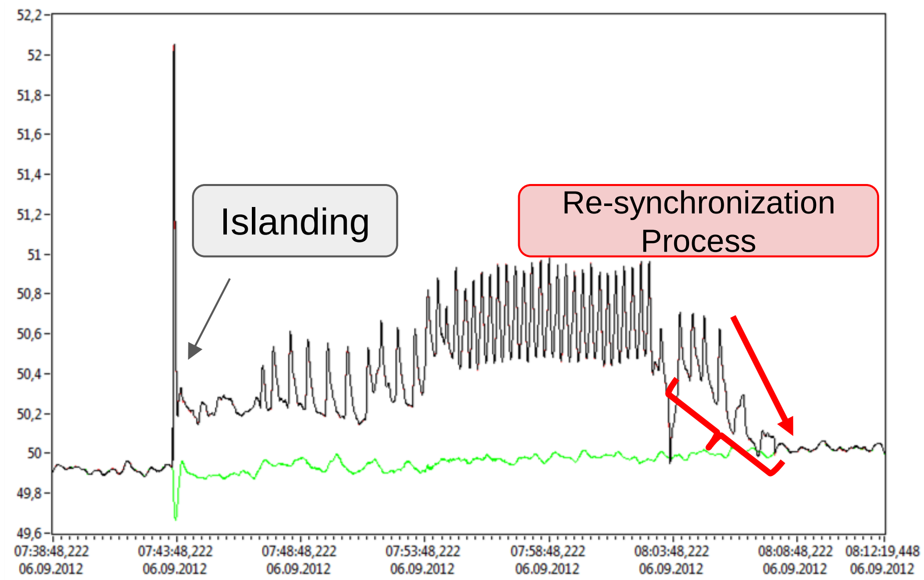

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New Synchrophasor-Based Control Schemes for Autonomous Microgrid Operation

(or coordinated Transmission and Distribution Operation)

Luigi Vanfretti | 04/10/2019
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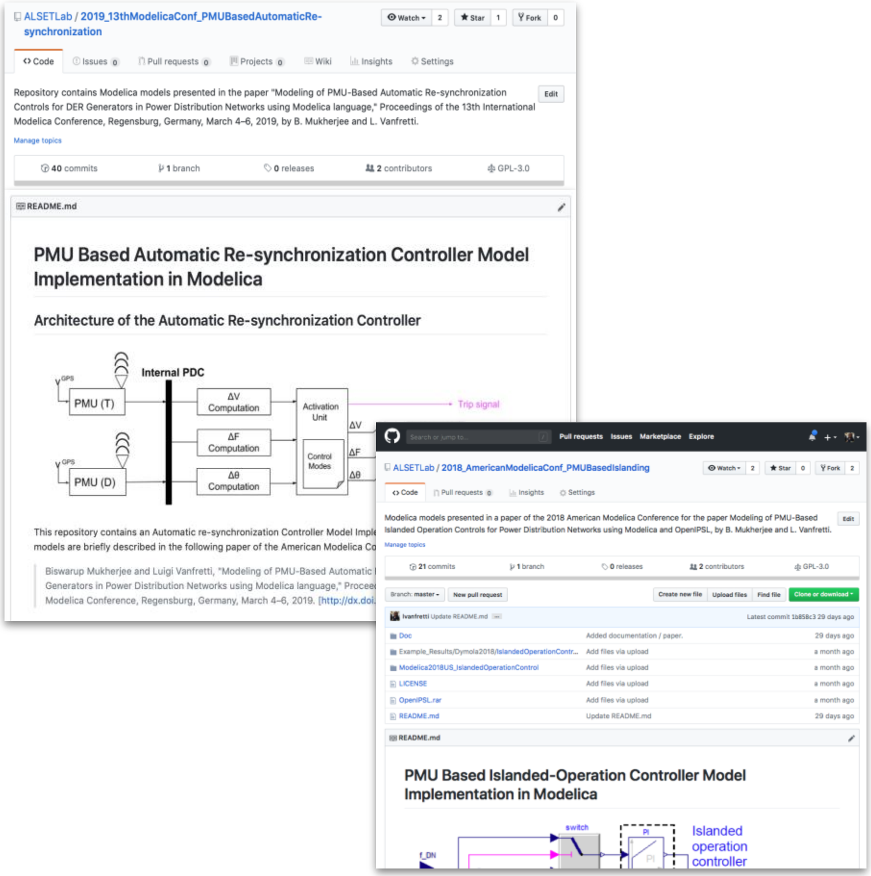
Outline

- Motivation
- Background & Previous Works

- Control Architecture
- Control Modes
  - Islanded Operation Control
  - Automatic Re-synchronization
  - Modeling and Implementation
- Power System Model
  - Transmission network
  - Generator Models
  - The Simulation Set-up
- Case Studies
- Conclusions



- Research Reproducibility:
  - Models and results from this presentation were presented in two conference papers, and are available at: https://github.com/ALSETLab/2019_13thModelicaConf_PMUBasedAutomaticRe-synchronization https://github.com/ALSETLab/2018_AmericanModelicaConf_PMUBasedIslanding

Motivation:

Need for grid observability and controllability

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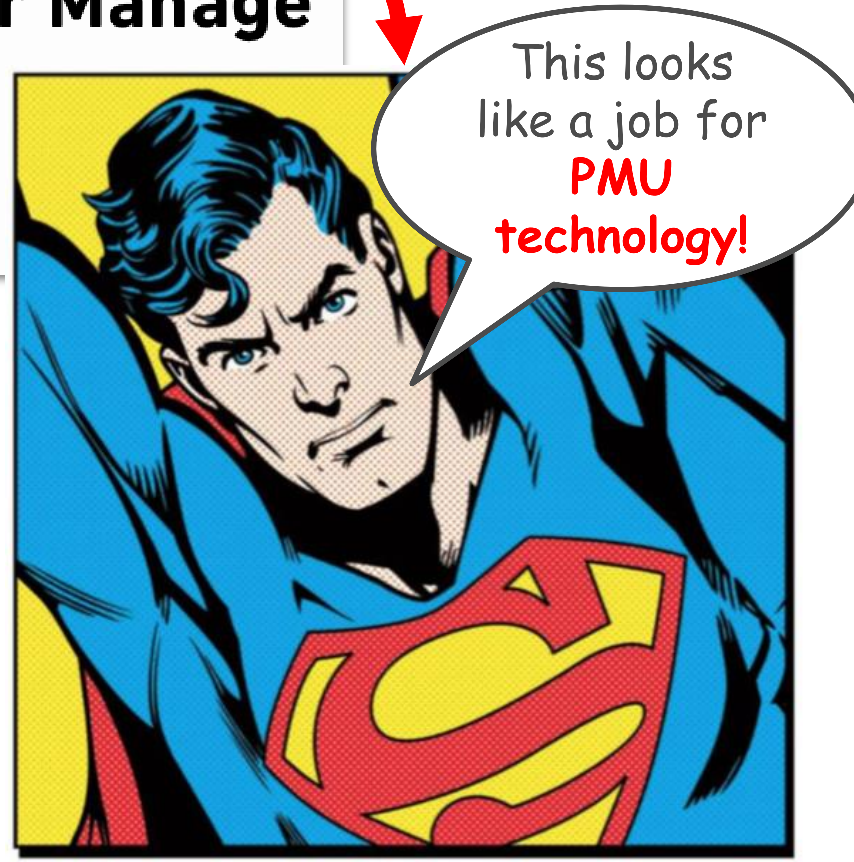
REGULATION & POLICY

Utilities, Grid Operators Tell FERC They Need Real-Time Data to Better Manage DERs

It's unclear how federal regulators will tackle the problem.

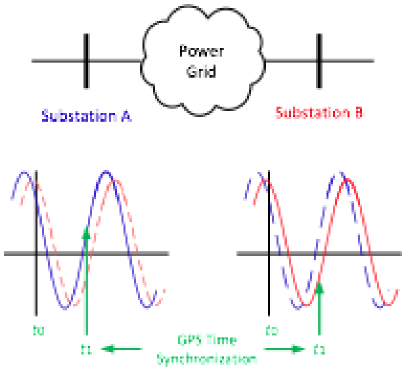
LACEY JOHNSON | APRIL 12, 2018

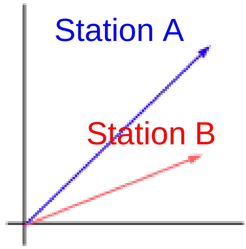
- Utilities and grid operators stressed the **need for real-time information** on distributed energy resources to a Federal Energy Regulatory Commission panel in Washington, D.C. on Wednesday (04/11/2018):
- "The worst thing that could happen for distribution companies is to not have visibility on…that distributed energy resource,"
- "We need to know where it is, the size of it, and how it's being operated on a real-time basis."
- "Communication today with DER is really low-tech. It's phone and it's emails,"



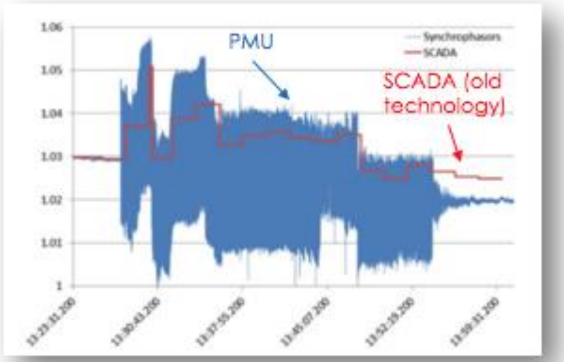
Motivation:
Synchrophasor measurement units (PMUs)

- What is a PMU?
- PMUs provide t**time-synchronized measurements that can be networked** into a synchrophasor system.
- Real-time measurement **data exchange between different asset owners and grid operators**, using a broadly adopted standard for communications.
- Higher resolution than traditional measurement systems used at SCADA/DMS/EMS: 30,50,60,120 Hz.





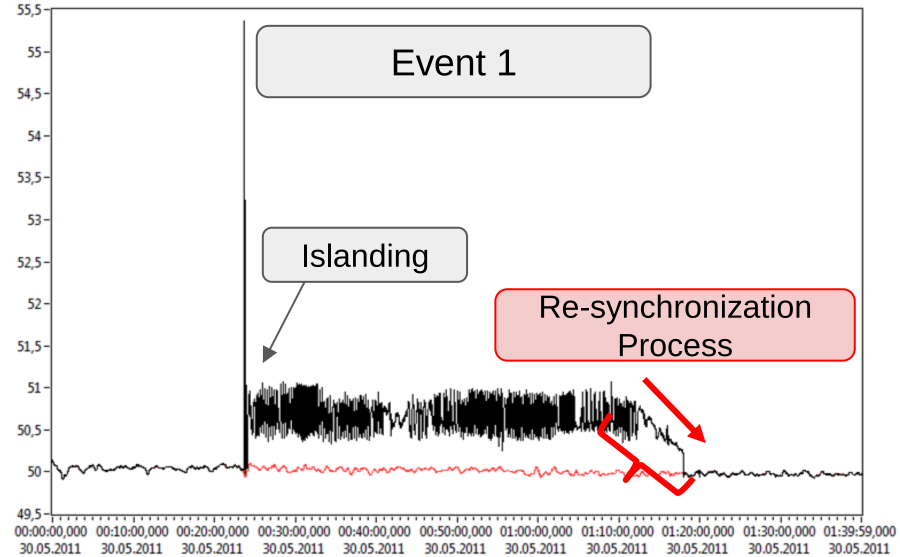
- Why use PMU-based controller?
- **Time-synchronized *data* that could be used to *exchange between different operational boundaries* (i.e. gen., transmission, distribution, and DER)**
- Frequency is a derived variable from computed phasors (phase angle is provided from PMUs), readily available - no need for additional sensor/device.
- Some manufacturers (SEL, GE, …) provide PMU functionality within existing relays, feasible to implement (link)
- Use of standardized comms protocols for Interoperability: limits vendor lock-in.

