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Synchrophasor Applications Facilitating Interactions between Transmission and Distribution Operations

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- SUPPORT -

COOPERATION

Thank you!

- Four years of sharing with us!
- Brazil has an enormous heart:
  - It’s the ***generosity*** of it’s people!

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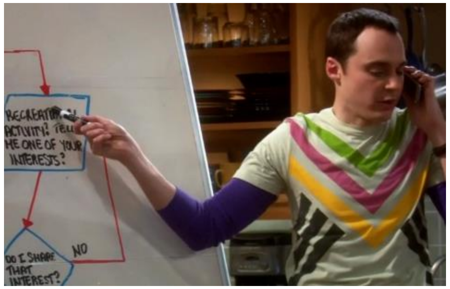
COOPERATION

Outline

- Introduction: PMUs in distribution networks?
- PMU Application Use Case Definition using SGAM
- Methods and Tools
  - Development, Implementation and Testing using RT-HIL Simulation
  - The Reference Distribution Grid Model
- Handling PMU Data:
  - PMU Data Feature Extraction
- Applications:
  - Steady State Model Synthesis
  - Dynamic Line Rating for Distribution Feeders
  - Small-Signal Dynamic Analysis
- Conclusions

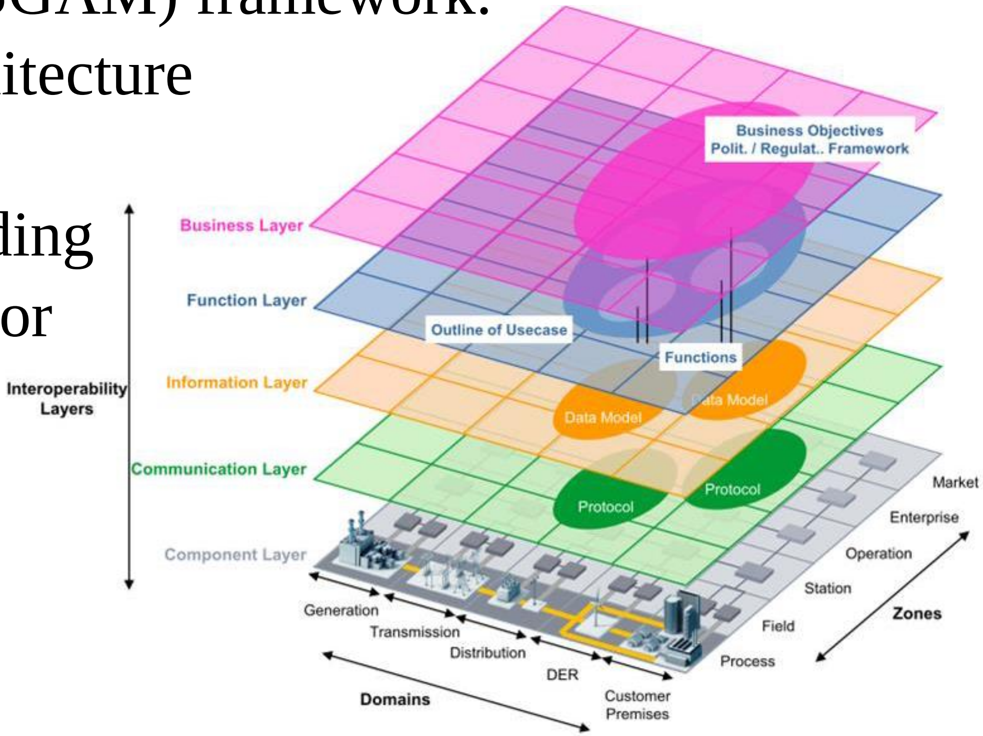
Introduction (1/2)

- It is becoming necessary to increase observability between T&D grids, because of emerging dynamics active distribution networks due to renewables
  - Fast changing conditions in the network
  - Fast behavior of components
  - Traditional monitoring technology not capable of satisfying requirements: types of signals, time-synchonization and speed of data acquisition
- There is great potential of utilizing real-time Synchrophasor data from PMUs (Phasor Measurement Unit) to extract key information related to fast changing conditions and dynamic behavior.
- The implementation of such PMU-based “information exchange” has to go through a properly designed and implemented architecture.



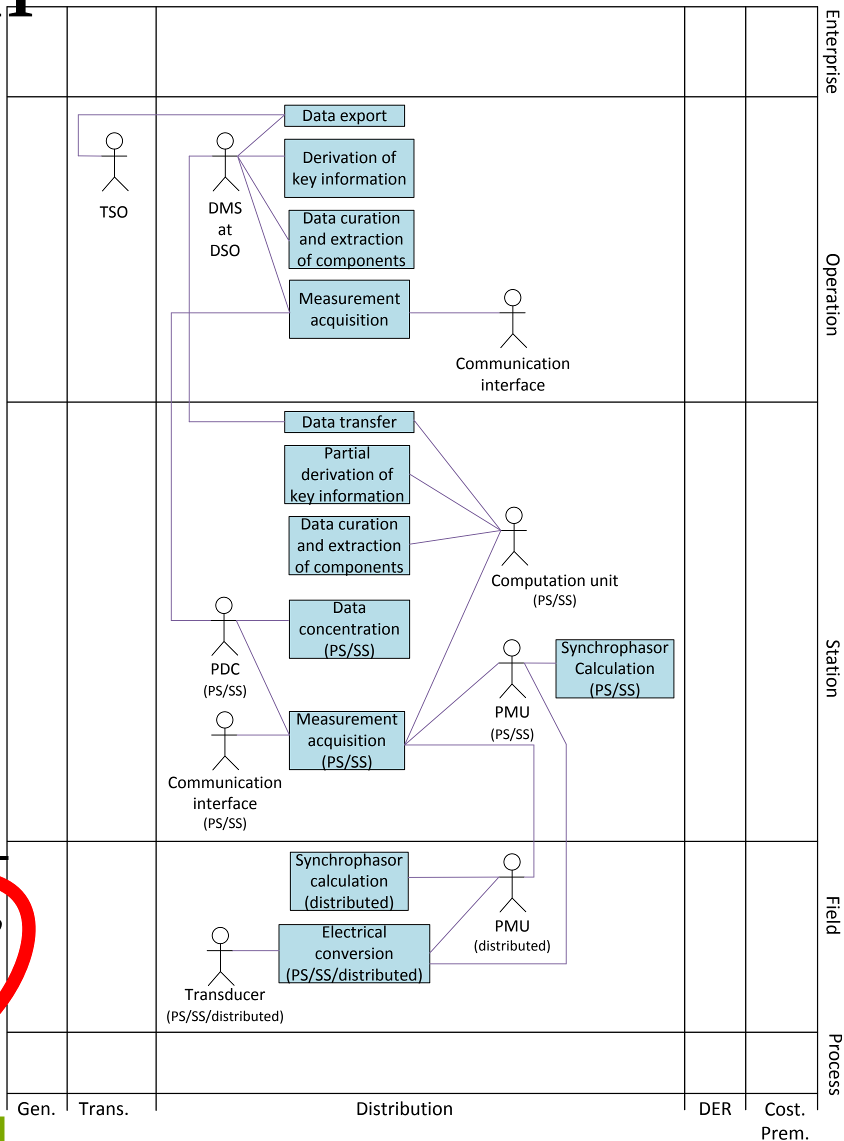
Introduction (2/2)

- The IDE4L architecture is built upon the 5-layer Smart Grid Architecture Model (SGAM) framework.
- The main inputs to the architecture design are the use cases.
- The IDE4L use case, including the PMU-based functions for dynamic information extraction, is presented in this presentation.



