The Evolving Electric Power Grid
-Energy Internet, IoT and AI

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@CURENT Strategic Planning Meeting
Outline

1. Recent Development: Energy Internet and IoT
2. The New-gen. AI Technologies
3. Challenges and Opportunities
Unbalance in Resources and Load

**Resource**
- 76% of coal in North and Northwest
- 80% of hydropower in Southwest, mainly in upper stream of Yangtze River
- All inland wind in Northwest
- Solar resources mainly in Northwest

**Load**
- 70%+ of load in Central and Eastern parts

**Transmission**
- Distances between resource and load center reaches up to 2000+km
- UHVDC and UHVAC are good options to transfer huge amount of power over long distance

**Challenges**
- Hybrid operation of AC and DC systems
- System stability, security, and reliability
UHVDC

Loss/MW: 50%
Investment/MW: 28%

Transmission Options:
- UHVDC
- HVDC or HVAC

Energy Sources:
- Hydro
- Thermal
- Solar
- Wind
The existing load control methods are of low granularity, and the load response is slow.

The load monitoring/control is highly dependent on the SCADA network and it costs much to extend to end-user level.

It is urgent to develop cost-effective methods to integrate higher levels of renewable generation.

Developmental Trend: Internet-of-Things (IoT)

- Advanced metering infrastructure (AMI)
- SCADA (supervisory control and data acquisition)
- Smart inverters
- Remote control operation of energy consuming devices
- Various type of interconnected sensors

Developmental Trend: Energy Internet (Interconnection)

The shape of grids to come?

Conventional electrical grid
Centralised power stations generate electricity and distribute it to homes, factories and offices.

Energy internet
Many small generating facilities, including those based on alternative energy sources such as wind and solar power, are orchestrated using real-time monitoring and control systems.

Offices or hospitals generate their own power and sell the excess back to the grid. Hydrogen-powered cars can act as generators when not in use. Energy-storage technologies smooth out fluctuations in supply from wind and solar power.

Distributing power generation in this way reduces transmission losses, operating costs and the environmental impact of overhead power lines.

Sources: The Economist A9B

Known Challenges and Opportunities

**Challenges**

- Increasing dynamics and stochastics.
- Traditional operational rules and procedures, which are derived from offline studies or historical experiences, tend to be less optimal (over-conservative or risky).
- Limited capabilities to adapt to various, including unknown, system operating conditions.
- Causes
  - Increasing penetration of DERs
  - Transportation electrification
  - Fast demand responses
  - New market behaviors
  - Inaccurate grid models

**Opportunities**

- The need for faster and enhanced system situational awareness tools/platforms.
  - WAMS with good coverage of PMUs
  - Point-on-wave measurements/devices
  - Progress in computation/simulation
  - Recent progress in AI (Deep learning)
- The need for faster, preferably real-time, decision-support tools/platforms.
  - Most existing operational rules are offline determined considering the worst-case scenarios
  - Lack of preventive/corrective measures to mitigate operational risks
  - Proven capability of AI in decision making/support under highly complexed situations.

Lack of approaches to collect and synthesize overwhelming amounts of data from millions of smart sensors nationwide to make timely decisions on how to best allocate energy resources.
Changes in Way of Thinking

Traditional Approach (Model-centric)

Automatic Program (Fixed and pre-determined rules, automatic execution)

New Approach (Data-centric, hybrid approaches)

Autonomous Program (Intelligent and evolving)

Dec. 2018, AlphaStar mastered the real-time strategy game StarCraft II and beat top teams, by learning from human and then self play.

Robot arms learn to pick things up, hard and soft objects in different ways, with little human interference.

Core technologies: Deep learning + Reinforcement learning

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Deep Mind Founded</td>
</tr>
<tr>
<td>2014</td>
<td>Google acquired Deep Mind</td>
</tr>
<tr>
<td>2015</td>
<td>AlphaGoFan (5:0 vs Hui Fan)</td>
</tr>
<tr>
<td>2016</td>
<td>AlphaGoLee (4:1 vs Lee Sedol)</td>
</tr>
<tr>
<td>2017</td>
<td>AlphaGoMaster (3:0 Jie Ke)</td>
</tr>
<tr>
<td>2017</td>
<td>AlphaZero</td>
</tr>
<tr>
<td>2018</td>
<td>AlphaStar</td>
</tr>
<tr>
<td>2019</td>
<td>MuZero</td>
</tr>
</tbody>
</table>

Notes:
- No/limited labeled data (raw data input), play against itself for improvement.
- Learn from human, and then play against itself for improvement.

