Modeling & Co-optimizing Integrated Transmission & Distribution Systems

Juan Ospina, *Ph.D*.

Scientist
A-1 Information Systems and Modeling Group

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Outline

Part I: Los Alamos National Laboratory

- Introduction to Los Alamos National Lab.
- Introduction to A-1 Information Systems & Modeling Group

Part II: Research in T&D Optimization

- Background & Challenges
- Introduction to PowerModelsITD.jl
- Using PowerModelsITD.jl
- Experimental Test Cases

Los Alamos National Laboratory (LANL)

- **LANL** is one of the world's largest and most advanced scientific institutions.

- **Primary mission:**
  - provide scientific and engineering support to national security programs.
  - solve national security challenges through excellence.

- Located in **Northern New Mexico**, Los Alamos


A Common Goal (Video)

https://www.youtube.com/watch?v=g_QOV3UAjuk

https://www.lanl.gov/

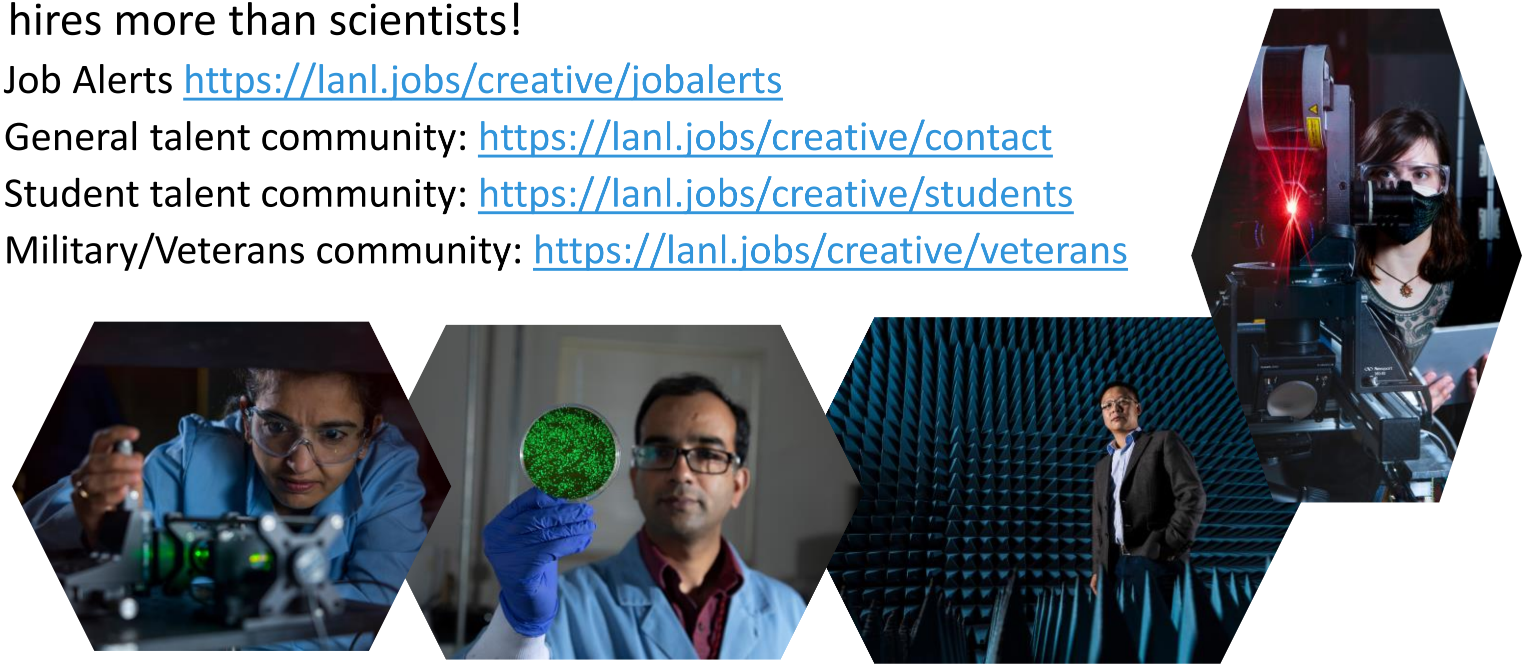
https://www.linkedin.com/company/los-alamos-national-laboratory/

Los Alamos National Laboratory (LANL)

Jobs: https://lanl.jobs/

LANL hires more than scientists!

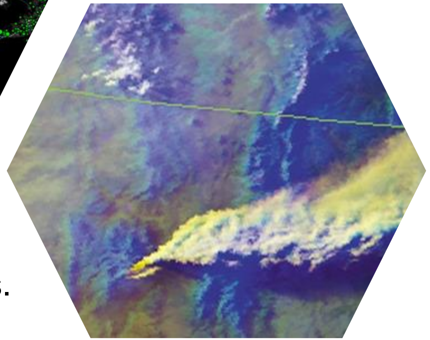
- Job Alerts https://lanl.jobs/creative/jobalerts
- General talent community: https://lanl.jobs/creative/contact
- Student talent community: https://lanl.jobs/creative/students
- Military/Veterans community: https://lanl.jobs/creative/veterans



LANL: A-1 Information Systems and Modeling Group

1. **Critical Infrastructure Modeling Team**
   - **Basic** & **applied research** focused on:
     - Modeling the nation’s critical infrastructures (e.g., Gas, Power, Water)
     - Quantifying vulnerabilities in the nation’s critical infrastructures
     - Developing algorithms for the nation’s critical infrastructures

2. **Advanced Data Analytics and Forecasting Team**
   - **Basic** & **applied research** focused on:
     - Modeling and understanding emerging threats
       - Disinformation
       - Disease outbreaks
       - Political instability
       - Nuclear proliferation



3. **Chemical, Biological, and Radiological Agent Dispersion Modeling Team**
   - Provides **research** and **modeling tools** to national organizations to
     - Protect and respond to chemical, biological, radiological, and other threats.

https://organizations.lanl.gov/a-1/

LANL: A-1 Information Systems and Modeling Group

Building capabilities for **decision support** for the:

- Department of Energy (DOE)
- Department of Defense (DoD)
- Federal Emergency Management Agency (FEMA)
- State government agencies (e.g., NM during COVID)
- and even up to the White House.

LANL: A-1 Critical Infrastructure Team

1. **Electric Power Systems**
   - Transmission (PowerModels.jl)
   - Distribution (PowerModelsDistribution.jl
   - T&D (PowerModelsITD.jl)
   - Networked Microgrids (PowerModelsONM.jl)

   2023 R&D 100 WINNER

   https://www.youtube.com/watch?v=D5k-lMicMPM

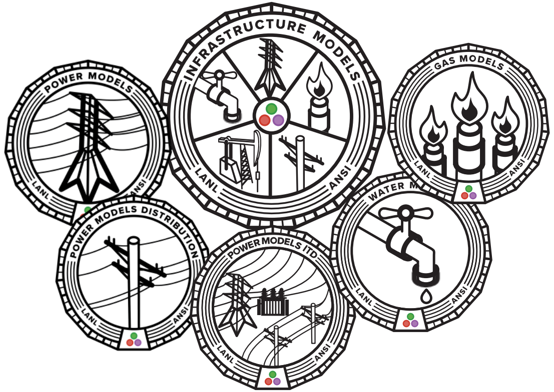
2. **Natural Gas Transmission Systems**
   - Natural Gas (GasModels.jl)
   - Gas + Power (GasPowerModels.jl)

3. **Potable Water Distribution Systems**
   - Potable Water (WaterModels.jl)
   - Water + Power (PowerWaterModels.jl)