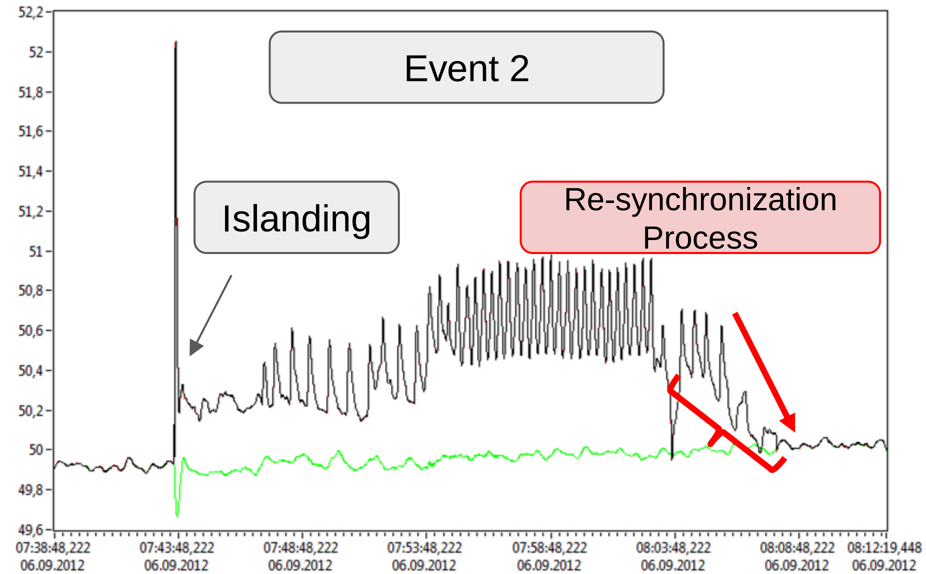


Motivation:

Challenges of Islanding and Re-synchronization Maneuvers

- Islanding events in northern Norway.
  - Event 1 (2011), ~ 1hr duration.
  - Event 2 (2012), ~ 25 min duration.
- Islanding:
  - Difficult for islanded network operator to maintain adequate frequency quality and power balance.
  - *Can this be improved/automated?*
- Resynchronization maneuver is done via operators of two (or more) entities:
  - Transmission operator coordinates with power plant operator via telephone!
  - Ramp up in power plant output
  - Synchronize voltages at reconnection point
  - *Can this be automated?*





Background and Previous Work

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Modeling of Frequency Measurements for Control

- In conventional power system simulation a **washout filter (WF) (Milano & Ortega, 2017)** is used for frequency estimation → phase angle of bus voltage is used to compute the bus "speed" deviation.

Frequency control in an islanded grids

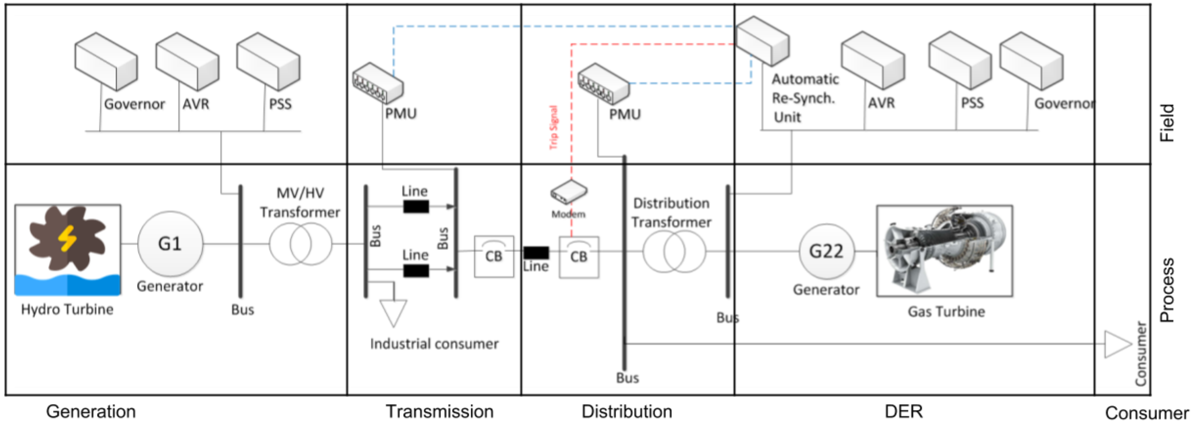
- Restore the power/frequency balance. Solutions include:
  - Different **governor configurations**; **isochronous governor required.**
  - Use of additional controls with remote sensing (Taranto & Assis, 2012)
  - Converter power synchronization function, proprietary tech. different to each vendor

Re-synchronizing an isolated grid

- Voltage and speed control strategy proposed for automatic re-connection. Solutions include:
  - Conventional auto-synchronizers (limited measurements/networking, vendor lock-in, not interoperable).
  - Using remote sensing of voltage and frequency signals together with conventional synchronism check relays (Taranto & Assis, 2012).
- The phase angle difference is important for re-synchronization. Therefore **control of the phase angle difference** across the circuit breaker can be beneficial during re-synchronization (Belyaev et al., 2015).

Suitable for Deployment in a multi-entity environment

Monitoring and Control Architecture across the "Smart Grid" plane



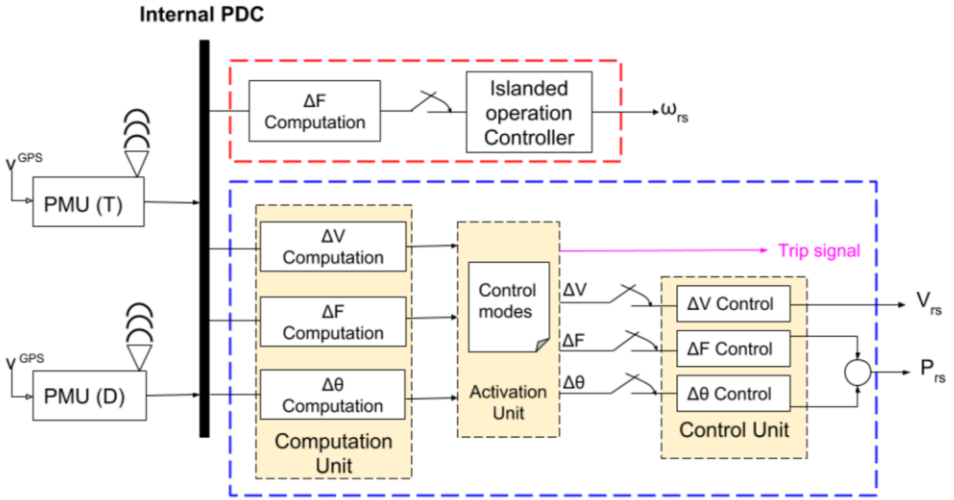
Islanded Operation

- Use frequency estimation from **PMUs** for an **islanded operation controller**
- Advantages of such control scheme:
  - No need for isochronous governor, could be deployed in any generator unit.
  - Minimize wear on DER equipment (shaft torque, converter heating, etc).

Automatic Re-synchronization Controller

- Use estimated voltage phasors (voltage magnitude and angle) and frequency from **PMUs** for an **automatic re-synchronization controller**
- Use **unwrapped angle difference** calculated from the wrapped angle differences

Control Architecture
with multiple control modes



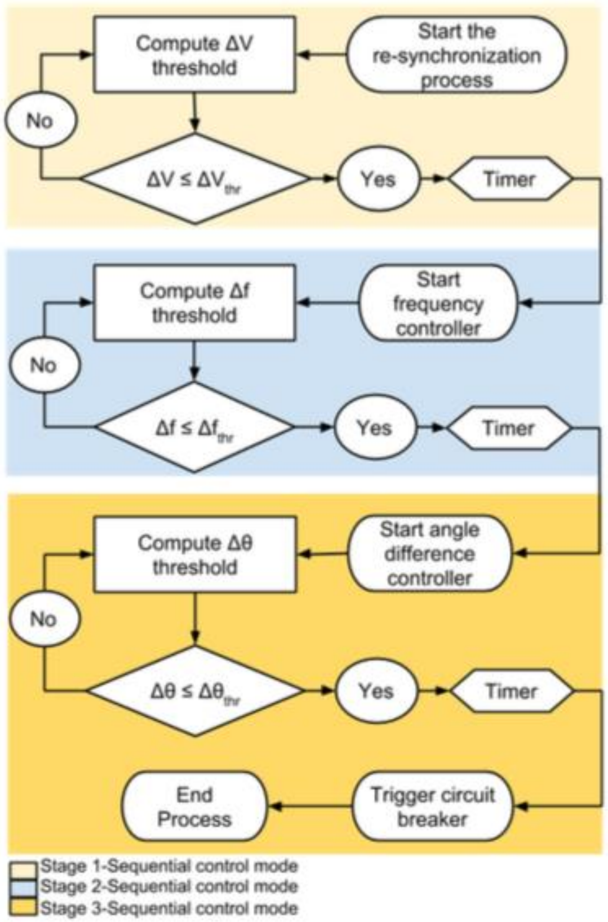
The **Control Architecture** contains three major functions or units**:**

- **Computation unit** computes the bus voltage, frequency and angle differences (i.e. ΔV, ΔF, Δθ)
- **Activation unit** is used to trigger the individual controllers after checking thresholds for the synchronization variables (i.e. ΔV, ΔF, Δθ)
- **Control unit** includes ΔV, ΔF and Δθ controllers

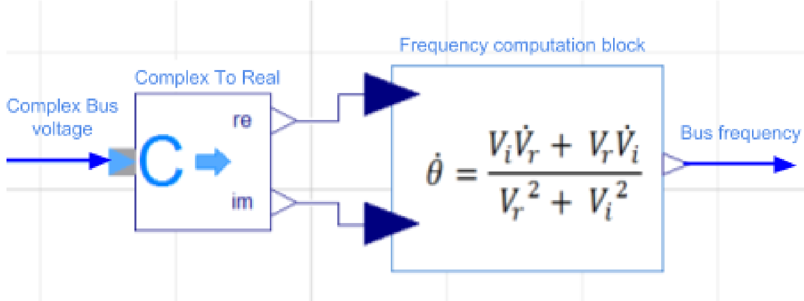
The same functions can be used by different **control modes**:

- Islanded operation (uses ΔF for control)
- Automatic re-synchronization

Sequential Re-Synchronization Control Mode



Input: `u, u1`
Bus voltage phasor, real and imaginary components



Output: `y`
Bus frequency deviation, in per until.

