Modelling Frequency Variations in Power System Models for Transient Stability Analysis

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Biography

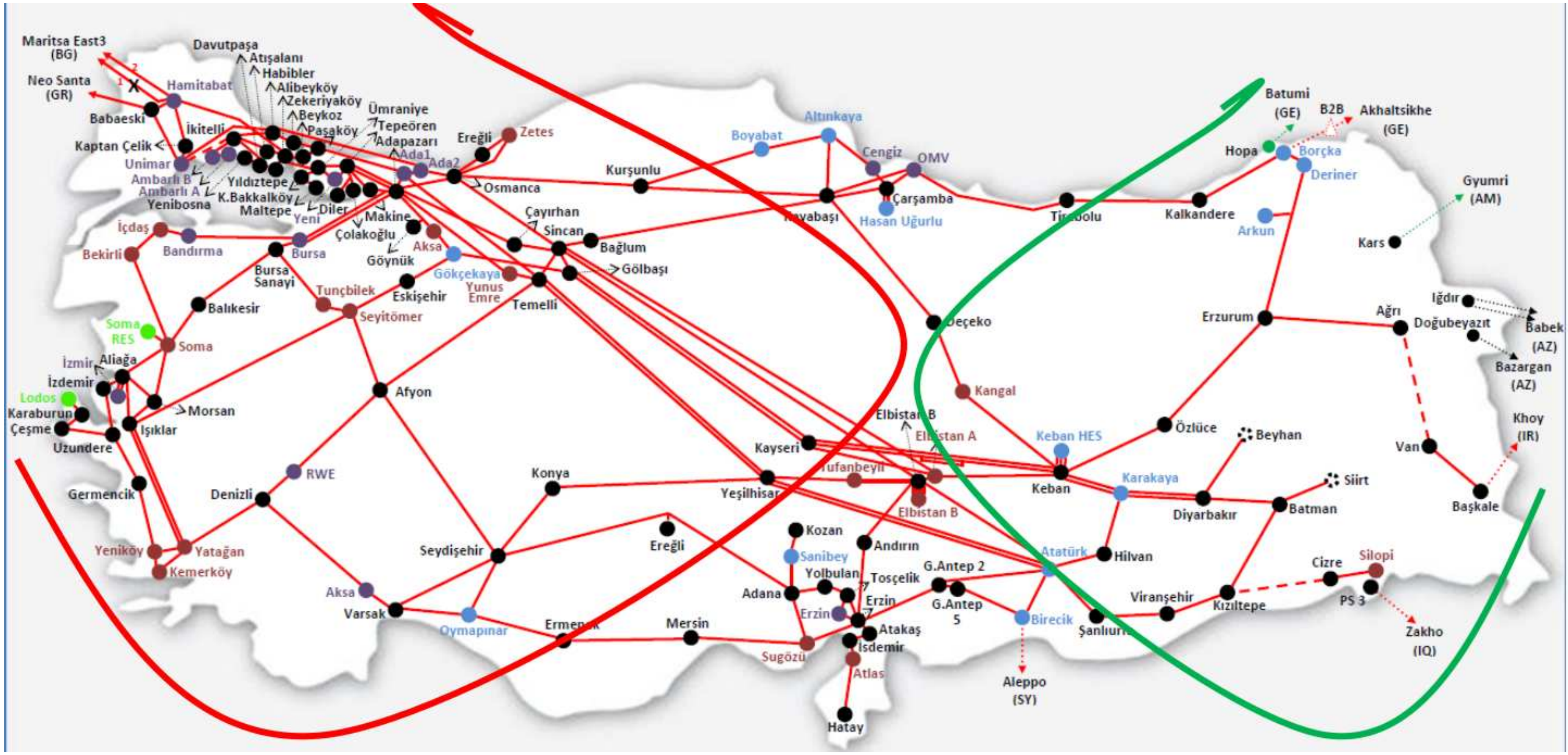
- Álvaro Ortega (S'13, M'16) received the degree in Industrial Engineering from Escuela Superior de Ingenieros Industriales, University of Castilla-La Mancha, Ciudad Real, Spain, in 2013.
- In 2017, he received the Ph.D. degree in Electrical Engineering from the School of Electrical and Electronic Engineering, University College Dublin, Dublin, Ireland.
- Since January 2017, he is a post-doctoral researcher with the same School.

Contents

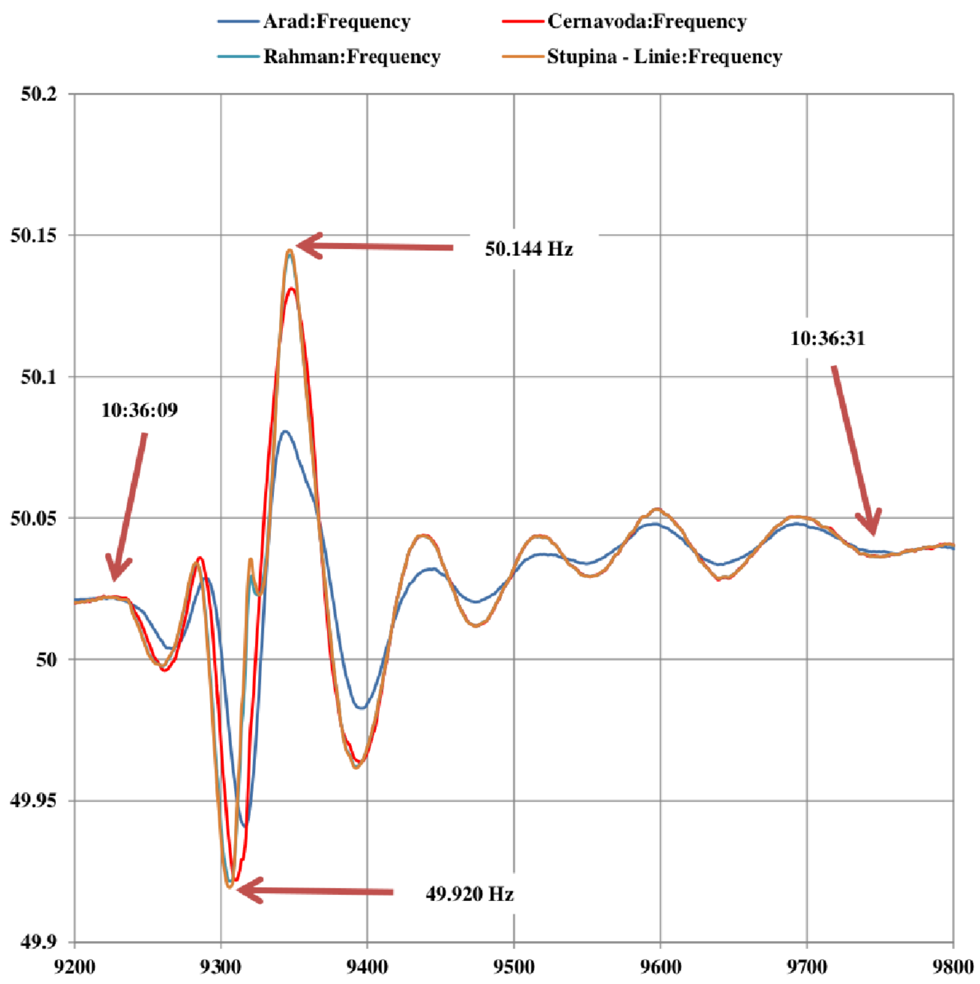
Motivations

Turkey Blackout on 31st of March 2015 – I

- The blackout in Turkey led to the outage of 32 GW.



