Destroy Your Power Grid as a Service (DYPGaaS)

How Novel Grid Analysis Improves Grid Expansion Planning

Eric MSP Veith <eric.veith@uol.de>, 2023-03-13
In A Nutshell

- Journey from grid expansion to Multi-Agent Systems to Agents destroying the power grid to grid expansion.
- Grid expansion suffers from run-time resilience analysis.
- Too many actors, grid becomes too intelligent to calculate robustness beforehand.
- AI for grid testing AND resilient operation — but needs safeguards, online learning, explainability
- There will be no “flag day,” so we need to develop the hybrid scenario all the way.
% whoami

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▶ Currently head of a junior research group at University of Oldenburg, Germany
▶ Computer scientist by heart: First ICT, then distributed heuristics, then Multi-Agent Systems, now advanced Deep Reinforcement Learning
▶ PhD in 2017: “Universal Smart Grid Agent for Distributed Power Generation Management.”
▶ Creator of the Adversarial Resilience Learning methodology (advanced DRL in CNIs)
Electricity Demand Rising

After significant decline in 2022, European electricity demand is set to recover

Year-on-year relative change in electricity demand, Europe, 2019-2025

<table>
<thead>
<tr>
<th>Year</th>
<th>European Union</th>
<th>Europe</th>
<th>Germany</th>
<th>France</th>
<th>Italy</th>
<th>Spain</th>
<th>United Kingdom</th>
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<td>-6%</td>
<td>-4%</td>
<td>-2%</td>
<td>0%</td>
<td>2%</td>
<td>-4%</td>
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<td>-3%</td>
<td>1%</td>
<td>3%</td>
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<td>0%</td>
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<td>2%</td>
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<td>10%</td>
<td>8%</td>
<td>10%</td>
<td>12%</td>
</tr>
</tbody>
</table>
Renewables Are Replacing Fossil Fuels

Following two years of increases, CO₂ intensity starts to decline again from 2023 onward

Year-on-year change in electricity generation, European Union, 2019-2025

Development of average CO₂ intensity, Europe, 2019-2025
Electricity Demand + DERs = Grid Expansion

- DERs are volatile
- Consumer behavior becomes multi-faceted, no longer easy to average (direct market access, battery swarms, ...)
- “Typical” grid usage largely atypical
Grid Expansion Planning Today

Step 1: Data Acquisition

- Acquisition of GIS data
- List of local network stations
- Most probably load-flow calculation not possible;
- ... so manual labor to create digital grid plan
Grid Expansion Planning Today

Step 2: Modelling

- Local network stations get prognosis assigned
- Stochastic distribution of DERs according to prognosis
Grid Expansion Planning Today

Step 3: Limits

- Simulate, calculate
- Document limits & violations
- Mostly thermic limits, voltage band limits; also wear & tear of tap transformers

dena-Verteilnetzstudie
Grid Expansion Planning Today

Step 4: Expansion

- Split subgrids: add local stations
- Split subgrids: add parallel lines
- Rinse & repeat

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Grid Expansion Planning

- Modern grid expansion based on scenarios
- Data prognoses
- Modern tools allow to automatically propose expansions
- Calculate fault conditions, potential overloads, etc.
- But what scenarios are possible, which ones are unrealistic?
- Expansion vs. efficient operation (?)
AI as Promise of an Alternative

- Multi-Agent Systems promise local, more efficient grid operation
- Each node (subgrid, ...) an agent
- Nodes (agents) forecast local power generation/consumption
- On disequilibrium, match forecasts to achieve equilibrium
Agent Design

**Input**
- Grid
- Local Env.
- Training

**Agent**
- Demand—Supply
- Reserve
- Learner
- Forecaster
- Data Extraction
- Logging
- Hardware Interface
- Messaging
- Constraint Calculation

