Merging Power Systems and Power Electronics for Smart Grids with SIMBA, Python, and Julia

By Marcelo Godoy Simoes, Luca Ferranti and Peyman Razmi

March 28th, 2024

POWERSYS

Vaasan yliopisto
UNIVERSITY OF VAASA

Our today's speakers

Pr Marcelo Godoy Simões

Marcelo Godoy Simões is Professor in Flexible and Smart Power Systems at the University of Vaasa, Finland. Prior positions include 11 years at the University of São Paulo (Brazil), 21 years at the Colorado School of Mines (USA), visiting-professorships at Georgia Tech, L'École Normale Supérieure de Cachan and Université de Technologie Belfort-Montbéliard in France, Petroleum Institute in Abu Dhabi (UAE), and Fulbright Scholar at Aalborg University. He developed several AI based power electronics for renewable energy and smart-grid integration, with several advanced applications, such as wind energy conversion, and early automation-control based-model of fuel cells. His current research interests include smart grid-based inverters for renewable energy, power electronics and power systems, power quality, renewable energy, artificial intelligence. He is a Fellow of the IEEE with citation "for applications of artificial intelligence in control of power electronics systems."

Peyman Razmi

Peyman Razmi, a PhD scholar in Power Electronics at Vaasa University, is also a skilled Data Scientist and AI Specialist. Proficient in programming languages including Python, Java, and Julia, Peyman combines his expertise in power electronics with advanced data science and AI techniques. His work prominently features in both academic and professional realms, where he contributes

to the development of sustainable electronic systems and the innovative application of machine learning in his field.

Luca Ferranti

Luca Ferranti is a doctoral researcher at the University of Vaasa, Finland. His research interests lie in scientific computing, computer algebra, automated reasoning, fuzzy logic and their applications. He is also interested in open-source software development and promoting its role in academia. He is a Julia enthusiast and has developed research software in Julia and worked as Julia software engineer.

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AGENDA

10h05: Introduction of Powersys and the guest speakers

10h10: Unified modeling and simulation analysis of power electronics, power systems, and smartgrids (Marcelo)

10h30: Python and SIMBA simulation case study (Peyman)

10h45: Live Pluto Notebook software-based presentation of Julia for Electrical Engineering Systems (Luca)

11h05: Q&A based on written chat questions

11h15: Announcements, follow-up and conclusion

POWERSYS

University of Vaasa
FINLAND

Who we are

- Specialist in electrification since 2002.
- Experts in model-based design simulation software
- 30+ electrical engineers: North America, Europe, Asia
- Focused on EV

