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Electrical & Computer Engineering

Robust and Comprehensive Power Flow for Future Smart Grids

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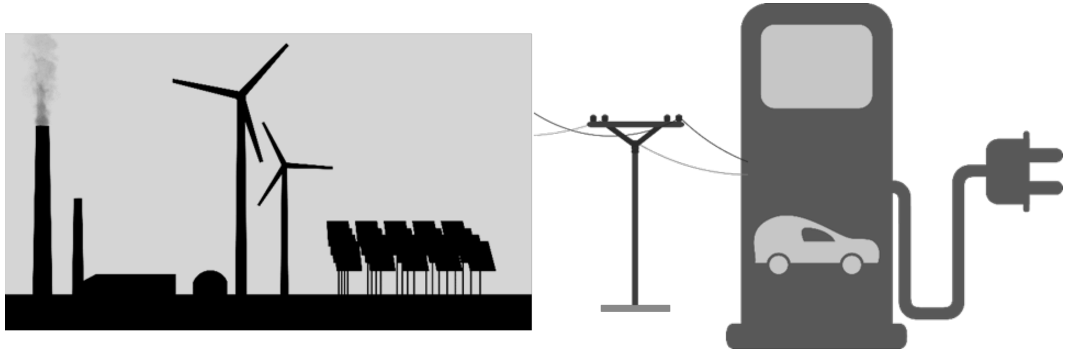
Ideal Power Flow "Simulation"

- Given a network (grid) with expected loads and some or all planned generation sources, power flow *should* always include:
  - Modeling of the generation that changes set-point to balance power
  - Changes in frequency as a function of power balance
  - Control systems that respond to power requirements and flow

- AVR
- Gov. response
- AGC
- Smart control
- Reserves
- OPF/UC



- Voltage sensitivity
- Freq. sensitivity
- Load shedding
- Smart control
- Demand response

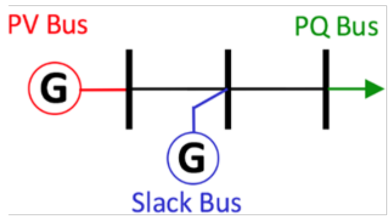
Increasing Modeling Complexity

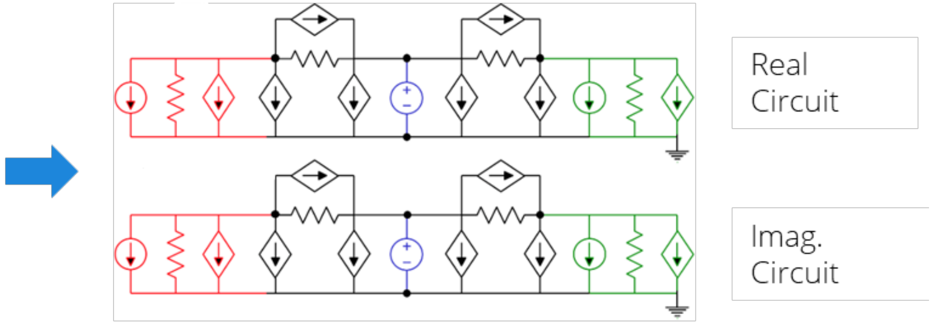
Next Generation Models and Analyses

- Abstractions used in commercial steady-state analysis tools do not fully capture grid behaviors
  - E.g., insufficient for modeling cascading failures
- Our approach is based on developing two capabilities for a more *robust and comprehensive* power flow:
  1. **Physics-based modeling and simulation**
  2. **Integrated optimization** when the most complicated modeling abstractions are incompatible with simulation

SUGAR – An Equivalent Circuit Approach

- Circuit-theoretic framework for modeling, analysis, and optimization





Split equivalent circuit with I-V variables linearized for (k+1)th Newton-Raphson iteration

- No need to separate T&D, or three-phase from positive sequence
  - Combined T&D handled naturally
- Mathematically corresponds to current-injection method
  - Circuit-formalism preserves physical intuition and enables robustness

