GRID MODERNIZATION INITIATIVE PEER REVIEW
Project 1.4.18: Computational Science for Grid Management

MIHAI ANITESCU, ARGONNE NATIONAL LABORATORY

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Sheraton Pentagon City – Arlington, VA

Computational Science for Grid Management

High Level Summary

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U.S. Department of Energy

Project Description

Future driven by DER, Renewable, …

(a) rapidly increasing complexity, (b) vastly increased dynamics ranges, and (c) greater uncertainty in supply and demand results in >100 times "real" time for computational analyses.

In this project, we aim to reduce this by >100x by using parallelism and new algorithms of optimization, uncertainty and dynamics.

Project Objectives

- ✓ Prototype integration of solvers for OUD for increased performance for *entire problem classes.*
- ✓ Design and Instantiate an advanced framework (AMICF) that allows 10x faster prototyping of computationally intense analyses.
- ✓ Adjust and tune open source OUD solvers to compute 100x faster by harnessing parallelism.
- ✓ Identify high value use cases for demonstrating benefits framework and solvers at scale.

Value Proposition

- ✓ Improve time-to-solution for optimization + uncertainty + dynamics (OUD) by 100x, 10x.
- ✓ All margins and reliability computations are OUD driven, would help GMI in its margin reduction and reliability increase objectives.

Example OUD Outcome

- ✓ SCACOPF – security constrained AC OPF is a required technique for computation of LMPs.
- ✓ Currently solved with sequential linearization and contingency filtering -- 4-20 active contingencies.
- ✓ Uncertainty may need hundreds – thousands active contingencies – we aim to solve them with *full nonlinearity, at scale, in real time*

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Project Team

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Project Participants and Roles

- Mihai Anitescu (ANL): PI. Task Lead 1.1 (O) Optimization and Integration.
- Cosmin Petra(LLNL): Task 1.1 Parallel optimization, automatic differentiation.
- Slaven Peles (LLNL). Task Lead 1.2 (D) Dynamics Interfaces and Solvers.
- Jean-Paul Watson (SNL). Task Lead 1.3 (U) Interfaces and support for stochastic and chance-constrained optimization paradigm.
- Russel Bent (LANL). Task 1.3 (U) Robust Formulations.
- Zhenyu (Henry) Huang (PNNL): +1. Task Lead 2.1 (A) Computation and Visualization Functions.
- Wesley Jones (NREL), Task Lead 2.2 (W): Workflow and data generation and access.

PROJECT FUNDING

Lab	FY16 $	FY17$	FY18 $
ANL	290K	50K	50K
PNNL	263K	50K	50K
NREL	157K	30K	30K
LLNL	220K	70K	70K
SNL	85K		
LANL	85K		

Industry Partners:

- PJM -- Jianzhong Tong
- NEISO -- Eugene Litvinov

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Relationship to Grid Modernization MYPP

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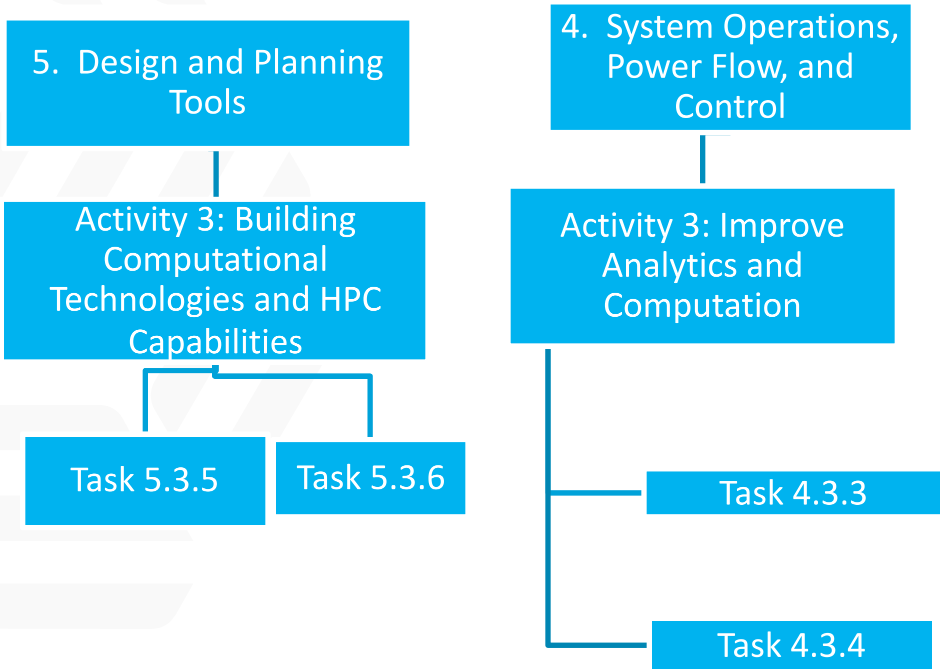
<u>MYPP Vision</u>: … develops the next generation of modeling and simulation tools needed for power system planning …. handle emerging needs driven by changing technologies and operational capabilities, larger and more complex models, more challenging forecasting (…)