What we do

Manage technological evolution

Increase e-drive robustness

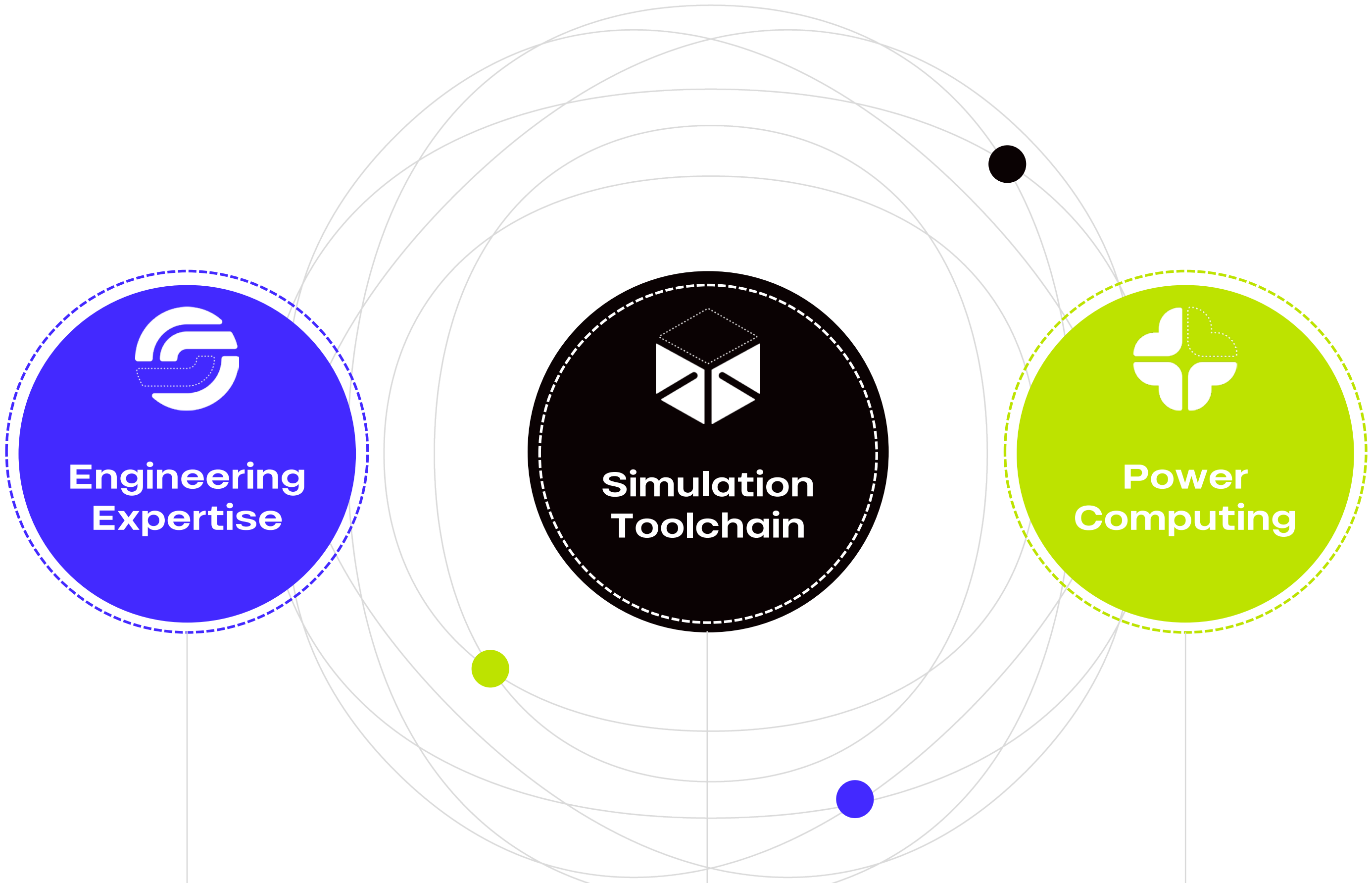
Mitigate production phase risks

Decrease your time-to-market

Powersys Value Proposition

Customized Turn-Key Design Platform

An electric design optimized for performance and for manufacturability



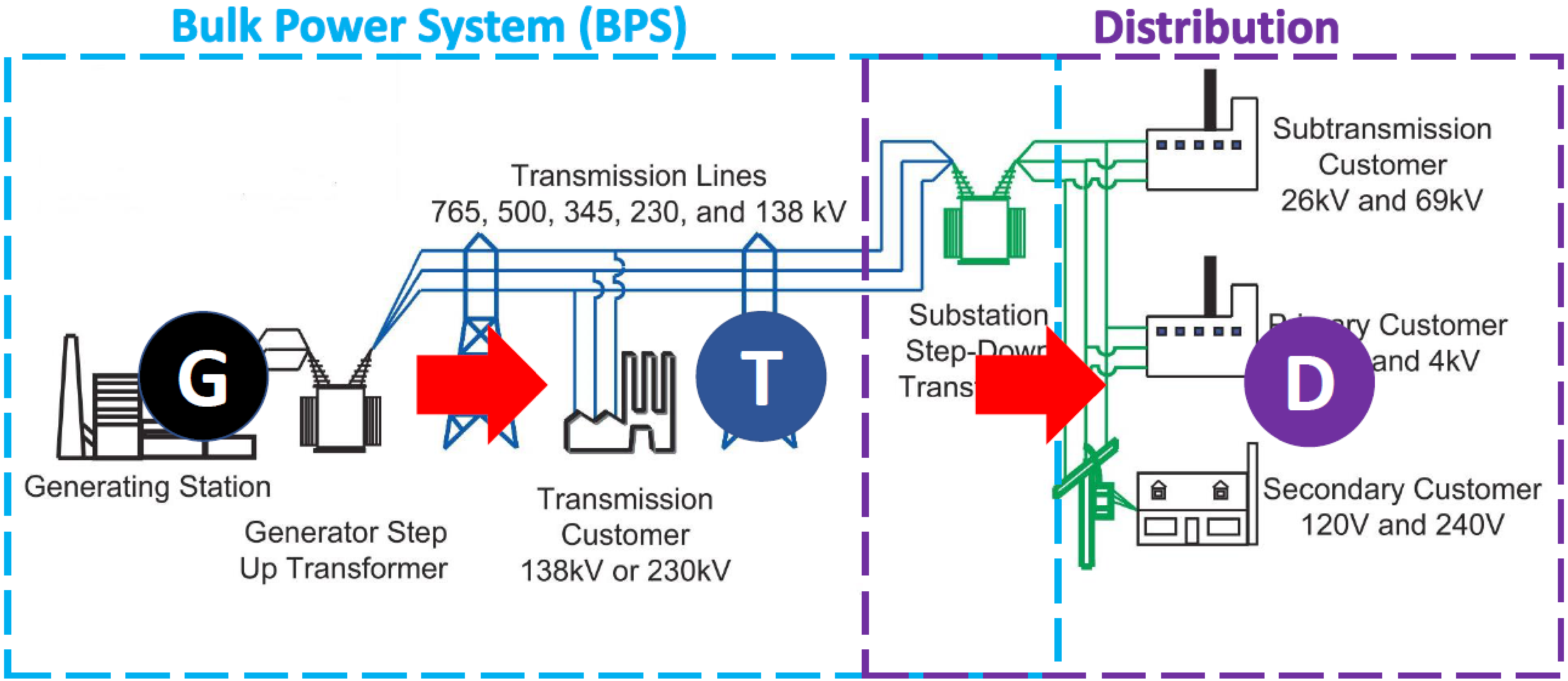
-25%
REDUCTION TIME OF YOUR DEVELOPMENT PROJECT

x20
TIMES FASTER CALCULATION

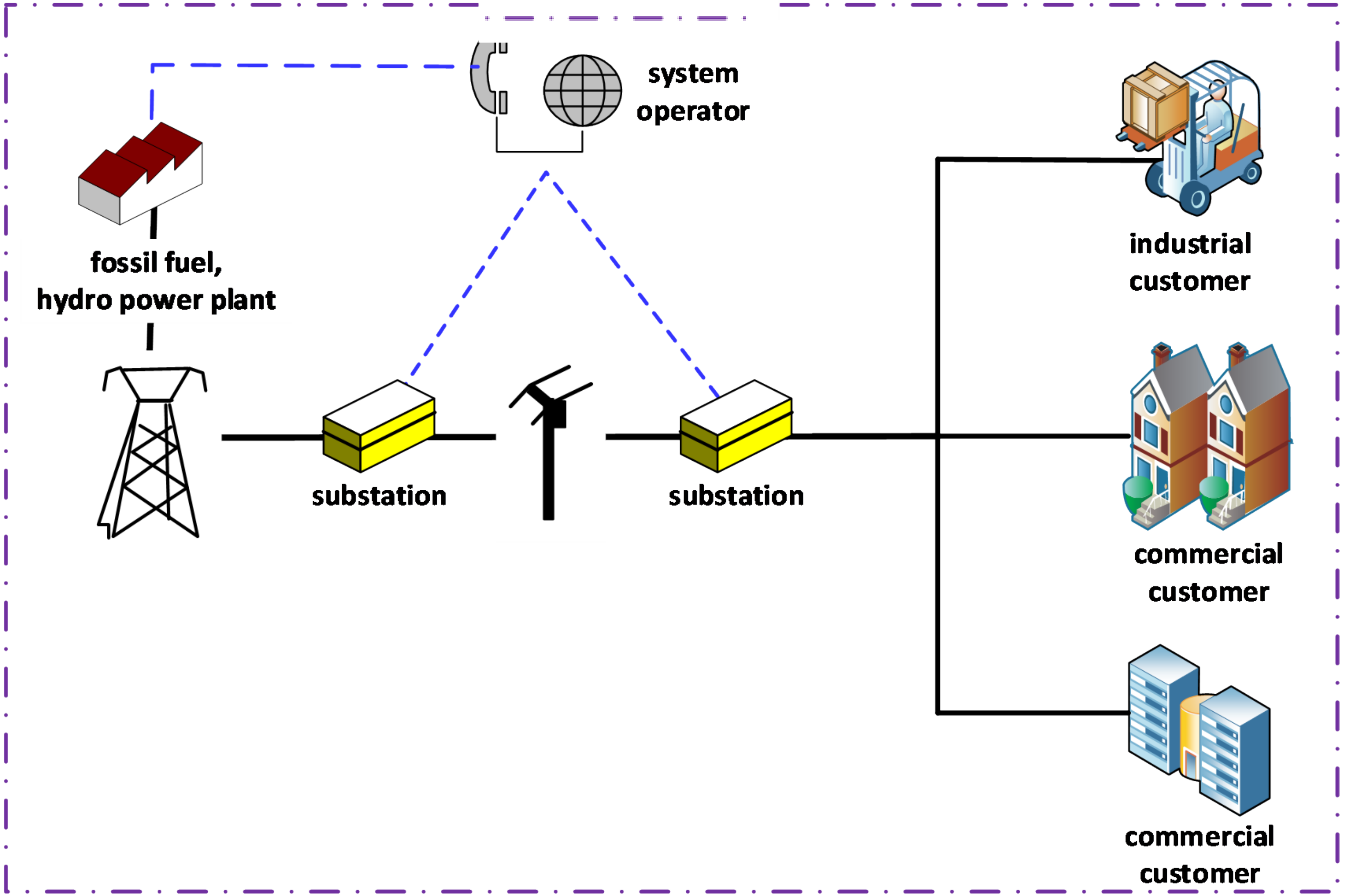
-80%
CALCULATION TIME

INITIAL IDEAS

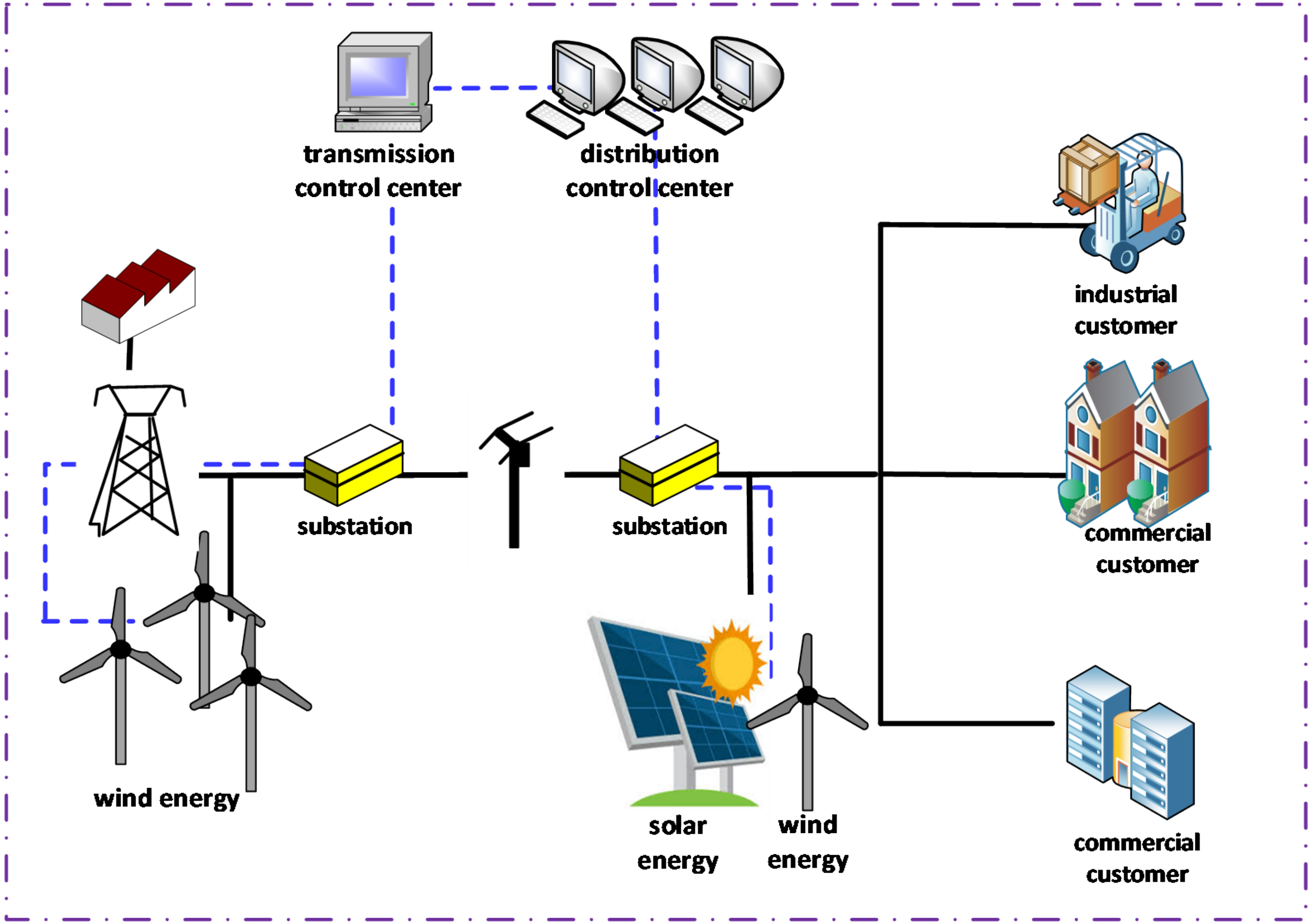
Traditional Way to Teach, Model, and Analyze the T&D Power System