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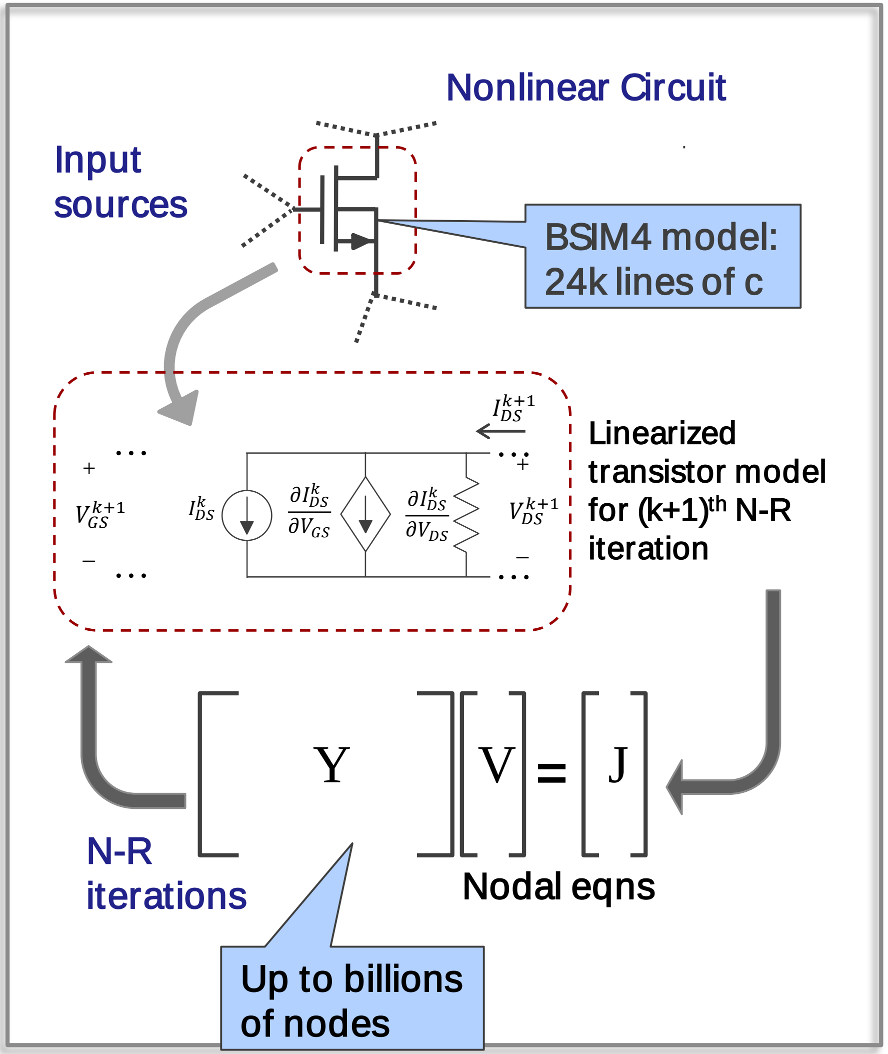
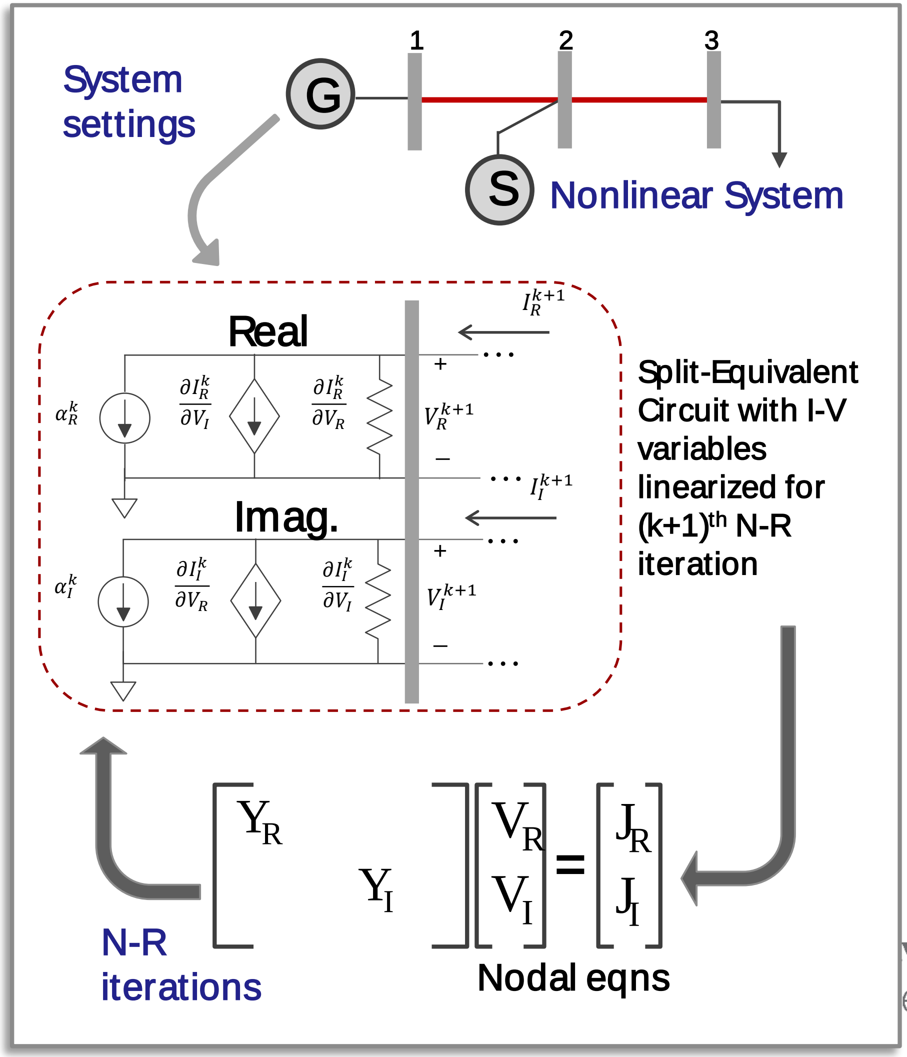
SPICE and SUGAR

