EASY-RES

SUMMER SCHOOL
"ENABLING DRES TO OFFER ANCILLARY SERVICES"
20TH – 24TH SEPTEMBER 2021

The Extraction of the Dynamic Distribution Grid Model for Distribution Grids With High DRES Penetration

Dr. Kontis Eleftherios // 22/09/2021

This project has received funding from the European Union´s Horizon 2020 Programme for research and innovation under Grant Agreement no 764090.

Contents

slido

How system operators integrate distribution networks in stability studies?

ⓘ Start presenting to display the poll results on this slide.

Existing Modeling Practices for DN Analysis

- Traditionally, DNs were modeled as aggregated loads
  - Until recently 72% of power system operators worldwide used **static** load models to represent DNs in system stability studies
    - 53% of power system operators worldwide use the **exponential** load model
    - 19% power system operators worldwide use the **ZIP** model
  - System operators used to underestimate the impact of DRESs on stability studies
    - 40% completely **neglect** the impact of DRES on the dynamic performance of DNs
    - 28% simply represent DRESs as **negative loads**

[1] CIGRE Working Group C4.605: "Modelling and aggregation of loads in flexible power networks," Technical Report, 2014.

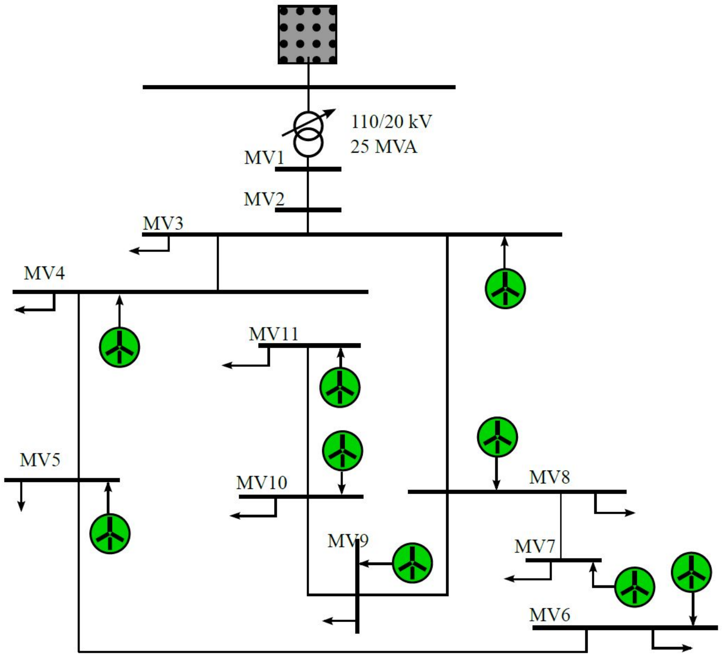
[2] J. V. Milanovic, K. Yamashita, S. Martinez Villanueva, S. Z. Djokic and L. M. Korunoviz, "International industry practice on power system load modeling," IEEE Transactions on Power Systems, vol. 28, no. 3, pp. 3038-3046, Aug. 2013.

Existing Modeling Practices for DN Analysis

- Nowadays, penetration of converter-based DRESs in DNs steadily increases
- DRESs, located in DNs, provide voltage and frequency support functions to the system, influencing power system dynamics
- **Research question:**
  - How accurate and reliable are the conventional modeling approaches in this new environment???

Brief Assessment of Conventional Modeling Practices

- Examined Grid:
  - CIGRE MV benchmark
  - 100% DRES penetration
  - DRES provide inertial and primary frequency response (PFR) as ancillary services to the system
  - A frequency disturbance is introduced
  - Performance of two static load models (exponential & ZIP) is investigated



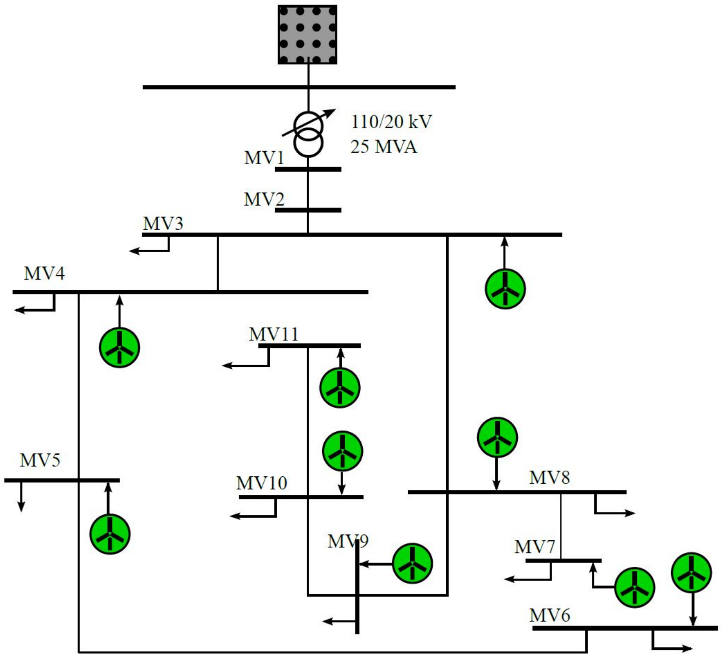
Brief Assessment of Conventional Modeling Practices

- Examined Static Load Models:
  - Exponential:

$$P = P_n \left(\frac{V}{V_n}\right)^a \left(\frac{f}{f_n}\right)^b$$

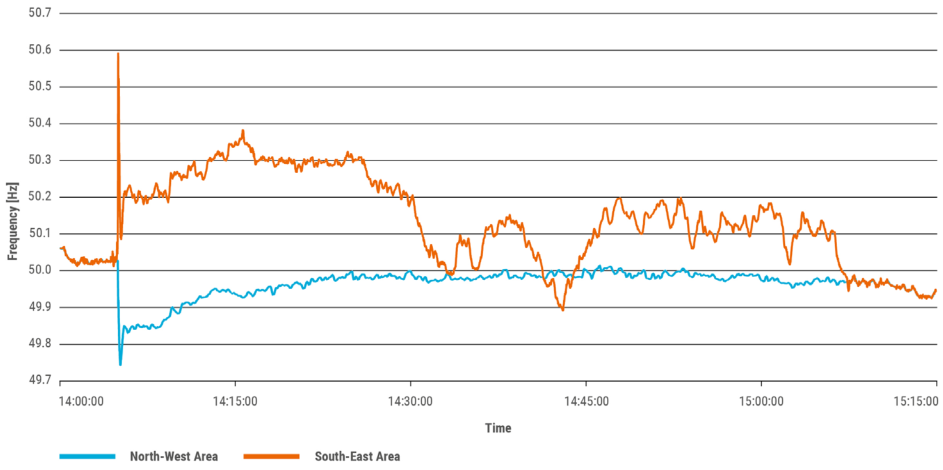
  - Polynomial (ZIP) Model:

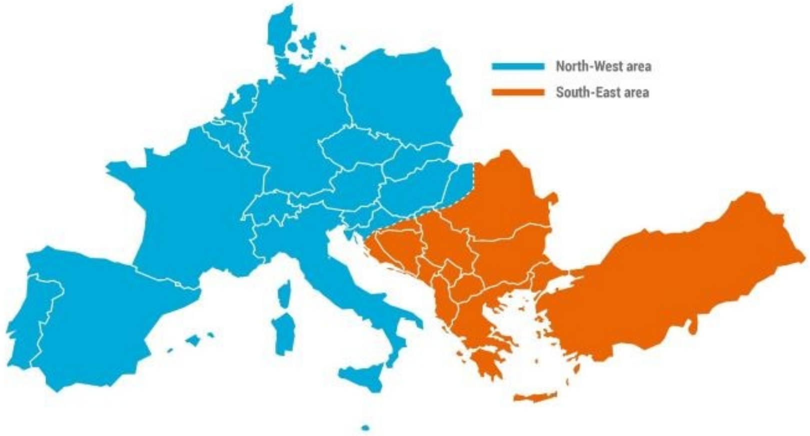
$$P = P_n \left[p_1 \left(\frac{V}{V_n}\right)^2 + p_2 \left(\frac{V}{V_n}\right) + p_3\right] (1 + c\Delta f)$$