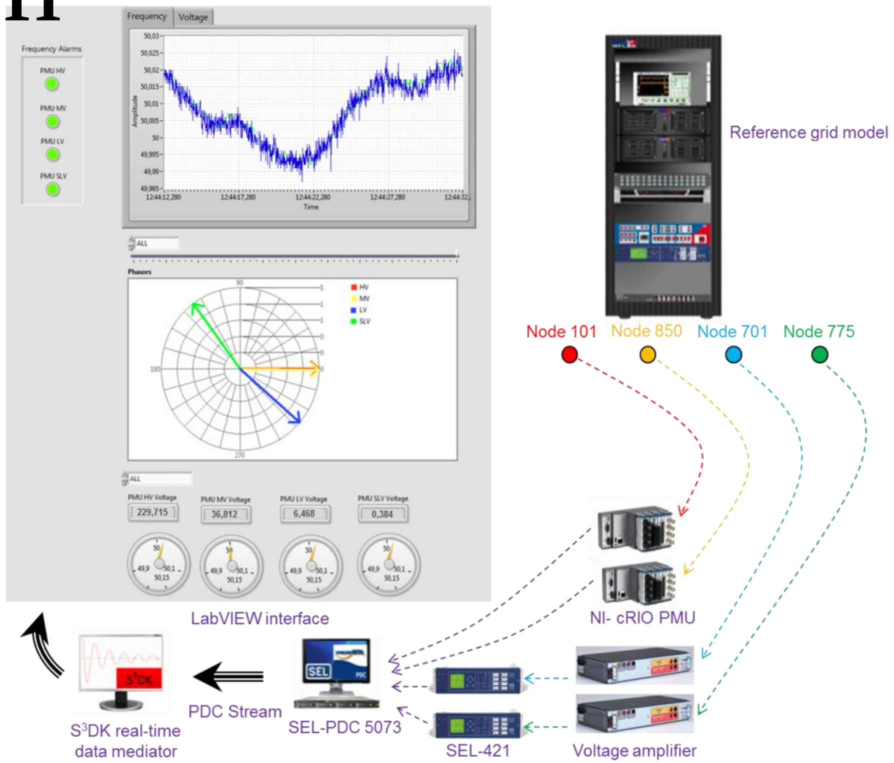
Use Case Definition

- Data flows from PMUs => PDC => Super PDC => DMS computers (where dynamic information is extracted) => TSO.
- Data processing and information derivation can occur at both the station (partially) and the operation (i.e. DMS computers) zones.
- Actors: Instrumentations, PMU, PDC, communication interface, DMS, and TSO
- Functions: electrical conversion, synchrophasor calculation, data acquisition, data concentration and time-alignment, data exporting, data curation, extraction of different time-scale components of the data, and derivation of key information out of the data.



Development, Implementation and Testing using RT-HIL Simulation

- The development of the applications has been carried out using real-time hardware-in-the-loop simulation consisting of:
  - A real-time simulation model of active distribution networks.
  - The real-time simulation model is interfaced with PMUs in HIL.
  - PMU data is streamed into a computer workstation through PDC.



  - The computer makes available software development tools within the LabVIEW environment.
  - All data acquisition chain is carried out using the corresponding PMU standards.

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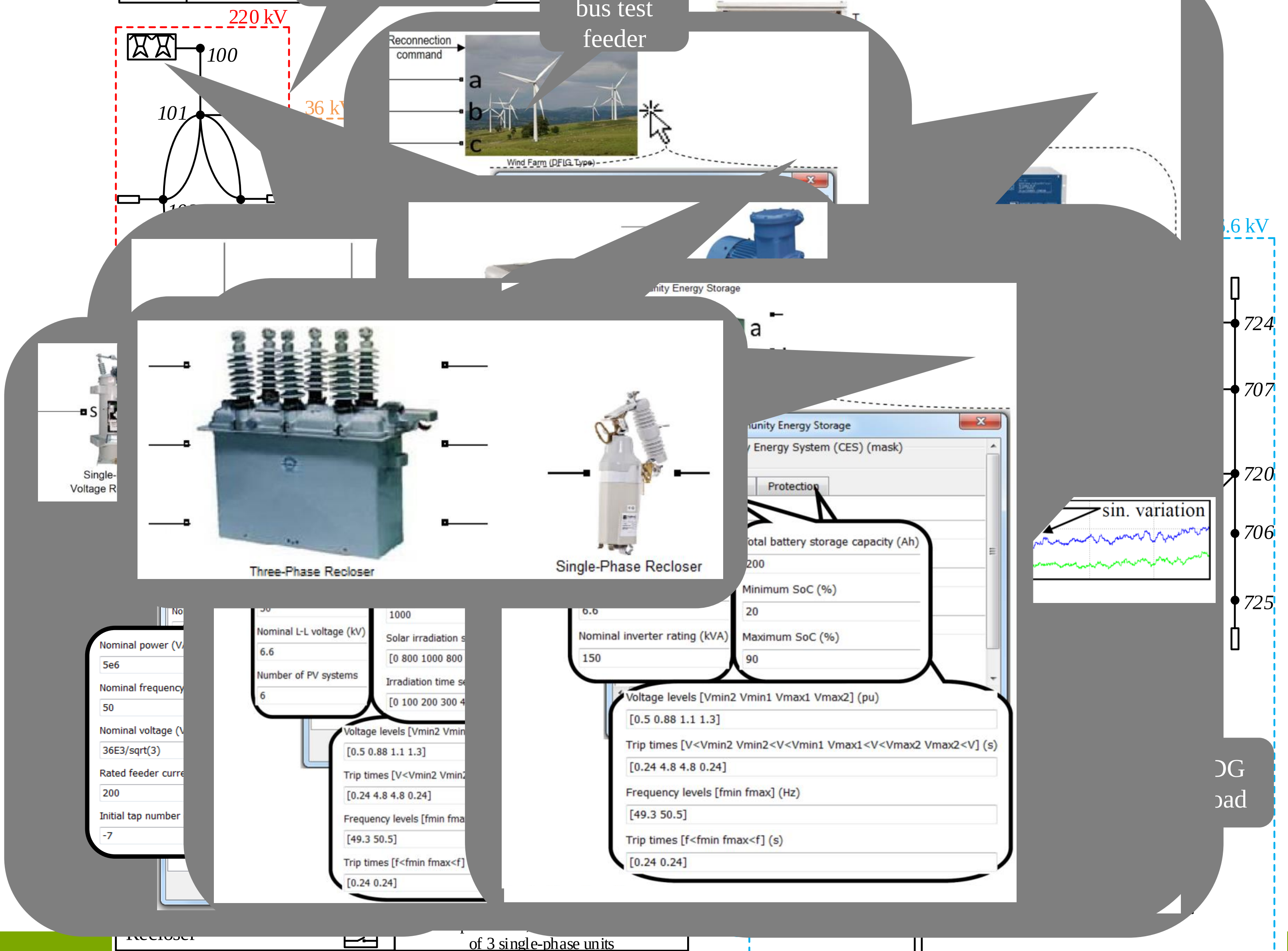
The Reference Distribution Grid Model (1/2)

	Rated Voltage	No. of buses	Number of branches
HV	220 kV	6	7 three-phase
MV	36 kV	[illegible]	[illegible]ree-phase, 8 single-phase
LV	6.6 kV	[illegible]	39 three-phase
RLV	0.4 kV	[illegible]	1 t[illegible]