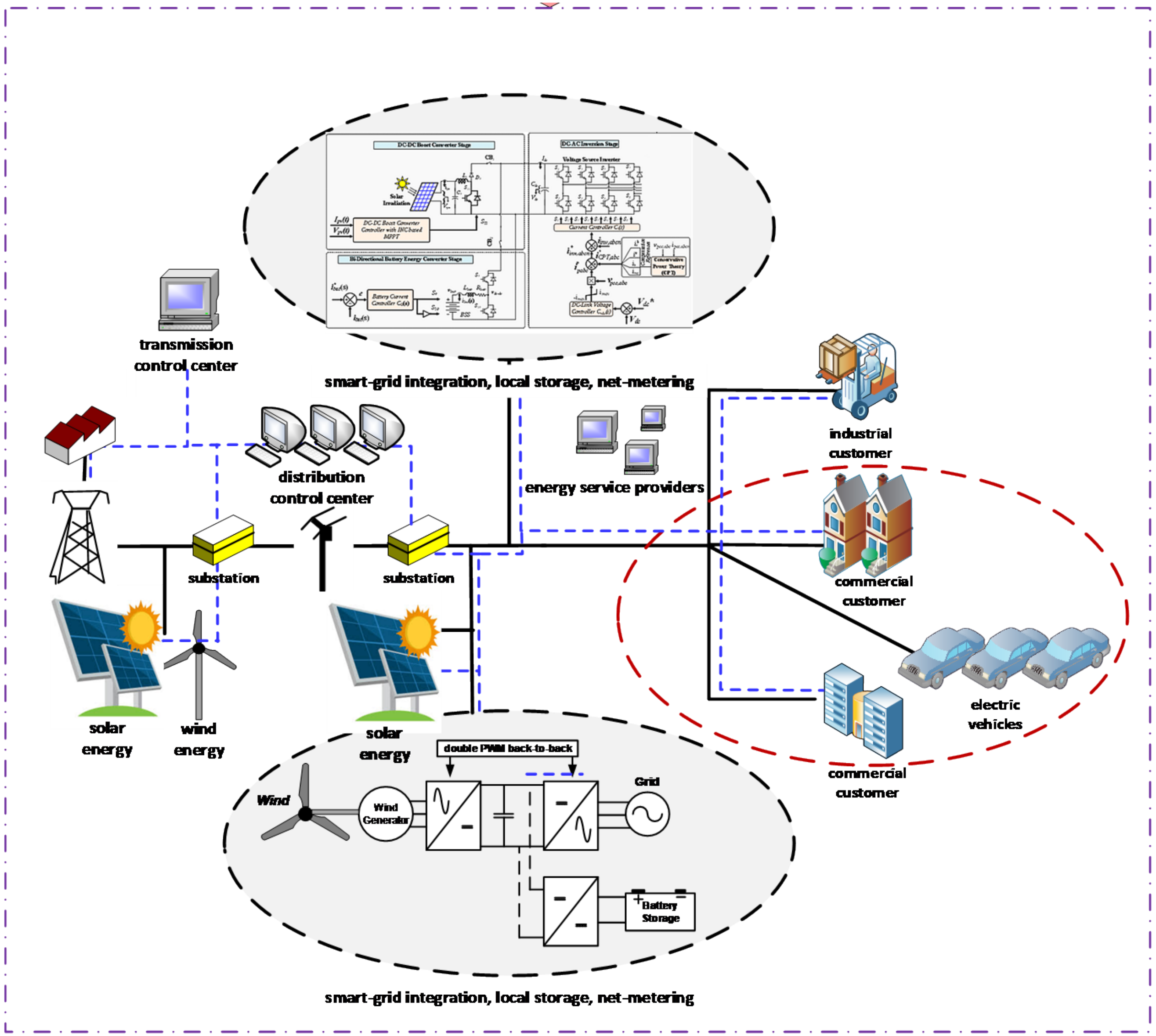
PAST


system
operator
fossil fuel,
hydro power plant
substation
substation
industrial
customer
commercial
customer
commercial
customer

PRESENT


transmission
control center
distribution
control center
industrial
customer
substation
substation
commercial
customer
wind energy
solar
energy
wind
energy
commercial
customer

FUTURE



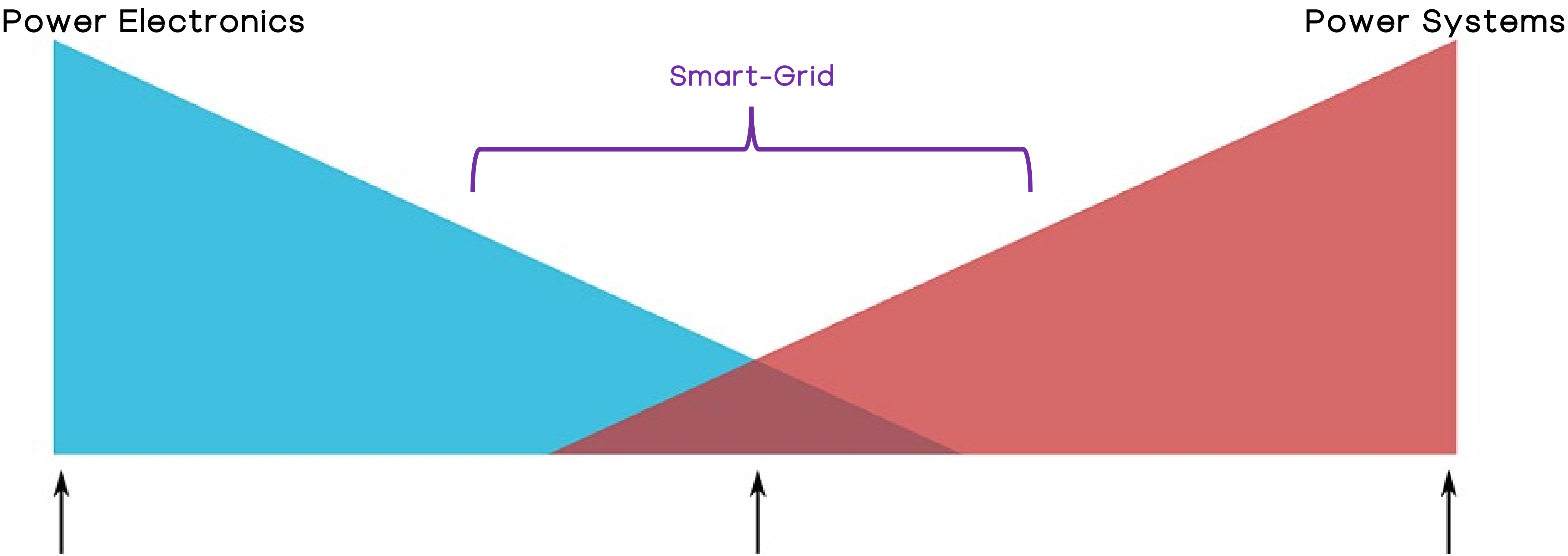
transmission control center
smart-grid integration, local storage, net-metering
distribution control center
energy service providers
industrial customer
substation
substation
commercial customer
solar energy
wind energy
solar energy
electric vehicles
commercial customer
double PWM back-to-back
Wind
Wind Generator
Grid
Battery Storage
smart-grid integration, local storage, net-metering

The smart-grid is the new infrastructure of today's grid

- The power system and electricity needs were simpler in the last 100 years.
- The grid was designed to deliver unidirectional electricity.
- The original structure is difficult for the rising demand ever changing needs of 21st century.
- The **smart-grid** is a two-way dialogue of electricity and information exchanged between the customers and the utility.
- Network of communications, controls, computers, automation, with new technologies and tools.
- The future grid must be efficient, more reliable, more secure and greener.
- A smart-grid enables new technologies to be integrated. Further wind and solar energy production. Plug-in electric vehicle charging. The smart-grid is the new infrastructure of today's grid.