Brief Assessment of Conventional Modeling Practices

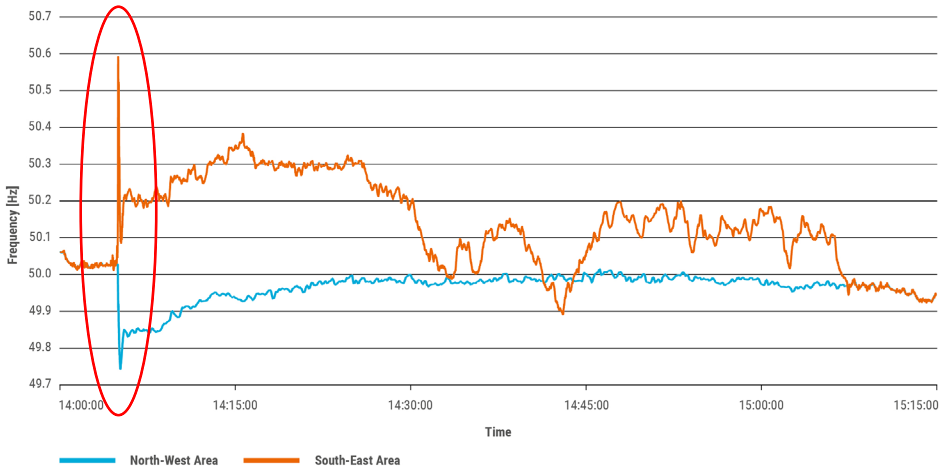
- Examined Disturbance:
    - Frequency separation event occurred at 8th of January in Europe

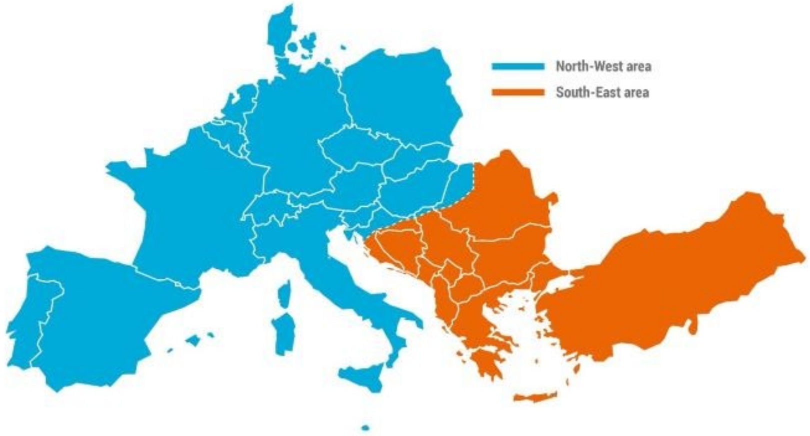




Brief Assessment of Conventional Modeling Practices

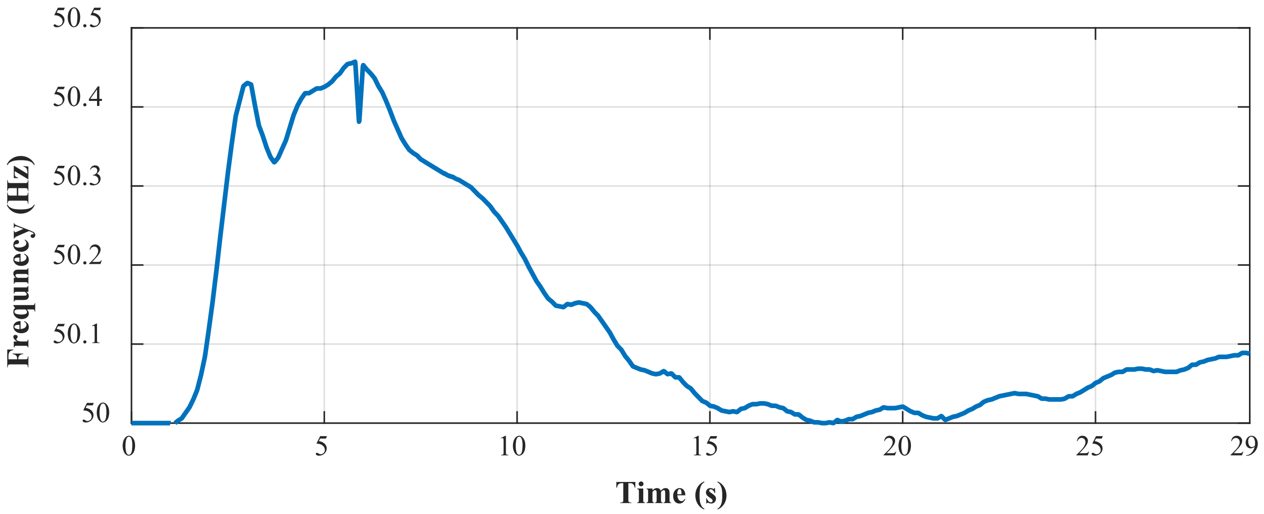
- Examined Disturbance:
  - Frequency separation event occurred at 8th of January in Europe





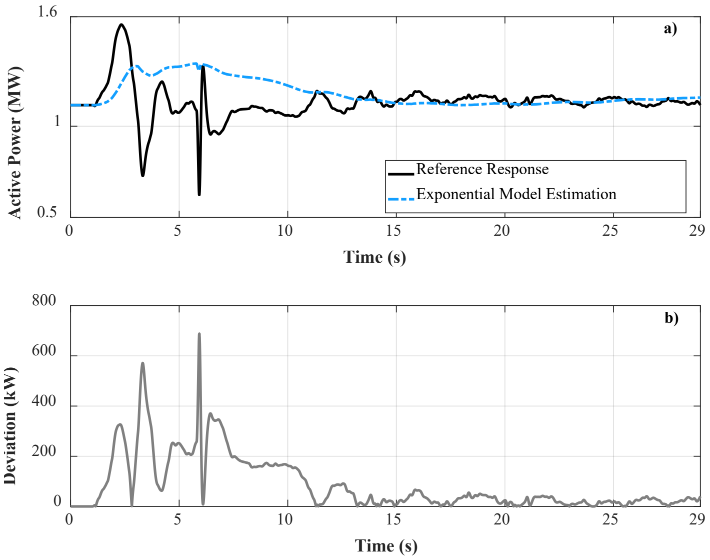
Brief Assessment of Conventional Modeling Practices

- Examined Disturbance:
  - Frequency separation event occurred at 8th of January in Europe