**Priority**
- Power Grid
- Micro Grid
- Local Unit
  - (Power plant)
- Device Layer

Automatic Hardware Control (e.g., failsafe, emergency shutdown)
Forecasting

RNN Context Layer
Initialization

Forecast Input

Forecast Result

Sliding Window

\[ x_m \]

JournalEntry

Time Interval
Wind Dir.
Wind Speed
Power

UnitConverter

\[ \text{Real Power [MW]} \]

\[ \text{Wind Speed [m/s]} \]

\[ \text{Power} \]

UnitConverter

Forecast

Time

\[ [0;1] [0;1] \]

\[ (0;1) \]

\[ [s; s) \]

\[ [s; s) \]

\[ \text{Wide Sharing Layer} \]

\[ \text{Adversarial Resilience Learning} \]
Forecasting
Forecasting

Bare Hill Wind Farm Power Output
Bare Hill Wind Farm Forecasted Power Output

Real Power [MW]
Training with Evolutionary Algorithms

- Evolutionary training algorithm
  - Each individual an ANN candidate
  - Fitness of an individual: the cost function
  - Moving through the search space by mutation and crossover
  - Advantage: possibly better to escape local minima

- A variant: REvol
  - Implicit gradient information
  - Dynamic reproduction probability density function
Properties of an Individual

- Parameter Vector: the genome
- Scatter Vector: limits parameter modification \( p_{t,i} = [-s_i \cdot p_{t-1,i}, s_i \cdot p_{t-1,i}] \)
- Time to Live (TTL)
- Fitness
Algorithm Behavior

Ackley's Function
REvol Population
Algorithm Behavior

 Ackley's Function
 REvol Population
 Implicit Gradient

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Four-Way Handshake
LPEP Routing

1. No Zombies
2. Match or Forward
3. Forwarding Ruleset
Forwarding

- $L_i$: Links of the $i$-th agent
- $l_{i,k}$: $k$-th link of $i$-th agent
- distance$(l_{i,k})$: Distance metric
- $m_j$: $j$-th message
- $M_i$: Message Journal of the $i$-th agent
Forwarding

- \( L_i \): Links of the \( i \)-th agent
- \( l_{i,k} \): \( k \)-th link of \( i \)-th agent
- \( \text{distance}(l_{i,k}) \): Distance metric
- \( m_j \): \( j \)-th message
- \( M_i \): Message Journal of the \( i \)-th agent

\[
M_i = \{m_1 \mapsto \{(l_{i,1}, m_1, \text{distance}(l_{i,1})), \ldots, (l_{i,n}, m_{n}', \text{distance}(l_{i,n}))\}; \ldots, \\
\quad m_n \mapsto \{(l_{i,1}, m_n, \text{distance}(l_{i,1})), \ldots, (l_{i,n}, m_{n}', \text{distance}(l_{i,n}))\}\}
\]
Forwarding

- $L_i$: Links of the $i$-th agent
- $l_{i,k}$: $k$-th link of $i$-th agent
- $\text{distance}(l_{i,k})$: Distance metric
- $m_j$: $j$-th message
- $M_i$: Message Journal of the $i$-th agent

\[ M_i = \{ m_1 \mapsto \{(l_{i,1}, m_1, \text{distance}(l_{i,1})), \ldots, (l_{i,n}, m'_1, \text{distance}(l_{i,n}))\}, \ldots, m_n \mapsto \{(l_{i,1}, m_n, \text{distance}(l_{i,1})), \ldots, (l_{i,n}, m'_n, \text{distance}(l_{i,n}))\}\} \]

\[ l_{i,1}(t) \leq l_{i,2}(t) \iff l_{i,1,\text{distance}}(t) \leq l_{i,2,\text{distance}}(t) \]
Forwarding

1. Respect *Constraint Notifications*:
   1.1 No answer if min \((M(m))\) a constraint notification to \(m\), additionally
   1.2 send *Withdrawal Notification* iff already answered
Forwarding