REAL TIME SYSTEMS

How can we change the teaching and research paradigm towards a unified understanding of Smart-Grid: Power Systems, Power Electronics, Power Quality, and Renewable Energy Systems?



- Core competencies
- Advanced Circuits, Electronics and Control
- Power Electronics and Power Quality
- Computer Project Based Analysis and Simulations Design

- Overlapping Skills
- Steady-State and Transient Analysis
- Advanced Control
- Artificial Intelligence

- Core competencies
- Power Theory, Electrical Power Circuits
- Power Quality, Network Theory
- Computer Oriented PowerFlow, Voltage Stability Analysis

1) Steady-state simulations:
- Power flow
- State estimation
- Steady-state security assessment
- N-1, N-1-1 contingency analysis
- Fault analysis, fault location analysis
- Volt/VAr optimization
- Symmetrical components and unbalanced faults
- Induction motor analysis
- Device coordination and selectivity
- Reliability assessment
- AMR/AMI integration
- Power system markets

2) Long-term planning (in years)
- Production costing
- Model validation of generators
- Reliability evaluation

3) Scheduling (in hours)
- Economic dispatch
- Optimal power flow (OPF)
- Unit commitment
- Hydro-thermal Coordination
- Preventive Security Constrained OPF
- Renewable energy storage
- Weather modeling and predictions

4) Slow dynamic simulations (in minutes)
- Voltage stability
- Loadability limit calculations
- Thermal analysis
- Battery storage

SLOW DYNAMICS

3) Scheduling (in hours)
- Economic dispatch
- Optimal power flow (OPF)
- Unit commitment
- Hydro-thermal Coordination
- Preventive Security Constrained OPF
- Renewable energy storage
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4) Slow dynamic simulations (in minutes)
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- Loadability limit calculations
- Thermal analysis
- Battery storage

5) Power, energy management (in seconds)
- Automatic generation control (AGC)
- Operator training simulator (OTS)
- Reactive power control
- Capacitor and inductor storage for power quality

6) Fast dynamic simulations (in milliseconds)
- Modal analysis of oscillations
- Oscillation damping control
- PSS, FACTS controller tuning
- Transient Stability
- Synchronous coupling
- Active power control
- Speed control of electrical machines
- Flux optimization
- Voltage quality metrics
- Islanding and reconnection control

7) Transient control (in microseconds)
- Pulse-width-modulation (PWM)
- Current quality metrics
- Synchrophasor integration
- d-q, p-q , CPT control of machines
- Torque control of electrical machines
- Harmonic mitigation, active filtering

FAST DYNAMICS

Electrical Circuits with Hardware-in-the-Loop Real Time Analysis, Modeling and Control

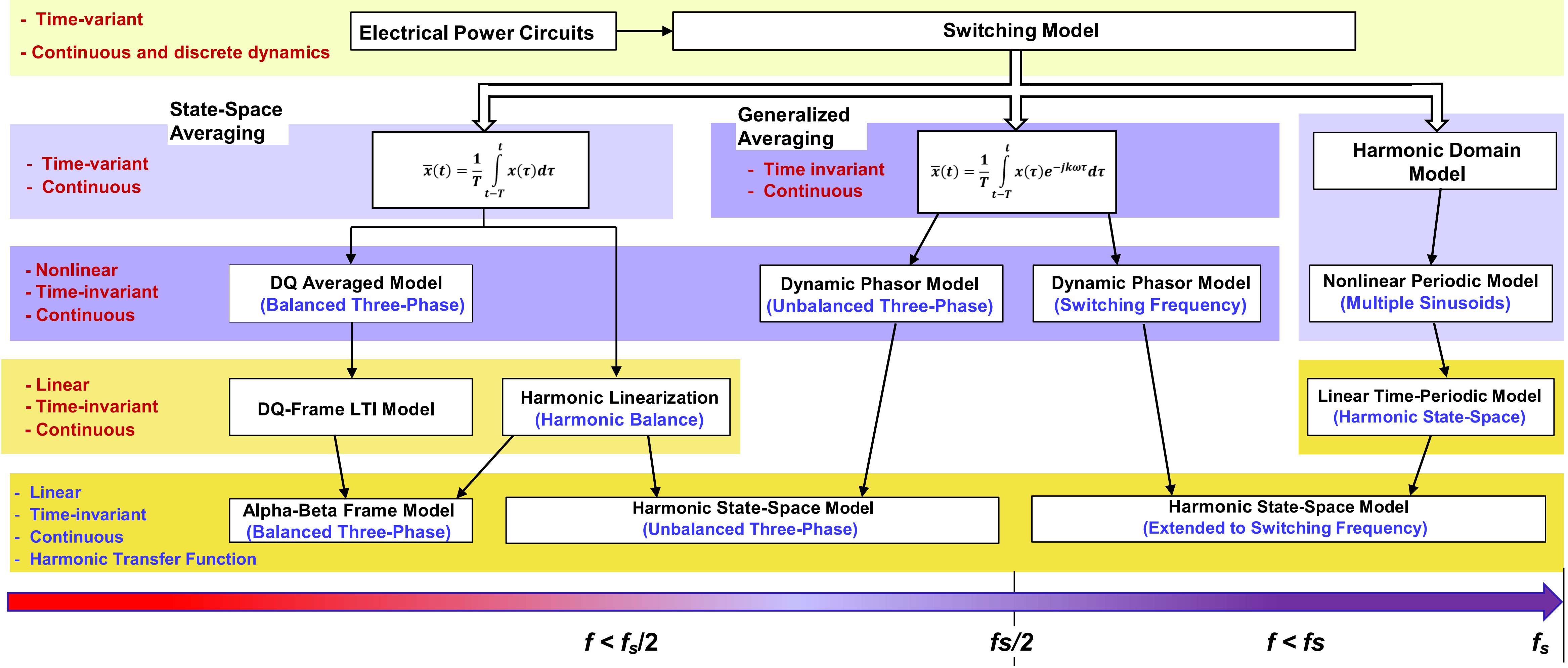
Methodology for Electromagnetic Modeling

- CIGRE and IEEE technical groups discuss that traditional transient stability analysis with simplified fundamental-frequency models can not any more estimate accurately the dynamic performance of modern low-inertia power grids.

- The current best method is to use electromagnetic models and simulation tools (EMT) capable to simulate details of fast power electronic systems.

- EMT simulation require time-step in the range of 10 us to 100 us, which leads to very large processing time when the system size increases unless parallel processing is used.

Unified Modeling of Smart-Grid, Power Systems, Power Electronics, Power Quality, and Renewable Energy System