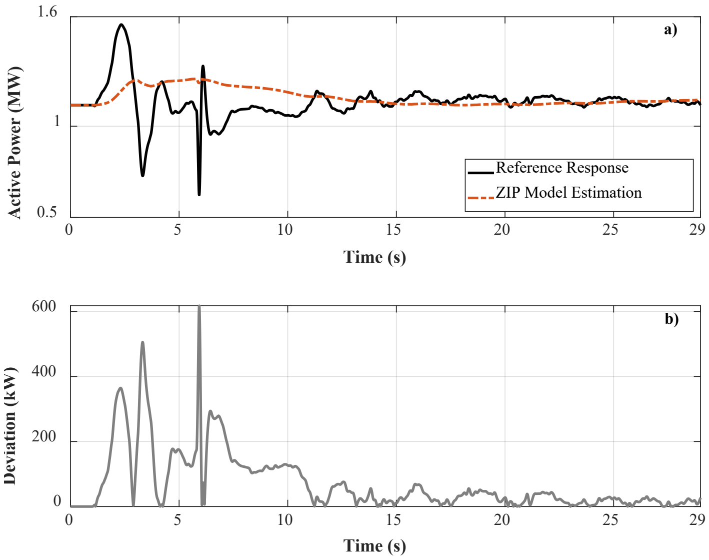


Brief Assessment of Conventional Modeling Practices

Performance of the Exponential Model:



Performance of the ZIP Model:



Dynamic Modeling and Analysis of DNs

- Conventional modeling practices become obsolete in this new environment, failing to provide accurate and reliable results

- **New** approaches (**models**) should be developed to facilitate simulation and analysis of modern ADNs

- These new type of models will allow TSOs to efficiently integrate ADNs into their dynamic simulation studies, thus identifying more accurately stability margins of their systems

- **Research question:**
    - What type of models should be used???

Dynamic Modeling and Analysis of DNs

- **Detailed modeling of DNs**
  - Pros:
    - Most accurate and reliable approach
  - Cons:
    - Impractical due to the increased computational complexity
    - In many countries DSOs cannot share detailed data of their system due to confidentiality issues

Dynamic Modeling and Analysis of DNs

- **Dynamic equivalencing**:
    - To overcome the above-mentioned limitations, DSOs shall undertake a more active role regarding the characterization of their grids by developing **reduced order equivalent models** up to the transmission-distribution substations
    - Reduced order equivalents are practically **aggregated models**, describing the dynamic properties of the examined system:
        - They can be used to replace ADNs is system stability studies
        - Ensure **reduced computational complexity** for system stability studies
        - Ensure the privacy of information (data **confidentiality**)

Dynamic Equivalencing of DNs – Main Approaches

- Modal analysis methods
- Coherency-based methods
- Measurement- or simulated-based methods
- Hybrid approaches (combine some of the above-mentioned methods)

[3] IEEE PES General Systems Subcommittee – Task Force on Dynamic System Equivalents "Dynamic System Equivalents: A Survey of Available Tecnhiques," IEEE Transactions on Power Delivery, vol. 27, no.1, pp. 411 – 420, Jan. 2021.

Dynamic Equivalencing of DNs – Main Approaches

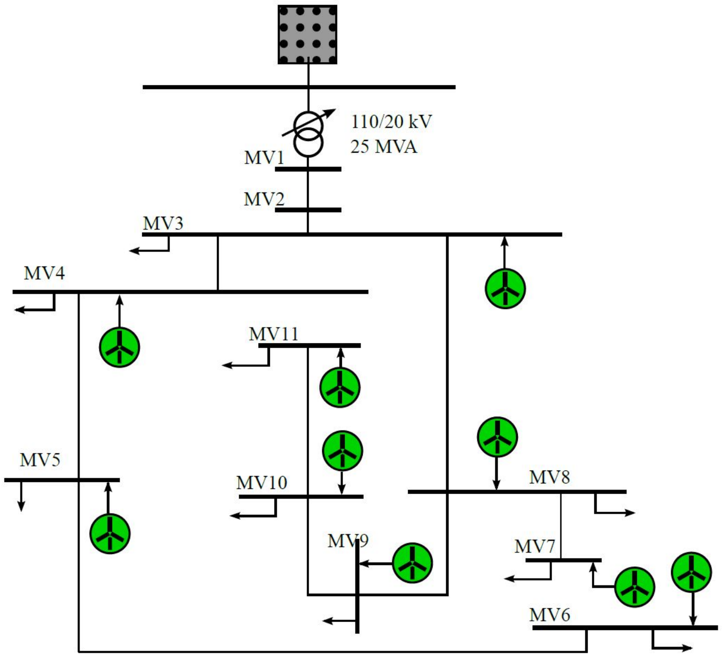
- Modal analysis methods
    - System linearization – calculation of system eigenvalues
    - Complex conjugate eigenvalues give oscillatory modes. Real part is the damping, while imaginary part corresponds to mode frequency
    - Modes with high damping decay faster compared to modes with lower damping
        - Relatively less damped modes are present in the dynamic response for a longer period, determining the overall response
        - Simplified equivalents can be developed using these modes
    - **Limited applicability range** (mainly for small-signal stability analysis)

Dynamic Equivalencing of DNs – Main Approaches

- Coherency-based methods
  - Identification of coherent groups of generators (groups that exhibit similar dynamic behavior)
  - Aggregation of coherent groups (aggregation of generator models and control devices)
  - Suitable for transient and frequency stability studies
  - **Limited applicability in DNs** (different types of DRES, discrete controls, etc)

Dynamic Equivalencing of DNs – Main Approaches

- Measurement- or simulation-based methods
  - Equivalents are developed by utilizing either in-situ measurements or simulated responses of the examined system
  - Typically, responses include voltage, frequency, real and reactive power at the point of interconnection with the transmission system



Dynamic Equivalencing of DNs – Main Approaches

- Measurement- or simulation-based methods
  - Equivalencing procedure consists of two main steps:
    - Initially, a suitable model structure for the equivalent should be specified
    - In the second step, identification techniques are applied to determine equivalent model parameters
  - Depending on the available information and insight of the examined ADN, three modeling approaches can be used:
    - White-box modeling
    - Black-box modeling
    - Grey-box modeling

Dynamic Equivalencing of DNs – Main Approaches

- Measurement- or simulation-based methods – **White-box modeling**:
  - Grid topology, load composition, type of DRESs and the associated control systems are considered *a priori* known
  - Model parameters are fine-tuned through in-situ measurements or simulated responses
  - White-box models are practically detailed representations of the examined system. Therefore:
    - Computational complexity issues are not resolved
    - Data confidentiality remains an open issue

Dynamic Equivalencing of DNs – Main Approaches

- Measurement- or simulation-based methods – **Black-box modeling**:
  - No prior knowledge of the examined system is required
  - Only input-output data are required (voltage, frequency, real/reactive power responses)
  - Aim of black-box modeling: to map the input data set to the output data set by properly adjusting model parameters in order to force equivalent outputs to become as similar as possible with the true system outputs (curve-fititng)
  - Main limitations:
    - Case sensitive parameters (DRES composition, type of disturbance, etc)
    - Limited physical meaning