Turkey Blackout on 31st of March 2015 – II



- As a consequence of the line outages and the blackout in Turkey, the Romanian system experimented severe frequency oscillations.
- Bigger oscillations were measured at locations geographically closer to Turkey.

Motivations – I

- The conventional power system model for transient stability analysis is based on the assumption of **quasi-steady-state phasors for voltages and currents.**
- The crucial hypothesis on which such a model is defined is that **the frequency** required to define all phasors and system parameters **is constant and equal to its nominal value.**
- This model is appropriate as long as only the rotor speed variations of synchronous machines are needed to regulate the system frequency through standard primary and secondary frequency regulators.

Motivations – II

- In recent years, however, an **increasing number of devices other than synchronous machines are expected to provide frequency regulation.**
- These include, among others:
  - distributed energy resources, e.g., wind and solar generation
  - flexible loads providing load demand response
  - HVDC transmission systems
  - energy storage devices
- However, **these devices do not impose the frequency** at their connection point with the grid.
- There is thus the **need to define with accuracy the local frequency** at every bus of the network.

Existing Methods

Center of Inertia

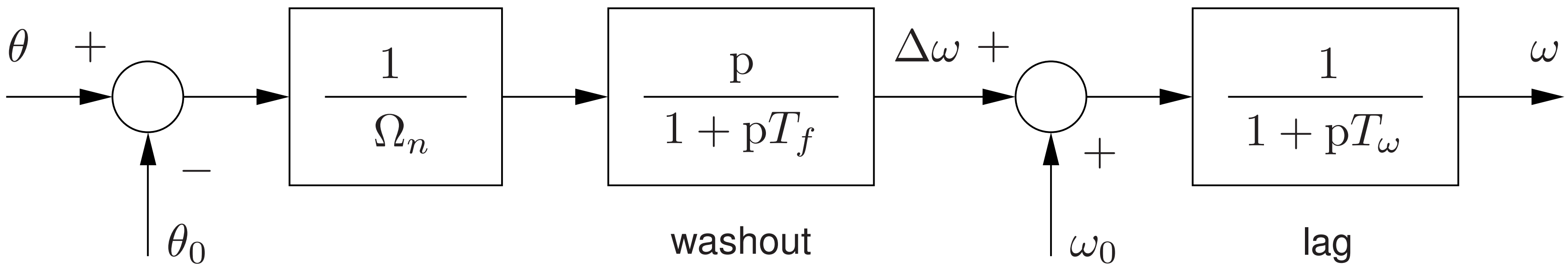
- The *center of inertia* (COI) is a weighted arithmetic average of the rotor speeds of synchronous machines that are connected to a transmission system:

$$\omega_{\text{COI}} = \frac{\sum_{j \in \mathcal{G}} H_j \omega_j}{\sum_{j \in \mathcal{G}} H_j}$$

where ω_j and H_j are the rotor speed and the inertia constant, respectively, of the synchronous machine j and $\mathcal{G}$ is the set of synchronous machines belonging to a given cluster.

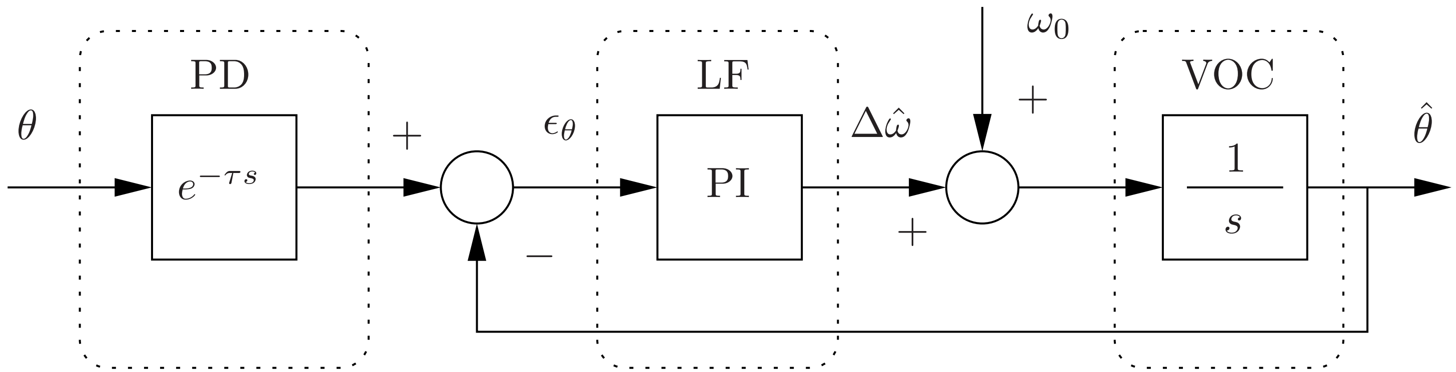
Derivative of the Bus Voltage Phase Angle (θ)

- The frequency estimation is obtained by means of a washout and a low-pass filter.
- The washout filter approximates the derivative of the input signal.
- $T_f = 3/\Omega_n$ s and $T_\omega = 0.05$ s are used as default values for all simulations.



Phase-Locked Loop

- In practice, the frequency regulated by power converter-based devices is measured locally through Phase-Locked Loop (PLL) devices.
- PLLs are used to synchronize power converters to the grid.
- PLLs consist of three parts: a phase detector (PD); a loop filter (LF); and a voltage oscillator control (VOC).
- An interesting by-product of any PLL is that the output of the LF is an estimation of the frequency deviation at the bus of connection.



Frequency Divider

Nodal Equations – I

- The very starting point is the **augmented admittance matrix**, with inclusion of synchronous machine internal impedances as it is commonly defined for fault analysis.
- System currents and voltages are linked as follows:

$$\begin{bmatrix} \bar{\boldsymbol{i}}_G \\ \bar{\boldsymbol{i}}_B \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{Y}}_{GG} & \bar{\mathbf{Y}}_{GB} \\ \bar{\mathbf{Y}}_{BG} & \bar{\mathbf{Y}}_{BB} + \bar{\mathbf{Y}}_{B0} \end{bmatrix} \begin{bmatrix} \bar{\boldsymbol{e}}_G \\ \bar{\boldsymbol{v}}_B \end{bmatrix} \tag{1}$$

where $\bar{\boldsymbol{v}}_B$ and $\bar{\boldsymbol{i}}_B$ are bus voltages and current injections, respectively, at network buses; $\bar{\boldsymbol{i}}_G$ are generator current injections; $\boldsymbol{e}_G$ are generator emfs behind the internal generator impedance; $\bar{\mathbf{Y}}_{BB}$ is the standard network admittance matrix; $\bar{\mathbf{Y}}_{GG}$, $\bar{\mathbf{Y}}_{GB}$ and $\bar{\mathbf{Y}}_{BG}$ are admittance matrices obtained using the internal impedances of the synchronous machines; and $\bar{\mathbf{Y}}_{B0}$ is a diagonal matrix that accounts for the internal impedances of the synchronous machines at generator buses.