4. **Other Projects**
   - Cyber-Physical Energy Systems
   - MG-RAVENS (Application Programming Interfaces for Grid Modeling)

https://github.com/lanl-ansi

Modeling & Optimization Ecosystem



Optimization

AC Polar

Variables:

$S_{g,k}, \forall k \in G$

$V_i, \forall i \in N$

$\theta_i, \forall i \in N$

$S_{ij}, \forall (i,j) \in E \cup E_R$

Minimize:

$$\sum_{k \in G_i} c_{2k} (\Re(S_{g,k}))^2 + c_{1k} (\Re(S_{g,k})) + c_{0k}$$

Subject to:

$\theta_r = 0, \forall r \in R$

$S^l_{g,k} \leq S_{g,k} \leq S^u_{g,k}, \forall k \in G$

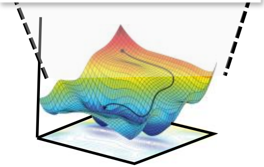
$v^l_i \leq |V_i| \leq v^u_i, \forall i \in N$

$$\sum_{k \in G_i} S_{g,k} - S_{d,i} - \sum_{(i,j) \in E \cup E_R} S_{ij} = 0, \forall i \in N$$

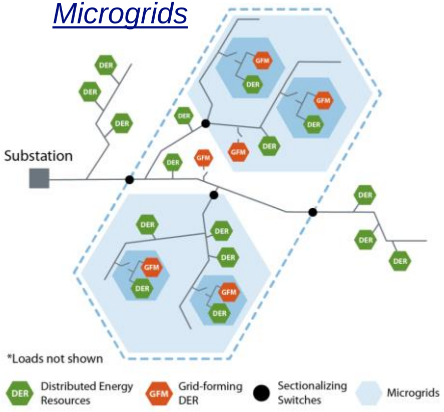
$\theta^{\Delta l}_{ij} \leq \theta_i - \theta_j \leq \theta^{\Delta u}_{ij}, \forall (i,j) \in E$

$|S_{ij}| \leq s^u_{ij}, \forall (i,j) \in E \cup E_R$

...



Microgrids



Gas Networks

LANL: A-1 Critical Infrastructure - Example Projects

1. A Framework for Exploring Power Flow Formulations
   - *Coffrin, C., Bent, R., Sundar, K., Ng, Y., & Lubin, M. (2018, June). Powermodels. jl: An open-source framework for exploring power flow formulations. In 2018 Power Systems Computation Conference (PSCC) (pp. 1-8). IEEE.*
   - PowerModels.jl: A Framework for Exploring Power Flow Formulations
2. GasModels.jl: Convex Relaxations for Gas Systems Modeling
   - *Tasseff, B., Coffrin, C., & Bent, R. (2021). Convex Relaxations of Maximal Load Delivery for Multi-contingency Analysis of Joint Electric Power and Natural Gas Transmission Networks. arXiv preprint arXiv:2108.12361.*
3. Phase-Unbalanced Power Distribution Network Optimization with PowerModelsDistribution.jl
   - *Fobes, D. M., Claeys, S., Geth, F., & Coffrin, C. (2020). PowerModelsDistribution. jl: An open-source framework for exploring distribution power flow formulations. Electric Power Systems Research, 189, 106664.*
   - PowerModelsDistribution.jl: A Framework for Exploring Distribution Network Power Flow Formulations
4. Microgrids for Resilience and Reliability
   - *Fobes, D. M., Bent, R., Jain, R., Flores-Espino, F., Pratt, A., Mahoney, R., ... & Reno, M. J. (2023). Quantifying resiliency benefits of networked microgrids using PowerModelsONM. jl.*
   - *Fobes, D. M., Nagarajan, H., & Bent, R. (2022). Optimal Microgrid Networking for Maximal Load Delivery in Phase Unbalanced Distribution Grids: A Declarative Modeling Approach. IEEE Transactions on Smart Grid, 14(3), 1682-1691.*
   - R&D 100 - PowerModels ONM
5. Towards the Secure Operation of Cyber-Physical Energy Systems
   - *Ospina Casas, J. J. (2022). Towards the Secure Operation of Cyber-Physical Energy Systems (CPES) (No. LA-UR-22-31034). Los Alamos National Lab.(LANL), Los Alamos, NM (United States).*
   - *Ospina, J., Venkataramanan, V., & Konstantinou, C. (2022). CPES-QSM: A Quantitative Method Toward the Secure Operation of Cyber–Physical Energy Systems. IEEE Internet of Things Journal, 10(9), 7577-7590.*

LANL: A-1 Information Systems and Modeling Group

OPEN POSITIONS

A-1 Jobs ›

Administrative Assistant 4 LEARN MORE	Power Systems Engineer/Electrical Engineer (Scientist 2) LEARN MORE	Critical Infrastructure and Data Analytics Scientist (Scientist 3) LEARN MORE	Infrastructure Modeling Undergraduate Summer Student LEARN MORE
Plume and Fire Modeling Scientist (Scientist 2) LEARN MORE	Post-Masters Science and Engineering Research Intern LEARN MORE	Post-Baccalaureate Science and Engineering Research Intern LEARN MORE	Quantum Computer Scientist 1/2 LEARN MORE

https://organizations.lanl.gov/a-1/#open-positions

Part II: Research in T&D Optimization - Outline

- Background & Challenges
- Introduction to **PowerModelsITD.jl**
- Using **PowerModelsITD.jl**
- Experimental Test Cases

Acknowledgements - Team & Funding

- David Fobes (A-1 LANL)
- Russell Bent (T-5 LANL)
- Andreas Wächter (Northwestern University)
- Xinyi Luo (Northwestern University)

