From Real-Time Synthetic Grids to Modular Power System Digital Twins

Dr. Georgios Konstantinou
School of Electrical Engineering and Telecommunications
UNSW Sydney

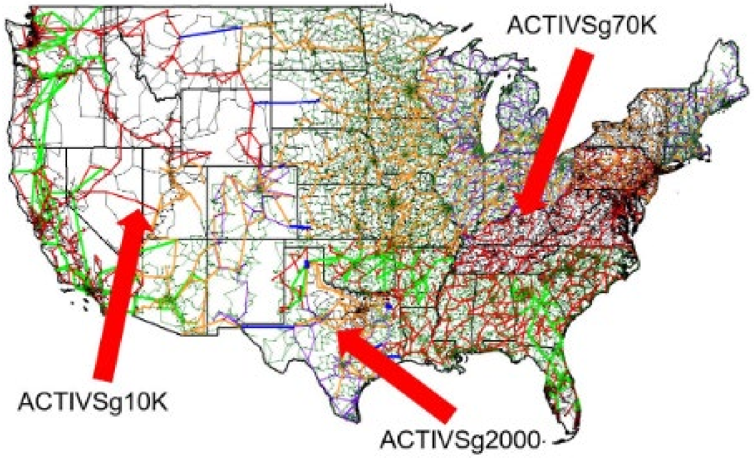
Real-Time Simulations Laboratory
RTS@UNSW

UNSW SYDNEY

Synthetic Grids

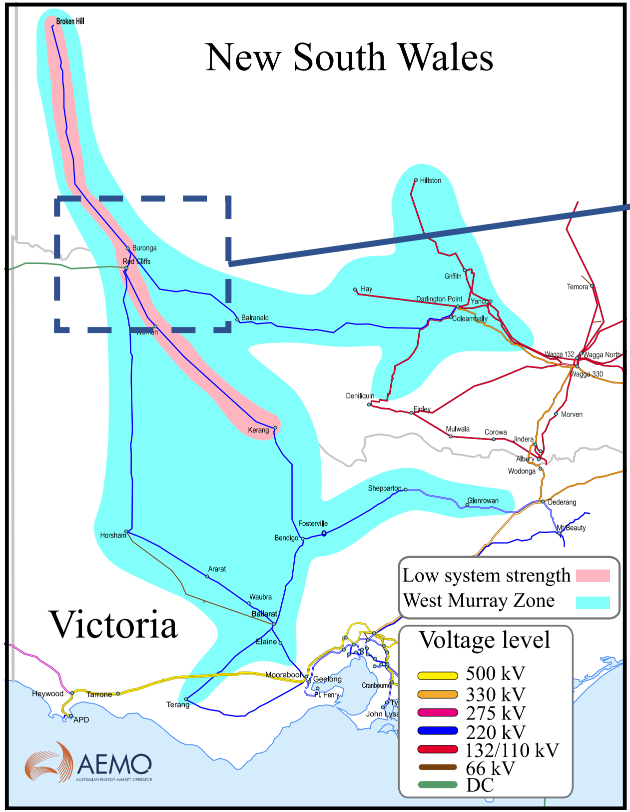
- *"A **fictitious network** that has a **similar topology and characteristics** of a real power system, without revealing sensitive information"*

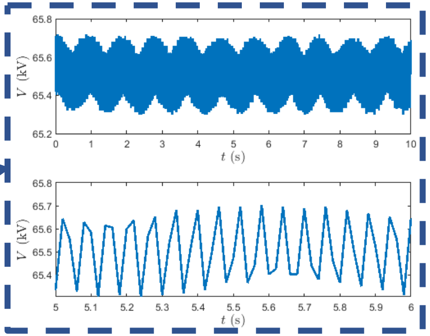
- Design, test and validation.
- Robust/meshed networks.
- Phasor-based (RMS) models.



https://electricgrids.engr.tamu.edu/

The Need for EMT / RT Simulations is Well Understood





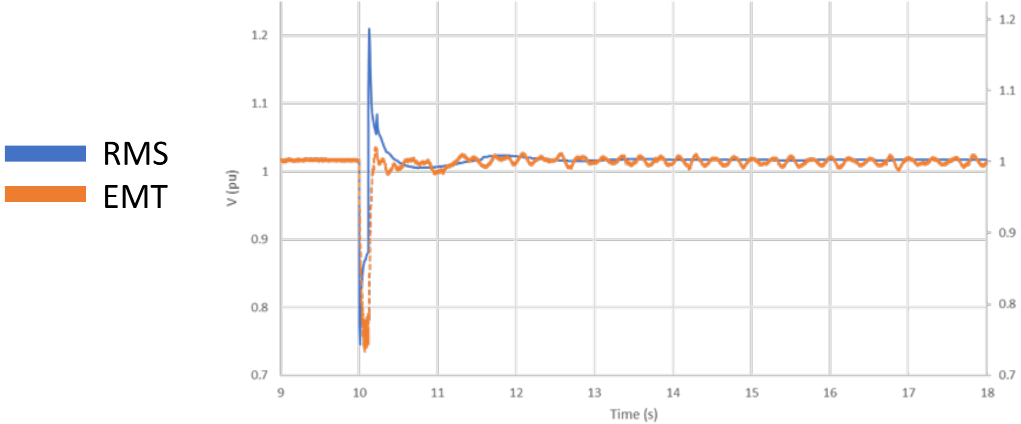
Voltage oscillation
(event captured at Red Cliffs)

- Oscillations may reach 5% peak-to-peak.
- Frequency varies from 7 to 19 Hz.
- Very low system strength increases the potential of resonance and converter-driven instabilities.
- New and existing variable renewable generation will be constrained.
- Full system strength impact assessment will be required
- Significant delays in project assessments.

https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/west-murray

The Need for EMT / RT Simulations is Well Understood

- EMT-type models can better represent power system dynamics

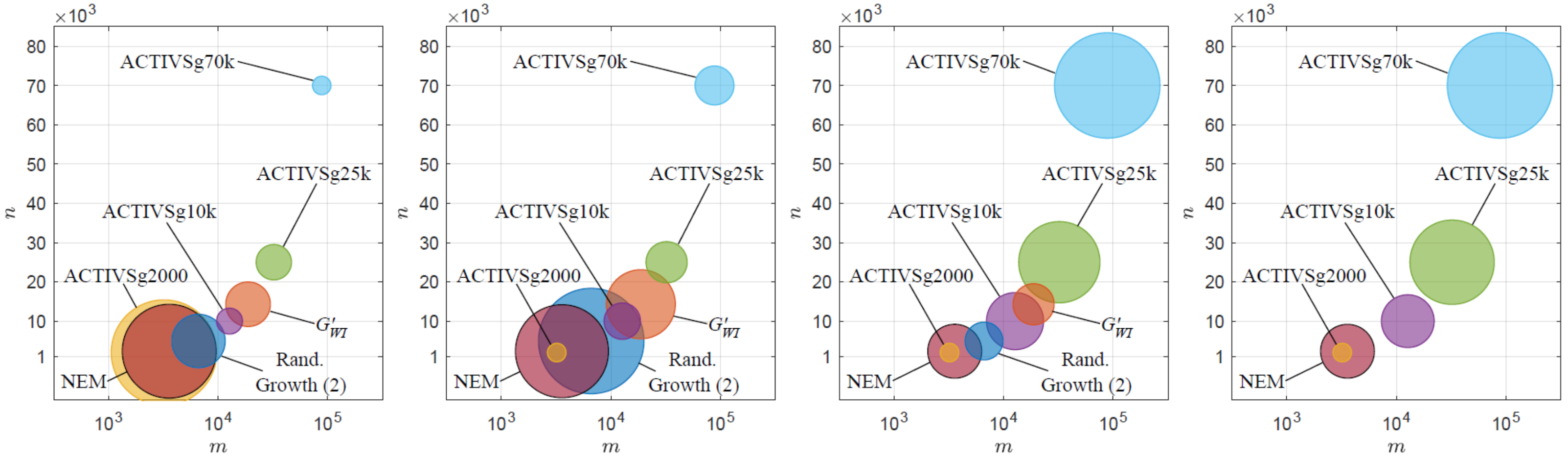


> *"RMS model does not predict sustained oscillations following a credible contingency in an inverter-domain network area"* [1]

- Real-time simulations interface with external devices (HiL, CHiL, PHiL) while improving computing time.
- Digital Twin technology provides an intelligent platform that accurately reflects a physical system.