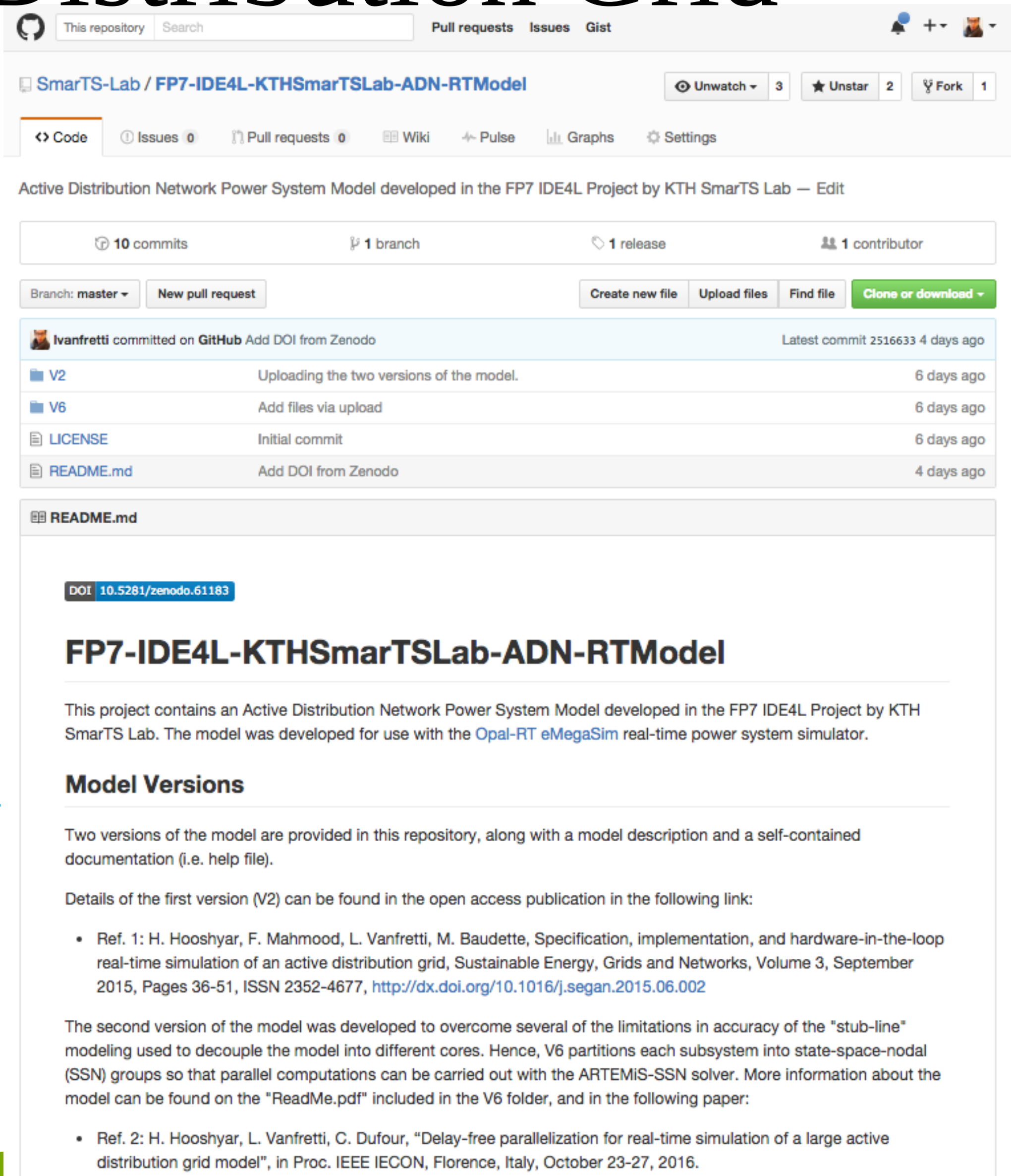


The Reference Distribution Grid Model (2/2)

- Runs on 4 cores using the State-Space-Nodal (SSN) solver with time-step of 100μs.
- The two different implementations of the grid model can be downloaded from the KTH SmarTS Lab Github repository at

  https://github.com/SmarTS-Lab/FP7-IDE4L-KTHSmarTSLab-ADN-RTModel

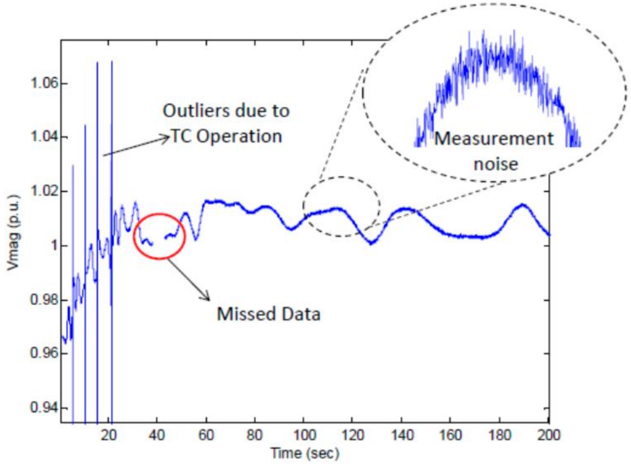
- The SSN implementation is also available in the ARTEMiS 7.0.5 demo section.



PMU Data Curation, Extraction of Different Time-Scale Components of the Data

(Data Processing)

PMU Data Processing



- PMU measurements are normally
- polluted with
  - Undesirable noise
  - Outliers
  - Missing data
- Measurements obtained from PMUs during different events in power systems contain different signal features at different time scales, i.e. features of different types of power system dynamics.
- So before being fed to the applications:
  - PMU measurements should be curated.
  - Signals required for each application should be extracted from the PMU measurements.

PMU Data Processing (2/3)

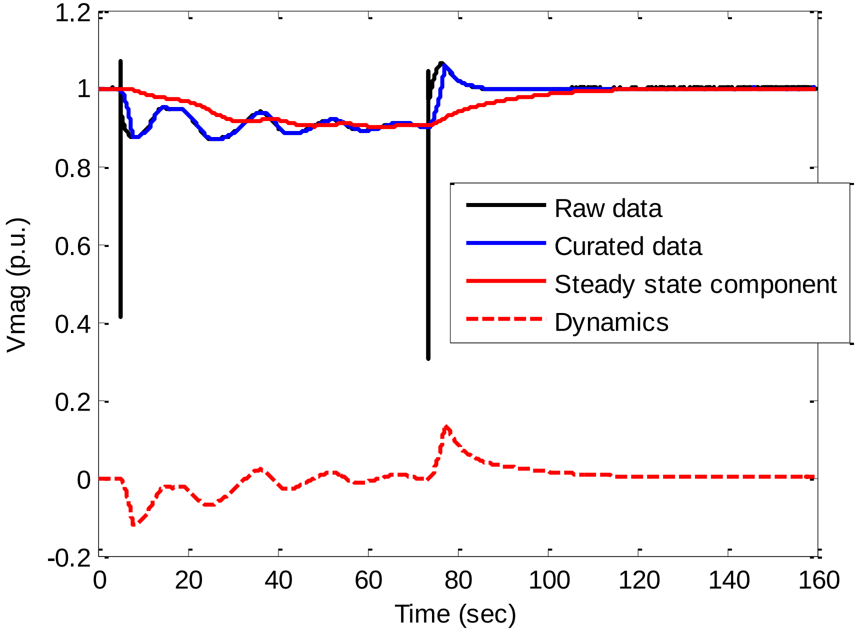
- An enhanced Kalman filtering technique has been utilized for both bad data removal, i.e. data curation, and extraction of the proper signal feature from the PMU data.

Step		Equation	Significance
1	**Prediction**	$\hat{x}_k^- = A\hat{x}_{k-1}^- + Bu_k$	Project the state ahead.
2		$P_k^- = AP_{k-1}A^T + Q$	Project the error covariance ahead.
3	**Correction**	$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$	Compute the Kalman gain.
4		$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-)$	Update estimate with measurement z_k.
5		$P_k = (I - K_k H)P_k^-$	Update the error covariance.

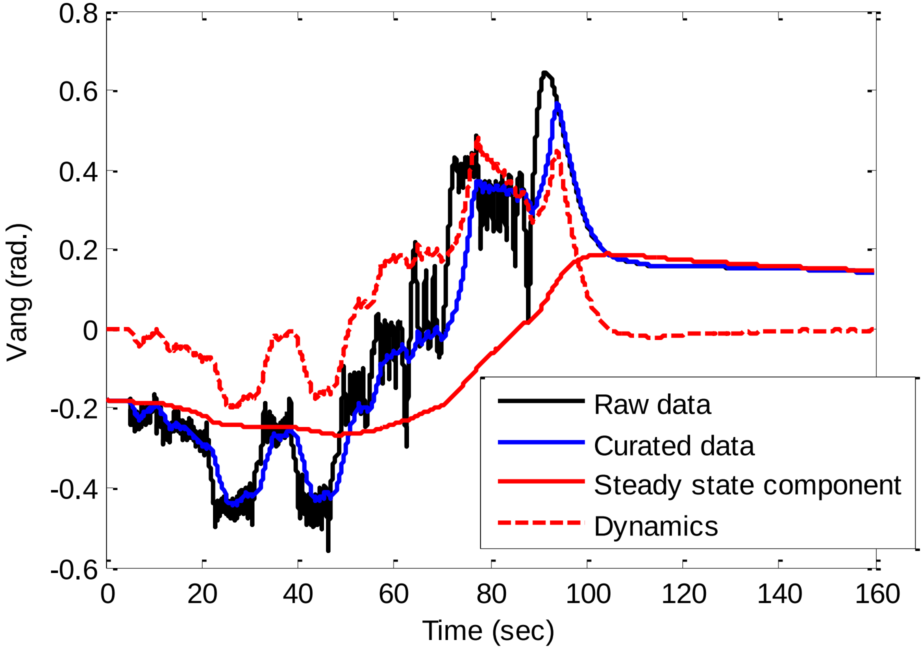
- R and Q (the measurement and process noise covariance matrices), can be updated in real-time to perform the data processing.

