Solving Optimal Power Flow (OPF) Problems Using the KNITRO Nonlinear Optimizer

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with

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Outline

- Background on KNITRO
- Optimal Power Flow (OPF) Background
- Security Constrained OPF (SCOPF) using the Integrated Power System Optimizer (IPSO)
- Results From a Real Example
- Summary

KNITRO Overview

KNITRO Overview

General purpose optimization software package:

- Unconstrained problems
- Bound constrained problems
- Equality constrained problems
- Linear programs
- Quadratic programs
- *General continuous nonlinear optimization problems*

min f(x)

s.t. h(x) = 0

g(x) >= 0

Coming soon...

- MPECs
- Multi-start global

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KNITRO Overview

- Motivation

  Diversity of nonlinear optimization problems requires diversity of algorithms/features

- Key Features

  Interior-point and Active-set algorithms

  Iterative and Direct approaches

  1st and 2nd derivative options

  Feasible/honor bounds options

  Adaptive techniques

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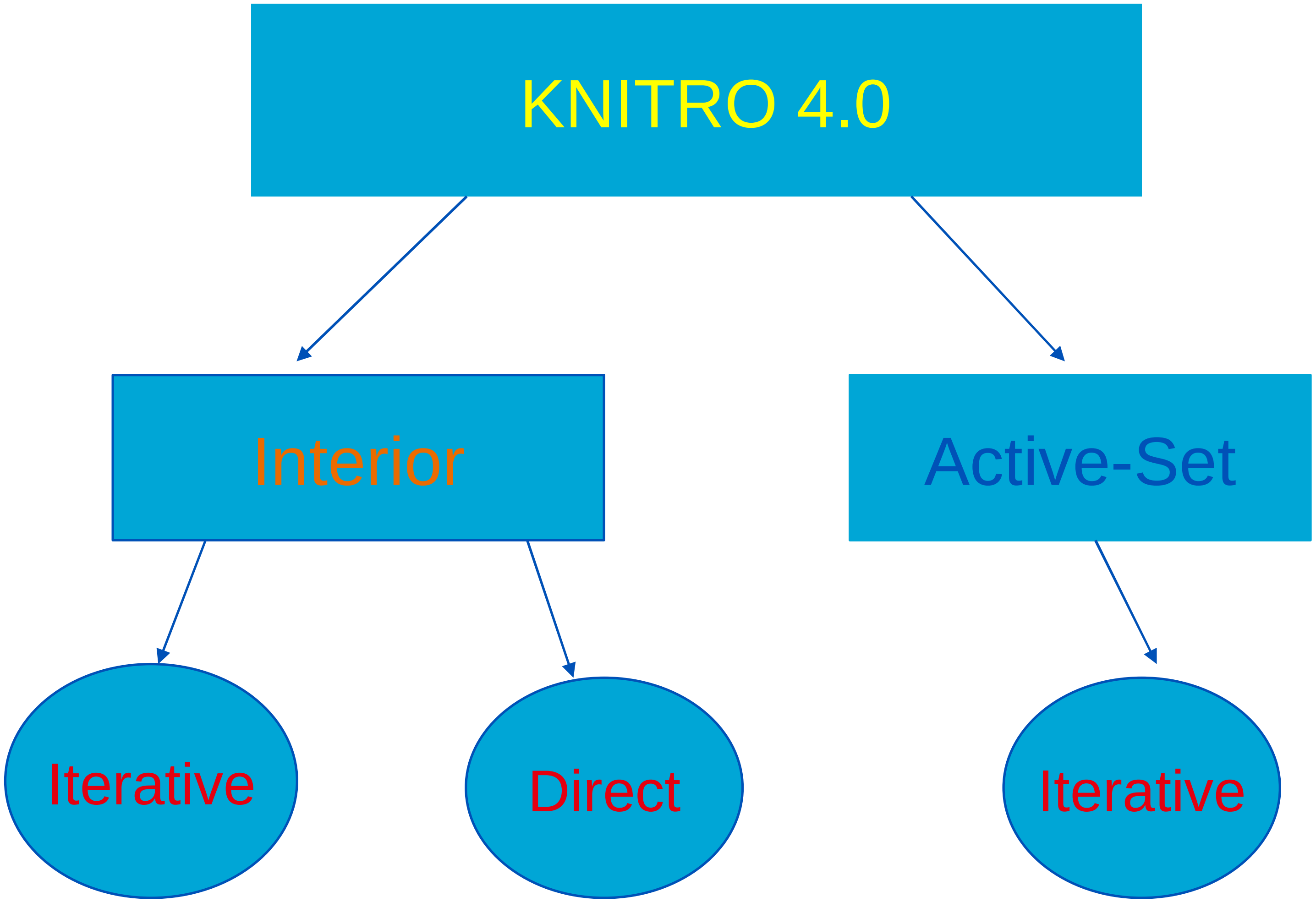
KNITRO Overview



Byrd, Waltz, Nocedal 2004

SLQP

KNITRO Overview

- KNITRO-Interior/CG:
  - Interior-point iterative approach
  - Good for large problems with dense Hessians
- KNITRO-Interior/Direct
  - Interior-point direct approach
  - Good for large ill-conditioned problems
- KNITRO-Active
  - SLQP active-set approach
  - Good for infeasibility detection and warm start

How to effectively integrate these different algorithms?