- *Task 4.3.4:* Demonstrate the application of parallel and distributed computing algorithms on existing and emerging computational platforms.
- *Task 4.3.3:* Develop efficient linear, mixed-integer, and nonlinear mixed-integer optimization solution techniques customized for stochastic power system models, novel bounding schemes to use in branch and bound, and structure exploiting algorithms.
- *Task 5.3.5:* Develop and distribute advanced libraries of algorithms, solvers, uncertainty quantification, and stochastic optimization modules.
- *Task 5.3.6:* Develop computing frameworks that enable the coupling of advanced computation tools, data, and visualization technologies with easy workflow management.



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Approach

- **State of art and practice:**
  - Dynamic Simulation WECC (30s) – 2minutes. Dynamics Security Assessment needed by new dynamical content >x1000.
  - Optimization and Dynamics are done by different tools and interact by files. Factors of 100s are lost in efficiency for transient constrained analyses without derivative information.
  - SCACOPF (~ISO, estimated) 20mins-3hours: Under Uncertainty (estimated) > 100 hours. Need to get it to minutes, or < 1 hr.
- **Task 1 – *Computational Core*** Creation of an advanced computational infrastructure for OUD. (ANL, with LANL, LLNL, and SNL). *Achieve a factor of 100 speed up in key computational patterns by enabling and tuning massive parallelism*. Subtasks:
  - 1.1 Optimization and integration. Open, fast, scalable environments and solvers for scenario-based optimization. Fast, automatic differentiation for nonlinear optimization.
  - 1.2 Dynamics. Novel dynamics algorithms and interfaces, improve performance and accuracy of design outcomes by online use of transient simulations in optimization with adjoint-based derivatives.
  - 1.3 Interfaces and Support for Optimization under Uncertainty: Novel scenario generation and robust formulations. Chance-constrained stochastic multi-period optimal power flow.
- **Task 2 – *Advanced Modeling and Integration Framework (AMICF)*** Definition and reference implementation of a framework for scalable integration of data, computation, and visualization functions. (PNNL, with NREL). *Achieve a factor of 10 increase in productivity of problem formulation/instantiation.* Subtasks:
  - 2.1 Computation and Visualization Functions. Design and implement a novel, compact, flexible, open framework for maximum performance. Engage stakeholders design and adoption.
  - 2.2 Data Functions. Create renewable energy forecasts and scenarios.
- *Task 1 and 2 interact through 3 use cases defined and refined at stakeholder workshop (below).*

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Key Project Milestones

Milestone (FY16-FY18)	Status	Due Date
Middle of the road parallel runs for SCOPF with the PIPS-NLP suite using StructJuMP annotations.	100%	09/30/16
Conduct a stakeholder workshop and produce framework design document.	100%	11/23/16
Demonstrate AMICF prototype on Industry inspired use case using NREL data.	100%	3/31/17
AMICF parallel nonlinear optimization under uncertainty capability run.	100%	03/31/17
Estimation of margins reduction due to transient expression in optimization problem.	100%	03/31/17
AMICF Reference Implementation.	100%	03/31/17
AMICF Documentation.	Not Started	09/30/17
Technical Publications.	Not Started	09/30/18

