Big Data Thinking for Cyber-Physical Energy System

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Electricity is a core of the whole energy chain, however, energy safety relies on not only power system, but also

• Clean alternative for the primary energy
• Electricity alternative for the end-use energy
Traditional analyses are under given boundary conditions, without considering the two ends of the energy flow.

More complicated multi-network-flow

Direct emission
Indirect emission
Direct emission
Emission rights
Primary energy
Power plant
Electric power
Trans. & Dist.
Demand side
Various energy

Energy flow
Capital flow
Info. flow
Smart Grids are confined to integrating the power grid and private networks

It cannot fully cover the mission of power system endowed by the new energy revolution

Challenges of high penetration of wind/PV generation

- Fluctuation, intermittence, uncontrollability
- Hard to predict
- Uncertainty
- Weak adaptability
- Power reserves
- Power quality
- Additional investment
Challenges of large scale charging loads

- Uncertain load impact
- Power quality
- V2G
- Reduction of CO2

Extension of the target physical system

macro energy thinking

power grids ➞ macro energy
Communication network extension

There are many other challenges for securities on energy, environment and economy

- The Severity of Various Natural Disasters
- UHV AC/DC hybrid grids
- Emission restriction
- Customer’s deep participance
- Market game
- More uncertainties & unpredictability
- Cyber security
Risk caused by electric power under-adequacy

Transmission-Distribution Joint Adequacy

Generation-Consumption Relative Adequacy

- Increase frequency
- Decrease frequency
- Real-time condition
- System degradation
- Online Matching and Closed-Loop Control
- Optimized dispatching
- Forecast information
- Generation Schedule
- Maintenance Reserve Pool
- Increase frequency
- Decrease frequency
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Risk caused by electric power under-adequacy

Risks can even caused by external non-energy domains

Social Develop.
Power Demanding

Emis. & Pollut.
Natural Disasters

Primary Ener.
Renewable Ener. Sources

DSM
Consumption Modes

Sys. Planning
Dispatch Optimization

Physical Pow. Sys.

Investment & Construction
Assets Manag.

R&D
Human Res.
& Training

Communica'.
Protection Control

Sudden Events
Emergency Management

Power Economics
Market Regulation
Risk caused by various natural disasters

- Ice & snow
- Contamination & moisture
- Charge accumulation
- Drying & fire
- Tropical cyclone
- Rainstorm
- Solar activity
- Freezing rain
- Partial discharge
- Lightning
- Partial discharge
- Forest fire
- Oceanic typhoon
- Overland typhoon
- Flood
- Magnetic storm
- GIC

WARMAP

Online evaluation of power grid fault probability

Risks caused by Emission Congestion

- Initiative emission management and blackout risk
- Suitable quantitative analysis methods are required

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Risks caused by information systems

Risks caused by market forces
Risks caused by improper regulation

Risk caused by participants’ behaviors
A cyber-physical energy system

Non-electrical energy systems + Electrical power systems + Relevant non-energy systems

The whole energy system and relevant socio-technical scenarios are deeply merged with the whole cyber systems

CPES is based on all causal / behavioral / statistical data

Big data
- Causal data
- Behavioral data
- Statistical data

Mathematical models
- Response of others' behaviors

Data-driven models
- Statistical analysis of behaviors

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Energy systems merge with cyber systems by using big data

![Diagram showing data extension from traditional data to big data](image)

Smart Grid: A Cyber-Physical Power System

CPPS cannot accomplish the tasks alone to support dominated REG and active load participation.
Extending a smart grid to a cyber-physical energy system

Can big data thinking help model driven tasks?

- Current success of big data is largely confined to network financial and personalized services
- There is lack of applying the big data thinking to power system analysis and control, where causal analyses are usually dominated
Ways to integrate statistical data with causal data and behavioral data

- Causal data
- Model simulation
- Behavioral data
- Way 3
- Hybrid simul.
- Statistical data
- Data driving

Way 1: Raising calculation efficiency
Way 2: Improving analysis accuracy
Way 3: Hybird simul.