Simulation Program with Integrated Circuit Emphasis



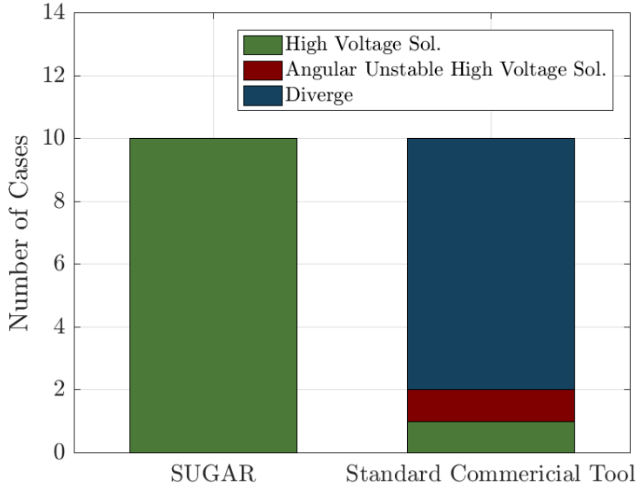
Simulation with Unified Grid Analyses and Renewables



Robust Convergence

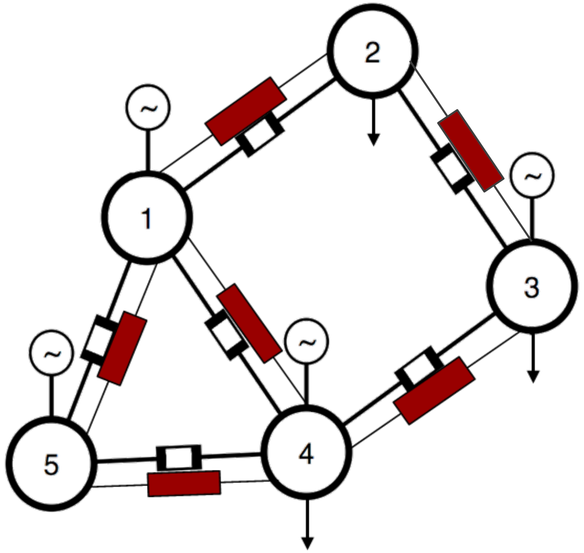
- Existing power flow tools rely heavily on 'expert' users
- Physical circuit framework can be used to guarantee convergence:
  - Limiting methods constrain the system variables in physical space
  - Homotopy methods help where limiting is insufficient

10 'Good' Initial Conditions



13k+ PEGASE Case with Limiting

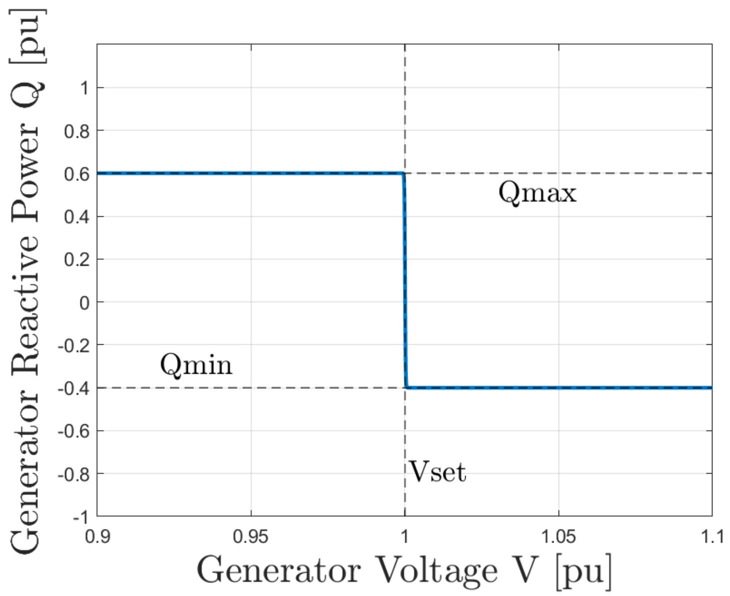
Tx-Stepping Homotopy Method



1. "Virtually short" the system initially to produce a trivial problem
2. Gradually reduce the added admittance until original problem is solved

How Much Can We Model Directly?