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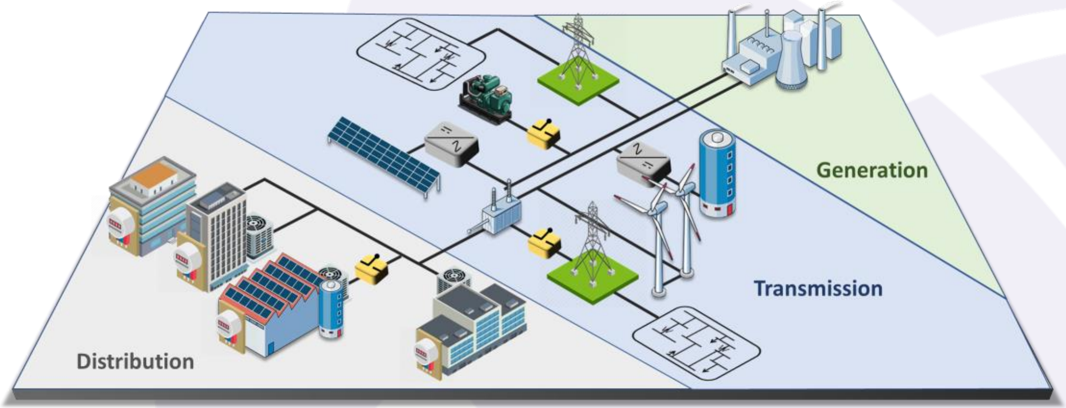
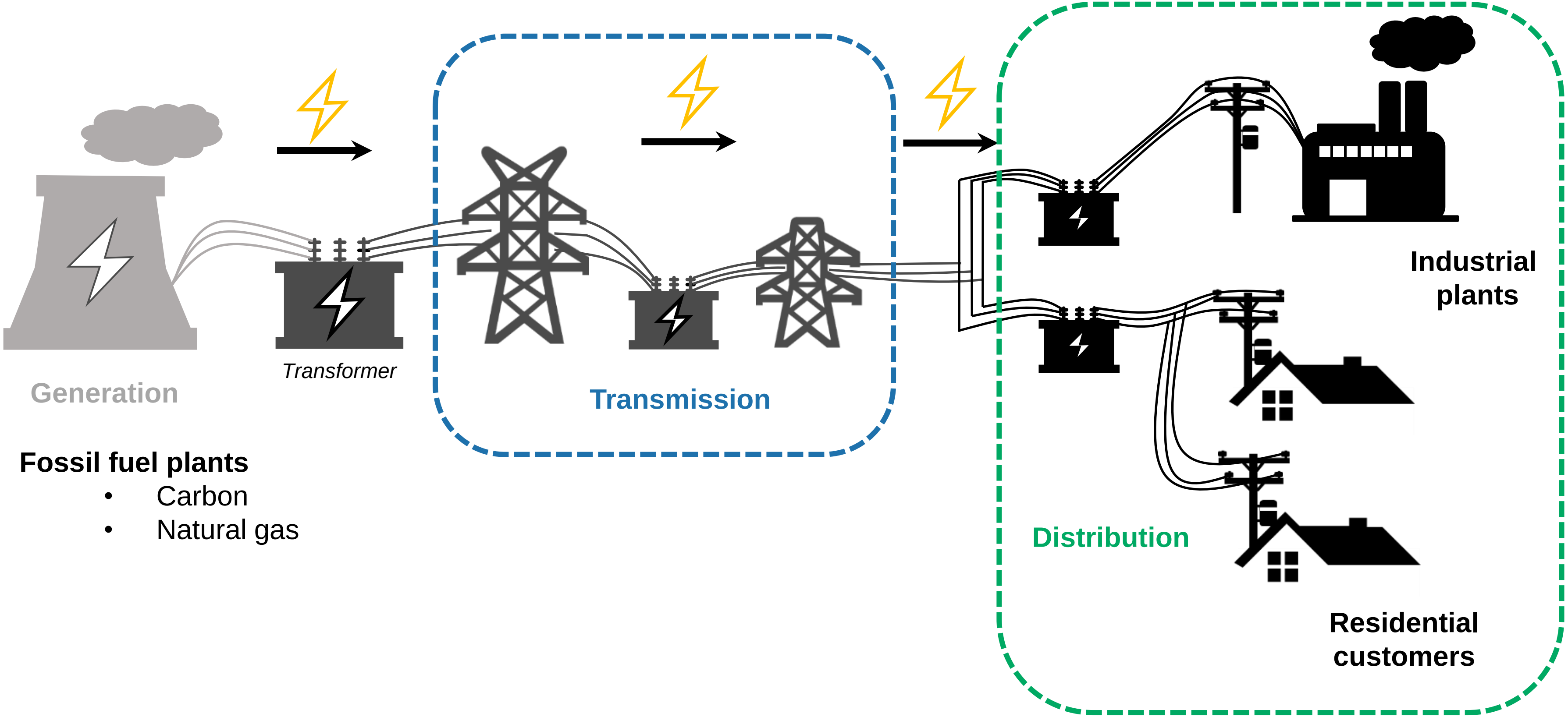
Background

- Conventional electric power systems (EPS) are composed of:
  - **Generation**
  - **Transmission**
  - **Distribution**

- Managed independently by:
  - Transmission system (TSOs)
  - Distribution system operators (DSOs).



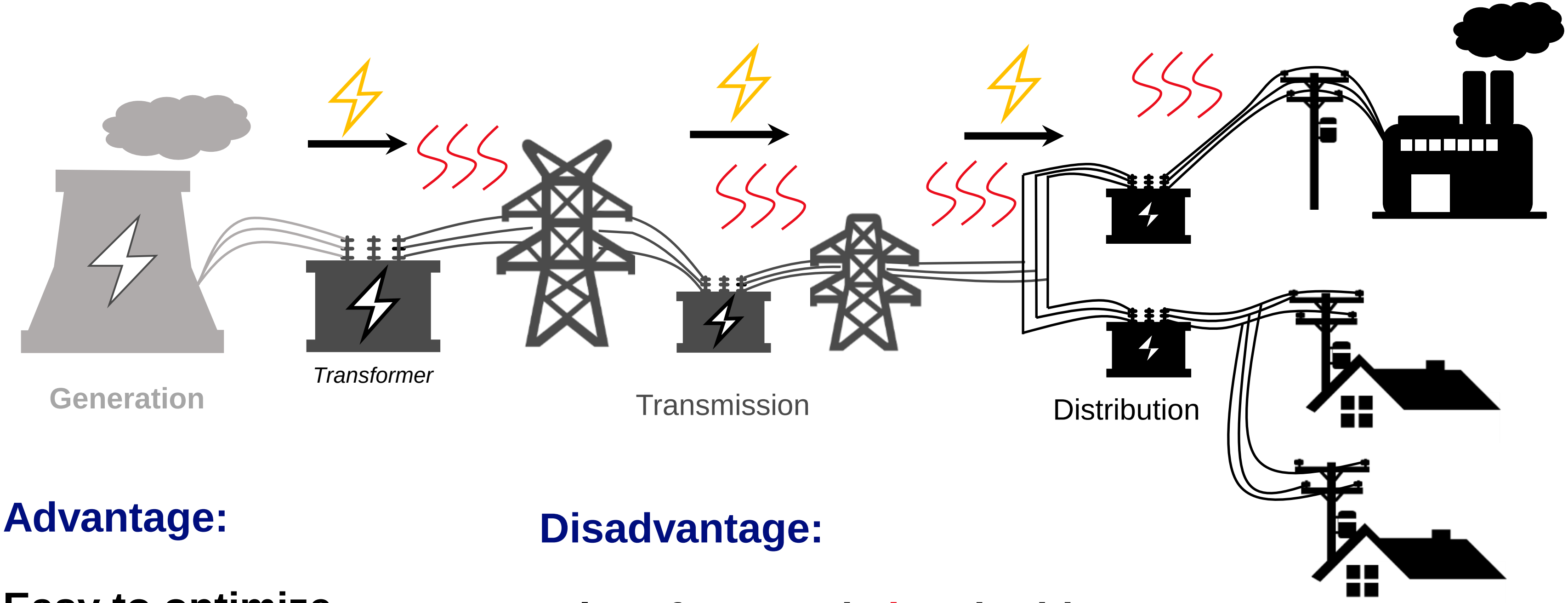
Traditional Power Generation/Consumption



Fossil fuel plants

- Carbon
- Natural gas

Advantages & Disadvantages



Advantage:

Easy to optimize
(All coming from monolithic Generation sites)

Disadvantage:

A lot of energy is lost in this process!

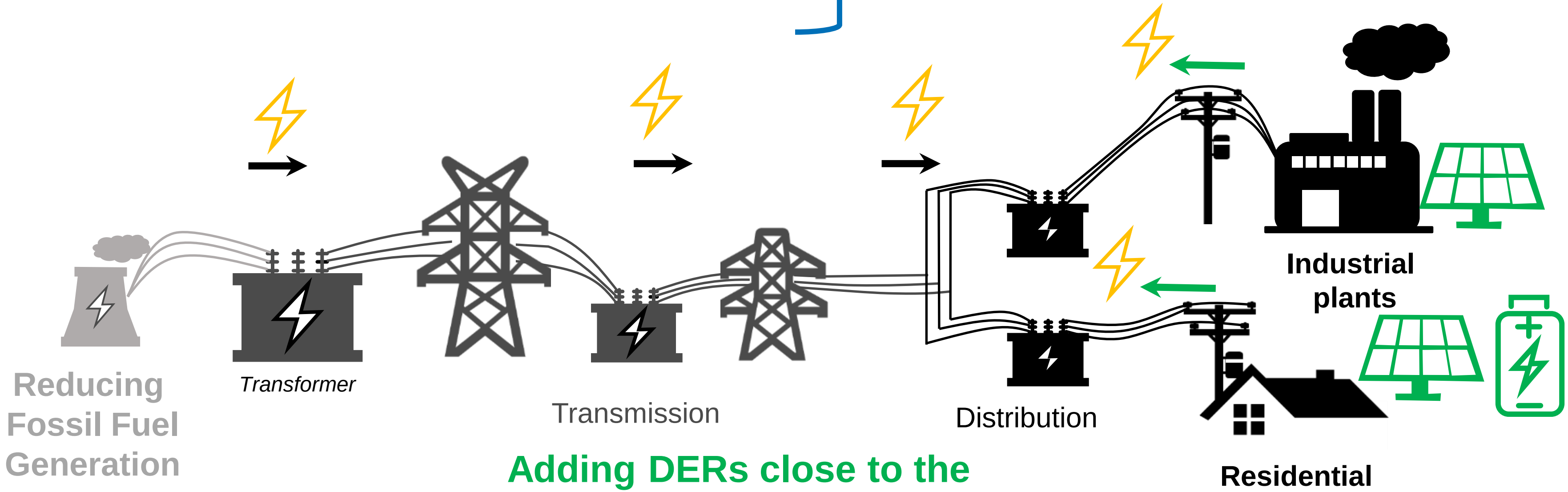
- Around 2-6% in transmission
- Around 4% in distribution