Nodal Equations – II

- All quantities in (1) depend on the frequency.
- However, **the dependency of the admittance matrices above on the frequency is neglected.**
- To further elaborate on (1), let us assume that **load current injections $\bar{\boldsymbol{i}}_B$ can be neglected** (the equivalent load admittance, in transmission systems, is typically one order of magnitude smaller than that of the diagonal elements of $\bar{\mathbf{Y}}_{BB} + \bar{\mathbf{Y}}_{B0}$):

$$\begin{bmatrix} \bar{\boldsymbol{i}}_G \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{Y}}_{GG} & \bar{\mathbf{Y}}_{GB} \\ \bar{\mathbf{Y}}_{BG} & \bar{\mathbf{Y}}_{BB} + \bar{\mathbf{Y}}_{B0} \end{bmatrix} \begin{bmatrix} \bar{\boldsymbol{e}}_G \\ \bar{\boldsymbol{v}}_B \end{bmatrix} \tag{2}$$

- **Bus voltages $\bar{\boldsymbol{v}}_B$** are thus a function of generator emfs and **can be computed explicitly:**

$$\begin{aligned} \bar{\boldsymbol{v}}_B &= -[\bar{\mathbf{Y}}_{BB} + \bar{\mathbf{Y}}_{B0}]^{-1} \bar{\mathbf{Y}}_{BG} \bar{\boldsymbol{e}}_G \\ &= \bar{\mathbf{D}}\, \bar{\boldsymbol{e}}_G \end{aligned} \tag{3}$$

Assumptions and Hypotheses

- The quasi-steady-state phasor can be approximated, during an electromechanical transient, to the dq-frame quantity.
- Variations of the frequency are “slow” when considering electromechanical power system model for transient stability analysis.
- Parameters of transmission system, loads and generator are constant.
- $\bar{\boldsymbol{v}}_B \approx \mathbf{1}$ pu and $\bar{\boldsymbol{e}}_G \approx \mathbf{1}$ pu;
- The conductances of the elements of all admittance matrices utilized to compute $\bar{\mathbf{D}}$ are negligible, e.g., $\bar{\mathbf{Y}}_{BB} \approx j\mathbf{B}_{BB}$;
- **All simplifications above are motivated by usual assumptions and typical parameters of transmission systems.**

Frequency Divider Formula

- All previous assumptions lead to **the proposed frequency divider formula**:

$$\boxed{\omega_B = \mathbf{1} + \mathbf{D}(\omega_G - \mathbf{1})} \quad (4)$$

where

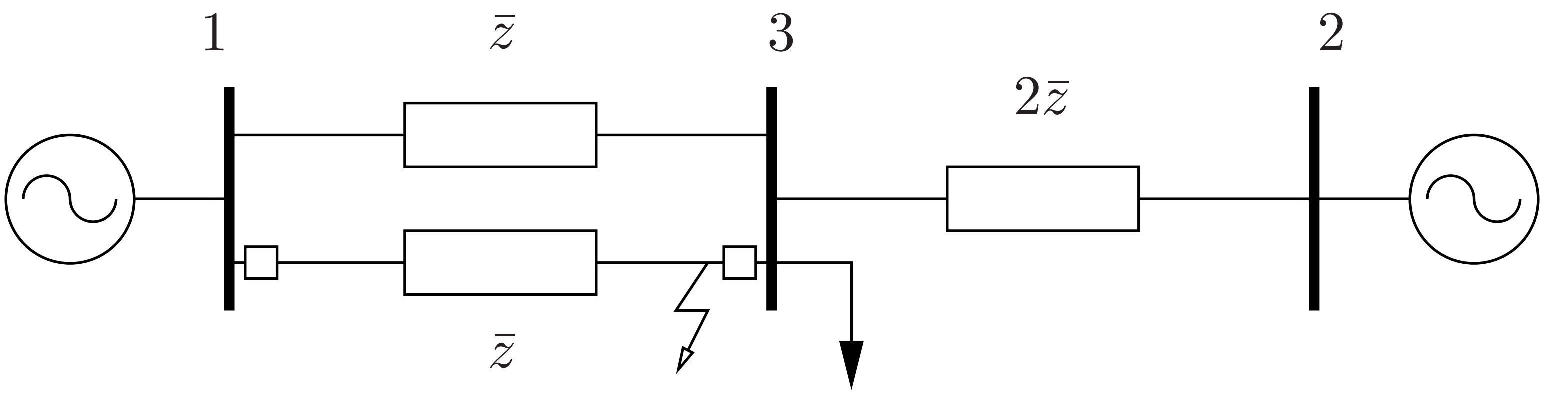
$$\mathbf{D} = -(\mathbf{B}_{BB} + \mathbf{B}_{B0})^{-1}\mathbf{B}_{BG} \quad (5)$$

- The formula has the same formal structure of voltage dividers in resistive dc circuits.
- The frequency divider formula can be easily modified to include frequency measurements as provided, for example, by PMU devices.