- Robust simulation engine facilitates more complex models
  - Control actions that are abrupt switching changes can now be modeled
- Existing approaches model such control actions as discontinuous, and can suffer from divergence or convergence to non-physical solutions
  - E.g. PV/PQ generator switching
- Future models likely to be more complex
  - Circuit formalism generalizes mapping of I-V behavior



Analytical vs. Piecewise Model for Generator

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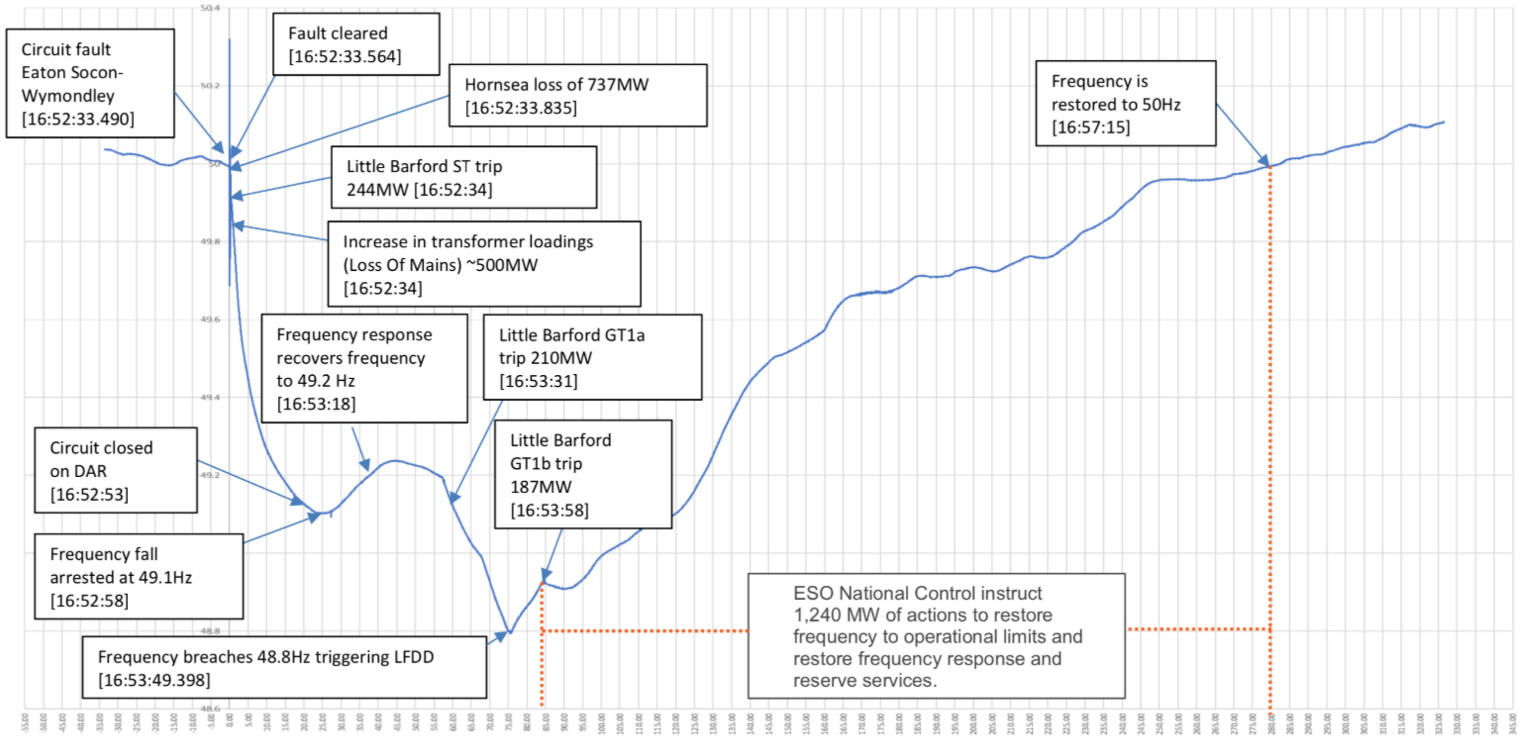
Modeling Frequency in Power Flow

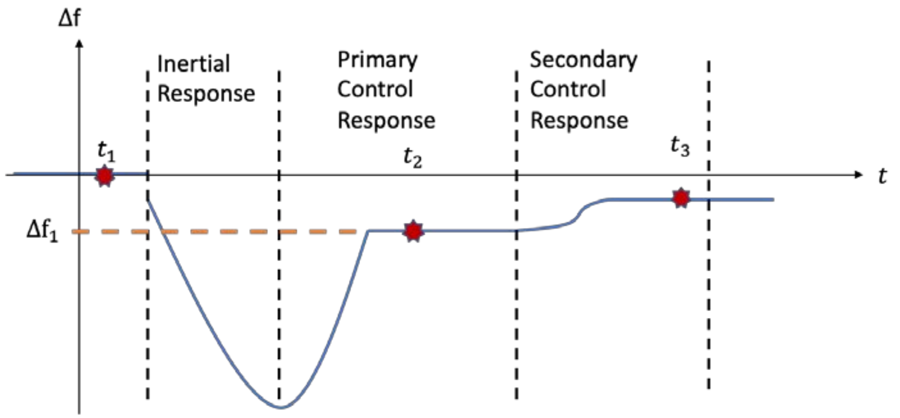
- Commercial power flow tools do not capture frequency controls
  - Needed for understanding events such as partial blackout in UK [1]

