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Application of Machine Learning to Power Grid Analysis

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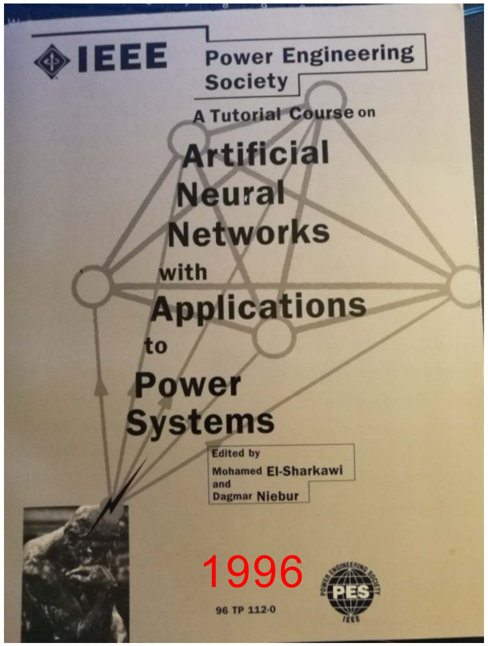
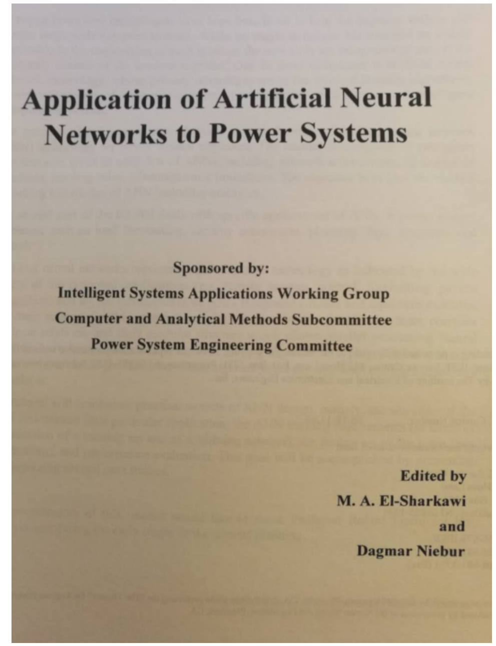
Agenda

☞ • Introduction
• Open Platform for Applying Machine Learning (ML)
• Power Grid Model Service
• Research on Applying ML to Online DSA
• ML Research Roadmap of CEPRI

Why ML Research Again?




Application of Artificial Neural Networks to Power Systems

Sponsored by:
Intelligent Systems Applications Working Group
Computer and Analytical Methods Subcommittee
Power System Engineering Committee

Edited by
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and
Dagmar Niebur

- AlphaGo Showcase – “impossible for at least 10 more years”
- "Artificial Intelligence is the New Electricity“ – Andrew Ng
- Open-source ML tools (Google TensorFlow [1])

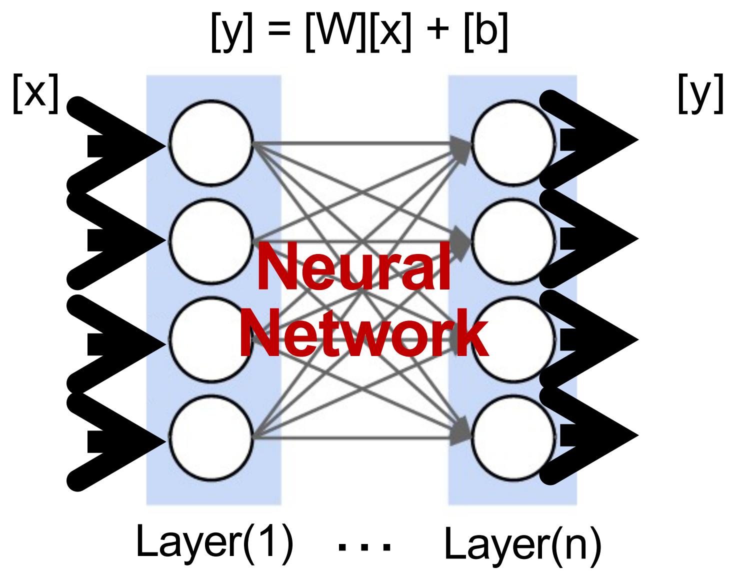
[1] “TensorFlow: An open-source software library for Machine Intelligence”, https://www.tensorflow.org/

Basic Idea

In power system steady-state analysis, the problem usually can be formulated as to solve a set of non-linear equations, as shown below:

$$\boldsymbol{y} = \boldsymbol{f}(\boldsymbol{x}) \quad \boldsymbol{x}, \boldsymbol{y} \in \mathrm{R}^{\mathrm{n}} \qquad (1)$$

The non-linear equation is commonly solved by some numerical method, such as Newton-Raphson for loadflow analysis.