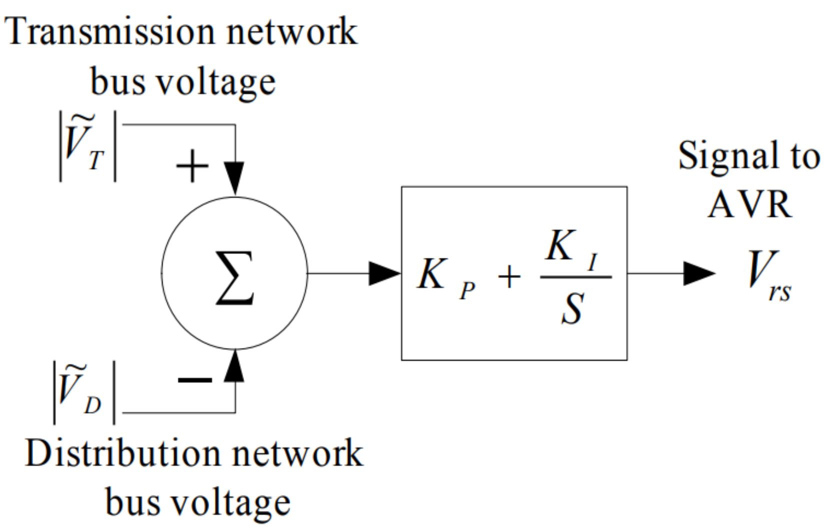
```
model frequencyCalculatiionBlock
  Modelica.Blocks.Interfaces.RealInput u;
  Modelica.Blocks.Interfaces.RealInput u1;
  Modelica.Blocks.Interfaces.RealOutput y;
  Modelica.Blocks.Continuous.Derivative
 derivative;
  Modelica.Blocks.Continuous.Derivative
 derivative1;
equation
  y =  (u*(derivative1.y) + u1*(derivative.y))/ ((u^2) + (u1^2));
  connect(u1, derivative1.u);
  connect(u, derivative.u);
end frequencyCalculatiionBlock;
```

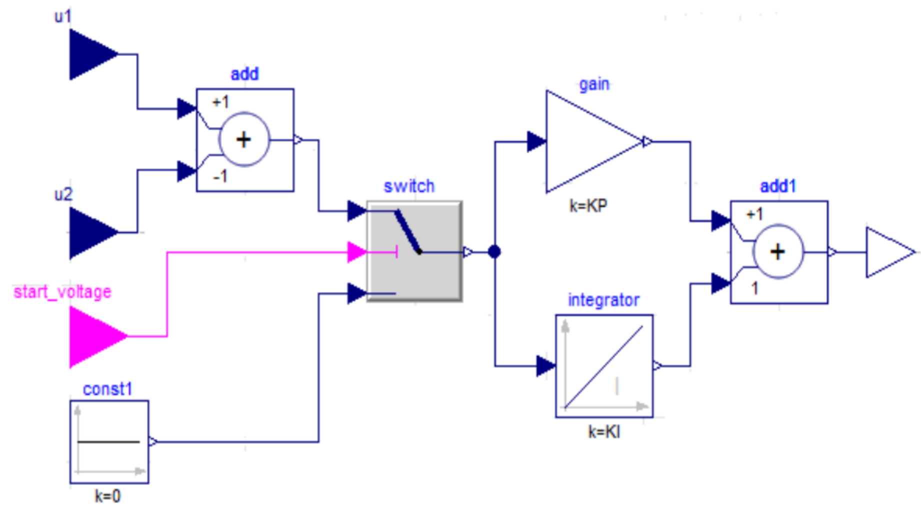
Textual representation of the **Frequency computation block**

- If frequency is calculated from bus angle directly it may corrupt the frequency calculation (due to angle wrapping).
- To obtain the correct frequency for control purposes, this computation block is used.

Modeling of the ΔV, ΔF and Δθ control functions

- The Δ**V**, Δ**F** and Δ**θ** controllers are modeled inside the control unit and implemented using the Modelica language.
- Both the **voltage controller** and the **frequency controller** use a **PI** function while the **angle difference controller** requires a **PID** function
- The schematic and Modelica implementation of the Δ**V** controller are shown below. The other controllers (Δ**F** and Δ**θ**) use similar implementations.





The output truth table of the Δ**V** **controller**

Boolean Input signal	Output (y)
True	$y = \Delta V \left(K_P + \frac{K_I}{S} \right)$
False	0

Proposed Islanded Operation Control Mode

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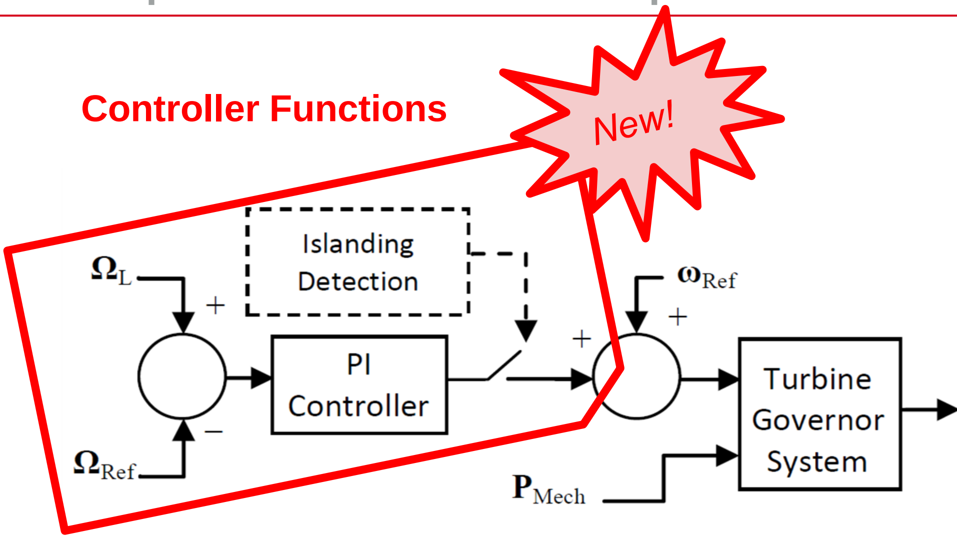
Controller Functions



- Once an islanding condition is detected, the PI controller modulates the speed error signal of the governor within a turbine.
- This cascade connection makes it more attractive for a *practical implementation*, as only an additional control module needs to be integrated with legacy controllers.
- In the figure, the variables listed are:

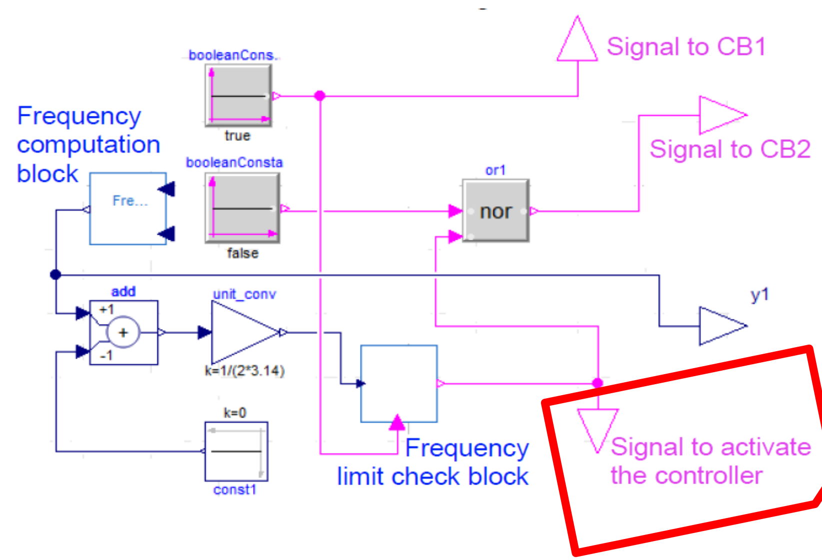
Ω_L = Islanded network frequency

Ω_{Ref} = Reference frequency

ω_{Ref} = Reference speed

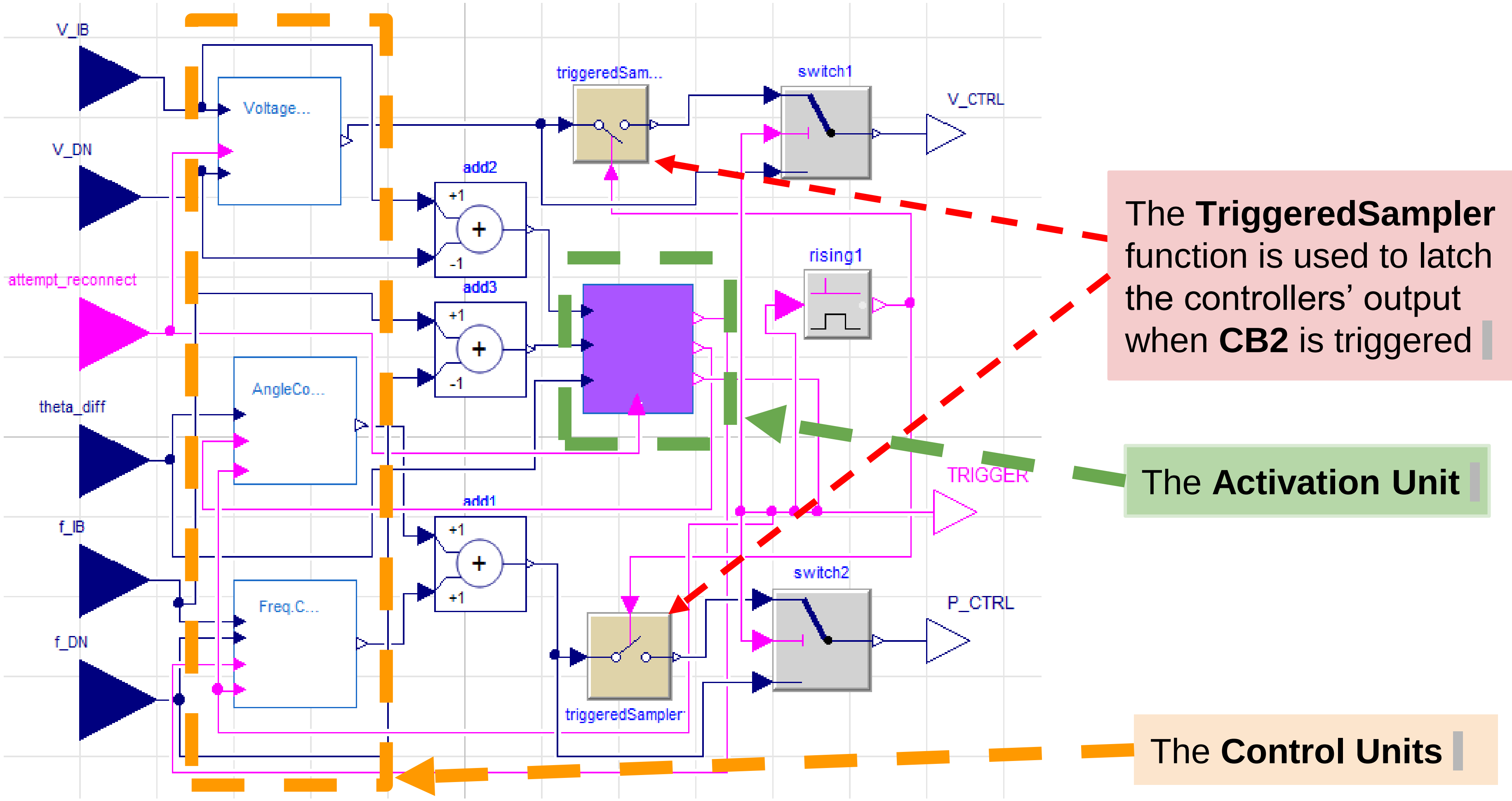
P_{Mech} = The mechanical power set-point corresponding to a prescribed power dispatch