[1] https://aemo.com.au/learn/energy-explained/system-strength-workshop

Structural Characteristics of Networks - Graphs



(a) Average vertex degree $\overline{k}$

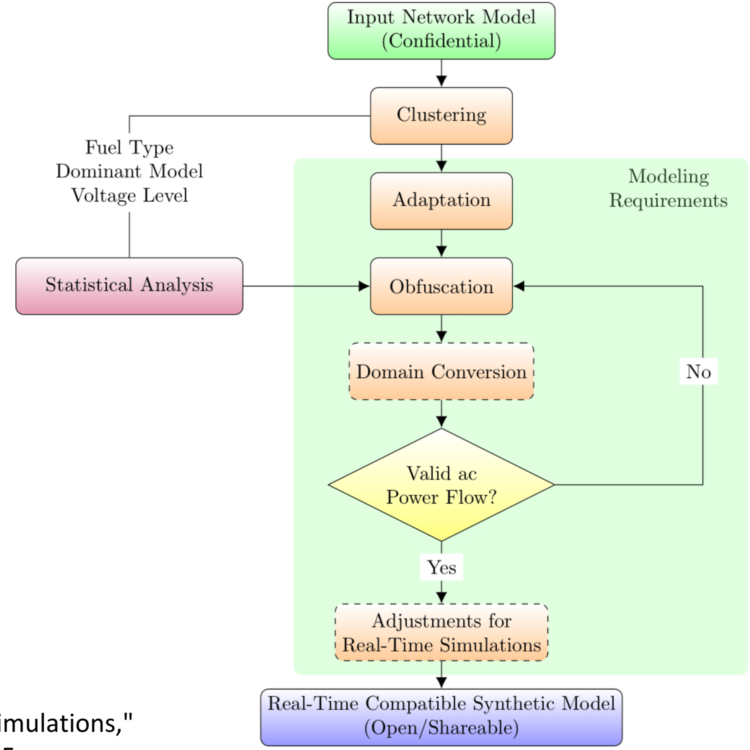
(b) Average clustering coefficient $\overline{C}$

(c) Average (shortest) path length $\overline{l}$

(d) Diameter $d_{\max}$

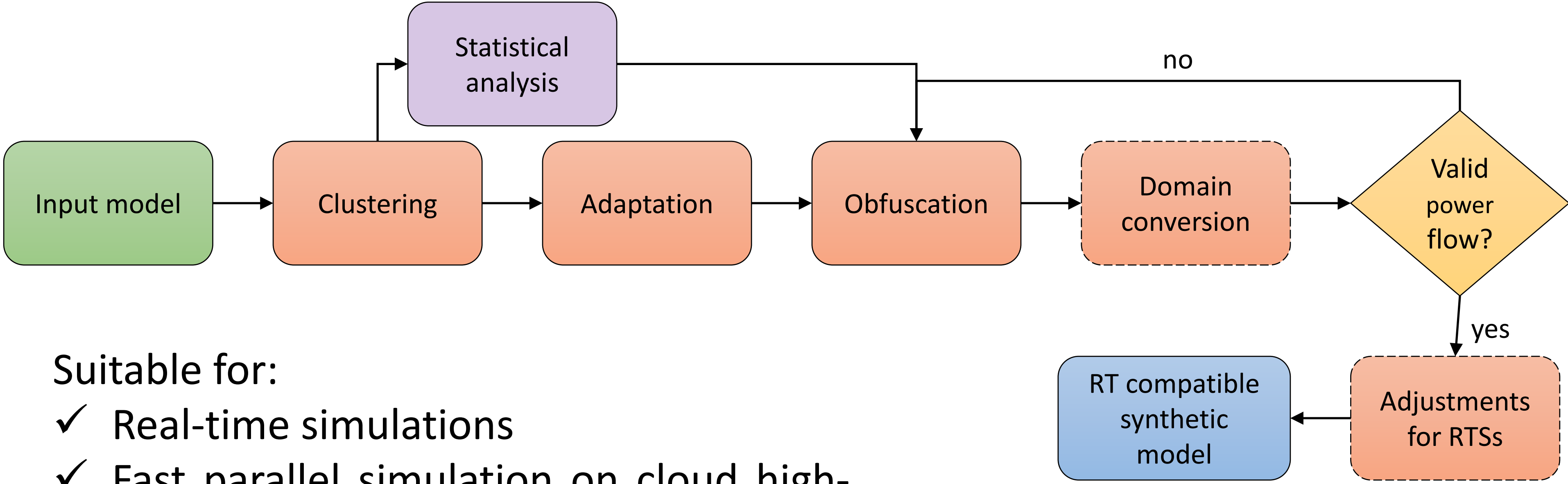
Methodology for Creating RT Compatible Models

- Synthetic grid:
  - Emulates the size, structure and complexity of modern power systems
  - Does not contain confidential nor sensitive information
  - Shareable



F. Arraño-Vargas and G. Konstantinou, "Synthetic Grid Modeling for Real-Time Simulations," *2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)*, 2021, pp. 1-5,

Methodology for Creating Synthetic Grids

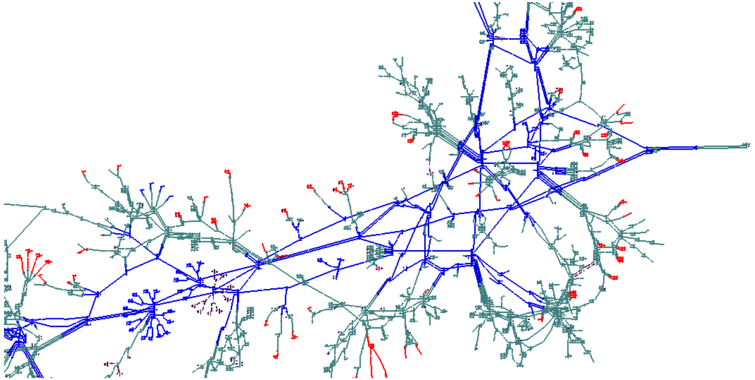


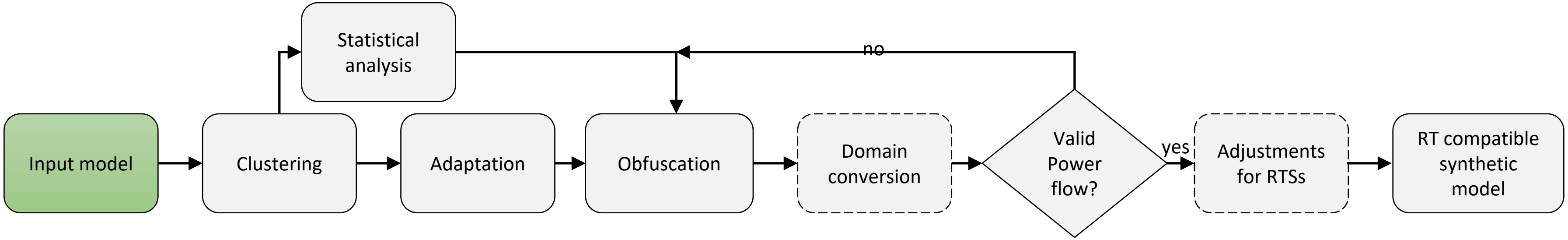
Suitable for:

- ✓ Real-time simulations
- ✓ Fast parallel simulation on cloud high-performance computers
- ✓ Offline simulation tools (PSCAD, EMTP)

Input Model

- Phasor-based model of the NEM (PSS/E):
  - +2,400 buses
  - +350 machines
  - +1,800 transmission lines
  - +1,500 transformers
  - +450 user-defined models

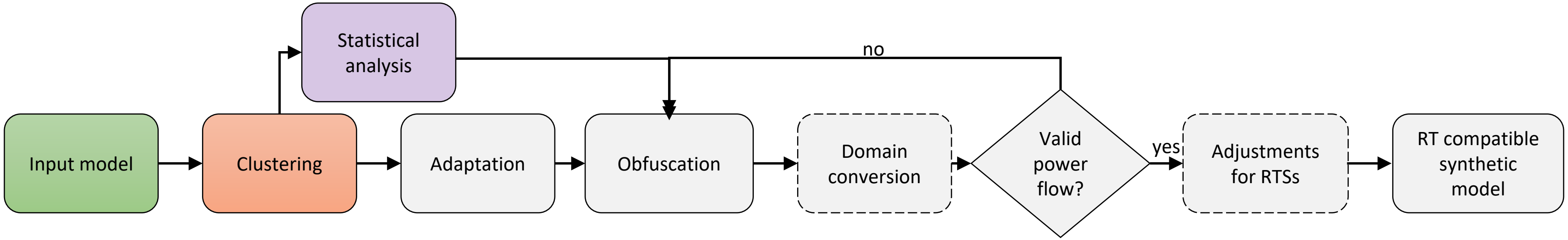




Clustering and Statistical Analysis

- Group of common components:
    - Dynamic models
    - Control models
    - Voltage level
- Identification of prevalent models

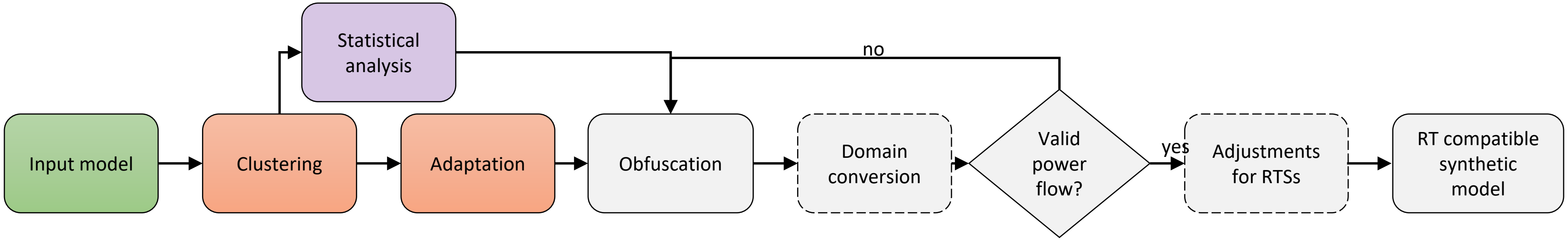
Category	Model	Participation
Sync. generators	GENROE GENSAL GENSAE GENROU	29% 18% 14% 13%
SVCs	CSVGN4 CSVGN1	2% 1%
User-defined models	Machines Wind systems HVDC link	14% 6% <1%