1. Respect *Constraint Notifications*:
   1.1 No answer if \( \min(M(m)) \) a constraint notification to \( m \), additionally
   1.2 send *Withdrawal Notification* iff already answered

2. \( m_{\text{isAnswer}} \): forward on best connect (\( \min(M(m_{\text{answerTo}})) \))
Forwarding

1. Respect *Constraint Notifications*:
   1.1 No answer if $\min(M(m))$ a constraint notification to $m$, additionally
   1.2 Send *Withdrawal Notification* iff already answered

2. $m_{\text{isAnswer}}$: forward on best connect ($\min(M(m_{\text{answerTo}})))$

3. *Selective Broadcast* for requests:
   3.1 Replace request with *Constraint Notification*, if necessary
   3.2 $M(m) = \emptyset$: forward on $|L| - 1$ links
   3.3 $m' = \min(M(m'))$: Update by forwarding
   3.4 Otherwise: no forwarding
How to Decide...?

1. Local forecasting shows demand or oversupply of energy
2. Requests are sent
3. Other nodes make offers
4. Offers reach requestor
5. Decision about offers?
Power Balance Concept

Set of Mappings $[t_1; t_2) \mapsto P$. 

Leistungs-Disequilibrium
Problem Statement

‘Power Balance Algebra’:

\[ \{ [t_1; t_3) \mapsto P_1 \} \cup \{ [t_2; t_4) \mapsto P_2 \} = \]

\[ \{ [t_1; t_2) \mapsto P_1, [t_2; t_3) \mapsto P_1 + P_2, [t_3; t_4) \mapsto P_2 \} \, , \quad (1) \]

\[ [t_1; t_2) \mapsto P_1 \subseteq [t_3; t_4) \mapsto P_2 \]

\[ \Leftrightarrow \quad t_1 \geq t_3 \land t_2 \leq t_4 \land P_1 \leq P_2 \; ; \quad (2) \]
Problem Statement

‘Power Balance Algebra’:

\[ \{[t_1; t_3) \mapsto P_1\} \cup \{[t_2; t_4) \mapsto P_2\} = \{[t_1; t_2) \mapsto P_1, [t_2; t_3) \mapsto P_1 + P_2, [t_3; t_4) \mapsto P_2\}, \quad (1) \]

\[ [t_1; t_2) \mapsto P_1 \subseteq [t_3; t_4) \mapsto P_2 \quad \Leftrightarrow \quad t_1 \geq t_3 \land t_2 \leq t_4 \land P_1 \leq P_2 ; \quad (2) \]

Distance Function:

\[ d(r_i) : r_i \mapsto \mathbb{R} \quad (3) \]
Problem Statement

'Power Balance Algebra':

\[
\{[t_1; t_3) \mapsto P_1\} \cup \{[t_2; t_4) \mapsto P_2\} = \\
\{[t_1; t_2) \mapsto P_1, [t_2; t_3) \mapsto P_1 + P_2, [t_3; t_4) \mapsto P_2\} ,
\]

\[
[t_1; t_2) \mapsto P_1 \subseteq [t_3; t_4) \mapsto P_2
\]

\[\iff t_1 \geq t_3 \land t_2 \leq t_4 \land P_1 \leq P_2 ;\] (2)

Distance Function:

\[d(r_i) : r_i \mapsto \mathbb{R}\] (3)

Problem Statement:

\[
\sum_i b_i r_i \subseteq r_0 , \ i \neq 0, b_i \in \{0, 1\} ,
\]