Examples

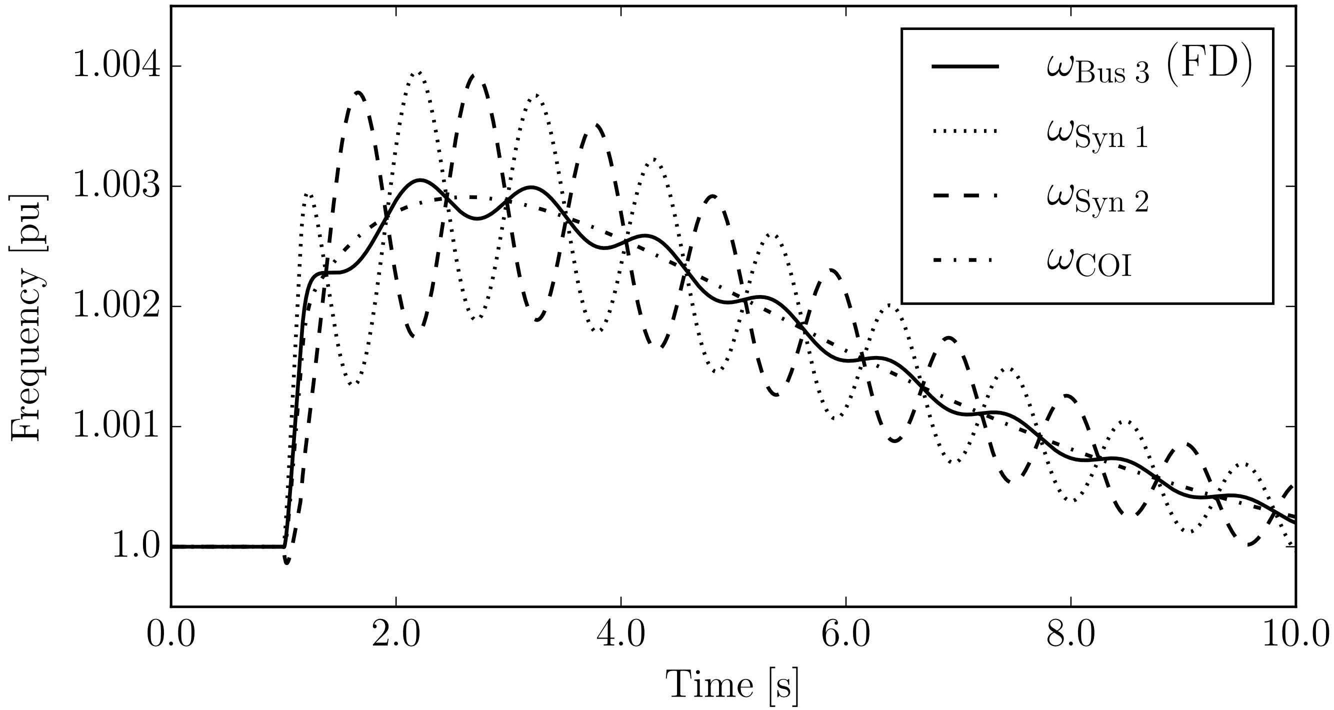
Example – I

- Let's first consider a standard model for transient stability analysis where transmission lines are lumped and modeled as constant impedances and generator flux dynamics are neglected.
- **Generators are equal and are modeled as a 6th order** synchronous machine with AVRs and turbine governors.
- **The load is modeled as a constant admittance. The disturbance is a three-phase fault** that occurs at bus 3 at $t = 1$ s and is cleared after 150 ms by **opening one of the two lines connecting buses 1 and 3.**



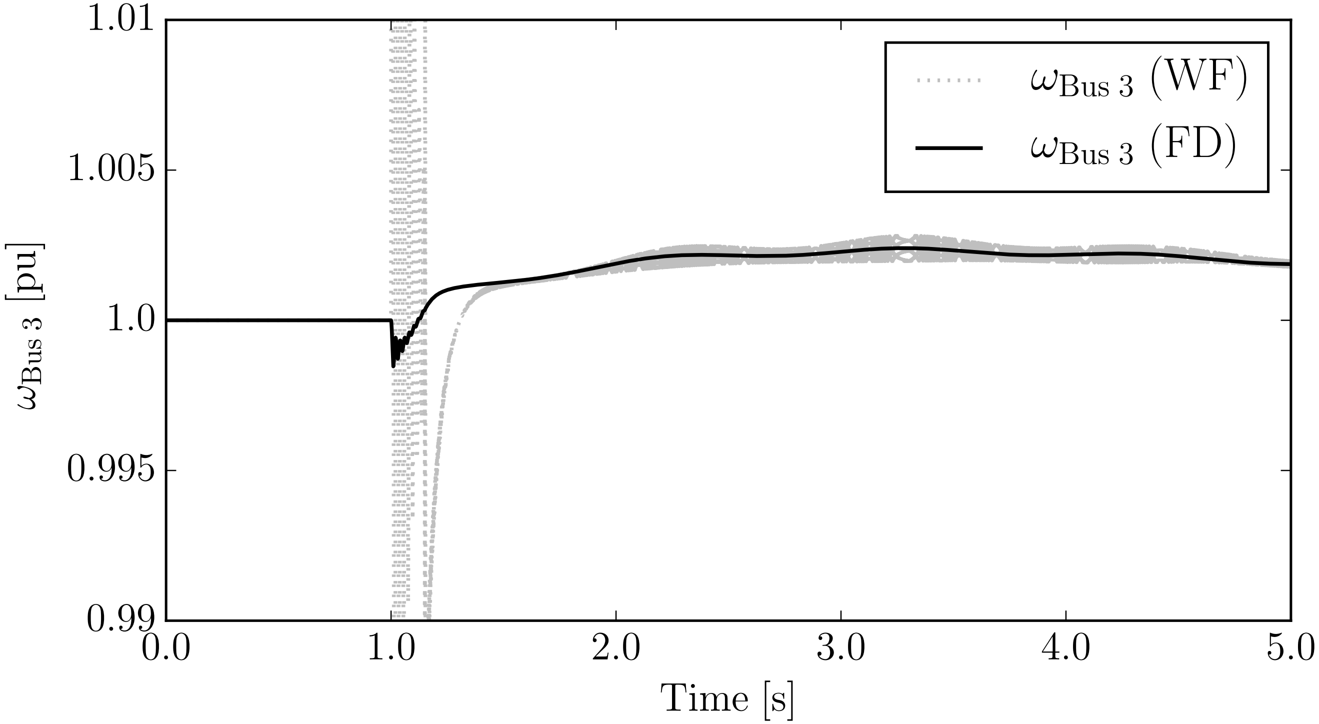
Example – II

- Transient behavior of synchronous machine rotor speeds, the frequency of the COI (ω_{COI}), and the estimated frequency at the load bus using the proposed frequency divider approach.