Dynamic Equivalencing of DNs – Main Approaches

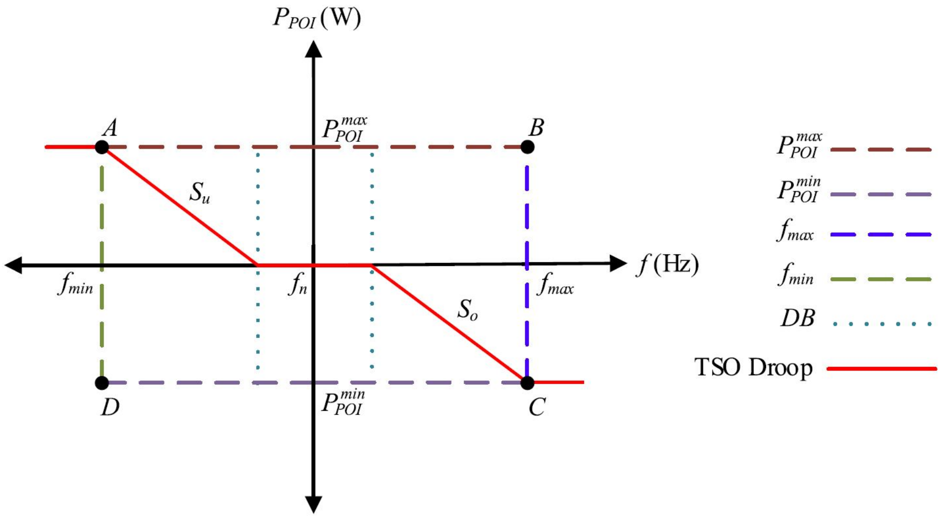
- Measurement- or simulation-based methods – **Grey-box modeling**:
  - Higher flexibility in parameter estimation than white-box models and more physical meaning than black-box counterparts
  - Basic information concerning load composition, DRES type, control systems is required to define the structure of the model
  - Input-output responses are required to estimate model parameters
  - Main limitations:
    - Discrete blocks are required to simulate different functionalities. Thus, several training data are required to estimate model parameters
    - Model parameters are highly dependent on load and DRES composition

Proposed Dynamic Distribution Grid Models

- **Preliminary questions:**
  - In which type of applications the derived DDGMs will be used?
    - Equivalent models are formulated based on specific stability problems
    - Here, the focus is given in the development of equivalents that will replace ADNs in frequency stability studies
    - TSOs can use these equivalents to conduct contingency analysis and determine inertia and PFR requirements of all interconnected ADNs
  - Which ADN characteristics should be captured/simulated??

Proposed Dynamic Distribution Grid Models

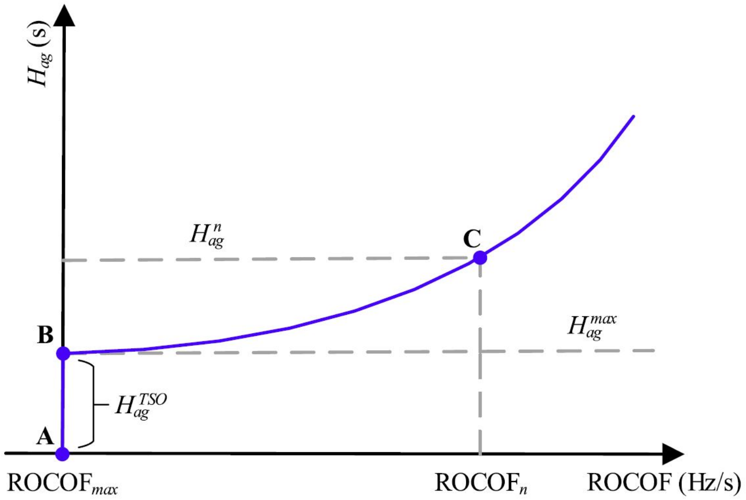
- Modeling of PFR:
  - Previous algorithms estimate the range of the aggregated *P-f* droop curve at POI
  - DDGM should capture the evolution of power in time (e.g. potential oscillations, overshoots, etc.)



$$\Delta P(t) = \begin{cases} S_u(\Delta f + DB)G_u(t), & \text{if } f \leq f_n - DB \\ 0, & \text{if } f_n - DB < f < f_n + DB \\ S_o(\Delta f - DB)G_o(t), & \text{if } f \geq f_n + DB \end{cases}$$

Proposed Dynamic Distribution Grid Models

- Modeling of inertial response:
  - Previous algorithms estimate the maximum aggregated inertia constant
  - DDGM should capture time domain evolution



Proposed Dynamic Distribution Grid Models

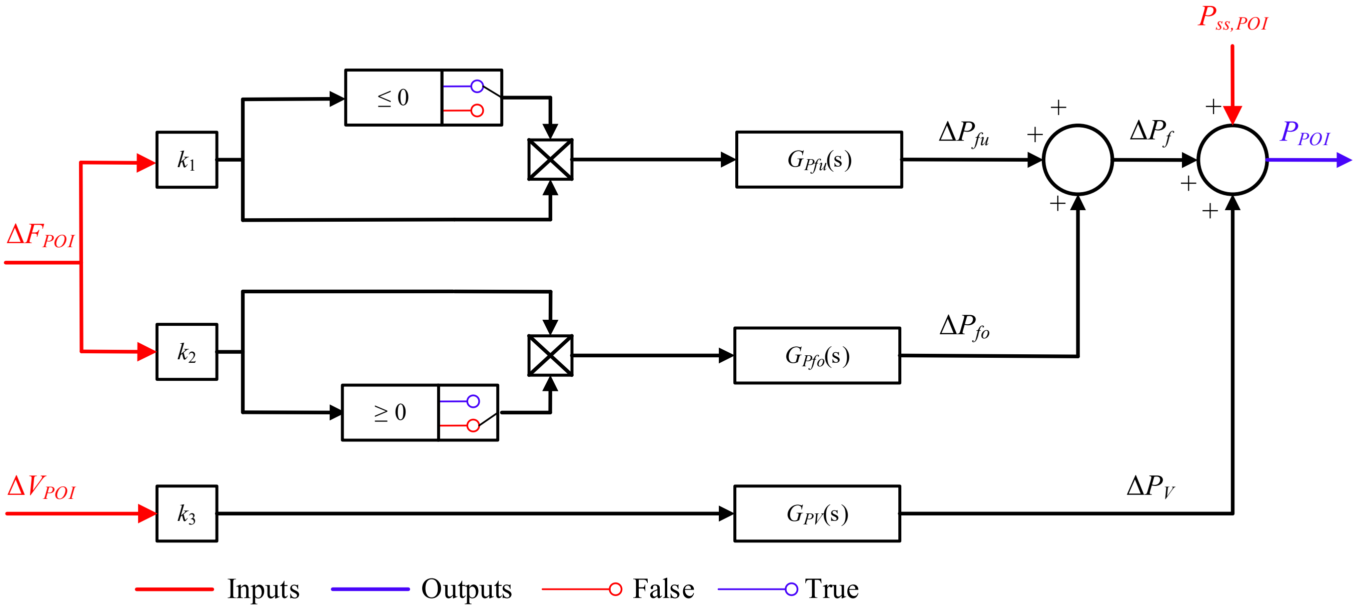
- **Modeling requirements:**
  - To preserve low computational complexity, we develop DDGMs based on low order transfer functions
  - Optimal order of required transfer functions is defined automatically based on an iterative procedure
  - Model parameters are determined using only dynamic responses recorded at the POI. Thus, confidentiality concerning parameters of individual ADN components is ensured

Proposed Dynamic Distribution Grid Models

- **Potential model structures:**
  - Simple black-box model (BBM)
    - The simplest approach. However, its structure does not allow the separate modeling of inertial and primary frequency response
  - Enhanced black-box model (EBBM)
    - More complex model structure, simulating separately inertia and PFR
  - Grey-box model (GBM)
    - Details concerning control logic are integrated into the model structure. Most accurate model