ML Application Areas

- Image Recognition
- Self Driving Car
- Automation
- Robotics
- **Predictive Analytics**
  - Power grid analysis has been guiding the operation successfully
  - Power grid analysis so far is model-driven
  - Data-driven ML approach will be supplemental

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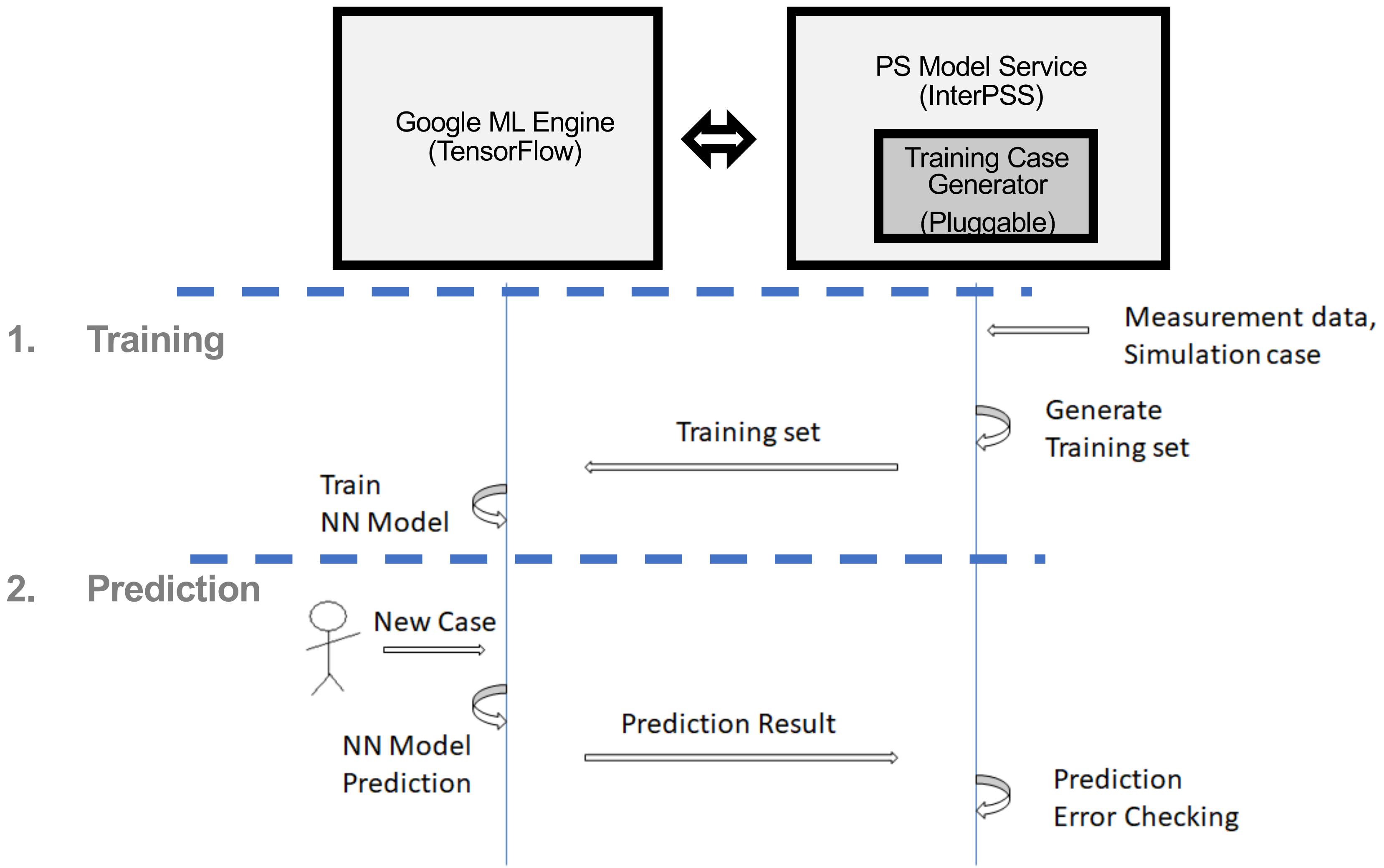
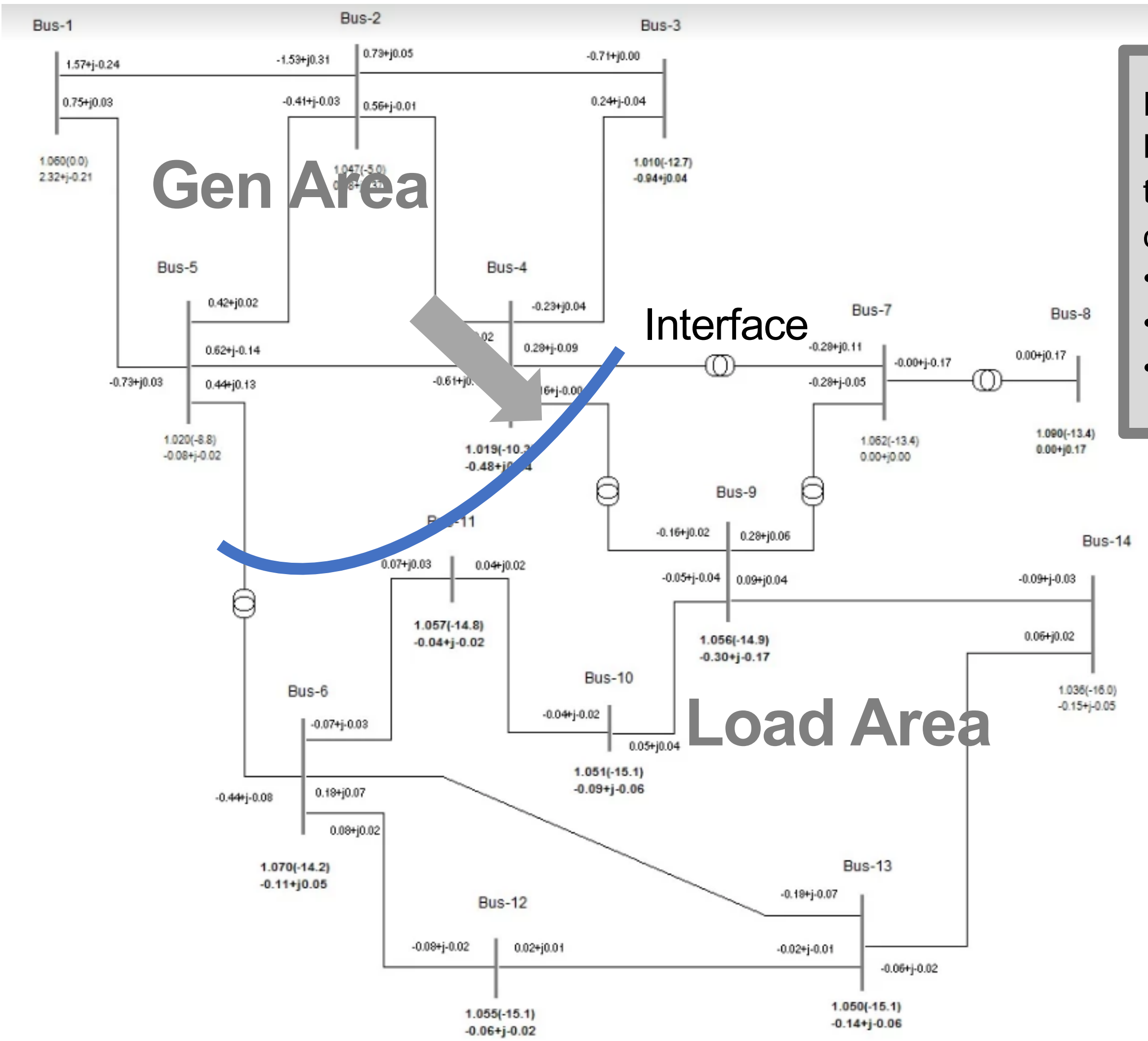
NN Model Training Data

- ML Main Steps: 1) Training; 2) Prediction
  - Training data is the foundation for ML
- Training data set collection
  - Large user data set collected by Google, Facebook
- Training data set generation
  - Power grid operation depends on the simulation
    - Guide the grid operation with proven record
    - Contingency analysis could be done only through simulation
  - Need grid analysis training data generation tools/platforms
- Open Platform for Application of ML to Power Grid Analysis has been created

Platform Architecture



Sample Study Case



NN-Model Prediction

IEEE-14 Bus case as the basecase. Power is flowing from the Gen Area to the Load Area. When the operation condition changes,