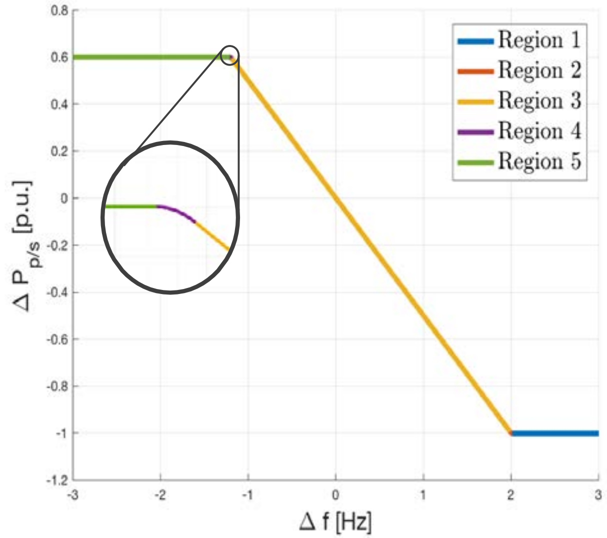


[1] National Grid ESO, "Interim Report into the Low Frequency Demand Disconnection (LFDD) following Generator Trips and Frequency Excursion on 9 Aug 2019," August 16,2019

Modeling Frequency within SUGAR

- Generator real power (P) varies with frequency (f)
  - Model primary and secondary control implicitly while respecting limits
- Other models like under-frequency load shedding (UFLS) equally critical
  - Critical for simulating events like 2019 UK grid-controlled blackout

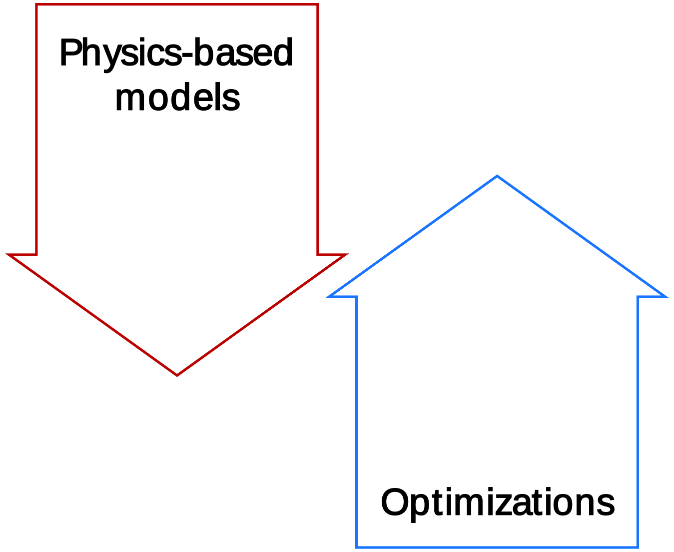




Implicit modeling of ΔP change due to Δf

Simulation or Optimization?

- Example: Cascading outage analysis requires:
  - Models that capture voltage and frequency dependence
  - Arobust engine that can simulate N-k contingency
  - Modeling of protective relaying and associated control
  - Distinguishing between stressed and collapsed state
  - Other generator and load control strategies
  - Optimizations that represent decision making
  - …