Subject to: \[\min \sum_i b_i d(r_i), \ i \neq 0, b_i \in \{0, 1\} .\] (5)
Atomization

\[ P = (|P_0|, |P_1|, \ldots, |P_i|, |P_C|), \]
\[ t = (t_{2,0} - t_{1,0}, t_{2,1} - t_{1,1}, \ldots, t_{2,i} - t_{1,i}), \]
\[ \Delta P = gg^T(P), \]
\[ \Delta t = gg^T(t), \]
Atomization

\[ P = (|P_0|, |P_1|, \ldots, |P_i|, |P_C|) , \]
\[ t = (t_{2,0} - t_{1,0}, t_{2,1} - t_{1,1}, \ldots, t_{2,i} - t_{1,i}) , \]
\[ \Delta P = \text{ggT}(P) , \]
\[ \Delta t = \text{ggT}(t) , \]
\[ x_{i,t,P} = \begin{cases} 
1 & \text{if agent } i \text{ influences the grid in time-subinterval } \tilde{t} \text{ with power from the power-subinterval } \tilde{P}, \\
0 & \text{else.} 
\end{cases} \]
Atomization Illustrated

Leistungs-Disequilibrium

\[ \bar{P} = 4 \]
\[ \bar{P} = 3 \]
\[ \bar{P} = 2 \]
\[ \bar{P} = 1 \]
Model of the Disequilibrium

A symmetric function for each time-subinterval:

\[ S^n_k(x_i, \bar{t}=k, \bar{P}) = \begin{cases} 1 & \text{if } n \text{ variables in } x_i, \bar{t}=k, \bar{P} \text{ equal } 1, \\ 0 & \text{else}; \end{cases} \]

Full Disequilibrium:

\[ S = \bigcap_{k=1}^{m} S^n_k(x_i, \bar{t}=k, \bar{P}) \]
Modelling Responses

Acceptance Function:

\[ r_i(x_i, t, \hat{P}) = \begin{cases} 
1 & \text{if } x_i, t, \hat{P} \text{ describes a valid interval for accepting the response of } i, \\
0 & \text{else.} 
\end{cases} \]

\[ r_2(x_i, t, \hat{P}) = \overline{x_{2,3,1}} \land \overline{x_{2,3,2}} \land \overline{x_{2,4,1}} \land \overline{x_{2,4,2}} \]

\[ \lor x_{2,3,1} \land x_{2,3,2} \land \overline{x_{2,4,1}} \land \overline{x_{2,4,2}} \]

\[ \lor x_{2,3,1} \land x_{2,3,2} \land x_{2,4,1} \land x_{2,4,2} \]
Equilibrium

\[ S = \bigcap_{k=1}^{m} S^n_{k}(x_i, \tilde{t}, k, \tilde{p}) \]

\[ R = \bigcap_{i \in I', \tilde{t}, \tilde{p}} r_i(x_i, \tilde{t}, \tilde{p}) , \]

\[ C = S \cap R . \]
Equilibrium

\[ S = \bigcap_{k=1}^{m} S_k^n(x_i, \bar{t} = k, \bar{p}) \]
\[ R = \bigcap_{i \in I', \bar{t}, \bar{p}} r_i(x_i, \bar{t}, \bar{p}) \]
\[ C = S \cap R. \]

- Best solution through ordering: \( r_i \leq r_i' \iff d(r_i) \leq d(r_i') \)
- Generating next vector in \( S \) through permutation
- Exploiting the commutative property of the intersection operator:
  \( R_n \cap (\ldots \cap (R_2 \cap (R_1 \cap S))) \)
Efficiency

Data Effect

\[ \kappa = \frac{W}{D} \left[ \frac{\text{kWh}}{\text{kB}} \right] \]

Data Efficiency

\[ \xi = \frac{\Delta P}{D} \left[ \frac{\text{kW}}{\text{kB}} \right] \]
Comparison

Comparison with BDD approach by Inoue et al. (2014):

<table>
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<th>BDD</th>
<th>Universal Agent</th>
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<tbody>
<tr>
<td>Loss Avoided ($\Delta P$)</td>
<td>17 208 kW</td>
<td>17 208 kW</td>
</tr>
<tr>
<td>Runtime</td>
<td>&gt; 16 min</td>
<td>&lt; 11 min (simulated)</td>
</tr>
<tr>
<td>D</td>
<td>100 MB</td>
<td>28.9 MB</td>
</tr>
<tr>
<td>$\xi$</td>
<td>0.168 kW/kB</td>
<td>0.581 kW/kB</td>
</tr>
</tbody>
</table>
Universal Agent Efficiency

- BDD approach in low-load situation: 100 kB
- *Universal Agent* concept especially useful in complex load situations
AND THIS, GENTLEMEN

IS HOW YOU RUN YOUR GRID.
THEY SAY THEIR SYSTEMS RUN THEIR GRID.