Islanding Detection

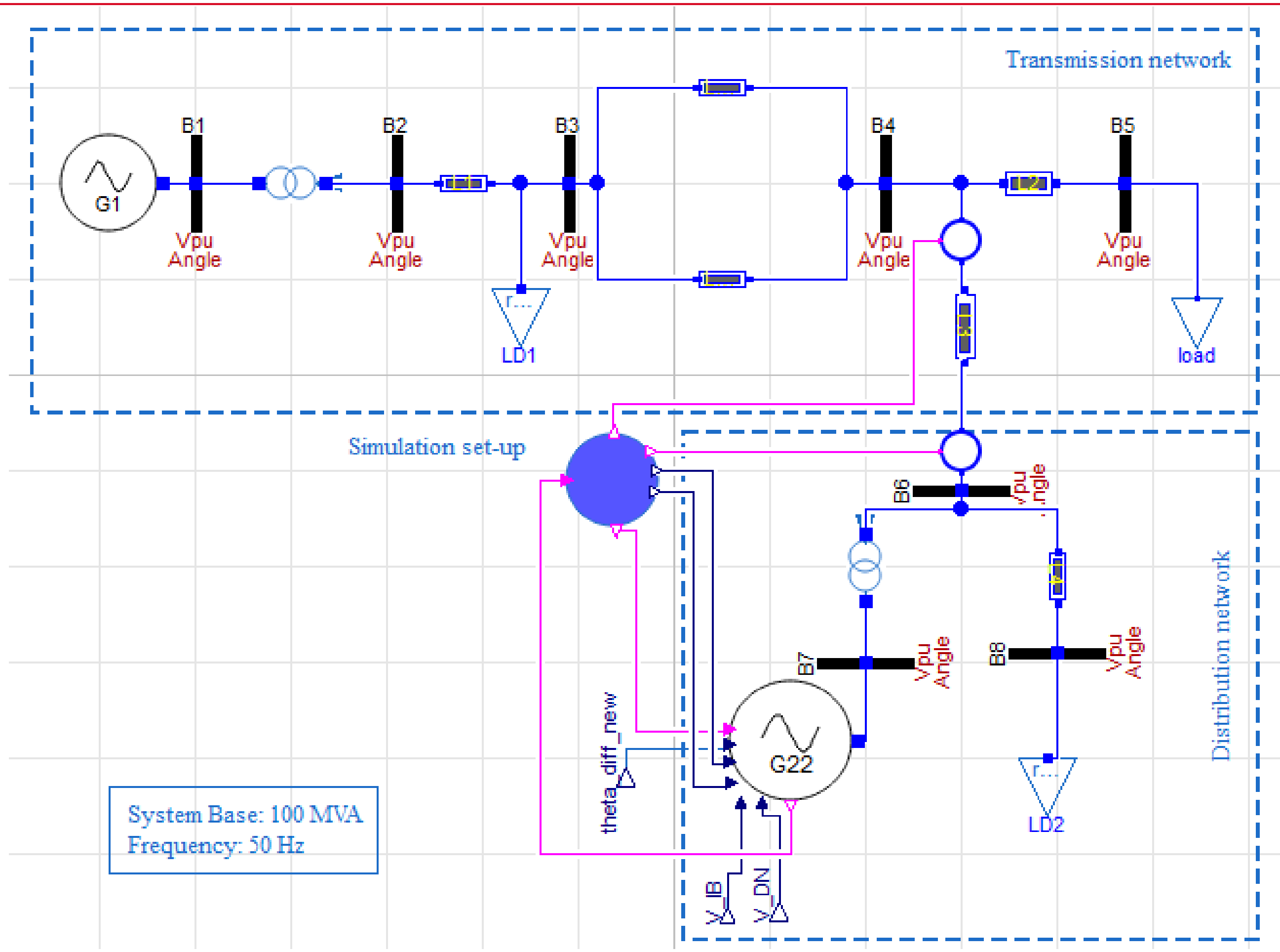


- Synchronization variables, Δ**V**, Δ**F** and $\Delta\boldsymbol{\theta}$ can all be used to determine islanding.
- In this presentation, the Δ**F**, synchronization variable is used.
  - Not difficult to include the others.
- The scheme below is used to generate a signal to activate the PI controller for islanded operation.

Automatic Re-Synchronization Control Mode

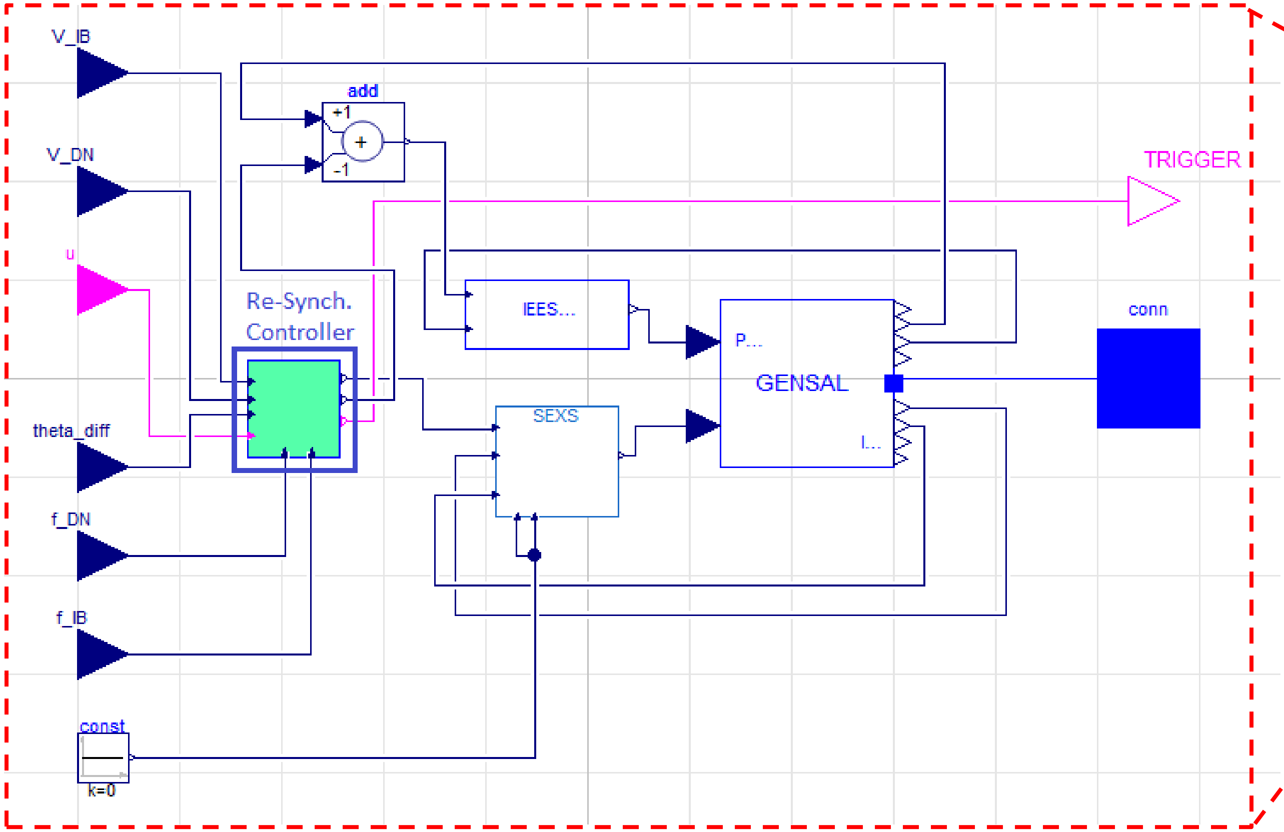


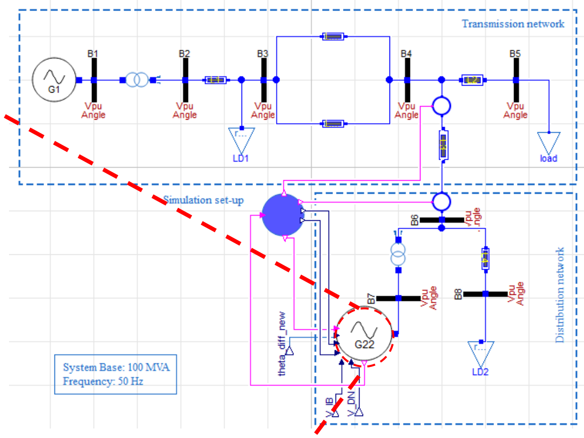
- The Boolean output signal from the re-synchronization unit is applied to the circuit breaker **CB2** when all three limits are satisfied



- The circuit breakers **CB1** and **CB2** are controlled using logic equations implemented in a **Simulation Set-up** block which is used to create the islanding event and to activate the islanded operation controller.

Control Scheme Implementation

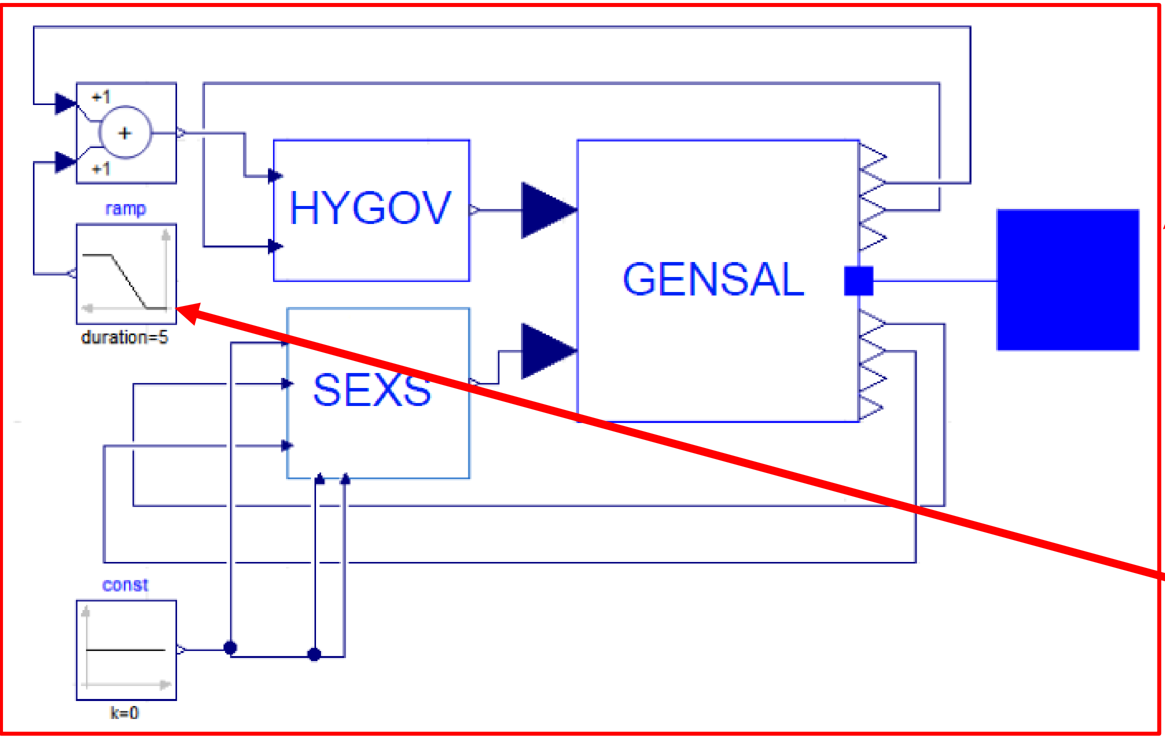


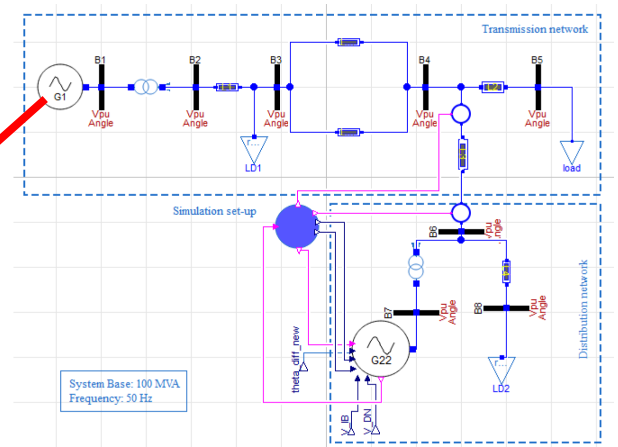


The DER generator model (G22) implementation

- **GENSAL** block corresponds to the synchronous generator
- **IEEESGO** corresponds to the gas turbine and governor model
- **SEXS** corresponds to the excitation control system of the generator