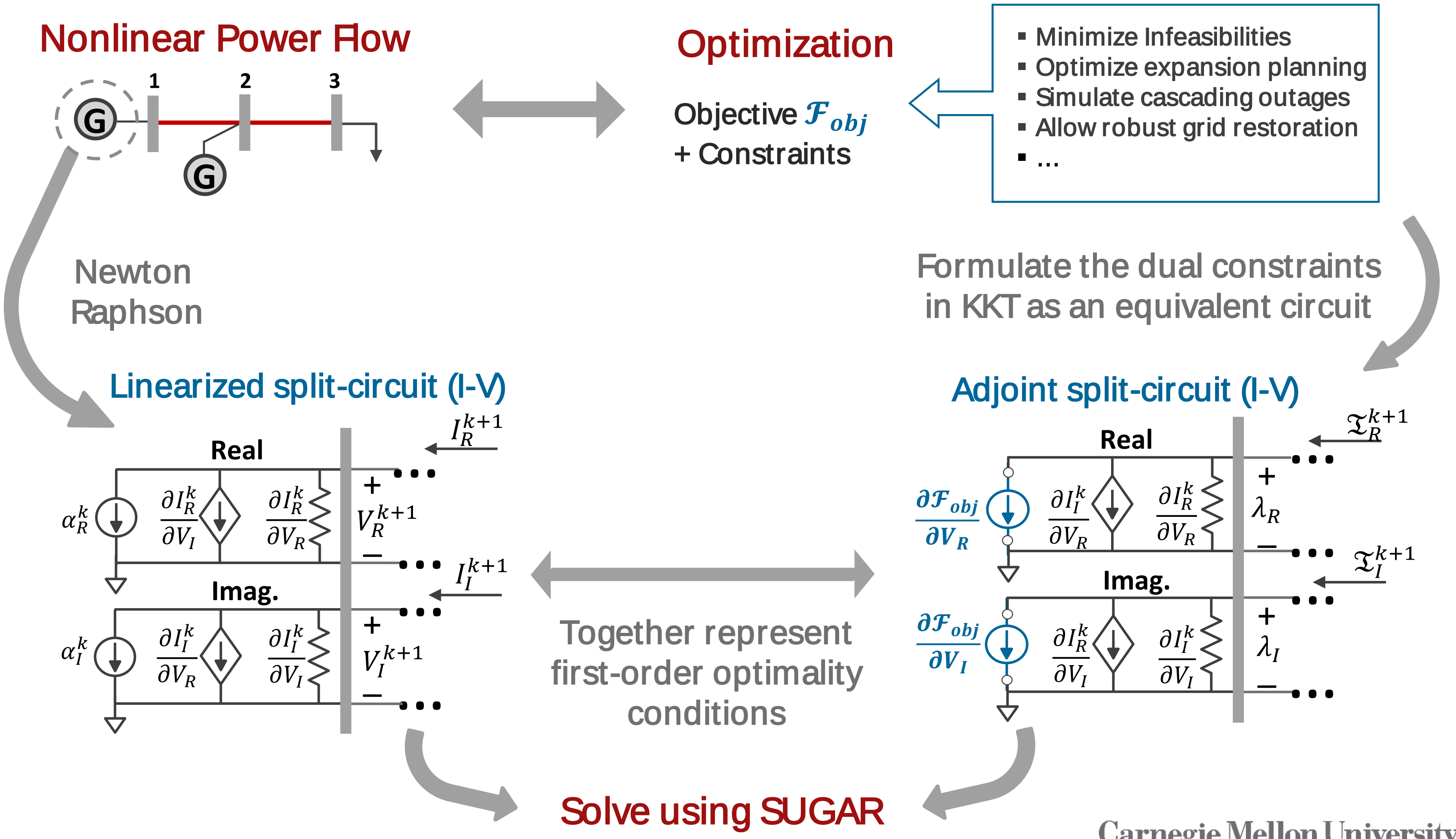
Hard-to-solve vs. Infeasible Networks

- Existing solvers cannot differentiate hard-to-solve networks from power deficient networks
- Ex.: Four difficult cases from an ISO
  - Must be able to distinguish collapsed from hard-to-solve networks

Case	#Nodes	Standard Commercial Tool[1]		SUGAR[1]	
		From Input File	From Flat Start	From Input File	From Flat Start
Hard to Solve Network 1	5944	×	×	✓	✓
Hard to Solve Network 2	7023	✓	×	✓	✓
N-1-1 Contingency 1	7029	×	×	✓	✓
N-1-1 Contingency 2	7028	×	×	✓[2]	✓[2]

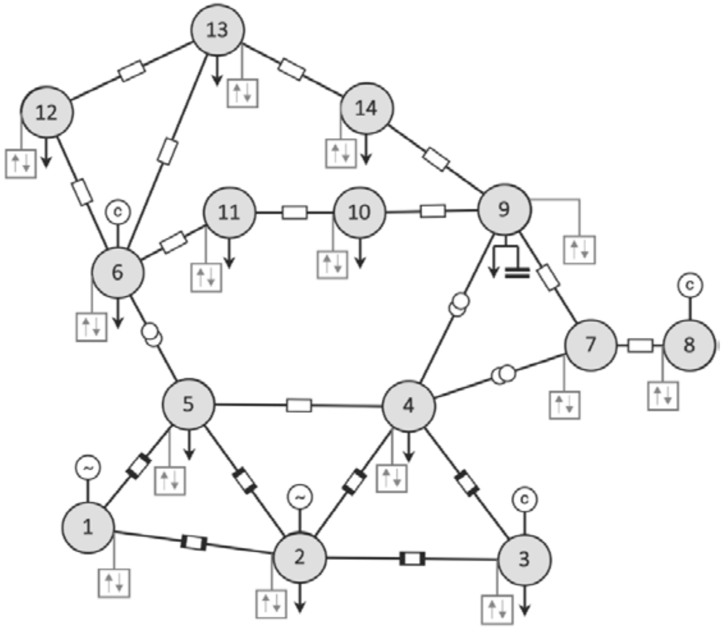
[1] Ran with default settings
[2] Infeasible solution found

Built-In Optimization



SUGAR for Infeasible Grid Networks

- Place slack sources (⍐) at all (or selected) buses
  - Minimize the injected power while satisfying network constraints