- Bus voltage, P, Q prediction
- Interface flow prediction
- N-1 CA max branch power flow

Training Case

- Load bus P,Q adjusted by a random factor [0~200%], load Q is further adjusted by random factor [+/-20%]
- The load changes are randomly distributed to the generator buses

Bus Voltage Prediction

(AC Loadflow)

- AC Power Flow
  - Given bus PQ, compute bus voltage (mag, ang), such that max bus power mismatch (dPmax, dQmax) < 0.0001 pu
  - 1000 training date sets are generated and used to train the NN-model
    - Input: bus P, Q, P^2
    - Output: bus voltage, …
- Prediction Using NN-Model
  - 100 testing cases are generated using the same process as the training data set, using the random load adjustment factors.
  - The trained NN-Model is used to predict the bus voltage

	dV(mag)	dV(ang)	dPmax	dQmax
Maximum	0.00118 pu	0.00229 rad	0.00937 pu	0.00619 pu
Average	0.00028 pu	0.00055 rad	0.00225 pu	0.00171 pu

dV(msg,ang): Bus voltage predicted is compared with the accurate AC Power Flow results

dP/Qmax: Bus voltage predicted is used to compute the network max bus power mismatch

Bus/Interface PQ Prediction
(AC Loadflow)

- Bus P, Q
  - Swing Bus P, Q prediction (100 testing cases)
    - Average difference : 0.00349 pu 0.35 MW/Var
    - Max difference: 0.01476 pu 1.48 MW/Var
  - PV Bus Q prediction (100 testing cases)
    - Average difference : 0.00353 pu 0.35 MVar
    - Max difference: 0.02067 pu 2.07 Mvar
- Interface Flow
  - Interface branch set [5->6, 4->7, 4->9]
  - Interface Flow P,Q prediction (100 testing cases)
    - Average difference : 0.00084 pu 0.08 MV/Var
    - Max difference: 0.00318 pu 0.32 MV/Var

Max Branch Power Flow Prediction
(N-1 CA)

- N-1 Contingency Analysis (CA)
  - In N-1 CA, the branch power flow is calculated when there is a branch outage. Furthermore, the max branch flow of each branch considering all contingencies to check limit violation or for screening .
  - 1000 training date sets are generated and used to train the NN-model
    - Input: bus P, Q, P_2
    - Output: max branch power flow
- Prediction Using NN-Model
  - 100 testing cases are generated using the same process as the training data set.
  - Max branch power flow prediction is compared with the accurate simulation results
    - Average difference : 0.0134 pu 1.34 MW
    - Max difference: 0.0509 pu 5.09 MW

Open Platform for
Application of ML to Power Grid Analysis

(Summary)

- Integration of Google TensorFlow and InterPSS [2]
  - TensorFlow as ML engine
  - InterPSS
    - Provides power grid simulation model service
    - Pluggable training data generator
- The Platform has been open-sourced
  - Apache-2.0 License
  - Open-source Project Location GitHub: https://github.com/interpss/DeepMachineLearning

[2] "The InterPSS Community Site", www.interpss.org

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Power Grid Model Service

- The Need For Creating the Training Data
  - Power grid measurement data is not enough
  - Training data for security analysis need to be created
    - N-1 CA, transient/voltage stability limit
- Valid NN Model Prediction Accuracy
  - Common ML Approach
    - Collected Data set => Training set + Testing set
  - Model service creates data on-demand randomly or according certain rules
- Based on InterPSS Simulation Engine
  - Accurate power grid simulation model behind

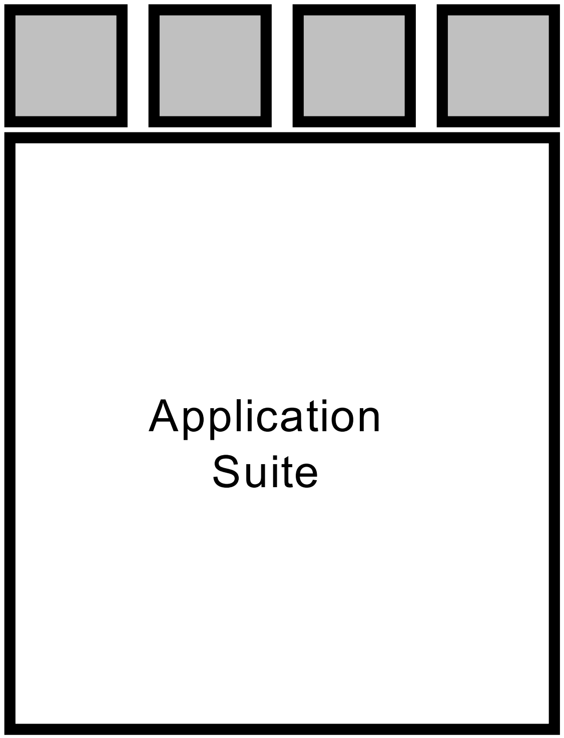
About InterPSS

"*Solving power system simulation problem using modern software approach*" [3]