LETS ADD SOME SURPRISES.
“There are only two types of companies: those who have been hacked, and those who don’t yet know they have been hacked.”
— John T. Chambers
Cyber attack causes blackout in the Ukraine

3 DSOs targeted

High level of automation helps attackers

Operative intrusion in OT; disconnection of several substations

Several months in preparation
Energieversorgung in Deutschland

Stromhändler zocken fast bis zum Blackout

Der deutsche Strommarkt stand in den vergangenen Tagen mehrfach vor dem Zusammenbruch. Laut Bundesnetzagentur waren dafür aber nicht die Kälte oder der Atomausstieg verantwortlich, sondern Energiehändler - die offenbar ihre Profite maximieren wollten. Die Aufsichtsbehörde ist alarmiert.
Systemstabilität - Minutenreserve

- Abgerufene Menge (+)
- Abgerufene Menge (-)
- Arbeitspreis (+)
- Arbeitspreis (-)
- Vorgehaltene Menge (+)
- Vorgehaltene Menge (-)
- Leistungspreis (+)
- Leistungspreis (-)
The Adversary

- Consumer behavior (prosumers), VPP, outages, weather effects: probabilistic modelling
- DERs
  - Prognosis deviations
  - VPP, direct marketing: highly non-deterministic
- Terrorist
  - Goal: Demolition
  - No route back needed in some cases
  - No sophisticated tactics necessary
- Military
  - Goal: destruction & takeover
  - Damage to CNIs is mostly collateral damage (or explicitly wanted)
  - Usually, CNIs are “don’t care,” but should be usable afterwards
- Businesspeople
  - Goal: (short-term) profit maximization
  - Damage to CNIs unexpected (or simply “don’t care”)
  - Uses loopholes and grey areas in codices
Learning Resilient Control

▶ Interconnected CPS have always attack surface due to their inherent complexity
▶ Low latency of ICT and OT
▶ High interdependence
▶ Complexity in breadth and depth
▶ Critical Services as SPOF (DNS, BGP, SCADA, SDL)
▶ Learning Strategies for automatic issue management
▶ “Adversarial Resilience Learning”

Adversarial Resilience Learning

Shared Environment
(Digital Twin of a CPES)

Interaction via Sensors & Actuators

"Attacker" Agent

"Defender" Agent

Reward / Objective
Observation
Action

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Adversarial Resilience Learning

"Attacker" Agent

Interaction via Sensors & Actuators

"Defender" Agent

Adversarial System-of-Systems Reinforcement Learning
ARL Agent Interaction

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ARL Agent Can Discover Attacks

- Attack on voltage level
- Attacker controls Q feed-in
- Known attack: Oscillating behavior
- ARL agent independently discovers attack, but also finds variant
Multi-Agent Autocurricula

- ARL is an autocurriculum setup
- Independently known & verified to work
- Example Setup: Two groups of agents play hide and seek
- No domain information; agents learn strategies and tool use independently
- Result: Agents learn to exploit bugs in the underlying game engine
  - Holes in walls
  - Sliding boxes
  - Edge/corner jumps
ARL Works

To summarize...

▶ ARL works for finding attack vectors ("easy")
▶ ARL defender learn resilient control ("not quite so easy, but still...")
▶ ARL agents learn faster & more robust strategies through the autocurriculum setup ("prove me, I'm only circumstantial evidence!")
▶ ARL defender agents can control modern power grids ("ha-ha, as if that would be acceptable...")