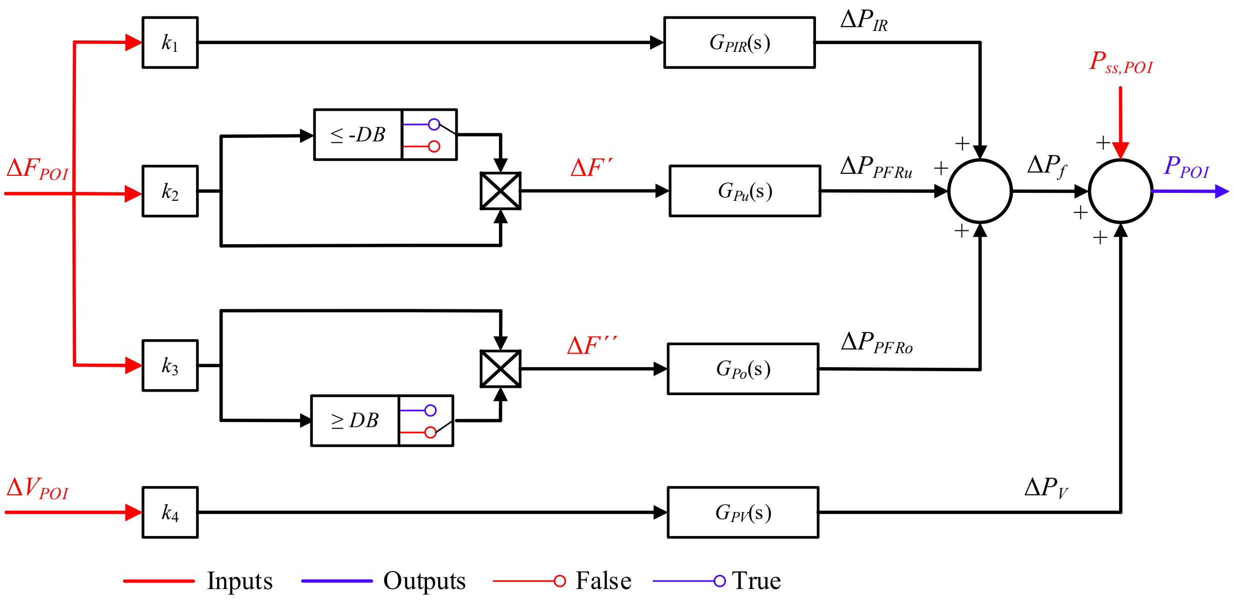
Proposed Dynamic Distribution Grid Models

- **Simple black-box model:**



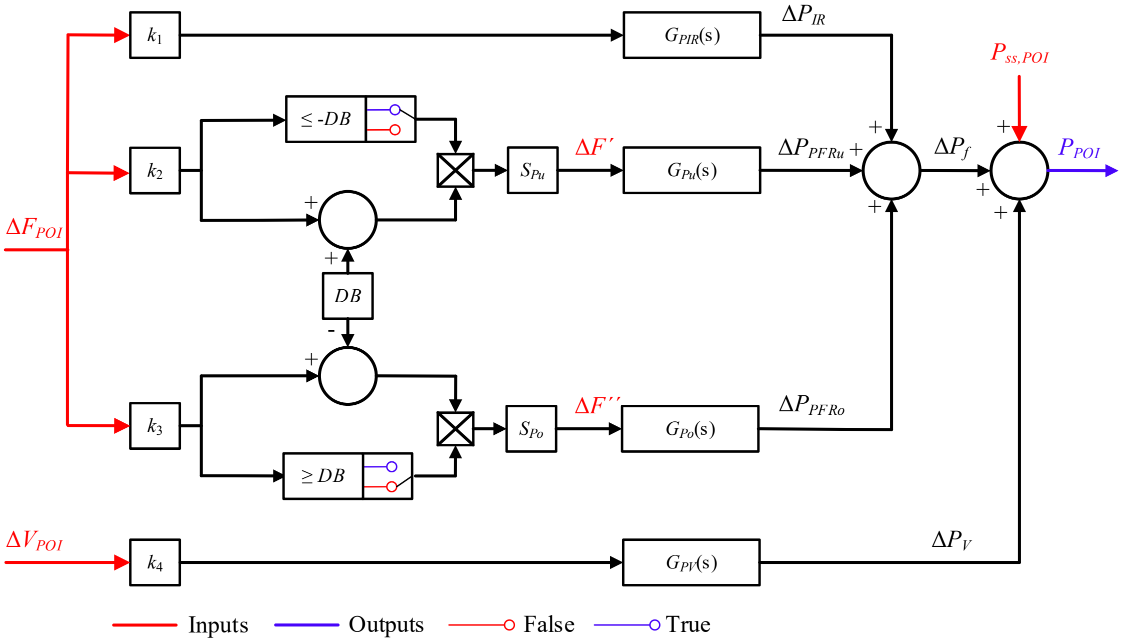
Proposed Dynamic Distribution Grid Models

- **Enhanced black-box model:**



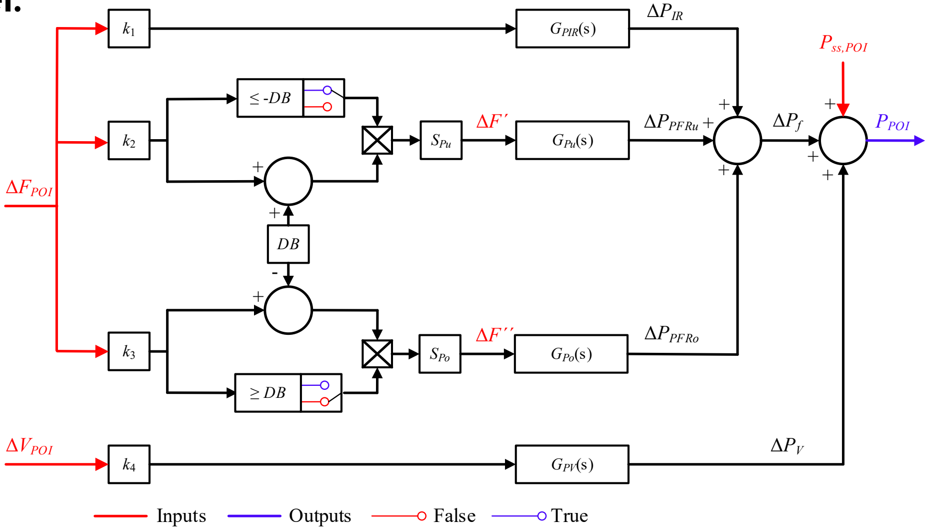
Proposed Dynamic Distribution Grid Models

- **Grey-box model:**



Proposed Dynamic Distribution Grid Models

- **Grey-box model:**

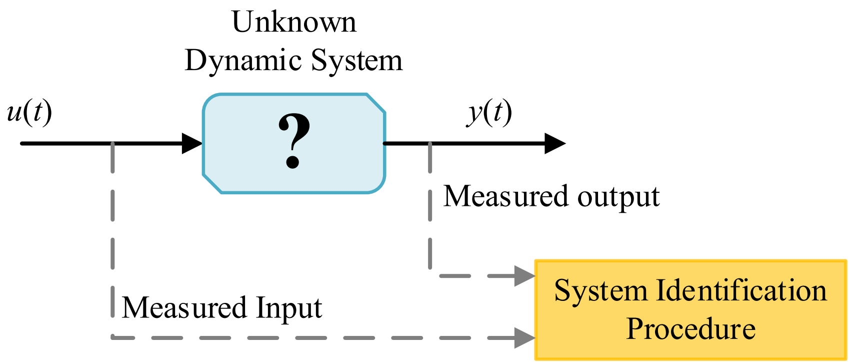


$$\Delta P(t) = \begin{cases} S_u(\Delta f + DB)G_u(t), & \text{if } f \le f_n - DB \\ 0, & \text{if } f_n - DB < f < f_n + DB \\ S_o(\Delta f - DB)G_o(t), & \text{if } f \ge f_n + DB \end{cases}$$