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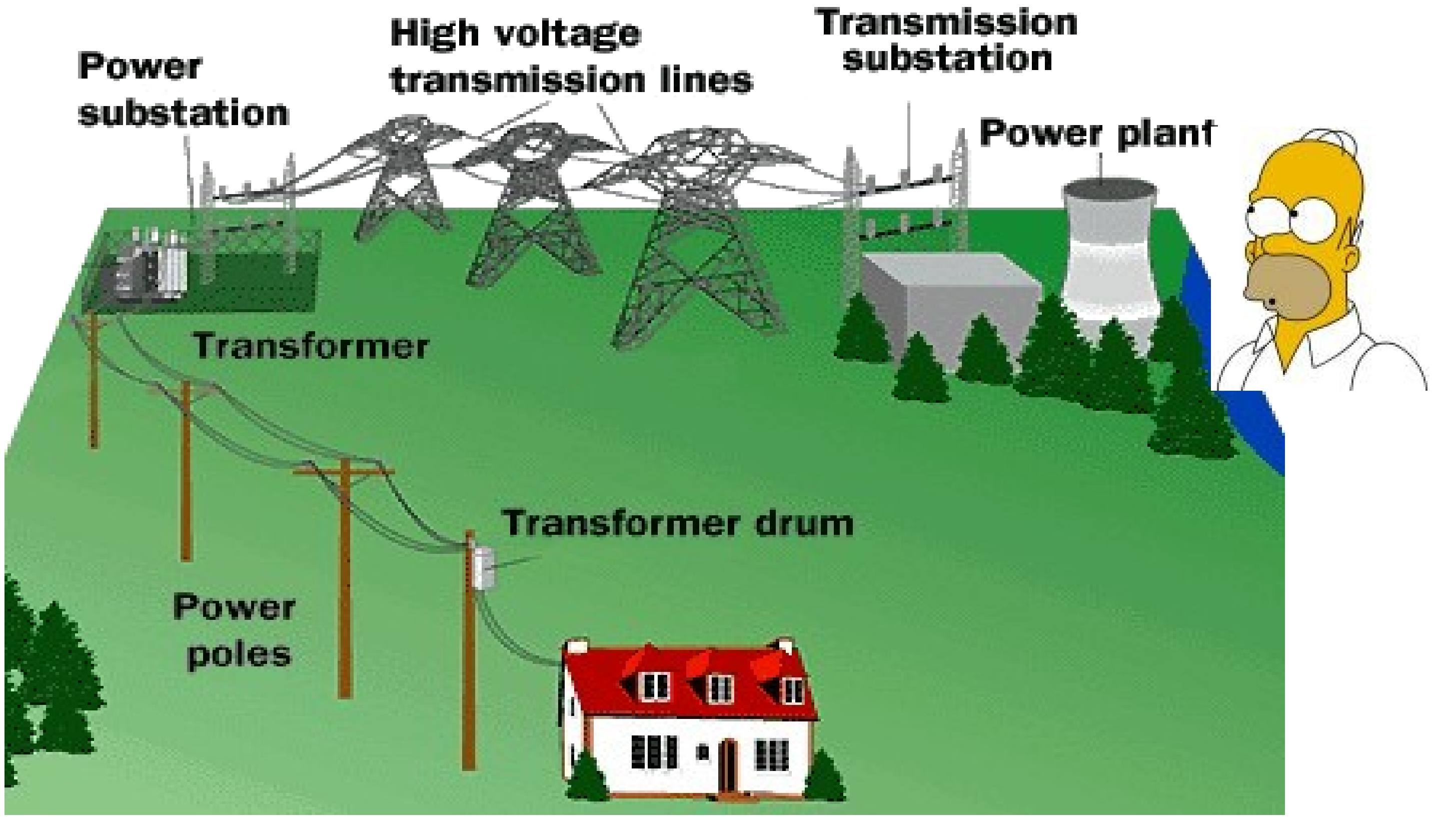
Industrial Applications of KNITRO

- Automotive/aerospace design
- Portfolio optimization
- Circuit design
- Medical applications (e.g. Imaging)
- Energy: oil, *power systems*

OPTIMAL POWER FLOW (OPF) Background

Electricity Transmission System Overview



Optimal Power Flow : Problem Definition

$$\min f(x,u)$$

$$s.t.\begin{cases} g(x,u)=0 \\ h(x,u)\leq 0 \\ a\leq x,u\leq b \end{cases}$$

- An Optimal Power Flow problem can be expressed as a classical mathematical program
- ***x*** and ***u*** represents respectively the states and controls variables