http://insideenergy.org/2015/11/06/lost-in-transmission-how-much-electricity-disappears-between-a-power-plant-and-your-plug/
https://www.eia.gov/energyexplained/us-energy-facts/

Efforts to Reduce Losses and Improve Efficiency

1. Renewable energy sources (RES)
2. Energy storage devices (Batteries)

Distributed Energy Resources (DERs)

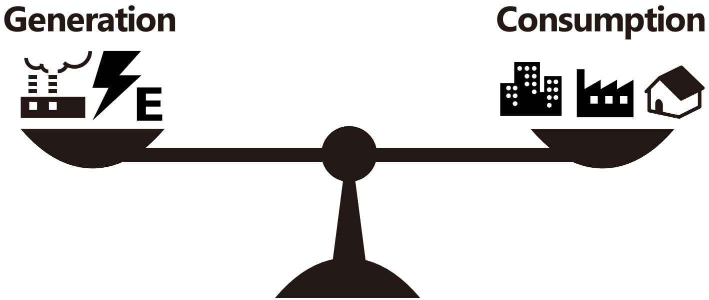


Adding DERs close to the consumption (At the distribution)

Adding DERs (Issue)

- Just adding **DERs everywhere** is not a **realistic** solution
  - A balance between **Generation** & **Consumption** needs to be **always maintained**

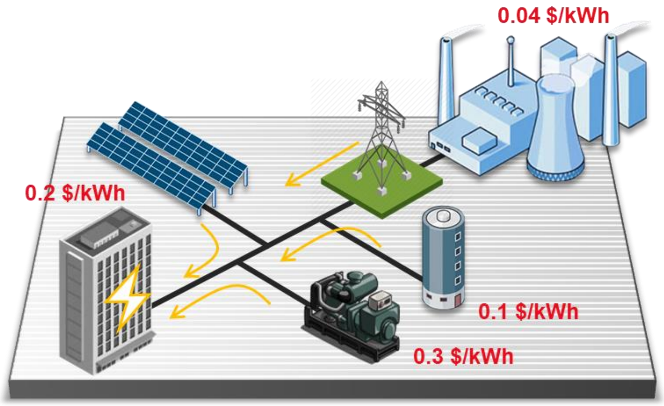
  - **If balanced is not maintained**
    - **Blackouts** can occur
    - **Transformers** can explode
    - **Protection devices** can be triggered

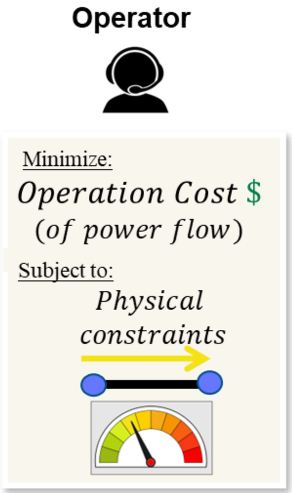


Solution: Optimal control of DERs (Optimization)

We need to **optimize** the **power/energy dispatch** from **DERs**.

Obtain the exact **power** that each **DER** needs to **dispatch (i.e., OPF).**



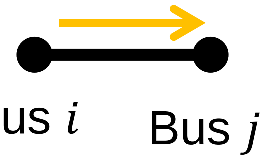


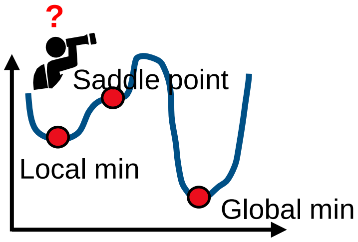
Optimizing is not that simple!

Power Flow Formulations:

- Physical models that describe how the **power** flows on the lines.

$$\mathrm{P_{ij}} = \mathrm{g_{ij}V_i^2} - \boxed{\mathrm{V_iV_j}}(\mathrm{g_{ij}}\boxed{\cos(\theta_i - \theta_j)} + \mathrm{b_{ij}}\boxed{\sin(\theta_i - \theta_j)})$$