- InterPSS: Internet Technology-based Power System Simulator
- InterPSS project started in 2005
  - Object-oriented, Java programming language
  - PSS/E, BPA , PSASP(China EPRI) similar functions
  - Free software

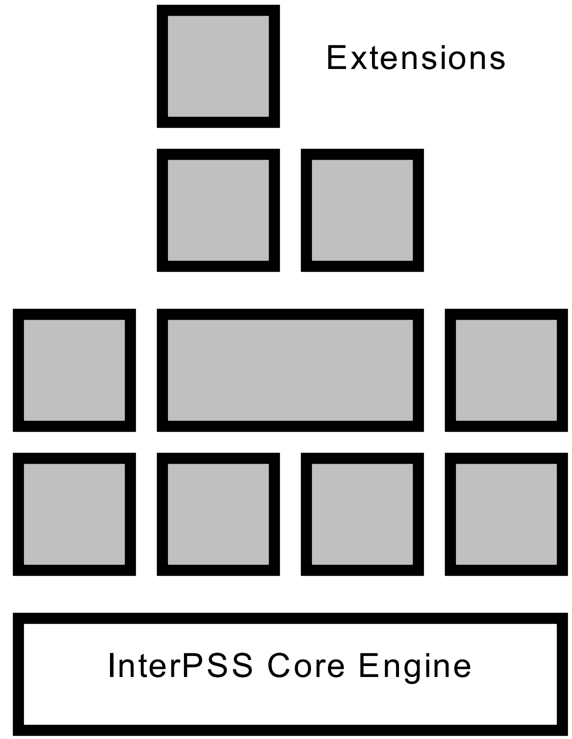
[3] M. Zhou, "Solving Power System Analysis Problems Using Modern Software Approach," *US Gov FERC Increasing Market and Planning Efficiency through Improved Software Meeting*, DC June 2010.