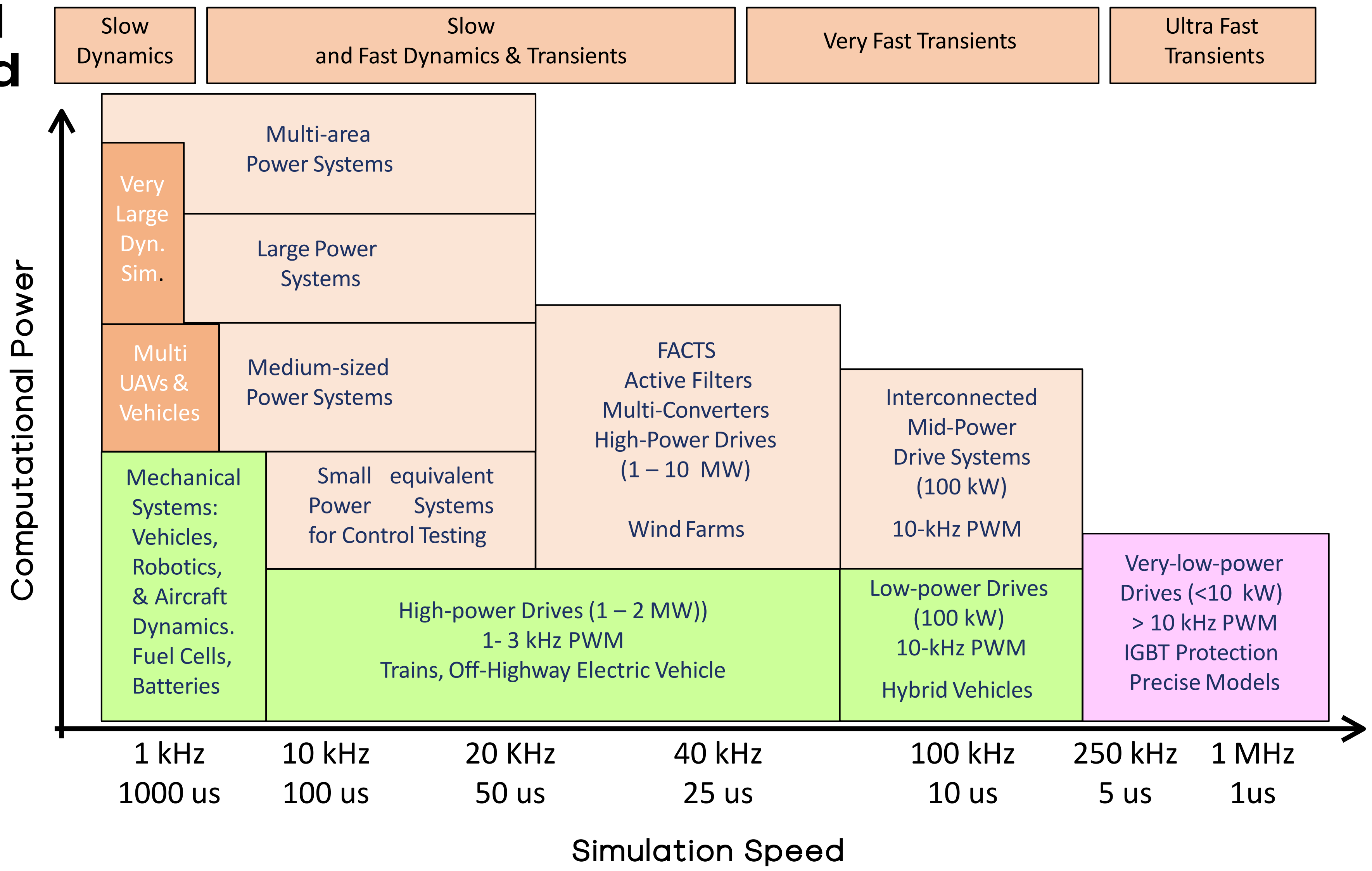


Electrical Circuits with Hardware-in-the-Loop Real Time Analysis, Modeling and Control

SLOW DYNAMICS ⟷ FAST DYNAMICS

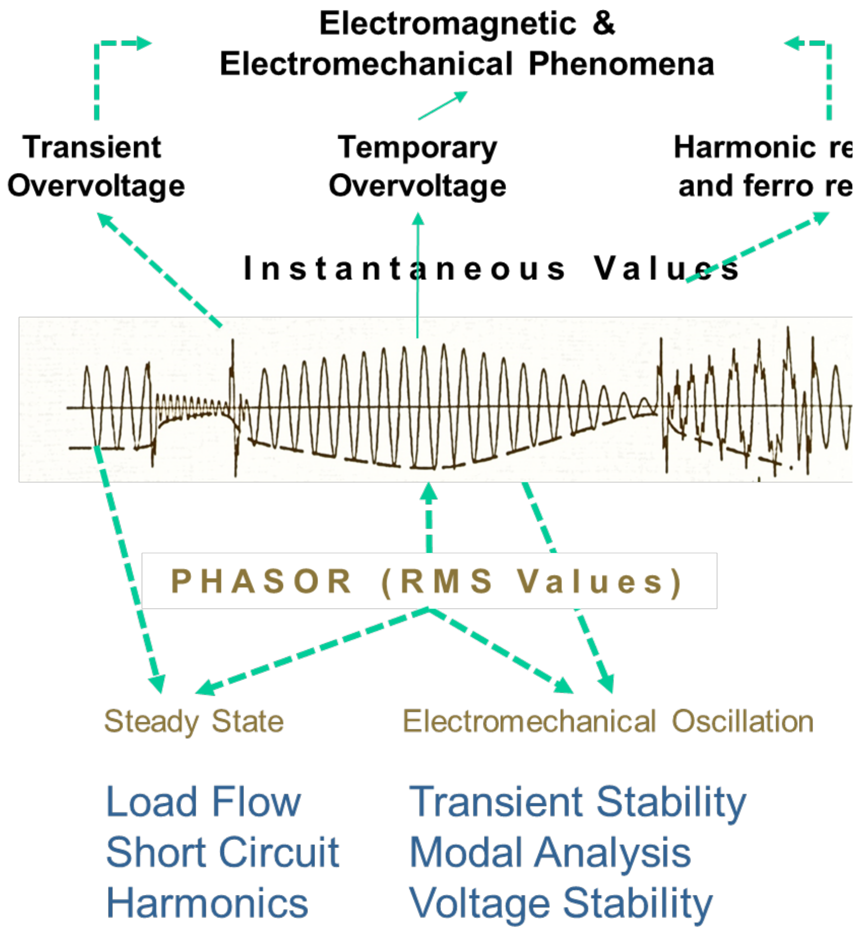
Computational Power Required for Various Electrical Engineering Systems

- Based on the use on INTEL 3.2 GHz i7 multi-core processors
- Benchmark must be done
- About 150 3-ph busses per core at 50 us



Source: Bélanger, Jean & Venne, P & Paquin, Jean-Nicolas. (2010). The what, where, and why of real-time simulation. Planet RT. 37-49.

Electromagnetic Analysis, Phasors, Steady State, Transient Simulations, Energy Management



- transient control – microseconds
- fast dynamic simulation – milliseconds
- power energy management – seconds
- slow dynamic, stability – minutes
- scheduling – hours
- long-term planning - years

Time Domain, Transient Analysis

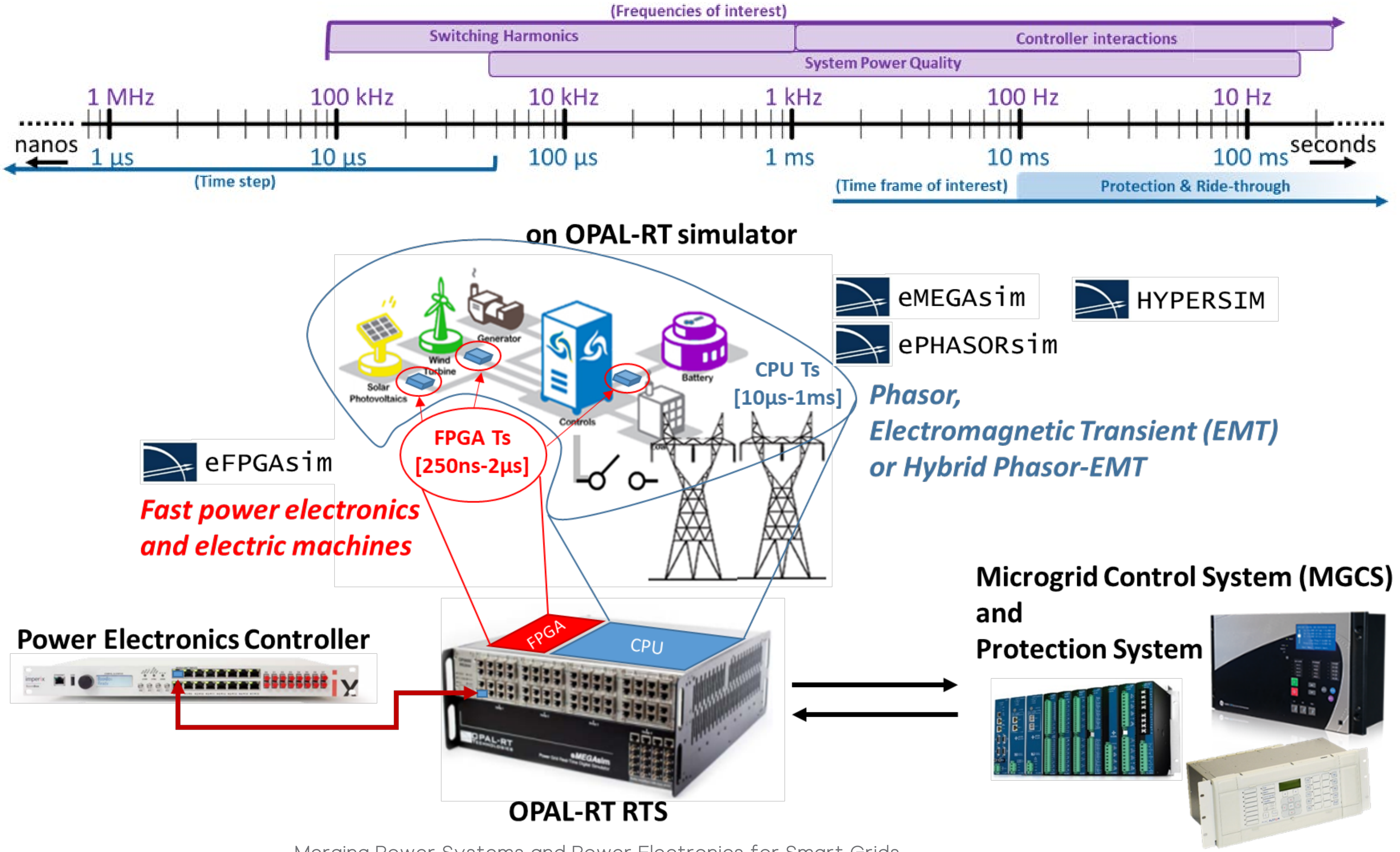
Steady State, Phasor Analysis

Harmonics, Fourier Analysis

Energy Management, Optimization

Simulation time step of 10 to 20 milliseconds are used

Multiple Sampling Real Time for HIL Based Analysis



Step by Step Methodology for Control and Protection Validation

- Validate controller model and closed-loop parameters
- Test inverter response with faulty scenarios
- Fine-tune inverter and converter controls (PV, battery, electrical machines)
- Study power quality, commutation, dead-time, shoot-through, delays
- Test robustness of inverter synchronization and control settings
- Study ride-through faults, islanding and system protections