Hints for power system applications:
- Lack of large amount of labeled data, especially event data.
- Generate reasonable data sets based on existing/typical data/operating conditions.
- Combine AI with classical power system theories/computations/metrics.
Deep Learning is part of the machine learning family based on artificial neural network with many layers. Deep learning can be supervised, unsupervised and semi-supervised.

DRL = DL + RL
The Grid Mind Vision

- **Grid Mind**: A measurement-driven, grid-interactive, self-evolving, and open platform for power system autonomous dispatch and control.

- In the short term, create EXAMPLES of AlphaZero in power systems.
- In the mid-term, Grid Mind serves as an assistant to grid operators.
- In the long term, Grid Mind will be the core of power system operation ROBOT.

**Goal**: To develop a platform and tools that can transform massive amount of measurements into actionable decisions in real time.
Autonomous Voltage Control (AVC) on IEEE 14-Bus System

Either no violations or one action taken
Two actions taken
Three actions taken
Four actions taken
Five actions taken

60%-120% random system load changes

Reward

60%

States – Bus Voltage (Episode 8 and 5000)

<table>
<thead>
<tr>
<th>bus1</th>
<th>bus2</th>
<th>bus3</th>
<th>bus4</th>
<th>bus5</th>
<th>bus6</th>
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<th>bus8</th>
<th>bus9</th>
<th>bus10</th>
<th>bus11</th>
<th>bus12</th>
<th>bus13</th>
<th>bus14</th>
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<td>1.01797</td>
<td>1.02025</td>
<td>1.07</td>
<td>1.06204</td>
<td>1.09</td>
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<td>1.03698</td>
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</tr>
<tr>
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<td>1.01</td>
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<td>1.06047</td>
<td>1.09</td>
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<td>1.04913</td>
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<td>1.05036</td>
<td>1.03339</td>
<td>5000</td>
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<td>1.01</td>
<td>0.95</td>
<td>0.9627</td>
<td>0.96341</td>
<td>1.025</td>
<td>1.01158</td>
<td>1.05</td>
<td>1.00331</td>
<td>0.99898</td>
<td>1.00803</td>
<td>1.00845</td>
<td>1.00369</td>
<td>0.98341</td>
<td>5000</td>
</tr>
</tbody>
</table>

Actions – Vset (Episode 8 and 5000)

<table>
<thead>
<tr>
<th>gen1_vset</th>
<th>gen2_vset</th>
<th>gen3_vset</th>
<th>gen6_vset</th>
<th>gen8_vset</th>
<th>episode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.05</td>
<td>1.025</td>
<td>0.95</td>
<td>1.05</td>
<td>0.975</td>
<td>8</td>
</tr>
<tr>
<td>0.975</td>
<td>1.025</td>
<td>0.95</td>
<td>1.05</td>
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<tr>
<td>0.95</td>
<td>0.95</td>
<td>1.05</td>
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<tr>
<td>0.95</td>
<td>0.95</td>
<td>1.05</td>
<td>0.95</td>
<td>0.95</td>
<td>5000</td>
</tr>
</tbody>
</table>
AVC: DQN and DDPG Agents for Illinois 200-bus System

60%-120% random load changes are applied to each episode

Regional voltage control is considered for DQN agent: 5 adjacent generators with 30 interconnected buses in the neighborhood subsystem

After 10,000 episodes’ learning, the designed DRL agents start to master the voltage control problem in the 200-bus system by making decisions autonomously.

*The Illinois 200-bus system model is from https://egriddata.org/dataset/illinois-200-bus-system-activsg200
Further Testing-200 Bus System with Random N-1

- Test the DRL agent under different loading conditions: heavily loaded, fully loaded, and lightly loaded.
- Consider different topological changes. For example, random line tripping contingency or N-1 conditions.