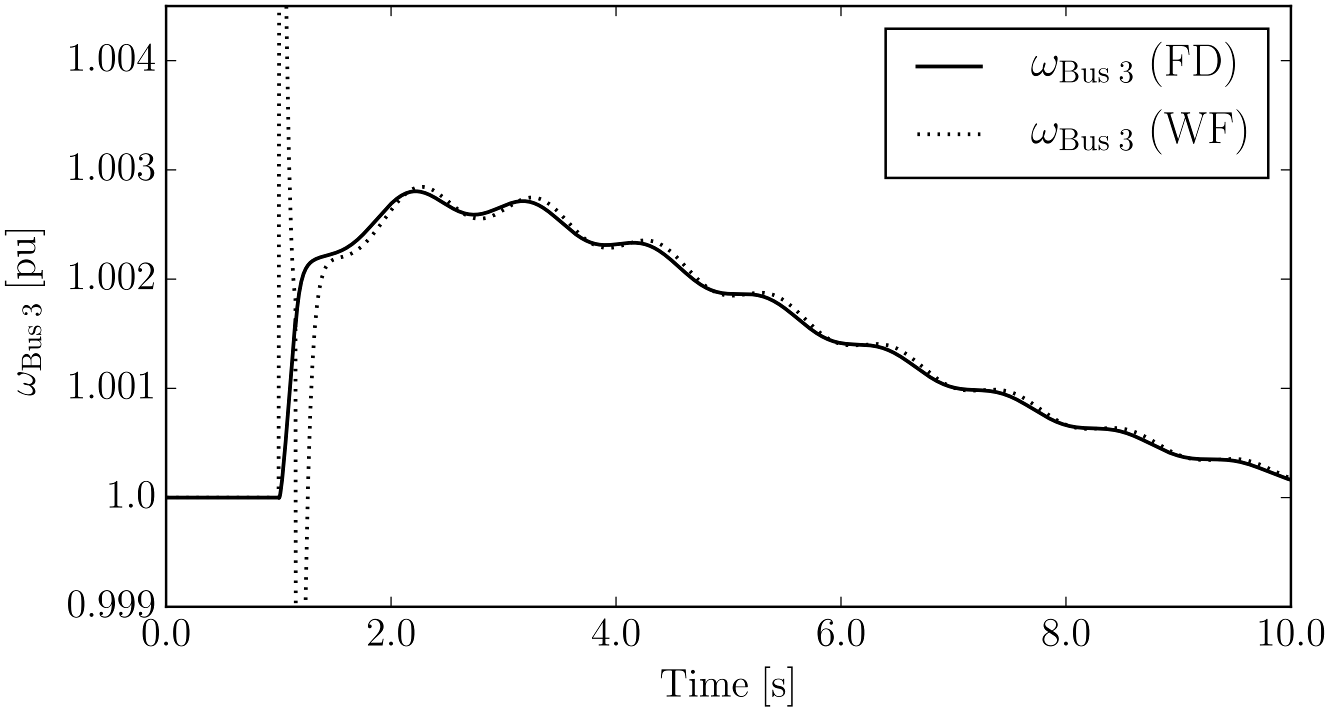
Example – III

- Frequency at bus 3 estimated with the frequency divider (FD) and the conventional washout filter (WF). **The system is simulated using the fully-fledged dq-axis model.**



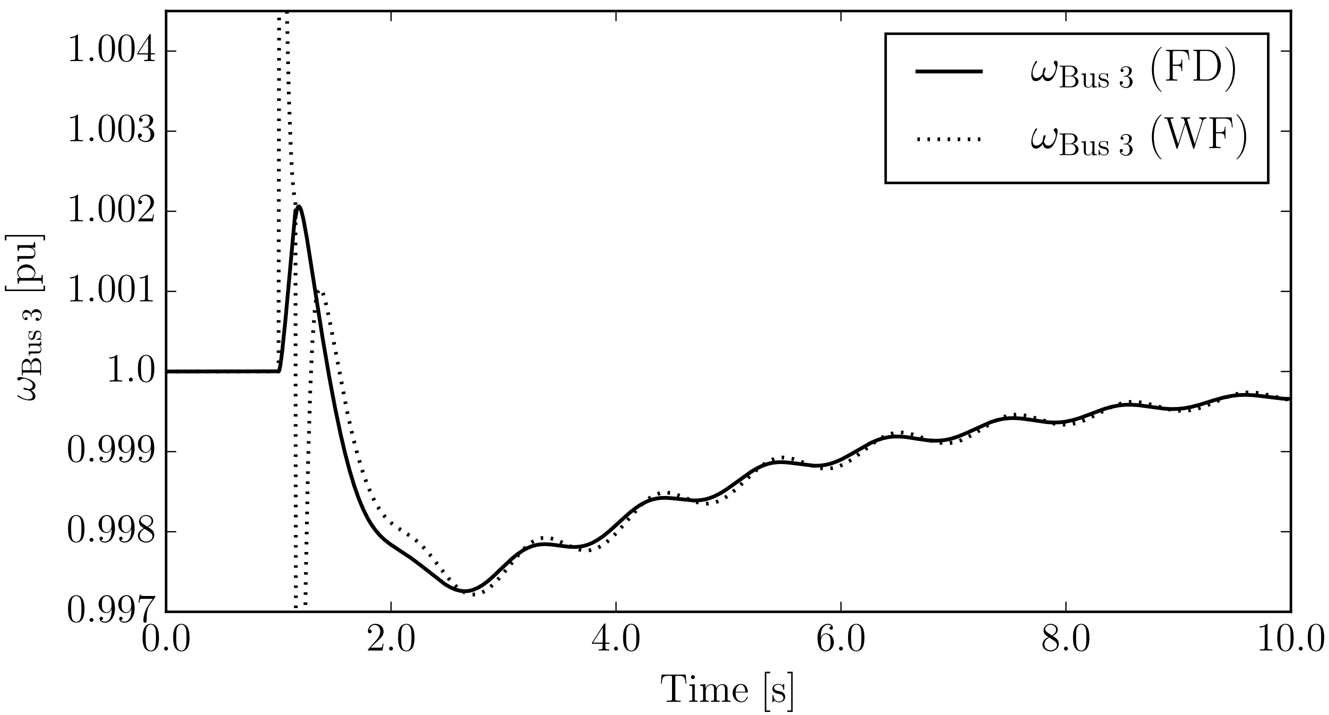
Example – IV

- Frequency at bus 3 estimated with the frequency divider (FD) and the conventional washout filter (WF). The load is modelled as a **frequency-dependent load** representing an aluminum plant



Example – V

- Frequency at bus 3 estimated with the frequency divider (FD) and the conventional washout filter (WF). The load is a **squirrel cage induction motor** with a 5th-order dq-axis model.