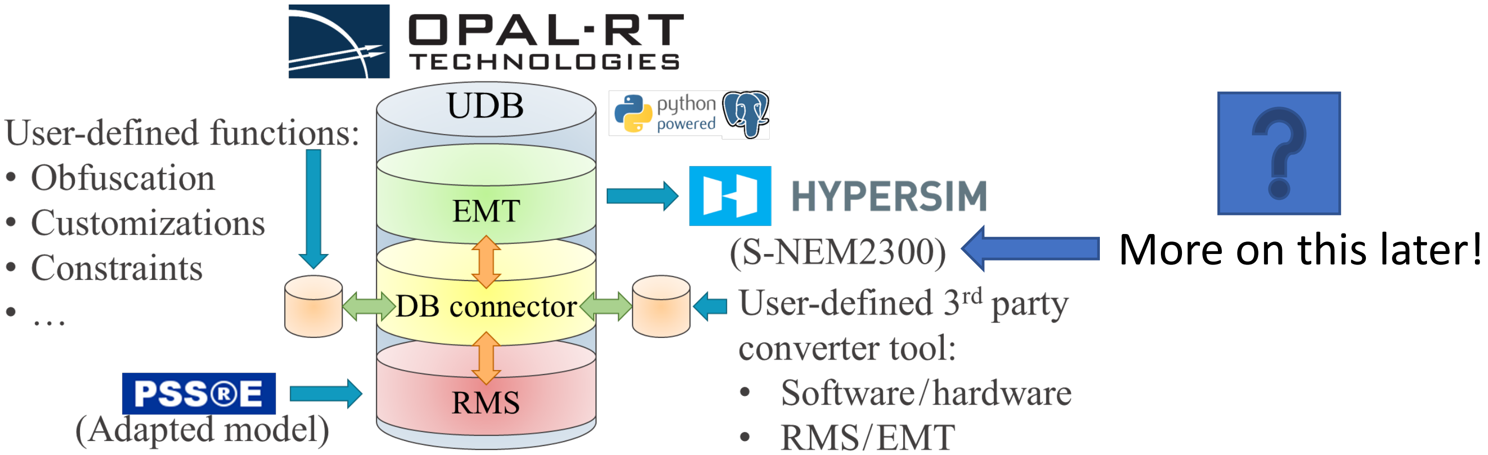
Adaptation

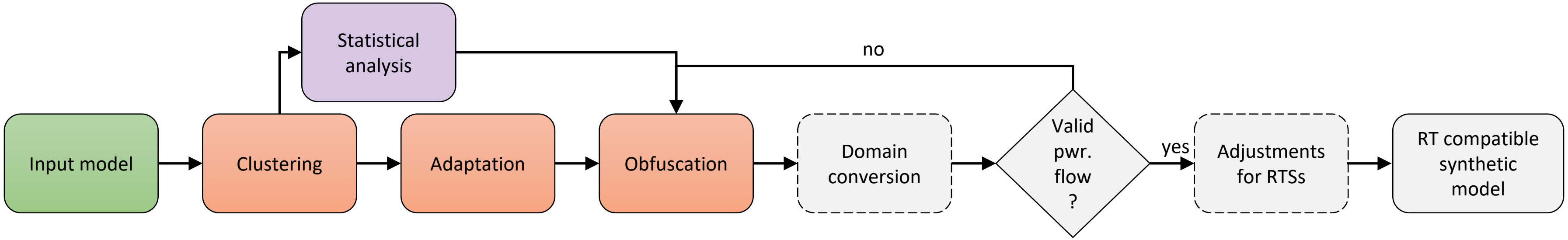
- Definition of models to use:
  - Constant parameter lines ($\sqrt{LC} \geq t_s$)
  - PI lines ($\sqrt{LC} < t_s$)
  - Dynamic loads
  - 2 types of synchronous generators
- Replacement of user-defined models

Component	Thermal Units	Hydro Units
Machine	GENROU GENROE	GENSAL GENSAE
Governor	TGOV1	HYGOV
Exciter	IEEET1	
Stabilizer	PSS2B	



Obfuscation

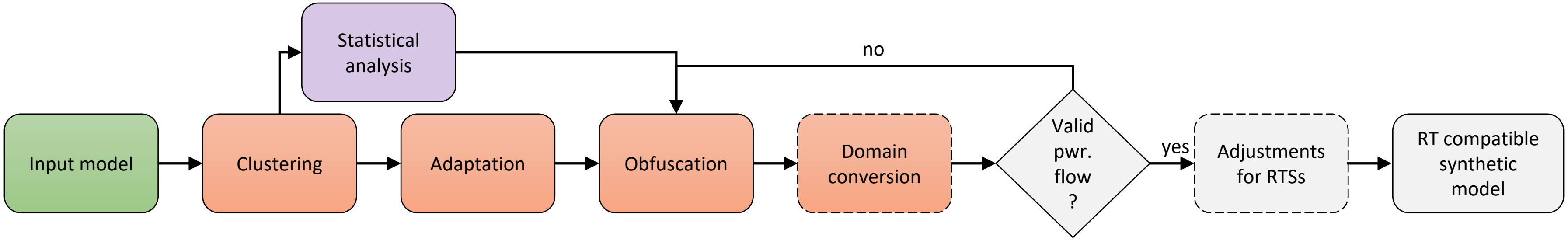




Domain Conversion

- RMS to EMT domain
- Assumptions:
  - Balanced network
  - Typical values of transmission line reactances
    - $\frac{R_0}{R_1} = 10, \frac{L_0}{L_1} = 3, \frac{C_0}{C_1} = 0.5$

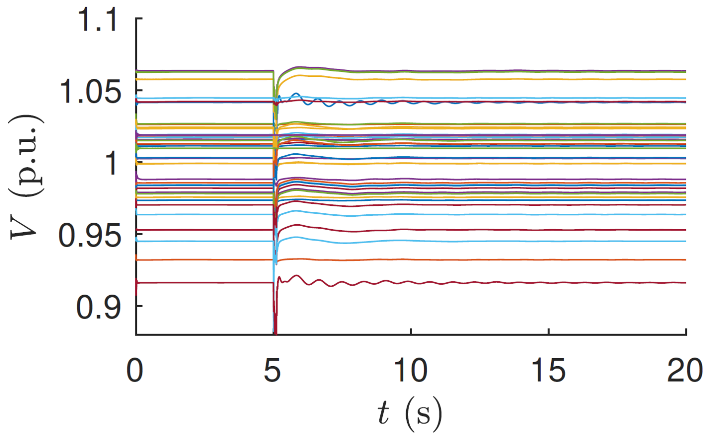
Voltage (kV)	X (Ω/km)
6.6 – 220	0.5
275 – 330	0.39
500	0.3



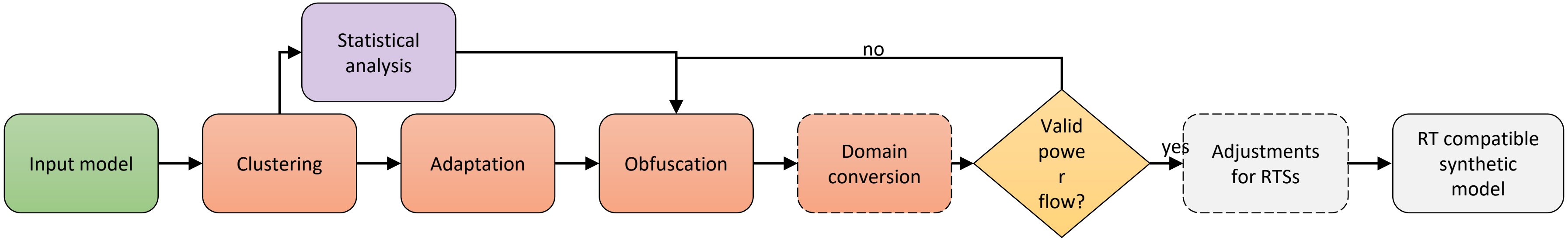
Initial Validation

- Transmission lines:

$$v = \frac{1}{\sqrt{LC}} < c$$

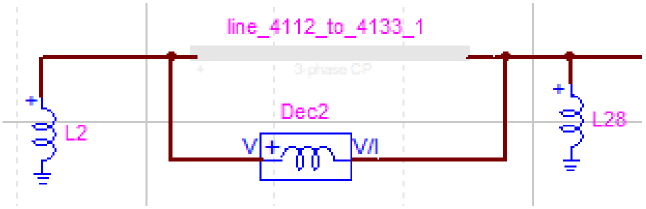


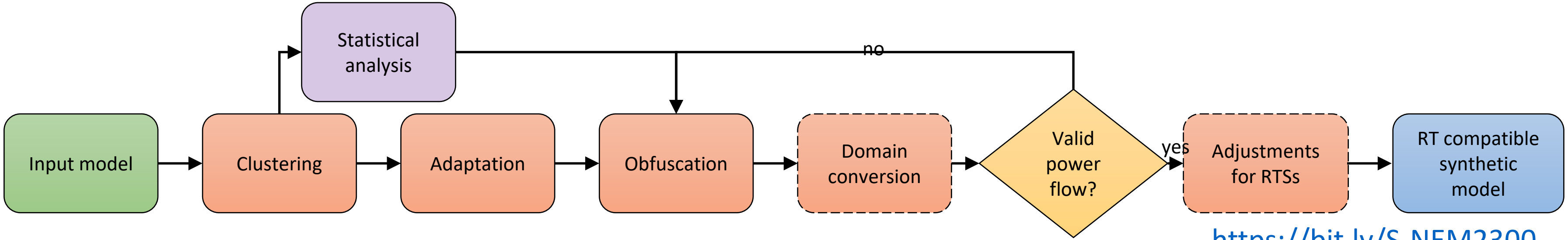
- Load convergence:
  - 5 iterations
  - 0.94 MW mismatch (0.003%)



Adjustments

- Addition of decoupling elements
- S-NEM2300-bus benchmark model:
  - +2,300 buses, ≈200 synchronous machines
  - +43,500 kms of transmission lines
  - Spans over 3,700 km