**DDPG; 60%-140%; Enforcing Q limit**

- Either no violation or 1 iteration step

**DQN; 60%-140%; Enforcing Q limit**

- 2 iteration steps
- 3 iteration steps
- 4 iteration steps
- More than 5 iteration steps

**Observations:**

1. With little human interference, the designed agents work very well under all testing conditions.
2. The results comply with basic power system principles and engineering judgement very well.
3. The proposed framework is promising for power system autonomous operation and control.
Demo

Step 1: Perturb the system

Step 2: Check for voltage violations

Step 3: Run Grid Mind

Step 4: See the results

Check the following links for the demo:

https://geirina.net/assets/pdf/GridMindDemo_JD4.mp4

https://geirina.net/assets/pdf/JiangsuDemo.mp4
Deployment of Grid Mind at Jiangsu Grid

220kV and Above at ZhangJiaGang
Two Pilot Projects at ZhangJiaGang and NingBei of Jiangsu

- 45 substations and power plants
- 12 generators
- 3 500kV substations
- 37 220kV substations
- ~100 T-lines
- 50 buses
- Max load 3500MW
- Max gen. 5800MVA
Interface with Existing EMS and Data Flows
Pre-deployment Training and Testing

- **Generate Reasonable Data Sets based on Existing Data**
  - Perturb the following data files 2019-07-30-10-00, 2019-07-30-13-00, 2019-07-30-15-00, 2019-07-30-17-00, 2019-07-31-13-00 (of entire Jiangsu Grid), by changing its load between 80%-120%, with N-1 and N-1-1
  - Generate a total of 24000 system snap shots, use 12,000 of them as the training data and the rest for testing

- **Control Objectives**
  - Bus voltages of 220kV and above stay within range
  - 220kV-and-above lines should not be overloaded
  - Reduce the loss for all lines at 220kV and above

- **Testing Results are shown in the table**

<table>
<thead>
<tr>
<th>No. of Iterations</th>
<th>No. of Cases</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11670</td>
<td>97.25</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
<td>0.16</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>0.067</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0.042</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>0.025</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>0.025</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0.0083</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>0.0083</td>
</tr>
<tr>
<td>20</td>
<td>200</td>
<td>1.67</td>
</tr>
</tbody>
</table>

**Summary of Results**

- Success rate in term of voltage control: 99.9917% (for only one case, voltage issue got relieved but not completely solved, 1/12000)
- Success rate in term of line flow control: 100%
- Success rate in term of loss reduction: 98.33%, averaged loss reduction at 1.27%

**Possible causes (needs further investigation):**
1) Unreasonable data set (random load perturbation was considered)
2) Action space can be enlarged (shunts and Xfrm taps)
3) The case itself is difficult to solve (potential byproduct critical snapshot identification)

**Offline training & online execution:**

Train the AI agent from scratch offline to “college” level, the agent has to learn itself in the online environment to “graduate”
During online training, 571 snapshots have violations, all solved by AI agent.

During online execution, 239 snapshots have violations, all solved by AI agent.

Reward function: positive if violations in Vs and Flows are solved; negative otherwise; the more loss it reduces, the higher the reward.

For all cases, voltage and line flow violations are solved, with an average reduction in system loss of 3.87%.
Observations: validated by the EMS

1) following the decisions of the AI agent, all voltage violations are solved;
2) for one snapshot, voltage violations are solved, loss slightly increases;
3) other than the one case, loss reductions are observed, with highest number reaching ~6%;
4) for all snapshots, before and after control, no violation in flow is observed.
Display of one event (screen shots from one video)...

- **Performance**
  - Voltage violations at two Substations
  - Decision takes 2.2 ms

- **Computation time**
  - Problem solved after taking the suggestion from AI agent

- Actions suggested
Deployment at NingBei

- **Objective**: to relieve the high-voltage problem during the Spring Festival and national holidays

- **Special operating conditions**
  - Close to HVDC terminal station
  - Forecasted load of Jiangsu Grid during this period drops to 1/3 of peak load (~33,500MW)
  - One transformer being maintained, 4x60MVar shunt reactors offline
  - Multiple generators operates in under-excitation mode with negative Q
Results

Jan. 1, 2020-Feb. 12, 2020, a total of 10919 snapshots

- **Training**: 2864 snapshots with violations
- **Execution/testing**: 707 snapshots with violations
- **100% success rate**
Bus Voltages

220kV-and-above buses

NingHua Thermal Plant

NanRe Power Plant

500kV-and-above buses
Real Time Optimal Topology Control (L2RPN) -- Problem Formulation

- **Time-Series Optimal Control through Topology Adjustment**

**Optimization problem:**

- **Input Data**
  - *Objective* (Objective)
  - *Subject to* (s.t.)
  - Constraint_1
  - Constraint_2
  - Constraint_3
  - ...
  - Constraint_i
  - Constraint_j
  - ...