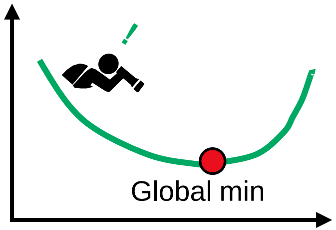
AC Polar

More Accurate

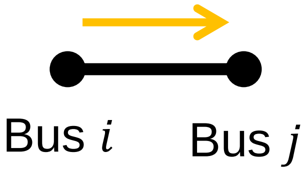
Harder to solve

Non-Convex

$$\boxed{\mathrm{P_{ij}} = -\frac{1}{x_{ij}}(\theta_j - \theta_i)}$$



Convex



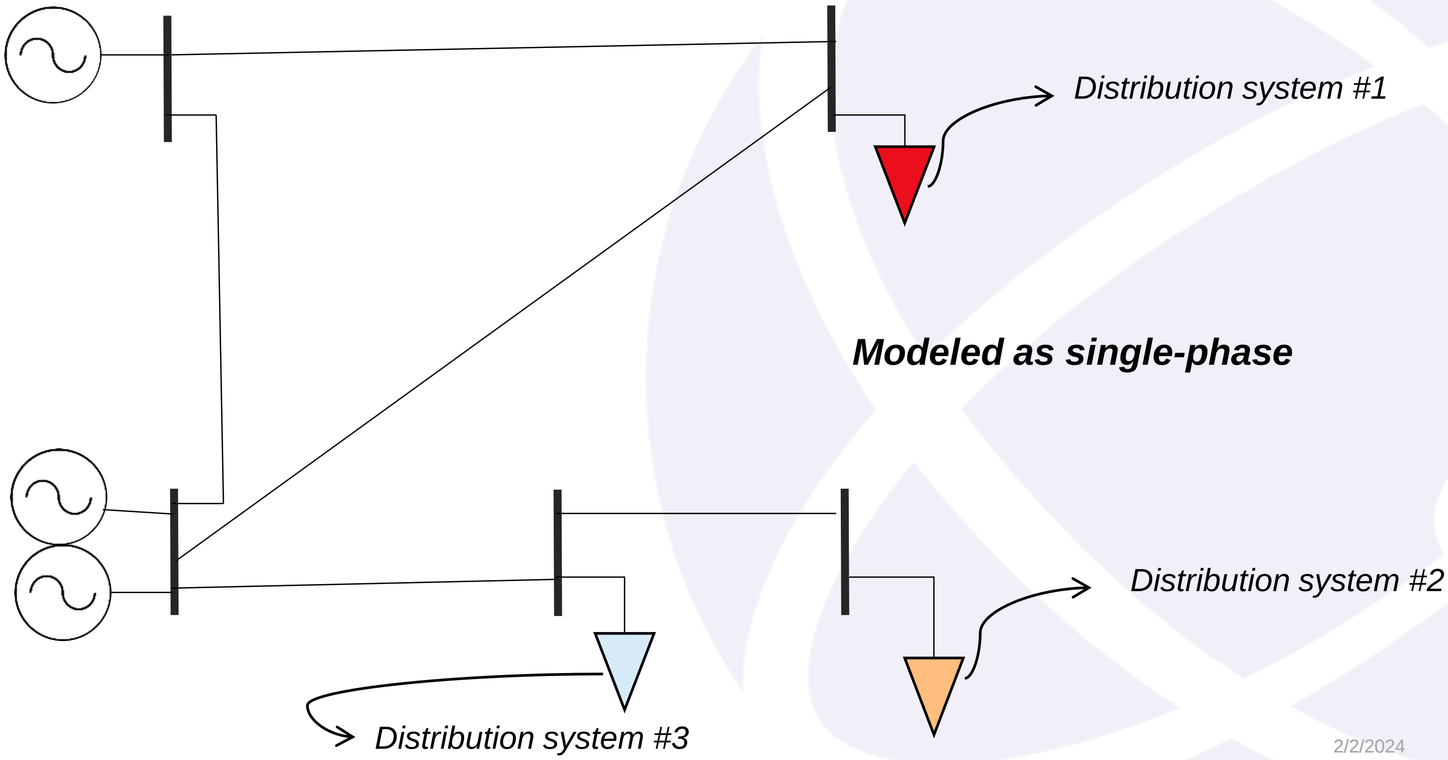
DC approximation

Less Accurate

Easier to solve

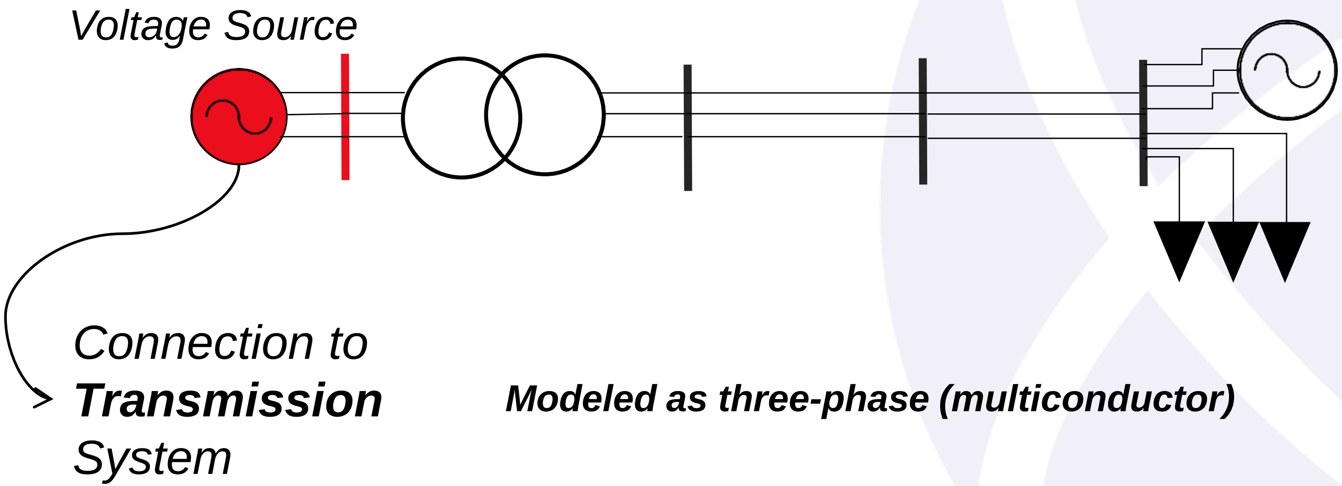
Modeling Problems: TSOs

- TSOs traditionally model distribution systems as consumers (**loads**).



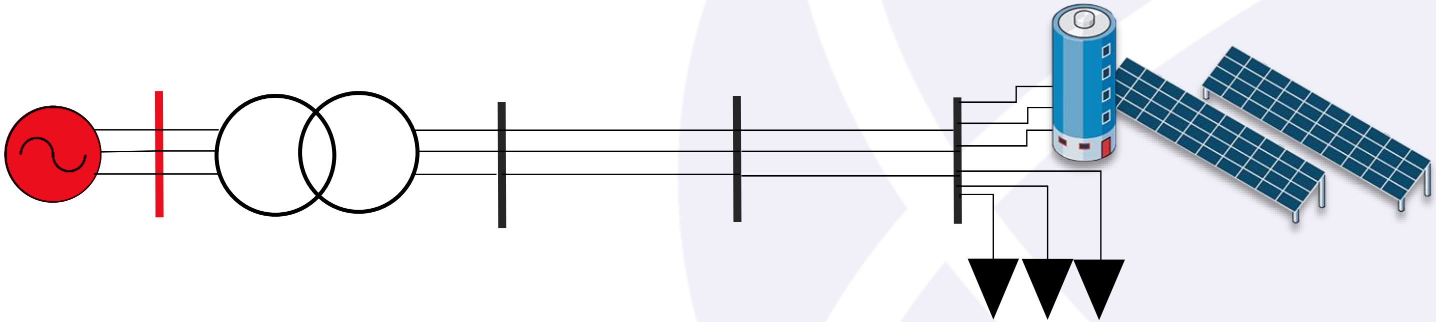
Modeling Problems : DSOs

- DSOs traditionally regard transmission systems as buses with **unlimited resources** (often modeled as **voltage sources**).



Modeling Problems: Integration of DERs

- Distribution systems are becoming more **active**:
  - Integration of **Distributed Energy Resources** (DERs)
  - Integration of **Information & Communication** Technologies (ICTs).



The **assumption** of <u>distribution</u> being just a **passive load** is **unreasonable** for **optimal** T&D **operation**.

Challenges

- Traditionally **owned and operated** by separate entities.
- **Centralized models** may not be scalable and hard to solve. (*Assumption*)
- **Convergence issues** with AC OPF (nonlinear, nonconvex formulations)
- **No coordination** of resources across T&D boundaries

Coordination between **T&D** networks will be **imperative** for the **optimal operation** of the power grid.

To **fill this gap**, we developed a **first-of-its-kind tool** that **supports** and **enables** the **Co-optimization** of **T&D systems**

Outline

- Background & Challenges
- Introduction to **PowerModelsITD.jl**
- Using **PowerModelsITD.jl**
- Experimental Test Cases

InfrastructureModels.jl

- **Core** package for **multi-infrastructure modeling** and **optimization** ecosystem

https://github.com/lanl-ansi/InfrastructureModels.jl

PowerModelsITD.jl

- Open-source tool (Written in **Julia**)
- Based on **LANL multi-infrastructure ecosystem**
- Used for **modeling** and **optimizing T&D systems**
- Solve steady-state **ITD Optimal Power Flow (OPF)**
- Evaluate diverse **network formulations**
- Common research platform for **emerging formulations**

GitHub

[1] https://github.com/lanl-ansi/PowerModelsITD.jl

[2] Ospina, J., et al. (2023). Modeling and Rapid Prototyping of Integrated Transmission-Distribution OPF Formulations with PowerModelsITD.jl. IEEE Transactions on Power Systems.

[3] Ospina, J., et al. (2023). On the Feasibility of Market Manipulation and Energy Storage Arbitrage via Load-Altering Attacks. Energies, 16(4), 1670.