System Identification

- System identification is a process used to derive mathematical models of unknown physical systems by utilizing observations (measurements) of input and output data

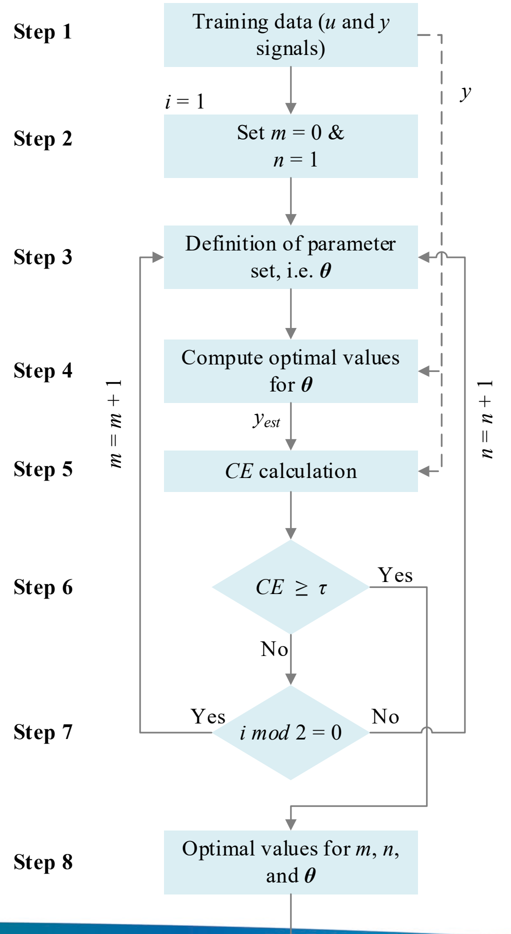
$$G(s) = k\frac{\prod_{i=1}^{m}(s - z_i)}{\prod_{i=1}^{n}(s - p_i)}$$



Parameter Estimation

- Optimal order of the required transfer function as well as the corresponding parameters are identified through an iterative procedure

$$CE = \left(1 - \frac{\sum_{t=1}^{T}(y[t] - y_{est}[t])^2}{\sum_{t=1}^{T}(y[t] - \bar{y})^2}\right) * 100\%$$

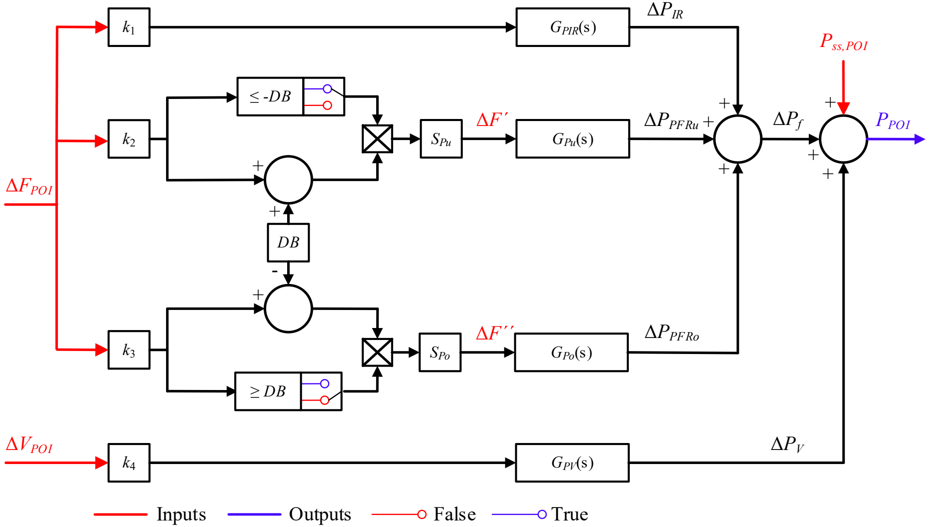


Acquisition of Training Data

- To obtain the input-output signals required for parameter estimation, appropriate disturbances (identification tests) must be defined
- Each test should trigger specific grid dynamics (simulated by a specific branch of the DDGM). This way, accurate identification of model parameters is ensured
- Identification tests must be carefully designed to ensure that interference between model branches is avoided

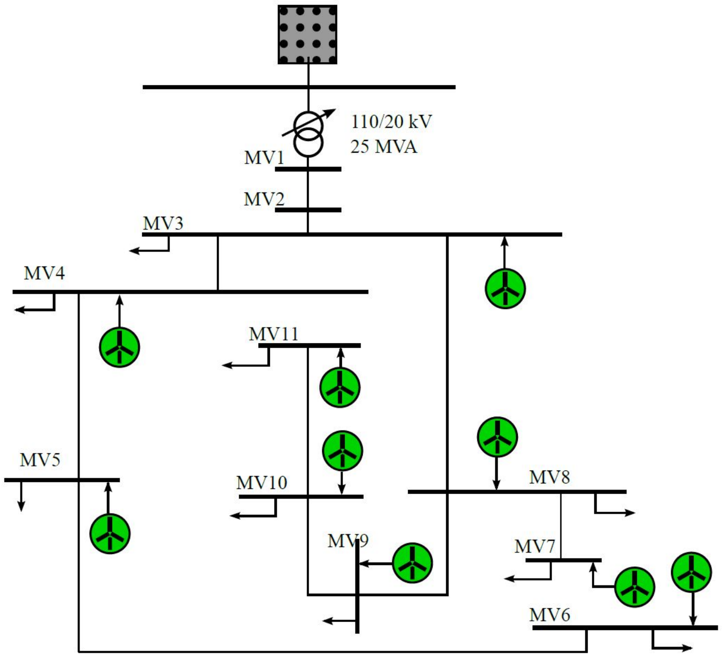
Identification Tests for the Derivation of the GBM

- **Test#1:** Voltage disturbance
- **Test#2:** Under-frequency event (only inertial response is activated)
- **Test#3:** Under-frequency event (only PFR is activated). Magnitude?
- **Test#4:** Over-frequency event (only PFR is activated). Magnitude?



Probabilistic Evaluation

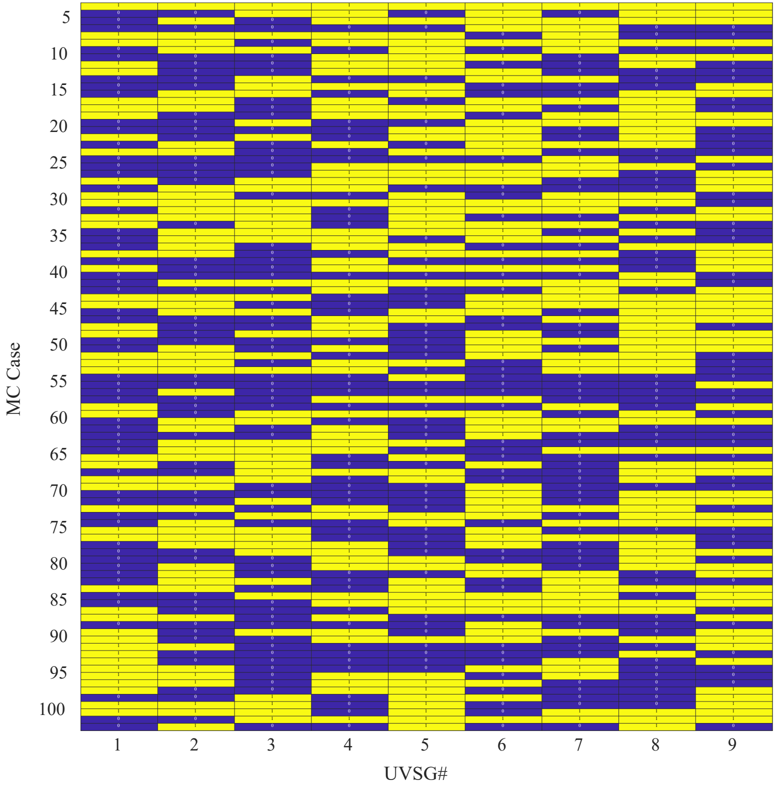
- The CIGRE MV grid is used
- DRESs are equipped with inertia and PFR functionalities
- Proposed models are validated using data obtained during the system separation event of 8th of Januray
- 100 MCs are generated by randomly connecting and/or disconnecting DRESs