InterPSS Software Architecture



Traditional Approach

Little could be extended and customized



Desktop Edition

Cloud Edition

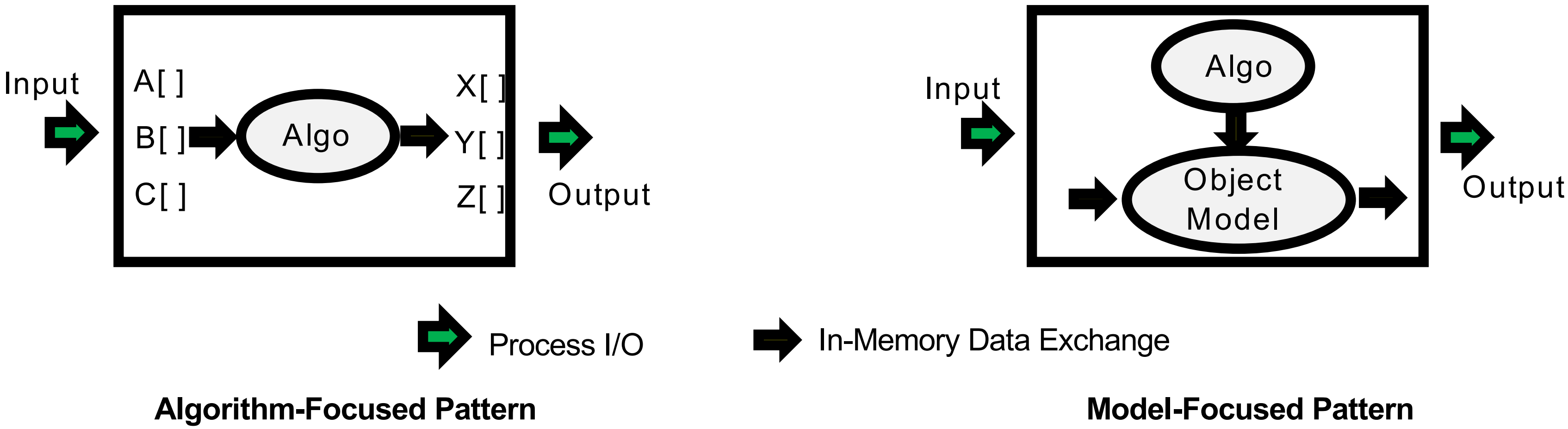
✓ **Integration with other systems**

InterPSS Approach

Application created by extension, integration and customization

Power Network Object Model

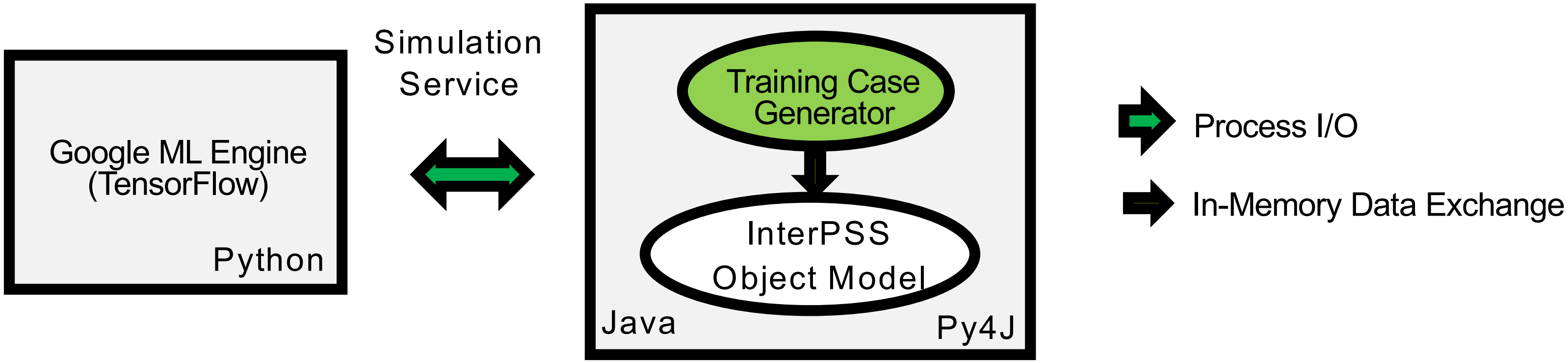
[4,5]



- Data Processing Patterns
  - Algorithm-focused
    - Procedure programming approach
    - PSS/E, BPA, PSASP (China EPRI) based on this pattern
  - Model-focused
    - Object-oriented approach
- InterPSS uses the Model-Focused Pattern

[4] E. Zhou, "Object-oriented Programming C++ and Power System Simulation," *IEEE Trans. on Power Systems*, Vol. 11, No. 1 Feb. 1996.
[5] M. Zhou, Q.H. Huang, “InterPSS: A New Generation Power System Simulation Engine," submitted to *PSCC* 2018

Training Case Generation



- Object and Algorithm Decoupled Relationship
- Common Algorithm Implemented
  - Topology Analysis, Loadflow, N-1 CA, State Estimation
  - Short Circuit Analysis, Transient Stability Simulation
- Training Data Generator
  - Training data generation implemented as a special algorithm
  - Use Py4J [6] as the runtime to host the object model and interface with TensorFlow (Python)

[6] "Py4J - A Bridge between Python and Java", https://www.py4j.org/

Power Grid Model Service

(Summary)

- Based on InterPSS Simulation Engine
- Provide Flexible Power Grid Model Service
  - InterPSS power network model hosted in a Java runtime environment
  - Pluggable training data generator
    - Create custom training data generator using InterPSS power network object model API

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DSA Challenges

[7]