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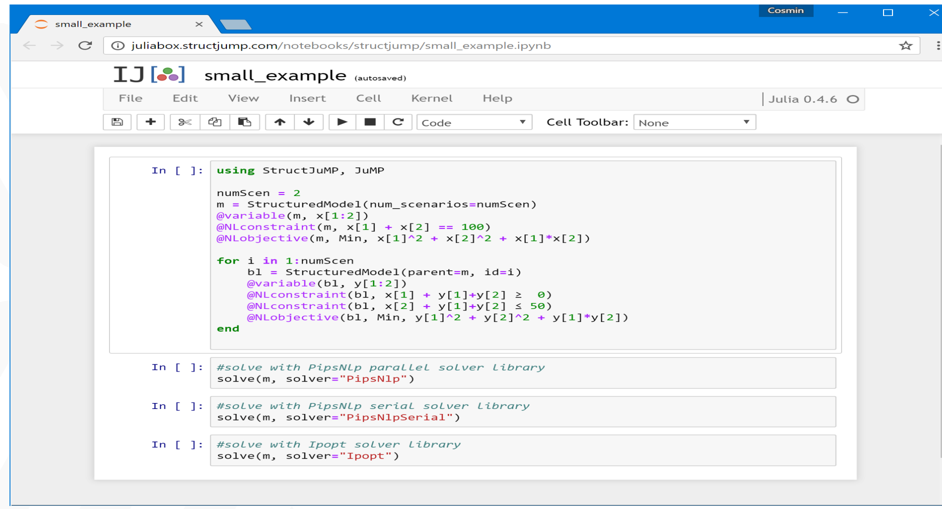
Technical Details: AMICF-StructJuMP; FY 16 Q2

- In FY16, Q4, released StructJuMP, a scalable, open, free, Julia-based Environment for massively parallel nonlinear optimization.
  - high-level, high-performance, open-source dynamic language for technical computing
  - keeps productivity of dynamic languages without giving up speed (2x of C/C++/Fortran)
  - Very efficient to extend by use of macros (@)
- StructJuMP: Algebraic modeling framework; faster derivative support for scenario-driven optimization.*
- *C -like performance with Matlab-like syntax, and full parallel support* by means of the other 1.4.18 tasks.
- It accelerates the development time by a factor of 10.
- Deployed on Amazon Cloud and clusters.



#procs	Model initiation (seconds)	Structure building (seconds)	Function & derivative evaluation (seconds)	Total time (seconds)
1	6.42	2.09	20.56	390.34
2	4.70	1.59	10.19	279.15
4	4.21	1.58	5.96	230.16
8	4.10	1.49	3.5	208.48
16	4.14	1.46	1.86	192.85
24	4.09	1.42	1.47	179.96
48	3.96	1.31	0.72	191.75

C. G. Petra, F. Qiang, M. Lubin, J. Huchette, "On efficient Hessian computation using the edge pushing algorithm in Julia",

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Accomplishments highlight: Integrated NLP-Uncertainty

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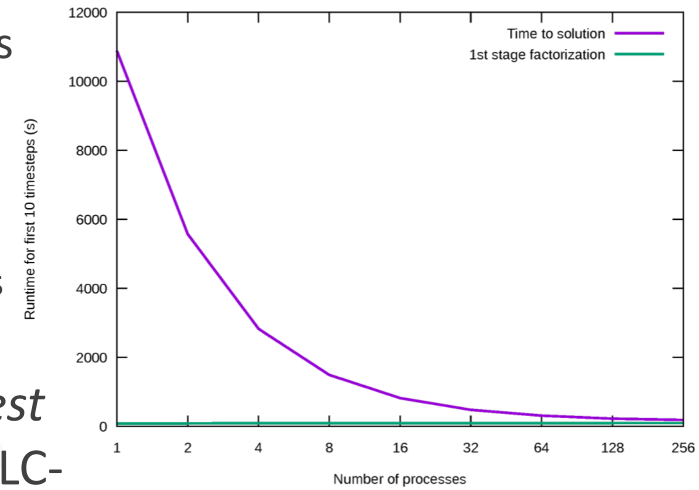
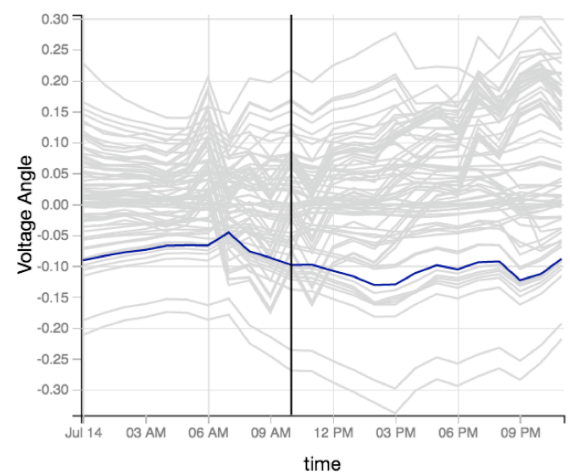
- Highest Performance Nonlinear Optimization under Uncertainty integrated with Planning Models, in the user's language (integration level ~ 80%), around *StructJuMP.*
  - Gridpack-AMICF module converts PSS/E to *StructJuMP*.
  - PIPS-NLP solver takes *StructJuMP* input and runs in parallel.
  - AMICF-Data/Viz interacts w. Planning (PLEXOS, 1.4.26); runs *StructJuMP*; and returns/displays system metrics.
- Demo capability: (a) SCACOPF Pegase, *possibly largest bus x scenario ever in under 10 minutes*; and (b) GMLC-RTS uncertainty ACOPF for computation of uncertainty-induced voltage swings, integrated w. planning.
- Pleasant surprise: Algebraic-centric StructJuMP allowed much faster integration of data/uncertainty and planning function than even we expected!
- *Can solve ANY scenario-driven nonlinear optimization at scale*.