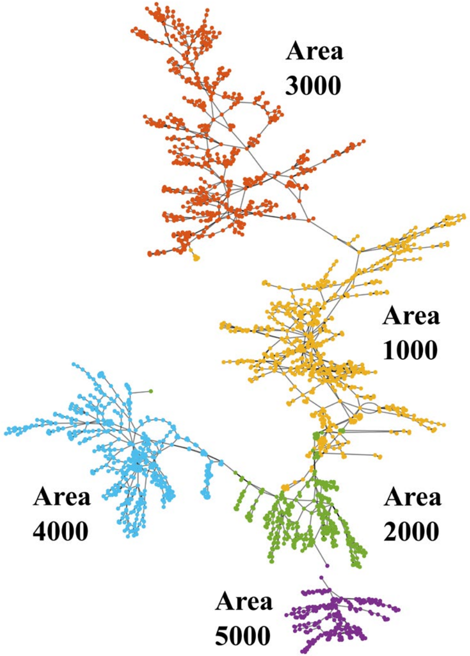


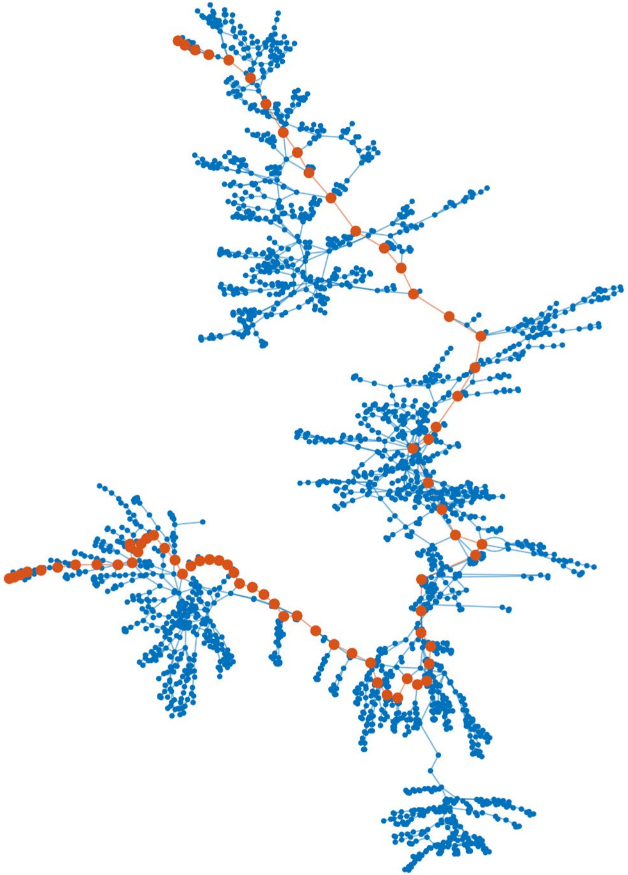


https://bit.ly/S-NEM2300

Real-Time Simulations Laboratory RTS@UNSW

Output





Real-Time Simulations Laboratory
RTS@UNSW

Properties and Comparison

Property	NEM[†]	S-NEM2300	Variation
n	2,340	2,340	0
m (#)	3,579	3,579	0
m (km)	43,564	43,578	+14
$\overline{k}$	3.059	3.059	0
$\overline{C}$	0.0936	0.0936	0
$\overline{l}$ (edges)	21.393	21.393	0
$\overline{l}$ (km)	1,223	1,213	-10
d_{max} (edges)	53	53	0
d_{max} (km)	3,826	3,793	-33

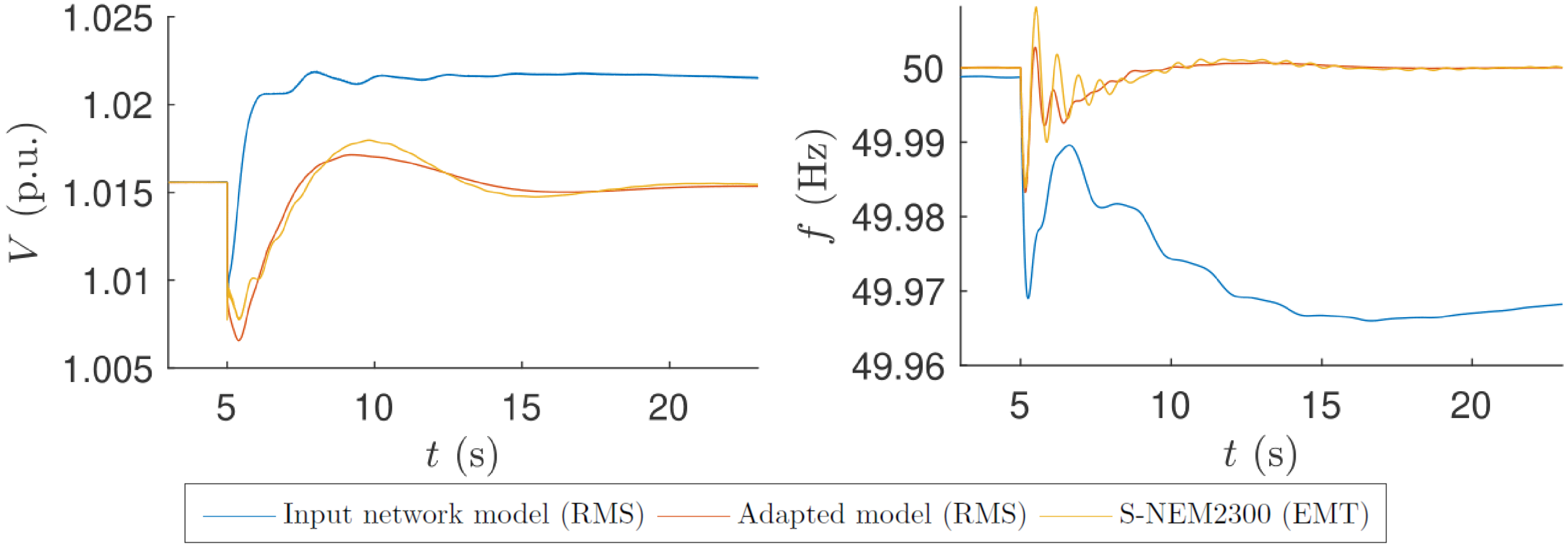
- Evaluation Metrics:
  - Number of nodes (*n*)
  - Number and length of lines (m)
  - Average vertex degree (k)
  - Clustering co-efficient (C)
  - Average path length (l)
  - Diameter of graph (d)

The Real "Real-Time" Part

- Implemented in HYPERSIM
  - Load Flow convergence in 7 iterations (0.94 MVA mismatch)
  - 50-µs simulation timestep
  - Would require ~400 cores for RT simulation
  - RTS@UNSW has 7 cores on an Intel(R) Xeon(R) CPU E5-2667
    - 10 seconds of simuation -> 450 seconds

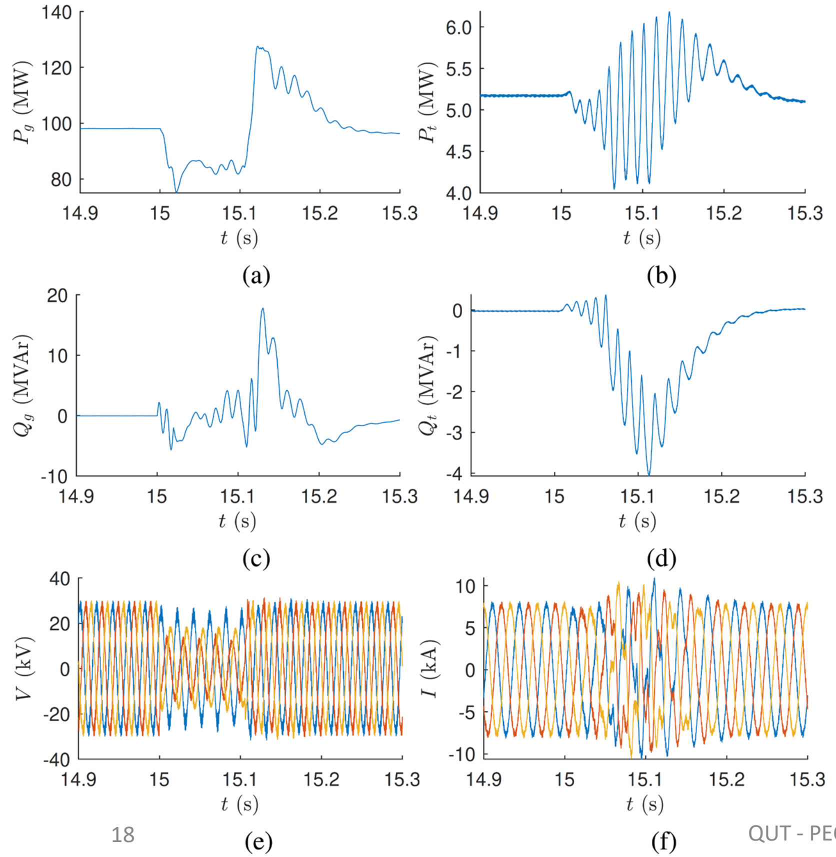
  - The "other" challenges of RT simulation for very large models