Feasible system

Source values are zero, power flow solution unchanged

Infeasible system

Nonzero injected power at buses that cause infeasibility

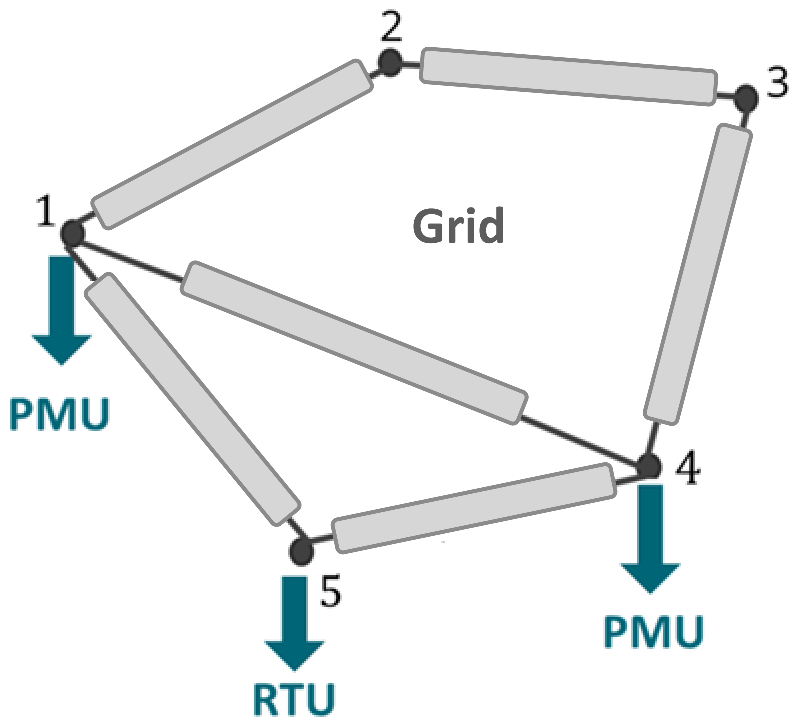
- Insufficient models to do this as a physics-based *simulation*

Incorporating Measurement Data

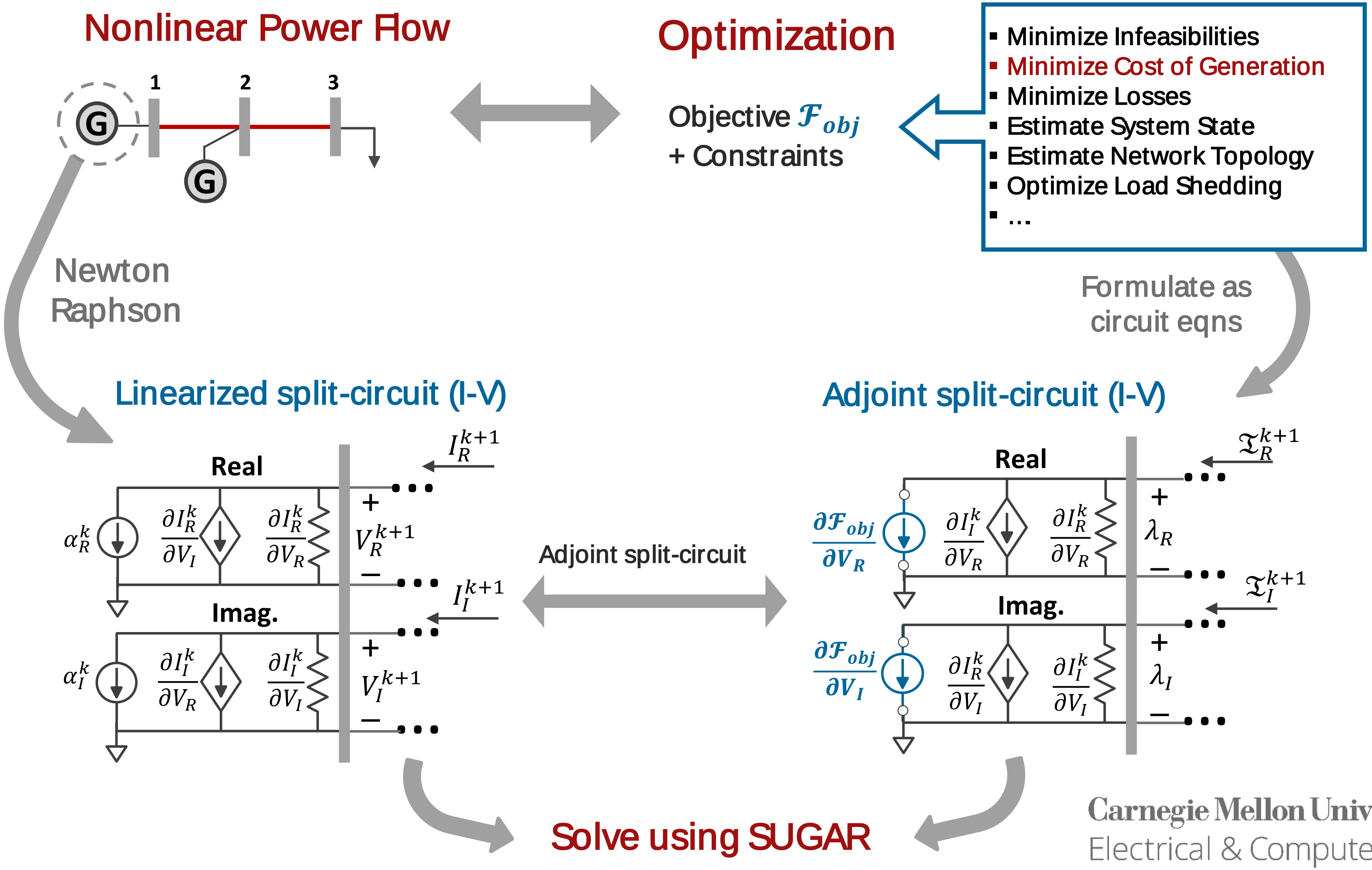
- Presently done separately as State Estimation (SE)
- SE is a mathematical abstraction that has roots in Estimation Theory
  - Does not necessarily capture complete network topology
  - Solutions dependent on accuracy of network models
- Can be naturally incorporated into equivalent circuit framework