PMU Data Processing (3/3)

- Sample results.



voltage magnitude (per unit)



voltage angle (radian)

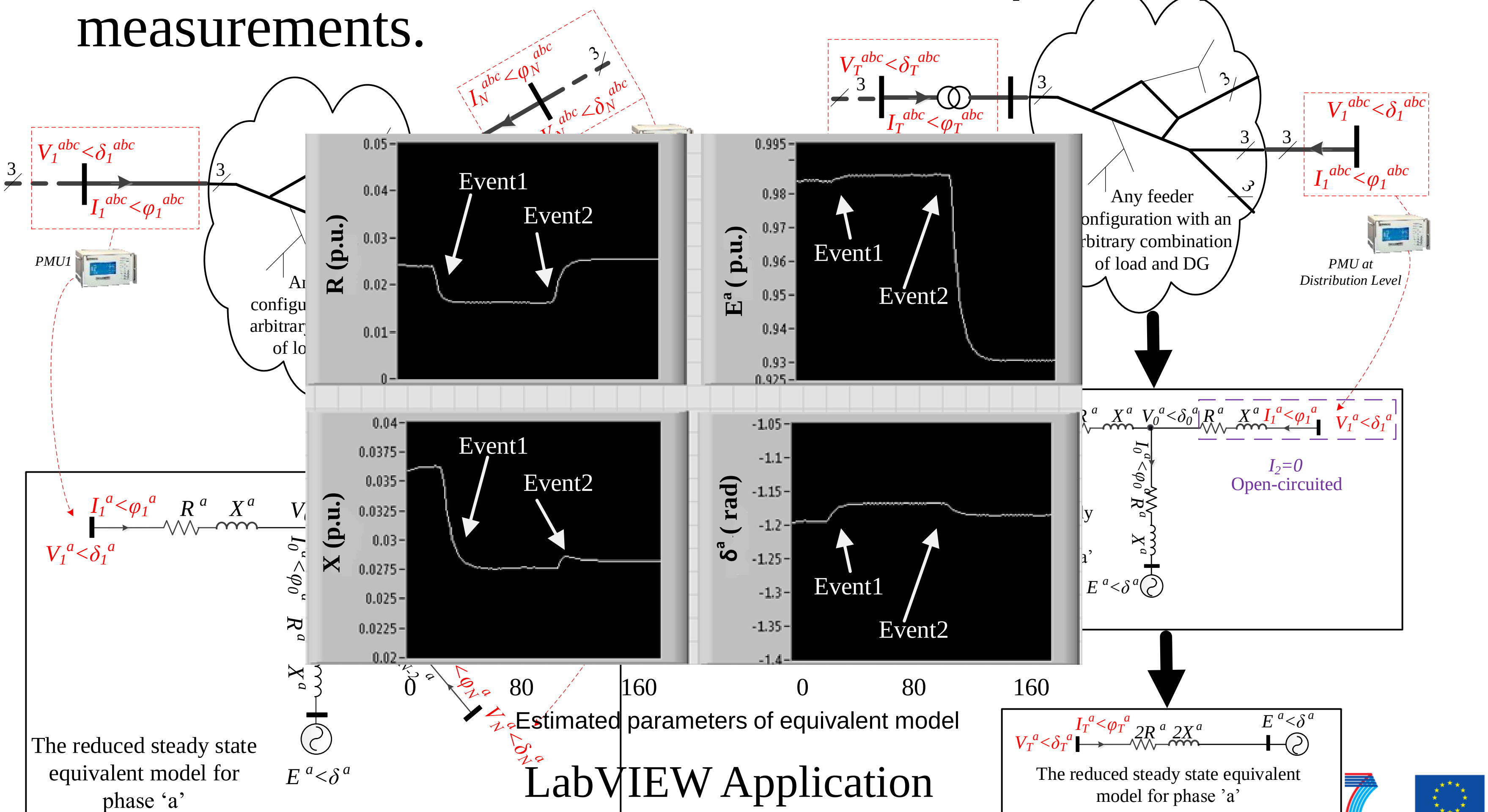
Real-Time Steady State Model Synthesis of Distribution System

Background

- Currently, TSOs maintain reduced models of portions of the distribution networks, however:
  - The models covers limited portions of the distribution network due to the lack of network observability (measurement points) and computational burden associated with simulating large joint T&D models.
  - The models are not updated frequently.
  - The reduction methods, used by TSOs, often make assumptions that are no longer valid for active distribution networks.

Methodology and Application

- Model parameters are obtained by writing KVL equations across the model branches and equate V_i's and I_i's to PMU measurements.

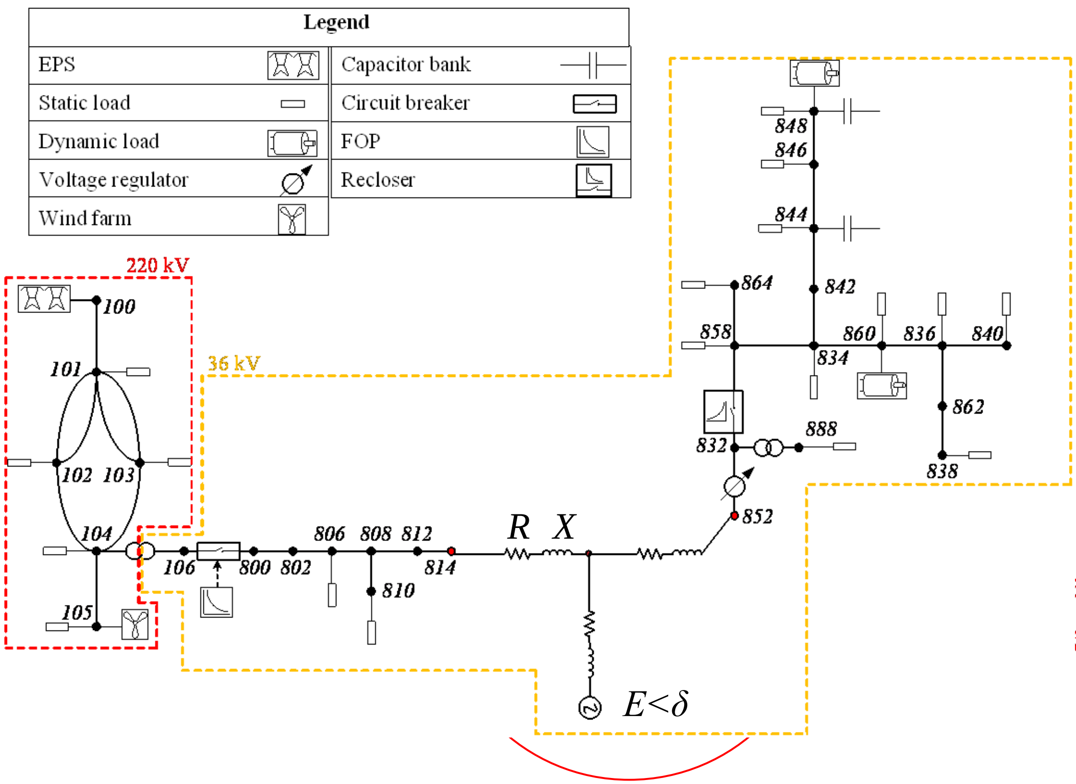


With *N* available PMUs

With *1* available PMU

Illustration Example (1/2)

- Steady state model of a portion of the reference grid is estimated during wind curtailment at different dispatch levels.