▶ **There is still a lot missing:**
  ▶ Behavior guarantees
  ▶ Adhere to constraints (rulesets)
  ▶ Learn from existing domain knowledge
  ▶ Adapt during production use (not just retraining)
  ▶ ...

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ARL Agent Architecture

- Learn from sensor inputs (policy: DRL)
- Deploy & forget, don’t design policy networks: Neuroevolution
- Explainability
- Learn from domain knowledge
- Follow rules, if given
Learning from Domain Knowledge

Example: Misuse Cases

- **Stage 1**: (Mis)Use Case Template
  - Structured, archived domain knowledge; not machine readable

- **Stage 2**: Expert Knowledge
  - Unstructured, not archived domain knowledge

- **Stage 3**: UML Diagram
  - Structured, archived domain knowledge, limited to the depicted information

- **Stage 4**: XML file
  - Structured, archived domain knowledge; limited to the information of the file this is exported from; machine readable

- **Stage 5**: Experiment file
  - Executable experiment file for the ARL toolchain. Contains the information given in the XML file
Behavior Cloning

- **Behavior cloning**: Observe actions of expert
- **Expert**: well-known controllers (e.g., Q), scripted MUC behavior, domain knowledge in terms of rules/constraints


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XRL

- No trust without explanation
- Extract rulesets from DRL policies
- Decision trees can become huge! Use TVLs instead
- Rulesets are only intermediary format for actual explaining
XRL

- No trust without explanation
- Extract rulesets from DRL policies
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- Rulesets are only intermediary format for actual explaining
AGENTS... CYBER... BOOLEAN... AND...

GRID EXPANSION PLANNING!?
Hybrid Renewable Energy Systems

- Grid Expansion is part of the **HRES** perspective
- **HRES: Hybrid-Renewable Energy System**
  - Power grids with mixed DERs and fossil generation
  - ... a transition perspective
- Central question: How to expand the grid to accommodate more DERs?
  - Lines
  - Sizing of transformers and other assets
  - Placement of DERs, batteries
- **HRES are an optimization problem.**
HRES Optimization Loop

Start ➔ Generate initial solution candidates ➔ Simulate solution candidates ➔ Optimize solution candidates ➔ Calculate performance of solution candidates ➔ Termination condition reached ➔ End
HRES Optimization Metrics

- **Common optimization goals:**
  - **Economic** Cost of Energy generation (COE)
  - **Technical** Loss of Power Supply Probability (LPSP)
  - **Environmental** CO₂ Emission of System

- **Examples of common optimization techniques:**
  - Evolutionary Algorithm (EA)
  - Particle Swarm Optimization (PSO)

- **Common simulation techniques**
  - Specialized software, e.g., HOMER
  - Manual simulation per timestep
Open Question: Resilience

HRES optimization does currently not take resilience into account.

Can we apply algorithmic optimization to HRES in order to lessen vulnerabilities discovered with ARL — by improving robustness and implementing resilient behavior?

This shortcoming is true also for today’s grid expansion, as it calculates only robustness.
HRES Optimization, Extended

Sub-RQ 1:
How can intelligent heuristics be used to force disturbances upon the HRES within the simulation so that they are required to react resiliently by downgrading functionality?

Sub-RQ 2:
How can the ability of a system to intelligently react to unexpected disturbances be integrated into the simulation of HRES?

Sub-RQ 3:
How can robustness of a HRES be measured so that it can be used as a performance metric in HRES optimization?

Sub-RQ 4:
How can HRES be optimized under consideration of traditional performance metrics and robustness?
A Lookout

- The journey towards highly automated grid operation & extension has just begun.
- AI can help testing future grids, be part of certification processes
- AI itself needs safeguards: Rulesets, explainability, and eventually certification, too. (Insurance...?)
- We will see sophisticated agent architectures in the near future.
- If you want to see interesting code, head over to http://palaestr.ai or shout out to eric.veith@uol.de!