Time to Solution



PEGASE 2869 buses 512 scenarios



GMLC-RTS model with planning integration (PLEXOS) (100 scenarios)

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Accomplishments highlight: Stakeholder Workshop

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In November 2016, conducted a stakeholder workshop and produce framework design document in Richland.

- Three use cases defined to derive solver adjustment and framework design: (UC1) SC(AC) OPF under uncertainty, (UC2) transient security assessment under uncertainty, (UC3) transient security constrained optimal power flow under uncertainty.
- Framework design document produced.
- Stakeholder workshop refined the framework requirements based on industry input
- Use cases were tweaked and "value proposition" demos recommended.
  - An increased focus on planning (see integration of StructJuMP w PLEXOS, planned multiperiod work).
  - An increased focus on representation of uncertainty from reduced distribution models.
- Participants included Lab Scientists, and 10 Industry Participants from utilities and software vendors.

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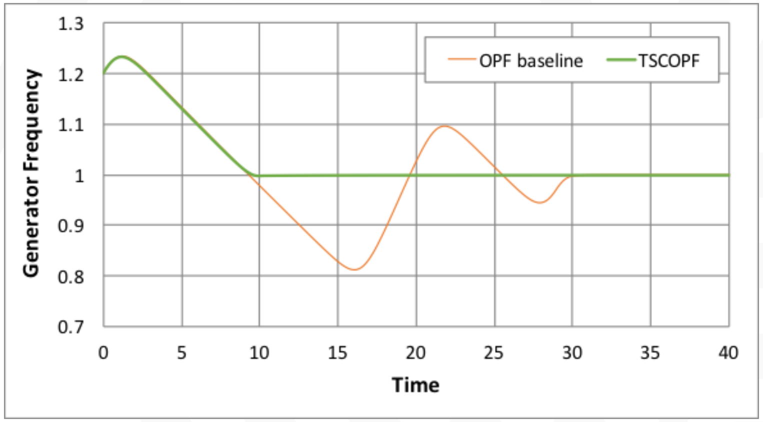
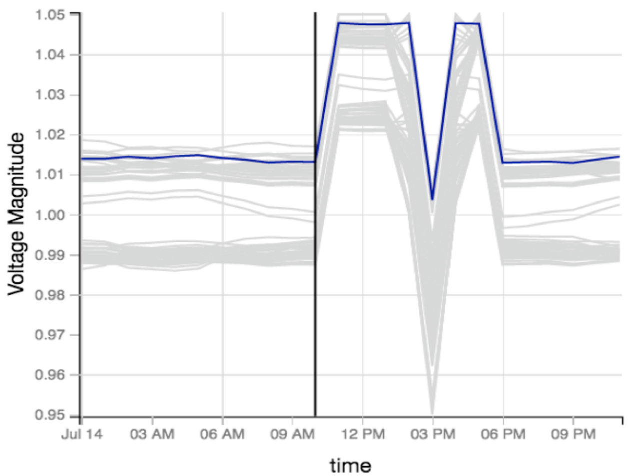
Response to December 2016 Program Review

Recommendation	Response
While DOE appreciates the scientific merit of the effort, the principal investigators need to do a better job to communicate the benefit of this work to the grid.	Demos were designed that quantify the benefits for physical quantities-of-interest, and viz tools to display relevant metrics were created.



Improvement in Generator Response from Transient-constraint optimization (v. static)



Effects of wind-power uncertainty on voltage swings; GMLC-RTS model with planning integration (PLEXOS) (100 scenarios)

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Project Integration and Collaboration

Collaborations with GMLC projects and activities

Framework Openness and flexibility has allowed us to prototype new functions in 6-8 weeks what would take ~ 10 months in C++. Coupled with the 100X speed increase and generality, it can impact several other GMLC projects.