- **Decision Variables**

**Goal:** Maximize the remaining power transfer capability of the entire system (all lines) over all time steps for all scenarios

---

**Transfer Capability at a Time Step:**

- Step_single_line_margin = \( \text{Max}(0, \frac{1}{\text{ThermalLimit}}) \times 2 \)
- Step_single_line_score = \( 1 - (1 - \text{Step_singel_line_margin}) \times 2 \)
- Step_total_score = Sum(Step_single_line_score) over lines

**Transfer Capability for one Scenario:**

- Scenario_Score = 0, if Game Over (when certain constraints are violated)
- = Sum(Step_total_score) over all timesteps, otherwise

**Transfer Capability of All Scenarios:**

- Total_score = Sum(Scenario_Score) over all scenarios

---

**Combination** of Node Splitting/Rejoining and Line Switching on/off

- Node Splitting/Rejoining (156 for 14 nodes)
- Line Switching On/Off (20 lines)

*Note: A Maximum of 1 action at the node + 1 action at a line per timestep is allowed

A total of 3120 possible actions in a single timestep!
**Constraints**

- **Game Over** if any of the following “**hard**” constraints is violated:
  - Load should be met over all time steps of all scenarios
  - No more than 1 power plants get disconnected over all time steps of all scenarios
  - The grid should not get split apart into isolated sub-grids over all time steps of all scenarios
  - AC power flow solution should converge over all time steps of all scenarios

  **Single-timestep Constraints**

- Violation on “**soft**” constraints may lead to **certain consequences** though not immediate “game over”:
  - Line overload should be controlled over all time steps of all scenarios:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Consequence</th>
<th>Time Steps to Recover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Flow &gt;= 150%</td>
<td>Line immediately broken and disconnected</td>
<td>10</td>
</tr>
<tr>
<td>100% &lt; Line Flow</td>
<td>Wait for 2 more timestep to see whether the overflow is</td>
<td>3</td>
</tr>
<tr>
<td>&lt; 150%</td>
<td>resolved; If not, line gets disconnected</td>
<td></td>
</tr>
</tbody>
</table>

- Cooldown should be considered: 3 steps of cooldown is required before a line or node can be reused, the violation on this will cause: 1) step score to be 0; 2) the action will not be taken, resulting in no action.

  **Multi-timestep Constraints**
Problem Complexity

Total number of possible trajectories:

3120

5184

Action space for each time step

Total time steps of 1 scenario
(18 days with 5 mins intervals)
Solve this Using Conventional Optimization Approach?

Formulation for a single-time-step (without considering multi-time-step constraints):

The objective is to maximize the system available transmission capacity, an auxiliary variable $\lambda_k$ is introduced.

**Objective Fun.:**

$$\max \sum_{k \in \Omega_k} \lambda_k \quad \lambda_k \geq 0, \forall k$$

$$\lambda_k \geq 1 - \left( \frac{S_k}{S_{k}^{\max}} \right)^2, \forall k$$

**Constraints:**

- $-M^g(1-z_i) \leq \theta_{i1} - \theta_{i2} \leq M^g(1-z_i), \forall i$
- $-M^v(1-z_i) \leq V_{i1} - V_{i2} \leq M^v(1-z_i), \forall i$

$$P_{n1}^g = (1-z_n)P_{n1}^{g0}, \forall n \in G / \mathcal{G}_{st}$$

$$P_{n2}^g = z_nP_{n2}^{g0}, \forall n \in G / \mathcal{G}_{st}$$

$$-(1-z_n)M^g \leq P_{n1}^g \leq (1-z_n)M^g, \forall n \in G \setminus \mathcal{G}_{st}$$

$$-z_nM^g \leq P_{n2}^g \leq z_nM^g, \forall n \in G \setminus \mathcal{G}_{st}$$

$$-(1-z_n)M^q \leq Q_{n1}^g \leq (1-z_n)M^q, \forall n \in G \setminus \mathcal{G}_{st}$$

$$-z_nM^q \leq Q_{n2}^g \leq z_nM^q, \forall n \in G \setminus \mathcal{G}_{st}$$

- $P_{m1}^d = (1-z_m)P_{m1}^{d0}, \forall m \in \mathcal{T}$

$$P_{m2}^d = z_mP_{m2}^{d0}, \forall m \in \mathcal{T}$$

$$-(1-z_{m1})M^d \leq P_{m1}^d \leq (1-z_{m1})M^d, \forall k$$

$$-z_{m1}M^d \leq P_{m2}^d \leq z_{m1}M^d, \forall k$$

$$-(1-z_{m2})M^q \leq Q_{m1}^d \leq (1-z_{m2})M^q, \forall k$$

$$-z_{m2}M^q \leq Q_{m2}^d \leq z_{m2}M^q, \forall k$$

Constraints on bus voltage, generators, lines, and loads at a substation

Constraints on real and reactive power, volt., power flow, apparent power of a line

Constraints on power balance at a bus bar, number of bus splitting, and number of line switching.
**Dueling DQN with Imitation Learning and Early Warning**

- **Architecture design**
  - Dual Q Function (DQN) structure and Performance
  - Early Warning System
  - Test trained models on 200 unseen chronics, each has 5184 continuous steps
  - Autonomously controlling the grid for up to a month!!!