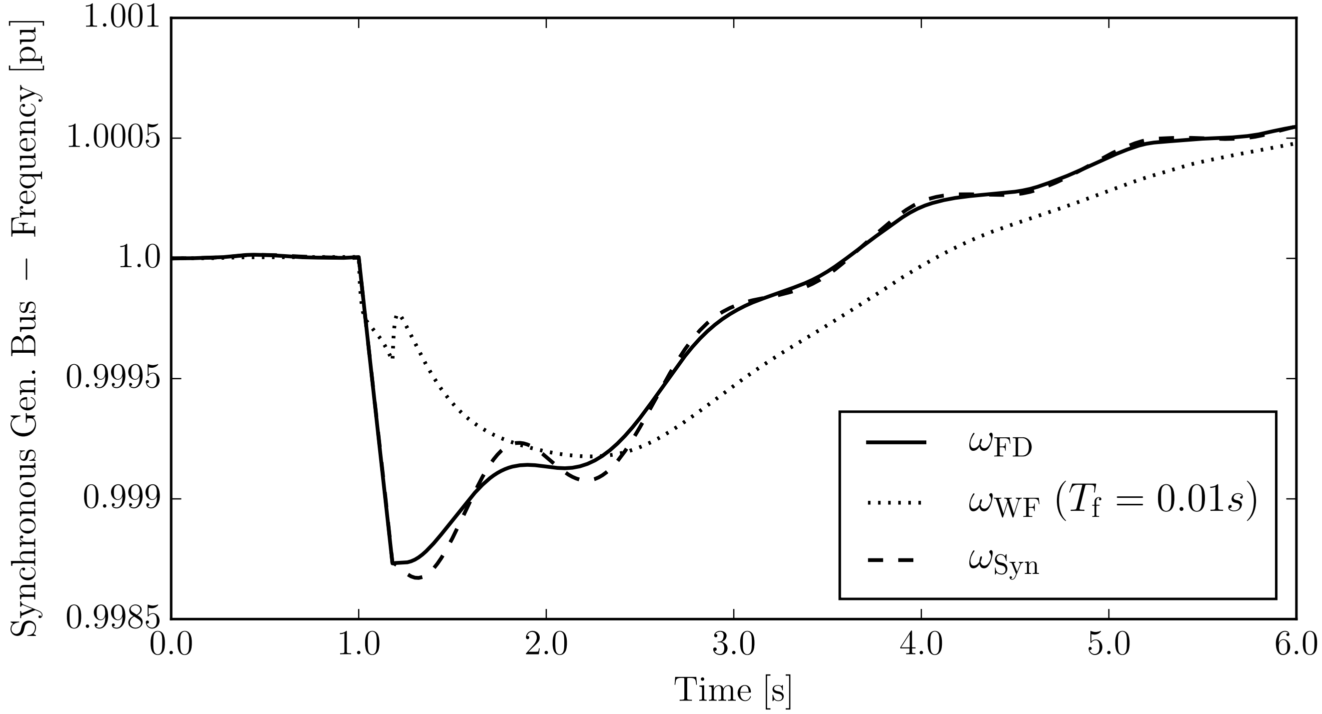


Irish Transmission System – I

- This system includes 1,479 buses, 1,851 transmission lines and transformers, 245 loads, 22 conventional synchronous power plants modeled with 6th order synchronous machine models with AVRs and turbine governors, 6 PSSs and 176 wind power plants, of which 34 are equipped with constant-speed (CSWT) and 142 with doubly-fed induction generators (DFIG).
- The **large number of non-conventional generators based on induction machines and power electronics converters** makes this system an excellent test-bed to check the accuracy of the proposed frequency divider.

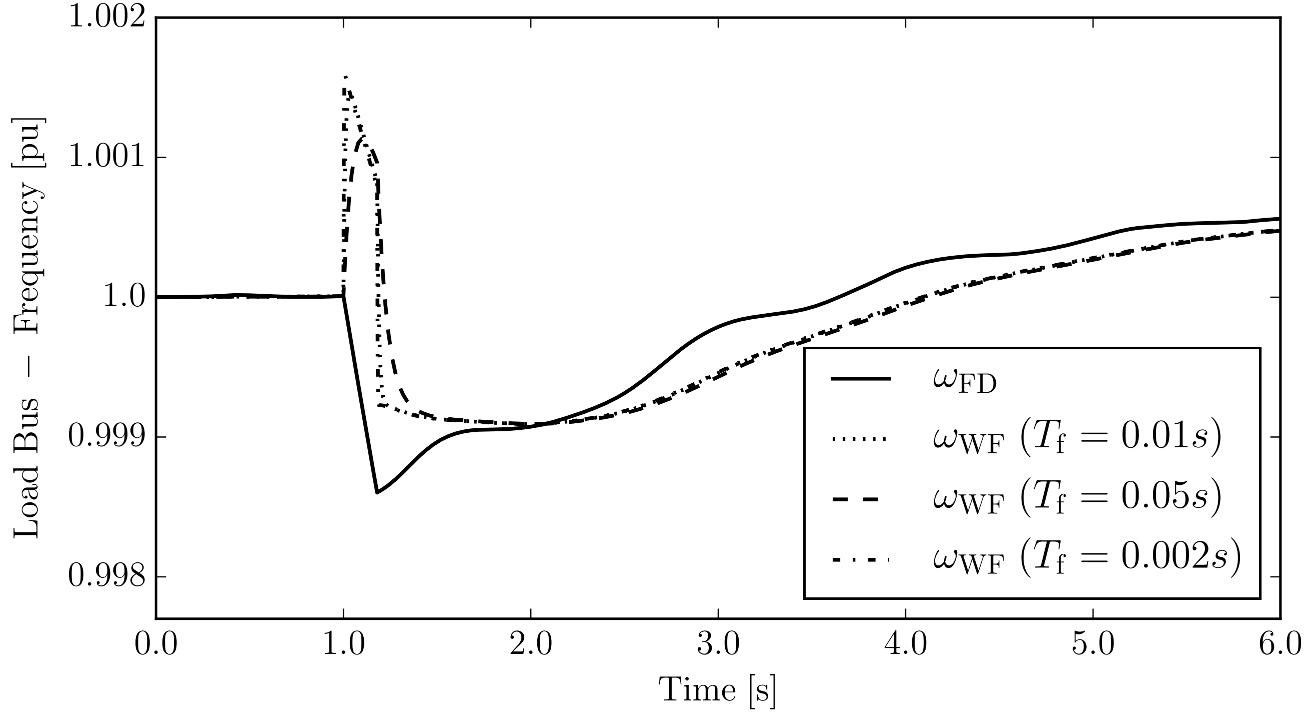
Irish Transmission System – II

- Fault close to a synchronous machine and a load. Frequency at the generator bus.



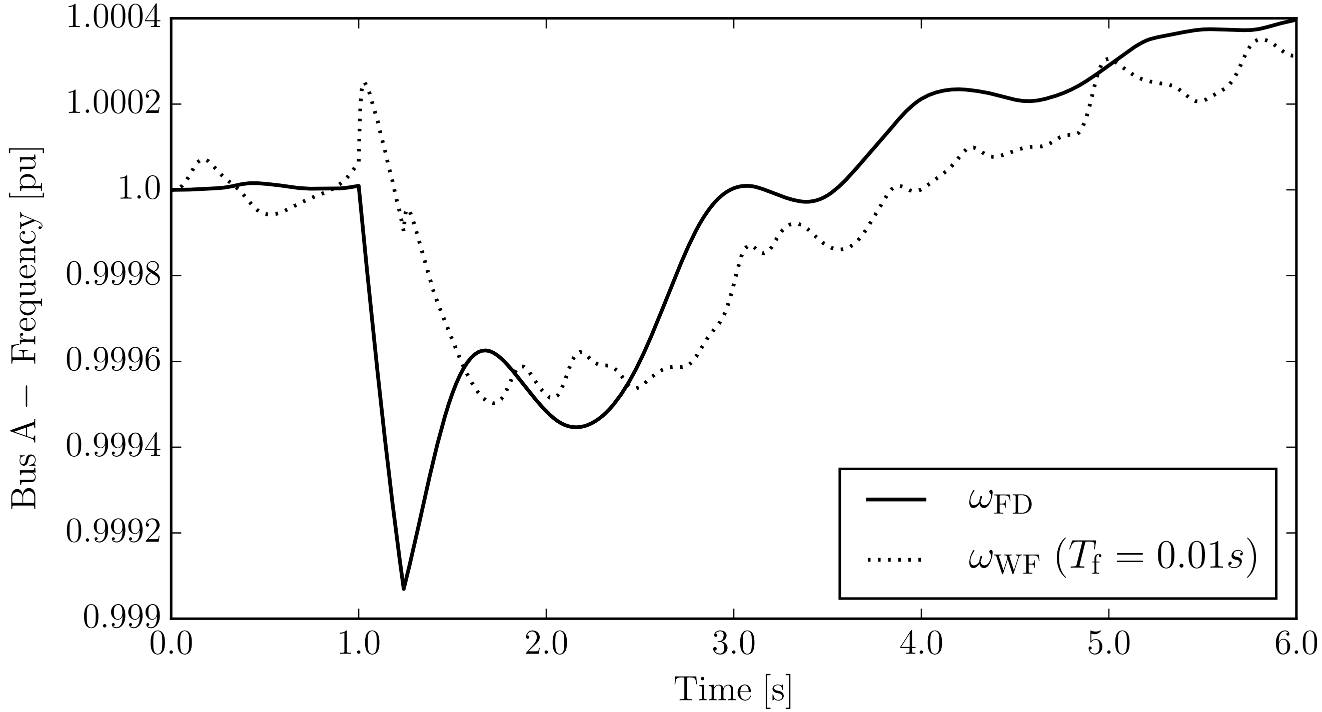
Irish Transmission System – III

- Fault close to a synchronous machine and a load. Frequency at the load bus.