Activities carried out:

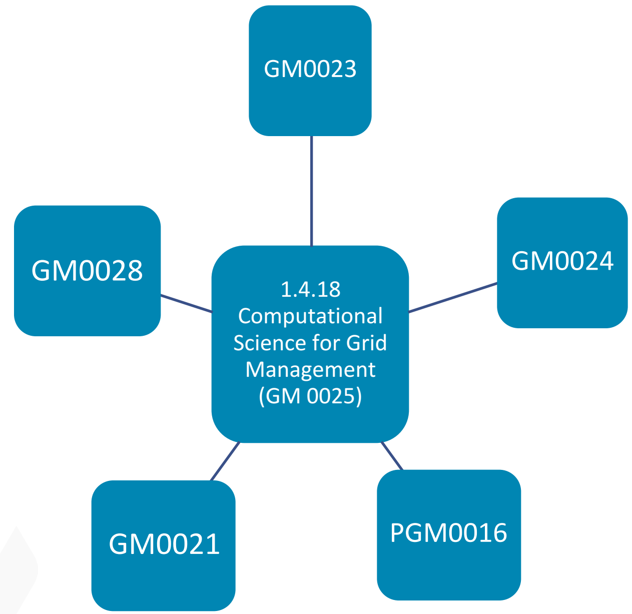
- GM0021: Control Theory: For this project we collaborate in providing new tools for optimal control accounting for transient response (Peles)
- GM0028: Development and Deployment of Multi-Scale Production Cost Models. We provide data workflow and scenario reduction tools (Watson, Jones)
- GMLC Planning and Design Team - Data and Software Working Group (Jones)

Planned/In Discussion.

- PGM0016: Midwest Interconnection Seams Study: (Jones)
- GM0023: Development of Integrated Transmission, Distribution, and Communication (TDC) Models. (Huang)
- GM0024 Extreme Event Modeling. (Bent).

Collaborations with ASCR projects and activities

- The Multifaceted Mathematics for Complex Energy Systems (MACS); GMLC focused on use case development and tuning, M2ACS on mathematical framework design and algorithms.
- The Exascale Project for Grid Optimization (ExaGrid) – massive parallel architecture solver and framework tuning.



Communications

- Stakeholder workshop (Richland, November 2016).
- The Exascale all-hands project meeting.
- The IEEE HPC working group.
- Publication: C. G. Petra, F. Qiang, M. Lubin, J. Huchette, ”On efficient Hessian computation using the edge pushing algorithm in Julia”.

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Next Steps and Future Plans

Value Demonstrations:

- Determine the optimal and safe selection of margins under realistic uncertainty while accounting for voltage effects – GMI: Reduce Margins.
- Quantify voltage swing mitigation/feasibility benefits of advanced forecasts with uncertainty – GMI: Increase Reliability.

Technical Capabilities

- Scalable **multi-period nonlinear optimization** problems under uncertainty to improve analytics for longer horizons decisions (planning) and reduced decision time scales.
- **Bi-directional functional integration** of optimization under uncertainty and dynamics with planning models.

- Tune optimization solvers for emerging massively multi-core architectures, e.g KNL.
- Extend the framework for seamless dynamic simulation and integration of dynamics and optimization, efficient adjoint computations. Tune and adjust dynamical solvers at scale.
- Formulate a cascade mitigation/response optimization problem using 1.4.17 tools and models.

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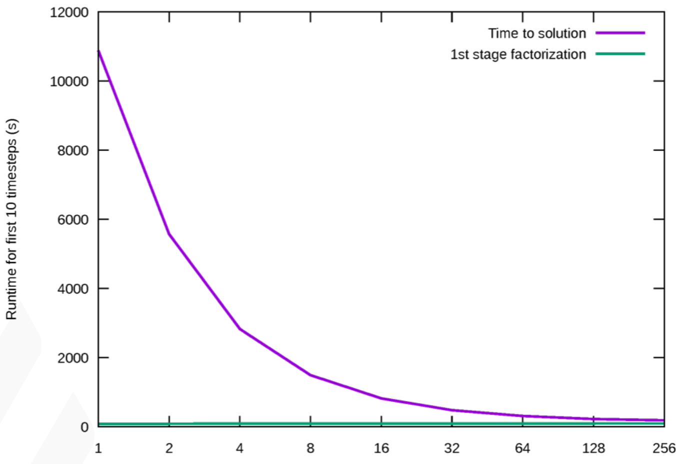
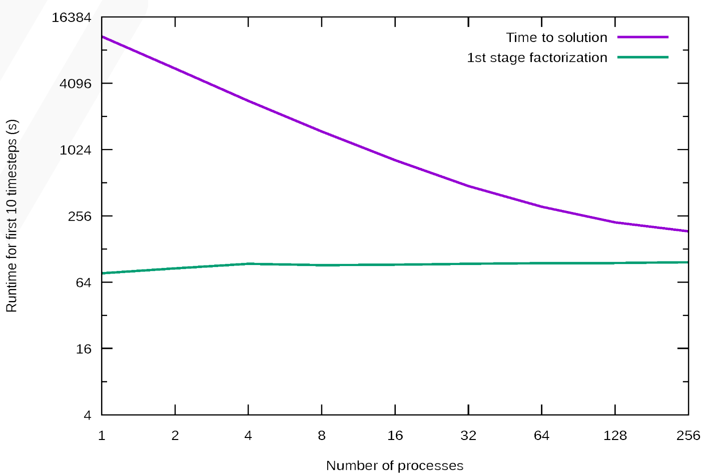
Technical Details: Optimization; FY 17 Q1