- Simulating faulty condition, power systems protection
- Seamless stand-alone/grid-connected transition schemes
- DER coordination, load scheduling
- Linearized average inverter models speed up simulations

Smart-Grid Real-Time Simulation Analysis and Design

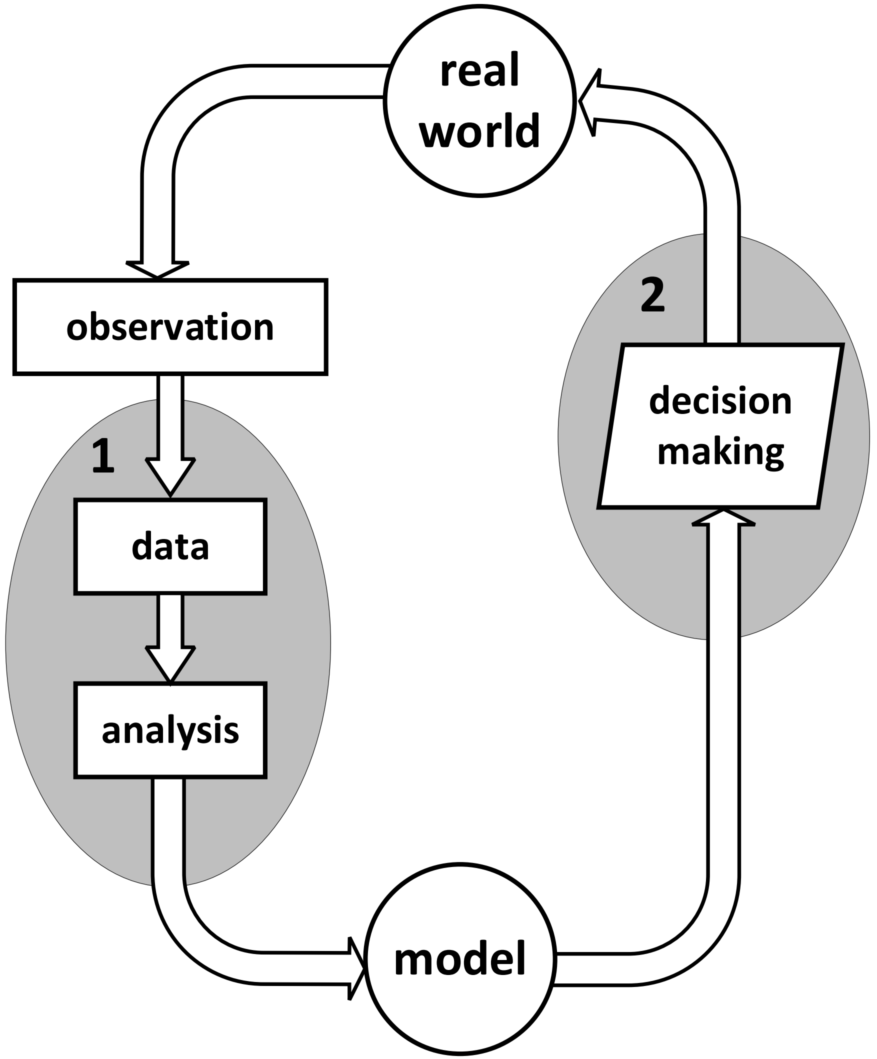
- Using Opal-RT with all their software suite we can verify all features, fine-tune algorithms, work with transistor-based switching models, or linearized models, study the transient response, or use phasor for simulation of steady-state requirements.
- Typhon is also a very interesting HIL as capable and as powerful.
- There are other simulation frameworks, Matlab/Simulink, PSIM, PLECS, RTDS, PSCAD, DigiSilent, Modelica.
- Integration with electromagnetic design can be done with JMAG, ANSYS/Simplorer

The best environment is the one that allows an interdisciplinary team to cooperate

Scientific Methodology

Observing the real-world to perform analysis - obtain a model for decision-making; act on variables that control the real-world phenomena.

"As complexity rises, precise statements lose meaning and meaningful statements lose precision"
– Lotfi A. Zadeh



Industrial Applicability of Artificial Neural Networks

Industrial systems may be modeled for condition monitoring, fault detection and diagnosis, sensor validation, system identification or design, and optimization of control systems. ANNs have the power to solve many complex problems. They can be used for function fitting, approximation, pattern recognition, clustering, image matching, classification, feature extraction, noise reduction, extrapolation (based on historical data), and dynamic modeling and prediction. ANN-based model building process include system analysis, data acquisition and preparation, network architecture, as well as network training and validation. Fuzzy logic systems and neural networks share the following features:

- estimate functions from sample data;
- do not require mathematical model;
- are dynamic systems;
- can be expressed as a graph, with nodes and edges converting numerical inputs to numerical outputs;
- process inexact information inexactly;
- have the same state space;
- produce bounded signals;
- a set of n neurons defines n-dimensional fuzzy sets;
- learn some unknown probability function p(x);
- can act as associative memories;
- neural networks can model any system provided the number of nodes and hidden layers are sufficient.

ANN Structures for Pattern Recognition

Associative memory, optimization, function approximation, modeling and control, image processing, and classification purposes

Functional Characteristics	Structure
Pattern Recognition	MLP, Hopfield, Kohonen, PNN
Associative Memory	Hopfield, Recurrent MLP, Kohonen
Optimization	Hopfield, ART, CNN
Function Approximation	MLP, CMAC, RBF
Modeling and Control	MLP, Recurrent MLP, CMAC, FLN, FPN
Image Processing	CNN, Hopfield
Classification and Clustering	MLP, Kohonen, RBF, ART, PNN

Activity:

Prediction, classification, data association and conceptualization, data filtering with neural network applications

Activity	Network Topology	Network Application
Prediction	• Backpropagation • Delta Bar Delta • Extended Delta Bar Delta • Directed Random Search • Higher Order Neural Networks • Self-Organizing Map	Use input values to predict some output, choose the best stocks in the market, predict weather, identify people with health risks
Classification	• Learning Vector Quantization • Counterpropagation • Probabilistic Neural Networks	Use input values to determine the classification (e.g. is the input the letter A, is the blob of video data a plane and what kind of plane is it)
Data Association	• Hopfield • Boltzmann Machine • Hamming Network • Bidirectional Associative Memory • Spatiotemporal Pattern Recognition	Like Classification, but it also recognizes data that contains errors (e.g. not only identify the characters that were scanned but identify when the scanner isn't working properly)
Data Conceptualization	• Adaptive Resonance Network • Self-Organizing Map	Analyze the inputs so that grouping relationships can be inferred (e.g. extract from a database the names of those most likely to buy a particular product)
Data Filtering	• Recirculation	Smooth an input signal (e.g. take the noise out of a communication signal)

Smarter Power Systems

Several issues will have to be taken in consideration, for efficient energy conversion for electrical power systems. advanced by Artificial Intelligence on these premises:

- Parameter variation that can be compensated with designer judgment
- Processes that can be modeled linguistically but not mathematically
- Settings with the aim to improve efficiency as a matter of operator judgment
- When the system depends on operator skills and attention
- Whenever one process parameter affects another process parameter
- Effects that cannot be attained by separate PID control
- Whenever a fuzzy controller can be used as an advisor to the human operator
- Data intensive modeling (use of parametric rules)
- Parameter variation: temperature, density, impedance
- Non-linearities, dead-band, time delay
- Cross-dependence of input and output variables