Validation



Load increase

Application Examples

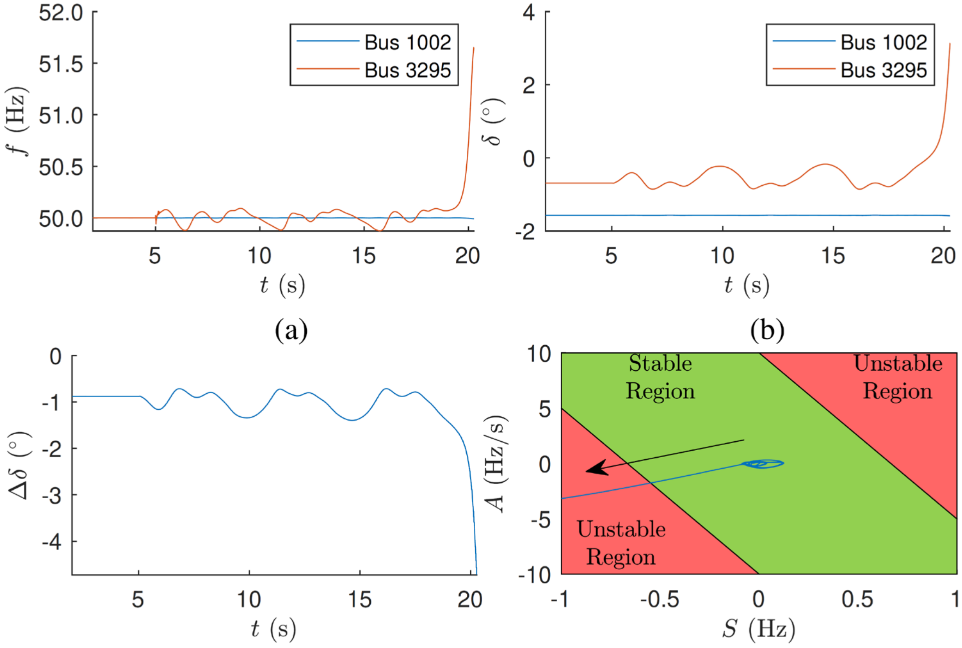


- Assessing the performance of renewable energy integration into weak grids.

Arraño-Vargas F, Shen Z, Jiang S, Fletcher J, Konstantinou G. Challenges and Mitigation Measures in Power Systems with High Share of Renewables—The Australian Experience. *Energies*. 2022;

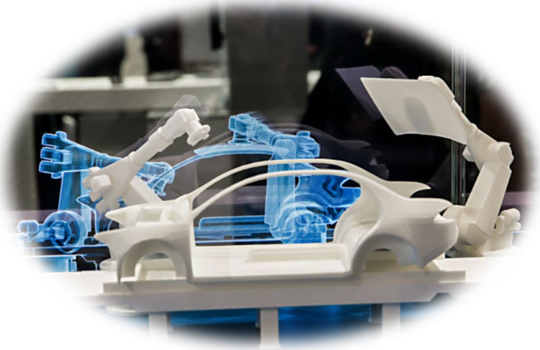
Application Examples

- Testing 'what-if' scenarios.
  - Real-time models are updated based on measurements from the grid, and potential threats are analyzed under realistic circumstances and alarms can be raised accordingly



What is a Digital Twin?

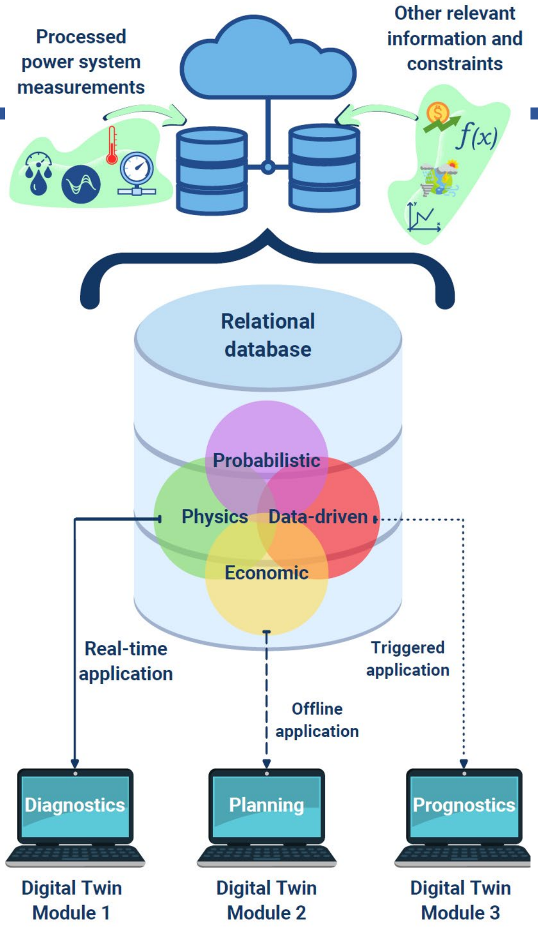
"virtual representations of physical systems and/or processes, enabled through data and simulators, that allow real-time monitoring, controlling, prediction, optimisation, and improved decision making"[1]



[1] A. Rasheed, O. San, and T. Kvamsdal, "Digital Twin: Values, Challenges and Enablers From a Modeling Perspective"

Key Elements of a PSDT

- The physical counterpart
- The digital [part]
- Communication infrastructure
- Data / Models
- Services



Digital Twins in Power Systems

FINGRID

nationalgrid

AMERICAN ELECTRIC POWER

Asset and operation management

Improve efficiency, reliability, and utilisation of distributed assets

Enable better coordination of network model information

Digital Twins in Power Systems

The NEM's digital twin and the imperatives for new market signals

At a CEDA event exploring 'Opportunities in the Future Energy Market', AEMO's Audrey Zibelman and a lineup of energy thought leaders highlighted the need to value firming services in the new asynchronous energy market, and heralded real-time visualisation of grid and asset performance in the form of digital replicas of the NEM and WEM.

SEPTEMBER 9, 2019 NATALIE FILATOFF

"Digital twin": Online simulator to help wind and solar farms connect to the grid

Giles Parkinson 19 August 2021 2

Utilidata And Sense Team Up To Create End-To-End Digital Twin Of Electric Grid

Utilidata
July 2, 2019

February 23, 2022

OPAL-RT TECHNOLOGIES and Coordinador Eléctrico Nacional (CEN) Sign a Collaboration Agreement to Model a Digital Twin of the Chilean Electrical Network

[MONTREAL, February 23rd, 2022] OPAL-RT TECHNOLOGIES is pleased to announce a collaborative agreement with Coordinador Eléctrico Nacional (CEN) of Chile to start using OPAL-RT's real-time simulation expertise and experience in the modeling of a digital twin of their electrical network. CEN is responsible for coordinating the operation of the Chilean electric network in order to ensure its security and economic operation. The network includes 35,501 km of transmission lines, extended over 3,100 km of territory, and has the capacity to generate 25,284 MWs of energy—sufficient for around 97% of the Chilean population.

AEMO completes pilot testing for world-first grid connections simulator

PUBLISHED: 21/09/2022 2 min

An Evolving Concept

- DTs remain an **evolving** concept in the context of power systems.
- The setup and implementation of power system DTs vary depending on the **requirements for the services provided**.
  - A DT should create comparable behaviors of its physical counterpart in a digital environment and provide insights or predictive analytics of the physical system.
  - Within a DT-enabled system, a DT can establish **comprehensive digital models** of physical entities with full support for bi-directional communications to enable real-time interactions between digital system and its physical counterpart.
  - Data measured on the physical twin are used to update the DT concurrently so that the DT can follow up and analyze the latest status of its physical entity.
  - Analyzed results of the DT can be sent back to the physical system so that actual systems can be manipulated or guided by advanced data analytic technologies.

One-to-one Power System Digital Twin (PSDT)

- Power systems are **large and complex physical systems**.

➡ A PSDT is limited to smaller portions of the grid, or focuses on specific aspects of its behaviour due to high costs of implementation and maintenance.

- A power system is **critical infrastructure** that contains sensitive and confidential information.

➡ Information is often protected from public disclosure which restricts the research that can be done.

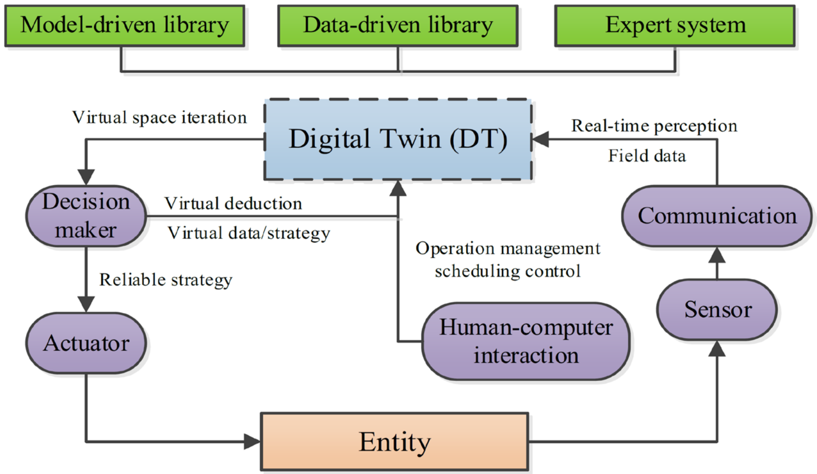
One-to-one Power System Digital Twin (PSDT)

- A flexible and versatile PSDT implementation would allow to:
  - **integrate** a variety of services and applications, making the expansion of the DT possible, even beyond the electricity network (e.g., gas, hydrogen industries),
  - **unlock** the full potential of DT technology, increasing the breadth and depth of services and applications,
  - **provide** a robust and adaptable solution for monitoring, operating, and planning future power systems, and
  - **accommodate** a potential environment for R&D outside the industry, integrating new actors such as research institutes and universities.