Transmission Network Generator Model

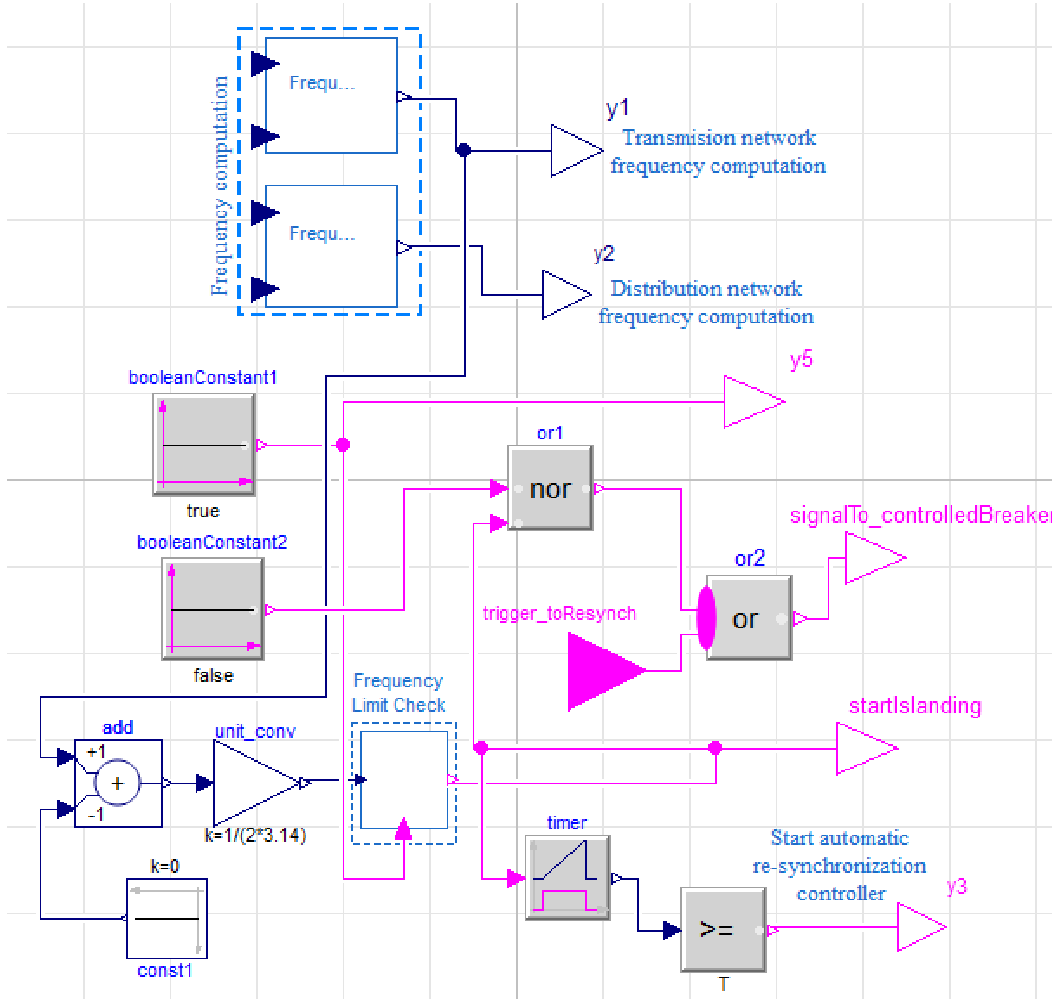


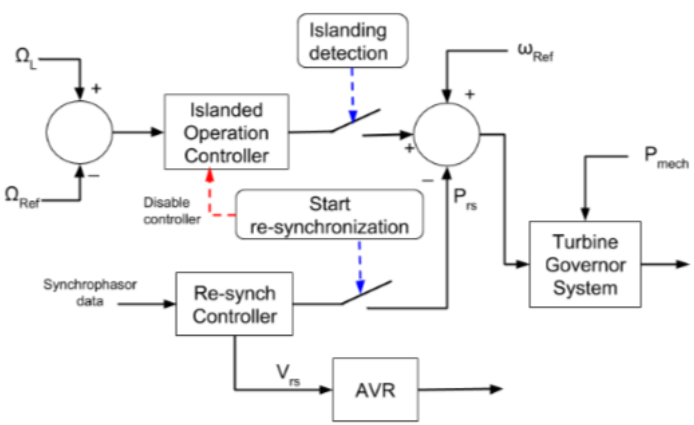


The overall system frequency is varied by introducing a **speed change** in the governor system

- **GENSAL** block corresponds to the synchronous generator
- **HYGOV** corresponds to the hydro turbine and governor model
- **SEXS** corresponds to the excitation control system of the generator

- A Boolean true signal keeps the circuit breaker **CB1** closed in the transmission side network while maintaining the transmission line energized
- The controller needs to use frequency measurements, these need to be estimated from the angle of the voltage phasor.
- The different control modes are activated and deactivated by a discrete control logic.





- **Case 0: Frequency computation modeling impact on control function**

- **Case 1: Control Performance**
  - Islanded operation mode performance for 10 MW dispatch from G22
  - Sequential control mode performance of the resynchronization controller for a dispatch of 10 MW from generator G22
- **Case 2: Effect of Frequency Computation and Angle Unwrapping**
  - This case study exhibits the performance of the angle control for both wrapped and unwrapped angle calculations for a dispatch of 10 MW from generator G22
- **Case 3: Angle Control Response for Multiple Dispatch**
  - This case study is performed to illustrate the effect of angle difference on the total time taken for the resynchronization process for different dispatch levels from generator G22
- **Case 4: Effects of Stochastic Load Behavior**
  - This case study shows the impact on the re-synchronization reclosure time due to stochastic variations in the consumer behavior.

Case 0 - Frequency computation modeling impact

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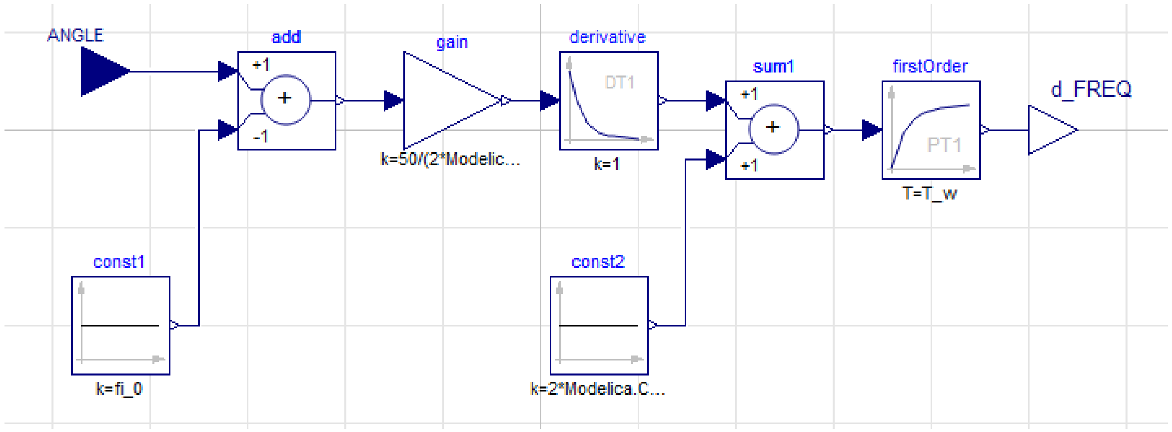
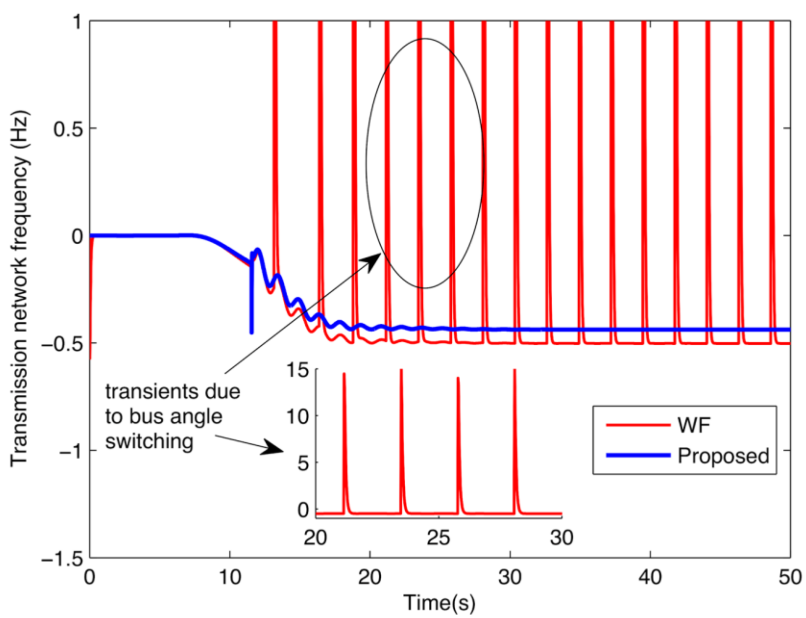
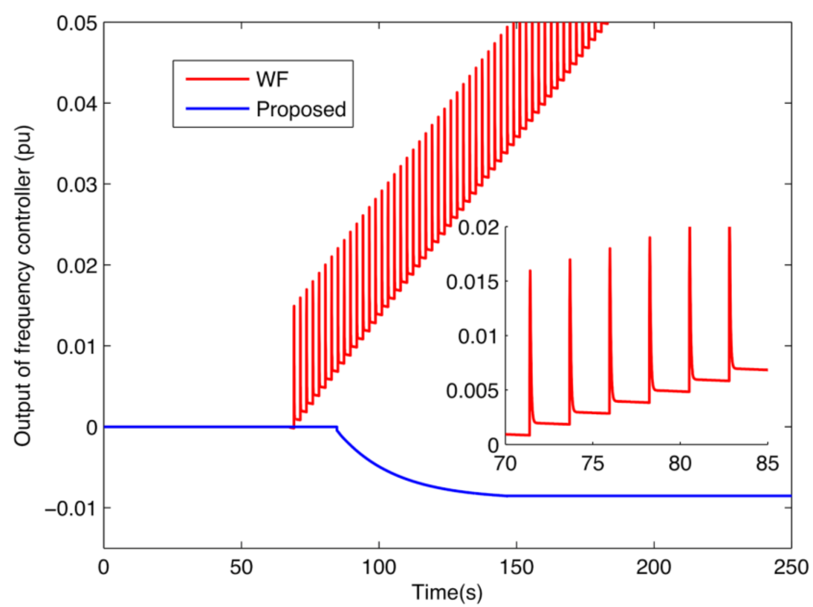
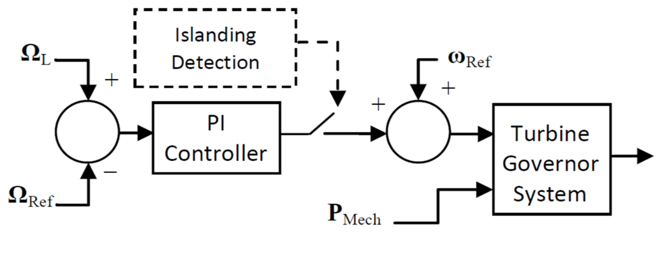
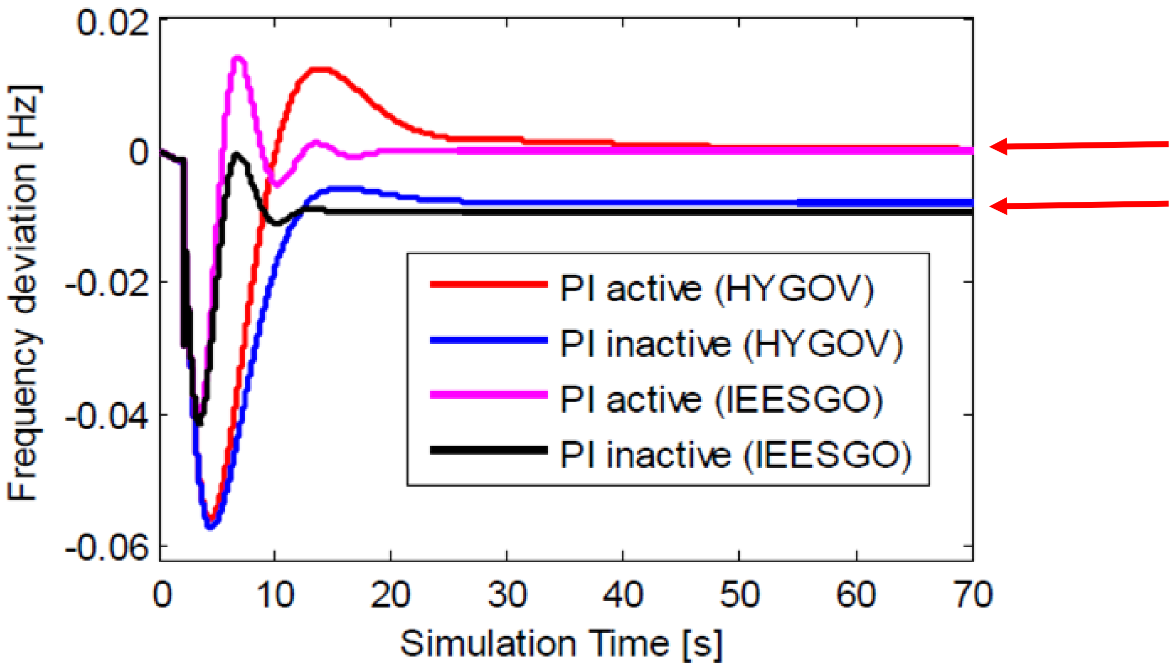


Modelica implementation of the Conventional WF-Based Freq. Computation Method (used in PSS/E, and all other power system simulation software)









- Regardless of turbine-governor system type, the controller is capable of reset the island's frequency to the prescribed reference.
- IEESGO turbine-governor system:
  - Max. instantaneous values of frequency deviations are 0.0414 Hz and 0.0405 Hz respectively when the controller remains inactive and active.
- HYGOV turbine-governor system:
  - Max. instantaneous values are 0.057 Hz (when control action remains inactive) and 0.055 Hz (when control action remains active).