- OUU: Scenario-Based Nonlinear Optimization is a prevalent computational pattern (SCACOPF, Stochastic OPF), our Use Case 1.
- In FY17 Q1, accelerated the PIPS-NLP solver and deployed on massively parallel architecture.
- Created OUU SCOPF instantiation from PEGASE 2869 buses (MATPOWER); created 512 contingency data, in StructJuMP
- **Speedup: 63=11000/173** (s, 10 iter) on 256 cores.
- Takes about 10 minutes (35 iters) to solve at industry standard (1e-3).
- Possibly largest number of SCACOPF contingencies ever solved simultaneously (512; seen 75 on 16 cores,30).

Time to Solution



Strong Scaling Limit



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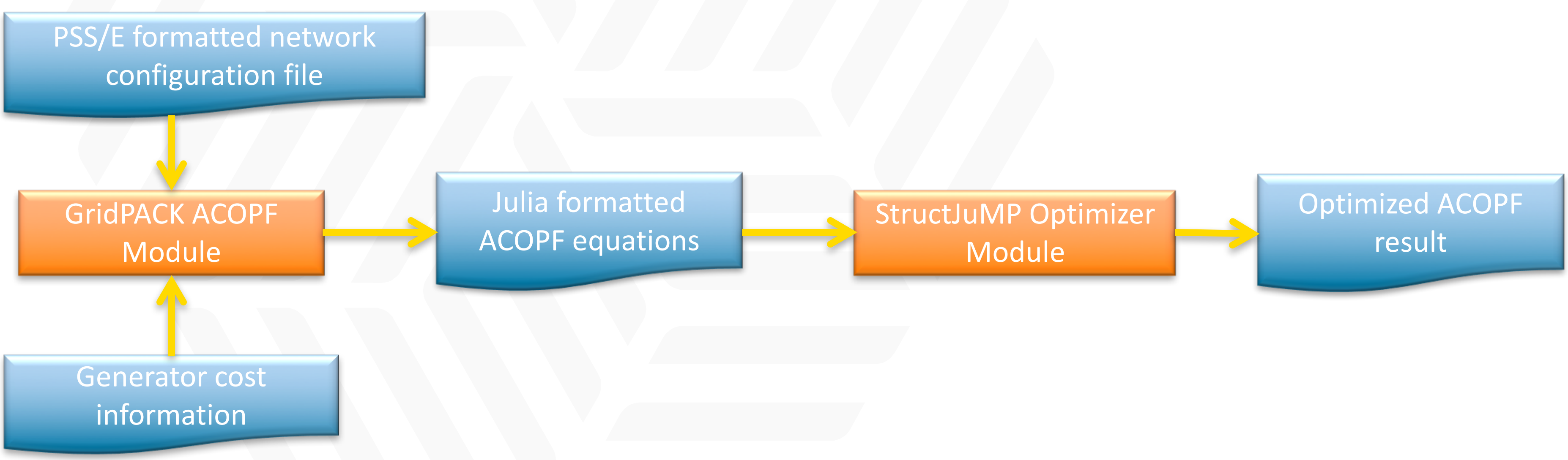
Technical Details: AMICF Computation Support; FY 17 Q1

- In Q2 FY 17, we created the novel AMICF OU framework.
- By extending GridPACK while using the Q4 FY16 Julia-based deliverable StructJuMP, users can create scalable OU instances from PSS/E input.
- The AMICF/PIPS-NLP allow (in principle) maximum performance access at scale (thousands of buses, thousands of scenarios, parallel computing), for **~0 additional development cost, and entirely open source** for OU such as SCOPF.