**Combine power system physics with AI technologies to obtain the best results**

- **Early Warning System**
  - Warning Flag = \[
  \begin{cases}
  \text{True} & \text{if } \frac{lineflow_i}{\text{thermallimit}_i} > \theta, \ \forall i \in \{1,2,\ldots,20\} \\
  \text{False} & \text{otherwise}
  \end{cases}
  \]

**Test trained models on 200 unseen chronics, each has 5184 continuous steps**

<table>
<thead>
<tr>
<th>Agent</th>
<th>Game Over</th>
<th>Mean Score All</th>
<th>Mean Score w/o Dead</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW (\theta = 0.90)</td>
<td>17</td>
<td>75491.63</td>
<td>82504.51</td>
</tr>
<tr>
<td>EW (\theta = 0.91)</td>
<td>15</td>
<td>76345.36</td>
<td>82535.52</td>
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<td>EW (\theta = 0.92)</td>
<td>15</td>
<td>76353.23</td>
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<td>EW (\theta = 0.93)</td>
<td>15</td>
<td>76353.23</td>
<td>82544.03</td>
</tr>
</tbody>
</table>

Autonomously controlling the grid for up to a month!!!
Demo on A Hard Sample Case

If Agent does nothing …

- Line 5-6, 4-5, 4-7, 4-9 are forced to switch off continuously, leading to game over.

Trained Agent

- Switch off line 10-11, line 5-6 loadflow alleviated
- Switch off line 13-14, line 2-5 loadflow alleviated
- Successfully goes through the system peak-load time
Learn Load Dynamics using AI - WECC CLM

A two-stage approach is proposed for ZIP+IM, CLOD, and WECC CLM with as many as 130+ parameters.

The approach is robust for fault at different locations, different fault types, different fault clearing times. The results using the identified model match the dynamic response of the system.

For one Fault

Diff. Fault Locations

Diff. Fault Types

Diff. Fault Clearing Time

Accuracy for $P$, RMSE 0.12%

Accuracy for $Q$, RMSE 0.64%

In the first stage, DRL is utilized to identify the percentage of each component; in the 2nd stage, parameters of each component can be identified.
Method Validation

The left animation shows the identification process of different load components of the WECC CLM; the right one shows the tracking error. The algorithm converges pretty fast.
Other Applications We’ve Developed/Are Developing

- Online learning for AI agents in face of significant topology and operating pattern changes
- Autonomous line flow control
- Learn generator/load dynamic model & parameters
- Data-driven AC OPF
- Multi-agent cooperative control for larger systems

Multiple Cooperative Dispatch Robots
Developmental Trend

- Model validation and calibration
- Excitation and damping control
- Maintenance Scheduling
- Renewable Forecasting

- Intelligent monitoring & early warning
- Intelligent diagnosis of equipment
- Image recognition of power lines
- Situational awareness

- Knowledge map & intelligent reasoning
- Fault detection and location
- Intelligent analysis and self-healing ctrl

- Demand forecasting
- Load clustering and par. identification

Trend of AI in Power Systems

- Monitoring
- Diagnosis
- Forecasting

Reasoning/planning
- Decision making
- Autonomous control

Potential Applications

- Power system operation and control
- Power system planning
- Power system asset management
- Power system economics and market

- RNN
- LSTM
- CNN
- GAN
- GNN
- SVM...

- (D)DQN
- PPO
- DDPG
- SAC
- A3C
- TRPO...
Challenges & Opportunities

• Data sets

• Platform

• Competitions based on common data sets & platform

In 2020, two Power System AI Competitions will be hosted: [https://l2rpn.chalearn.org/](https://l2rpn.chalearn.org/)
Related Publications


8. X. Wang, Y. Wang, J. Wang, and D. Shi, “Residential Customer Baseline Load Estimation Using Stacked Autoencoder with Pseudo-load Selection,” IEEE Journal on Selected Areas in Communications (J-SAC) issue on Communications and Data Analytics in Smart Grid, 2019


Thank You!

www.geirina.net