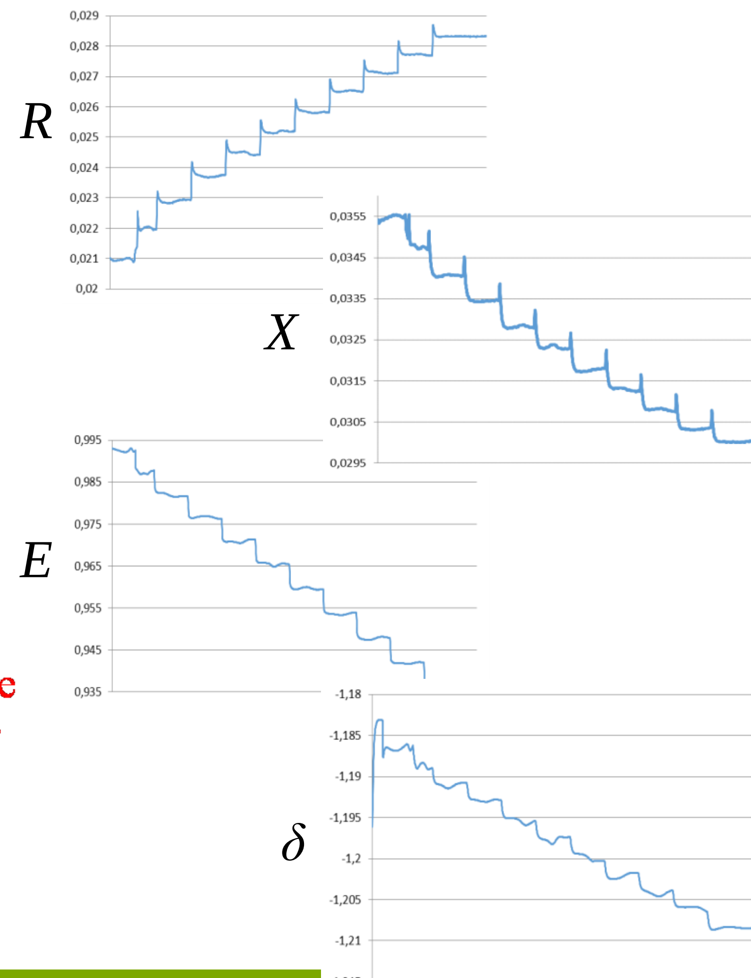


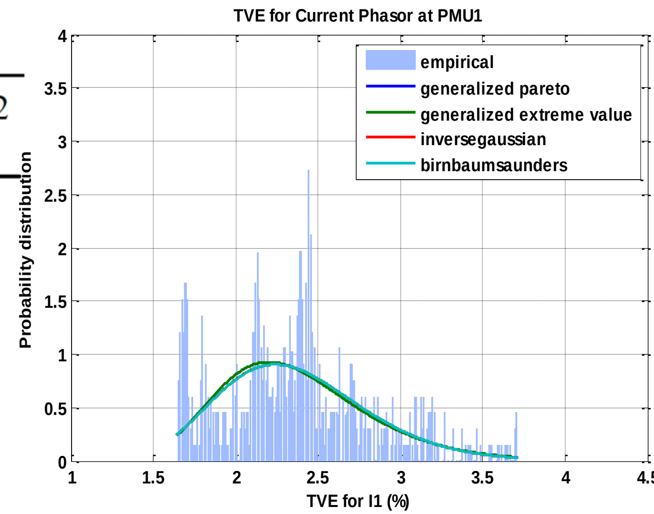
Illustration Example (2/2)

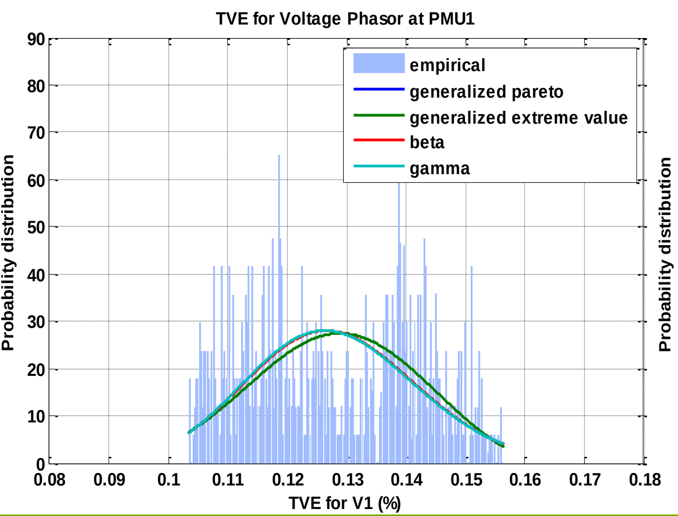
- True and reproduced current and voltage phasors are compared using *TVE*.

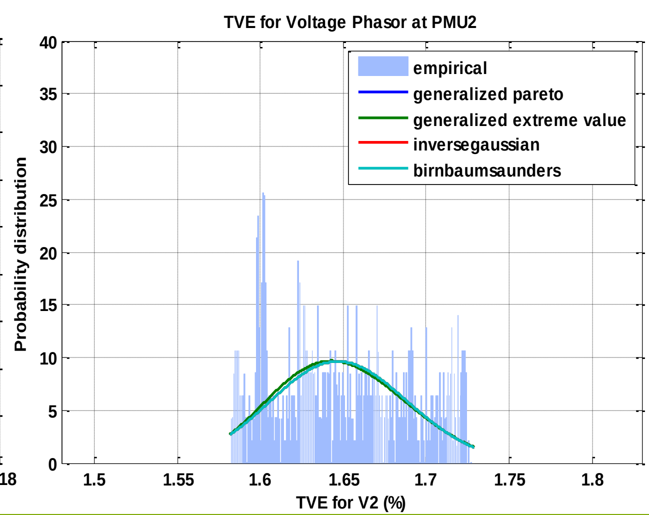
$$TVE(n) = \sqrt{\frac{(\hat{V}_r(n) - V_r(n))^2 + (\hat{V}_i(n) - V_i(n))^2}{V_r(n)^2 + V_i(n)^2}}$$

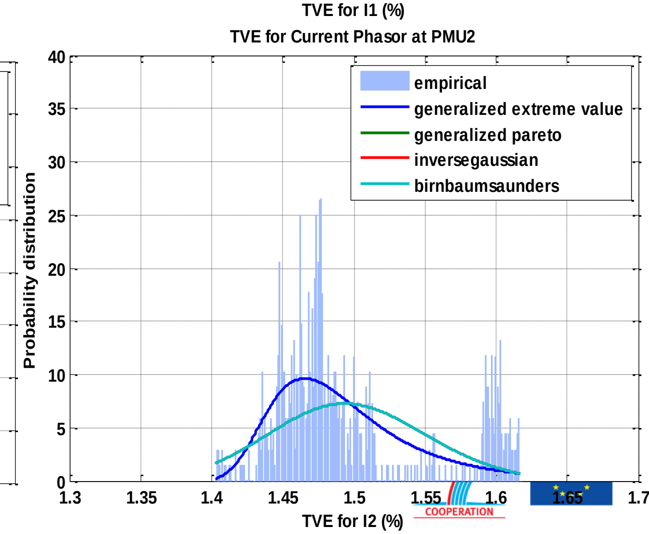
Variables with hat are reproduced ones.

- The mean TVE is less than 2.5%.