Circuit-Theoretic SE

- Circuit Substitution Theorem:
  Replace existing models with measurement models
  - Incorporate both RTU and PMU models
- Network topology becomes represented by linear models – greatly simplifying SE
- Must be solved by optimization though, since measurement errors can otherwise violate conservation of charge/energy



More Optimization – Optimal Power Flow



Security Constrained AC-OPF

- Robust SC-OPF can result in 5-10% electricity cost reduction in the U.S.
- Non-convex optimization problem with more than a billion variables
- Equivalent circuit approach can map SC-OPF problem into an aggregated circuit
- Circuit heuristics with distributed computing robustly solves the problem
  - SUGAR is one of the top performers in ARPA-E Grid Optimization Competition – and it *includes all physics-based models*

Solving Billion-Size SC-OPF Problems

Pearl Street TECHNOLOGIES

Minimize cost of generation

- Satisfy power flow equations and operational limits

- Ensure feasibility across K contingencies

↓

N-bus Base OPF Split-Circuit

+

Contingency Split-Circuit #1 · · · Contingency Split-Circuit # k

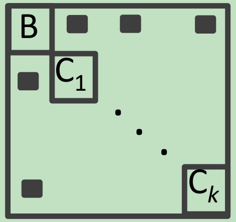
↓

Base Split-Circuit — Base **Adjoint** Split-Circuit

+

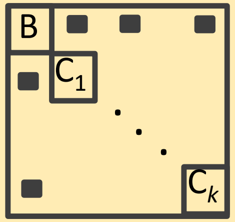
Cont. Split-Circuit #1 — Cont. **Adjoint** Split-Circuit #1 ... Cont. Split-Circuit # k — Cont. **Adjoint** Split-Circuit # k

↓ **N-R linearization**



kN x kN matrix at each iteration

→

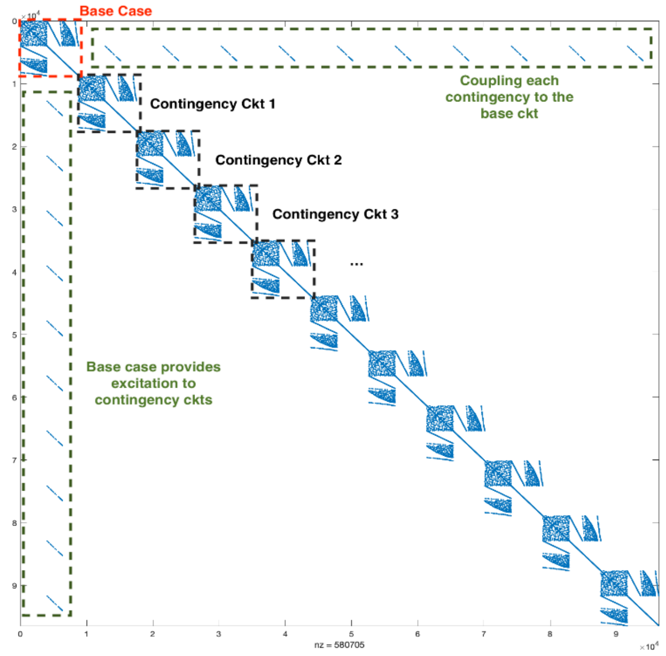


Parallel sparse LU factorization

B^*, C_1^*, ⋮, C_k^*

N-R iterations

Nonzero matrix pattern of **Security Constrained AC Optimal Power Flow Problem** solved in SUGAR



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Conclusions

- **Robust:** SUGAR can guarantee convergence for feasible and infeasible networks
- **Advanced Models:** Accommodates highly non-linear continuous analytical models
- **Accurate State Estimation:** Circuit-theoretic SE is linear yet more accurate
- **Scalable and Distributed:** Inherently parallelizable for large scale grid problems such as expansion planning

Contributors to Presentation

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