PowerModelsITD.jl: Problem Specifications

- Integrated T&D Power Flow (*pfitd*) – Power Flow
- Integrated T&D Optimal Power Flow (*opfitd*) – Optimal Power Flow
- Integrated T&D Optimal Power Flow with storage costs (*opfitd_storage*)
- Integrated T&D Optimal Power Flow with on-load tap-changer (*opfitd_oltc*)

PowerModelsITD.jl: Formulations

NLP Formulations

- ACP-ACPU
  - Power-Voltage, polar coordinates, non-linear (NLP)
- ACR-ACRU
  - Power-Voltage, rectangular coordinates, non-linear (NLP)
- IVR-IVRU
  - Current-Voltage, rectangular coordinates, non-linear (NLP)

Linear Approximations

- NFA-NFAU
  - Network Flow Approximation
  - Active power only, lossless, linear (LP)
- BFA-LinDist3Flow
  - Branch Flow Approximation - Linear Approximation

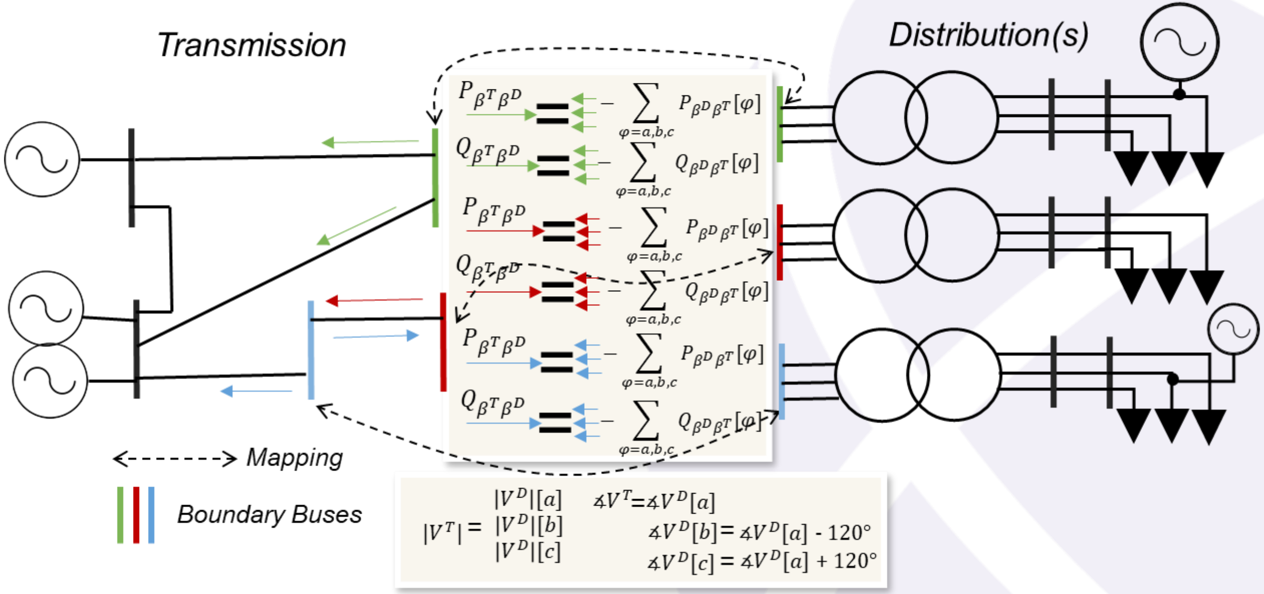
Relaxations

- SOCBFM-SOCUBFM
  - Second Order Cone Branch Flow Model Relaxations – W-space.

Hybrid Formulations (Experimental)

- ACR-FOTRU
  - Power-Voltage NLP, rectangular coordinates, First-Order Taylor Approximation
- ACP-FOTPU
  - Power-Voltage NLP, polar coordinates, First-Order Taylor Approximation
- ACR-FBSU
  - Power-Voltage NLP, rectangular coordinates, Forward-Backward Sweep Approximation
- SOCBFM-LinDist3Flow
  - Second Order Cone Branch Flow Model Relaxation – W-space.
  - Linear Approximation.

Mathematics at the T&D Boundaries



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Using PowerModelsITD.jl

The **files** needed to run **OPFITD** are:

Transmission file

```
function mpc = case5
mpc.version = '2';
mpc.baseMVA = 100.0;

%% bus data
%       bus_i   type    Pd      Qd      Gs      Bs      area    Vm      Va      baseKV  zone
mpc.bus = [
        1       2       0.0     0.0     0.0     0.0     1       1.07762         2.80377
        2       1       300.0   98.61   0.0     0.0     1       1.08407         -0.73465
        3       2       300.0   98.61   0.0     0.0     1       1.10000         -0.55972
        4       3       390.0   131.47  0.0     0.0     1       1.06414         0.00000
        5       1       0.0     1.2     0.0     0.0     1       1.00000         0.00000
        10      2       0.0     0.0     0.0     0.0     1       1.06907         3.59033
];

%% generator data
%       bus     Pg      Qg      Qmax    Qmin    Vg      mBase   status  Pmax    Pmin
mpc.gen = [
        1       40.0    30.0    30.0    -30.0   1.07762         100.0   1       40.0    0.0;
        1       170.0   127.5   127.5   -127.5  1.07762         100.0   1       170.0   0.0;
        3       324.498         390.0   390.0   -390.0  1.1     100.0   1       520.0   0.0;
        4       0.0     -10.802         150.0   -150.0  1.06414         100.0   1       200.0
        10      470.694         -165.039        450.0   -450.0  1.06907         100.0   1
];

%% generator cost data
%       2       startup shutdown        n       c(n-1)  ...     c0
mpc.gencost = [
        2       0.0     0.0     3       0.000000        14.000000       0.000000        2.000
        2       0.0     0.0     3       0.000000        15.000000       0.000000        2.000
        2       0.0     0.0     3       0.000000        30.000000       0.000000        2.000
        2       0.0     0.0     3       0.000000        40.000000       0.000000        2.000
        2       0.0     0.0     3       0.000000        10.000000       0.000000        2.000
];

%% branch data
%       fbus    tbus    r       x       b       rateA   rateB   rateC   ratio   angle   status
mpc.branch = [
        1       2       0.00281         0.0281  0.00712         400.0   400.0   400.0   0.0
        1       4       0.00304         0.0304  0.00658         426     426     426     0.0
        1       10      0.00064         0.0064  0.03126         426     426     426     0.0
        2       3       0.00108         0.0108  0.01852         426     426     426     0.0
        3       4       0.00297         0.0297  0.00674         426     426     426     1.05
        4       10      0.00297         0.0297  0.00674         240.0   240.0   240.0   0.0
        2       5       0.00297         0.0297  0.00674         426     426     426     0.0
];
```

MATPOWER (“.m”)

PSS(R)E v33 specification (".raw")

(support PowerWorld for PSSE conversions)

