GRID MODERNIZATION LABORATORY CONSORTIUM
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Use Case 3: Optimization under Uncertainty with Transient Security Constraints

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Context/Need: In current practice, controls for power generators governed by optimal power flow determine set point levels of assets. Levels are determined based on economic considerations where the mathematics of the formulation are deterministic, do not include inertia of the rotating elements and may not include consideration of failure of assets in real time operation. As renewable energy sources augment and replace traditional assets, uncertainty in production will become an element that must be addressed. In addition, loss of traditional rotating inertia will require both its consideration in the optimization and its inclusion in contingency analysis to ensure non-steady-state excursions during contingency events do not affect the stability of the grid. This defines an emerging need to consider uncertainty, dynamics, contingency and AC physics together in the real time to enable large penetrations of renewable energy without affecting grid stability or higher cost via larger reserves and is addressed with Optimization under Uncertainty with Transient Security Constraints. In the absence of uncertainty, solutions to the transient security constrained optimal power flow have been proposed in the past though have generally been demonstrated for small systems [1],[2],[3].

Problem: Minimize objective (cost, distance to allowable boundary) while maintaining transient security of the system under a set of prescribed contingencies and under uncertainty in load, generation, or other parameters.

Applicability:

- Preventive rescheduling of power systems subject to stability constraints for contingencies and uncertainty in load/generation (extension of [1]).
- Stability constrained interchange limits under renewable energy uncertainty (extension of [4]).
- Determination of optimal reserve margins on the renewable energy uncertainty in operations while considering transient security.

Mathematical representation:

$$\min_{\{x\},\{y_i\},\{u_i\}} \frac{1}{S}\sum_{i=1}^{S} h(x,y_i,u_i,\omega_i)$$
$$0 = f_a(x,y_i,u_i,\omega_i)$$
$$g(x,y_i,u_i,\omega_i) \le 0$$
$$R(x,y_i,u_i,\omega_i) = TRUE$$

where transient security constraints hold; $R(x,y_i,u_i,\omega_i) = TRUE \Leftrightarrow$

$$\forall c \in \mathcal{C}: \begin{cases} \int_0^{T_j} \psi_j(x^c(t),y^c(t)) \le a_j, \forall j \in \mathcal{J}_c \\ \psi_i(x^c(t),y^c(t)) \le a_i, \forall i \in \mathcal{I}_c, t \le T_j \end{cases} : \begin{cases} \frac{dx^c}{dt} = f_d^c(x^c,y^c;u_i,\omega_i) \\ 0 = f_a^c(x^c,y^c;u_i,\omega_i) \\ x^c(0) = x_i \end{cases}$$

States, Controls, Indices:

i – scenario index

x_i, y_i - dispatchable and algebraic variables (e.g. generation levels, flows)

u_i - forcing terms (e.g generation levels, load levels)

ω_i, S: uncertainty scenarios and their total number. (e.g renewable load/generation outcome)

Functions:

h(): cost function; (e.g production cost)

f_a - function describing algebraic constraints (e.g. Kirchhoff laws)

g – path (nominal) inequality constraints (e.g ACOPF voltage limits)

ψ_i, ψ_j: functions describing transient system restrictions (e.g voltage or frequency limits).

$\mathcal{C}$:contingency index set (e.g N-1)

f_d^c, f_a^c: dynamic /algebraic contingency evolution (e,g. swing equations with topology change and Kirchoff)

Data Needs: uncertainty scenario data ω_i; cost function h() parameters/forecasts ; system steady-state and transient constraint and evolution functions, both for economics layer (PF) f_a and transients f_d^c, f_a^c: (including generator parameters for e.g swing equation) ; post-contingency limit requirement functions ψ_i, ψ_j (post-contingency voltage and frequency limit functions).

Challenges: Scalability and Accuracy of the Framework/Evaluation and Computation. Details: Efficient Expression/Computation of the Model with/for Nonlinearity (Gradients/Hessians); Fast Transient Simulation Requirements; Memory Limitations of Direct Transcription; Cost of computation of adjoint capability for transient constraints.

References:

[1] Nguyen, Tony B., and M. A. Pai. "Dynamic security-constrained rescheduling of power systems using trajectory sensitivities." *IEEE Transactions on Power Systems* 18.2 (2003): 848-854.

[2] Xia, Y., K. W. Chan, and M. Liu. "Direct nonlinear primal-dual interior-point method for transient stability constrained optimal power flow." IEE Proceedings-Generation, Transmission and Distribution 152.1 (2005): 11-16.

[3] Gan, Deqiang, Robert J. Thomas, and Ray D. Zimmerman. "Stability-constrained optimal power flow." IEEE Transactions on Power Systems 15.2 (2000): 535-540.

[4] Sauer, P. W., K. D. Demaree, and M. A. Pai. "Stability limited load supply and interchange capability." IEEE transactions on power apparatus and systems 11 (1983): 3637-3643.