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Technical Details: AMICF Data Services; FY 17 Q1

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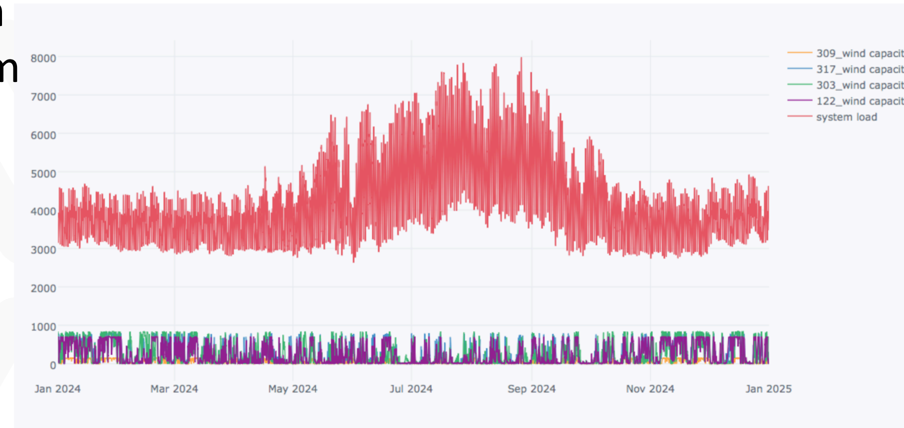
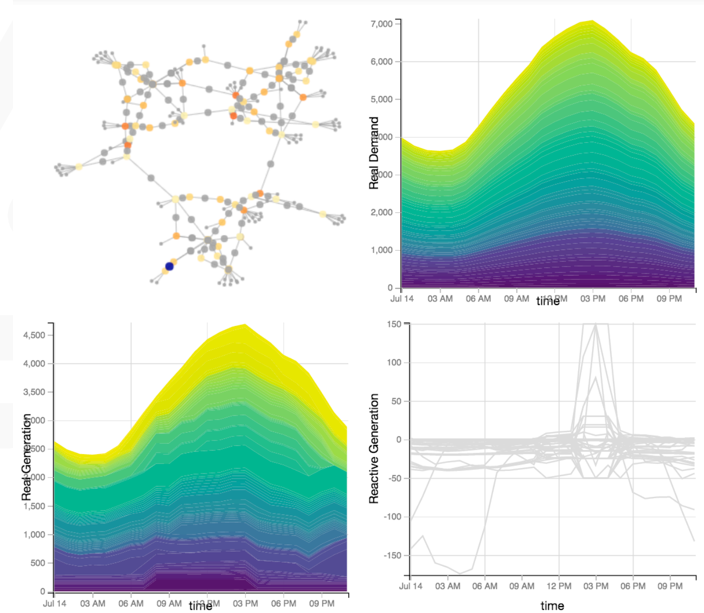
- Delivered Modules to process uncertainty in wind generators by site and time of day from NREL data, and display output.
- Integration with OU through StructJuMP Stochastic ACOPF modeling/solver.
- Integration of Production Cost Modeling (PCM: PLEXOS) with Day-Ahead unit commitment to inform 5-minute economic dispatch.
- An HPC and Cloud ready interface for execution of workflow
- Demo: updated **GMLC-RTS system** with 73 buses, 96 thermal generators, and 4 wind plants.
- Ready to answer optimal margin selection under wind uncertainty, and voltage swing/limit questions, in an operations/planning context.