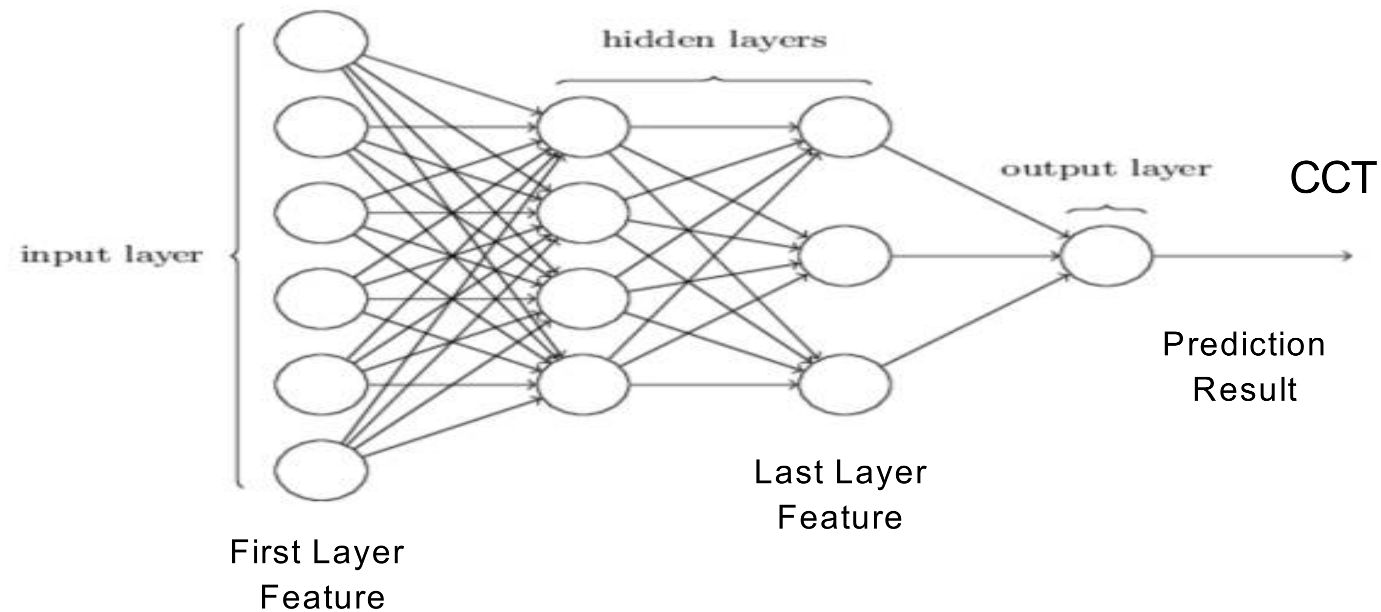
- Current DSA
  - Repackage of off-line simulation programs (TS, Small-signal)
  - Running in the batch mode periodically (15 min)
  - In China State Grid dispatching center, a round trip takes 6-10 min to complete
  - The online analysis model size is large-scale (40K buses)
- Challenges
  - The time-domain simulation has limited speed-up room
  - The simulation results are not intuitive for the operators
  - Remedy actions cannot be directly derived from the results

[7] M. Zhou, et al, "Development of Fast Real-time Online Dynamic Security Assessment System," IEEE SmartGrid NewsLetter, June 2016.

CCT Prediction

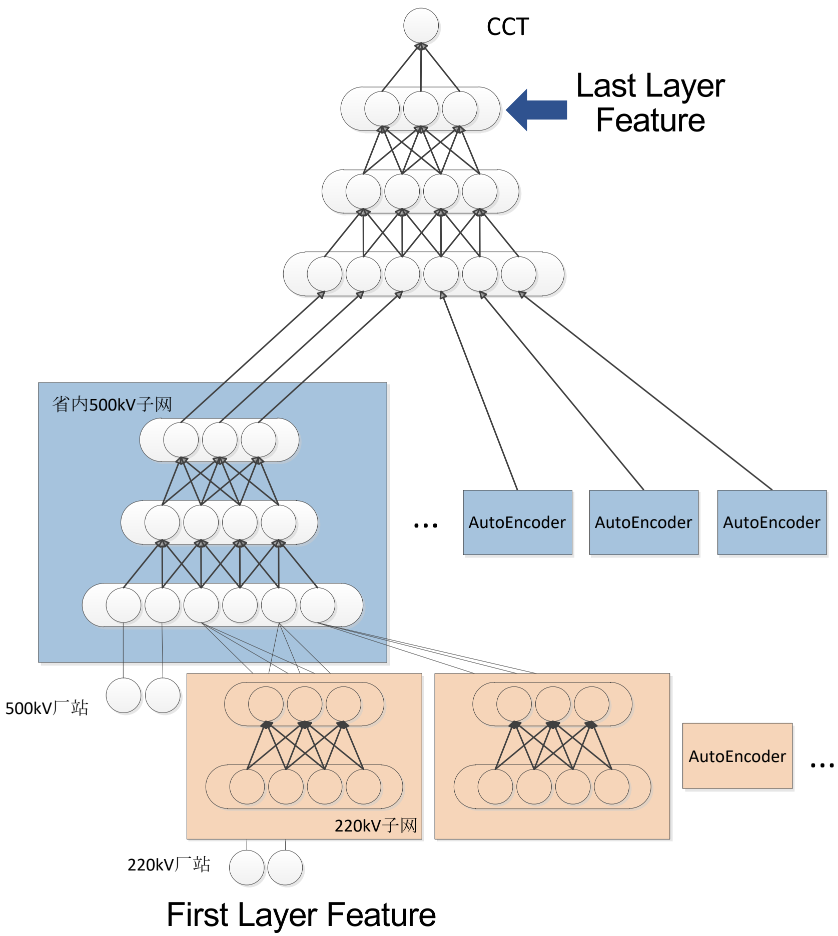
- Critical Clearing Time (CCT)
  - Maximum time during which a disturbance can be applied without the system losing its stability.
  - Determine the characteristics of protections
  - Measure quantitatively system dynamic security margin
- CCT Computation
  - ~100 sec using the simulation approach (40K Bus)
  - ML-based approach: using Neural Network(NN) model to predict CCT