An Ex. of way-1
EEAC method quantizes power system stability

- It is difficult for empirical interpretation to explore stability mechanism and optimize decisions
- EEAC method promotes stability analysis from experience interpretation to qualitative assessment
- EEAC separates observation space from integral space, identifies the dominant model, and quantizes stability
- The N&S conditions of stability is derived by EEAC
- EEAC reveals causal mechanism of stability from trajectory
Security domains of various stabilities

1. Data Acquisition
2. Quantitative anal. for faults
   Sensitivity analysis
3. Insecure degree
   Decision making
   Control

\[ V \sin (\omega t + \phi) \]

\[ \phi \]

Voltage SD
Global SD
Frequency SD

Control optimization needs effectiveness-cost index to guide searching

\[
\text{min} \sum_{i=1}^{m} \frac{C}{n_i} \\
\text{s.t.} \quad \eta(n_1, n_2, \ldots n_m) > \varepsilon \\
\quad n_i \leq n_{i,\text{max}} \quad (i = 1, \ldots m) \\
\quad \sum_{i \in k} n_i \leq n_{k,\text{max}} \\
\]

Contour map of the index \( W_i \) in high dimensional space

\[ W_i = \frac{\Delta n_i}{\Delta J} \]
Fusion of research forms for stability study

- Behavior analysis for injection power
- Causal analyses
- Orthographic projection
- Independent trajectory
- Stability margin
- Statistical analyses

Wide ARRea Monitoring Analysis Protection-control (WARMAP)

- Power systems
- Data acquisition
- Knowledge extraction
- Decision support
- Close-loop control
- Open-loop control

Decision support system

- Protection-control
- Operators

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WARMAP has effectively served for 4/5 provincial level and above power grids in China

It has made great contributions to avoiding system-wide blackouts in China
Blackout defense systems are adaptive to the relevant external elements

Non- elec. elements

Data acquisition

prediction

Risk assessments

DSS

Power systems

Data acquisition

Inner-fault scenarios

Operating condition

Blackout risk assessment

Multi-line defense DSS

Non-elec. elements...interactions

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An Ex. of way-2

Fast analysis of cascading outage with confidence control

• Distribution factor method is based on linearized load flow equations and greatly reduces calculation burden. However its error is uncontrollable
• Strong correlations between the error and the 2nd-order sensitivity matrix
• An approximate 2nd-order sensitivity matrix can be got quickly, and its second norm can evaluate the credibility of distribution factor method
• Distribution factor method is used at first, then its result’s credibility is estimated to decide if a full ACPF should be run
• The threshold value is obtained by statistical analysis
• The rapidity of distribution factor method and the precision of ACPF are integrated together

Multi-source multi-mode heterogeneous data

Causal data

Model simulation

Statistical data

Data driving

Way 2

Improving analysis accuracy
A Credibility Index based Algorithm for Fast Estimating PF for Cascading Failures

\[ P_i = V_i \sum_{j=1}^{V_i} V_i (G_{ij} \cos \theta_j + B_{ij} \sin \theta_j) \]
\[ Q_i = V_i \sum_{j=1}^{V_i} V_i (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j) \]

Decision making

Knowledge extraction

Main error source

\[ 0.5 H (\Delta X)^2 \]

\[ P_i = \sum B_{ij} \theta_j \]

Distribution factors PF

\[ J \Delta X + \]

Injection Power Vector

Causal analyses

DFPF results accepted

ACPF

\[ \mathcal{R} < \epsilon? \]


Way-3. Behavior-involved Projects can be Studied by Using Hybrid Simulations

Actual Behavior

Multi-agents

Mathematical Models

Experimental Economics Simulations Platform

Actual participants

Behavioral data

Way 3 Hybrid simul.