Case 1- Sequential Control Mode Performance

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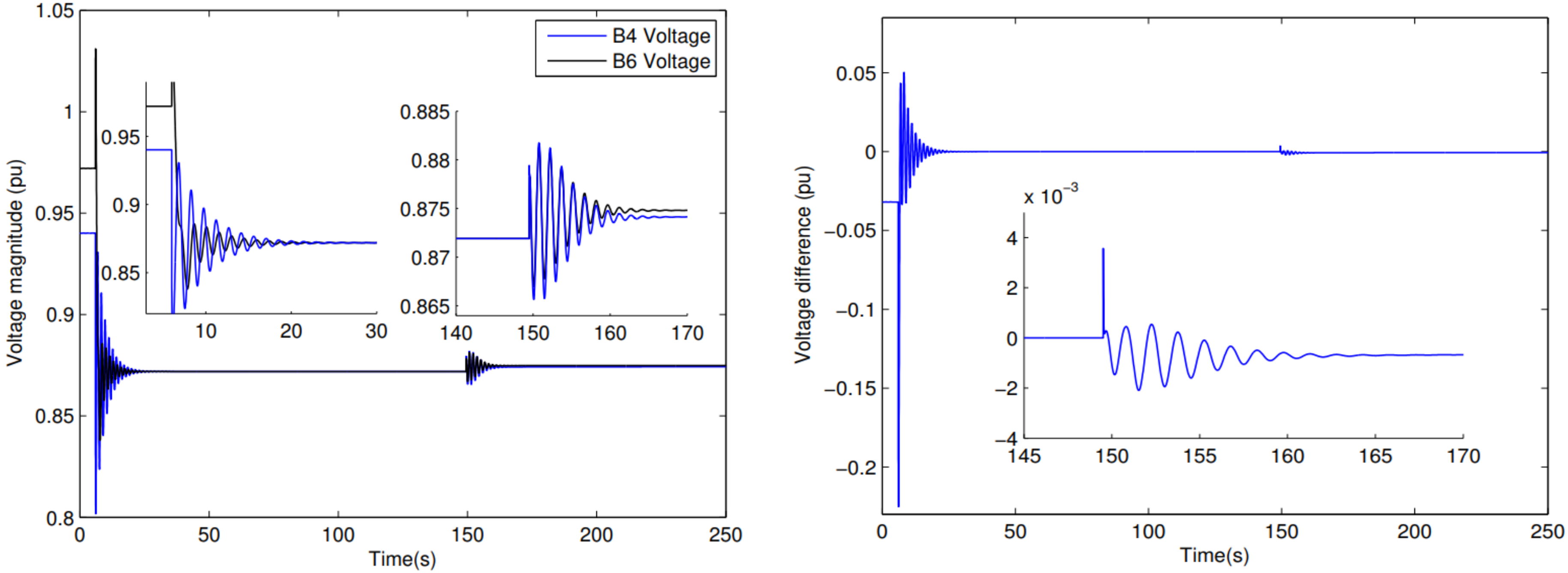


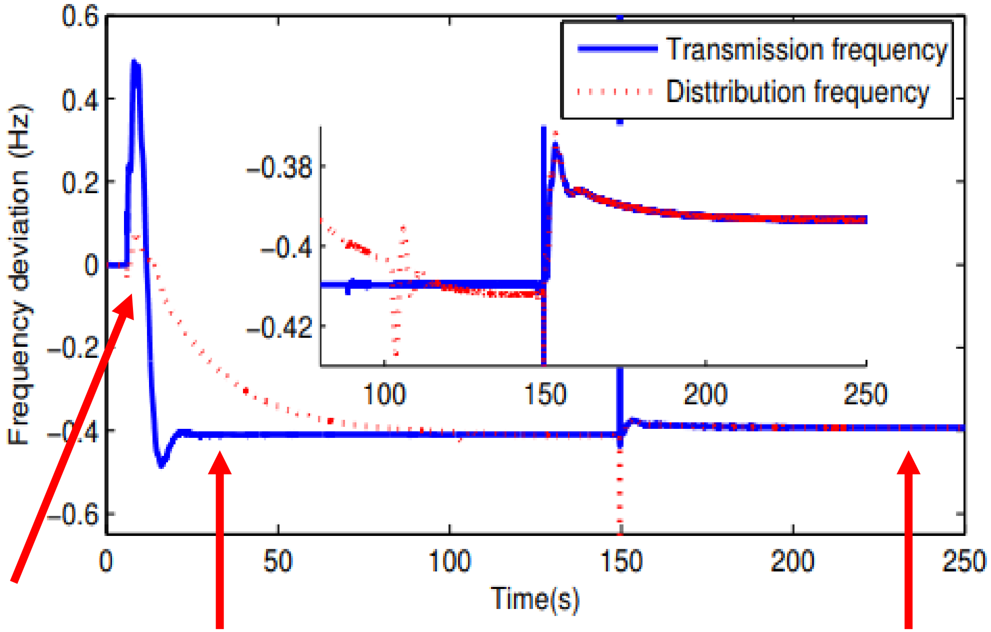
- As soon as the resynchronization process starts at 6.01 seconds the **voltage controller starts working and effectively reduces the voltage error in the bus voltages (Bus 4 and Bus 6 voltage).**
- After the re-synchronization occurs at 150 seconds the voltage controller still works minimizing the error in the voltage difference for both the buses (Bus 4 and Bus 6).

Case 1- Sequential Control Mode Performance (Contd.)

- Both T&D network frequencies experience change in the frequency deviation. This raises the question:
  - *Why does the error do not return to zero?*

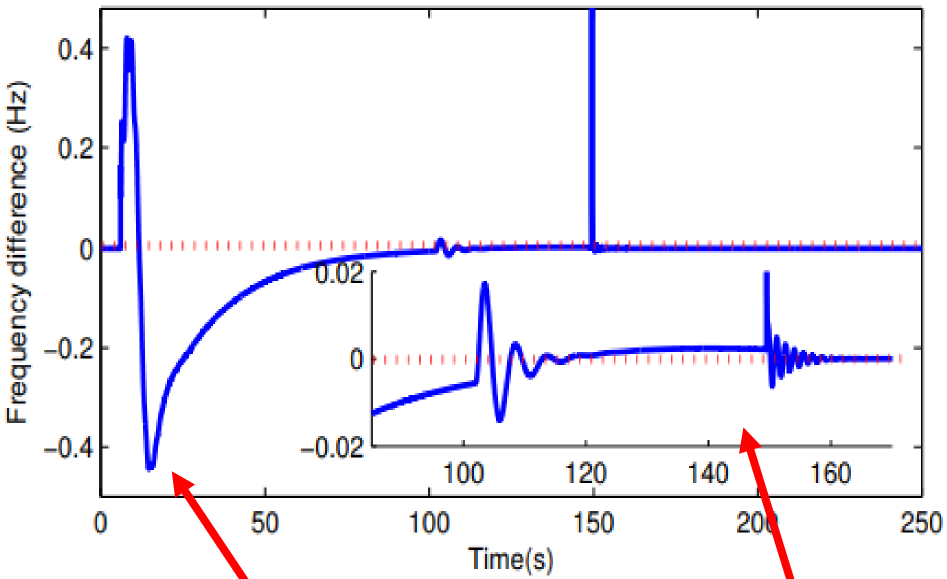
- Modeling choices:

  - We don't use the "infinite bus" artifact to artificially force a set-frequency in both networks, as this modeling assumption is only valid when analyzing responses of up to 10 sec.
  - We do not model the so-called Automatic Generation Control (AGC) dispatch control system used by operators in North America, as we wanted to address the general case where such mechanisms are not used.



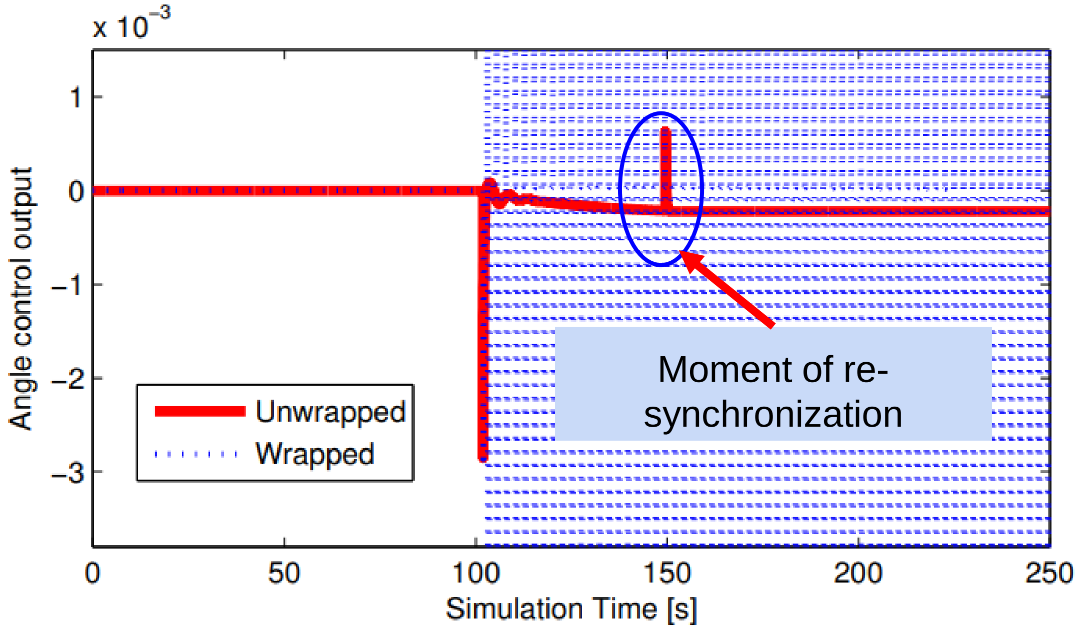
- With these modeling choices:
  - Frequency difference is governed by the droop and limits of the "larger" system.
- The resynchronization function does not force the DER to return to a "fixed" value, but instead, adapts to the frequency of the system to be re-synced to.

Case 1- Sequential Control Mode Performance (Contd.)



- The resulting frequency deviation between the transmission and distribution network undergoes the following range during the following events:
  - For the initial islanding: *-0.4≤ Δf ≤-0.4*
  - *At the re-synchronization trip signal: -0.02<Δf ≤0.02*
- This reduction is thanks to the sequential control actions from t = 6 to 150.
- The frequency controller reduces the **frequency deviation to zero** after the distribution network is re-connected with the transmission side.