Distribution file(s)

```
New Circuit.3bus_bal
!  define a really stiff source
~ basekv=230 pu=1.00 MVAsc3=200000 MVAsc1=210000

! Substation Transformer
New Transformer.SubXF Phases=3 Windings=2 Xhl=0.01
~ wdg=1 bus=sourcebus conn=wye kv=230   kva=25000    %r=0.0005
~ wdg=2 bus=Substation   conn=wye kv=13.8  kva=25000   %r=0.0005

!Define Linecodes
New linecode.556MCM nphases=3 basefreq=60  ! ohms per 5 mile
~ rmatrix = ( 0.1000 | 0.0400    0.1000 |  0.0400    0.0400    0.1000)
~ xmatrix = ( 0.0583 |  0.0233    0.0583 | 0.0233    0.0233    0.0583)
~ cmatrix = (50.92958178940651  | -0  50.92958178940651 | -0 -0 50.92958178940651  ) ! small cap

New linecode.4/0QUAD nphases=3 basefreq=60  ! ohms per 100ft
~ rmatrix = ( 0.1167 | 0.0467    0.1167 | 0.0467    0.0467    0.1167)
~ xmatrix = (0.0667  |  0.0267    0.0667  |  0.0267    0.0267    0.0667 )
~ cmatrix = (50.92958178940651  | -0  50.92958178940651 | -0 -0 50.92958178940651  )  ! small ca

!Define lines
New Line.OHLine  bus1=Substation.1.2.3  Primary.1.2.3  linecode = 556MCM   length=1 normamps=600
New Line.Quad    Bus1=Primary.1.2.3  loadbus.1.2.3  linecode = 4/0QUAD  length=1 normamps=6000 e

!Loads - single phase
New Load.L1 phases=1  loadbus.1.0   ( 13.8 3 sqrt / )   kW=3000   kvar=1500  model=1
New Load.L2 phases=1  loadbus.2.0   ( 13.8 3 sqrt / )   kW=3000   kvar=1500  model=1
New Load.L3 phases=1  loadbus.3.0   ( 13.8 3 sqrt / )   kW=3000   kvar=1500  model=1

!GENERATORS DEFINITIONS
New generator.gen1 Bus1=loadbus.1.2.3 Phases=3 kV=( 13.8 3 sqrt / )  kW=2000 pf=1 conn=wye Model

Set VoltageBases = "230,13.8"
Set tolerance=0.000001
set defaultbasefreq=60
```

```
!Loads - single phase
New Load.L1 phases=1  loadbus.1.0   ( 13.8 3 sqrt / )   kW=3000   kvar=1500  model=1
New Load.L2 phases=1  loadbus.2.0   ( 13.8 3 sqrt / )   kW=3000   kvar=1500  model=1
New Load.L3 phases=1  loadbus.3.0   ( 13.8 3 sqrt / )   kW=3000   kvar=1500  model=1

!GENERATORS DEFINITIONS
New generator.gen1 Bus1=loadbus.1.2.3 Phases=3 kV=( 13.8 3 sqrt / )  kW=2000 pf=1 conn=wye Model

Set VoltageBases = "230,13.8"
Set tolerance=0.000001
set defaultbasefreq=60
```

OpenDSS (".dss")

Boundary file

```
[
    {
    "transmission_boundary": "5",
    "distribution_boundary": "3bus_unbal.voltage_source.source"
    },

    {
    "transmission_boundary": "6",
    "distribution_boundary": "3bus_bal.voltage_source.source"
    }
]
```

JSON (".json")

other proprietary file formats supported via **DiTTo [25]**

https://lanl-ansi.github.io/PowerModelsITD.jl/stable/manual/fileformat.html

[25] “DiTTo (Distribution Transformation Tool),” 2021, Accessed: Aug. 06, 2021. [Online]. Available: https://github.com/NREL/ditto

Using PowerModelsITD.jl

Simple User Interface

```julia
using PowerModelsITD
import Ipopt
ipopt = Ipopt.Optimizer

# Path for the files
pmitd_path = joinpath(dirname(pathof(PowerModelsITD)), "..")

# Files
pm_file = joinpath(pmitd_path, "test/data/transmission/case5_with2loads.m")
pmd_file1 = joinpath(pmitd_path, "test/data/distribution/case3_unbalanced.dss")
pmd_file2 = joinpath(pmitd_path, "test/data/distribution/case3_balanced.dss")
boundary_file = joinpath(pmitd_path, "test/data/json/case5_case3x2_unbal_bal.json")

pmd_files = [pmd_file1, pmd_file2] # vector of files
pmitd_type = NLPowerModelITD{ACPPowerModel, ACPUPowerModel}

result = solve_opfitd(pm_file, pmd_files, boundary_file, pmitd_type, ipopt)
```

Case w/ 2 distro. systems

Beginners Guide (Other examples)

https://lanl-ansi.github.io/PowerModelsITD.jl/stable/tutorials/BeginnersGuide.html

Results

```
julia> result
Dict{String, Any} with 8 entries:
  "solve_time"         => 0.12712
  "optimizer"          => "Ipopt"
  "termination_status" => LOCALLY_SOLVED
  "dual_status"        => FEASIBLE_POINT
  "primal_status"      => FEASIBLE_POINT
  "objective"          => 18146.3
  "solution"           => Dict{String, Any}("multiinfrastructure"=>true, "it"=>Dict{String, Any}("pmd…
  "objective_lb"       => -Inf
```

Transmission

```
julia> result["solution"]["it"]["pm"]
Dict{String, Any} with 6 entries:
  "baseMVA"      => 100.0
  "branch"       => Dict{String, Any}("3"=>Dict{String, Any}("qf"=>206.656, "qt"=>-202.276, "pt"=>221.006, "pf"=>-220.308), "4"=>Dict{String, Any}("qf"=>-217.108, "qt"=>221.882, "pt"=>79.0383, "pf"=>-78.3924), "1"=…
  "gen"          => Dict{String, Any}("4"=>Dict{String, Any}("qg"=>56.3262, "pg"=>18.0328), "1"=>Dict{String, Any}("qg"=>30.0, "pg"=>40.0), "5"=>Dict{String, Any}("qg"=>-201.205, "pg"=>461.003), "2"=>Dict{String, A…
  "multinetwork" => false
  "bus"          => Dict{String, Any}("4"=>Dict{String, Any}("va"=>-1.06955e-34, "vm"=>0.9), "1"=>Dict{String, Any}("va"=>3.95367, "vm"=>0.917681), "5"=>Dict{String, Any}("va"=>-0.949629, "vm"=>0.937736), "2"=>Dict…
  "per_unit"     => false
```

Distribution

```
julia> result["solution"]["it"]["pmd"]
Dict{String, Any} with 7 entries:
  "line"        => Dict{String, Any}("3bus_unbal.quad"=>Dict{String, Any}("qf"=>[1344.85, 1503.97, 1502.46], "qt"=>[-1333.33, -1500.0, -1500.0], "pt"=>[-3333.33, -2333.33, -2333.33], "pf"=>[3351.62, 2340.39, 2344.9…
  "settings"    => Dict{String, Any}("sbase"=>100000.0)
  "transformer" => Dict{String, Any}("3bus_bal.subxf"=>Dict{String, Any}("q"=>[[1508.51, 1508.51, 1508.51], [-1508.41, -1508.41, -1508.41]], "p"=>[[2351.59, 2351.59, 2351.59], [-2351.58, -2351.58, -2351.58]]), "3bu…
  "generator"   => Dict{String, Any}("3bus_unbal.gen1"=>Dict{String, Any}("qg_bus"=>[-0.0, -0.0, -0.0], "qg"=>[-0.0, -0.0, -0.0], "pg"=>[666.668, 666.668, 666.668], "pg_bus"=>[666.668, 666.668, 666.668]), "3bus_bal…
  "load"        => Dict{String, Any}("3bus_unbal.l2"=>Dict{String, Any}("qd_bus"=>[1500.0], "pd_bus"=>[3000.0], "qd"=>[1500.0], "pd"=>[3000.0]), "3bus_bal.l3"=>Dict{String, Any}("qd_bus"=>[1500.0], "pd_bus"=>[3000.…
  "bus"         => Dict{String, Any}("3bus_unbal.loadbus"=>Dict{String, Any}("va"=>[-1.10106, -120.971, 119.172], "vm"=>[7.38801, 7.42776, 7.41273]), "3bus_bal.substation"=>Dict{String, Any}("va"=>[-1.08179, -121.0…
  "per_unit"    => false
```