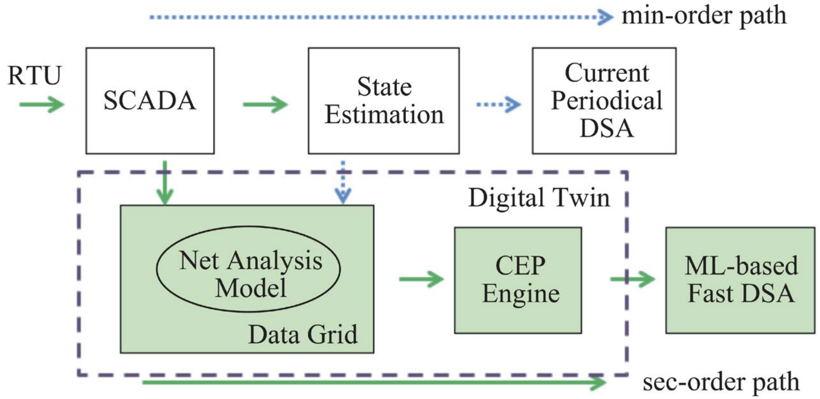
Current Approaches for PSDT Implementation

Asset oriented → Application: prognostics → User: Owner of the asset

System oriented → Application: situation awareness → User: TSO



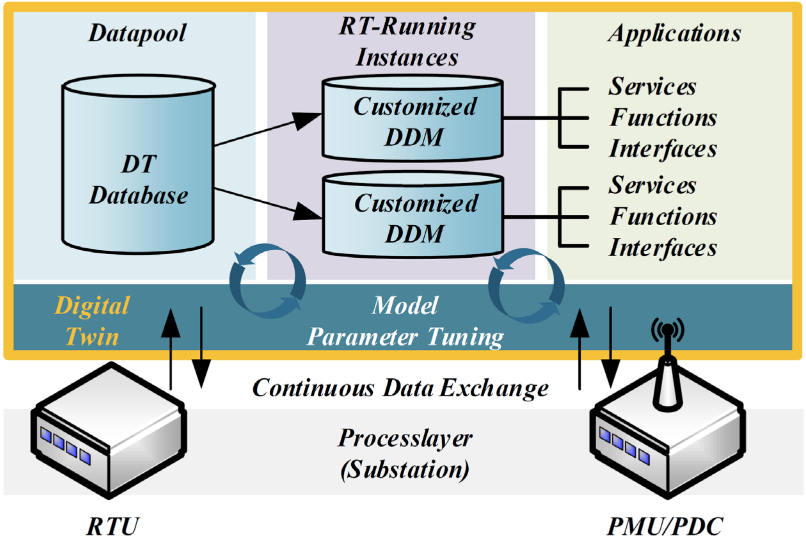
H. Pan *et al.*, “Digital Twin and Its Application in Power System”



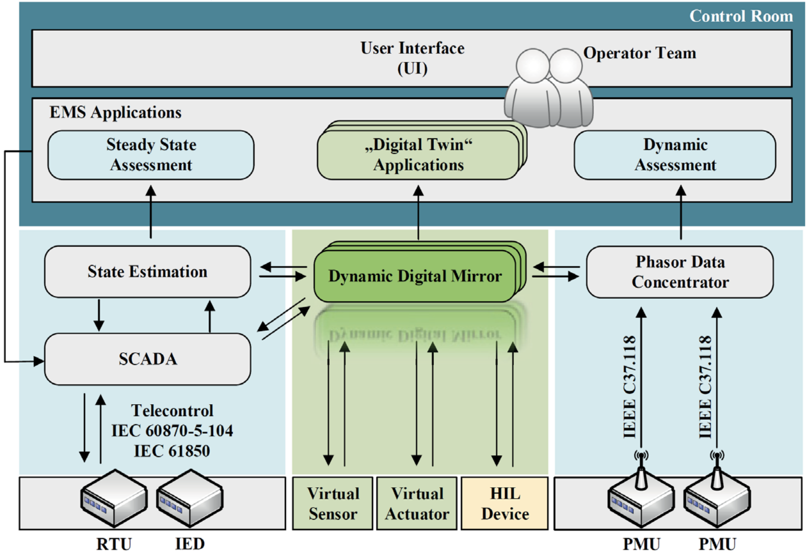
M. Zhou *et al.*, “Digital Twin Framework and Its Application to Power Grid Online Analysis”

Current Approaches for PSDT Implementation

Grid oriented → Application: grid assessment → User: TSO



C. Brosinsky *et al.*, "Recent and Prospective Developments in Power System Control Centers"



C. Brosinsky *et al.*, "Digital Twin– Concept of a Continuously Adaptive Power System Mirror"

Current Approaches for PSDT Implementation

Limitations

Electrical-related measurements from the asset or grid.

Only one user is envisioned to operate the PSDT or benefit from it.

PSDT includes self-adaptation and/or limited number of services, but no room for expansion.

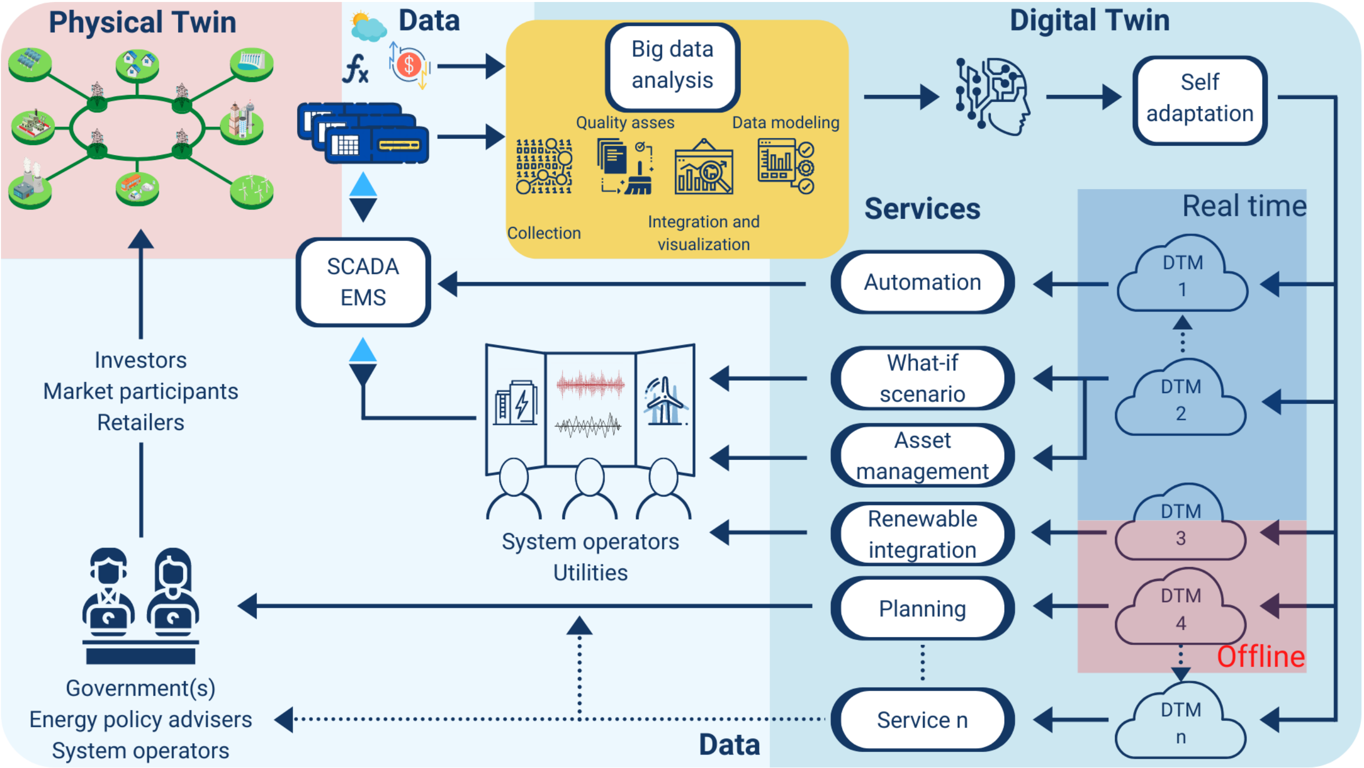
Potential Improvements

Other sources: weather conditions, spot prices, operational constraints, thermal measurements, etc.

Additional parties can be included: energy policy advisers, investors, utilities, retailers, researchers, etc. measurements, etc.

Streamlining design procedure when implementing PSDTs. measurements, etc.

Modular Power System Digital Twins



F. Arraño-Vargas and G. Konstantinou, "Modular Design and Real-Time Simulators Toward Power System Digital Twins Implementation," in *IEEE Transactions on Industrial Informatics*. (Early Access). DOI: 10.1109/TII.2022.3178713