Irish Transmission System – IV

- Frequency response of the Irish transmission system facing a three-phase fault close to a wind power plant.

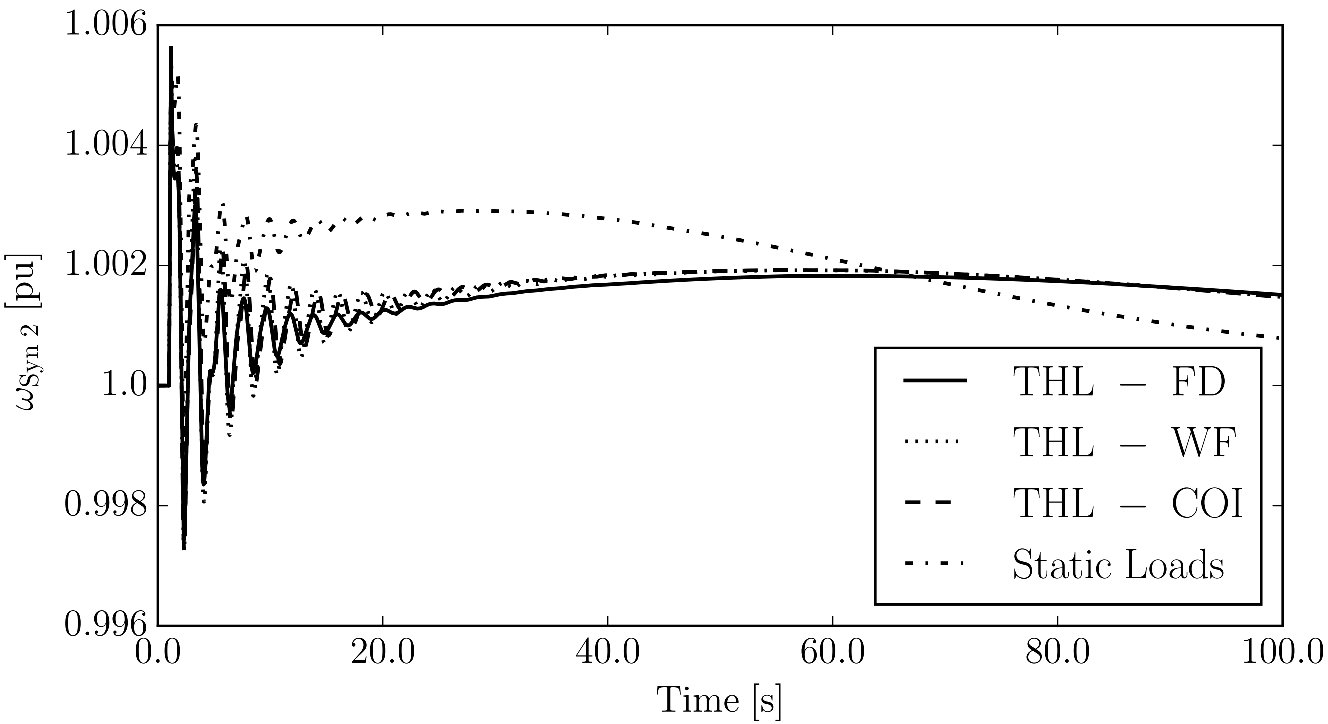


New England 39-bus, 10-machine System – I

- This benchmark network contains 19 loads totaling $7,316.5$ MW and $1,690.9$ MVAr of active and reactive power, respectively (20% load increase with respect to the base case is assumed).
- The system model also includes generator controllers such as primary voltage regulators, as well as both primary and secondary frequency regulation (turbine governors and AGC).
- The system includes also **thermostatically controlled loads, which are the 20% of the total load.**
- The **contingency is a three-phase fault** at bus 21, **cleared by the opening of the line** connecting buses 16 and 21 after 160 ms.

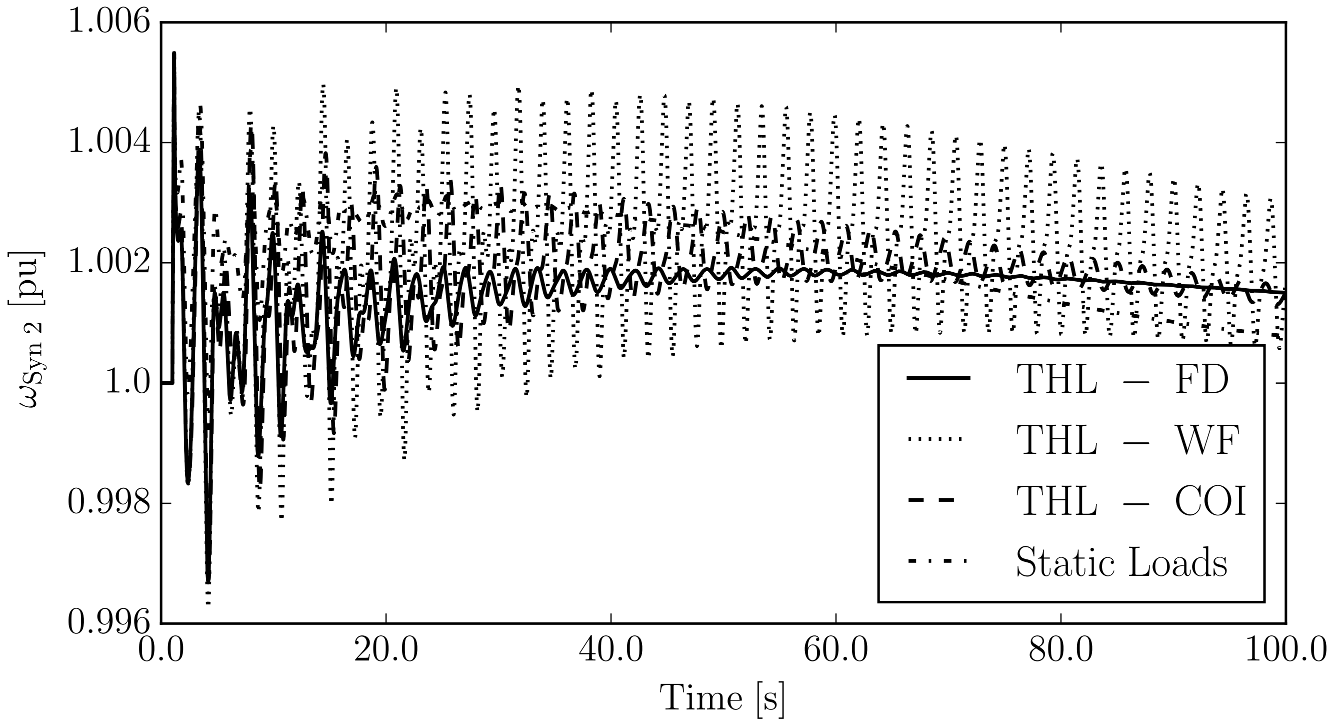
New England 39-bus, 10-machine System – II