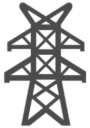
Boundary

```
julia> result["solution"]["it"]["pmitd"]["boundary"]
Dict{String, Any} with 4 entries:
  "(100001, 5, voltage_source.3bus_unbal.source)" => Dict{String, Any}("pbound_fr"=>[8068.8], "qbound_fr"=>[4367.42])
  "(100001, voltage_source.3bus_unbal.source, 5)" => Dict{String, Any}("pbound_to"=>[-3367.36, -2346.47, -2354.97], "qbound_to"=>[-1355.14, -1507.53, -1504.75])
  "(100002, voltage_source.3bus_bal.source, 6)"   => Dict{String, Any}("pbound_to"=>[-2351.62, -2351.62, -2351.62], "qbound_to"=>[-1508.64, -1508.64, -1508.64])
  "(100002, 6, voltage_source.3bus_bal.source)"   => Dict{String, Any}("pbound_fr"=>[7054.87], "qbound_fr"=>[4525.93])
```

Outline

- Background & Challenges
- Introduction to **PowerModelsITD.jl**
- Using **PowerModelsITD.jl**
- Experimental Test Cases

Experimental Test Cases: OPF ITD



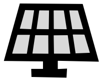
PGLib 500 bus

224 Gens

Boundary Bus

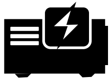
2	R1-25-1
3	R1-1247-1
4	R1-1247-2
5	R1-1247-3
6	R1-1247-4
12	R2-25-1
13	GC-1247-1
14	R2-1247-1
15	R2-1247-2
29	R4-1247-2
55	R5-25-1
56	R5-35-1
57	R5-1247-4

PVs

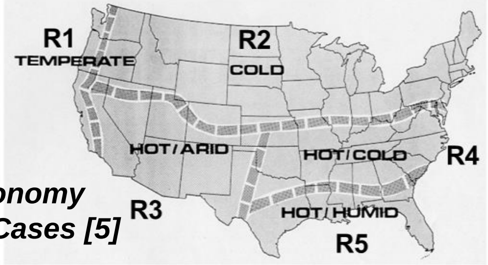


55

DGs



17



Taxonomy PNNL Cases [5]

13 distribution systems w/ **759** - **3,403** nodes (range)

Test Cases	N	E
case_r1_25_1	759	762
case_r1_1247_1	3403	3583
case_r1_1247_2	1450	1527
case_r1_1247_3	168	165
case_r1_1247_4	970	981
case_r2_25_1	1617	1681
case_gc_1247_1	96	93
case_r2_1247_1	1731	1750
case_r2_1247_2	1207	1275
case_r4_1247_2	1155	1202
case_r5_25_1	3116	3250
case_r5_35_1	1435	1505
case_r5_1247_4	2030	2088

Totals:

Buses/Nodes: 19,637 (w/ +500 from transmission)

Edges: 20,595 (w/ +733 from transmission)

[5] Schneider, Kevin P., et al. *Modern grid initiative distribution taxonomy final report*. No. PNNL-18035. Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2008.

Experimental Test Cases: OPF Results

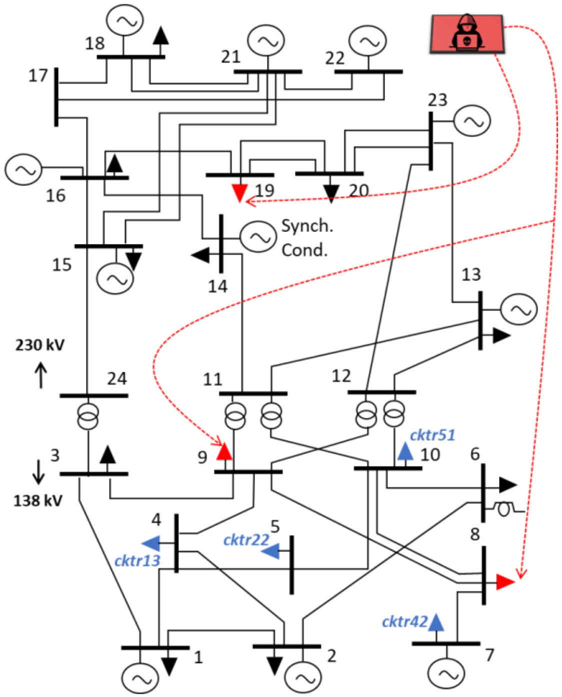
CPU: x6 Cores @ 2.80 Ghz
RAM: 128 GB

Solver:
Ipopt vers.: 3.14.4
MUMPS vers.: 5.4.1

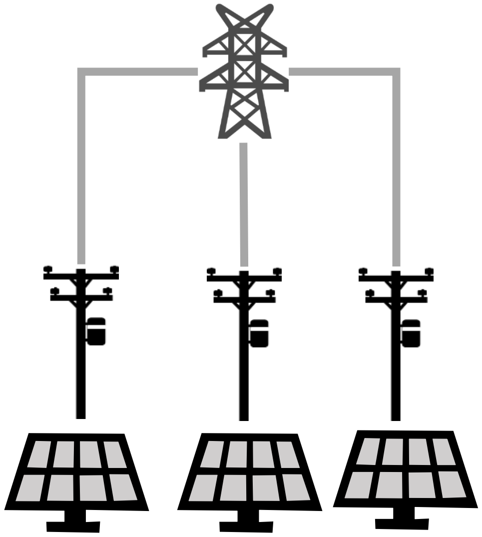
Formulation	$/hr	Time (s)	Iterations
ACP-ACPU	422,095.2350	525.154	94
IVR-IVRU	422,095.2348	360.954	99
NFA-NFAU	412,286.7567	10.860	24
ACR-FBSUBF	422,074.7218	226.852	97
BFA-LinDist3	412,286.7567	146.084	45
SOCBF-LinDist3	421,529.7893	241.203	75

Other Use Cases

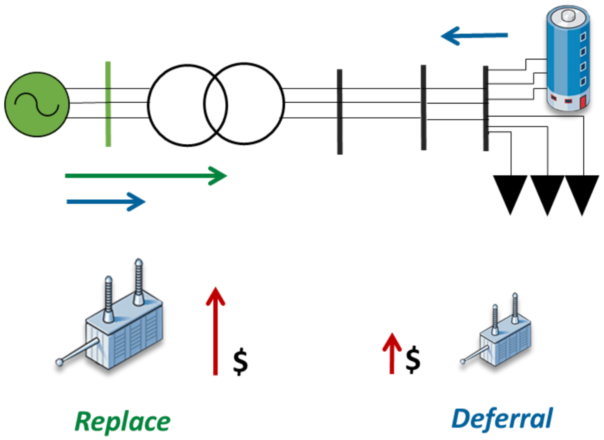
T&D Cyberattack evaluation [6]



Hosting Limit Capacity for T&D



T&D Coordination Transformer Deferral



[6] Ospina, J., Fobes, D. M., & Bent, R. (2023). On the Feasibility of Market Manipulation and Energy Storage Arbitrage via Load-Altering Attacks. *Energies*, *16*(4), 1670. url: https://www.mdpi.com/1996-1073/16/4/1670

Future Work

1. Support new **ITD formulations**

   - Relaxations
   - Approximations
   - Hybrids

2. Support **decomposition-based formulations** that allow:
   - Parallel computation of large-scale problems

3. Build **realistic** T&D datasets
   - Sufficiently large T&D networks
   - Realistic
   - Lack of reliable large distribution systems datasets* (Open-source)

4. Explore **applications** & **research (Collaborations)**
   - EVs/DERs integration and optimization studies
   - Transformer Deferral Studies
   - Cybersecurity-related studies in T&D networks

Thank you
Questions?

Contacts:

- Juan Ospina: jjospina@lanl.gov
- David M Fobes: dfobes@lanl.gov