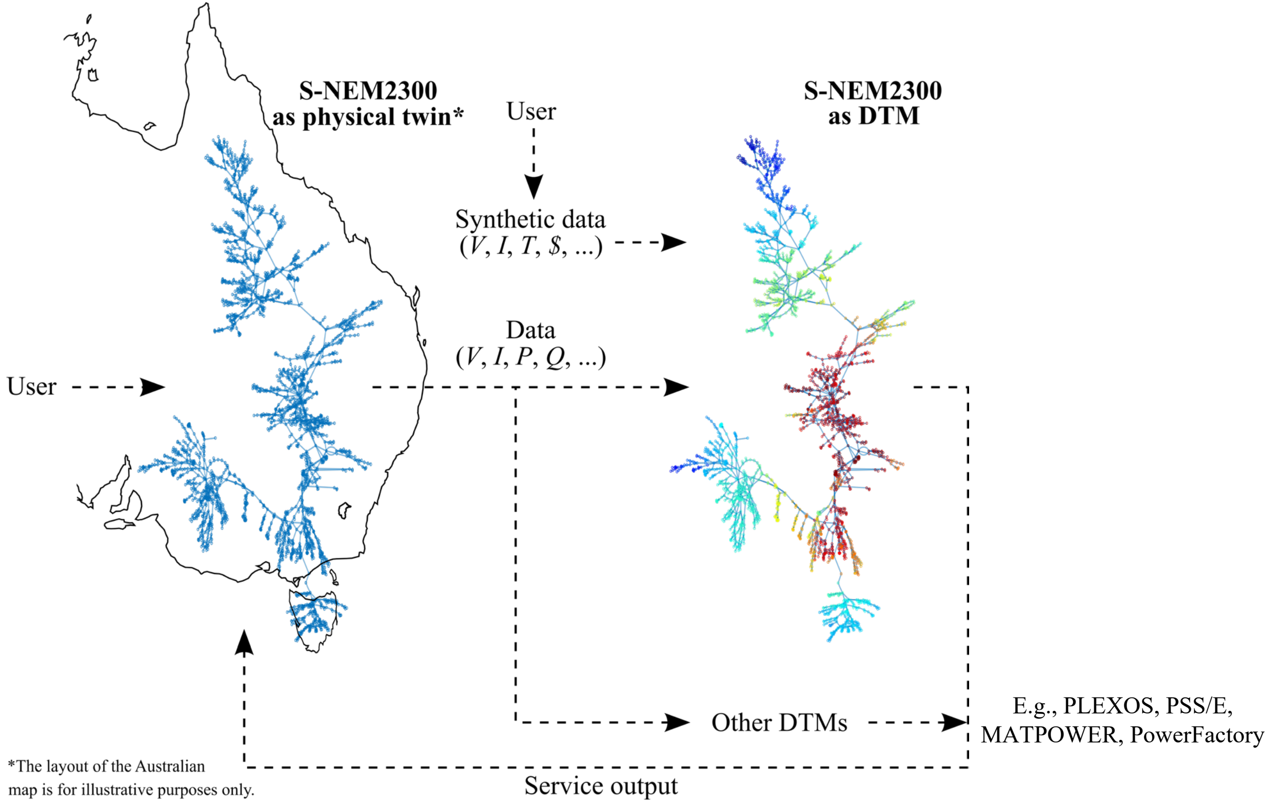
Digital Twin Module (DTM)

- Basic, function unit of the modular PSDT that co-exists with other DTMs.
- It inherits the capabilities and functionalities of a DT.
- It plays the role of a DT for a specific component, asset, or system, and provides a service or a set of services.
- A DTM can be supervised or self-regulated.
- A DTM can run in real time, automatically or manually triggered, or executed in offline mode when required by (one of) the user(s).

Digital Twin Module (DTM) – App. Examples

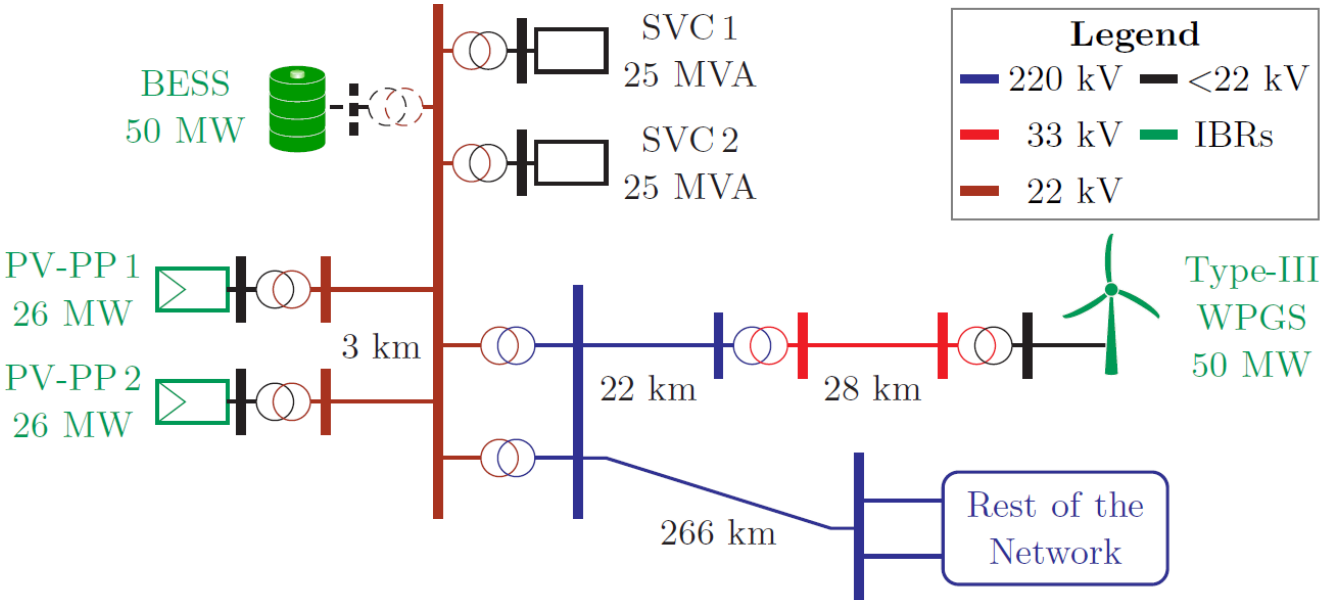
- **Monitoring and controlling** a power system assets and/or grid in real time.
- **Diagnostics** based on multi characteristic measurements and parameters together with algorithms to determine cause of failures.
- **Prognostics** of power system components and assets.
- **Forecasting and prediction** of generation, demand, and faults among other conditions.
- **Grid integration applications** to support, test, and validate studies.
- **Training** of system operators, maintenance personnel, etc.
- **Integrated system planning** to meet security of supply, grid reliability and network resilience targets.

Implementing a Synthetic Digital Twin of the NEM



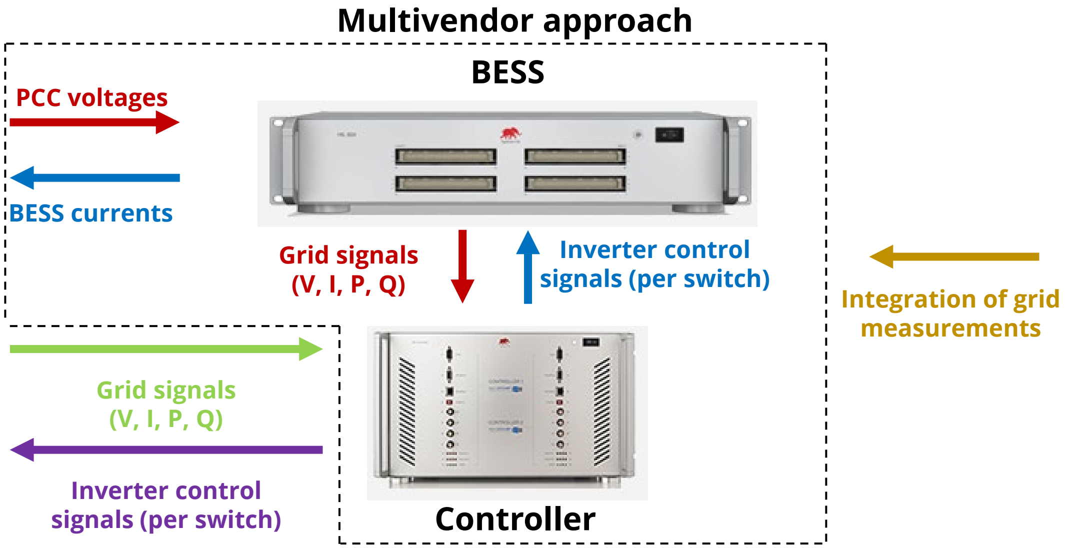
Real-Time Simulations Laboratory
RTS@UNSW
UNSW SYDNEY

Digital Twin of Weak Area of the NEM



Digital Twin of Weak Area of the NEM: CHiL

West Murray Zone and BESS



Data Concerns in AI Applications

Data Availability

- Sufficient datasets required for training, testing and validation
- Limited timely data in real-world applications

Source Diversity

- Information across multiple domains
- Different types of data (e.g., time-series, numerical, categorical data)

Data Quality

- Demanding requirements for more detailed information
- Synthetic and offline simulation data with certain simplifications

Time-Sensitivity

- Operational data representative for a short time period
- Effectiveness and timeliness of (close-to) real-time applications

Shen, Z., Arraño-Vargas, F., & Konstantinou, G. (2023). Artificial intelligence and digital twins in power systems: Trends, synergies and opportunities. *Digital Twin*, *2*, 11.

Challenges of AI Implementation

Interpretability

- Internal logic of AI algorithms are not easily explainable, which compromises the use on security-critical system.

Repeatability

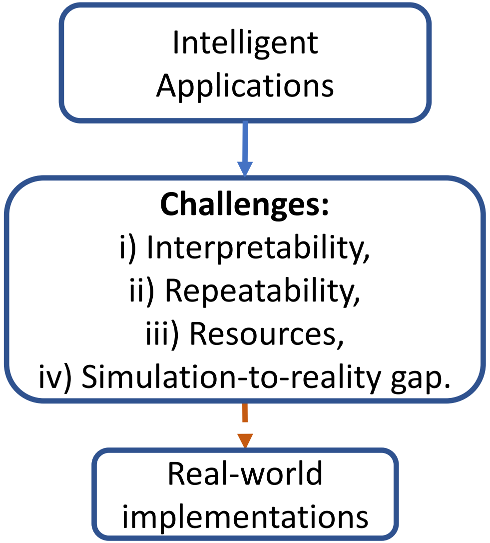
- Successive tests under well-defined and identical configurations are required to validate and tune applications.

Resources

- Extensive computation and storage resources are needed to operate AI applications at scale in real power systems.