Case 2- Performance of the Angle Control Function

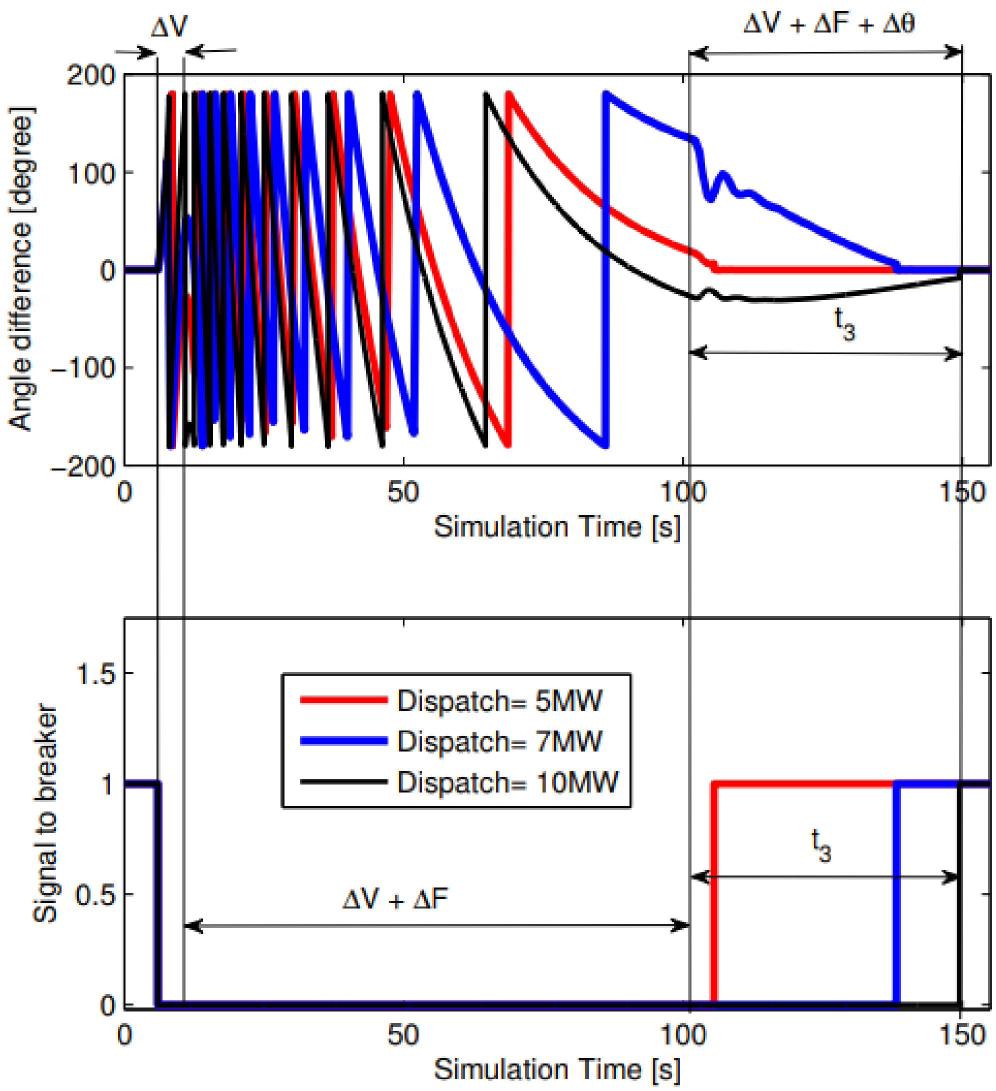


Performance of the angle difference controller due to angle measurement unwrapping

- Observe from the **red trace**, the unwrapped angle difference calculated from the wrapped angle differences **produces no transients in its response**.
    - This was achieved through the implementation on the right code:
- This makes the angle controller effective during the automatic re-synchronization process

```
equation
theta_diff = (-B6.angle) + B4.angle;
theta_diff_new = homotopy(actual =
   smooth(0, noEvent(if theta_diff >
    180 then theta_diff - 360 else
   if theta_diff < (-180) then
   theta_diff + 360 else theta_diff)
   ), simplified = theta_diff);
connect(theta_diff_new,
   G22.theta_diff);
end;
```

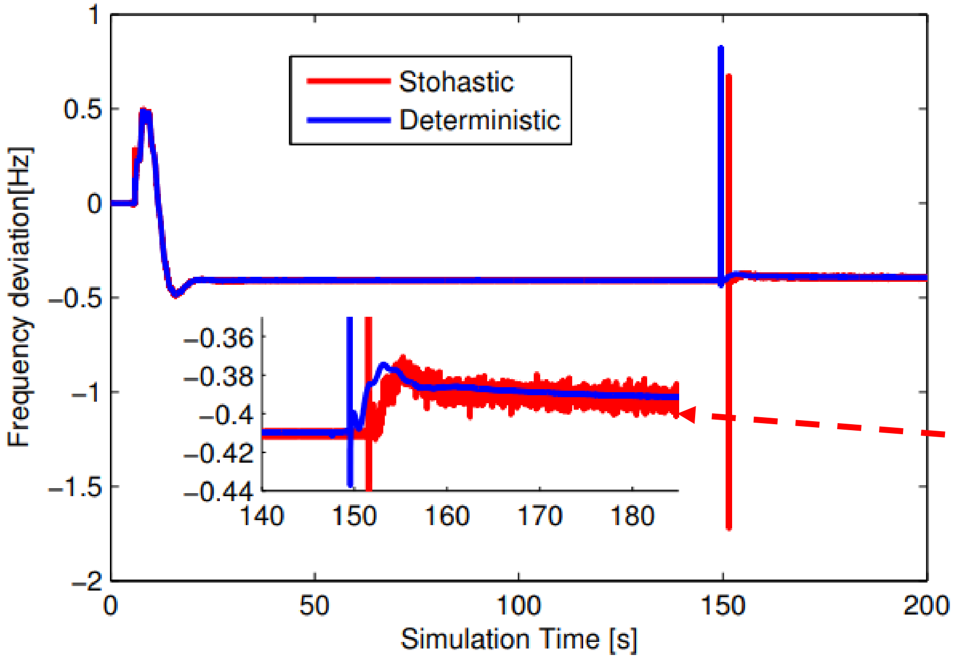
Case 3 - Angle Difference Controller Performance for Different Dispatch Scenarios



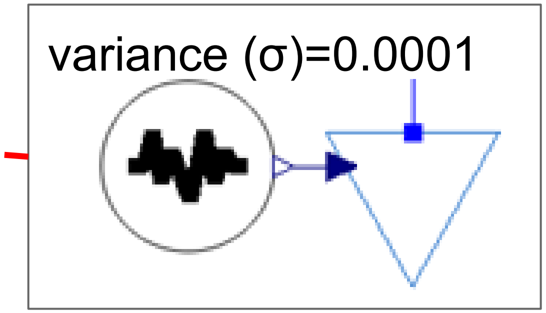
- When the **angle difference** between the distribution and transmission network bus voltage phasors reaches a steady state value, **CB1** receives a **trigger signal** for automatic re-closure.

- For **lower dispatches** the angle difference controller is **faster** because the generator has a larger bandwidth (i.e. available capacity) to minimize the angle difference by speeding up the active power output.

Case 4 - Effect of Stochastic Load Behavior



Plot shows transmission network frequency deviation with both deterministic and stochastic load models.



Stochastic load modeling approach using **Modelica Noise** features

- **Stochastic load model** introduces uncertainties in the load response, affecting the voltage phasor values.
- Thus the estimated frequency will vary, and consequently, the controller activation time can no longer be determined or designed deterministically.
- This shows that it is important to use statistical-based methods for control/protection scheme design.

Conclusions

- A simple **new frequency computation technique** that uses bus voltage data and can be used during dynamic simulations for control scheme design has been proposed.
- A new control architecture that uses PMU measurements allows for the implementation of different control modes for DERs in different operating conditions:
    - I**slanded operation control**
    - An **automatic re-synchronization control**
- The **angle difference control function** is required to perform seamless automatic re-synchronization process.
- This controller could be attractive for new distributed energy resource (DER) integration in low-voltage distribution grid and micro-grids.

Future work would focus on:

- Coordinating multiple DERs through similar control schemes.
- Application/re-design for to renewable DER.
- Modeling of communication and information technologies.
- Prototyping and testing in ALSETLab

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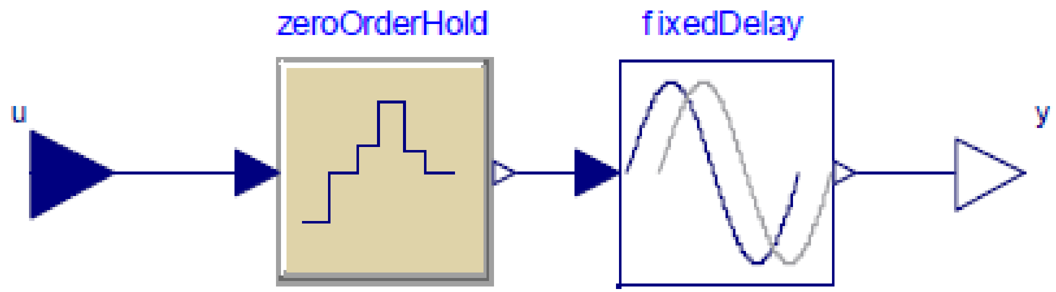
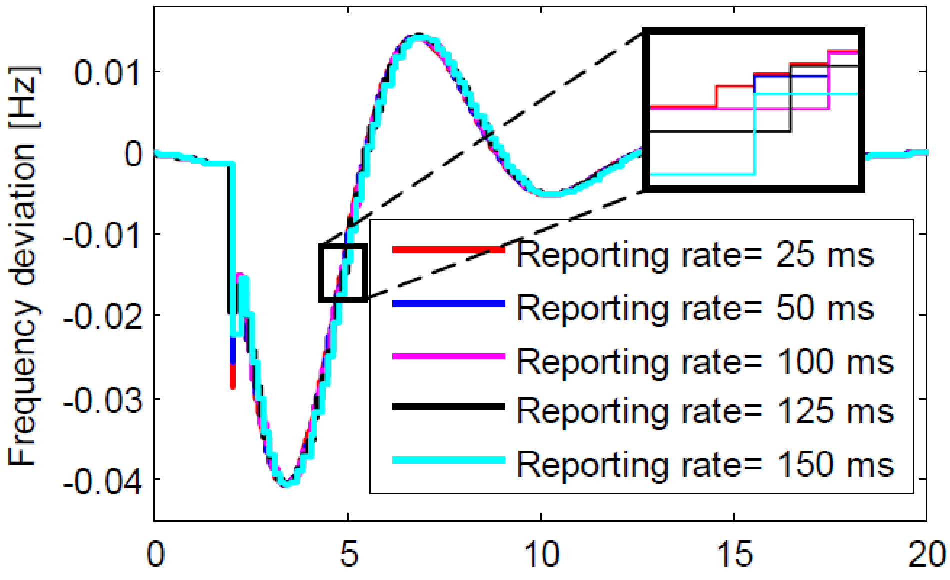
Back-up / Extra Slides



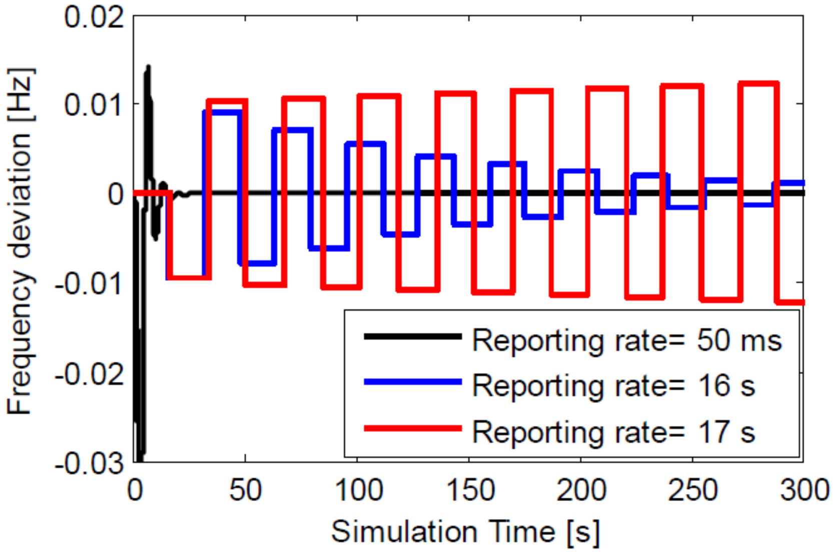
- A **Zero Order Hold (ZOH)** block from **Modelica Standard Library** is used to simulate different phasor **reporting rates**, streamed by a PMU device.
    - Note: reporting rate is the output of the PMU, the PMU internally samples at kHz level and computes phasors.