Causal analyses

Model simulation

Multi-source multi-mode heterogeneous data

Statistical data

Data driving

Causal data
Dynamic Simulation platform for Macro-Energy Systems (DSMES)

DSMES supports dynamic interactive simulations of cross-domain to study interactions among physical power system, power market, emission trading, etc.
The Decoupling-Aggregating Simulation of Complex Systems Crossing Multi-domains

- The interactions have been studied in three closed-loop systems
  - the adequacy of primary energy ↔ the adequacy of electrical power
  - the emission management ↔ the blackout risk
  - the reliability of power systems ↔ the reliability of power economics

- The simulation should not pursue to solve multi-domain equations simultaneously
  - Select targeting models based on specific research purposes, and encapsulate other models through designed boundary conditions
  - The large difference in model categories and time scales requires decoupling the simulation tasks in certain ways, and aggregate the results
Policy effects on carbon emission

- In order to ensure the security of energy and environment, the whole trajectories must be derived
- Based on the actual game data and/or hybrid simulation data, participants’ model is established
- Effectively evaluate different emissions reduction schemes, effect and risk control ability, support decision making

A Simulation Platform for CPES s.t. carbon emission
Our study on interactions between EVs and SG

EV purchase, travel, V2G multi-agent modeling and simulation

- More sample set from the excavation of the psychological characteristics of the joint probability distribution of threshold value, use the tree frequency reflect the correlation between adjacent level important decision matrix
- Through the monte carlo method to build people intend to distributed multi-agent model
- Use of multi-agent simulation decision-making behavior of the crowd or intend to
- At the same time, by a small amount of real people reflect the special groups of subjective intention
- Combination of these two can end type research involves a large number of participants of social problems, to provide scientific decision support
Experimental Economics Research on EV Purchase Willingness

1. Questionnaires
2. Extract information
3. Factors affecting purchase decisions
4. Ranking of factors’ importance
5. Psychological threshold distribution of a single factor
6. The joint distribution of all factors’ psychological thresholds
7. Agents’ probabilistic model based on the joint distribution
8. Tested EV types
9. Creating agents
10. Tested trip scenarios
11. Questionnaires of EV users’ travel behaviors
12. Extract information
13. Factors affecting EV user’s travel behaviors
14. Ranking of factors’ importance
15. Probability distribution of a signal factor
16. The joint distribution of EV users’ behaviors
17. Agents’ probabilistic model based on the joint distribution
18. Tested trip scenarios
19. Creating agents
20. Tested trip scenarios
21. Verification of multi-agent model accuracy
22. Passed
23. Hybrid simulation with true participants and verified agents
24. Agent-1 ...
25. Agent-n
26. Questionnaire-1 ...
27. Questionnaire-n
28. Statistics
29. EV user’s experience
30. Vehicle performance
31. User anxiety
32. Estimation of recharge times
33. Features affecting EV users’ travel behaviors strongly correlated

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Conclusion

• Sustainable development of human society relies on renewable energy and electricity substitutions.

• Power system reliability is a central part of energy, environment and social securities.

• A physically secure power system can be unreliable for power supply due to restriction on emission, primary energy, market power, etc.

• The reliability of electricity should be extended to that of comprehensive energy networks.

“Energy internet” is just a CPS for energy

“Energy Internet” = Cyber

[priv. net + Internet]

Physical System

[power systems
non-elec. energy sys.
non-energy sys.]

Big data

[causal data
statistical data
behavior data]
The Combination of Big Data Technologies and Experimental Economics

- Big data acquisition
- Big data simulation
- Hybrid dynamic simulation
- Dynamic process
- Knowledge extracting

Big data thinking supports CPES

- Macro energy thinking promotes
  - “clean energy substitution” of the upstream primary energy
  - “electricity substitution” of the downstream end-use energy
- Private networks combines with Internet to break down the barriers between operation and business activities
- Big data thinking regards all kinds of data as fundamental
- The integration of the two kinds of thinking becomes the foundation of highly intelligent energy systems
Thank you

Photo of Bipeng Gou
by Y.Xue