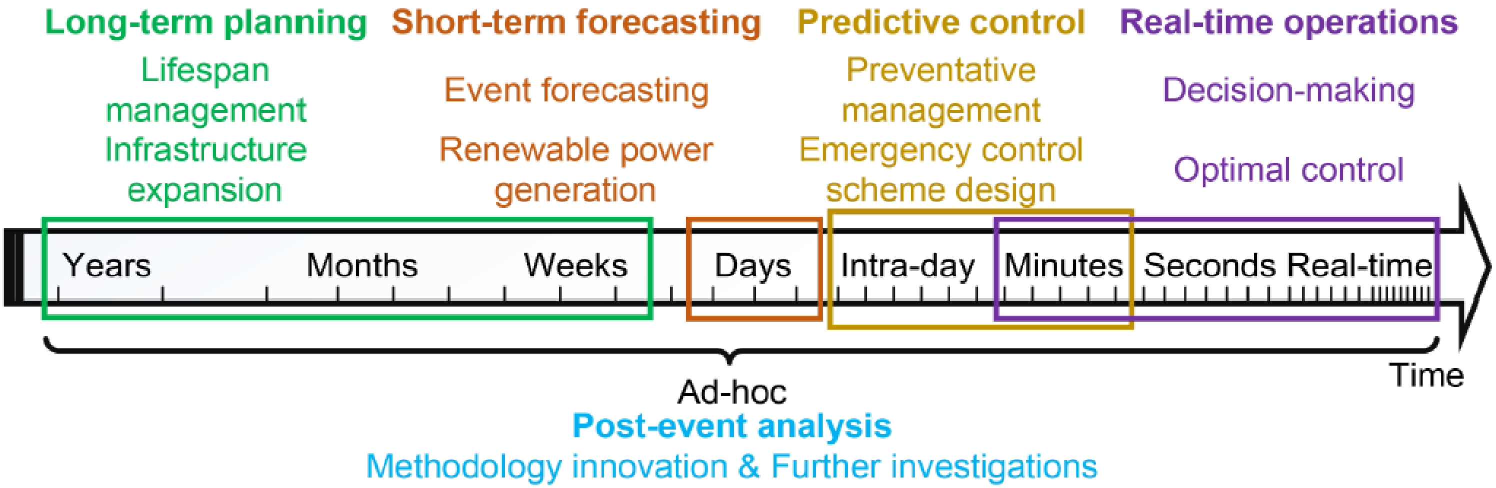
Simulation-to-reality gap

- Since differences exist between model/datasets and real system, robustness and safety should be ensured.



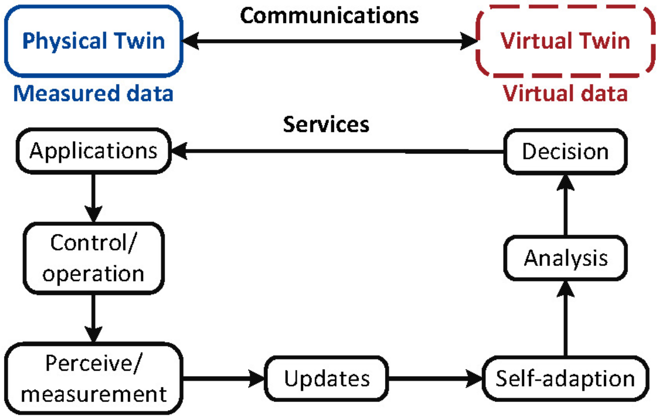
Time-Scales for Applications

Time-related issues are concerned in power system applications that have different levels of time-sensitivity of data.



High level structure of a DT-based system

- Bi-directional communications are built between physical twin and virtual twin.
- Data is measured from physical twin to update/self-adapt virtual twin to continuously reflect its behaviors.
- Virtual data is generated by virtual twin to support the applications based on additional data, intelligent decision-making and insights.



Power Grid Digital Twins

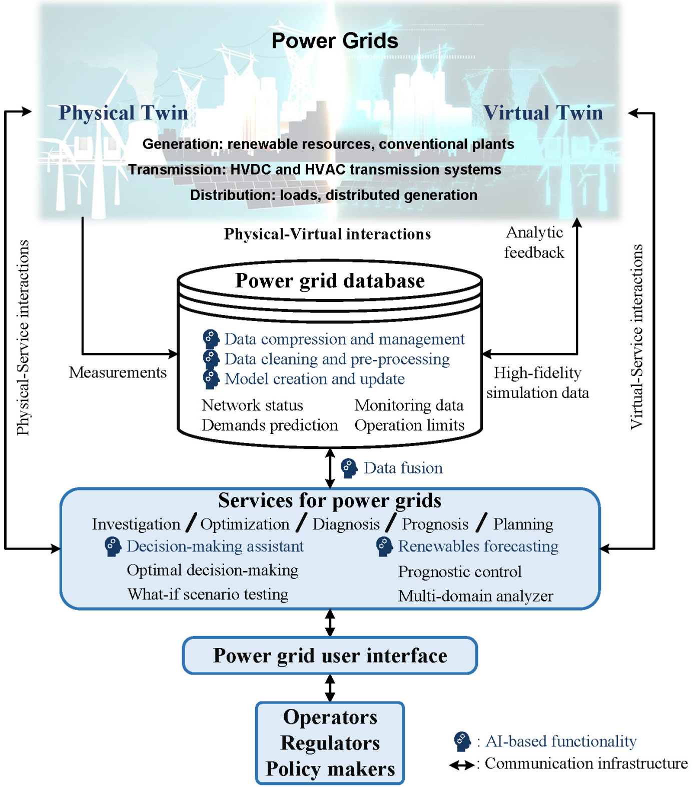
Services: across different domains from generation to trading and consumption, for instance,

- AI-enhanced optimal decision-making toolbox
- AI-supported prognostic control
- AI-aided "what-if" scenario testing
- AI-based multi-domain analyzer

Virtual twin: digital representation of one or more specific domains of power grids

Database: storage of operational data from PT and virtual datasets from VT for further applications

Function of AI: high volume of data from both power grid and its virtual twins to support operations



Power Asset Digital Twins

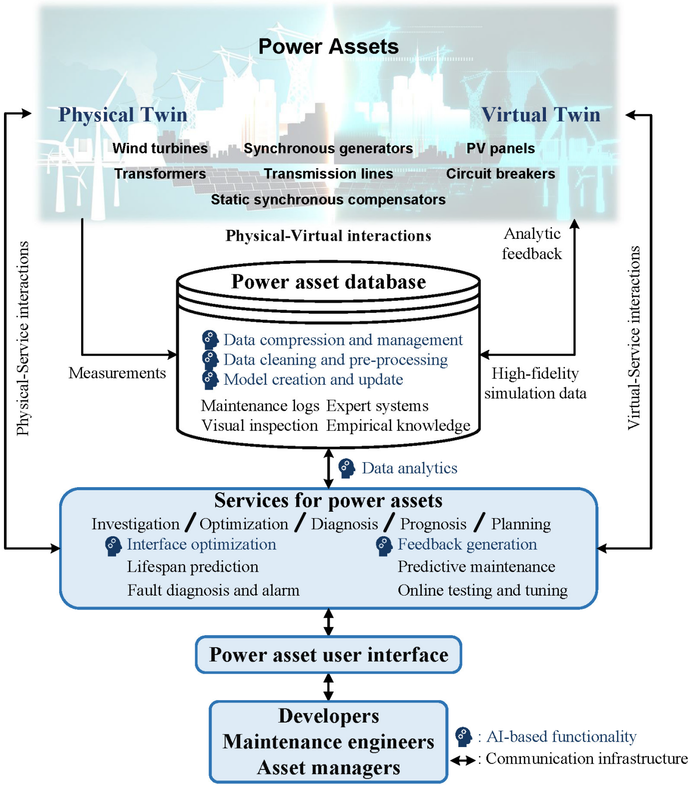
Services: through the whole life span of power assets, such as,

- AI-aided lifespan prediction
- Predictive maintenance with AI support
- Fault diagnosis and alarms with AI enhancement
- AI-based asset testing & optimization

Virtual Twin: digital replica to easily access the operational data and identify erroneous behaviours

Database: storage of maintenance data and historical information for a series of components

Function of AI: online prediction and identification of the potential issues of critical assets



Summary / Conclusion

- **Synthetic networks** provide open benchmark to **design, test and validate** any proposed implementation.
- The proposed methodology for **development of synthetic grid models** is aimed at **real-time simulations** compatible open models**.**
- The **S-NEM2300-bus benchmark** preserves the main characteristics and topology of a longitudinal power system.
- The S-NEM2300-bus benchmark will allow **better visualization** of fast phenomena and dynamic stability evaluation.

Summary / Conclusion

- Most critically, Real-time Simulations **are a key element** in the development and deployment of **Digital Twins in Power System applications.**
- **Model-driven design for DTs**
- A **modular approach** allows for enables the expansion of the twin beyond power system components and facilitates the integration of multiple services and users, without affecting the functionality of existing modules.
- Integration of multiple services that can represent distinct domains

Summary / Conclusion

- Power system digital twins (PSDTs) can uplift how data from power grids and their equipment is processed, providing operators new ways to visualize and understand the information.
- A modular design allows to potentially achieve a one-to-one digital twin of any power grid and its assets.
  - Addresses key implementation barriers
  - Connects existing and additional services to a unified platform
  - Allows for participation and actions from new and external actors
  - Unlocks advanced and dedicated applications
- A synthetic PSDT is seen as a testbed that can be used by researchers to test, develop, and propose new methods and applications that can be implemented in real PSDTs.

Questions

Thank you to Felipe Arraño-Vargas and Zhiwei Shen for their input to this presentation