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Optimization Variables

- States Variables : Voltage magnitude & Voltage angle

- Control Variables :
  - Active & Reactive Power of Generation Units
    - > **Active** power: power for end-use consumption
    - > **Re-active** power: power produced for maintaining the system and ensuring steady voltage
  - Capacitor/Reactor Banks Steps
  - Load Shedding Ratio
  - Transformers Taps

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Functions

- Most of the constraints represents the operational constraints or the automatic response of the power system

- Most of the objective functions represents economical or security aims

- These functions are nonlinear. Most of them involve trigonometric expressions

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Main Constraints

- Kirchoff relations on active & reactive parts of the power
- Flow on Individual Branches
- Bounds on State & Control Variables
- Import/Export limits between areas (countries for instance)

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Main Objective Functions

- Power Loss Minimization
- Production/Importation Economic Dispatch
- Production/Load Shedding Economic Dispatch
- Voltage Maximization

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Security Constrained Optimal Power Flow (SCOPF)

Description of IPSO

IPSO 1.3 : OPF under Security Constraints

- Main Ideas :
  - Obtain an optimal solution for normal state
  - While computing feasible solutions for contingency states
  - Embedded in the same mathematical problem

- Normal operation steady state
  - The set of equality and inequality constraints (called **transmission constraints**) necessary to model this state are satisfied.

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IPSO 1.3 : Security strategies

- **Corrective secure steady state** with regard to a set **K** of contingencies

  The set of normal operation constraints are satisfied

  If a contingency belonging to the set **K** occurs, the new network steady state must be such that within a short time period t_{rest} (called restoration time), it can be shifted by means of controls from a possibly violated network state back to a normal operation steady state.

- The **preventive secure steady state** is a particular case of the corrective secure steady state (for $t_{rest} = 0$).

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IPSO 1.3 : Modeling

Minimize: $\boldsymbol{f^0(x^0,u^0,x^k,u^k)}$

Subject to equality and

inequality constraints:

$\boldsymbol{g^0(x^0,u^0) = 0}$

$\boldsymbol{h^0}_{min} <= \boldsymbol{h^0(x^0,u^0)} <= \boldsymbol{h^0}_{max}$

$\boldsymbol{g^k(x^k,u^k) = 0} \qquad k \in \mathbf{K}$

$\boldsymbol{h^k}_{min} <= \boldsymbol{h^k(x^k,u^k)} <= \boldsymbol{h^k}_{max}$

$-t^k_{rest}[\Delta \boldsymbol{u}/\Delta t]_{max} <= \boldsymbol{u}^k - (\boldsymbol{u}^0 + \Delta \boldsymbol{u}^k) <= t^k_{rest}[\Delta \boldsymbol{u}/\Delta t]_{max}$

- $\boldsymbol{x}^0,\boldsymbol{u}^0,\boldsymbol{x}^k,\boldsymbol{u}^k$: state and control variables in pre- and post-contingency *k* network.
- $\Delta \boldsymbol{u}^k$: change in control variables due to response of power system automatic control.
- $[\Delta \boldsymbol{u}/\Delta t]_{max}$: maximum allowable rate of change of control variables.

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IPSO 1.3 : A real-life application

Maximizing Transfer Capability between France and Belgium (compute TTC)

$$f(x,u) = -\sum_{i,j \in T} P_{i,j}(x,u)$$

T: set of branches

$P_{i,j}$: active power on branch from bus *i* to bus *j*

- **IPSO with KNITRO (Interior/CG, exact gradients, FD Hessian approx)**
- **One normal state, N-1 post-contingency networks represented by the loss of a branch.**
- **About 2300 buses, 4600 branches, 48000 constraints and 46000 variables.**

	without contingencies	with contingencies
TTP (MW)	2906	2000
Time (sec)	~3	~40

Intel P4

3.2 GHz

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IPSO 1.3 : A real-life application (larger example)

Maximizing Transfer Capability between France and Belgium (compute TTC)

$$f(x,u) = -\sum_{i,j \in T} P_{i,j}(x,u)$$

T: set of branches

$P_{i,j}$: active power on branch from bus *i* to bus *j*

- **IPSO with KNITRO (Interior/CG, exact gradients, FD Hessian approx)**
- **One normal state, N-1 post-contingency networks represented by the loss of a branch.**
- **About 98000 constraints and 89000 variables.**
- **Solves in about 80 seconds on Intel P4, 3.2 GHz machine.**

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KNITRO info: Interfaces/Partners

- AMPL
- GAMS (beta release, official release coming soon)
- Frontline Systems (Excel interface)
- NEOS (free version used via internet)
- Tomlab (Matlab interface)
- Callable library (C/C++/Fortran API)
  Artelys (Europe) www.artelys.com
  Ziena (US and non-Europe)

www.ziena.com/knitro.html (student version)

www.ece.northwestern.edu/~rwaltz

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