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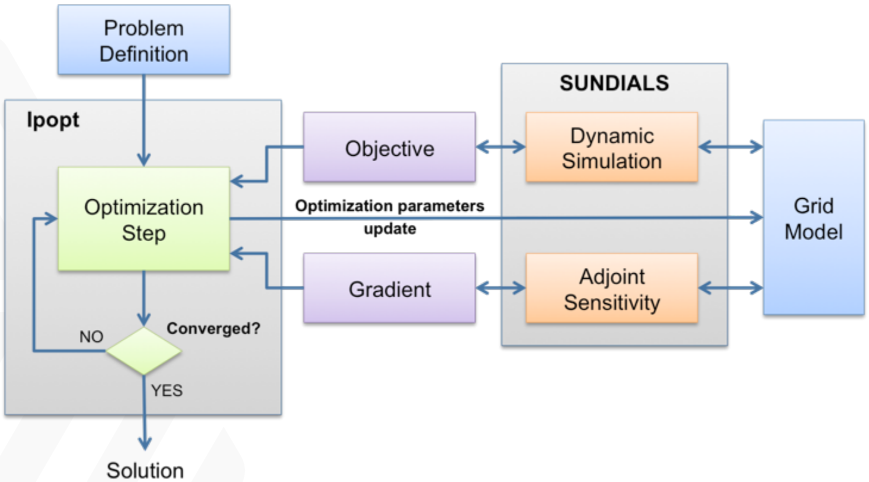
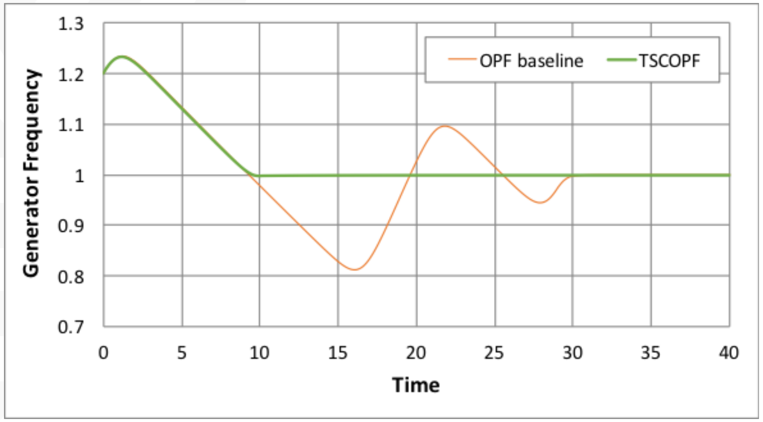
Technical Details: Dynamics; FY 17 Q1

- In current practice, optimal design in power grid does not directly account for transient performance.
- This results in higher margins and/or decreased reliability.
- Use Case 3: Optimization under Dynamics and Uncertainty, aims to cover this gap.
- In FY17 Q2, we have developed an integrated Transient Constrained Optimization approach (top figure).
- It results in far improved governor control parameter selection (bottom figure).





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Technical Details: Optimization/UQ; FY 17 Q1

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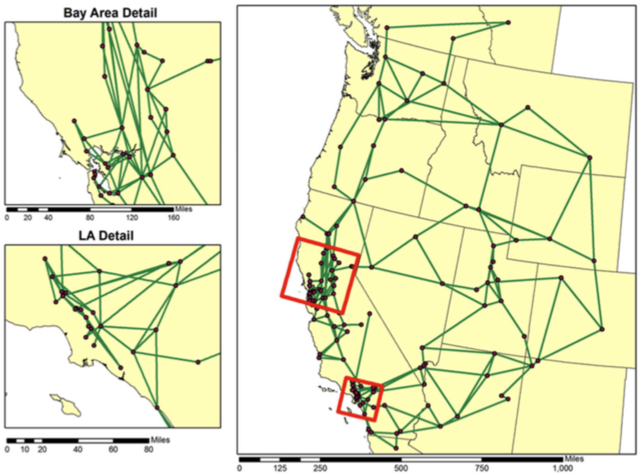
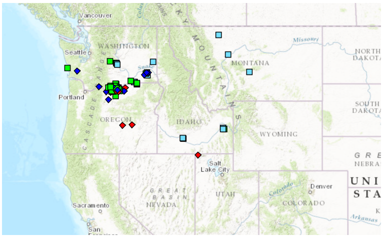
Multi-period OPF with wind: Chance-constraints and stochastic programming approaches

- Developed data needs and software API for modeling multi-period OPF with uncertain wind production that supports
  - Chance constrained OPF
  - Two-stage stochastic programming OPF
- Computational Framework
  - OPF models implemented in JuMP (Julia) and Pyomo (Python)
  - Open source
  - Ready for integration with Computational Framework under development by PNNL.
- Case Study Demonstration
  - WECC 240 System
  - Wind data from BPA: actuals and forecast
  - Compare the results and computational performance of Chance constraint modeling and stochastic programming modeling.





Appendix: Industry Technical Contacts

Participated with the 1.4.18 team at the two-day Frameworks Workshop Nov 9-10

Name	Organization
Ting Chan	Global Energy Interconnection Research Institute North America
Kwok Cheung	General Electric
Eugene Litvinov	ISO New England
Guangyi Liu	Global Energy Interconnection Research Institute North America
Teems Lovett	United Technologies Research Center
David Sun	Glarus Group
Fengyu Wang	Midcontinent Independent System Operator
Zhiwei Wang	Global Energy Interconnection Research Institute North America
Lei Wang	PowerTech Labs
Jun Wen	Southern California Edison