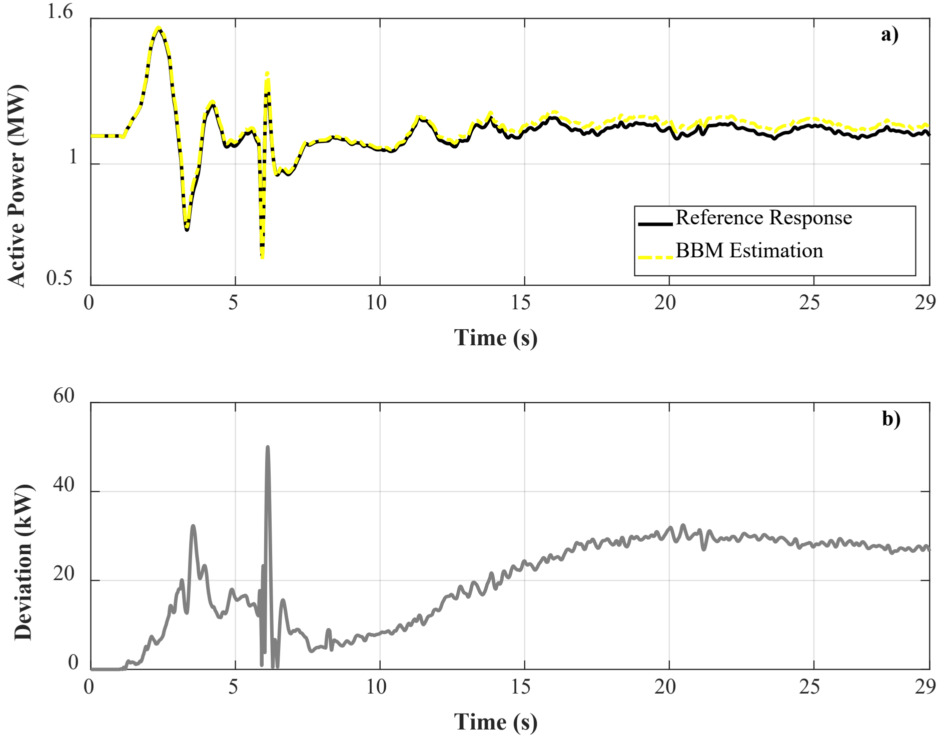
Probabilistic Evaluation

- Validation Index:

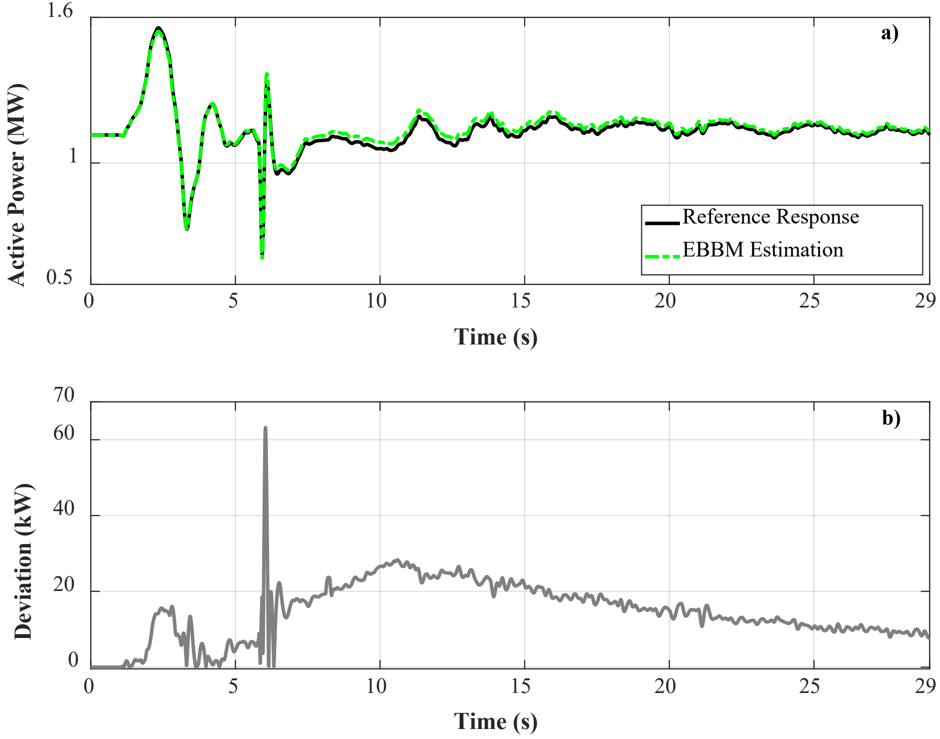
$$MD(\%) = \frac{mean|y_{ref}[t] - y_{est}[t]|}{y_{ref}^{pd}} * 100\%$$



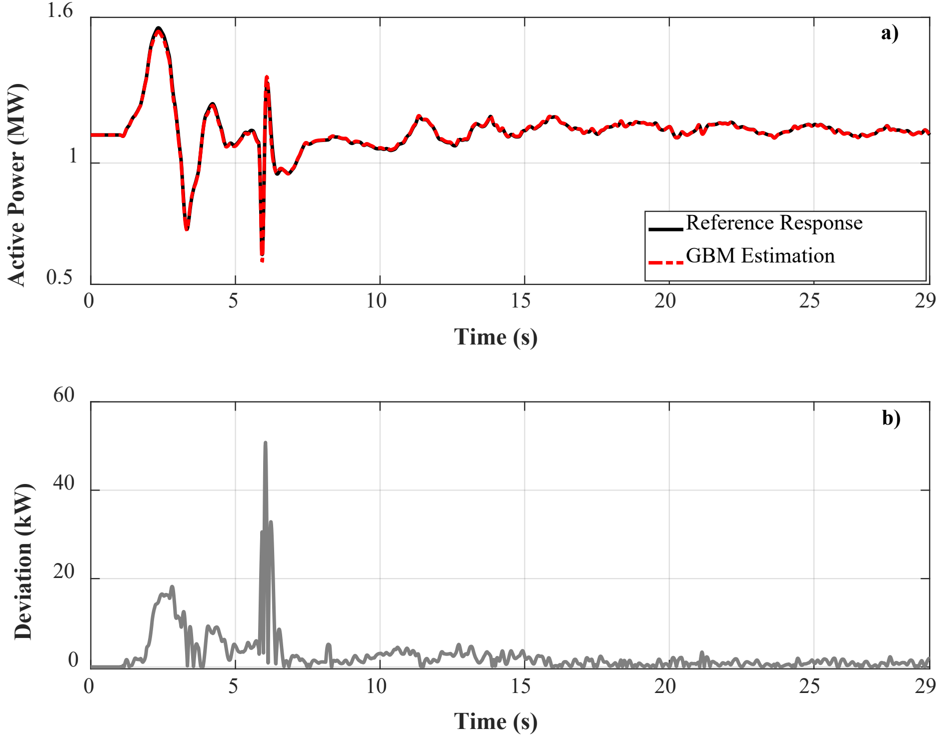
Instance of MC simulations – BBM (MD=1.76%)