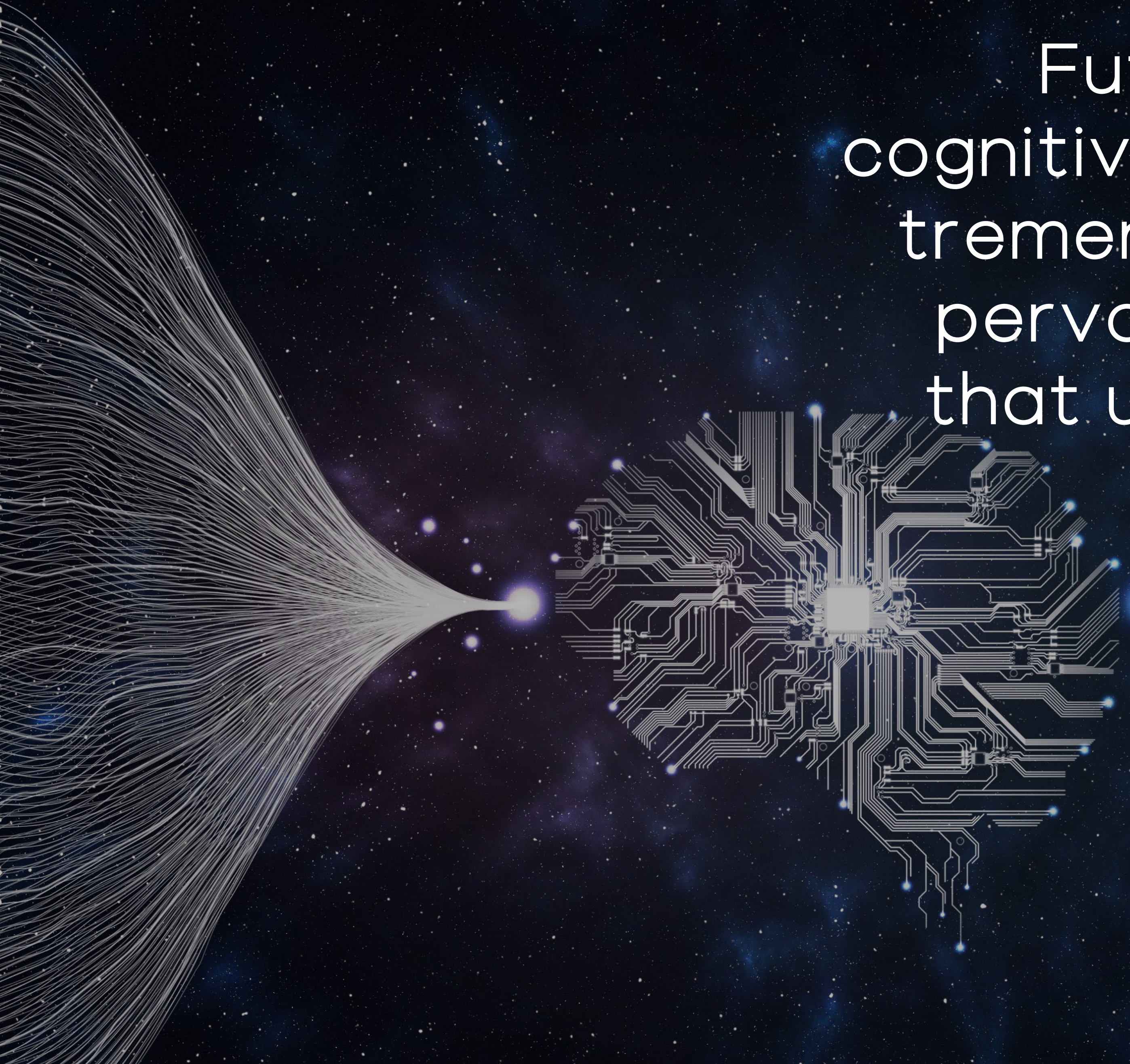
The Age of Deep Learning

- By the middle of 80's, it was accepted that neural networks should be shallow, just one hidden layer, or maximum two hidden layers.
- Backpropagation training method, used in most supervised learning tasks, suffer from the problem of vanishing gradients.
- Backpropagation computes the gradient of a loss function with respect to the NN weights, using calculus chain rule, i.e. a cumulative multiplication of gradient terms.
- As the error signal from the output layer goes back through the hidden layers to the input, there is an exponential decrease of the resulting gradient product to less than 1.
- Early layers either train very slowly or do not move away from their random starting positions; input layers are very important, because they detect features.
- Deep learning started about 2005 to 2010, particularly when new activation functions were introduced to tackle the vanishing gradient problem (ReLUs) with very great performance achieved with convolutional and recurrent networks.

There is increasing high penetration of solar and wind power in the electric grid, with evolving bidirectional power, mobile prosumers (such as HEVs), integrated communications, and advanced infrastructure

Scheduling and operation of smarter power systems are compromised with challenges of uncertainty, random generation, and mobile flexible loads.

Accurate forecasting of energy demands at different echelons in an integrated power system is very important for reliability and resilience.



Future smart-meters and cognitive-meters will provide a tremendous opportunity with pervasive and massive data that useful for deep learning algorithms.

Capabilities on most of power systems with Artificial Intelligence Based on Machine Learning

Machine Learning (ML)		
Supervised Learning		Unsupervised Learning
Classification	Regression	Clustering
Machines (SVM)	(GLM)	K-Means
Decision Trees	Support Vector Regression (SVR)	Hierarchical
Naive Bayes	Ensemble Methods	Gaussian Mixture
Nearest Neighbor	Decision Trees	Hidden Markov Model
Neural Network	Neural Network	Neural Network

Classic Applications of ANN Based Power Systems

- Classification: predicting categorical labels of new input data based on past classifications from historical data; historical health patterns of smart-metering data, it could be used in binary classification to predict whether a smart meter has been hacked.
- Regression: statistical analysis, used for forecasting load, weather conditions, renewable energy generation, power system optimization of generation and load profiles, as well as electricity pricing in dynamic energy markets.
- Clustering: Clustering techniques organize data into subgroups, such as power systems load profiling for electricity pricing, power quality use clustering techniques for load disaggregation based on electrical power signal signatures and pattern recognition.
- Summarization: compact description when there are redundant variables, useful to to reduce the amount of data in both transmission and storage, alleviating big data issues.
- Association: variables in power systems may be correlated to outcomes, such as the impact of forecasted weather on the next-day demand and generation for load profile.
- Sequence Analysis: finding sequential patterns in data sets. This could be useful for analysis of cascade failures to identify critical assets to the electric grid.

Future Applications for AI in Power Electronics and Power Systems

- Smart-grid and sustainable energy systems powered by renewable energy, required cloud platform, edge computing, fog computing.
- Electric and plug-in hybrid electric vehicles are dynamic mobile power plants with capacity of energy transfer on different grid nodes.
- Electric vehicles are, in addition to a transportation solution, a portable power and storage plant. Artificial intelligence will enable complex computing for motor torque estimation, safety and driverless control, and cognitive heuristic techniques.
- Artificial intelligence, fuzzy logic, classic neural networks, and deep learning architectures can be implemented in cloud platforms, where smartphones and portable devices converge with databases, personal information, and data from Internet of Things (IoT) devices.
- Advanced cloud environments will allow great integration of data storage with massive distributed computing power, imbuing complex data analytics for smart grid data streaming, processing, analyzing, and storage.

SmartGrid Systems and Deep Learning

- Deep learning and further AI applications in power electronics enabled power systems will have implementations on edge and fog computing, at low-latency applications.
- The current increasing portfolio of customers purchasing electric or plug-in hybrid electric vehicles, will make AI techniques integrated on plug-in hybrid electric vehicles.
- Artificial neural networks will be integrated in predictive controllers, fuzzy logic will mimic human behavior, and intelligent systems will allow safe and efficient operation of modern systems in the 21st century.
- Deep Learning Based Smart-Grid, allows advanced metering infrastructure, multi-objective optimization algorithms, disaggregation techniques non-intrusive load monitoring, modelling and RTS, Internet-of-Things cooperative user/environment, demand response and smart-grid computation, data driven analytics, descriptive, diagnostic, predictive, and prescriptive performance, interoperability and integrated to smart-city ecosystem.
- Future will bring about new theories and applications of machine learning in smart grid design and development.

AI Based Control System for Smarter Power Systems

In a wind-farm the overall system must be designed for intelligent monitoring and protection.