- Rotor speed of the synchronous generator in bus 31 (Gen 2) using 3^{rd} **order synchronous machine models.**



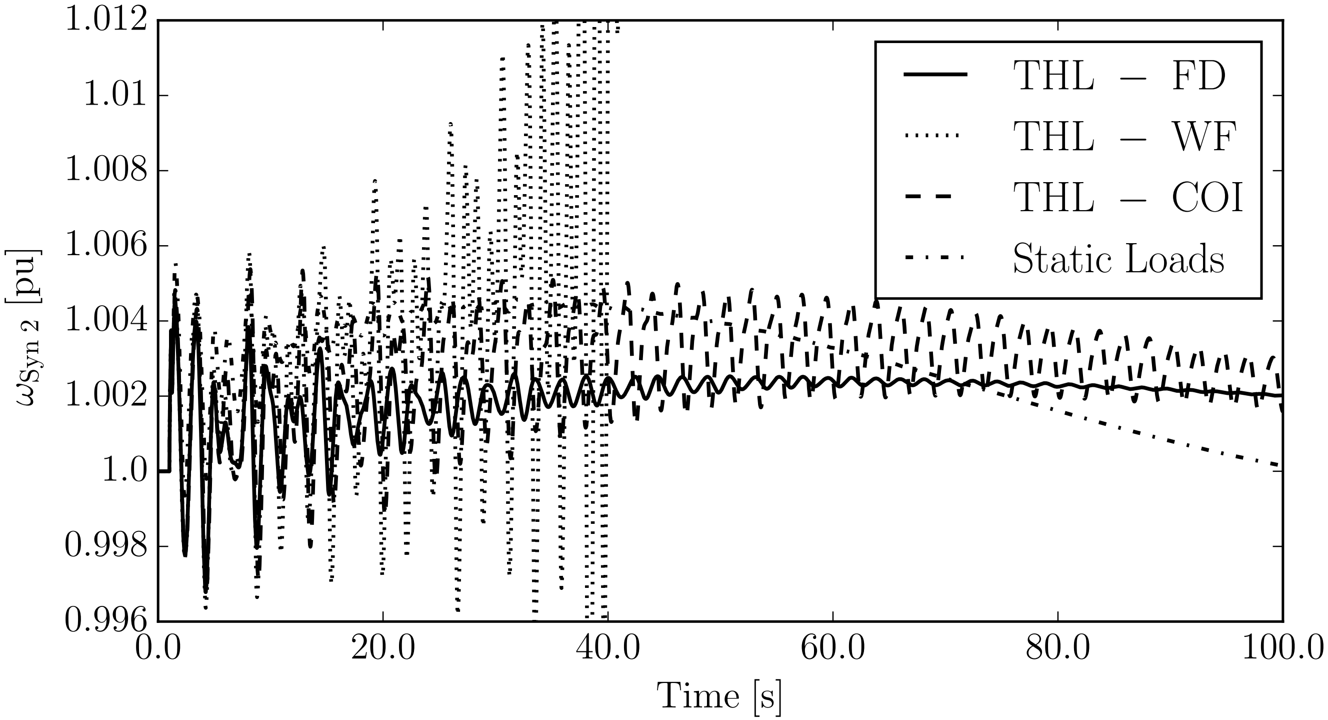
New England 39-bus, 10-machine System – III

- Rotor speed of the synchronous generator in bus 31 (Gen 2) using 6^{th} **order synchronous machine models.**



New England 39-bus, 10-machine System – IV

- Rotor speed of the synchronous generator in bus 31 (Gen 2) using 8^{th} **order synchronous machine models.**



ENTSO-E Transmission System – I

- The model includes 21,177 buses (1,212 off-line); 30,968 transmission lines and transformers (2,352 off-line); 1,144 coupling devices, i.e., zero-impedance connections (420 off-line); 15,756 loads (364 off-line); and 4,828 power plants.
- Of these power plants, 1,160 power plants are off-line. The system also includes 364 PSSs.

ENTSO-E Transmission System – II

- Size and number of non-zeros (NNZ) elements of matrices $\mathbf{B}_{BB}$, $\mathbf{B}_{G0}$, $\mathbf{B}_{BG}$ and $\mathbf{D}$ for the ENTSO-E system.

Matrix	Size	NNZ	NNZ $\%$
$\mathbf{B}_{BB}$	$21,177 \times 21,177$	$72,313$	0.0161
$\mathbf{B}_{BG}$	$21,177 \times 4,832$	$4,832$	0.0047
$\mathbf{B}_{G0}$	$21,177 \times 21,177$	$3,245$	0.0007
$\mathbf{B}_{BB} + \mathbf{B}_{G0}$	$21,177 \times 21,177$	$72,313$	0.0161
$\mathbf{D}$	$21,177 \times 4,832$	$86,169,456$	84.2

$$\mathbf{D} = -(\mathbf{B}_{BB} + \mathbf{B}_{B0})^{-1}\mathbf{B}_{BG} \tag{6}$$

ENTSO-E Transmission System – III

- **The inverse of a sparse matrix can be very dense . . .**
- . . . and trying to actually compute $\mathbf{D}$ leads to memory overflow for the ENTSO-E system!
- Hence, the most efficient implementation of the frequency divider formula is the **following *acausal* expression:**

$$\mathbf{0} = (\mathbf{B}_{BB} + \mathbf{B}_{G0}) \cdot (\boldsymbol{\omega}_B - \mathbf{1}) + \mathbf{B}_{BG} \cdot (\boldsymbol{\omega}_G - \mathbf{1})$$

Conclusions, Future Work

and References

Conclusions (for now . . .)

- A general expression to estimate frequency variations during the transient of electric power systems has been deduced.
- The proposed expression is derived based on standard assumptions of power system models for transient stability analysis and can be readily implemented in power system software tools for transient stability analysis.
- The formula is aimed at improving the accuracy of bus frequency estimation in traditional electromechanical power system models.
- Simulation results show that the proposed formula is accurate, numerically robust and computationally efficient.

Open Challenges

- How to take into account fast flux transients and wave propagation?
- Effect of loads?
- What if there is **no** synchronous machine?
- Thorough testing is required . . .
- PMU measurements are needed!

References

- F. Milano, Á. Ortega, *Frequency Divider*, IEEE Transactions on Power Systems, vol. 32, no. 2, pp. 14931501, March 2017.
- Á. Ortega, F. Milano, *Comparison of Bus Frequency Estimators for Power System Transient Stability Analysis*, IEEE PowerCon, Wollongong, Australia, September 28th – October 1st, 2016.

Horizon 2020 Project

- RE-SERVE – *Renewables in a Stable Electric Grid*
- 3 years, started on the 1st of October, 2016
- Work Package 2 (leader UCD): Frequency stability analysis
  - Novel frequency controls based on non-synchronous generation
  - Modelling freqeuncy variations in transient stbaility models
  - Angle and frequency stability for system with low inertia
  - 5G telecommincation technology
  - Recommendation to ISOs re frequency regulation

Thanks much for your attention!