Instance of MC simulations – EBBM (MD=1.31%)



Instance of MC simulations – GBM (MD=0.23%)

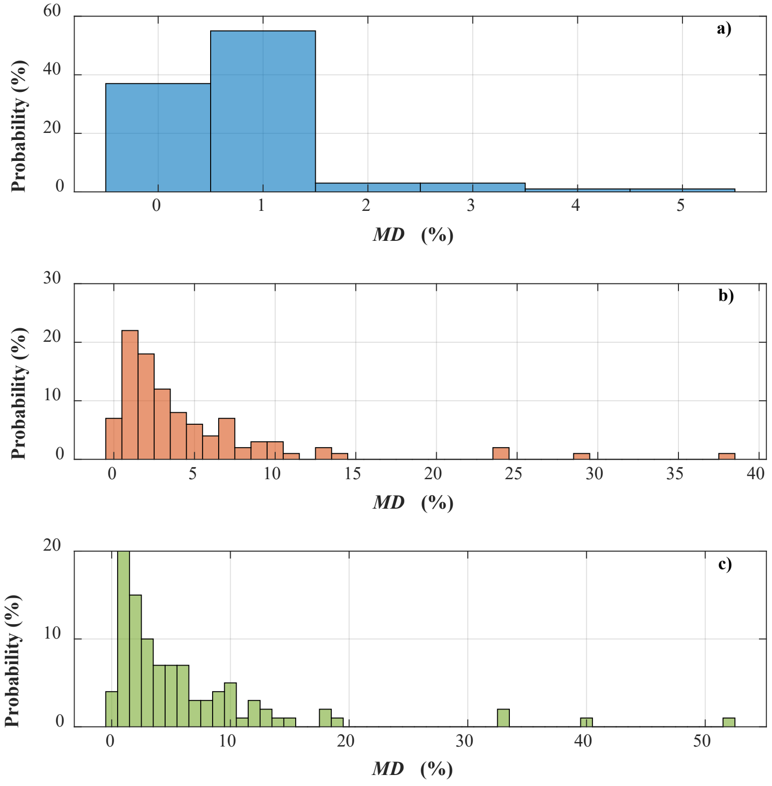


Probabilistic Evaluation

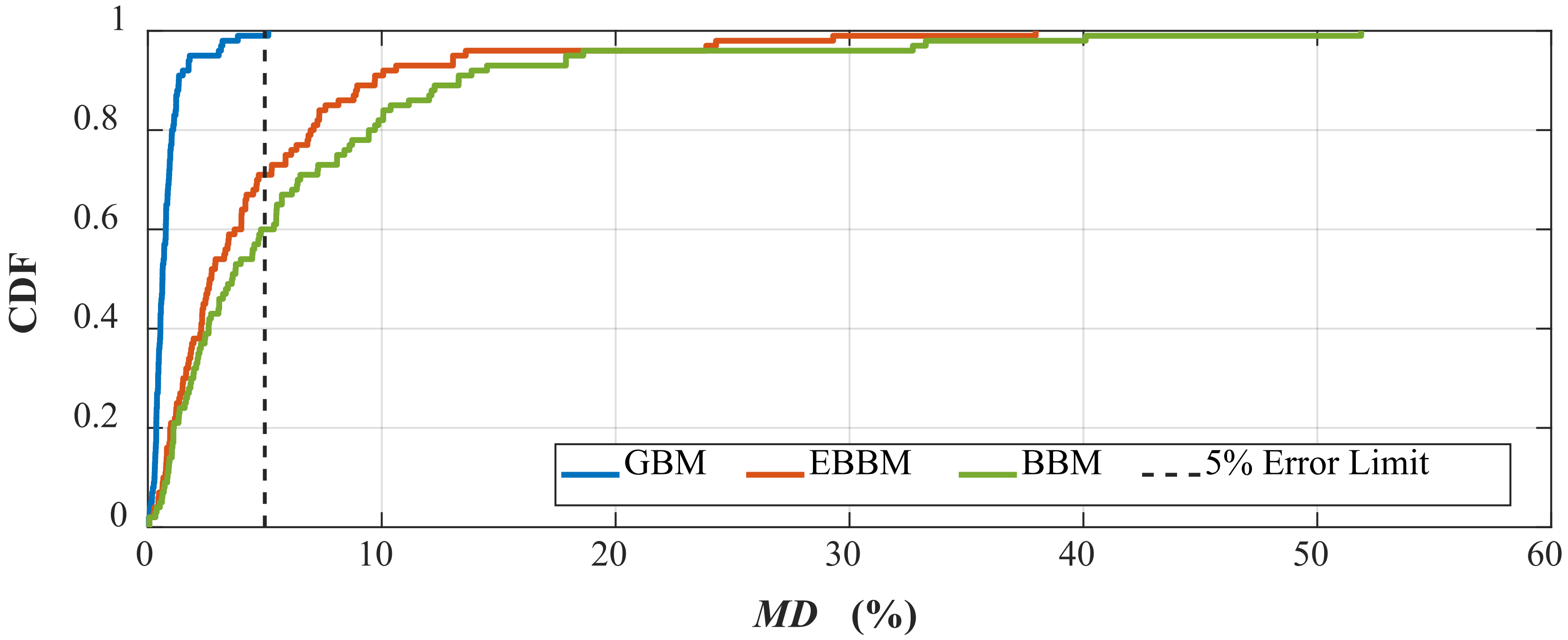
a) GBM

b) EBBM

c) BBM



Probabilistic Evaluation



slido

Measurement-based dynamic equivalents can be used to represent distribution systems in:

ⓘ Start presenting to display the poll results on this slide.

Grey-box models outperforms black-box equivalents because:

ⓘ Start presenting to display the poll results on this slide.

Summary

- Conventional load models cannot be used for dynamic analysis of ADNs
- New modeling approaches are required to accurately simulate the complex dynamic behavior of modern distribution systems → Reduced order aggregated equivalents:
    - Ensure reduced complexity
    - Ensure data confidentiality
        - Grey-box models are more suitable (integration of control strategies, separate modeling of different functionalities, etc)
        - Simulated-based approaches can be used to derive grey-box equivalents

Item 4: The EASY-RES Consortium

The Consortium

ARISTOTLE UNIVERSITY OF THESSALONIKI

UNIVERSIDAD DE SEVILLA

UNIVERSITÄT PASSAU

Lancaster University

TU Delft

ΑΔΜΗΕ
ΑΝΕΞΑΡΤΗΤΟΣ ΔΙΑΧΕΙΡΙΣΤΗΣ ΜΕΤΑΦΟΡΑΣ ΗΛΕΚΤΡΙΚΗΣ ΕΝΕΡΓΕΙΑΣ

elektro gorenjska

Stadtwerke LANDAU a.d.ISAR

stadtwerk haßfurt

fenecon
ENERGY ENGINEERING

ZD.B ZENTRUM DIGITALISIERUNG. BAYERN

This project has received funding from the European Union´s Horizon 2020 Programme for research and innovation under Grant Agreement no 764090.

Thank you!

Presenter‘s name

Affiliation: Aristotle University of Thessaloniki

Phone: +302310996379

E-Mail: kontislefteris@gmail.com

EASY-RES website: http://www.easyres-project.eu/