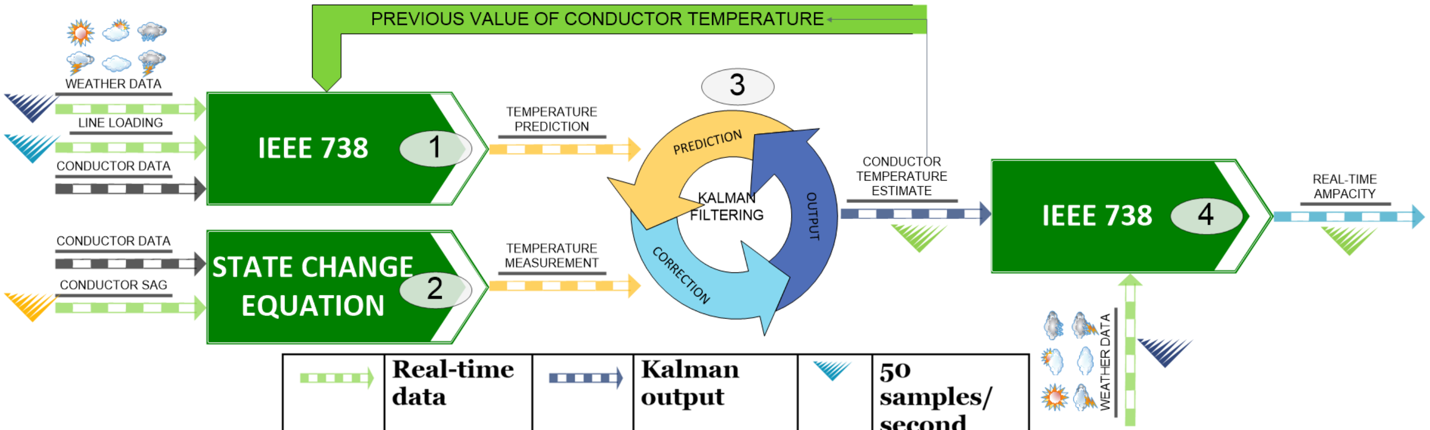


Dynamic Line Rating for Distribution Feeders

Background

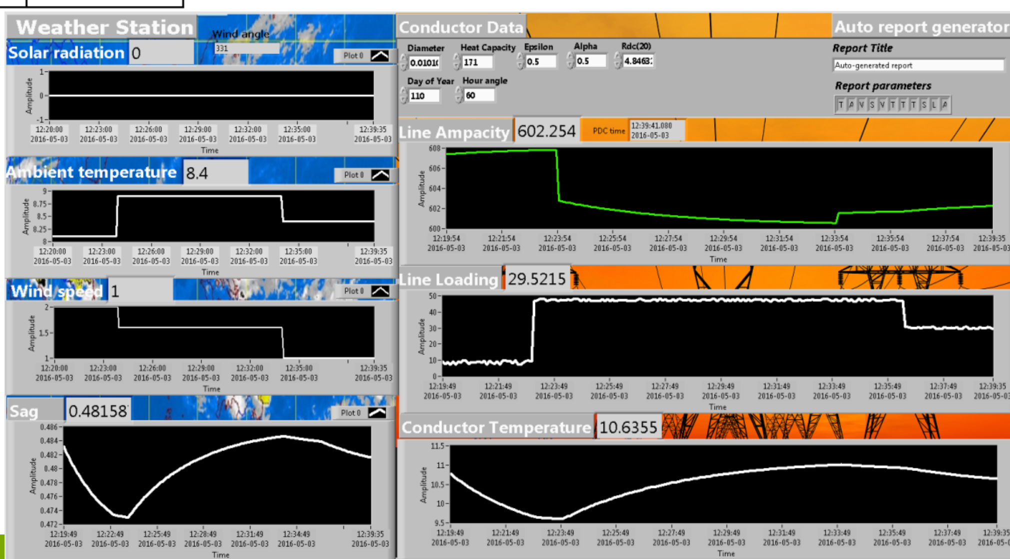
- Dynamic line rating (DLR) is a way to optimize the ampacity of transmission and distribution lines by measuring the effects of weather and actual line current.
- The inputs needed for the method:
  - Ambient data => provided by a close-by weather station.
  - Line loading => provided by PMU
  - Real-time sag => provided by a GPS-based measurement device.

Methodology and Application



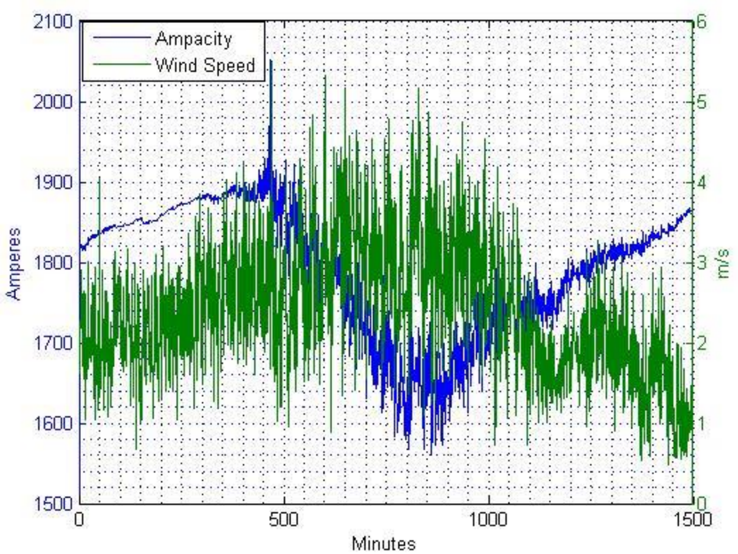
	Real-time data		Kalman output		50 samples/ second
	Constant values		Final output		1 sample/ minute
	Kalman input		1 sample/10 minutes		1 sample/5 seconds

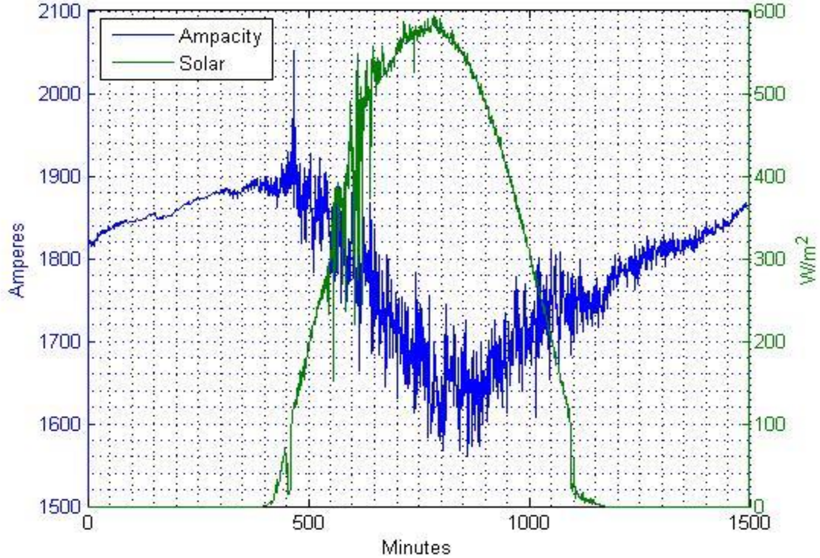
LabVIEW Application

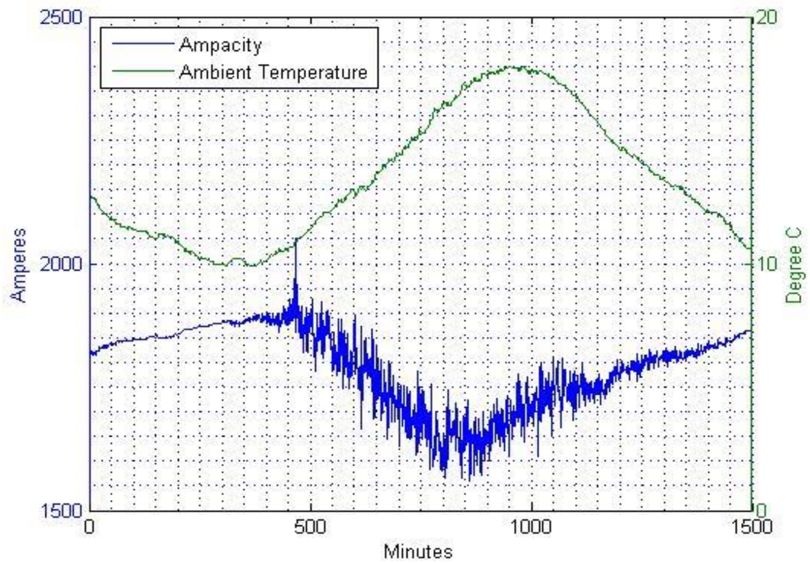


Sample Results

- Results are obtained by applying the method on data from a real feeder.
- Output shows accurate correlation with different inputs.