NN-Model Based CCT Prediction



- NN-Model (per contingency) is constructed (trained) for the CCT prediction;
- NN-Model input (First Layer Features) : power grid measurement info, such as Gen(P, V); Substation (P,Q), and z(i,j) between substations;
- A set of Last Layer Features are derived and used for CCT Prediction.

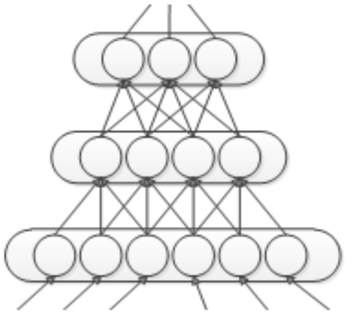
Preliminary Results



Network Size	40K+ Buses, 3370 Substations
NN-Model Output	CCT for a Fault
First Layer Features	Gen (P、V)；Substation(P, Q)；$Z_{i,j}$ between substations；(Dimension : 8772)
Last Layer Features	About 20
Feature Reduction	Basic NN unit: AutoEncoder

CCT Calculation	Average error	Max error	Training case	Testing case	Time NN-Model	Time Simulation	Acc Ratio
A Fault	2.65%	28.69%	24594	4660	2ms	~100s	1:50000

Basic NN unit: AutoEncoder



"The aim of an AutoEncoder is to learn a representation (encoding) for a set of data, typically for the purpose of dimensionality reduction."

- About 30 min training time (one GPU, 40K-bus network)
- NN Model Input (First Layer Features)
  - Gen P, V; Substation P, Q; $Z_{I,J}$ between substations (total 8K+ variables)
  - The goal is let AI to select through training a set of last layer features (artificial) for predicting CCT
- The Current Practice
  - A set of key features (physical, such as interface flow) are selected by human expert to monitor the stability
  - Use physical features or artificial last layer features to determine the security margin?

Potential Benefit

- Speed-up DSA System Response Speed
  - For CCT prediction: 50K times faster (40K-Bus, 2ms vs 100s)
- Produce More Intuitive Results
  - NN model to digest large-scale simulation outcome to create more intuitive results
  - The “lookup” approach is very close to human operator experience
- Enhanced Decision Support
  - NN model turns/reduces First Layer Features (P, Q, V) to Last Layer Features
  - Use the Last Layer Features to compare the current case with historic simulation cases to identify “similar cases”
  - If remedy actions are needed for the current case, they could be found in the similar historic simulation cases.

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CEPRI Power System Simulation Group
ML Research Roadmap(1)

- New super simulation center (China State Grid)
  - Massive processing power (750 Blades, 20K cores)
  - Massive storage room (2.4 PB, ~2M cases)
  - Production support for State Grid dispatching centers in China
- Training data set
  - Collect real-world simulation cases and results
  - Based on the human experience to generate more scenarios based on the recorded history operation cases
  - Use to train NN-models for the predictive analysis

CEPRI Power System Simulation Group

ML Research Roadmap(2)

- Simulation result processing
  - The new simulation center will generate massive simulation result
  - The human experts are not capable to process the result
  - Digest massive simulation results using NN-model
  - Discover knowledge to guide China’s UHV power grid operation

Summary

- AI, especially ML, landscape has been fundamentally changed over the last 5~10 years
  - The development speed is unprecedented
  - Many breaking-through successful stories
- The enabling technologies are accessible to everyone
  - Powerful computing hardware (CPU+GPU)
  - New open source software tools
- The right time to renew/restart research on application of ML to power grid
  - Open collaboration approach is recommended

Thank You
Q&A