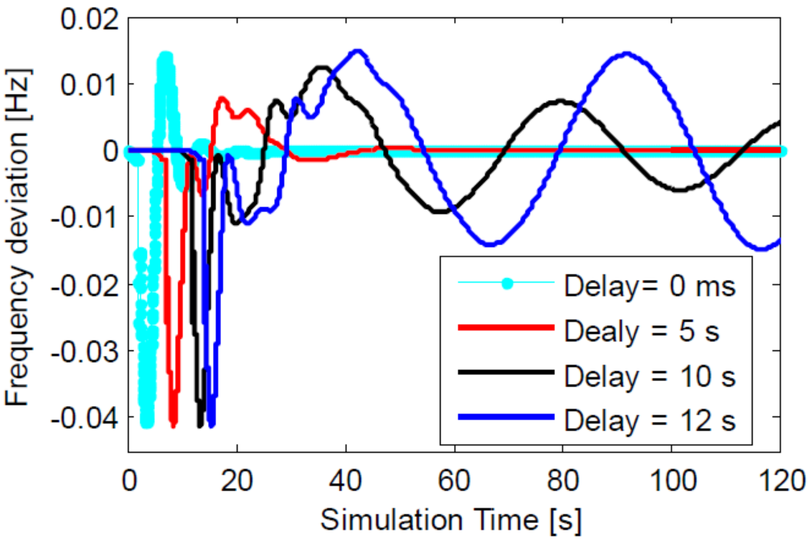
- The **time delay** due to data transmission from a PMU to Phasor Data Concentrator (PDC) and the controller is modeled using the **FixedDelay** block from the **Modelica Standard Library**.

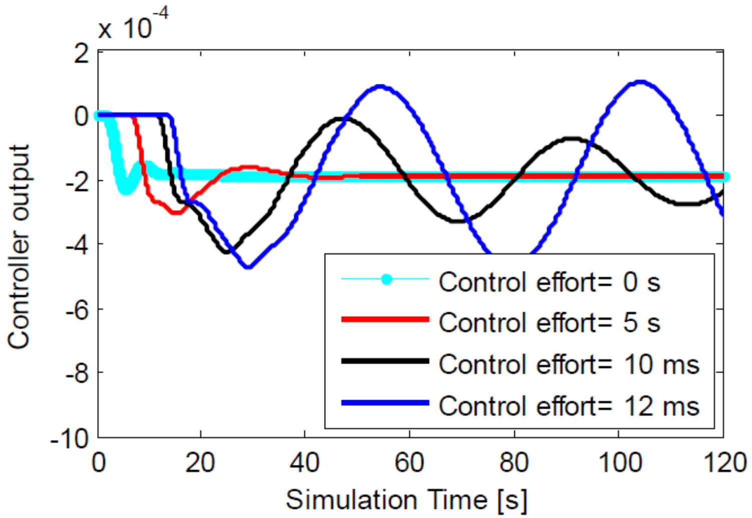


It is to observe that **delays** from **25 to 150 ms** have no major impact on the controller's performance, this is because the frequency dynamics being controlled are much larger than typical PMU reporting rates.

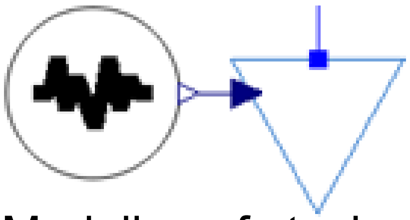
When the **reporting rate** is set to tens of seconds, the control loop becomes **unstable** i.e. **for the reporting rate > 16 s**. This is a positive result, as typical PMU reporting rates are ≤ 16_s, i.e. 10, 30, 50, 60 samples per seconds.



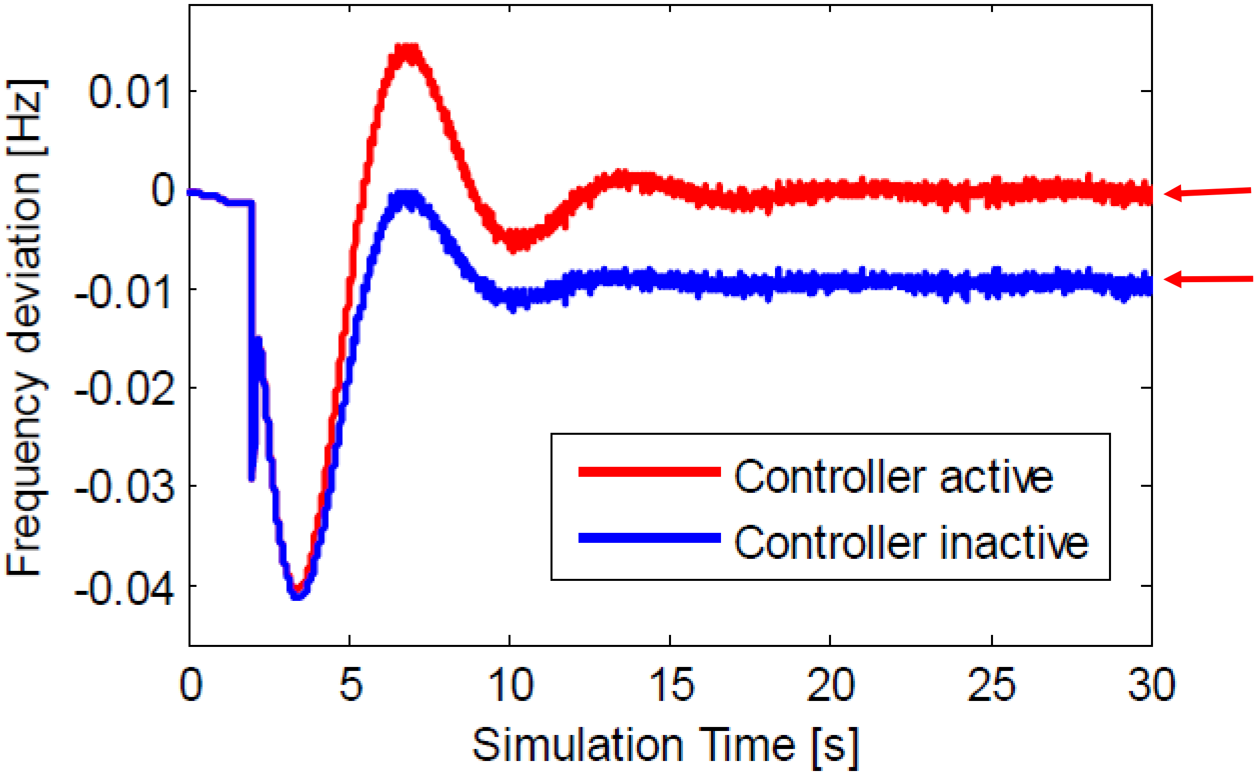




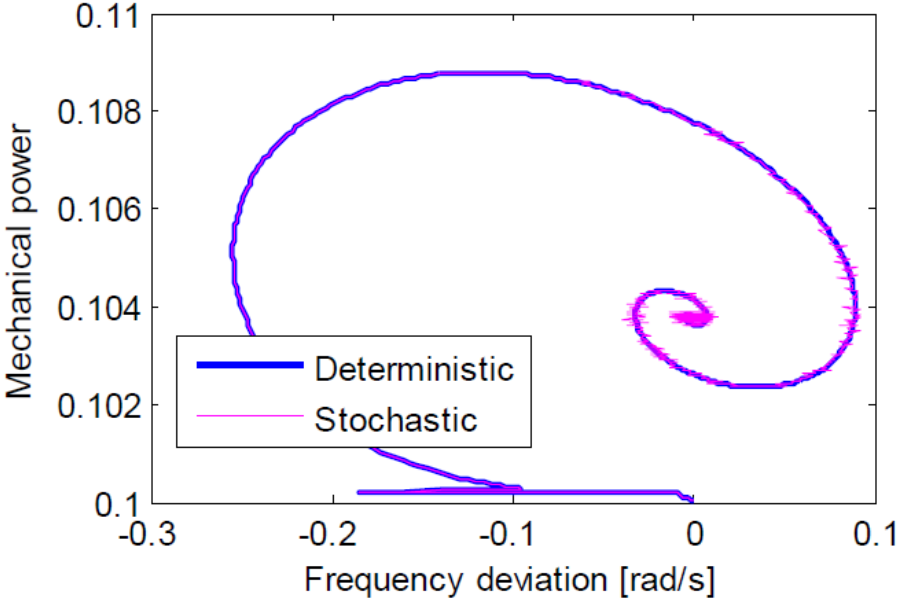
- A **FixedDelay** block is used to mimic the aggregate time-delay from a PMU device to the controller.
- As it can be observed in that the maximum delay bound is time delay ≈ 12s. These results are encouraging, as typical synchrophasor systems only incur in delays in the order of a 100s of milliseconds, up to a few seconds.

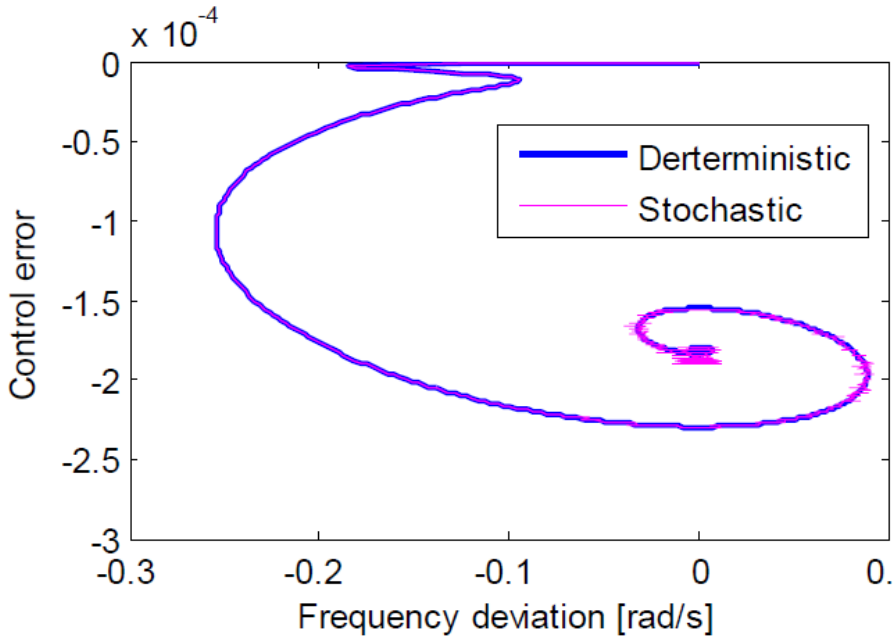


Modeling of stochastic load using **Modelica Noise** features



- The **stochastic load model** does not allow to accurately capture the frequency deviations due to time varying load changes. The controller is capable of reset the island's frequency to the prescribed reference in case of stochastic load.





- The increase in the frequency deviation, increases the mechanical power up-to 10.88 %. However for both deterministic load and stochastic load model the control error decreases up-to 0.023 %.
- **This shows that stochastic load modeling is necessary when analyzing turbine-governor control systems.**