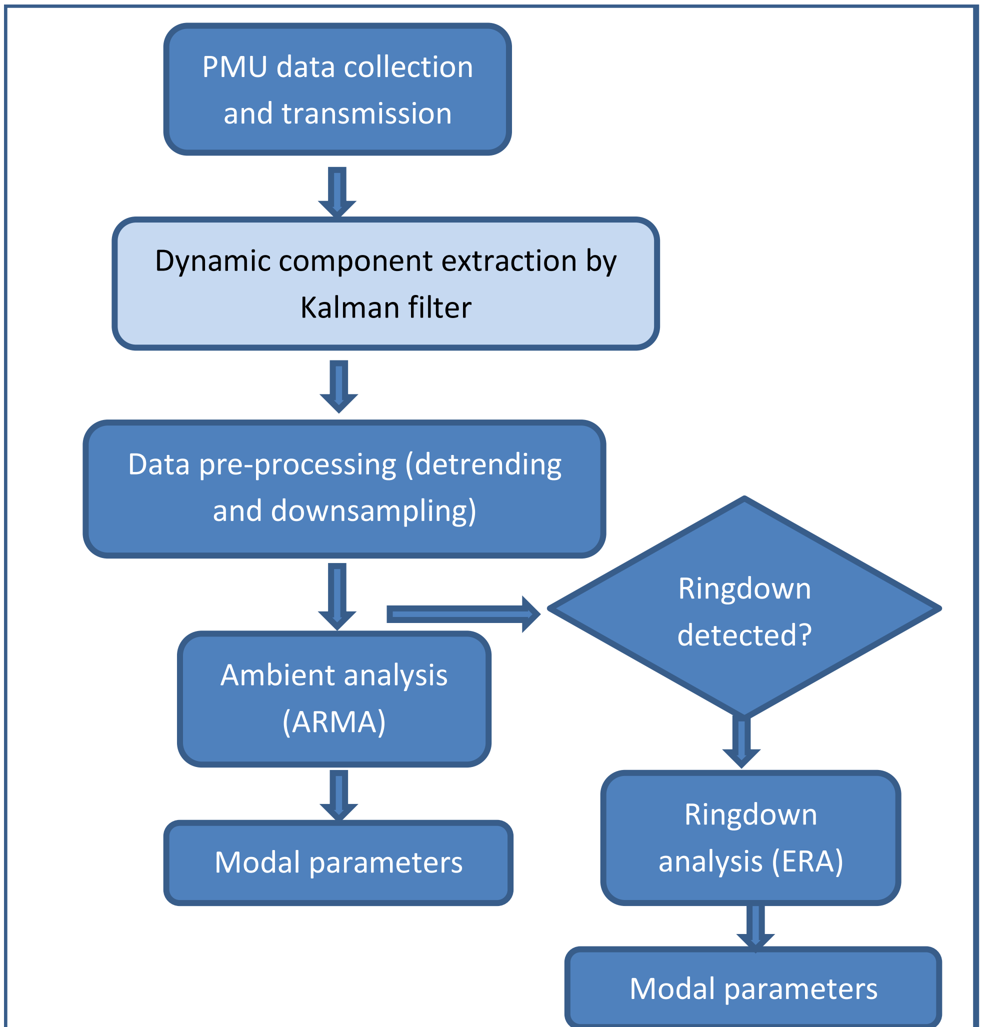


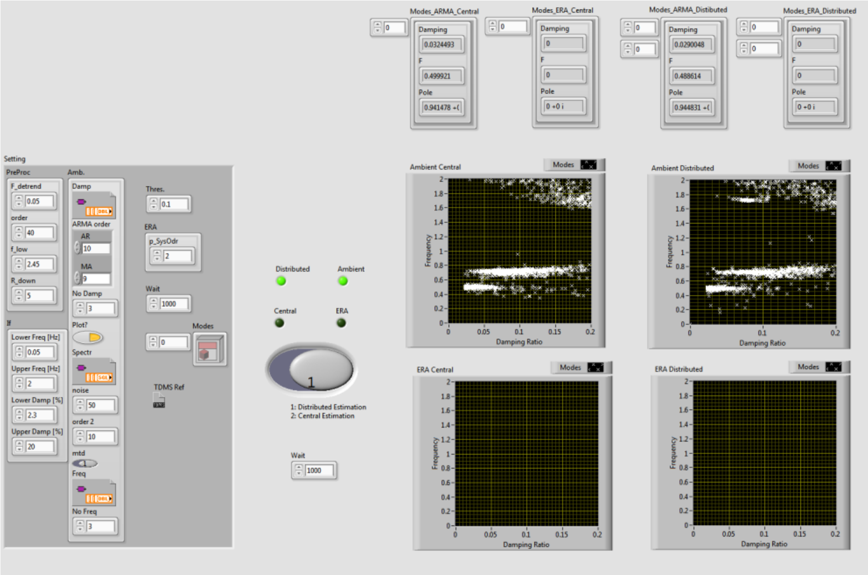
Small Signal Dynamic Analysis of Distribution System

Background

- For reliable operation of the power system, oscillations are required to decay.
- Accurate and real-time estimates of active distribution networks oscillatory modes has become ever so important.
- Timely extraction of these modes and related parameters from network measurements has considerable potential for near real-time dynamic security assessment.

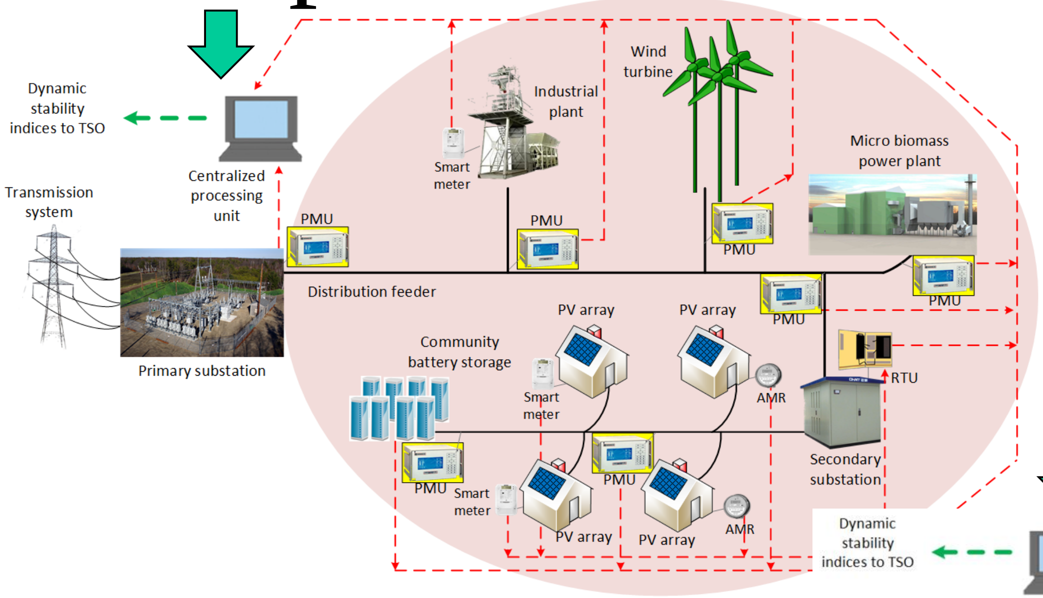
Methodology and Application





LabVIEW Application

Implementation Architectures



Centralized

Decentralized

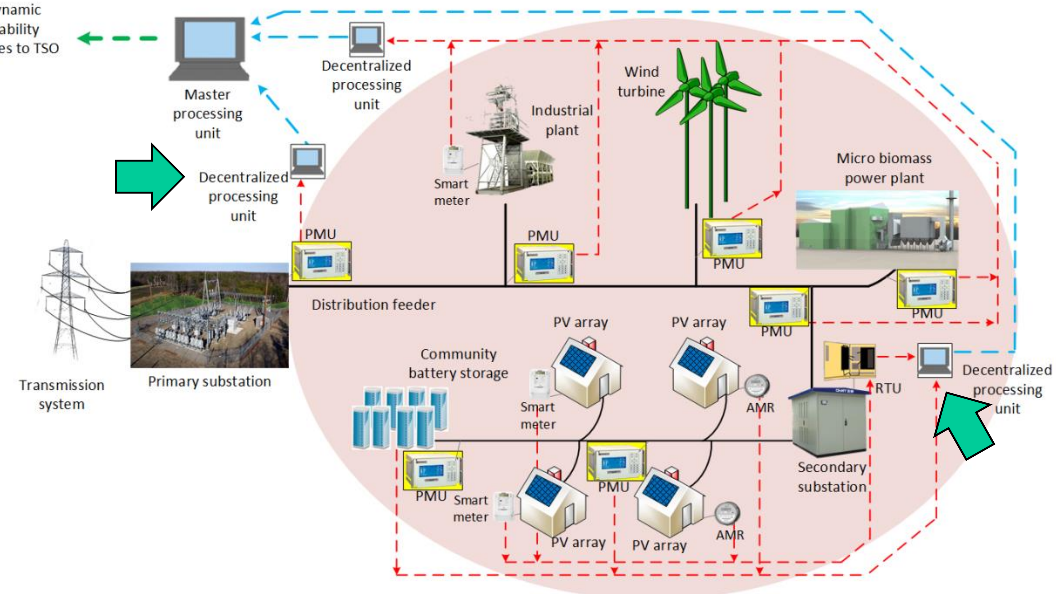


Illustration Example (1/2)

- 4 PMUs were deployed in the reference grid to be used for mode estimation under two different architectures of centralized and decentralized