– Wind Signals: velocity, wind direction, turbulence

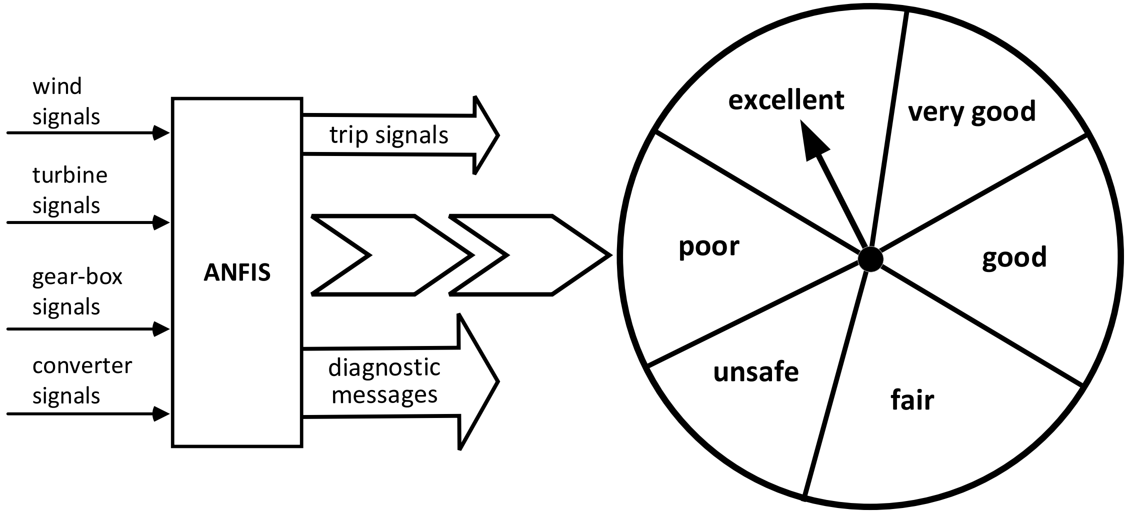
– Turbine Signals: Blade speed, shaft speed , pitch angle, bearing temperatures, vibration of blade, yaw angle, shaft torque, mechanical brake signal, tip-speed-ratio

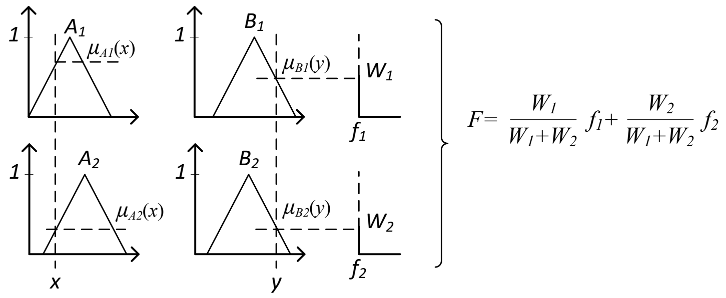
– Gear box: oil temperature, oil viscosity, noise intensity, vibration, nacelle temperature

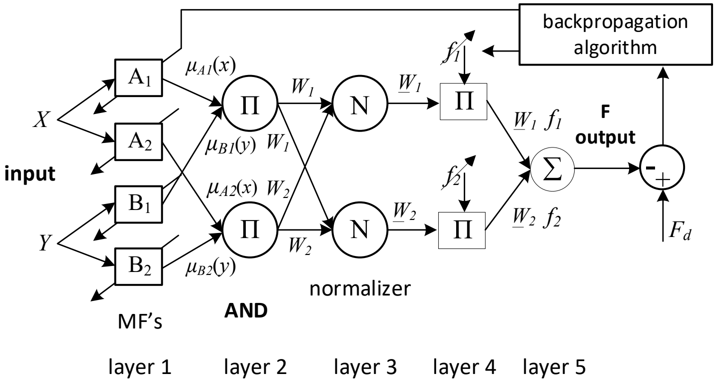
– Generator: Bearing temperatures, shaft vibration, stator winding temperature distribution, rotor magnet temperatures, shaft torque, stator voltages, phase sequence, percentage of terminal voltages and currents imbalance, stator currents RMS, average, peak, stator frequency, active power, reactive power

– Converter: Converter temperatures, cooling fluid velocity, dc-link voltage, dc-link current, dc-link power, ac line voltages, output frequency, phase unbalance of voltages, ac line currents, phase unbalance of currents, active power, reactive power, motoring/regeneration mode

– Fourier and Wavelet expansion of selected signals



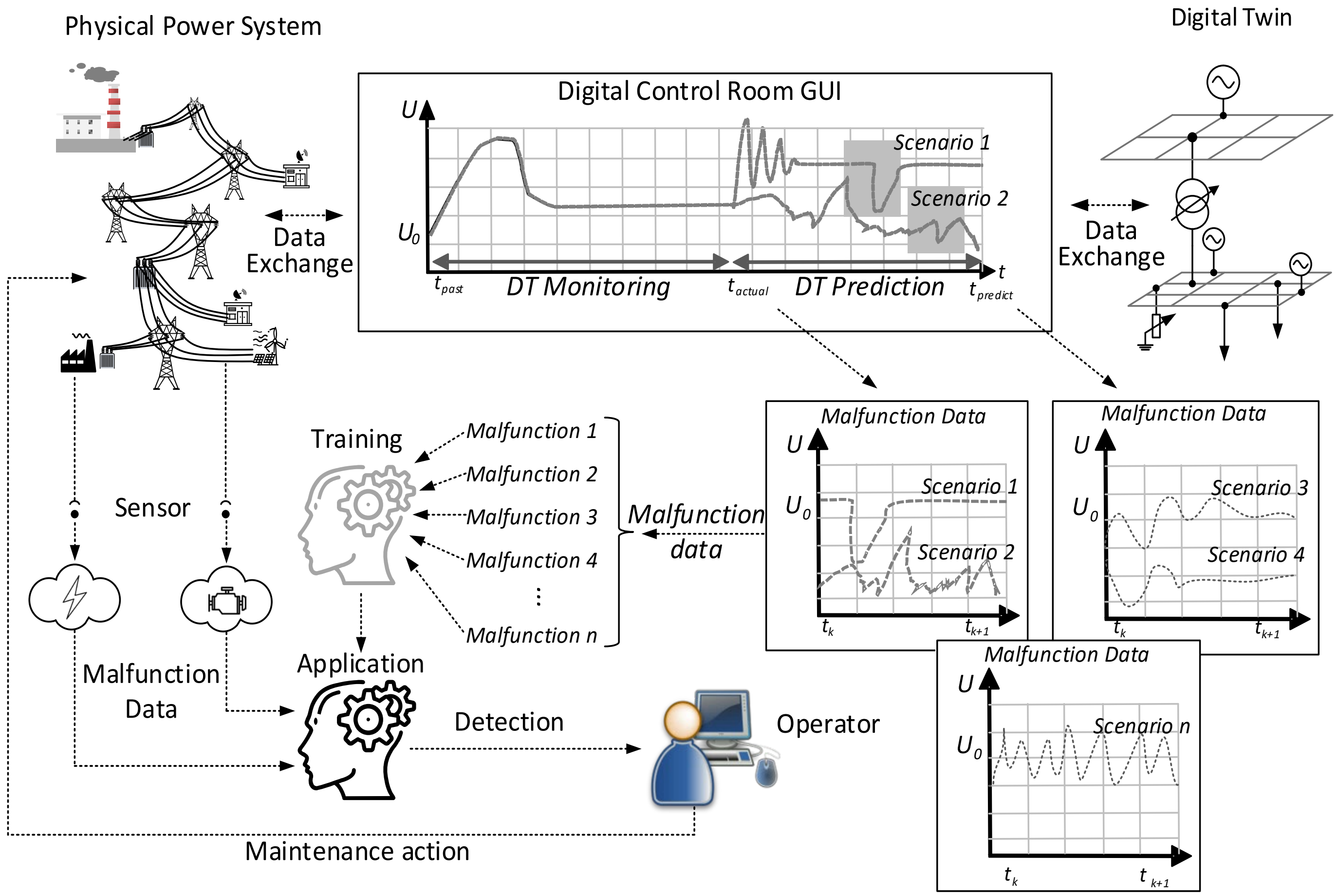




Digital Twin

Virtual model based RTS, allows a dynamic, evolving, and an 'intelligent' entity so that it changes over time as the physical system evolves.

A Digital Twin has the following attributes: (i) a digital model in a simulated environment, (ii) the physical entity in real space, and (iii) a connection between the virtual model and the physical entity for the data flow. The figure shows a Cyber-Physical Surveillance and Security Assessment, where a DT aided by neural networks allows continuous data exchange between the cyber and physical world. The DT is characterized by its ability to monitor the physical system accurately and adaptively on different scales of time, it can be a part of the cyber-physical system, which interacts with the physical entities, e.g. equipment, environment, and humans.



Marcelo Godoy Simões

Professor in Flexible and Smart Power Systems

Peyman Razmi

PhD scholar in Power Electronics

Luca Ferranti

Doctoral researcher

THANK YOU

To our speakers

POWERSYS