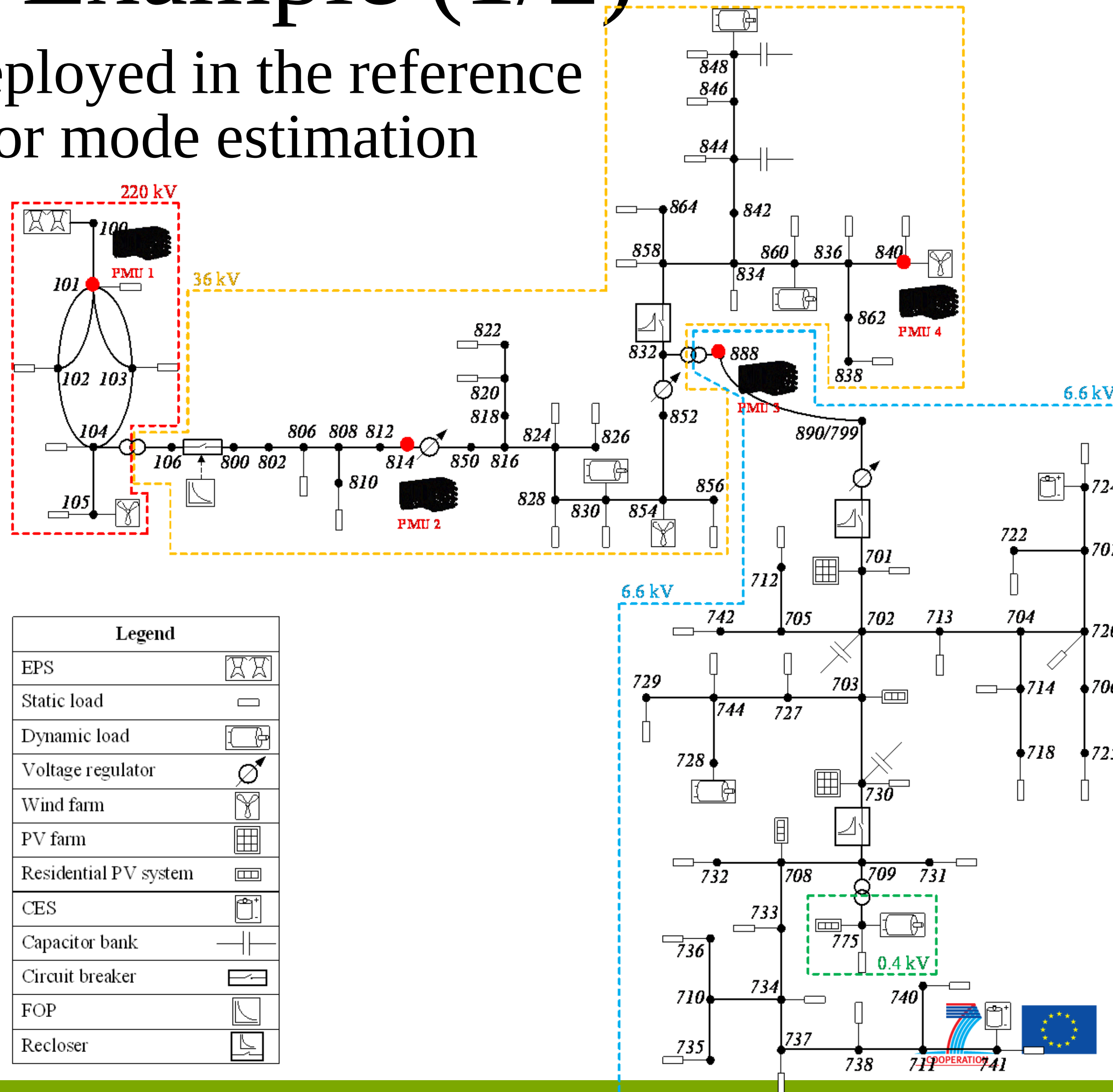
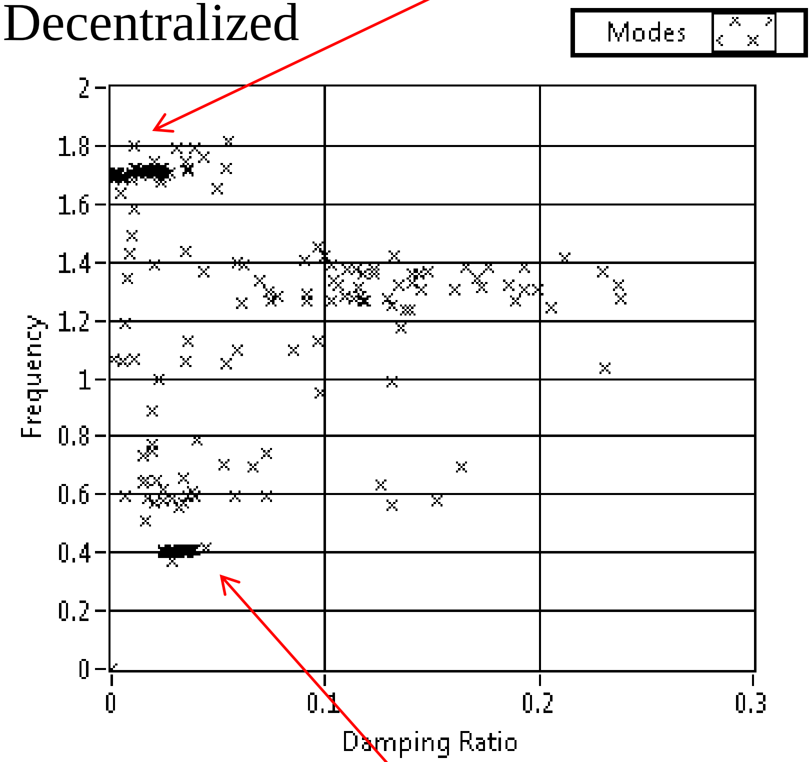


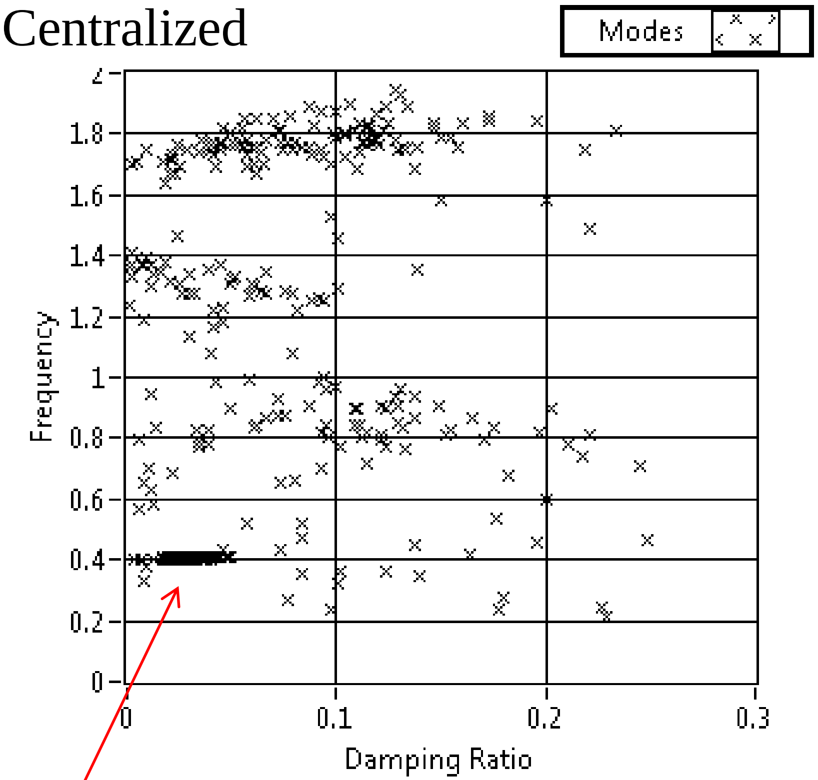
Illustration Example (2/2)

Forced local oscillatory mode detectable in decentralized architecture

Decentralized



Centralized



Inter-area oscillatory mode between HV section and rest of the grid

Conclusions

- The increase of intermittent renewable sources at the distribution network will bring challenges into DSO operations
- Synchrophasor measurements have a great potential in distribution networks
  - Applications will play the role of extracting key information about the operation of the grid
- TSOs-to-DSOs interaction
  - DSOs can enhance the way they operate by having better knowledge of the system's performance
  - TSOs can gain visibility of the phenomena at lower voltage levels

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Thank you!

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